# Groundwater dynamics, source and hydrochemical processes inferred from existing Otago Regional age and hydrochemistry data

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**GNS Science Report 2023/54**
**July 2024**

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## BIBLIOGRAPHIC REFERENCE

Moreau M, Coble MA, Clark GM, Morgenstern U, Houghton KM, Levy A, Anderson M, Ettema M. 2024. Groundwater dynamics, source and hydrochemical processes inferred from existing Otago Regional age and chemistry data. Lower Hutt (NZ): GNS Science. 67 p. (GNS Science report; 2023/54). https://doi.org/10.21420/FAGX-H847

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ISSN 2350-3424 (online)
ISBN 978-1-99-101350-7 (online)

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GNS SR2023-54_March2023_analyses.xlsx

GNS SR2023-54_Data_Output.xlsx

# ABSTRACT

This study aims to holistically describe the flow sources, pathways and lag times of water through the rivers and aquifers of the Otago region catchments. It brings together geochemical data from shallow and deep groundwater sources, providing an update to the last regional synthesis undertaken in 2001. This information is required to ground truth and improve groundwater flow models and management tools. This study was funded through the Ministry of Business, Innovation and Employment's (MBIE) Endeavour programme, Te Whakaheke o Te Wai, the Strategic Science Investment Fund National Groundwater Monitoring Programme and an Envirolink Medium Advice Grant.

Groundwater chemistry and age tracer data were assembled from a range of sources: (1) data from the National Groundwater Monitoring Programme, hosted by GNS Science, (2) Otago Regional Council's (ORC) regional datasets (State of the Environment monitoring and specific site investigations), (3) existing data from the Water Dating laboratory and (4) water samples collected in March 2023 as part of this study. The aggregated dataset consists of 281 sites and spans the period 1985–2024. The environmental tracer data (age tracers, stable isotopes, temperature, gas concentration and chemistry) were combined and interpreted using graphical analysis (e.g. Piper diagrams), spatial analysis and multivariate statistics. These analyses inform the characterisation of groundwater flow and hydrochemical processes for Otago's aquifers.

Otago's groundwater resources consist of distinct aquifer systems comprising Quaternary sediments, Tertiary sediments, volcanics and pre-Cretaceous fractured hard rock. Groundwater is generally of low total dissolved content and mostly of calcium-carbonate water type with strong distinctive features between aquifers, likely to reflect lithological differences. Short to long residence times (<10 to over 100 years) are typical even at shallow depths, and reducing conditions are prevalent in older waters. Longer residence times lead to increased water-rock interaction and, therefore, higher total dissolved content. Nitrate concentration hotspots in groundwater occur throughout the region and are often associated with high-intensity land use and septic tanks. Some of the highest concentrations occur in older groundwater (>30 years). Groundwater quality long-term trends were detected in multiple aquifer systems (e.g. freshening in Wakatipu; increasing nitrate concentrations in Oamaru).

Rivers and streams are hydraulically connected to shallow, unconfined groundwater systems in the region, however, strong local spatial controls affect this connectivity. This is reflected in the wide range of estimated recharge rates from low (0.5 m/yr for rainfall recharge to 1 m/yr for river/lake-recharge). Groundwater recharge rates or storage could not be assessed for the deeper, confined aquifers due to insufficient data.

Recommendations to address data gaps, and consolidate the existing quality and quantity monitoring networks include:

1. Triaging the current groundwater quality monitoring network into a Surveillance and Evaluative framework. This will support a review of national groundwater quality monitoring programmes to enhance regional to national representativeness.
2. Options to resolve data gaps on a system-by-system basis, complemented by regular synoptic surveys.
3. Refinement of the national hydrogeological map.

## KEYWORDS

Groundwater, Otago, age tracers, radon, isotopes, hydrochemistry, hydrogeology

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# 1.0 INTRODUCTION

In this section, an overview of the geology, climate and hydrology is provided as context for the analysis and interpretation of environmental tracers.

## 1.1 Background

A framework for integrated and sustainable management of the Otago region's freshwater resources by regulating various activities is provided in *The Regional Plan: Water for Otago* (RPW) (ORC 2022). The RPW highlights the region's reliance on water for social, economic and cultural wellbeing and aims to preserve water quality. The RPW also captures water-related values and concerns from Kai Tahu. The Otago Regional Council (ORC) manages the regional freshwater resources using a combination of Freshwater Management Units (FMUs) and rohe (Figure 1.1).

The Ministry of Business, Innovation and Employment's (MBIE) Endeavour Te Whakaheke o Te Wai (TWOTW; Contract CO5X1803) programme aims to holistically describe the flow sources, pathways and time lags of water moving through catchments at the regional scale (Morgenstern et al. 2017; Morgenstern et al. 2019; Moreau et al. 2021). In addition to modelling approaches to water mass balance, hydrochemistry and evaluation of age tracer and isotope data, this programme provides a consistent interpretation of all available hydrochemistry and tracer datasets. The resulting improved water age characterisation therefore enhances the understanding of observed hydrochemistry trends and flow rates. TWOTW also informs the assessment of hydraulic aquifer parameters and supports addressing region-specific water issues.

This study was undertaken as a collaboration between ORC and GNS Science to improve the understanding of groundwater dynamics in Otago and inform policy development (e.g. the new Land and Water Regional Plan) as part of the TWOTW programme. It brings together geochemical data from shallow and deep groundwater sources, providing an update to the 2001 regional synthesis (Heller 2001). Environmental tracers (age tracers, isotopes, temperature, gas concentrations and chemistry) are used to characterise: (1) the dynamics of the groundwater from recharge to discharge, (2) the groundwater interaction with surface water, (3) the source(s) of groundwater recharge and (4) the processes that control the hydrochemical properties (quality) of the groundwater (including sources of contaminants).

Particularly, this study aims to contribute to answering the following questions:

- How are groundwaters and surface waters connected in the aquifer systems?
- Where does the river-recharged groundwater flow within the aquifers?
- Where is groundwater recharged from local rain?
- What are the time scales of water flows through the aquifers?
- What are the drivers of nitrate levels in the groundwater?
- What are the flow pathways of surface contaminants, such as agricultural nutrients?

At the time of writing of this report, similar regional syntheses are being developed for the Gisborne, Tasman, Taranaki and Auckland regions.

This work was also co-funded by the MBIE's Strategic Science Investment Fund National Groundwater Monitoring Programme (Contract C05X1701) and the Envirolink Fund (Medium Advice Grant no. 2420-ORC009).

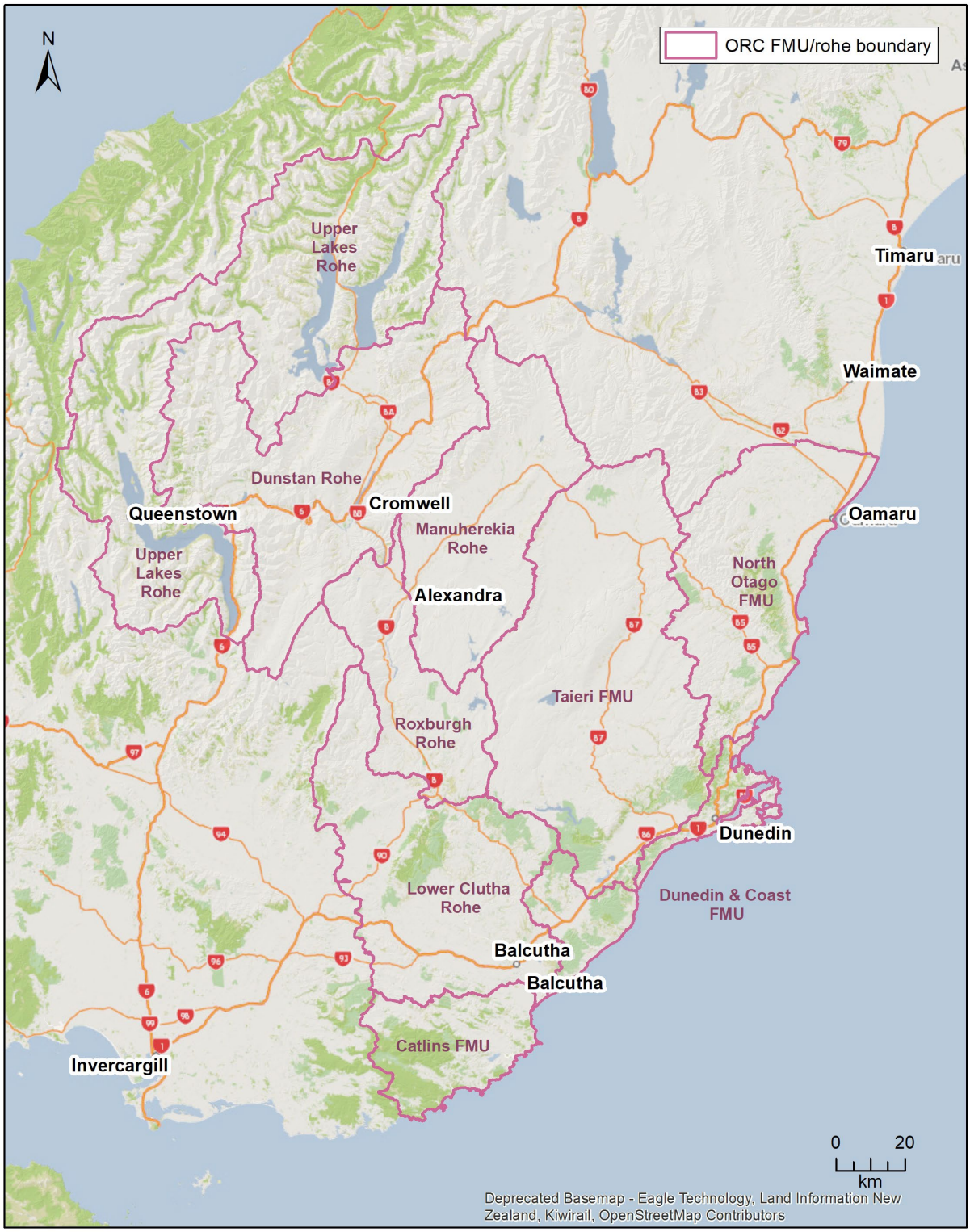


Figure 1.1 Location of Otago Regional Council's Freshwater Management Units (FMUs) and rohe (modified Levy et al. 2021).

# 2.0 SETTINGS

## 2.1 Geology

The Alpine Fault is a major active fault of the South Island and marks the geological boundary of the Australian and Pacific plates, moving westwards and northwards, respectively (Figure 2.1). Activity along the fault since the Miocene (Tertiary) resulted in the formation of the Southern Alps (Cox et al. 2007).

In the Otago region, the Southern Alps are approximately 50 km wide and trend roughly northeast parallel to the Alpine Fault. The region is heavily faulted with predominantly northeast-trending fault systems, resulting in broadly elevated areas (average elevation of Otago is ~300 m) dominated by folded and faulted ranges and basins (Figure 2.1). To the southeast of the Southern Alps is a broad area of uplands dominated by folded and faulted mountain ranges and basins. These extend eastwards, reaching the ocean near Palmerston and Waikouaiti. To the northeast and south are the alluvial plains of the Waitaki and Clutha rivers, respectively.

The geological Basement rock underlying Otago is known locally as the Otago Schist and originates from thick Carboniferous to Jurassic thick sequences of sedimentary rocks accreted to the Gondwanaland margin (Cox et al. 2007). These greywacke sandstones underwent metamorphism during the Cretaceous (Late Mesozoic) Era, approximately 150 Ma ago, during a period of orogenesis (Craw 2023). Subsequently, during the late Cretaceous (110–90 Ma), the schist was uplifted, faulted and eroded.

Between the late Cretaceous (Mesozoic) and Miocene (Tertiary), marine incursions deposited a series of sandstones and mudstones unconformably over basement rocks. These sediments primarily consist of mature gravels and sands, and kaolinitic mudstones with locally abundant organic material identified as coal and lignite (Mitchell et al. 2009). The marine transgression that peaked in the late Oligocene resulted in the deposition of these sediments over an older erosion surface known as the Waipoumanu Erosion Surface. This low-relief topographic surface forms a significant feature in central and eastern Otago (Landis et al. 2008). Both the erosion surface and the overlying sediments decrease in age inland, with older deposits on the east coast (Benson 1968) and younger deposits in central Otago (Mildenhall and Pocknall 1989). From the Late Oligocene to Miocene, magmatic intrusions centred on the Otago Peninsula occurred, with multiple isolated volcanic vents scattered over east Otago. A further eruptive phase occurred during the Miocene, forming volcanics in what is now the Taieri Plains. These volcanics are basic to intermediate in composition (Glassey et al. 2003). The Otago Peninsula has since undergone extensive marine and terrestrial erosion.During the Quaternary (Early Pleistocene to Holocene), alternating periods of cooling and warming occurred, resulting in glaciations and interglacial periods (Barrell 2011). During these glaciations, glaciers covered most of western and central Otago. These glaciers rounded and smoothed the schist surfaces and deposited large amounts of poorly sorted till material and outwash gravels. The lakes in the region are the result of this glacial activity.

The main geological features of the region are summarised below (Figure 2.1; Heller 2001; Levy et al. 2021):

- In the north Otago downlands Tertiary near-horizontal geological formations occur overlain by Quaternary gravels. The older Tertiary sediments are of terrestrial origin, transitioning to marine sediments during a mid-Tertiary marine transgression. Remnants of high terraces occur along the major rivers. During the Tertiary, submarine eruptions resulted in tuff and pillow lavas in Oamaru (Dunedin Volcanic Group).
- In central Otago, long, narrow and faulted tectonic basins are filled with soft, mid-Tertiary to Quaternary fluviatile sediments, including successive terrace deposits.
- The Taieri Graben was formed over the last two million years, as the western and eastern Basement blocks were uplifted through active faulting. The graben is bounded by the Titri and the Maungatua faults and also underwent subsidence as movement along the fault continued. The basin floor is estimated to be *c.* 300 m below sea level. This graben was filled with Tertiary to Quaternary terrestrial sediments with laterally extensive estuarine and lacustrine organic muds, shell beds and peats. The basin was rapidly inundated during sea level changes in the Holocene, turning the western and eastern parts of the graben (up to Mosgiel) into a coastal estuary. This inundation resulted in the deposition of a consistent silty, clayey sand (Waihola Silt-Sand) up to 25 m thick. More recently, Quaternary sediments were deposited by the meandering Taieri River. In the Mosgiel area, the Quaternary sediments are highly variable and generally poorly sorted, likely due to mixed sediment sources (e.g. local streams, outwash channels, floods).
- In the south Otago basins, surficial Pleistocene outwash gravels, moraine deposits and glacial till are common, forming a thin veneer over the weathered and faulted Basement units. The deposits are overlain by Holocene alluvium. The Basement units consist of tuffaceous greywacke and argillite (Muhiriki Terrane) grading to semi-schistose greywacke, schist and phyllite to the north (Caples Terrane).

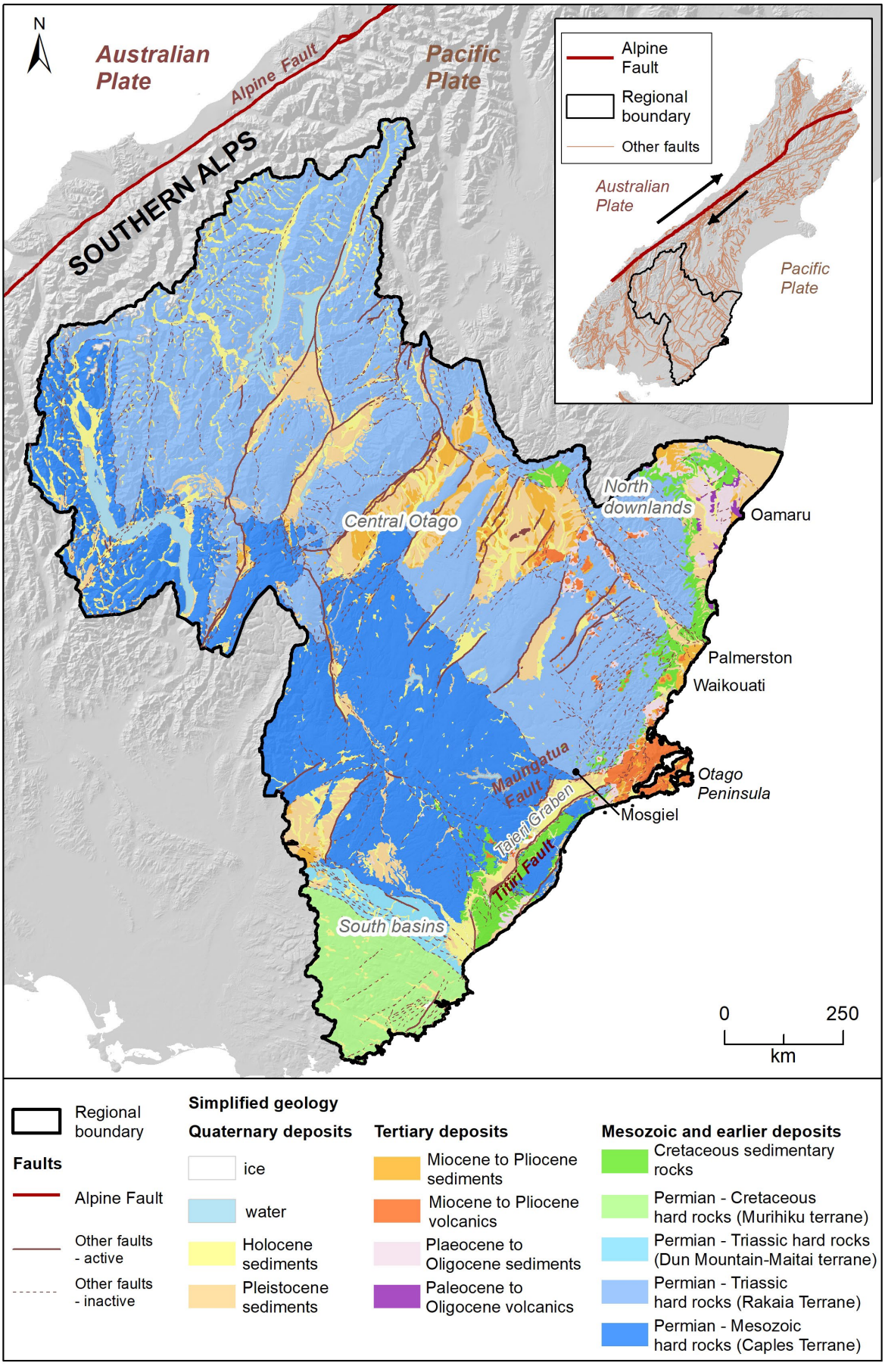


Figure 2.1 Simplified geology of Otago and major fault systems (modified from Heron 2023). Basement geology has been subdivided into the distinct terranes, noted in parentheses.

## 2.2 Climate and Hydrology

### 2.2.1 Climate

Otago's diverse climate and weather patterns are primarily caused by its wide geographic range and varied topography, as well as its location within the mid-latitudes, which are dominated by prevailing westerly winds. Anticyclones that move from west to east over New Zealand, along with their interstitial troughs of low pressure heavily influence the weather in Otago (Macara 2015).

The Main Divide of the Southern Alps acts as a barrier to the westerly air flows, significantly impacting the weather across the region and exacerbated by the region's irregular topography. As a result, central Otago experiences hot, dry summers (with maximum temperatures exceeding 28°C) and cold, dry winters (with minimum temperatures below -4°C) similar to ‘continental’ climates. Due to the adjacent sea surface temperatures and the absence of protection from south/southwest air movements, coastal parts of Otago receive cooler average temperatures (2–20°C) year-round.

Inland Otago experiences fewer rainy days than the region's westernmost and coastal areas. Due to the orographic impact of the Southern Alps, the mean annual rainfall for Otago varies from less than 400 mm/yr in central Otago to more than 2000 mm/yr at the highest elevations (Figure 2.2). Seasonal variance in rainfall is minimal, with some areas experiencing variability due to significant rainfall events rather than a greater number of total rain days.

Climate change is projected to impact Otago’s future rainfall and temperature. Projections for the end of the century (2081–2120), using four Representative Concentration Pathways (RCPs), indicate that (1) mean annual temperature may increase by 0.5–3.5°C, and (2) mean annual rainfall may rise by 5–20% for most of the region (Macara et al. 2019). Climate change projections are important for water resource management, as changing temperature and rainfall can impact groundwater recharge and water demand. For instance, Mourot et al. (2022b) estimated that rainfall recharge in Otago may (1) increase by up to 0.4 mm/day in the west, south and east; and (2) decrease by up to -0.4 mm/day in central Otago under a high-emission (RCP8.5) end-of-century horizon scenario (2081–2100). The seasonal variability of the future Otago climate under climate change is predicted to see an increase in summer precipitation in western areas and a decrease in central and coastal locations.

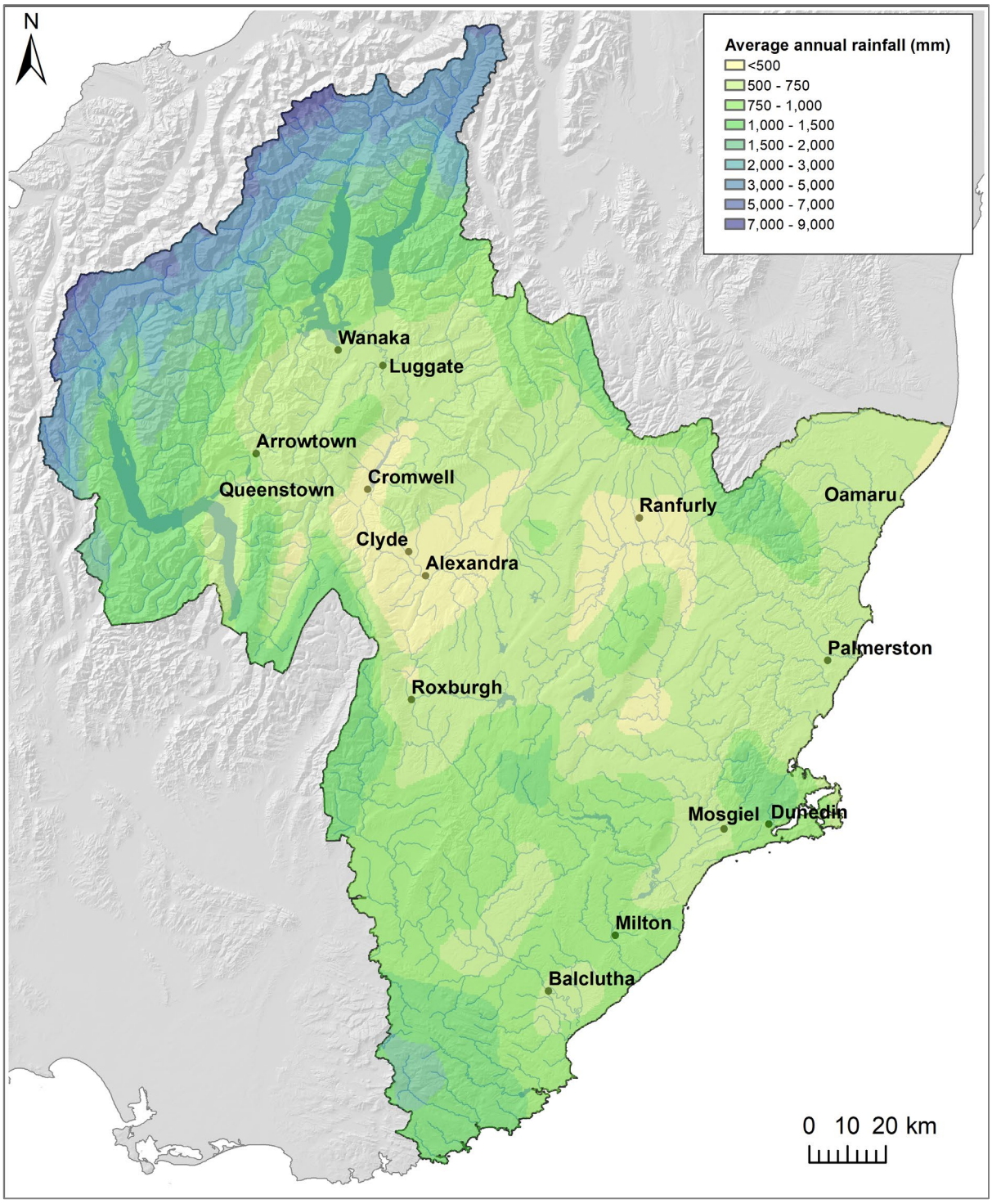


Figure 2.2 Mean annual rainfall in the Otago region for the 1972–2013 period (Ministry for the Environment 2016).

### 2.2.2 Hydrology

The Otago region covers an area of approximately 32,000 km$^2$, with its boundary stretching from the Waitaki River in the north to Brother's Point in the south, and inland to Lake Wakatipu and the Haast and Lindis passes (Figure 2.3).

Many rivers in the region have their origins in the Southern Alps (Figure 2.3). The region also comprises some of New Zealand's largest and most pristine lakes (LAWA 2023), which are used for hydroelectric power, irrigation and recreation. With headwaters high in the Southern

Alps, the combination of relatively high rainfall and steep mountains produces significant amounts of sediments that are flushed down tributaries. Most of the region is made up of mountains and basins to the northeast, with topography generally decreasing to form river floodplains near the coast. Due to the low elevation, these plains are susceptible to flooding and sea level rise.

There are 16 major rivers in Otago, with the larger two being the Clutha River (Mata-au) and the Taieri River, and many other smaller tributaries throughout the region (Figure 2.3). The Clutha River flows 322 km from Mt Aspiring National Park through Central Otago to its mouth near Balclutha. The river and its tributaries drain 20,586 $km^2$, equivalent to 66% of Otago's area, making it the largest river basin and river by volume in New Zealand (Mager and Horton 2018).

The Taieri River catchment, with an area of 5650 $km^2$ is considerably smaller than that of the Clutha River however, it is the second largest catchment in Otago. The Taieri catchment has one of the driest climates in New Zealand, with the central basin at Waipiata receiving only 380 mm of rain per annum (Mager and Horton 2018). This region is vulnerable to drought, making flow allocation an important aspect of the Taieri River's management. The lower catchment of the Taieri, which was once extensive wetlands, lies below sea level and is prone to flooding.

There are numerous lakes around Otago, notable ones being Wakatipu, Wānaka, Hāwea (the Southern Lakes), Dunstan and Waihola (Figure 2.3). The three largest lakes are Lake Wakatipu, Lake Wānaka and Lake Hāwea covering 293 $km^2$, 180 $km^2$ and 137 $km^2$, respectively.

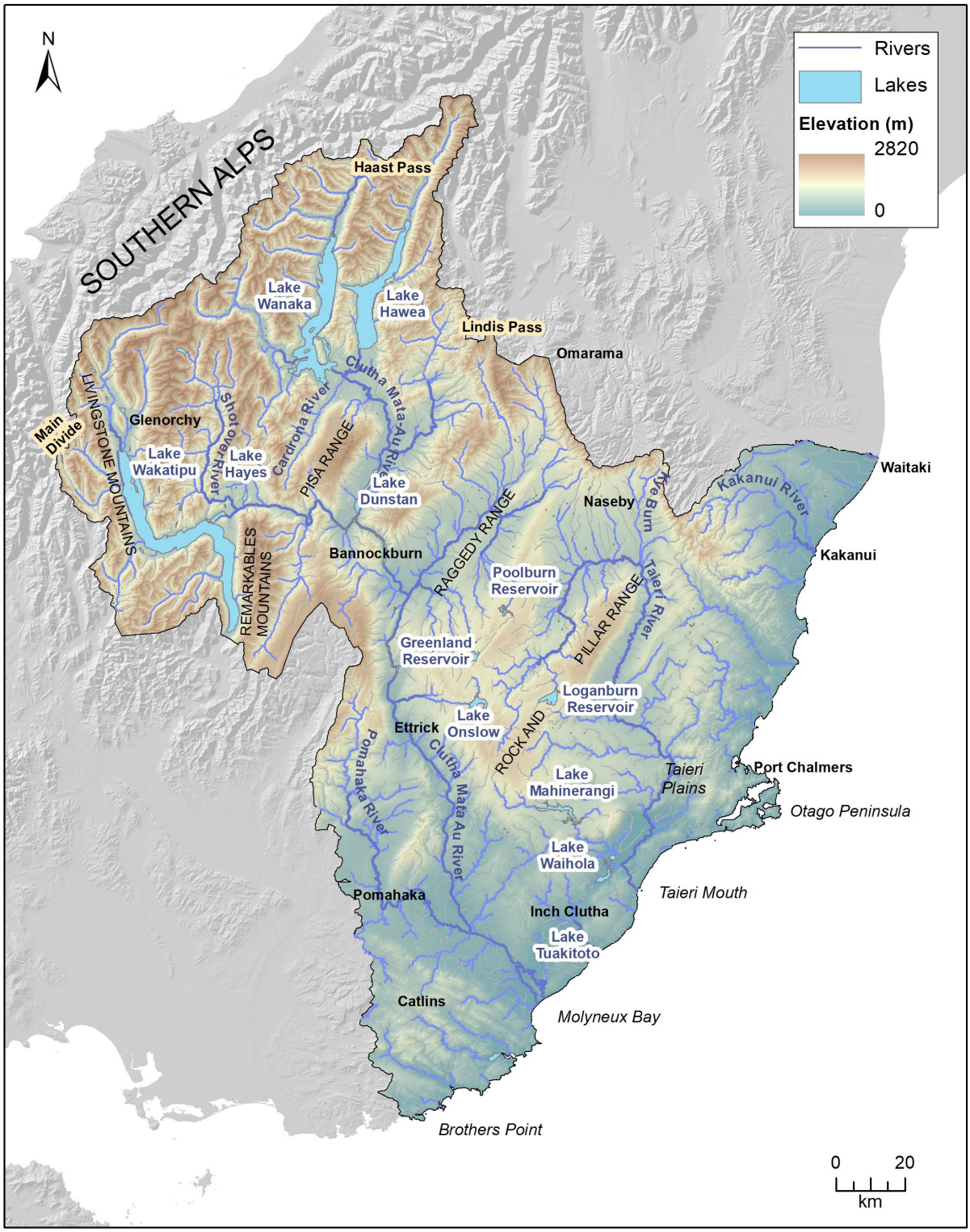


Figure 2.3 Lakes and rivers of the Otago region shown with elevation (LINZ 2019).

## 2.3 Hydrogeology

### 2.3.1 Resources

Otago's aquifers are hosted in Quaternary alluvial and outwash sediments, Tertiary sediments and volcanics, and pre-Cretaceous fractured hard rock. Most aquifers are hydraulically disconnected from one another and located in within geographical basins. Aquifer names and geological classifications of host rocks and extents have changed over time, as knowledge grew (Rekker et al. 2008) and for the remainder of this report, ORC aquifer names and groundwater management zones from the latest SOE report (Levy et al. 2021) are used (Table 2.1). In the following section, aquifers are grouped by geological units. A summary of aquifer names is provided in Appendix 1 to enable cross-referencing to historical names. Detailed descriptions of most aquifers can be found in Levy et al. (2021).

To provide a regional summary, aquifers are further grouped in this report by Hydrogeological Systems (HS), which are geographical areas with broadly consistent hydrogeological properties and similar resource pressures and management issues, mapped consistently at the national scale (Moreau et al. 2019). The use of HS as a reporting unit has been recommended for national reporting on groundwater quality to better reflect the distribution of New Zealand's groundwater resources (Moreau 2023).

HS were initially developed to stage the development of the New Zealand Hydrogeological Unit Map (HUM), a 2.5-D GIS dataset (overlapping, stacked polygons) that represents hydrogeological units (i.e. aquifers, aquitards, aquicludes and basement) and illustrates geological layering (White et al. 2019). This dataset aims to provide a nationally consistent, 3D aquifer map. Geological and depositional facies are key components of this map, as they enable the connection of spatial distribution with hydraulic properties. Surface facies are propagated in the subsurface using the HUM units. In the current (2023) version, depositional facies mapping is only available for coastal systems and is therefore not ready for use in this study. Both the HS and HUM datasets are currently in development, and updates are regularly released by GNS Science as part of its Groundwater Strategic Science Investment Fund (SSIF) programme. Consultation with regional authorities to refine the initial releases is essential, as mapping progresses.

In total, there a 29 HS mapped in the region, including Basement Hard Rock, which is regarded as an aquiclude nationally (Figure 2.4). Eighteen systems are reportedly hosting aquifers, including the Basement Hard Rock in south Otago (Table 2.1). The Maniototo, Oamaru and Taieri HS are described as either multi-layered or complex aquifer systems with aquifers of varying degree of confinement status.

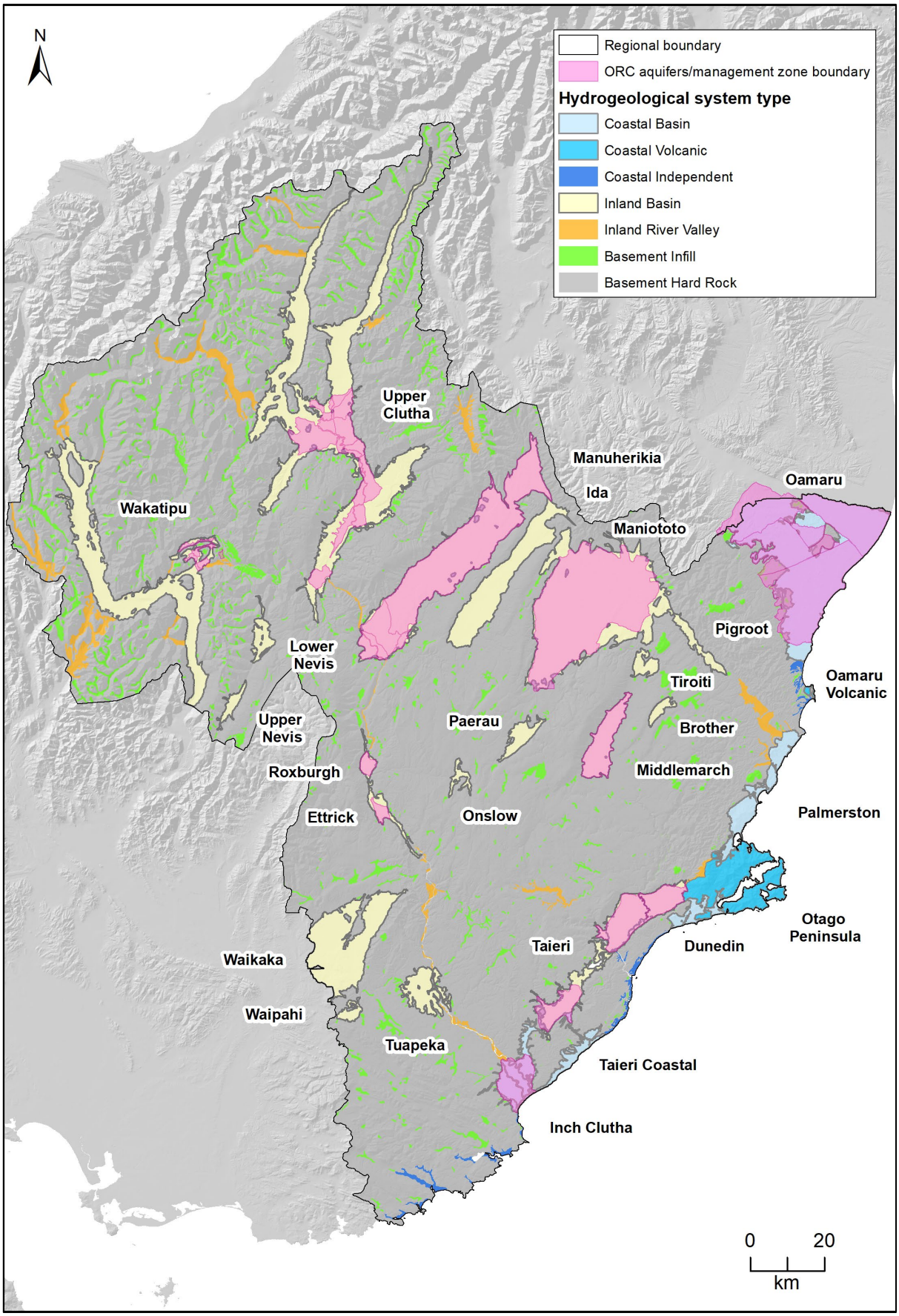


Figure 2.4 Otago hydrogeological systems and Otago Regional Council aquifer and groundwater allocation zone boundaries.

Table 2.1 Hydrogeological systems in the Otago region and corresponding aquifer names and/or groundwater management zones (Rekker 2001; Levy et al. 2021). The following 10 systems were excluded from this table as there is no associated ORC aquifer or groundwater management zone name: Brother, Lower Nevis, Oamaru Volcanic, Onslow, Otago Peninsula, Paerau, Pigroot, Taieri Coastal, Tiroiti, Upper Nevis.

| HS Name | Quaternary Sediment Aquifers | Tertiary Sediment Aquifers | Tertiary Volcanic Aquifers | Basement Hard Rock |
|---|---|---|---|---|
| Dunedin | South Dunedin Coastal | - | - | - |
| Ettrick | Ettrick Basin | - | - | - |
| Ida | Ida Valley | - | - | - |
| Inch Clutha | Inch Clutha Gravel, Lower Waitaki Plains | - | - | - |
| Maniototo | Maniototo Quaternary | Maniototo Tertiary | - | - |
| Manuherekia | Manuherekia Alluvium, Manuherekia Groundwater Management Zone, Earnscleugh Terrace, Dunstan Flats, Lower Tarras, Manuherekia Claybound | - | - | - |
| Middlemarch | Strath Taieri | - | - | - |
| Oamaru | Kakanui-Kauru Alluvial Ribbon, Lower Waitaki Plains | Papakaio | North Otago Volcanics | - |
| Otago | Shag Alluvium | - | - | - |
| Palmerston | Shag Alluvium | - | - | - |
| Roxburgh | Roxburgh East Aquifer, Roxburgh West Aquifer | - | - | - |
| Taieri | Mosgiel-Momona Confined and Henley Deep aquifers, Tokomairiro groundwater management zone | | - | - |
| Tuapeka | - | - | - | Kuriwao Basin, Clydevale-Wairuna Basin |
| Upper Clutha | Cardrona Alluvial Ribbon, Cromwell Terrace, Cardrona Gravel, Hawea Flat, Wanaka Basin, Luggate, Pisa and Queensberry Groundwater Management zones, Lindis Alluvial Ribbon, Lowburn Alluvial Ribbon | - | - | - |
| Waikaka | Pomahaka Alluvial Ribbon Aquifer | - | - | - |
| Waipahi | Clydevale-Wairuna Basin | - | - | - |
| Wakatipu | Glenorchy aquifer, Upper Mill Creek, mid-Mill Creek, Ladies Mile, Hawthorne-Speargrass, Morven, Frankton Flats, Kingston | - | - | - |

Otago's aquifers are discussed in more detail in the following subsections, grouped by the geological hosting material: Quaternary sediments, Tertiary sediments, volcanics and pre-Cretaceous fractured hard rock. More detailed descriptions of most aquifers can be found in Levy et al. (2021).

#### *2.3.1.1 Quaternary Sediment Aquifers*

Most of Otago's groundwater resources are hosted within Quaternary (Pleistocene to Holocene) sediments, and there are large variations in the thickness and hydraulic properties. The Quaternary sediments aquifers can be summarised as follows (Rekker and Houlbrooke 2010; Rekker 2014; Levy et al. 2021):

- Alluvial deposits composed of sand and gravels within topographical basins. Aquifers are mostly unconfined to confined. Saturated aquifer thickness can vary between a few meters to 20 m (e.g. Lower Waitaki Plains) (Heller 2001). The aquifers are delineated as spatially distinct units. These deposits are abundant in the region.
- Thin alluvial deposits overlying fractured hard rock formations. These aquifers are thin and generally unconfined. There are occurrences of poor groundwater quality (i.e. elevated nitrate concentrations, *E.coli* spikes). These aquifers are located in the Oamaru, Waikaka and Upper Clutha HS.
- Glacial outwash deposits comprising gravel lenses. These aquifers are mostly unconfined with saturated thickness ranging from a few meters to greater than 30 m (e.g. Wanaka Basin) (Heller 2001). Groundwater quality is variable and occurrence of elevated arsenic has been reported in the Kingston and Ladies Mile aquifers. These deposits occur in the Manuherekia, Ettrick, Roxburgh, Wakatipu and Upper Clutha HS.

Quaternary sediment aquifers are hydraulically connected to surface water and exhibit strong local controls. For instance, chemistry and radon sampling (summer and winter 2016–2017) indicated that in the Cardrona River Catchment, the river generally loses water over the fan through changing flow dynamics over the months, and the final reach of the river is primarily sourced by groundwater (Jackson 2018). In contrast in the Waihemo/Shag River, radon surveys on a 16 km reach identified that two separate groundwater systems with distinct radon signatures were likely discharging into the river (Martindale and Lovett 2017; Martindale et al. 2018; Mourot et al. 2022a).

Note that the South Dunedin Coastal Aquifer consists of reclaimed sands, estuarine dunes, gravel and silt, is hydraulically connected to the sea and monitored to assess the impact of sea level rise on Dunedin (Rekker 2012).

#### *2.3.1.2 Tertiary Sediment Aquifers*

In the Maniototo Inland Basin, the Maniototo Tertiary Aquifer consists of well-indurated Maniototo Conglomerate (Hawkdun Group, Pliocene to Miocene) underlain by quartz, conglomerate and sandstone with minor sandstone and lignite seams (Manuherekia Group, Miocene). This confined aquifer represents the largest aquifer (785 $km^2$) in Otago and can be locally artesian, particularly in the southern part of the basin. Groundwater flow direction is generally to the southeast, broadly following surface topography, and discharges into the Taieri River. Hydraulic property information for this aquifer is limited. Available transmissivity values range from 4 to 618 $m^2$/day, and abstraction is likely to impact the Taieri River flows (Levy et al. 2021). This Basin is regarded as over-allocated.

In the Oamaru Coastal Basin, the Papakaio Aquifer comprises non-marine quartz conglomerates from the Taratu Formation (Onekara Group, Paleocene–Cretaceous) which lie unconformably over schist basement rocks. The aquifer thickness ranges from 20 to 120 m, and the aquifer is regarded as mostly confined, with reported occurrences of artesian conditions (Levy et al. 2021). Declining groundwater levels were observed between 1991 and 1999, coincident with increased groundwater use. Groundwater quality in the Papakaio Aquifer has previously been reported as poor quality with low pH, and elevated concentrations of iron, manganese, aluminium, sulphate and chloride (Heller 2001).

In the Taieri Inland Basin, aquifers occur within the Quaternary and Tertiary deposits infill of the Taieri Graben. The Waihola Silt-Sand, up to 25 m thick towards the basin exit, acts as a confining unit separating the Quaternary sediments from the confined Mosgiel-Momona aquifer and the Henley Deep aquifer (Levy et al. 2021). The shallow aquifers are strongly connected to surface water. Historical over abstraction has lowered groundwater level in the Mosgiel area. Groundwater quality in this area can be poor with high nitrate-nitrogen concentrations associated with anthropogenic activity in oxidised environments and elevated iron and manganese elsewhere. Saline intrusion has also been reported in shallow groundwater in the West Taieri and with the Waihola Silt-Sand (Levy et al. 2021).

#### *2.3.1.3 Tertiary Volcanic Aquifers*

The North Otago Volcanic Aquifer is located southwest of Oamaru and consists of interbedded Miocene volcanics (Dunedin Volcanic Group) and Eocene marine sediments of Otatara limestone (Alma Group). The Dunedin Volcanic Group, formerly known as the Waiareka-Deborah volcanic field, comprises marine tuff beds, columnar jointed basalt intrusions, pillow lavas, siltstone with volcanic ash inclusions, and occasional diatomites, typical of submarine eruptions. The Otatara limestone includes the Totara and McDonald limestone.

This aquifer is mostly unconfined, except towards the coast where it is overlain by Miocene sandstone (Gee Greensand Formation, Kaierero Group) and siltstone (Mount Harris Formation, formerly known as Rifle Butts, Outakou Group) which acts as a semi- to fully-confining layer (Heron 2023; Levy et al. 2021). Intense and prolonged rainfall is required to replenish the aquifer, due to the strongly retentive nature of the overlying soil, with a duration of multiple years for a single recharge pulse (Rekker et al. 2008). Groundwater quality is impacted by high concentrations of geogenic sodium and land-use derived nitrate. Groundwater from the North Otago Volcanic Aquifer flows into the overlying Kakanui Alluvial Aquifer, as evidenced from higher groundwater levels and similar hydrochemistry, while no hydraulic connection was found with the adjacent Papakaio Aquifer (Rekker et al. 2008; Levy et al. 2021).

#### *2.3.1.4 Older Fractured Hard Rock Aquifers*

In southern Otago, towards Pomahaka, Wairuna, Clydevale and Kuriwao, groundwater occurs within weathered/hard rock overlain by carbonaceous clay-bound gravels. The hard rock comprises Permian to Triassic sandstone, siltstone and schists from the Caples and the Maitai groups (Basement Eastern Province), located to the north and south of the Livingstone Fault, respectively (Morris 2014; Heron 2023). Groundwater in these aquifers is stored within fractures and therefore yields are strongly influenced by fracture connectivity. Where groundwater analyses are available, the groundwater is classed as sodium-chloride type, likely to be due to water-rock interaction with marine sediments and/or prolonged residence time.

### 2.3.2 Monitoring

Groundwater is currently monitored in the region via two main programmes (Figure 2.5):

1. *ORC State of the Environment (SOE) groundwater monitoring programme* – combines study-specific bores and permanent monitoring bores used by ORC to produce regular environmental reports and support groundwater resource management. The current ORC SOE network comprises 55 bores for groundwater quality and quantity, of which 35 are continuously monitored by automated groundwater level loggers (Levy et al. 2021).
2. *National Groundwater Monitoring Programme (NGMP)* – a long-term (late 1990s to current) collaborative programme operated between GNS Science and all regional authorities. It aims to identify spatial patterns and temporal trends in groundwater quality at the national scale and relate them to specific causes. In this programme, groundwater samples are collected quarterly at *c.* 110 sites nationwide and analysed for over 17 chemical parameters. Water dating at all sites was undertaken in 2009, with irregular ongoing re-sampling. In Otago, the NGMP dataset consists of seven active and four occasional wells (one shared with the SOE network). This programme is funded by the MBIE Strategic Science Investment Fund.

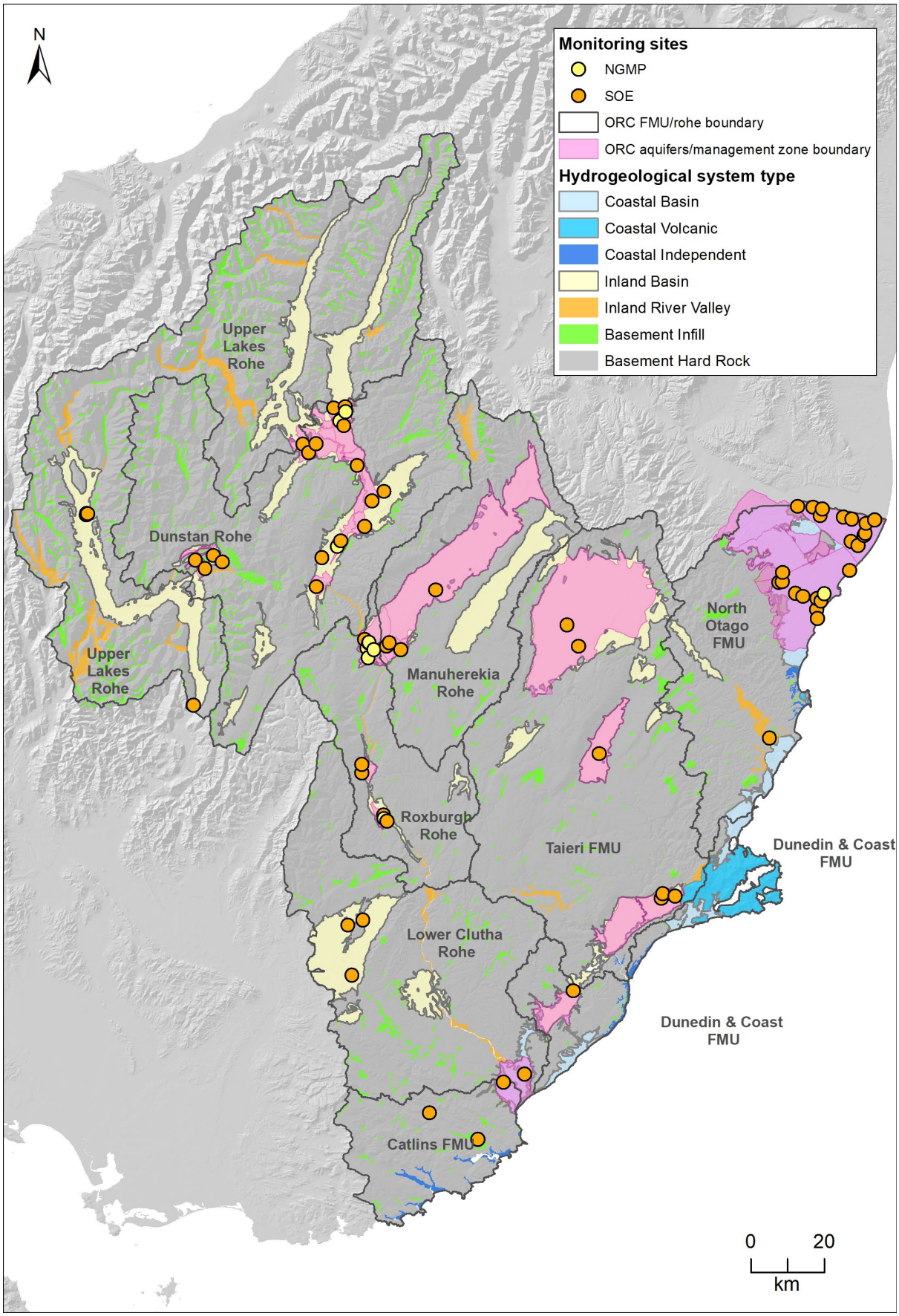


Figure 2.5 Locations of SOE and NGMP sites selected for this study.

## 3.0 METHODS

In this section, a general description of the method and interpretation techniques is presented for the following environmental tracers: water age tracers, radon, stable isotopes, hydrochemistry, temperature, argon and nitrogen gases.

### 3.1 Groundwater Dating

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 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 enhance the characterisation of groundwater recharge processes. The most robust and cost-effective age tracers in New Zealand were used in this study, i.e. tritium, sulphur hexafluoride ($SF_6$), chlorofluorocarbons (CFCs) and Halon-1301 (Figure 3.1). In this study, five types of tracers were used to establish residence times: age tracers with long-term, time-dependent input concentrations in the atmosphere or those exhibiting radioactive decay for groundwater dating in the age range of 1–100 years (tritium, $SF_6$, CFCs and Halon-1301), and radon (Radon-222) build-up in groundwater for dating periods of up to several weeks.

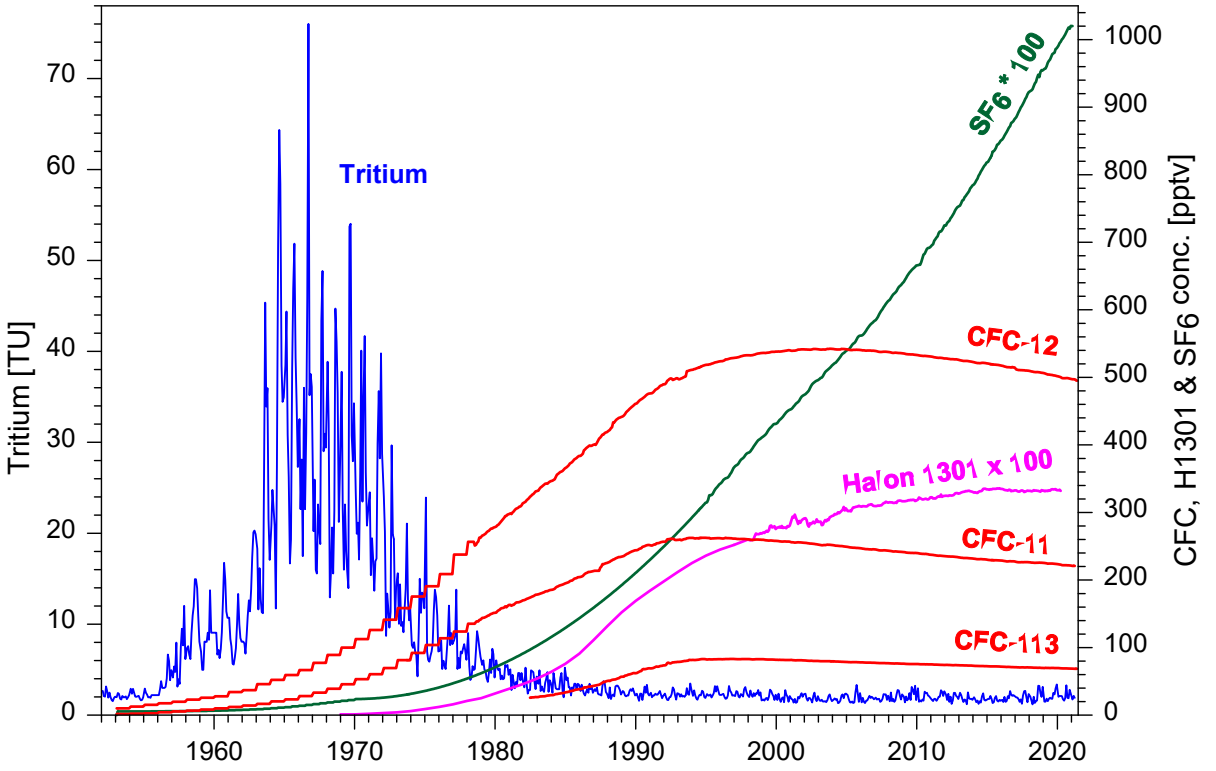


Figure 3.1 Tritium, CFCs, Halon-1301 and $SF_6$ input for New Zealand rain. Tritium concentrations have been measured in rain at Kaitoke, 40 km north of Wellington (monthly samples), and CFCs, Halon-1301 and $SF_6$ concentrations are for southern hemispheric air. TU = 1 represents a 3H/1H ratio of 10–18, and 1 ppt 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 (2000) and scaled to the southern hemisphere by a factor of 0.83 (CFC-11) and of 0.9 (CFC-12). Post-1978 CFC data were collected in Tasmania. Pre-1970 $SF_6$ data are reconstructed and 1970–1995 data are measured (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 with its historical input ($C_{in}$) using the convolution integral:

$$c_{out}(t) = \int_0^\infty c_{in}(t-\tau)\, e^{-\lambda\tau} g(\tau, f) d\tau \qquad \text{Equation 3.1}$$

where $t$ is the time of observation; $\tau$ is the transit time (age); $e^{-\lambda\tau}$ is a decay term, with $\lambda$ being $\ln(2)/T_{1/2}$ (radioactive decay of tritium with a half-life $T_{1/2}$ = 12.32 years); and $g(\tau,f)$ is a system response function (Maloszewski and Zuber 1982, 1991; Zuber et al. 2005; Cook and Herczeg 2000). 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. a 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 (2000). Stewart et al. (2017) showed that the exponential piston flow model covers the age distributions of typical groundwater discharges. The exponential piston flow model response function is given by:

$$g(\tau) = 0 \qquad \text{for} \quad \tau < (1-f) \qquad \text{Equation 3.2}$$

$$g(\tau) = (f t_t)^{-1} exp\left[-\left(\tau/_{f t_t}\right) + \left(1/_f - 1\right)\right] for \quad \tau < (1-f) \qquad \text{Equation 3.3}$$

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).

### 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 significantly higher tritium concentrations at that time (Figure 3.1). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground; subsequently the tritium concentration in the groundwater then decreases over time due to radioactive decay and is therefore a function of time that the water has been underground (age).

Tritium, with its pulse-shaped input, is a particularly sensitive tracer for identifying two unique age distribution parameters via the delay and dispersion of the bomb-pulse in the groundwater compared with the rain input. This approach is particularly useful for the age interpretation of wells with little other information on mixing of groundwater from varying depths and of different ages. The superimposed bomb-tritium can accurately and precisely 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. It 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 3.2 shows the tritium output of a typical transfer function for New Zealand in comparison with 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 still present in New Zealand's groundwater systems. In New Zealand, a monotonous decline in tritium output versus MRT was already observed 10 years ago, allowing determination of unambiguous 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 3.2, it can be derived that, in the coming years, bomb-tritium will 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.

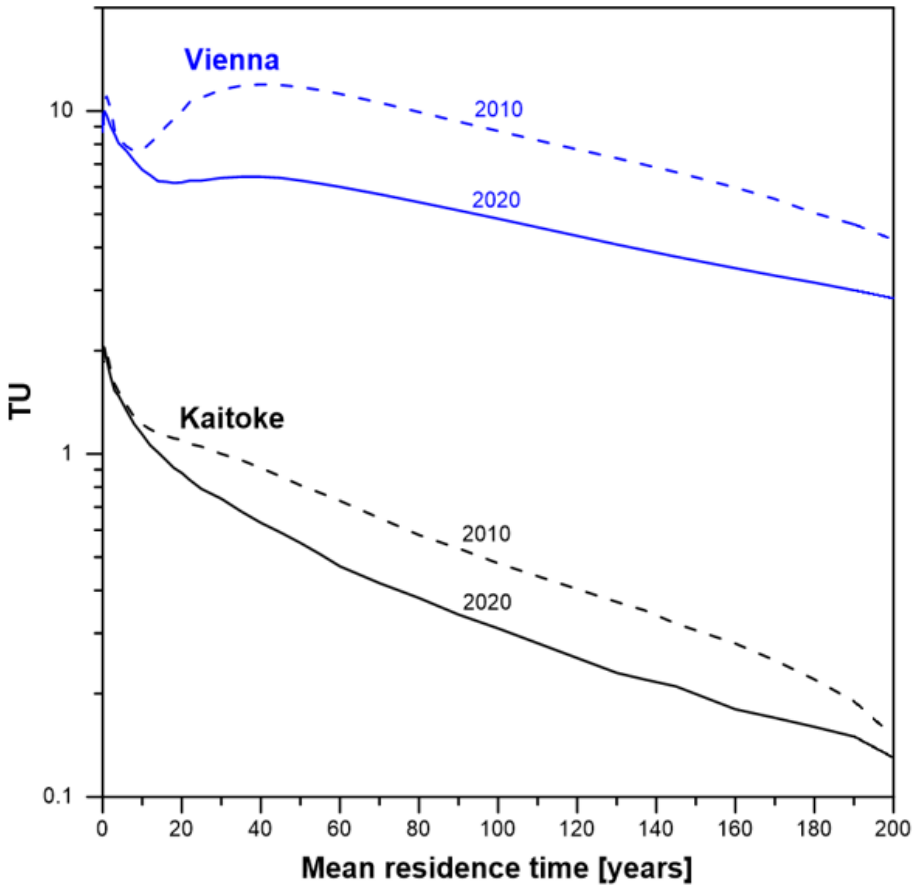


Figure 3.2 Tritium output for a typical transfer function of 80% exponential flow volume within an exponential piston flow model, calculated using the Kaitoke (New Zealand) and Vienna (Europe) tritium input. Solid lines are current tritium output; dashed lines are previous tritium outputs from 10 years ago for comparison to show the decline of bomb-tritium.

Tritium is now used to date 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 to understand 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 as bomb-tritium remains present. Therefore, these new opportunities offered by the tritium method in New Zealand are currently leading to increased understanding of hydrologic systems (McDonnell et al. 2021).

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 applicable for any location 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 of at least two years in length.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were mostly 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, atmospheric CFC concentrations rapidly reduced in the 1990s and concentrations continue to decrease, meaning that CFCs are not as effective for dating water recharged after 1990. CFCs are relatively long-lived and slightly soluble in water, therefore they enter groundwater systems with groundwater recharge. Their concentration in groundwater records the CFC atmospheric concentration from when the water was recharged, allowing determination of the recharge date of the water.

Another chemical compound, Halon-1301 ($CBrF_3$), shows promise to remain a more useful age tracer, due to its still slightly increasing concentrations in the atmosphere (Figure 3.1) and absence of local contamination sources that could interfere with 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.

$SF_6$ 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 increased atmospheric concentrations (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 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 groundwater. These concentrations are a result of the equilibrium between $^{222}Rn$ delivery and radioactive decay (half-life 3.8 days) and can vary considerably depending on the uranium content and $^{222}Rn$ 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 tracer informs on the presence of young (up to weeks) groundwater.

The 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 river water (Martindale et al. 2018). Conversely, fresh river water recharge into groundwater systems is indicated by low $^{222}$Rn concentrations in groundwater, as it takes approximately three weeks (five to six half-lives) for the $^{222}$Rn to equilibrate to the ambient concentration of groundwater.

## 3.2 Stable Isotopes

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 river or from local rainfall.

The stable isotope ratios $^{18}O/^{16}O$ and $^{2}H/^{1}H$ are expressed as $\delta$ 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. Stable isotope analysis was carried out in the Rafter Stable Isotope Laboratory at GNS Science using isotope ratio mass spectrometry.

## 3.3 Hydrochemistry

The hydrochemical composition of groundwater reflects its recharge conditions and evolutionary flow pathways. Various land-use activities or geological formations can result in specific groundwater chemistry signatures that can be traced back to a recharge source or origin. Increasing ion concentrations of water due to water-rock interaction within the aquifer can indicate flow pathways and groundwater processes.

### 3.3.1 State and Trend Analysis

To reflect the natural variability of groundwater chemistry, state and trends of groundwater quality is described using the following statistical metrics, which are consistent with previous SOE and national reporting (Moreau and Daughney 2015; Moreau 2018):

- *Median and median absolute deviation (MAD)*: the median is a measure of central tendency. It is a more robust measure than mean values because it is not affected by outliers. The MAD gives an indication of the data spread around the median; it is likewise more robust than the standard deviation, particularly to long distribution tails (Helsel et al. 2020).
- *Percentiles (5th, 25th, 75th, 95th)*: these inform the data spread around the median (Helsel et al. 2020).
- *Trend magnitude:* the rate of change in each parameter. In this report, the trend magnitudes are based on Sen's slope estimator, which is commonly used for environmental reporting (Helsel et al. 2020).

- *Trend category*: a descriptive category based on the sign of Sen's slope. A symmetric confidence interval around the trend is calculated. If this interval contains zero, the trend is described as 'uncertain'. If this interval does not contain zero, it is 'established with confidence' and assigned either a 'decreasing' or 'increasing' descriptor. This method was recently developed and applied to river quality state and trend assessments (Larned et al. 2016; McBride 2019).
- *Trend type*: this class is somewhat indicative of the confidence in the ability to detect the trend over the natural range of variability in measured concentrations, measured through the MAD (Moreau and Daughney 2021). A trend is classed as 'perceptible' if the change calculated using Sen's slope over the time period is greater than the median plus two MADs, and as 'imperceptible' elsewhere.
- *Statistical test p-values*: in this report, several statistical tests were conducted to assess either the statistical significance of a trend, seasonality or distribution difference. For each test, a hypothesis is formulated, and test statistics are calculated. An acceptable error rate is arbitrarily set to reject or accept the hypothesis, based on a data-calculated probability value (*p*-value). For this report, the significance level was arbitrarily set as $\alpha = 0.05$ for all tests, which is a common threshold used in environmental statistics reporting. Detailed information about the use of hypothesis tests in general and the tests used in this report can be found in Helsel et al. (2020).

### 3.3.2 Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) is a multivariate statistical method that categorises the chemistry data based on similarities in selected characteristics. We used HCA to assess variations in the hydrochemical composition of groundwaters within the region and their potential for distinguishing between different recharge sources (e.g. local rain versus river recharge) and identification of flow-evolutionary processes. HCA requires the use of complete cases, i.e. at least one analytical result (below or above detection limit) per parameter per site. The parameter selection represents a compromise between suitable data for processing and interpretation, including spatial coverage.

## 3.4 Recharge Temperature and Excess Air

Recharge temperature and excess air, derived from argon and nitrogen concentrations, can provide insight into the mechanisms controlling recharge. Ingram et al. (2007) found that excess air 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, usually have lower excess air concentrations than rainfall-recharged groundwater in areas with large groundwater level fluctuations.

Recharge temperature and dissolved excess air 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 excess air component. In other areas of New Zealand, this method enabled assessment of recharge sources and identification of paleo-groundwaters recharged during previous colder climates (Morgenstern et al. 2017).

## 3.5 Analytical Techniques

Tritium concentrations were determined at GNS Science using liquid scintillation in Quantulus™ ultra-low-level counters following vacuum distillation and electrolytic enrichment (Morgenstern and Taylor 2009). Tritium is expressed in tritium units (TU), in which 1 TU represents a $^{3}H/^{1}H$ ratio of 1 x $10^{-18}$. Tritium enrichment by a factor of 95 yields a detection limit of 0.02 TU at GNS Science, and deuterium calibration of each sample ensures a 1% reproducibility of tritium enrichment. Relative precision (1 SD) of routine individual analyses is 1.8–2.3%.

Concentrations of CFCs (CFC-11, CFC-12, CFC-113), argon, nitrogen and methane ($CH_4$) were analysed using an analytical system similar to 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 represent southern hemispheric air (where 1 ppt 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), and calculate 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. Liquid scintillation spectroscopy was used 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.

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

Groundwater chemistry samples were collected following the 2006 standardised sampling protocol for SOE monitoring, consistent with the current National Environmental Standards (Daughney et al. 2006; Milne 2019). The NGMP samples have been analysed at the New Zealand Geothermal Analytical Laboratory since 1993. The NGMP analytical suite includes: sodium (Na), calcium (Ca), magnesium (Mg), potassium (K), carbonate ($CO_3$), bicarbonate ($HCO_3$), chloride (Cl), sulphate ($SO_4$), nitrate-nitrogen ($NO_3$-N), ammonia-nitrogen ($NH_3$-N), dissolved iron (Fe), manganese (Mn) and dissolved reactive phosphorus (DRP) (Table 3.1). Hydrochemical analyses integrity of the NGMP samples is checked by calculating the charge balance error and/or ionic sum to ensure that the electroneutrality of the sample is verified (Moreau-Fournier and Daughney 2010). A historical reconstruction (starting from 1993) of changes in analytical methods used for each of the selected parameters monitored as part of NGMP is available elsewhere (Moreau and Daughney 2021). A temporal map of analytical methods and laboratories employed for the SOE network is not currently available.

Table 3.1 Current list of parameters monitored at National Groundwater Monitoring Programme (NGMP) sites. APHA stands for American Public Health Association, which is a reference for analytical methods (Baird et al. 2017).

| Parameter | Units | NGMP Analytical Method |
|---|---|---|
| $HCO_3$, $CO_3$ | mg/L | Titration APHA 2320B |
| Ca, Mg, K, Na, Fe, Mn, $SiO_2$ | mg/L | Induced Coupled Plasma-Optical Emission Spectrometry, APHA 3120B |
| DRP | mg/L | Flow Injection Analyser APHA 4500-P G (modified) |
| Cl, $NO_3$-N, $SO_4$, Br, F | mg/L | Ion Chromatography APHA 4110B |
| $NH_3$-N | mg/L | Flow Injection Analyser APHA 4500-$NH_3$-N |

## 3.6 Data Processing

### 3.6.1 Datasets

In total, the Otago aggregated dataset consists of groundwater levels and chemistry from the following sources (Table 3.2):

- Current monitoring datasets (SOE, NGMP).
- March 2023 sampling (including NGMP and SOE sampling) – groundwater samples were collected at 29 locations that had not been previously sampled by GNS Science or ORC.
- GNS Science Water Dating Laboratory dataset – this dataset consists of historical data accumulated through the years by the laboratory as part of its operations. To reflect the sensitivity of some of this data, exact coordinates were removed from the provided dataset.

The location of sites is provided in the data outputs attached to the PDF version of this report:

- *GNS_SR2023_54_Data_Output.xlsx*, and
- *GNS_SR2023_54_March2023_analyses.xlsx*.

Table 3.2 Dataset summary for hydrochemistry and groundwater age.

| Type | Groundwater | River | Lake | Rain | Source |
|---|---|---|---|---|---|
| Stable isotopes | 46 | 52 | 4 | 0 | Lachniet et al. 2021 |
| Age tracer | 164 | 3 | 0 | 10 | 1994–2023. This includes the March 2023 samples collected as part of this study. |
| Chemistry | 281 | 4 | 0 | 0 | NGMP and SOE (1985–2024) |
| Water level | 20 | 0 | 0 | NA | SOE (1986–2024) |

### 3.6.2 Age Interpretation

The relatively short radioactive half-life of tritium (12.32 years) makes it the most appropriate age tracer for dating young water (<200 years). To assist with ambiguous interpretation that may arise due to the tritium bomb peak, complementary gas tracers (Halon-1301, $SF_6$, CFCs) are also used during interpretation. Where these samples are collected, the confidence in the interpretation is higher if modelled ages are consistent between tracers. However, gas tracers can become contaminated and/or, in the case of chlorofluorocarbons, degrade in sediments.

Therefore, where discrepancies occur between ages modelled using various tracers, the modelled age derived from tritium measurements were preferentially selected.

Groundwater model ages for individual sites were calculated using the TracerLPM program from the U.S. Geological Survey (Jurgens et al. 2012). Tritium scaling factors change with latitude and elevation relative to the long-term monitoring site operated by GNS Science at Kaitoke, Wellington. Exponential piston flow models were used, with a percentage exponential age distribution within the total flow volume ranging from 0% to 100%, with 70% used at most sites for groundwaters and 60% for surface waters using scaling factors ranging from 1.25 to 1.5. Binary mixing models were only used when sufficient time series data were available. The age distribution parameters, MRT and fraction of exponential flow within the total flow volume (E%PM), are listed in the supplementary electronic file.

### 3.6.3 Hydrochemistry Data Processing

#### *3.6.3.1 State and Trend Analysis*

The hydrochemistry data for the Otago region consisted of time series ranging from less than a year to 38 years. State and trend analysis were performed using R Software (version 4.3.3), and the LWP-Trends (version 2101) and NADA (version 1.6-1.1) libraries. The LWP-Trends library was used to compute the Mann-Kendall trend test (seasonally adjusted or not), Sen's slope estimations and Kruskal-Wallis seasonality tests on censored and uncensored time series that have been processed with Non-Detects and Data Analysis (NADA) methods[1] (Helsel et al. 2020).

To calculate meaningful state and trend metrics, minimum data requirements were set as follows:

- *Descriptive statistics (indicative of state over the full time period)*: Where there is no censoring, median, MAD and percentiles were estimated using statistical formulas. For time series affected by less than 25%, median and MAD were estimated using Regression on Order Statistics (ROS) models and percentiles were calculated using statistical formulas. Above 25% and below 80% censoring, no percentiles were calculated; median and MAD were computed using ROS models. Above 80% censoring, there is no estimate of median, MAD or percentiles; values are shown as below the highest detection limit.
- *Kruskal-Wallis test (includes seasonal and trend time periods):* the number of seasons considered for the analysis is four (autumn, winter, spring and summer). The annual time period commences on 1 March of the first year (start of autumn). To enable seasonality state and trend assessments, all seasons must have at least one observation, and individual seasons require at least two data points.
- *Mann-Kendall test and Sen's Slope estimator (includes seasonal and trend time periods):* the time series must contain at least 10 data points, the maximum censored values must be smaller than the maximum observed values, and at least five unique observations must be required for each time series.

1 The NADA library implements the statistical methods to handle censored values (i.e. concentrations measured below the detection limit). It is used here to calculate medians and median absolute deviations for time series with left-censored values. For heavily censored datasets (i.e. more than 50% of results are recorded below the detection limit for a given parameter), a Regression on Order Statistics (ROS) model was used to calculate the median value. Above 80% censoring (i.e. more than 80% of results for a given parameter are below the detection limit), medians were not estimated. Sites that had been sampled only once were still included in the hydrochemical assessment to maximise the number of sites available.

#### *3.6.3.2 Hierarchical Cluster Analysis*

HCA was undertaken using the calculated site-specific median values of 10 different parameters: Ca, Mg, Na, K, Cl, $NH_3$-N, dissolved Fe and Mn, field pH and field electrical conductivity. In total, 129 groundwater sites had data for the selected parameters and were included in the HCA. Data for other parameters, such as DRP, $HCO_3$ and $SO_4$, were not included in the analysis, because these were not available at most sites. Total forms were not used as the dissolved and total forms are not directly comparable, as demonstrated by the reported significant decrease in Fe concentrations observed following a change in sampling protocol, specifically field-filtering, in the Wellington region in 2004 (Daughney and Randall 2009). $NO_3$-N in groundwater is mainly a reflection of the land use in the recharge area and is considered separately for assessment of the recharge source. Excluding $NO_3$-N from the HCA better helps to focus on groundwater evolutionary processes.

Approaches for HCA were based on best practice from previous experience in New Zealand and overseas (e.g. Güler et al. 2002; Daughney and Reeves 2005). HCA was initially conducted on log-transformed and normalised median concentrations, temperatures or conductivity using the nearest-neighbour linkage rule. This approach identifies sites where hydrochemistry is most different from other sites. 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 the HCA as the measure of similarity for both linkage rules.

# 4.0 RESULTS AND DISCUSSION

In this section, the water tracer results are interpreted with respect to (1) groundwater dynamics from recharge to discharge; (2) interaction with surface water; (3) recharge sources; and (4) understanding of the processes that control groundwater hydrochemistry, including sources and expected loads of nutrients. The water tracer techniques are complementary, and the results improve significantly by integrating all techniques. Note that data coverage is variable between systems and more detailed analysis was often limited to the data-rich Upper Clutha HS.

## 4.1 Data Outputs

All chemistry and age tracer data used in this report are provided in the digital data file *GNS_SR2023_54_Data_Output.xlsx* attached to the PDF version of this report, with the following worksheets:

- *Read_me*: caveat on the data.
- *Site_information*: site details (ID, well depth information, coordinates) for the sample locations. The last column indicates whether chemistry and/or age information is available at each site.
- *Units*: detailed information (acronym, units, form) for both chemistry and age tracer parameters.
- *Chemistry*: aggregated analytical results from sources detailed in Section 3.6.1.
- *Age*: aggregated age tracer measurements and interpretations from sources detailed in Section 3.6.1.
- *State_Trend*: groundwater chemistry state and trend metrics calculated over the time period available at each site, on a per site per parameter basis. Reported metrics are: median and MAD, percentiles ($5^{th}$, $25^{th}$, $75^{th}$, $95^{th}$), trend magnitudes and categories, and p-values for the Mann-Kendall and Kruskal-Wallis tests (Section 3.6.3).
- *HCA*: HCA cluster attribution, where applicable (Section 3.6.3).

The above dataset includes both historical data and samples collected in March 2023 as part of this project. Therefore, the official age tracer analytical results and interpretation from the March 2023 groundwater samples are provided separately in the digital data file *GNS_SR2023_54_March2023_analyses.xlsx* attached to the PDF version of this report, with the following worksheets:

- *Read_me*: caveat on the data.
- *Site_information*: contains site details (ID, well depth information, coordinates) for the sample locations.
- *Age*: contains the age tracer measurements and interpretation from the GNS Science Water Dating Laboratory.

## 4.2 Groundwater Levels

Groundwater elevations monitored at 20 bores located within eight HS illustrate seasonal variations of up to 2 m, and for some systems there are some strong, long-term temporal variations (e.g. in Roxburgh HS, there are increasing groundwater levels between 1995 and 2020, with a recent decrease between 2020 and 2023) (Figure 4.1). In systems where data were available at more than one site, significant variations (>2 m) were observed in measured groundwater levels (i.e. Upper Clutha, Oamaru and Taieri HS). This is consistent with hydraulically distinct aquifers observed in multiple basins in the region (Levy et al. 2021). Generally, groundwater elevations mimic the ground elevations with higher elevations inland (Figure 4.2).

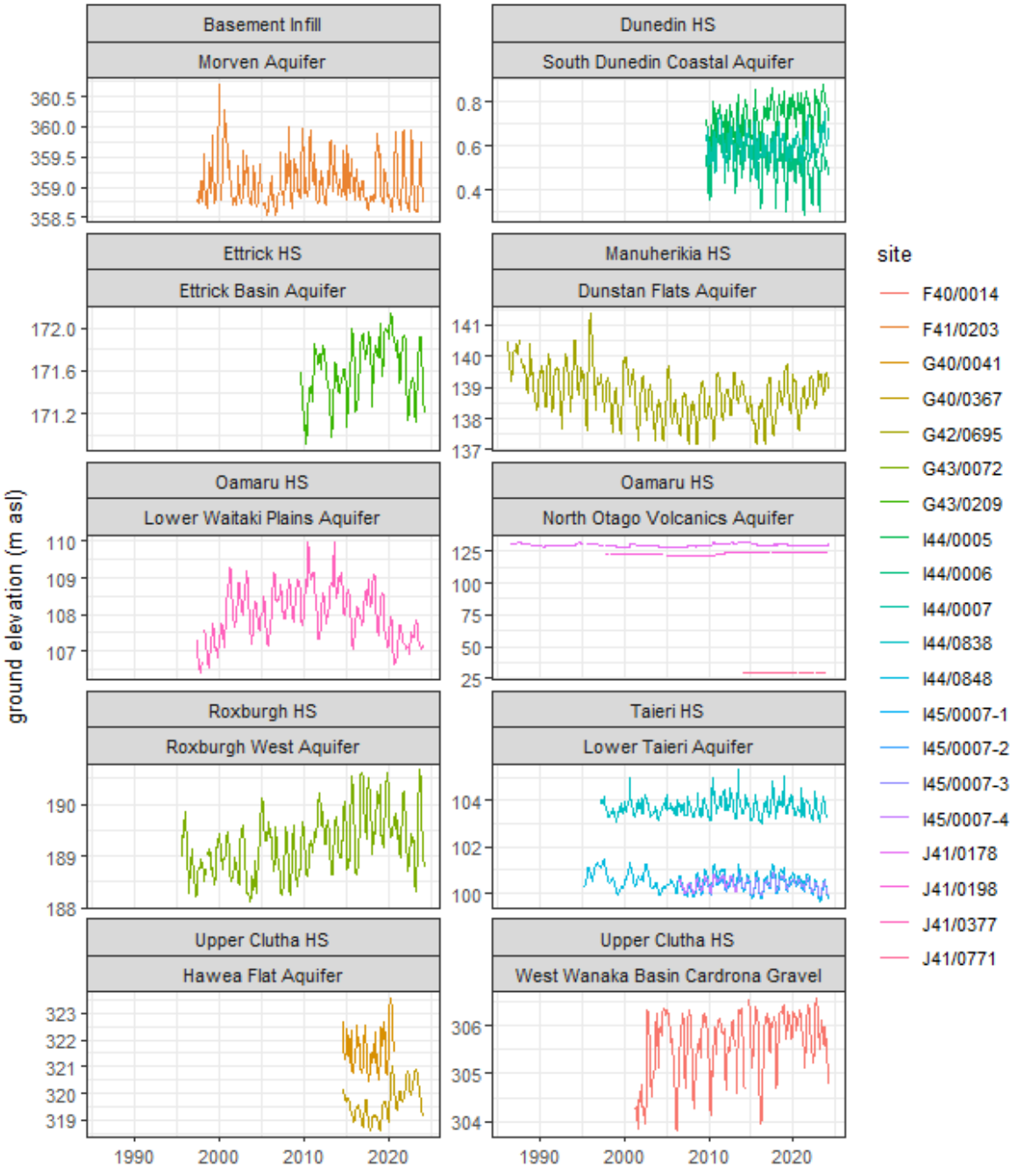


Figure 4.1 Groundwater elevation time series in metres above sea level (m asl) for Otago Regional Council groundwater level monitoring bores, grouped by HS and aquifers. Line colours refer to specific monitoring bores.

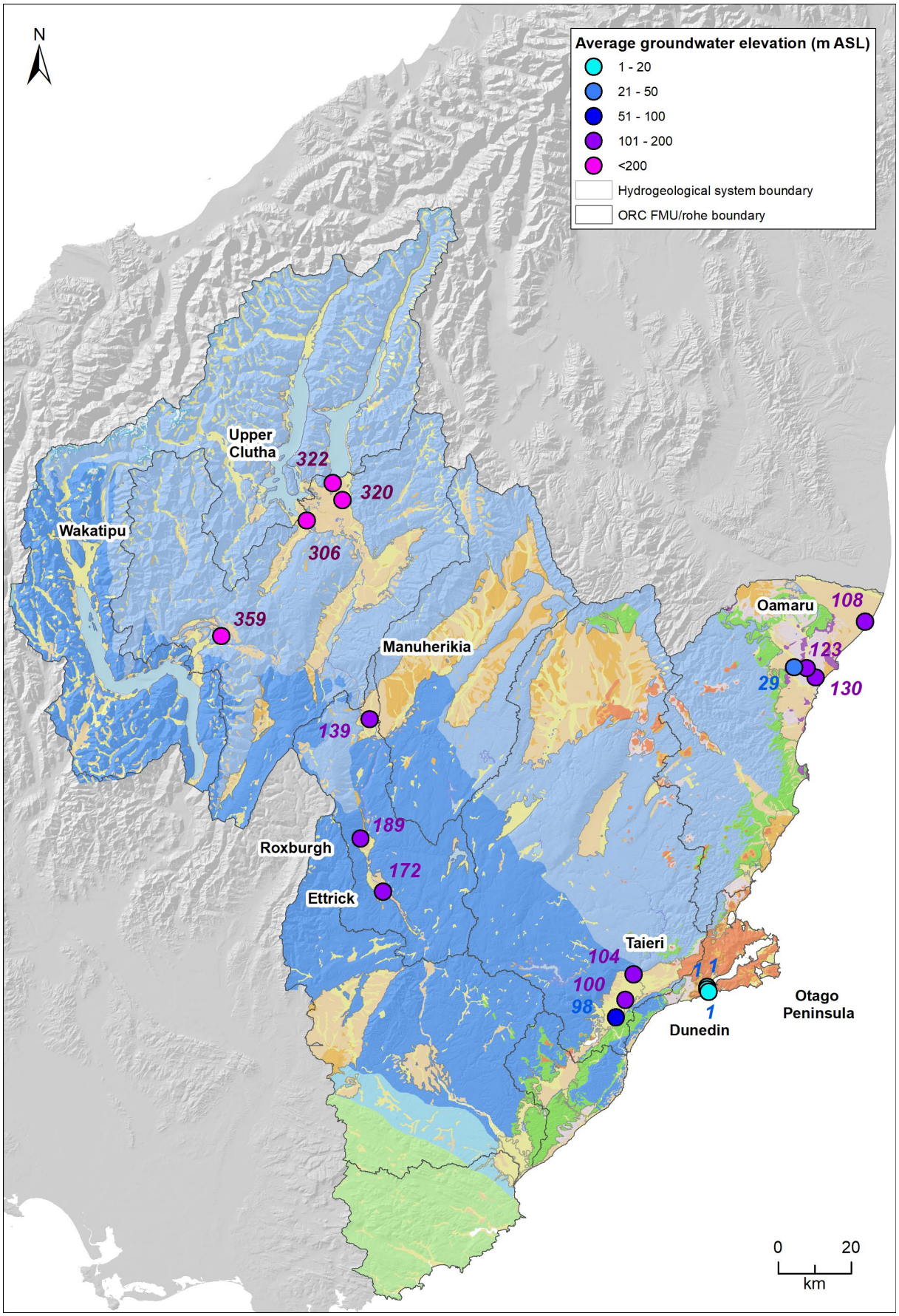


Figure 4.2 Spatial distribution of mean groundwater elevation for Otago Regional Council groundwater level monitoring bores in metres above sea level (m asl).

## 4.3 Hierarchical Cluster Analysis

HCA (Section 3.3) was performed on the hydrochemistry dataset to group sites with similar hydrochemistry. HCA results are displayed as a dendrogram (Figure 4.3). Each vertical line ends at a single sample site. Horizontal lines join hydrochemical groups. The similarity between sites and groups of sites is indicated by the height up the y-axis (distance) of the respective connecting horizontal line. Low horizontal lines join sites with the most similar chemistry. Selection of appropriate threshold lines divides the sites into clusters with similar chemistry.

### 4.3.1 First Clustering Threshold

At the highest threshold the data (n=123) can be divided into three clusters: A, B and C (Figure 4.3):

- Cluster A (n=20) comprises reduced groundwaters with low dissolved oxygen (DO), elevated concentrations of iron (Fe), manganese (Mn) and ammonia ($NH_3$-N).
- Cluster B (n=61) consists of low total dissolved content or conductivity (EC) and low acidity (pH).
- Cluster C (n=42) shows signs of land-use impact, manifested by elevated concentrations of calcium (Ca), magnesium (Mg), potassium (K), chloride (Cl), sulphate ($SO_4$), nitrate-nitrogen ($NO_3$-N), dissolved reactive phosphorous (DRP) and occasional high bicarbonate ($HCO_3$).

Measurements of dissolve silica ($SiO_2$) were only available for a limited number of sites, belonging to Cluster B.

### 4.3.2 Second Clustering Threshold

At the second threshold, Cluster A and Cluster C are each divided into two sub-clusters reflecting a range of aquifer systems and hydrochemical evolution. Five sub-clusters can be described as follows (Figure 4.3; Figure 4.4; Figure 4.5; Figure 4.6):

- Sub-cluster A1 (n=9) consists of reduced, high solute content, Ca-$HCO_3$ to Na-Cl type groundwaters. This cluster exhibits intermediate EC (centroid median of 455 µS/cm) and elevated Fe, Mn and $NH_3$-N concentrations (up to 31, 1.16 and 3.65 mg/L, respectively), indicating reduced conditions. Bores have very shallow depths (median of 6.2 m) and are located in the Shag Alluvium (Inland River Valley HS), the Maniototo Tertiary (Maniototo HS) and Inch Clutha Gravel (Inch Clutha HS) aquifers.
- Sub-cluster A2 (n=11) comprises reduced, dilute, Ca-$HCO_3$ to Na-$HCO_3$ type groundwaters. This sub-cluster shows lower EC (median of 151 µS/cm) but also exhibits reducing conditions (all median DO <0.5 mg/L). The maximum $NO_3$-N concentration is 0.065 mg/L. Bores are located within the Glenorchy and Kingston groundwater management zones and the Ladies Mile Aquifer (Wakatipu HS), the Tokomairiro groundwater management zone and the Lower Taeri Aquifer (Taieri HS) and unnamed aquifers from the Maniototo and Paerau HS.
- Sub-cluster B is the largest cluster (n=61) and consists of mostly oxidised, dilute, Ca-$HCO_3$ type groundwaters. EC ranges from 57 to 323 µS/cm. Where DO is recorded below 3.5 mg/L, it is not accompanied by elevated Fe or Mn concentrations. $NO_3$-N concentrations range from 0.03 to 5 mg/L. This cluster contains samples from the deepest bores (maximum 110 m), distributed mostly in the Upper Clutha HS.

- Sub-cluster C1 (n=26) comprises oxidised, intermediate solute content with signs of impacted groundwaters of mixed Ca-$HCO_3$ to Na-Cl type. This sub-cluster exhibits intermediate EC (median of 244 µS/cm) and mostly oxidised conditions. Where DO is recorded below 3.5 mg/L, it is not accompanied by elevated Fe or Mn concentrations. $NO_3$-N concentrations range from 0.01 to 12 mg/L. Bores have relatively shallow depths (<25 m) and are located regionwide, e.g. in the Ettrick Basin (Ettrick HS), the Manuherikia Alluvium and Claybound (Manuherikia HS), Kakanui-Kauru Alluvium, the Lower Waitaki Plains and the North Otago Volcanics (Oamaru HS), the Shag Alluvium (Inland River Valley HS), the Lower Taieri (Taieri HS), the Pomahaka Alluvial Ribbon and Pomahaka Basin aquifers (Waikaka HS), the Wairuna Basin (Tuapeka HS) and unnamed aquifers from the Paerau, Roxburgh HS.
- Sub-cluster C2 (n=16) consists of oxidised, impacted groundwaters of mixed Ca-$HCO_3$ to Na-Cl type. This sub-cluster displays the highest EC (median of 582 µS/cm) and mostly oxidised conditions. Where DO is recorded below 3.5 mg/L, it is not accompanied by elevated Fe or Mn concentrations. $NO_3$-N concentrations exhibit a wide range with a maximum of 19.8 mg/L. Higher $NO_3$-N concentrations are concurrent with elevated Ca, Mg, K, $HCO_3$ and $SO_4$ concentrations, which is consistent with land-use impact. Bores have relatively shallow depths (<25 m) and are located regionwide.

### 4.3.3 Separate HCA Analysis for the Upper Clutha HS

The majority of Cluster B sites (72%) are located in the Upper Clutha, inducing a statistical bias. As Otago's aquifer systems are hydraulically disconnected from one another, to further define hydrochemistry in the Upper Clutha HS, a separate HCA analysis was undertaken on only data from this area instead of using further separation thresholds to refine Cluster B. This second HCA analysis identified three subclusters:

- Sub-cluster UC1 (n=18) consists of higher solute content with a centroid EC median of 207 µS/cm. $NO_3$-N concentrations range from 0.04 to 19.8 mg/L. Bores are located along the rivers away from lakes Wanaka and Hawea, systemwide.
- Sub-cluster UC2 (n=19) comprises intermediate solute content with a centroid EC median of 137 µS/cm. $NO_3$-N concentrations range from 0.14 to 2.6 mg/L. Most bores are located downstream of lakes Wanaka and Hawea.
- Sub-cluster UC3 (n=7) consists of dilute Ca-$HCO_3$ groundwaters with a centroid EC median of 80 µS/cm. $NO_3$-N concentrations range from 0.17 to 1.7 mg/L. Most bores are located immediately south of Lake Hawea and sourced from the Hawea Flat, the High Terrace aquifers and the Luggate groundwater management zone.

For the remainder of the document, both HCA results are amalgamated to represent eight clusters (A1, A2, B, C1, C2, UC1, UC2 and UC3) (Table 4.1). This amalgamation means that one site from Sub-cluster C2 was reattributed to Sub-cluster UC1 (F41/0300) and 43 sites from Sub-cluster B were re-assigned to Sub-clusters UC1, UC2 or UC3.

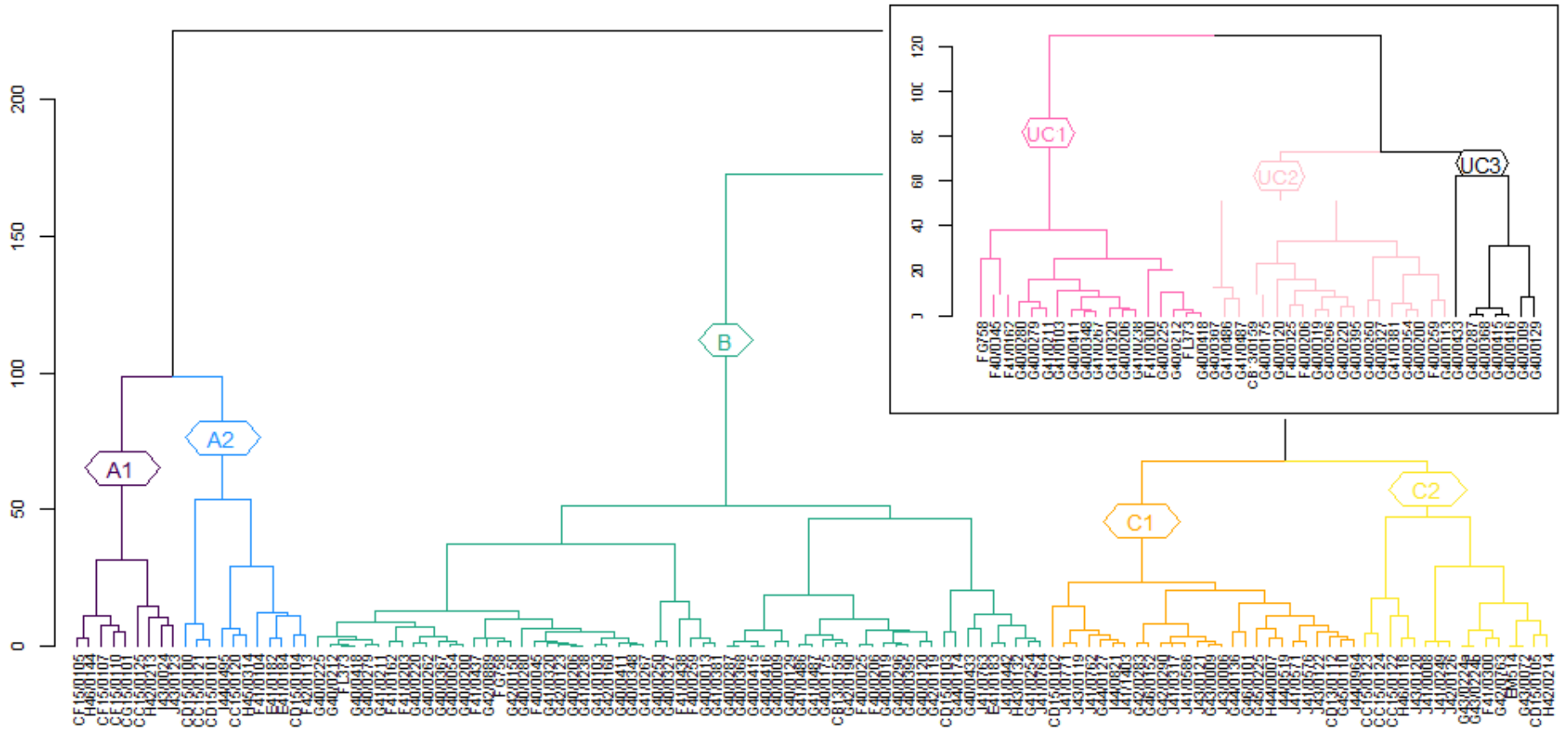


Figure 4.3 Dendrogram produced by hierarchical cluster analysis (HCA) for all Otago data (mainframe) and the Upper Clutha HS (inset). The vertical axis represents the distance or dissimilarity between clusters.

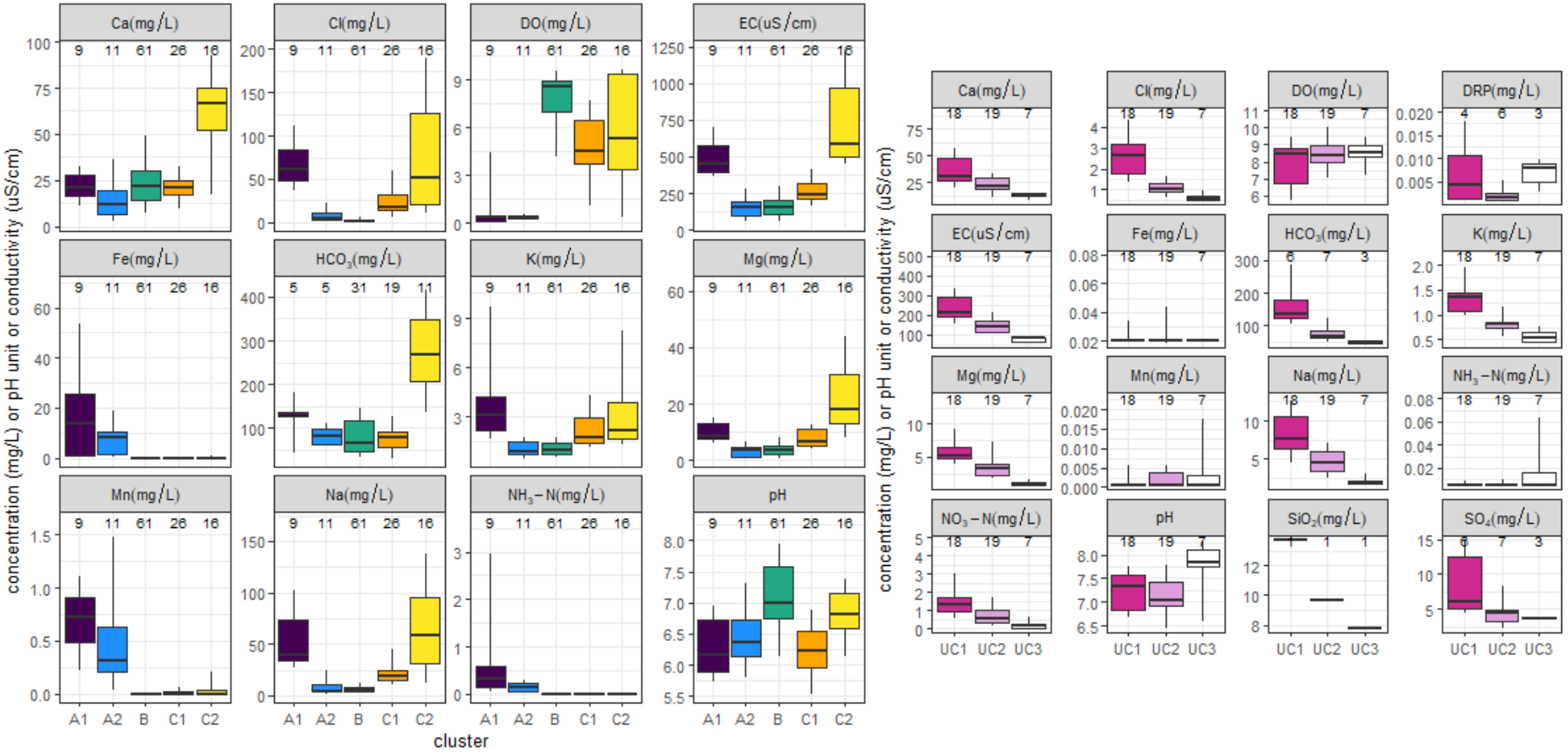


Figure 4.4 Box plots of hydrochemistry parameters organised by second threshold clusters for all Otago data and the Upper Clutha HS (inset). The number displayed above each box plot indicates the sample size. The horizontal lines in the middle of each box are median values and the upper and lower limit of the box are the 75$^{th}$ and 25$^{th}$ percentiles, respectively. The vertical lines extend from the 95$^{th}$ to the 5$^{th}$ percentiles.

Table 4.1 Hierarchical cluster analysis (HCA) sub-clusters, showing the number of bores represented, water type, and a general description of notable hydrochemistry for each sub-cluster after the re-attribution of some of the Sub-cluster B sites.

| Cluster | Number of Sites | Water Type | Description |
|---|---|---|---|
| A1 | 9 | Mixed water types: Ca-HCO3 to Na-Cl | Reduced, high solute content. |
| A2 | 11 | Mixed water types: Ca-HCO3 to Na-HCO3 | Reduced, dilute. |
| B | 17 | Ca-HCO3 | Oxidised, dilute. |
| C1 | 26 | Mixed water types: Ca-HCO3 to Na-Cl | Oxidised, intermediate solute content, signs of impact. |
| C2 | 15 | Mixed water types: Ca-HCO3 to Na-Cl | Oxidised, impacted. |
| UC1 | 19 | Ca-HCO3 | Higher solute content. |
| UC2 | 19 | Ca-HCO3 | Intermediate solute content. |
| UC3 | 7 | Ca-HCO3 | Dilute solute content. |

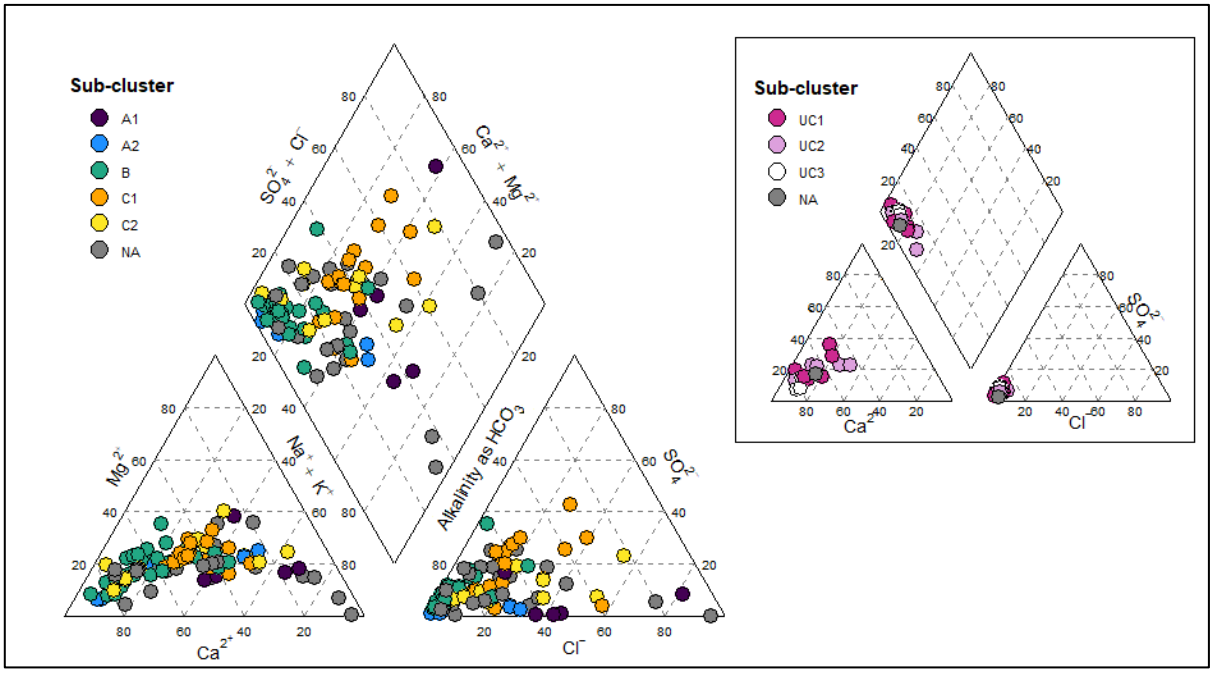


Figure 4.5 Piper diagram showing the variation of major ion chemistry by sub-clusters for all Otago data (mainframe) and for the Upper Clutha HS (inset). The left and right triangles show the major cation and anion ratios on an equivalence basis, respectively. The central diamond plots give projections based on the two cation and anion triangular plots. Sites are grouped into sub-clusters assigned by hierarchical cluster analysis (HCA). NA means that these sites were not assigned a cluster (i.e. not complete cases).

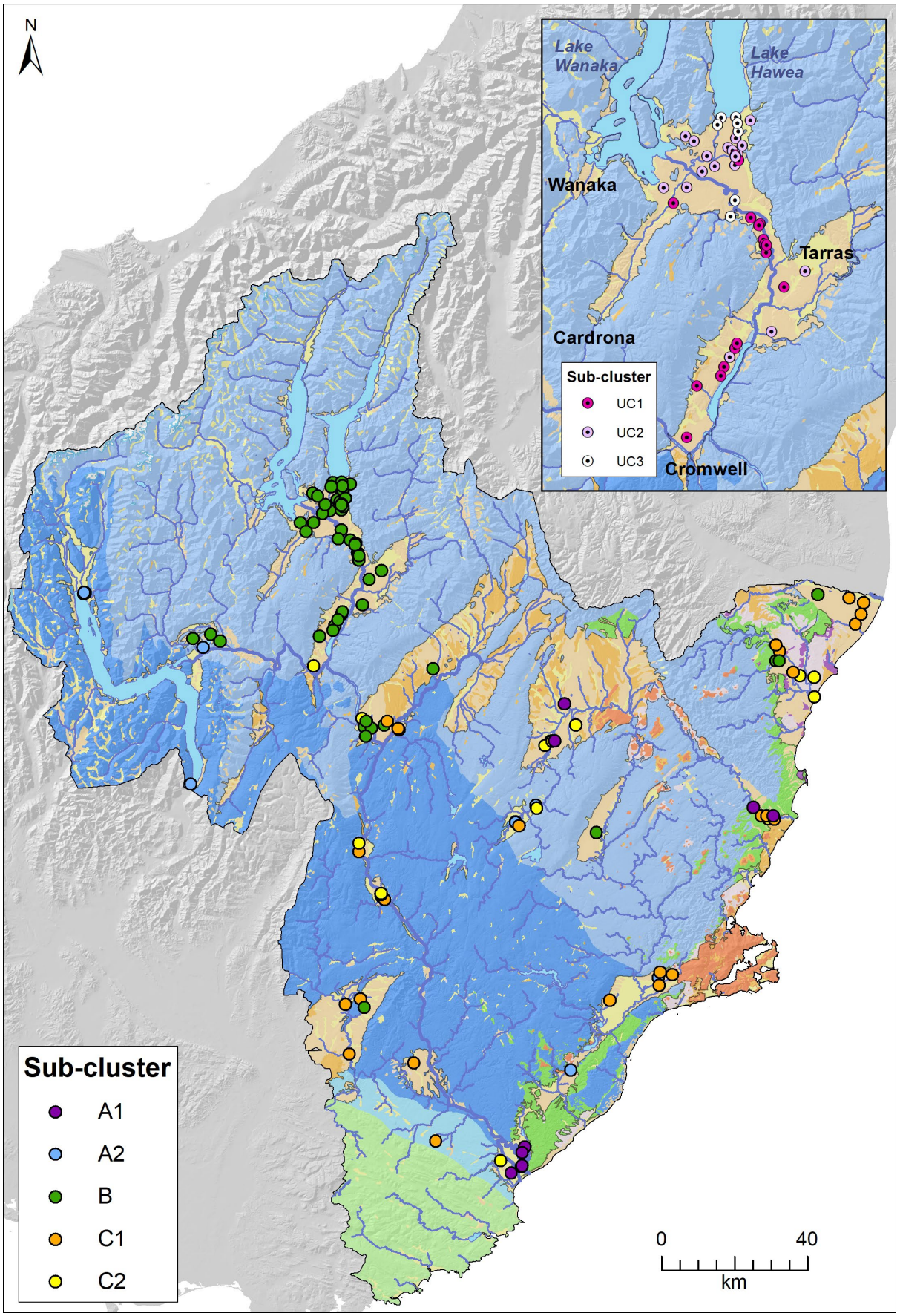


Figure 4.6 Geographic distribution of the study sites (bores) assigned to sub-clusters using hierarchical cluster analysis (HCA).

## 4.4 Water Age

### 4.4.1 Groundwater Residence Time

#### *4.4.1.1 Age Tracer Results*

Otago's groundwaters range from relatively young (MRT <5 years) to old water (MRT >200 years). Sub-cluster B and C2 sites are associated with very young waters and shallow wells. In contrast, the deepest and oldest groundwaters occur in Sub-clusters UC1, A1 and A2 (Figure 4.7). Wells located in the Basement Hard Rock and Basement Infill systems exhibit young ages (<10 years) (Figure 4.7; Figure 4.8). A wide range of MRTs are encountered in the inland systems (e.g. Manuherekia HS), with the Wakatipu HS and the Taieri HS exhibiting the widest ranges (Figure 4.7; Figure 4.8; Figure 4.9). At the coast, the Inch Clutha and Taieri HS exhibited older groundwaters (>50 years), with most measurements located in Mosgiel. Along the Shag Inland River Valley HS and the Oamaru HS, groundwaters are mostly young (<10 years) in the shallow aquifers. The oldest groundwaters appear as isolated cases, with one occurrence in a 30-m-deep well (Well CC18/0110) in the Oamaru HS and a 12.6-m-deep well located in the Dunedin HS (Well CE17/0106), which exhibits signs of saltwater intrusion.

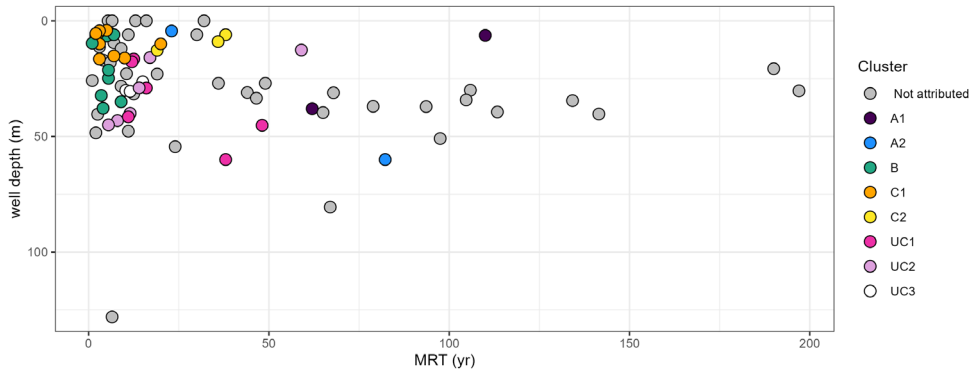


Figure 4.7 Mean residence time (MRT) (years) per well depth in m (right) for Otago's groundwaters.

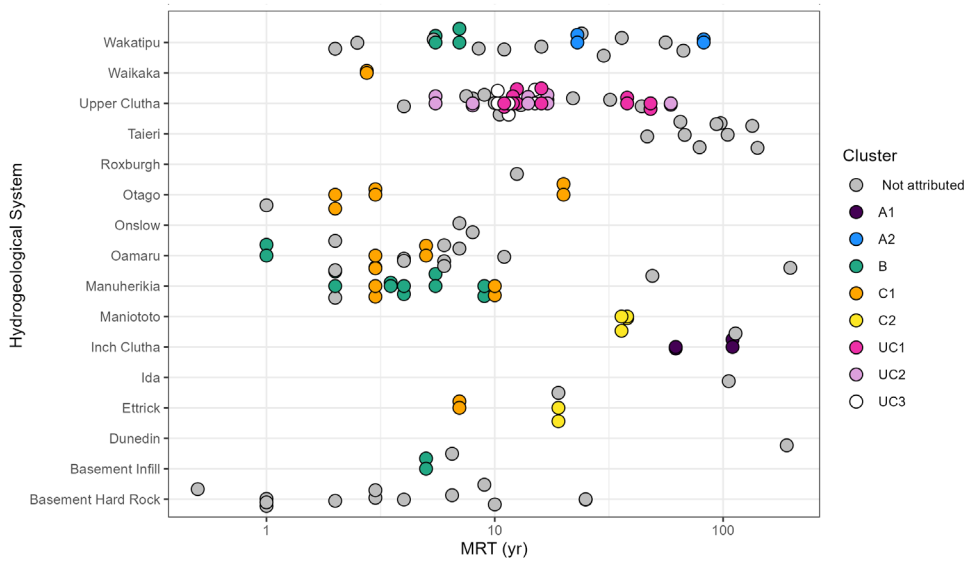


Figure 4.8 Mean residence time (MRT) (years) per Hydrogeological System (left) and well depth in m (right) for Otago's groundwaters. Data was allowed to jitter vertically to enhance visibility.

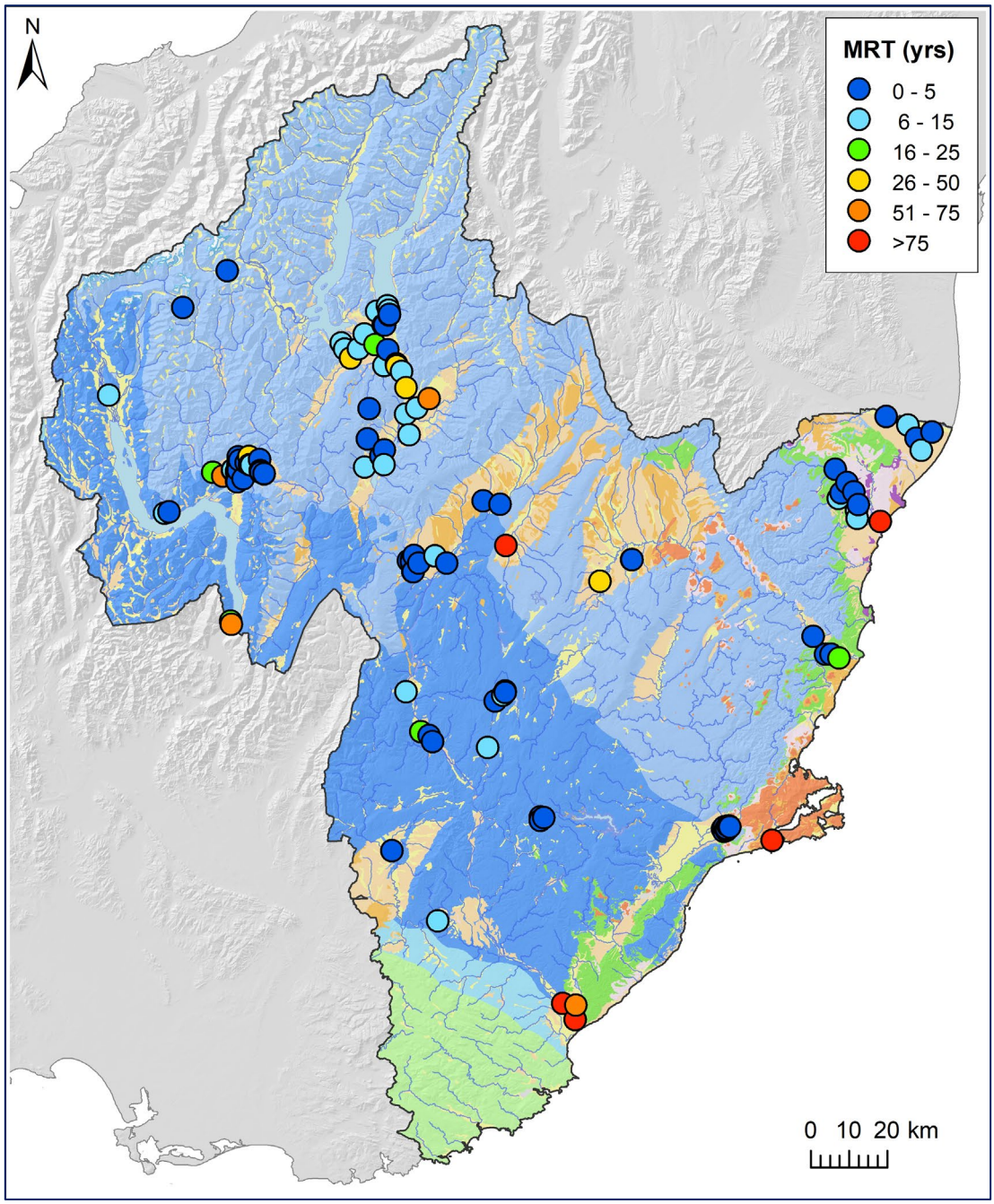


Figure 4.9 Map of groundwater mean residence time (MRT) in years.

For the interpretation of age tracers, it is important to keep in mind that gas tracers in groundwater samples can be contaminated due to air contact during sampling or in the well head, and in the aquifer due to anthropogenic sources in the recharge area (Section 3.1). Modern atmospheric concentrations of these gases are around 225 ppt, 510 ppt, 72 ppt, 3.5 ppt and 9.5 ppt, for CFC-11, CFC-12, CFC-13, Halon-1301 and $SF_6$, respectively. Concentrations above these levels are considered to be contaminated with other sources of these tracers. About 30% of the sampled sites show CFC contamination, indicating the presence of local contamination sources. These elevated point source CFC concentrations can be used to identify recharge from local rain, as elevated CFC concentrations do not occur in river water. $SF_6$ contamination can be seen in 10% of the sites (Figure 4.10). Age tracer contaminated sites occur in the Wakatipu, Upper Clutha, Oamaru, Manuherikia and Dunedin HS and at one location upgradient from the Upper Clutha HS (Figure 4.10). At these sites, gas tracer data was not used for age interpretation and was based on tritium measurements.

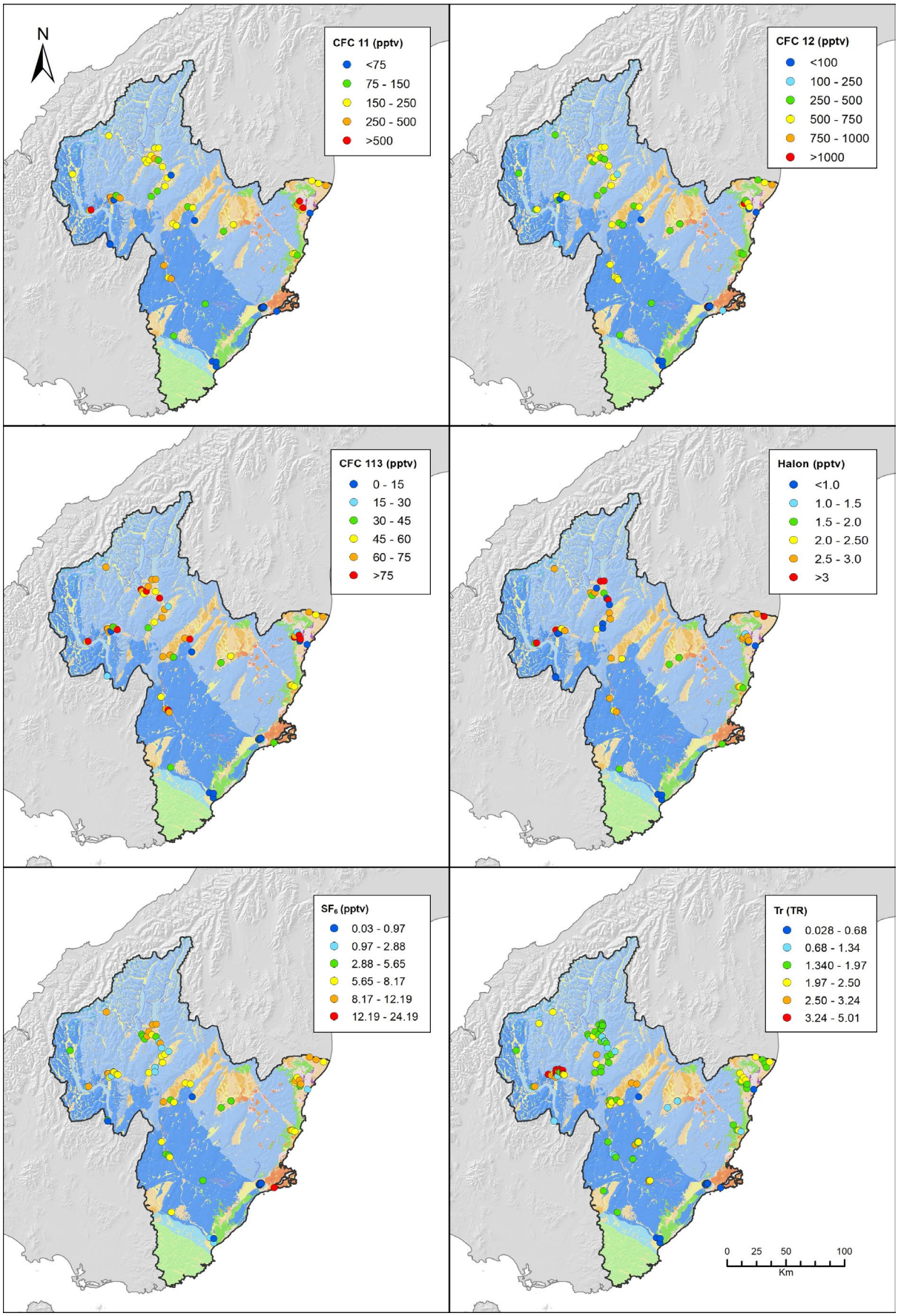


Figure 4.10 Age tracer measurements for groundwaters in Otago. Raw tritium ratios (TR) are displayed in tritium units. Modern atmospheric concentrations of these gases are around 225 ppt, 510 ppt, 72 ppt, 3.5 ppt and 9.5 ppt, for CFC-11, CFC-12, CFC-13, Halon-1301 and $SF_6$, respectively. Concentrations above these levels are considered to be contaminated with other sources of these tracers (shown in red).

## 4.5 Stable Isotopes

In the region, stable oxygen isotope values ($\delta^{18}O$) in groundwater are increasingly negative as elevation rises, indicating that rainfall-recharge is a dominant recharge process, with less negative ratios towards the coast (Figure 4.11; Figure 4.12).

Stable isotopes in rainfall are correlated with ground elevation, with less negative values occurring at the coast. Comparing surface water and groundwater $\delta^{18}O$ values, local differences suggest multiple recharge sources throughout the region (Figure 4.12; Lachniet et al 2021). For instance, in the data-rich Upper Clutha HS, $\delta^{18}O$ values of groundwater are bimodal with nine sites centred around -10.5 ‰ similar to surface water $\delta^{18}O$ values, whereas three sites exhibit less negative $\delta^{18}O$ values, *c.* -9 ‰, which matches the isotopic signature of tributaries located at higher elevation. This is consistent with a detailed piezometric survey from September 2011 (Wilson 2012). Groundwater at three sites in the Upper Clutha HS (Butterfields Spring, G40/0415 and G40/0416) is sourced from higher elevations and is less connected to surface water in the basin, whereas the remaining sites are likely to be in hydraulic continuity with the rivers. These three sites belong to Sub-cluster UC3. Similar bimodal groundwater distributions are observed in the Manuherikia and Oamaru HS. Coastal rainfall recharge, with less negative $\delta^{18}O$ values, can be seen in some groundwaters from the Inch Clutha and Oamaru HS.

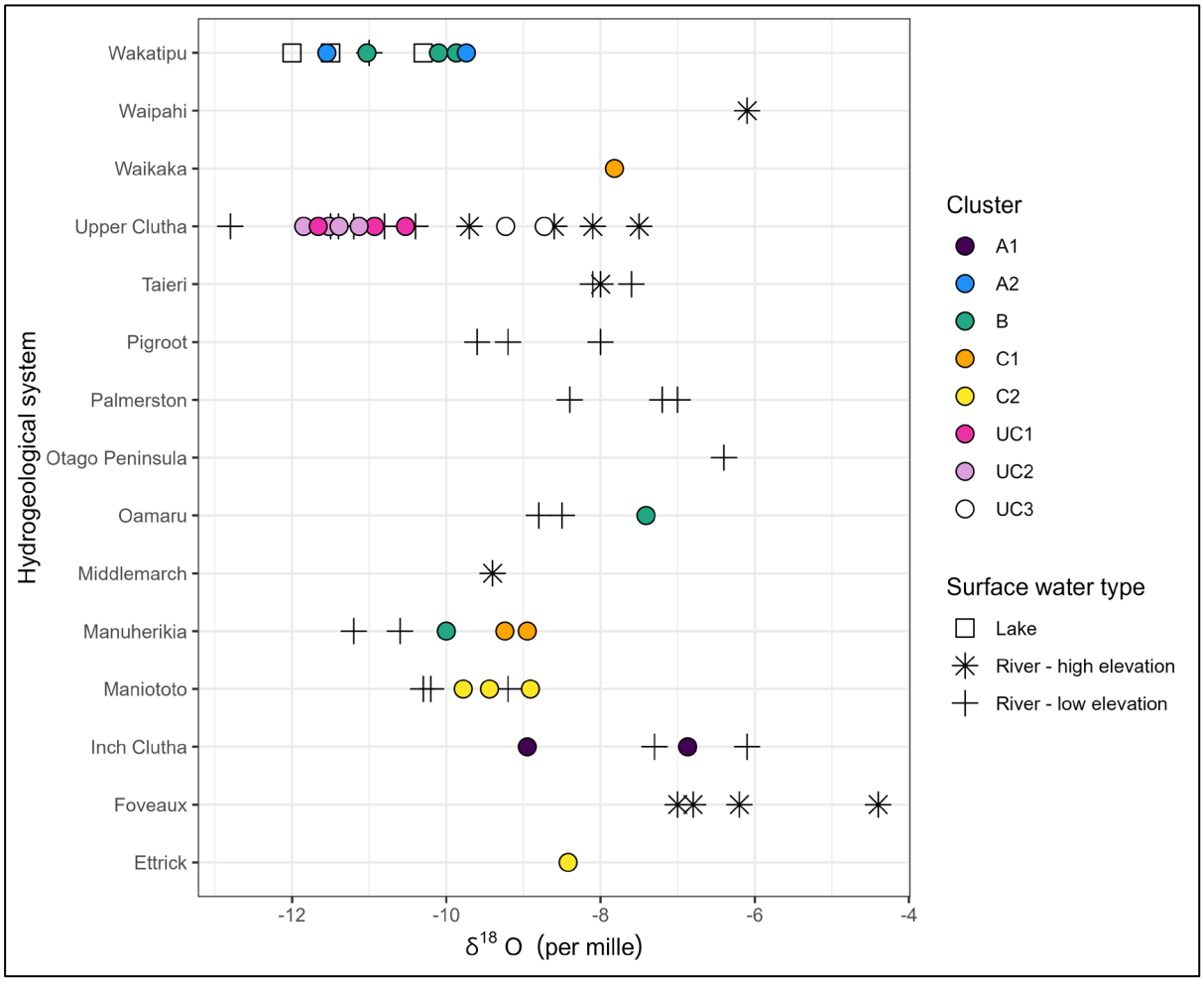


Figure 4.11 Groundwater and surface water $\delta^{18}O$ values grouped by hydrogeological systems and is shown by hierarchical cluster analysis (HCA) cluster. Surface water samples were obtained from multiple locations within each basin, including headwaters and tributaries, which explain the wide range in surface waters (Lachniet et al. 2021).

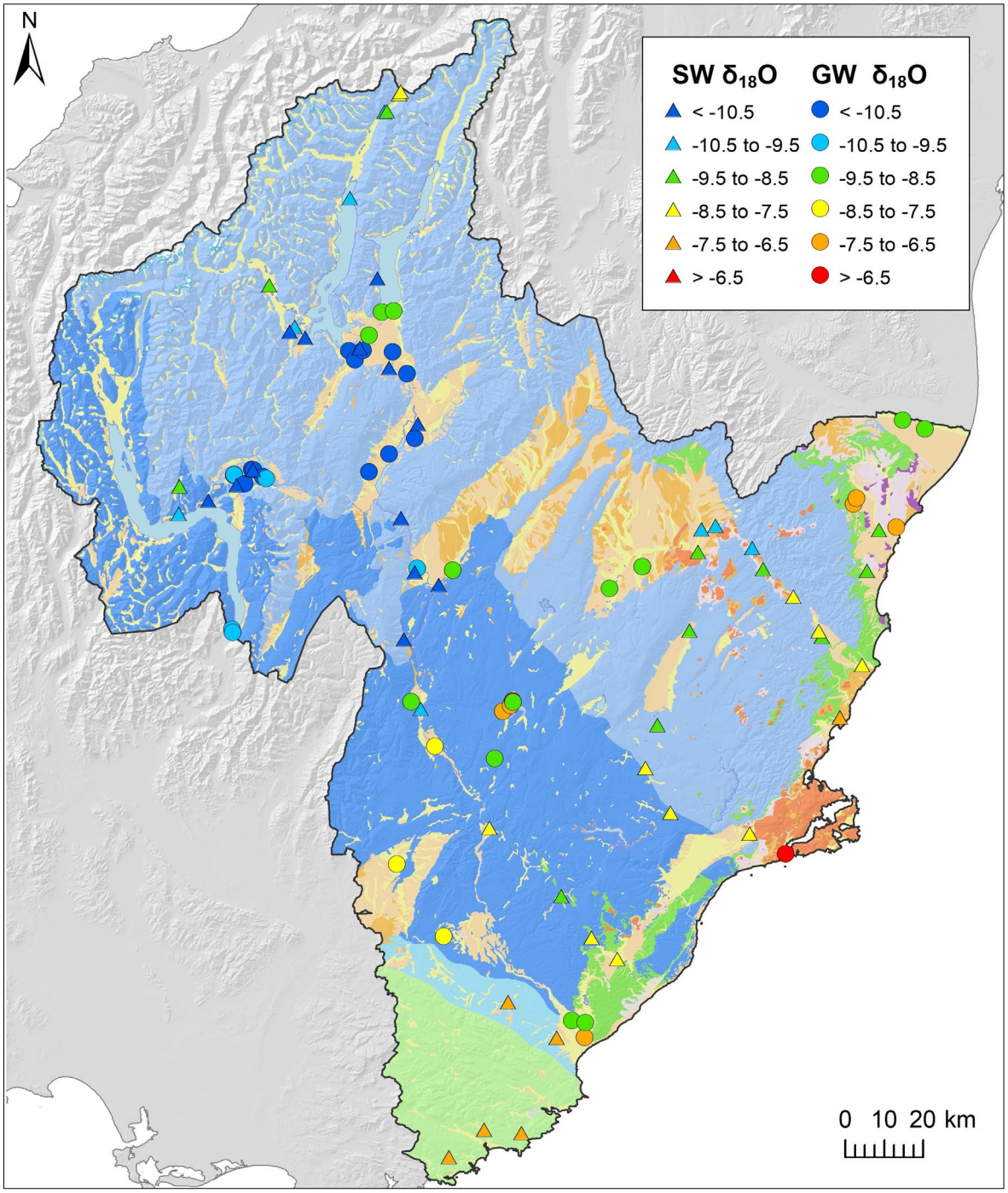


Figure 4.12 Spatial distribution of $\delta^{18}O$ values in groundwater (compiled in this study) and surface water samples from Lachniet et al. (2021).

## 4.6 Hydrochemistry

In the following figures, groundwater hydrochemistry parameters are shown versus MRT to identify drivers of hydrochemistry and the impacts of land use versus natural processes on groundwater quality. Note that all MRTs >100 years result from data close to the tritium detection limit and may be significantly older (potentially thousands of years). The numbers only indicate the estimated minimum MRT.

During the process of natural groundwater evolution, aquifer matrix minerals are progressively dissolved over time and increasing ion concentrations with increasing groundwater age indicate a geological source due to leaching from the aquifer material. In contrast, high

concentrations (in particular those of nutrients) in young groundwater indicate anthropogenic sources from land-use activities. Groundwater quality in the region is generally consistent with elsewhere in the country, with lower Na, Cl and K concentrations and occasional reducing conditions, and can be affected by seawater intrusion at the coast (Table 4.2).

Table 4.2 Hydrochemistry statistics, showing the number of wells, minimum and maximum concentrations and the 25th, 50th and 75th percentiles for all hydrochemistry data from wells with groundwater age-tracer data. The New Zealand percentiles, shown for comparison, are for groundwater quality data obtained from over 1000 sites collected as part of SOE monitoring programmes run by regional authorities and compiled by the New Zealand Ministry for the Environment (Daughney and Wall 2007).

| Parameter | Units | Otago Data | | | | | | New Zealand Percentiles | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Min. | 25% | 50% | 75% | Max. | 25% | 50% | 75% |
| **Ca** | mg/L | 256 | 0.74 | 12.9 | 20.8 | 32 | 164 | 9.6 | 15.5 | 30 |
| **Cl** | mg/L | 265 | 0.265 | 2.6 | 6.6 | 31 | 2100 | 7.3 | 15.3 | 30.1 |
| **$HCO_3$** | mg/L | 120 | 11 | 57.9 | 97 | 154 | 427 | 40 | 62.7 | 145 |
| **K** | mg/L | 165 | 0.18 | 0.85 | 1.39 | 2.2 | 27 | 1 | 1.6 | 3.7 |
| **Mg** | mg/L | 166 | 0.06 | 2.62 | 4.9 | 8.5 | 113 | 2.6 | 4.6 | 8.5 |
| **Na** | mg/L | 209 | 1.46 | 5.2 | 10.2 | 27.4 | 1020 | 9.4 | 15 | 29.6 |
| **$NO_3$-N** | mg/L | 250 | <0.01 | 0.30 | 1.12 | 2.94 | 26 | <0.001 | 1.3 | 4.4 |
| **$SiO_2$** | mg/L | 8 | 7.3 | 7.9 | 10.7 | 13.1 | 13.9 | 13.5 | 17 | 29.5 |
| **$SO_4$** | mg/L | 91 | 0.015 | 4.1 | 9.7 | 20.5 | 104 | 3 | 6.5 | 13 |
| **DRP** | mg/L | 21 | 0.0011 | 0.002 | 0.006 | 0.022 | 0.057 | 0.01 | 0.02 | 0.07 |
| **Fe** | mg/L | 158 | <0.005 | 0.007 | 0.032 | 0.38 | 69 | 0.01 | 0.03 | 0.23 |
| **Mn** | mg/L | 172 | <0.005 | <0.02 | 0.005 | 0.07 | 23 | <0.001 | 0.01 | 0.24 |
| **$NH_3$-N** | mg/L | 160 | <0.02 | 0.006 | 0.011 | 0.058 | 13.1 | <0.001 | 0.01 | 0.06 |
| **Cond.** | µS/cm | 248 | 24.5 | 137 | 206 | 373 | 6640 | 145 | 210 | 371 |
| **pH** | pH unit | 130 | 5.28 | 6.165 | 6.58 | 6.9575 | 9.4 | 6.4 | 6.8 | 7.2 |

### 4.6.1 Redox Conditions

Fully oxygenated water in equilibrium with air has a DO concentration of *c.* 10.5 mg/L. In groundwater systems the water is separated from the atmosphere, and in the presence of organic matter or other electron donors (e.g. pyrite) the oxygen is consumed by microbial oxidation reactions. Reduction of oxygen is energetically the most favourable reaction that micro-organisms use, with the result that other reduction reactions (including denitrification) typically do not occur until most of the dissolved oxygen has been consumed. These reactions take time, and older waters usually become increasingly anoxic (Böhlke et al. 2002). Oxidised groundwater may contain $NO_3$-N, but would not contain significant concentrations of any elements or compounds that are only mobile under reducing environment, such as Fe, Mn, As or $NH_3$-N (Daughney and Wall 2007 [and references therein]).

Otago aquifers exhibit a range of redox conditions (median DO concentrations range from 0.25 to 12 mg/L) typical of oxygenated within unconfined aquifers to locally severely reducing environments (e.g. median Fe concentrations of 12.4 mg/L at CE17/0106). Most groundwaters

younger than 50 years are oxic, whereas older groundwaters in the region are reducing (Figure 4.13). A single measurement of $CH_4$ concentration in excess of 2000 µmol/L at Site CF15/0109 (Inch Clutha HS, MRT >100 years) indicates an advanced state of methane fermentation, possibly facilitated by the occurrence of organic material. Sub-clusters A1 and A2 are characterised by low DO and occasionally elevated Fe, as well as slightly higher concentrations of $CH_4$ and $NH_3$-N (Figure 4.14). In contrast, Sub-clusters B, C1, C2, UC2 and UC3 exhibit a range of DO; however, low DO values are not accompanied by elevated Fe, $CH_4$ or $NH_3$-N concentrations.

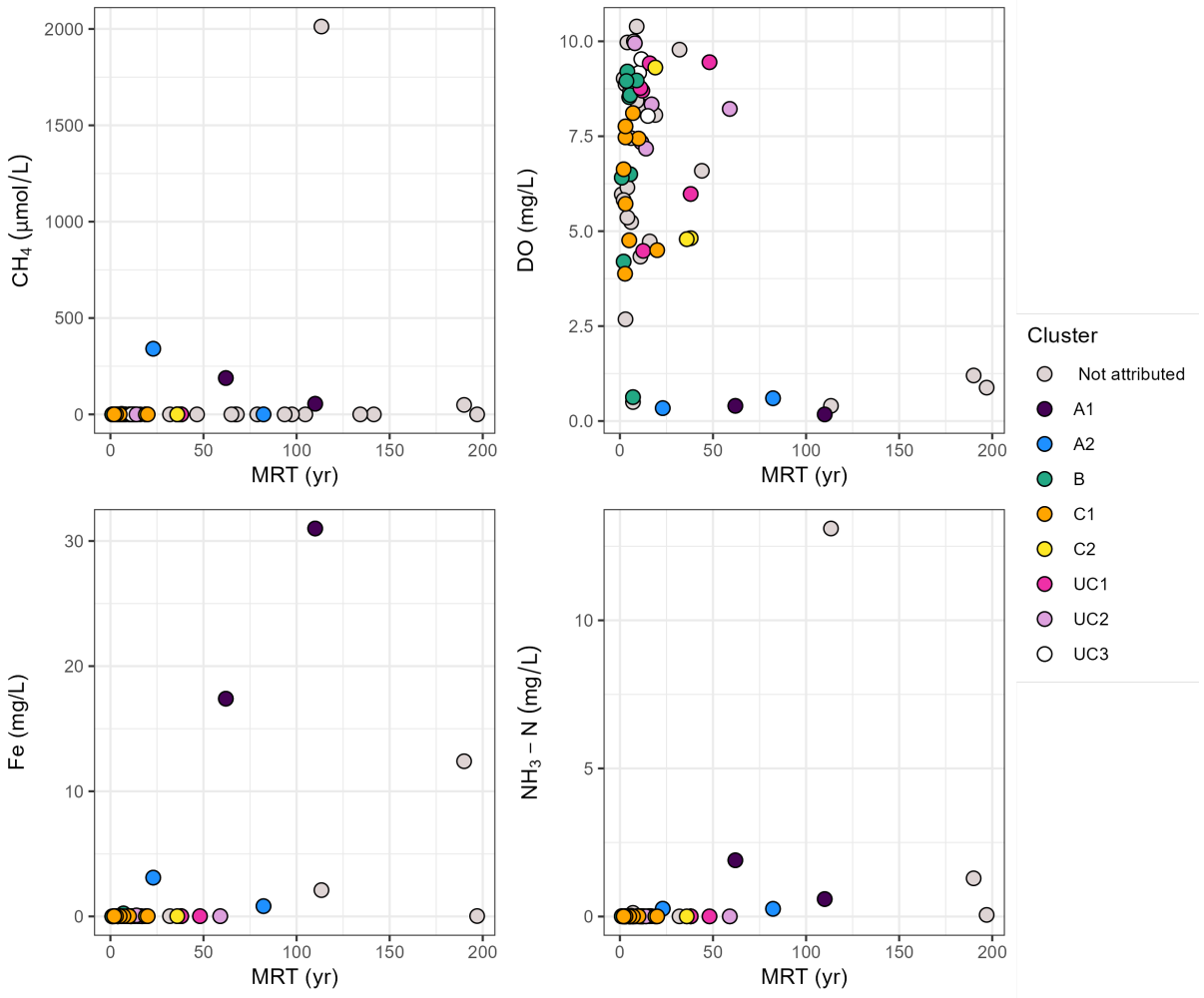


Figure 4.13 Dissolved oxygen, Fe, $CH_4$ and $NH_3$-N concentrations versus mean residence time for Otago groundwater. This hydrochemistry data originates from various sources over time. Note that this figure only includes sites at which both chemistry and age-tracer data are available, not the entire dataset.

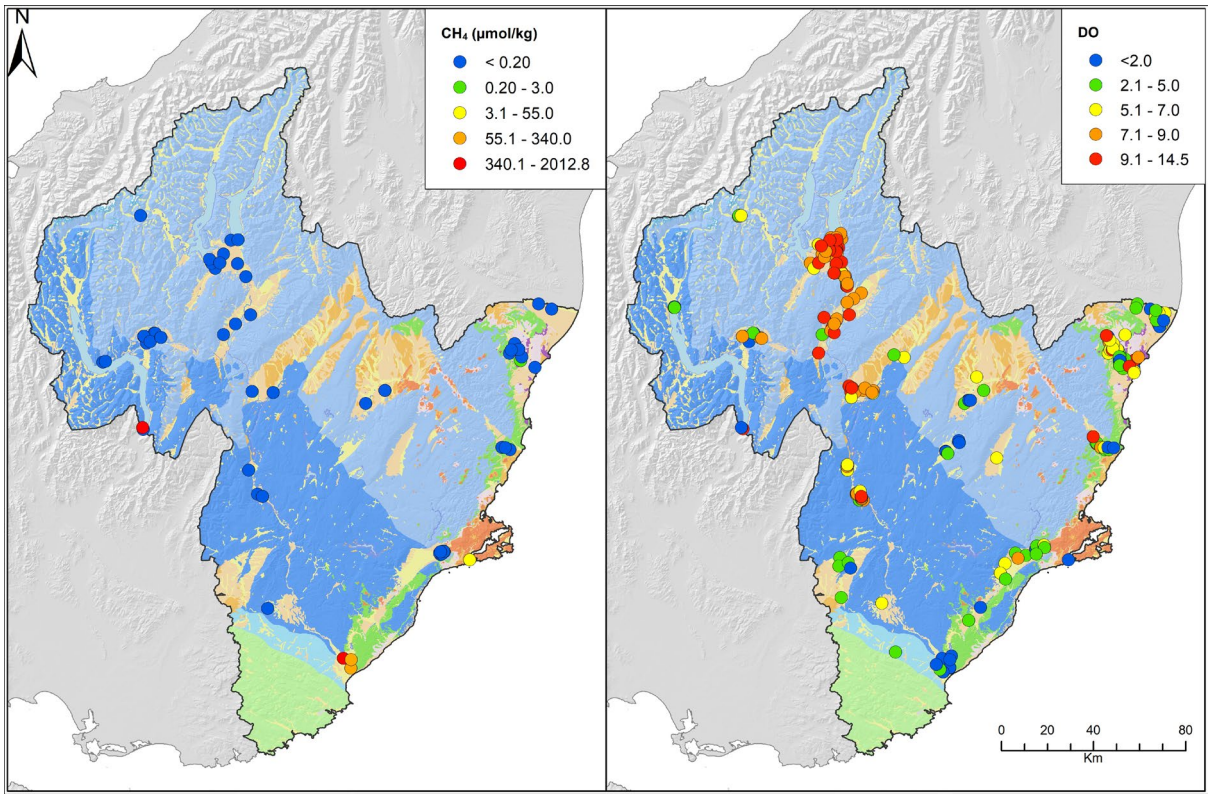


Figure 4.14 Maps of methane ($CH_4$) and dissolved oxygen (DO) in groundwater.

### 4.6.2 Nutrients

The main anthropogenic impacts on groundwater quality in New Zealand started with the onset of industrial agriculture in the 1950s, as deduced from the NGMP dataset (Morgenstern and Daughney 2012). Comparison of ion concentrations of recently recharged groundwater, and groundwater that was recharged before 1950, allowed the identification of the pre-industrial baseline groundwater quality and threshold concentrations for high-intensity land-use impacts on groundwater quality. Note that these thresholds are only applicable under oxic conditions (Table 4.3). At highly reduced sites, land use indicators, such as $NO_3$-N and $SO_4$, will naturally be converted into other forms, such as $NH_3$-N and sulphur gas, as part of the microbiologically facilitated reduction processes.

In Otago's oxic groundwaters (n=103), the $NO_3$-N, $SO_4$, Cl, Ca, Mg and Cr thresholds for impact by high-intensity land use in New Zealand were exceeded at 30%, 27%, 31%, 30%, 17% and 2% of the sites, respectively (Table 4.3). These exceedances were associated with shorter MRTs (<25 years).

High-intensity land use thresholds for $NO_3$-N and $SO_4$ were exceeded within Sub-clusters C1, C2 and occasionally B and UC1, with one C2 site exceeding the $NO_3$-N Drinking Water Standards Maximum Acceptable Value of 11.3 mg/L (Water Services Regulations 2022). Nitrate impacted sites were associated with MRTs ranging from two to 50 years, suggesting localised legacy loads or poor wellhead protection (Figure 4.15). The median $NO_3$-N concentrations ranged from 0.001 to 26 mg/L, with 73 sites above 2.5 mg/L. $NO_3$-N sources are likely due to land-use practices (e.g. agricultural activity or septic tanks) and bore security (Levy et al. 2021).

Table 4.3 Agricultural indicators for high-intensity land use, showing concentration ranges prior to high-intensity land use, threshold concentrations that indicate high-intensity agricultural land use and observed maximum concentrations in New Zealand (modified from Morgenstern and Daughney 2012). Threshold concentrations in brackets can be ambiguous as they may also be derived through other groundwater processes, such as water-rock interaction. * In this table, Site CE17/0106 (Dunedin System) was excluded as the chemistry indicated saltwater intrusion (Cl concentration >1,000 mg/L).

| Agricultural Indicator | Concentration Range Prior to High-Intensity Land Use (mg/L) | Threshold Concentration (mg/L) | Observed Maximum Concentration in Otago (mg/L) |
|---|---|---|---|
| $NO_3$-N | 0–2.5 | 2.5 | 26 |
| $SO_4$ | 0–12 | 12 | 104 |
| Cl | 0–60 | (60) | 342* |
| Br | 0–0.2 | (0.2) | 0.03 |
| Ca | 0–50 | (50) | 164 |
| Mg | 0–15 | (15) | 113 |
| Cr | 0–0.0015 | 0.0015 | 0.0026 |

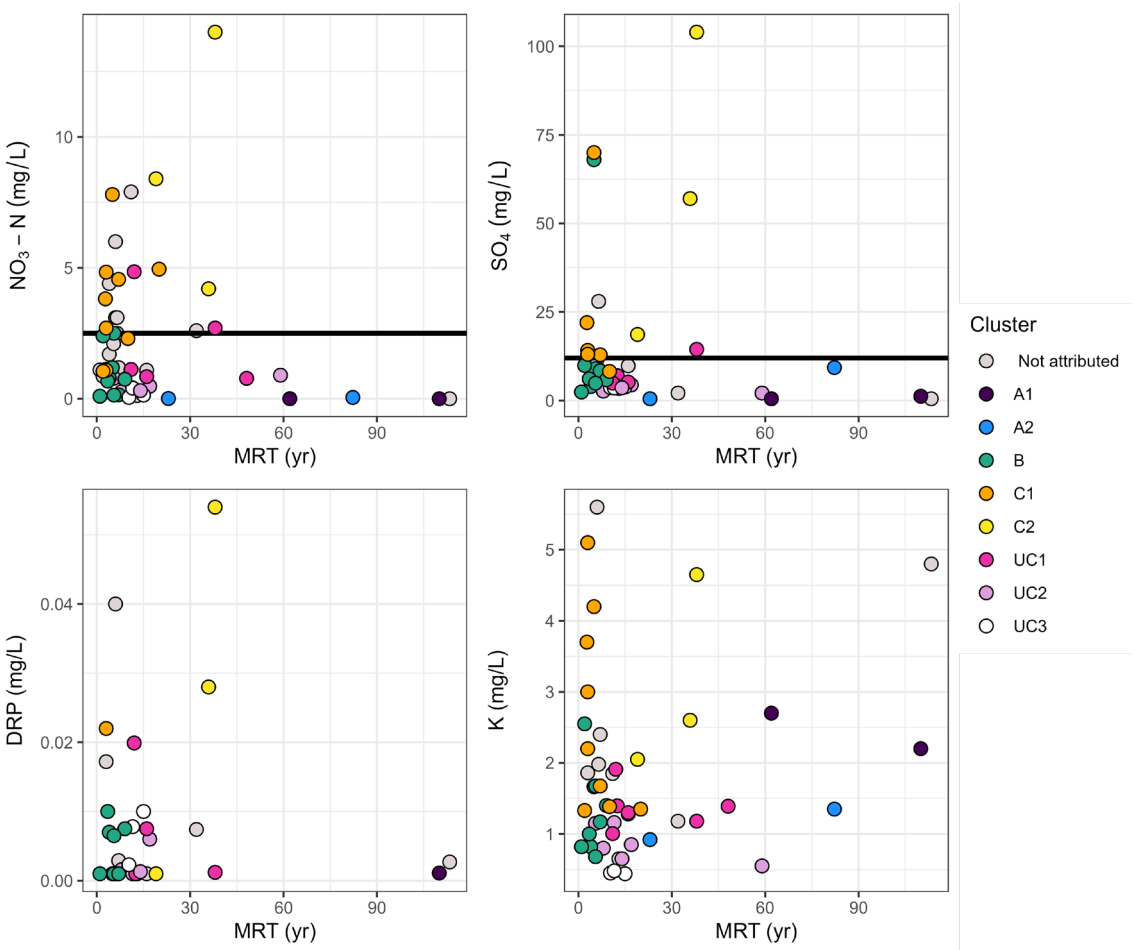


Figure 4.15 $NO_3$-N, $SO_4$, DRP and K concentrations versus mean residence time (MRT) for Otago groundwaters. Colour code refers to HCA clusters (Section 4.3.1). Solid lines indicate high-intensity land use thresholds (2.5 mg/L for $NO_3$-N and 12.5 mg/L for $SO_4$) for New Zealand groundwaters derived from hydrochemistry and age data (Morgenstern and Daughney 2012). Hydrochemistry data originates from various sources over time. Note this figure only represents sites at which both chemistry and age-tracer data were available. Samples with high MRT (>150) from CC18/0110 and CE17/0106 were excluded from this graph.

### 4.6.3 Hydrochemistry Evolution

Hydrochemical parameter concentrations are influenced by a range of underground processes, including dissolution of the aquifer material (Figure 4.16). Microbial redox processes can impact mineral dissolution, resulting in different trends of ion concentrations with MRT in many groundwaters of New Zealand (Morgenstern and Daughney 2012). The dataset is separated by HCA clusters, which reflect variations in the redox status of groundwaters.

Concentrations of Ca, Mg, Na, and $HCO_3$ generally increase with MRT (Figure 4.16). The highest concentrations for these species are observed in aquifers with MRT <50 years and consistent with land-use impact (Sub-cluster C2). Most groundwaters are close to the calcite dissolution line, albeit slightly depleted in Ca. The source of Ca and $HCO_3$ is likely to be limestone from the basement hills. The lower Ca concentrations are likely to be the result of cation exchange within clay surfaces, which occurs as MRT increases (Figure 4.17) (Wilson 2012). Samples from reducing Sub-clusters A1 and A2 exhibit higher MRTs, consistent with longer residence times.

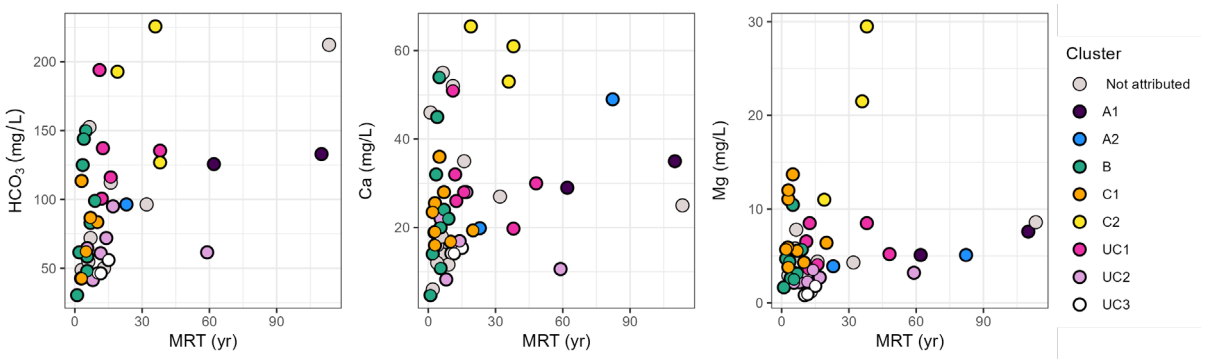


Figure 4.16 Ca, Mg and Na concentrations versus mean residence time (MRT) for Otago groundwaters.

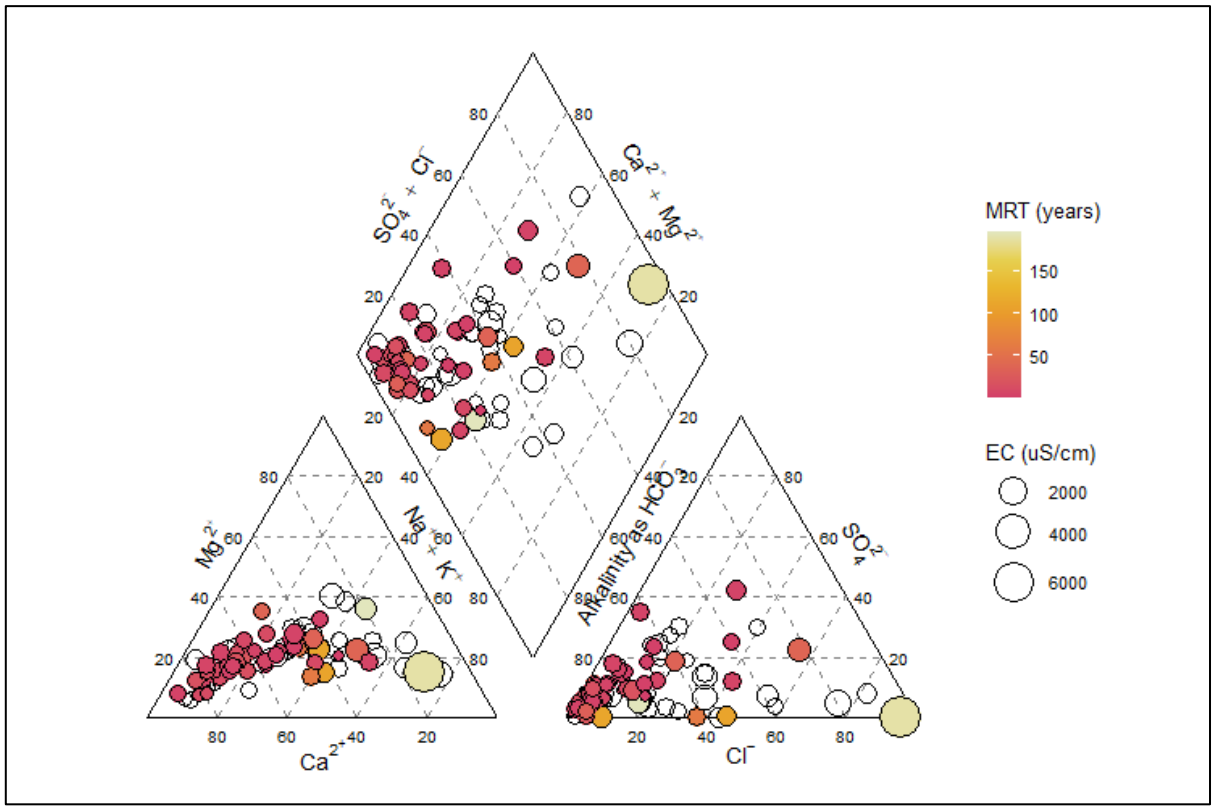


Figure 4.17 Piper diagram showing the variation of major ion chemistry for all Otago data. The left and right triangles show the major cation and anion ratios on an equivalence basis, respectively, and the centre diamond plots projections based on the two triangular plots. Sites are coloured by MRT and scaled by EC.

In the Oamaru HS, each aquifer exhibits a distinct chemical signature linked to the aquifer's lithology Figure 4.18:

- Dilute and Ca-$HCO_3$ type water in the Karu and Kakanui-Kaura alluviums and Lower Waitaki Plains.
- High total dissolved solids content, consistent with the dissolution of plagioclase for the basalt dominated North Otago Volcanics.
- Mineralised but virtually Ca-free for the Papakaio Aquifer (Tertiary basal conglomerate).

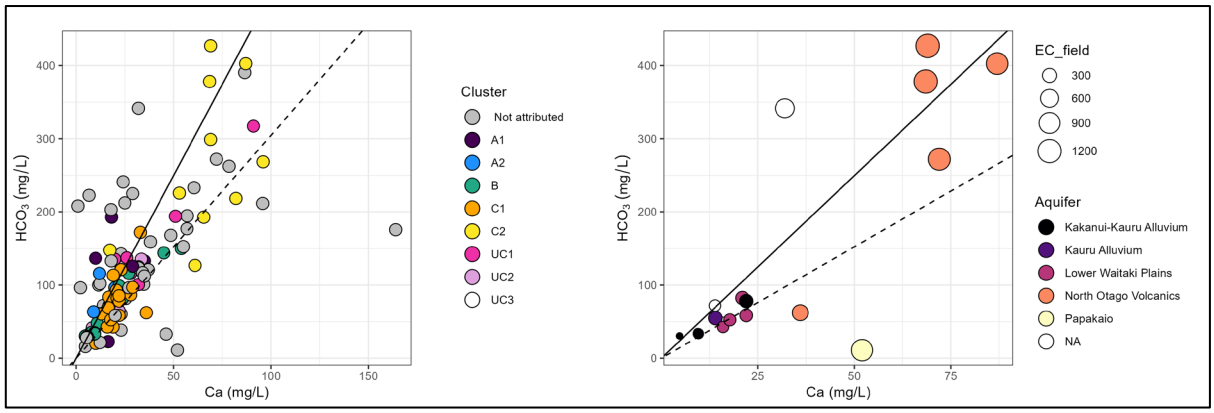


Figure 4.18 Plot of calcium against bicarbonate for groundwaters in the region (left) and the Oamaru System (right). The dashed line depicts ratios of bicarbonate and calcium that would be expected for the dissolution of plagioclase anorthite or calcite. The solid line indicates ratios of bicarbonate and calcium that would be expected for the dissolution of plagioclase.

### 4.6.4 Spatial Distribution of Selected Chemistry Parameters

In this section, examples of spatial distributions of chemistry parameters are shown that can inform recharge sources and flow patterns for the Otago groundwater systems.

#### *4.6.4.1 Chloride and $\delta^{18}O$*

Chloride ($Cl^-$) and $\delta^{18}O$ values are conservative tracers, which can be used to determine natural flow patterns in an aquifer, as long as there are no significant sources or sinks altering their concentrations. The stable isotope signature of meteoric water depends on the history of the water masses and temperature-dependent kinetic processes, such as seawater evaporation and re-precipitation. Rivers sourced from colder, higher-altitude catchments usually have a more depleted isotope signatures compared with low-altitude rain near the coast. Therefore, in the absence of sources and sinks, where groundwater has low Cl and $\delta^{18}O$ values, it indicates that it has been recharged by inland rivers or ice melt.

In the region, concurrently negative $\delta^{18}O$ values and low Cl concentrations occur inland in the west of Otago, suggesting recharge from rivers or ice melt (Figure 4.19). Although Cl concentrations are generally low in the region, coastal areas of Otago are higher, matched with higher $\delta^{18}O$ values suggesting recharge primarily from coastal rain rather than from rivers.

There were notable chloride hot spots near the coast, with one sample having a very high Cl concentration of 2100 mg/L (Well CE17/106, Dunedin), showing signs of saltwater intrusion.

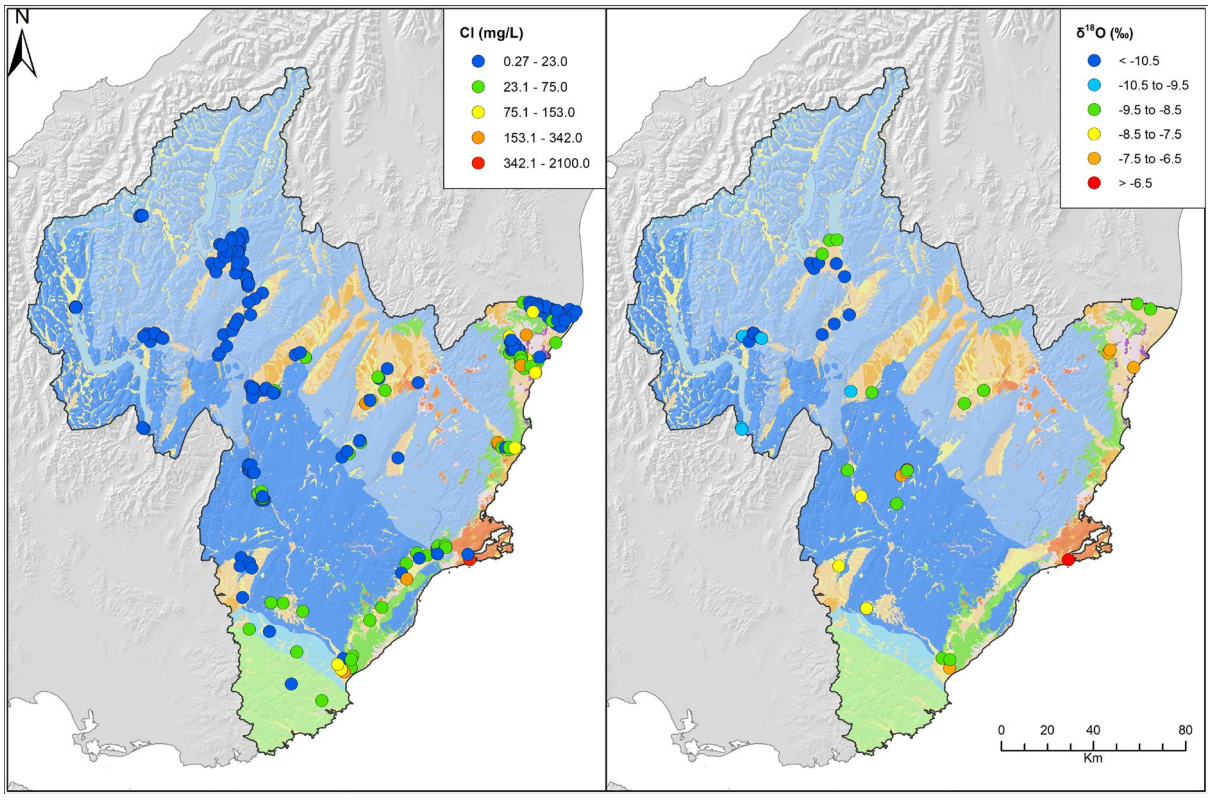


Figure 4.19 Spatial distribution of chloride (Cl) and oxygen stable isotope values ($\delta^{18}O$) in Otago's groundwaters.

### 4.6.4.2 Nitrogen

Nitrogen in its nitrate form is the most pervasive agricultural contaminant in New Zealand's groundwaters. In Otago, most sites exhibit moderate to high concentrations of nitrate-nitrogen, with several exceedances above the "high-intensity land use" threshold (Section 4.6.2) on several occasions at sites with MRT one to 50 years (Figure 4.20). Many of these aquifers are shallow. Ammonia-nitrogen hotspots occur in the deeper aquifers with older (MRT >100 years) likely to be linked with highly reducing conditions and organic material within the aquifer itself.

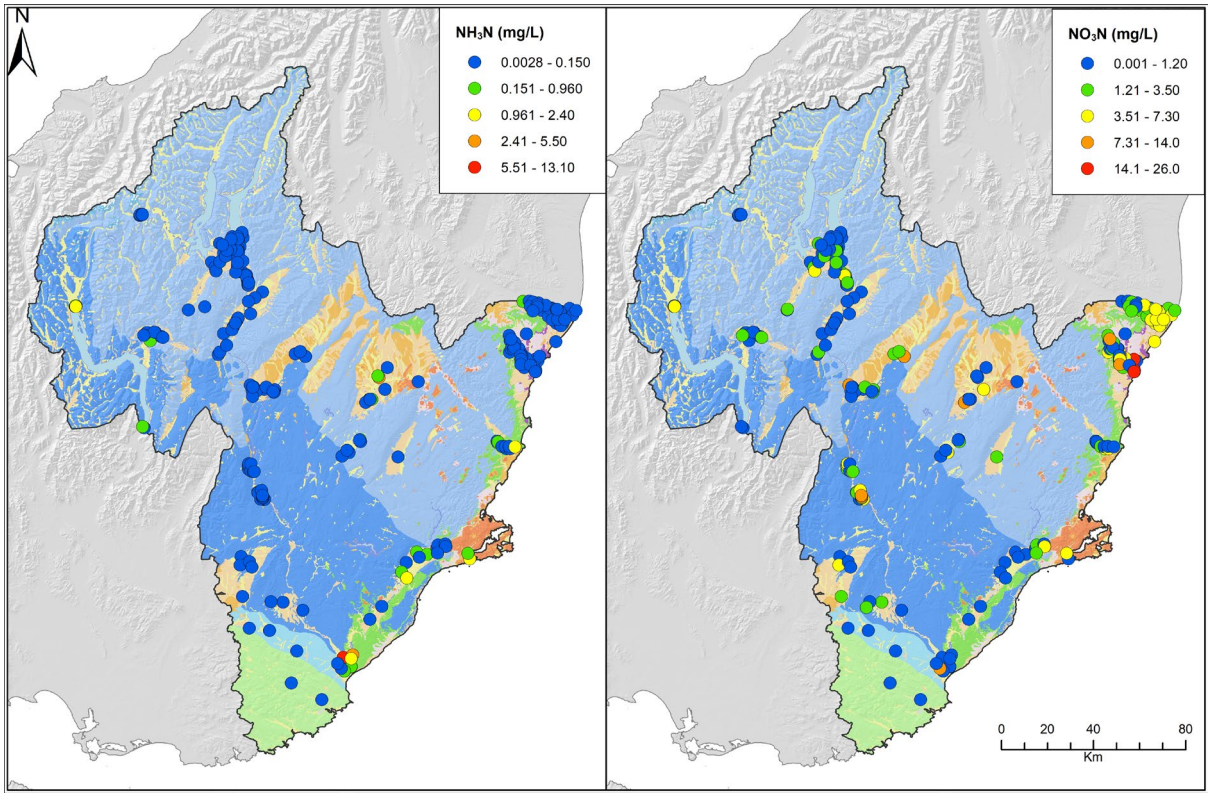


Figure 4.20 Spatial distribution of nitrogen ($NH_3$-N and $NO_3$-N) in Otago groundwaters.

### 4.6.4.3 Bicarbonate

The main sources of $HCO_3$ in groundwater are uptake of $CO_2$ from the atmosphere, uptake of $CO_2$ in the soil zone from microbial and plant root respiration, reduction reactions of organic matter and sulphate in the groundwater system, and dissolution of carbonate rocks. $HCO_3$ concentrations vary widely within individual systems, sometime due to aquifer lithology (Figure 4.21). Low $HCO_3$ concentrations occur in siltstone, mudstone and conglomerate dominated aquifers. Higher concentrations are found in volcanic or limestone derived sediments. The highest $HCO_3$ concentrations occur in locations with older MRTs >100 years, likely due to prolonged water-rock interaction.

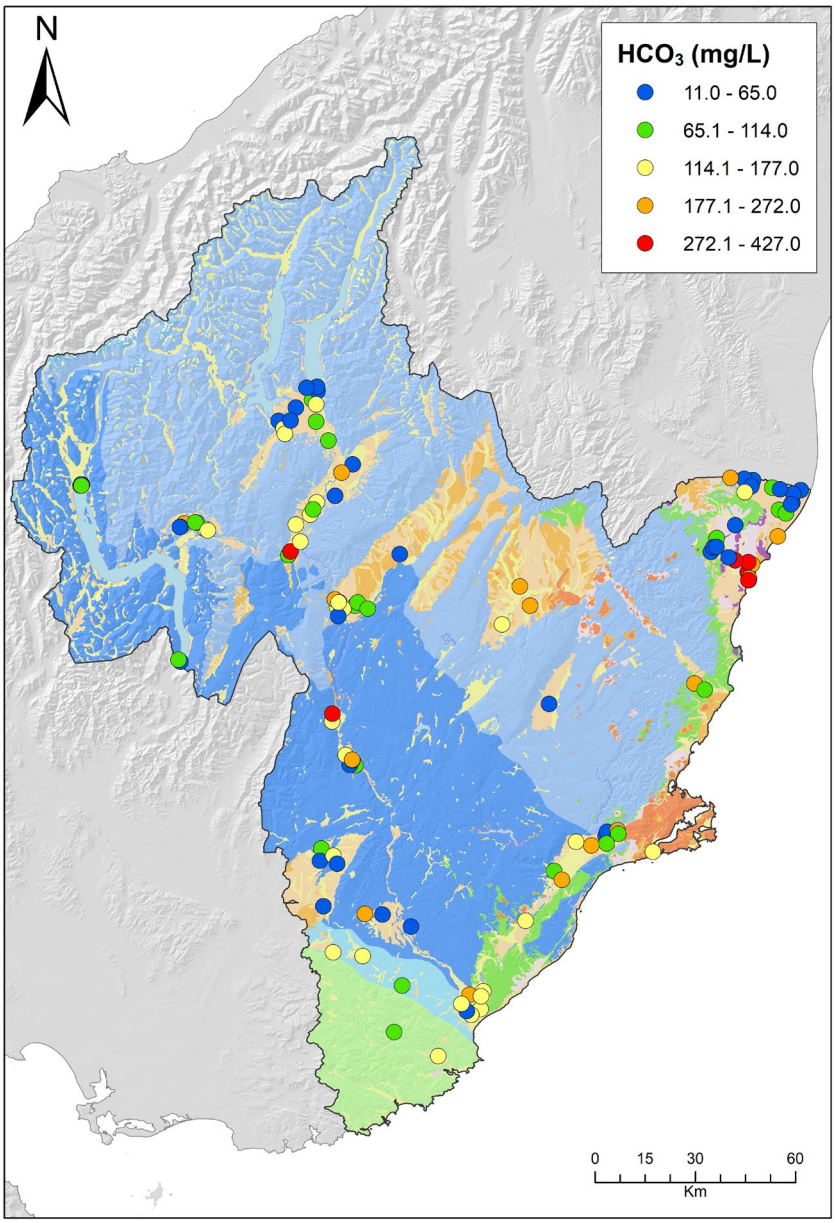


Figure 4.21 Spatial distribution of bicarbonate ($HCO_3$) in Otago groundwaters.

#### *4.6.4.4 Potential hydrogen (pH)*

Potential hydrogen or pH is a measure of the activity of hydrogen in groundwaters, which is a controlling factor of the solubility and biological availability of chemical constituents, such as nutrients (phosphorus, nitrogen and carbon) and heavy metals (lead, copper, cadmium, etc.). Low pH is generally associated with more soluble or mobile metals, but also decaying organic matter. New Zealand groundwater exhibits pHs ranging from 6 to 8, and the majority of Otago groundwaters fit this pattern.

Low pH (<6.5) groundwaters occur in the Oamaru alluvium aquifers and the Taieri, Inch Clutha, Middlemarch, Paerau, Waikaka and Tapeka HS (Figure 4.22). Higher pHs are indicative of alkaline waters, which occur in the Upper Clutha, the North Otago Volcanics from the Oamaru HS and locally within the Maniototo, Manuherikia, Waikaka, Wakatipu Tuapeka and Taieri HS.

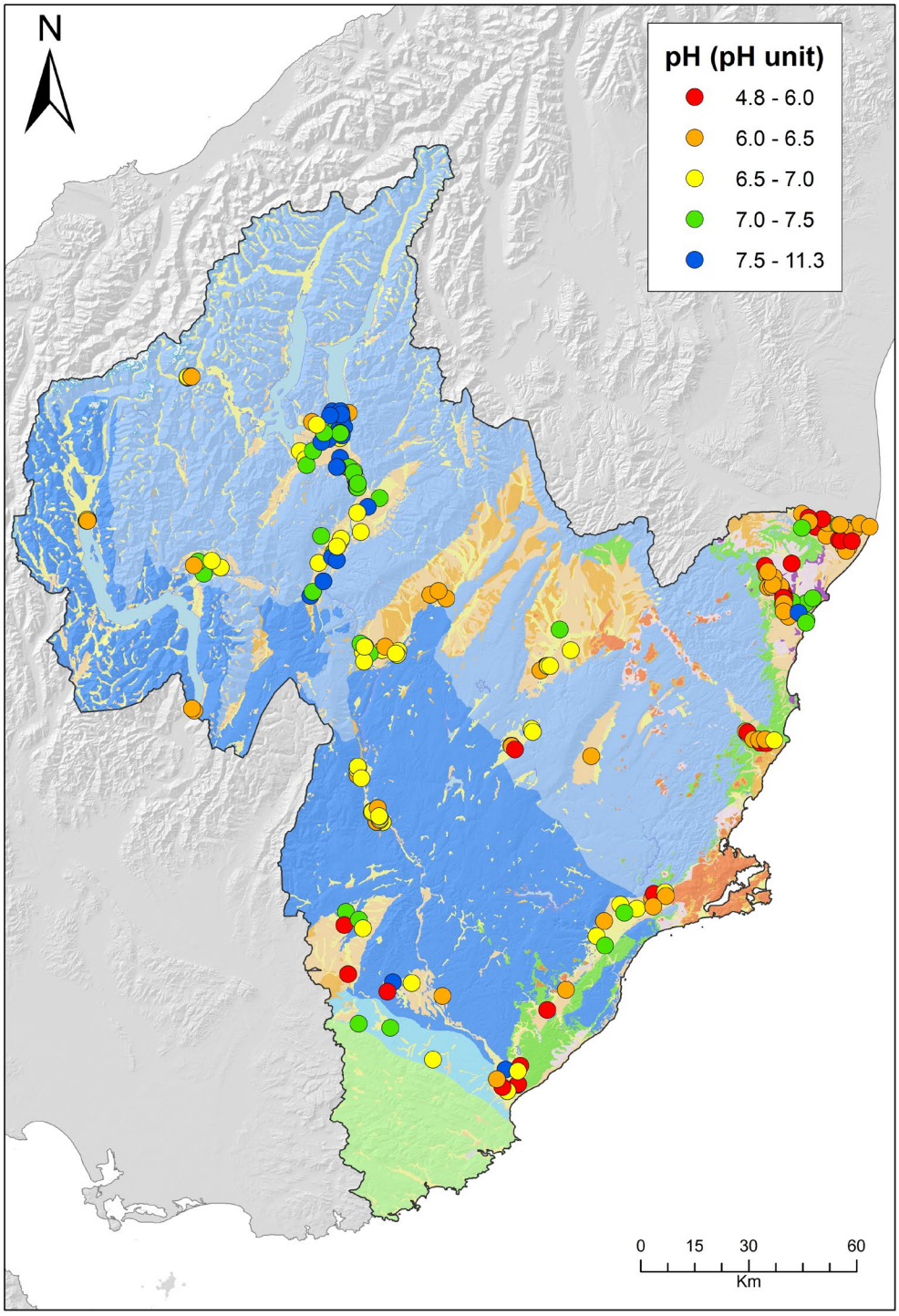


Figure 4.22 Spatial distribution of field pH in Otago groundwaters.

### *4.6.4.5 Conductivity and Dissolved Reactive Phosphorus (DRP)*

Electrical conductivity (EC), i.e. the ability to conduct an electrical current, is directly related to the concentration of dissolved ions in the water. High EC indicates a high concentration of dissolved ions, which could be due to various sources like mineral dissolution, seawater intrusion or contamination from agricultural or industrial activities. Most groundwaters in the region are of low dissolved solids content (EC <250 uS/cm), particularly inland, unless land-use impact occurs (Figure 4.23). Groundwater at the coast or south of Waikaka and Tuapeka HS, are slightly more mineralised. The highest conductivities occur in the North Otago Volcanic Aquifer (Oamaru HS) and at one location in Dunedin where saltwater intrusion occurs.

DRP refers to the portion of phosphorus in water that is readily available for biological use. High levels of DRP indicate increased nutrient levels, which can be due to contamination, e.g. from agriculture or natural geological sources. There are only a limited number of DRP concentrations available in the region and, where available, concentrations are below 0.004 mg/L. There are two DRP hotspots, one located within the Maniototo HS and the other in south Otago, which are known to be heavy agricultural land-use areas. MRTs in this area are less than <10 years (Figure 4.23).

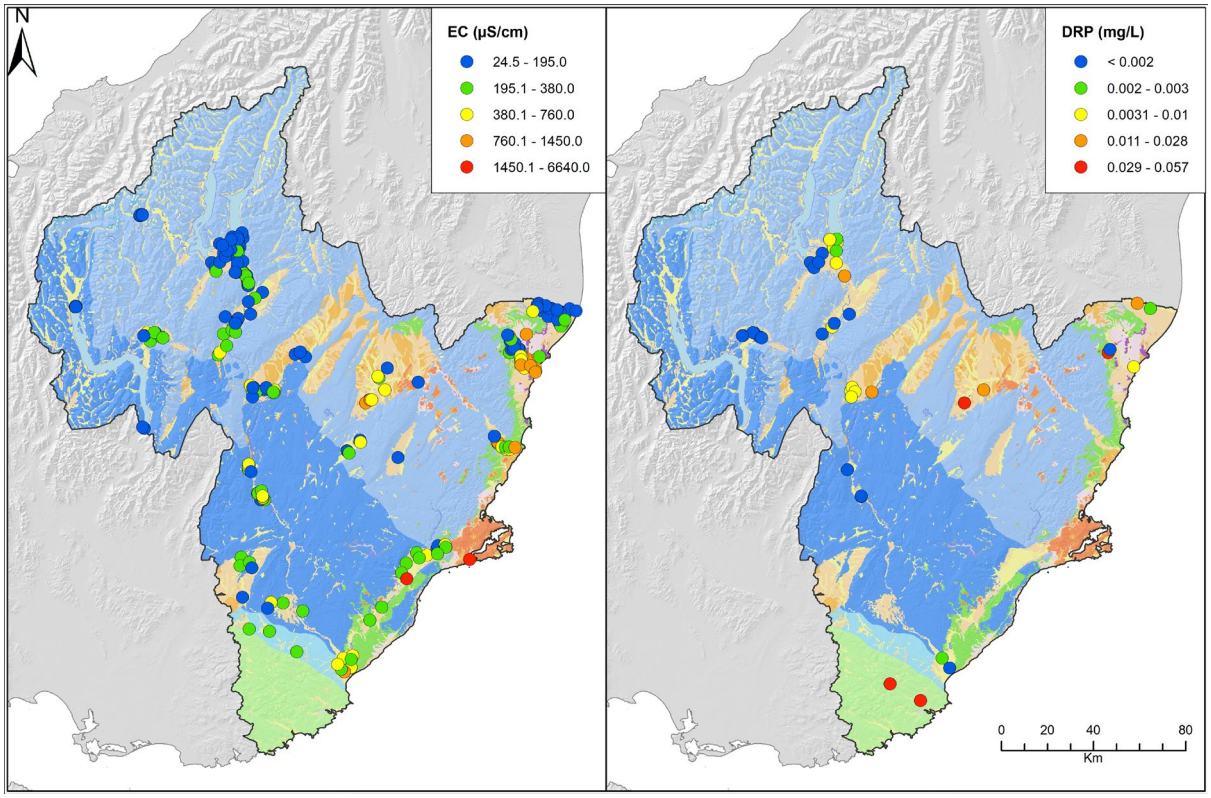


Figure 4.23 Spatial distribution of field electrical conductivity (EC) and dissolved reactive phosphorous (DRP) in Otago groundwaters.

### *4.6.4.6 Sodium and Magnesium*

Both sodium (Na) and magnesium (Mg) typically originate from the weathering of rocks and minerals and, therefore, can provide an indication of the source, pathways and age of groundwater.

There are strong spatial controls on Na concentrations in Otago's groundwaters (Figure 4.24). Most groundwaters found in the higher elevation systems exhibit low Na concentrations. This contrasts with the southern HS (Waikaka, Tuapeka, Taieri, Inch Clutha) where Na concentrations are higher and correspond to different lithologies: alluvial ribbons overlying the Basement in the south and volcanics in the north. Mg concentrations exhibit similar spatial distributions to Na concentrations. Older groundwaters are shown to have higher Mg concentrations (Figure 4.24) as minerals dissolve into the groundwater over time.

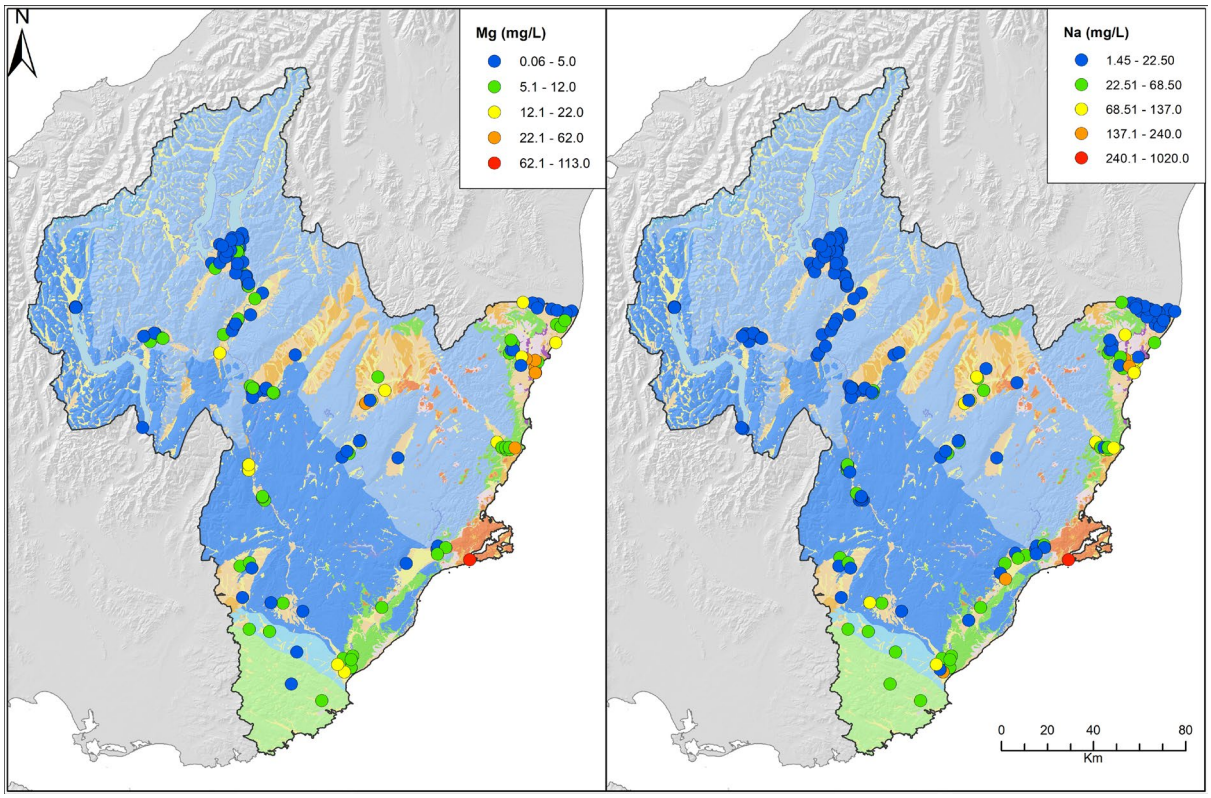


Figure 4.24 Spatial distribution of magnesium (Mg) and sodium (Na) in Otago groundwaters.

### 4.6.5 Temporal Variability

Statistically significant trends over the recorded period were observed at 87 sites for up to 14 parameters, in most cases with concurrent increases and decreases for different parameters (Table 4.4). Sampling time periods vary between individual wells.

The most frequent increases were Ca concentrations (39 sites), often accompanied by increasing Mg, K, $NO_3$-N and $SO_4$, which is consistent with previously reported trends and increasing land-use impact (Levy et al. 2021). The most likely reason is increasing application of agrochemicals (e.g. lime, superphosphate). The fastest Ca concentration increase was 4 mg/L at Well G43/0224a between 2018 and 2024 from Ca concentrations *c.* 75 mg/L in 2018.

The most frequent decreases were pH concentrations (46 sites), often concurrent with decreasing DO. This indicates changes in the physio-chemical conditions of the aquifers, which may in turn affect concentration parameters of more mobile elements in reducing environments (e.g. Fe or heavy metals). These changes may be caused by warming, increased pumping or less recharge from oxic water.

Both significant increases and decreases in $NO_3$-N concentrations are occurring at 16 and 27 sites, respectively. Most systems exhibited both increases and decreases, highlighting strong local drivers. The fastest increase occurred in the Oamaru System (up to 5.9 mg/L per year at Well J42/0076 between 2009 and 2014) and the fastest decrease was recorded in the Upper Clutha System (-0.89 mg/L at Well G40/0411 between 2018 and 2024 from $NO_3$-N concentrations *c.* 10 mg/L in 2018).

One noticeable trend pattern is the multiple decrease of total dissolved content observed at the monitoring well from the Wakatipu HS, which is concurrent with a decrease in pH and major ions (Ca, Mg, K), indicating a freshening of groundwater (Figure 4.25).

Table 4.4 Summary of trends detected with confidence for wells with more than 10 data points.

| Parameter | Units | # Sites | Increase | Decrease | Uncertain |
|---|---|---|---|---|---|
| Ca | mg/L | 82 | 9% | 48% | 44% |
| Cl | mg/L | 86 | 12% | 33% | 56% |
| $HCO_3$ | mg/L | 48 | 13% | 8% | 79% |
| K | mg/L | 60 | 17% | 23% | 60% |
| Mg | mg/L | 66 | 20% | 23% | 58% |
| Na | mg/L | 79 | 20% | 34% | 46% |
| $NO_3$-N | mg/L | 7 | 0% | 43% | 57% |
| $SiO_2$ | mg/L | 59 | 25% | 36% | 39% |
| $SO_4$ | mg/L | 5 | 40% | 0% | 60% |
| DRP | mg/L | 32 | 22% | 34% | 44% |
| Fe | mg/L | 42 | 29% | 17% | 55% |
| Mn | mg/L | 39 | 26% | 5% | 69% |
| $NH_3$-N | mg/L | 84 | 23% | 27% | 50% |
| Cond. | µS/cm | 81 | 57% | 5% | 38% |
| pH | pH unit | 82 | 9% | 48% | 44% |

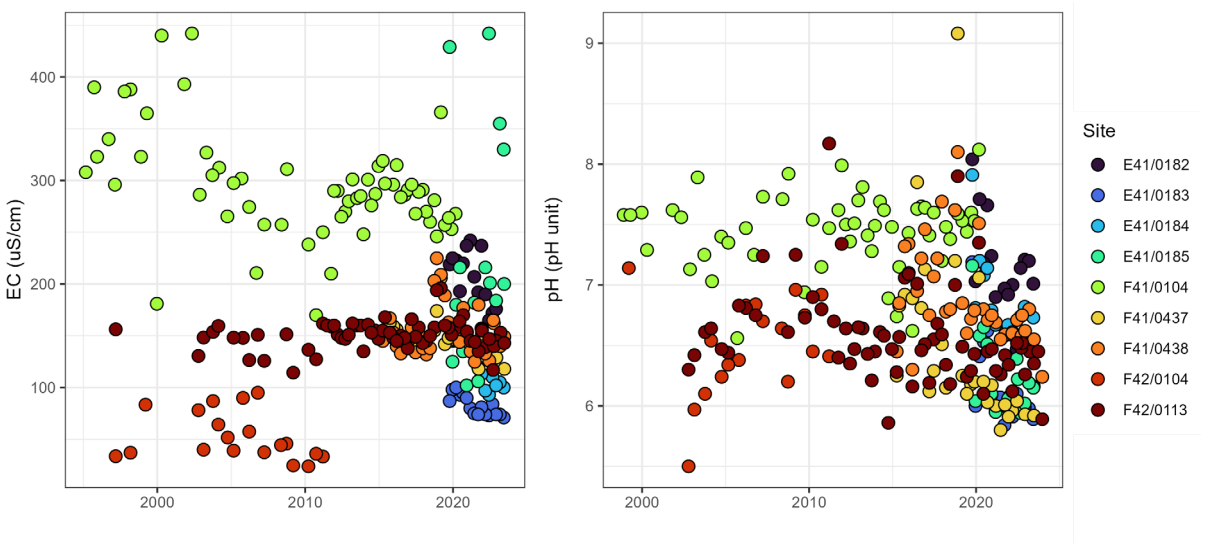


Figure 4.25 Example of statistically significant trends in total dissolved solids content (EC, left) and (pH, right) in groundwater in the Wakatipu HS.

## 4.7 Groundwater Flow Dynamics

This section provides a summary of the indications that can be derived from the previously discussed tracer concentrations regarding recharge source, recharge rates and flow connections.

### 4.7.1 Recharge Source of Groundwater and Connection to Surface Water

Where stable isotope data is available, multiple recharge sources occur throughout the region. In the data-rich Upper Clutha HS, $\delta^{18}O$ values in groundwater down gradient from the lakes are similar to surface water. Away from the lakes towards Cromwell, the connection is more tenuous, and recharge is more likely to come from tributaries. Local heterogeneity in gravel

continuity can be significant, for instance in the close vicinity and down gradient of Lake Hawea, where $\delta^{18}O$ values suggest tributaries or hill country recharge. This is consistent with a detailed piezometric survey from September 2011, indicating recharge from the east occurring south of Gladstone (Wilson 2012). Similar bimodal recharge processes were also observed in the Manuherikia and Oamaru HS.

### 4.7.2 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 4.26 shows groundwater age versus depth for Otago's groundwaters.

In Otago's aquifer systems, shallow aquifers are unconfined, with notable exceptions in the Maniototo, Taieri and Oamaru HS. Figure 4.26 shows groundwater age versus depth for shallow aquifers, separated into systems. Black dashed lines show estimated minimum and maximum recharge rates, assuming a porosity of 0.2. It should be noted that there are large variations in hydraulic properties through the region and also 0.2 has been reported in Hawea and Lower Waitaki (Heller 2001), lower values have also been recorded (e.g. 0.08 in the North Otago Volcanics) (Heller 2001).

Unsurprisingly, there is no unique overall trend between groundwater age and depth, which reflects the compartmentalisation of individual aquifers. The lowest regional estimate is 0.05 m/yr and the highest is 0.500 m/yr. The higher recharge rates (e.g. Upper Clutha HS) are likely to reflect river or lake recharge, whereas lower values are likely to reflect low hydraulic properties or limited connectivity between alluvial material. Two aquifers have age measurements at more than three sites: the Lower Taieri aquifer (n=9) and the Hawea Flat aquifer (n=5); the corresponding recharge rates were 0.075 m/yr and 0.3 m/yr, respectively. The recharge rates derived from age tracers are consistent with the 0.025 to 0.21 m/yr recharge rate modelled at 13 groundwater basins (Table 4.5) (Wilson 2011). There was no trend linking groundwater age, depth and dissolved oxygen (not shown). Note that these recharge rates are associated with relatively high uncertainty, because very little information is available as to the depth at which active groundwater flow into the wells occurs.

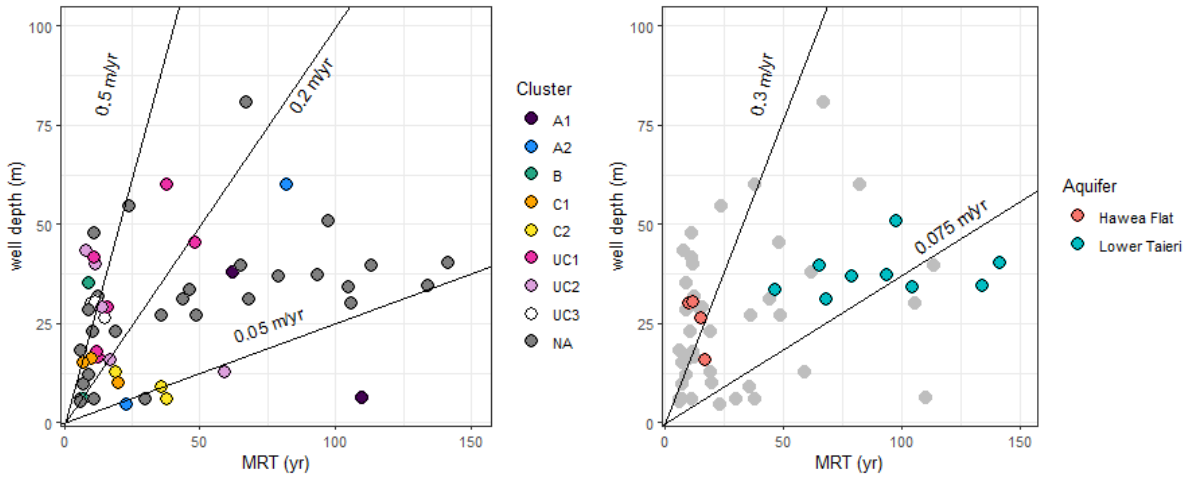


Figure 4.26 Groundwater mean residence time (MRT) vs. depth by cluster (left) and by oxygenation level (right). Age vs. depth trends for vertical recharge rates of 0.05, 0.2 and 1 m/yr are indicated by solid lines (assuming a porosity of 0.25).

Table 4.5 Median annual recharge (adapted from Wilson and Lu 2011).

| HS Name | Groundwater Basin | Median Annual Recharge (m/yr) | |
|---|---|---|---|
| | | Wilson and Lu (2011) | This Study |
| Basement Hard Rock | Clydevale-Wairuna | 0.152 | - |
| Basement Hard Rock | Kuriwao | 0.205 | - |
| Ida | Ida Valley | 0.061 | - |
| Inch Clutha | Inch Clutha | 0.076 | - |
| Maniototo | Maniototo | 0.029 | - |
| Manuherikia | Manuherikia | 0.064 | - |
| Middlemarch | Strath Taieri | 0.025 | - |
| Oamaru | Lower Waitaki | 0.075 | - |
| Roxburgh | Roxburgh | 0.088 | - |
| Taieri | Tokomairiro | 0.137 | 0.075 |
| Upper Clutha | Cromwell<br>Hawea | 0.053<br>NA | -<br>0.325 |
| Waikaka | Pomahaka | 0.212 | - |
| Wakatipu | Wakatipu | 0.184 | - |

# 5.0 CONCLUSION

This collaborative project between ORC and GNS Science aims to improve the understanding of the water dynamics through the Otago aquifers to enable robust policy development. Specifically, this report aims to contribute to the following questions and problems:

**How are groundwaters and surface waters connected in the aquifer systems?**

The shallow aquifers exhibit strong connection with river waters, with strong heterogeneity in gravel connectivity throughout the region. Lake-recharge occurs but is limited in extent. In multi-layered systems, the deeper aquifers are unlikely to be hydraulically connected to overlying aquifers (e.g. Maniototo deep aquifers, Papakaio Aquifer).

**Where does the river-recharged groundwater flow within the aquifers?**

River recharge to groundwater occurs within the inland basins along the Clutha and Taieri rivers. The highest estimated recharge rates for the region were observed in the Upper Clutha, with a possible maximum of 0.5 m/yr.

**Where is groundwater recharged from local rain?**

Rainfall is actively contributing to groundwater recharge at the coast in the unconfined aquifers and in the inland basins away from the main rivers. Where groundwater is slow moving, an estimated minimum recharge rate of 0.05 m/yr was derived for the region.

**What are the time-scales of water flow through the aquifers?**

Groundwater dynamics in the region range from fast flowing, with residence times of less than 10 years, to slow flowing, with residence times greater than 100 years. Younger groundwater MRT distributions are found in the inland systems, and in the sediment aquifers of Oamaru. In the larger basins, such as Wakatipu, Manuhereka and Upper Clutha HS, groundwaters with MRTs of up to 50 years can be found in the less connected gravels. Although closest to the sea, samples from Mosgiel (Taieri HS indicated slow groundwaters (50 to 150 years). Similarly, older groundwater can also be found towards the coast in the Inch Clutha HS.

**What are the drivers of nitrate levels in the groundwater?**

The driver for nitrate levels in groundwater is high-intensity land use. Some of the highest concentrations occur in older groundwater (>30 years), suggesting a legacy effect. In addition, localised areas exhibit sustained rising trends in nitrate concentrations.

**What are the flow pathways of surface contaminants, such as agricultural nutrients?**

Groundwater chemistry and age data clearly indicate some impact from anthropogenic activities, with pathways likely to be a combination of rainfall infiltration and surface water interaction. The current dataset is not suited to inform the interaction between groundwater and lakes in the region.

# 6.0 RECOMMENDATIONS

To support a review of ORC's monitoring network, we recommend to:

- Continue monitoring groundwater for chemistry and water levels across the region. This has contributed to the understanding of temporal variations in hydrochemistry and will inform on the efficiency of freshwater management measures under a changing climate.
- Undertake targeted hydrochemistry surveys to address data gaps. The comprehensive chemistry and age dataset for the region includes a good spatial coverage, with some temporal and spatial bias, which probably reflects groundwater use and development over time. Since 2021, ORC has increased the number of monitoring wells, including initiating monitoring in unexplored systems (e.g. Paerau HS). There remain some gaps (e.g. Ida) that would be useful to cover through synoptic surveys (i.e. a snapshot survey focussed on a HS with a denser site distribution than SOE) if bores or springs are available. In areas currently unmonitored, the establishment of long-term monitoring sites should be considered, if deemed applicable by council.
- Undertake five-yearly age-tracer monitoring for the bores with water older than several years, to detect changes in flow dynamics: for example, through changing abstraction or climate.
- Undertake targeted detailed piezometric surveys. These surveys (e.g. Wilson 2012) are very useful to ascertain groundwater-surface interactions and seasonal changes in flow direction. Ideally these summer surveys should be repeated at a regular interval (e.g every few years) and may be planned alongside synoptic surveys.
- Review the monitoring analytical suite to ensure major and minor ions are included, at least at low sampling frequency (e.g. annual). The geochemical interpretation undertaken as part of this project was at times limited by data availability. To increase interpretative power of monitoring data it is recommended to ensure that major and minor ions (Ca, Na, K, Mg, Cl, $SO_4$, $NO_3$-N, dissolved Fe and Mn, DRP and $SiO_2$) are included in SOE monitoring to elucidate processes along the flow paths. For cost efficiencies, the full suite may be analysed less frequently, while field parameters and conservative ions, such as Cl or land-use impact indicators, may be monitored more frequently (e.g. quarterly).
- Long-term groundwater chemistry changes were identified in the region. To elucidate their causes will require a system-by-system review. In the short term, this information could be used to categorise the current monitoring network within the Surveillance and Evaluative framework, which is currently being investigated by Waikato Regional Council (Hadfield 2023). Long-term or fast-increasing trends in $NO_3$-N indicate groundwater quality degradation, and in some cases 'a load to come' – which may require further investigation.
- Review field groundwater quality data. QA/QC highlighted some inconsistencies in field parameters in the provided data. There may be efficiencies for these checks arising from national reporting data compilation. QA/QC also identified monitored locations unassigned to a specific aquifer. In multi-layered systems, it is recommended to assess whether aquifers may be attributed based on lithological log and screen information, chemistry and/or water level. If not possible, it is recommended to transition monitoring to another site where aquifer information is available.

- Joint review (ORC and GNS Science) of the boundaries and aquifer attribution of HS and HUM units. In this report, ORC aquifers and groundwater management zones were mapped to the national HS dataset. Aquifers of local importance were identified across HS boundaries or within the Hard Rock Basement aquiclude system (Clydevale-Wairuna Basin and Morven aquifers). HS and HUM boundaries should be jointly reviewed to increase consistency between regional and national groundwater quality reporting.

## 7.0 ACKNOWLEDGMENTS

The authors thanks Sam Yeo and other ORC staff who helped with providing data and facilitating fieldwork during this study. All contributing bore owners are also thanked for enabling site access for the March 2023 sampling round. We are also grateful to Frederika Mourot (GNS Science) for her assistance in designing the sampling campaign, providing advice for the work and reviewing an earlier version of this report. Finally, Karyne Rogers, Zara Rawlinson and Conny Tschritter (GNS Science) are thanked for their constructive comments throughout the internal review process.

## 8.0 REFERENCES

Baird R, Eaton AD, Rice EW, Bridgewater L, editors. 2017. Standard methods for the examination of water and wastewater. 23rd ed. Washington (DC): American Public Health Association, American Water Works Association, Water Environment Federation. 1 vol.

Barrell DJA. 2011. Quaternary glaciers of New Zealand. In: Ehlers J, Gibbard PL, Hughes PD, editors. *Developments in quaternary sciences.* Amsterdam (NL): Elsevier. p. 1047–1064. https://doi.org/10.1016/B978-0-444-53447-7.00075-1

Benson WN. 1968. The W.N. Benson geological map of Dunedin District. Wellington (NZ): Department of Scientific and Industrial Research. 1 sheet + 1 booklet, scale 1:50,000. (New Zealand Geological Survey miscellaneous series map; 1).

Beyer M, Morgenstern U, Jackson B. 2014. Review of techniques for dating young groundwater (<100 years) in New Zealand. *Journal of Hydrology (New Zealand)*. 53(2):93–111. http://www.jstor.org/stable/43945058

Beyer M, Morgenstern U, van der Raaij R, Martindale H. 2017. Halon-1301 – further evidence of its performance as an age tracer in New Zealand groundwater. *Hydrology and Earth System Sciences*. 21(8):4213–4231. https://doi.org/10.5194/hess-21-4213-2017

Böhlke JK, Wanty R, Tuttle M, Delin G, Landon M. 2002. Denitrification in the recharge area and discharge area of a transient agricultural nitrate plume in a glacial outwash sand aquifer, Minnesota. *Water Resources Research*. 38(7):10-11–10-26. https://doi.org/10.1029/2001wr000663

Busenberg E, Plummer LN. 1992. Use of chlorofluorocarbons ($CCl_3F$ and $CCl_2F_2$) as hydrologic tracers and age-dating tools: the alluvium and terrace system of central Oklahoma. *Water Resources Research*. 28(9):2257–2283. https://doi.org/10.1029/92wr01263

Busenberg E, Plummer LN. 2000. Dating young groundwater with sulfur hexafluoride: natural and anthropogenic sources of sulfur hexafluoride. *Water Resources Research*. 36(10):3011–3030. https://doi.org/10.1029/2000wr900151

Cartwright I, Morgenstern U. 2012. Constraining groundwater recharge and the rate of geochemical processes using tritium and major ion geochemistry: Ovens catchment, southeast Australia. *Journal of Hydrology*. 475:137–149. https://doi.org/10.1016/j.jhydrol.2012.09.037

Cook PG, Herczeg AL, editors. 2000. Environmental tracers in subsurface hydrology. Boston (MA): Kluwer Academic Publishers. 529 p.

Cox SC, Barrell DJA, compilers. 2007. Geology of the Aoraki area [map]. Lower Hutt (NZ): GNS Science. 1 map + 71 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 15).

Craw D. [2023]. Geological evolution of Otago and its gold. Otago (NZ): University of Otago; [accessed 2023 Jul]. https://www.otago.ac.nz/geology/research/gold/otago-gold-background.html

Daughney C, Randall M. 2009. National groundwater quality indicators update: state and trends 1995–2008. Lower Hutt (NZ): GNS Science. 55 p. Consultancy Report 2009/145. Prepared for Ministry for the Environment.

Daughney CJ, Reeves RR. 2005. Definition of hydrochemical facies in the New Zealand National Groundwater Monitoring Programme. *Journal of Hydrology (New Zealand)*. 44(2):105–130. http://www.jstor.org/stable/43944920

Daughney CJ, Wall M. 2007. Groundwater quality in New Zealand: state and trends 1995–2006. Lower Hutt (NZ): GNS Science. 65 p. Consultancy Report 2007/23. Prepared for the Ministry for the Environment.

Daughney C, Jones A, Baker T, Hanson C, Davidson P, Zemansky G, Reeves R, Thompson M. 2006. A national protocol for state of the environment groundwater sampling in New Zealand. Wellington (NZ): Ministry for the Environment. 52 p. (GNS Science miscellaneous series; 5). https://environment.govt.nz/publications/a-national-protocol-for-state-of-the-environment-groundwater-sampling-in-new-zealand/

Glassey P, Barrell D, Forsyth J, Macleod R. 2003. The geology of Dunedin, New Zealand, and the management of geological hazards. *Quaternary International.* 103(1):23–40. https://doi.org/10.1016/S1040-6182(02)00139-8

Güler C, Thyne GD, McCray JE, Turner KA. 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeology Journal*. 10(4):455–474. https://doi.org/10.1007/s10040-002-0196-6

Hadfield J. 2023. Optimising Waikato groundwater quality monitoring [abstract]. In: *AGC NZHS 2023 Conference;* 2023 Nov 28 – Dec 1; Tāmaki Makaurau/Auckland. [Wellington] (NZ): New Zealand Hydrological Society.

Heaton THE, Vogel JC. 1981. “Excess air” in groundwater. *Journal of Hydrology*. 50:201–216. https://doi.org/10.1016/0022-1694(81)90070-6

Heller T. 2001. Otago. In: Rosen MR, White PA, editors. Groundwaters of New Zealand. Wellington (NZ): New Zealand Hydrological Society. p. 465–480.{Adane, 2018 #1104}

Helsel DR, Hirsch RM, Ryberg KR, Archfield SA, Gilroy EJ. 2020. Statistical methods in water resources. Reston (VA): U.S. Geological Survey. 458 p. (Techniques and methods; 4–A3). https://doi.org/10.3133/tm4A3

Heron DW, custodian. 2023. Geological map of New Zealand. 4th ed. Lower Hutt (NZ): GNS Science. Scale 1:250,000. (GNS Science geological map; 1). https://doi.org/10.21420/03PC-H178

Ingram RGS, Hiscock KM, Dennis PF. 2007. Noble gas excess air applied to distinguish groundwater recharge conditions. *Environmental Science & Technology*. 41(6):1949–1955. https://doi.org/10.1021/es061115r

Jackson KL. 2018. Understanding the water resources of the Cardrona River, Central Otago [MSc thesis]. Dunedin (NZ): University of Otago. 107 p. https://hdl.handle.net/10523/8264

Jurgens BC, Böhlke JK, Eberts SM. 2012. TracerLPM (Version 1): an Excel® workbook for interpreting groundwater age distributions from environmental tracer data. Reston (VA): U.S. Geological Survey. 60 p. Techniques and Methods Report 4-F3.

Landis CA, Campbell HJ, Begg JG, Mildenhall DC, Paterson AM, Trewick SA. 2008. The Waipounamu Erosion Surface: questioning the antiquity of New Zealand land surface and terrestrial fauna and flora. *Geological Magazine*. 145(2):173–197. https://doi.org/10.1017/S0016756807004268

Larned ST, Snelder T, Unwin MJ, McBride GB. 2016. Water quality in New Zealand rivers: current state and trends. *New Zealand Journal of Marine and Freshwater Research*. 50(3):389–417. https://doi.org/10.1080/00288330.2016.1150309

Lachniet MS, Moy CM, Riesselman C, Stephen H, Lorrey AM. 2021. Climatic and topographic control of the stable isotope values of rivers on the South Island of New Zealand. *Paleoceanography and Paleoclimatology*. 36(5):e2021PA004220. https://doi.org/10.1029/2021PA004220

Levy A, Ettema M, Lu X. 2021. State of the Environment: groundwater quality in Otago. Dunedin (NZ): Otago Regional Council. 192 p.

[LAWA] Land Air Water Aotearoa. 2023. About LAWA. [Wellington] (NZ): LAWA; [accessed 2023 Mar]. https://www.lawa.org.nz/about

[LINZ] Toitū Te Whenua Land Information New Zealand [dataset]. 2019. NZ building outlines. Wellington (NZ): LINZ; [updated 2021 Jun 14; accessed 2021 Sep 1]. https://data.linz.govt.nz/layer/101290-nz-building-outlines/

Lovett AP, Cameron SG. 2015. Development of a National Groundwater Atlas for New Zealand. Lower Hutt (NZ): GNS Science. 8 p. (GNS Science report; 2014/30).

Macara GR. 2015. The climate and weather of Otago. 2nd ed. [Wellington] (NZ): NIWA. 42 p. (NIWA Science and Technology Series; 67). https://niwa.co.nz/sites/default/files/Otago%20Climate%20book%20WEB%202021.pdf

Macara G, Woolley JM, Zammit C, Pearce P, Stuart S, Wadhwa S, Sood A, Collins D. 2019. Climate change projections for the Otago Region. Auckland (NZ): NIWA. 136 p. Client Report 2019281WN. Prepared for Otago Regional Council.

Mager S, Horton S. 2018. The Hydrology of Southern New Zealand. In: Strack MS, Wheen NR, Lovelock B, Thompson-Carr A, editors. *Riverscapes: research essays on the social context of southern catchments of Aotearoa New Zealand.* Dunedin (NZ): Catchments Otago. p. 17–29.

Mager S, Horton S. 2018. The Hydrology of Southern New Zealand. In: Strack MS, Wheen NR, Lovelock B, Thompson-Carr A, editors. *Riverscapes: research essays on the social context of southern catchments of Aotearoa New Zealand.* Dunedin (NZ): Catchments Otago. p. 17–29.

Maiss M, Brenninkmeijer CAM. 1998. Atmospheric $SF_6$: trends, sources, and prospects. *Environmental Science & Technology*. 32(20):3077–3086. https://doi.org/10.1021/es9802807

Małoszewski P, Zuber A. 1982. Determining the turnover time of groundwater systems with the aid of environmental tracers: 1. Models and their applicability. *Journal of Hydrology*. 57(3–4):207–231. https://doi.org/10.1016/0022-1694(82)90147-0

Maloszewski P, Zuber A. 1991. Influence of matrix diffusion and exchange reactions on radiocarbon ages in fissured carbonate aquifers. *Water Resources Research*. 27(8):1937–1945. https://doi.org/10.1029/91wr01110

Martindale H, Lovett AP. 2017. Groundwater – surface water interaction in the Shag River. Lower Hutt (NZ): GNS Science. 8 p. Consultancy Report 2017/45LR. Prepared for Otago Regional Council.

Martindale H, van der Raaij RW, Knowling MJ, Morgenstern U. 2018. Quantifying groundwater discharge into New Zealand rivers using radon and concurrent flow gauging. Lower Hutt (NZ): GNS Science. 39 p. (GNS Science report; 2018/25). https://doi.org/10.21420/g2093b

McBride GB. 2019. Has water quality improved or been maintained? A quantitative assessment procedure. *Journal of Environmental Quality*. 48(2):412–420. https://doi.org/10.2134/jeq2018.03.0101

McDonnell JJ, Gabrielli C, Ameli A, Ekanayake J, Fenicia F, Freer J, Graham C, McGlynn B, Morgenstern U, Pietroniro A, et al. 2021. The Maimai M8 experimental catchment database: forty years of process-based research on steep, wet hillslopes. *Hydrological Processes*. 35(5):e14112. https://doi.org/10.1002/hyp.14112

Mildenhall DC, Pocknall DP. 1989. Miocene-Pleistocene spores and pollen from Central Otago, South Island, New Zealand. Wellington (NZ): New Zealand Geological Survey. 128p. (New Zealand Geological Survey palaeontological bulletin; 59).

Milne J. 2019. Water quality. Part 1 of 4: sampling, measuring, processing and archiving of discrete groundwater quality data. [Place unknown] (NZ): National Environmental Monitoring Standards; [accessed 2021 Aug]. https://www.nems.org.nz/documents/water-quality-part-1-groundwater/

Ministry for the Environment. 2016. Average annual rainfall, 1972–2013. Wellington (NZ): Ministry for the Environment; [accessed 2021 Oct 11]. https://data.mfe.govt.nz/layer/53314-average-annual-rainfall-19722013/

Water Services (Drinking Water Standards for New Zealand) Regulations 2022; [accessed 2024 Jul]. https://www.legislation.govt.nz/regulation/public/2022/0168/latest/whole.html

Mitchell M, Craw D, Landis CA, Frew R. 2009. Stratigraphy, provenance, and diagenesis of the Cretaceous Horse Range Formation, east Otago, New Zealand. *Journal of Geology and Geophysics*. 52(3):171–183. https://doi.org/10.1080/00288300909509884

Moreau M. 2018. Update of national groundwater quality indicators: state and trends 1998–2017. Wairakei (NZ): GNS Science. 29 p. Consultancy Report 2018/118. Prepared for Ministry for the Environment.

Moreau M. 2023. Technical review of the 2020 groundwater quality indicator to support methodological improvements. Wairakei (NZ): GNS Science. 32 p. Consultancy Report 2023/19. Prepared for Ministry for the Environment.

Moreau M, Daughney CJ. 2015. Update of national groundwater quality indicators: state and trends, December 2004–2013. Wairakei (NZ): GNS Science 32 p. Consultancy Report 2015/16. Prepared for Ministry for the Environment.

Moreau M, Daughney C. 2021. Defining natural baselines for rates of change in New Zealand's groundwater quality: dealing with incomplete or disparate datasets, accounting for impacted sites, and merging into state of the-environment reporting. *Science of The Total Environment*. 755(2):143292. https://doi.org/10.1016/j.scitotenv.2020.143292

Moreau M, White PA, Mourot F, Rawlinson Z, Tschritter C, Cameron SG, Westerhoff RS. 2019. Classification of New Zealand hydrogeological systems. Lower Hutt (NZ): GNS Science. 28 p. (GNS Science report; 2018/35). https://doi.org/10.21420/42QW-MC74

Moreau M, Morgenstern U, van der Raaij RW, Horrox J. 2021. West Coast groundwater dynamics and hydrochemical evolution as inferred from regional water age and chemistry tracer data. Lower Hutt (NZ): GNS Science. 69 p. (GNS Science report; 2021/16). https://doi.org/10.21420/60DD-SQ44

Moreau-Fournier M, Daughney CJ. 2010. Procedure for checking laboratory water chemistry results prior upload to the Geothermal-Groundwater database. Wairakei (NZ): GNS Science. 62 p. Internal Report 2010/06.

Morgenstern U, Taylor CB. 2009. Ultra low-level tritium measurement using electrolytic enrichment and LSC. *Isotopes in Environmental and Health Studies*. 45(2):96–117. https://doi.org/10.1080/10256010902931194

Morgenstern U, Daughney CJ. 2012. Groundwater age for identification of baseline groundwater quality and impacts of land-use intensification – the National Groundwater Monitoring Programme of New Zealand. *Journal of Hydrology*. 456–457:79–93. https://doi.org/10.1016/j.jhydrol.2012.06.010

Morgenstern U, van der Raaij RW, Martindale H, Toews MW, Stewart MK, Matthews A, Trompetter V, Townsend DB. 2017. Groundwater dynamics, source and hydrochemical processes as inferred from Horizon's regional age tracer data. Lower Hutt (NZ): GNS Science. 63 p. (GNS Science report; 2017/15). https://doi.org/10.21420/g2j596

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

Morris R. 2014. Groundwater resource management review of the South Otago Basins. Dunedin (NZ): Otago Regional Council; [accessed 2024 Jun]. https://www.orc.govt.nz/media/1956/technical-item-3-south-otago-basins-groundwater-report.pdf

Mourot F, Coble MA, Moreau M, Herpe M. 2022a. Synthesis of the groundwater investigations in the Lower Waihemo/Shag River Valley. Wairakei (NZ): GNS Science. 80 p. Consultancy Report 2022/91. Prepared for Otago Regional Council.

Mourot FM, Westerhoff RS, White PA, Cameron SG. 2022b. Climate change and New Zealand's groundwater resources: a methodology to support adaptation. *Journal of Hydrology: Regional Studies*. 40:101053. https://doi.org/10.1016/j.ejrh.2022.101053

[ORC] Otago Regional Council. 2022. Regional Plan: Water for Otago. Dunedin (NZ): Otago Regional Council. https://www.orc.govt.nz/media/12843/regional-plan_water-for-otago-updated-to-3-september-2022-chapters-1-19.pdf

Plummer LN, Busenberg E. 2000. Chlorofluorocarbons. In: Cook PG, Herczeg AL, editors. *Environmental tracers in subsurface hydrology*. Boston (MA): Kluwer Academic. p. 441–478.

Rekker J. 2012. Cromwell Terrace Aquifer study. Dunedin (NZ): Otago Regional Council. 44 p. https://www.orc.govt.nz/media/3800/cromwell-terrace-aquifer-study-report-web.pdf

Rekker J. 2014. Investigation into the Wakatipu Basin Aquifers. Dunedin (NZ): Otago Regional Council. 56 p. https://www.orc.govt.nz/media/3798/wakatipu-aquifers-groundwater-investigation-report-web.pdf

Rekker J, Houlbrooke C. 2010. Lower Taieri groundwater allocation study. Dunedin (NZ): Otago Regional Council. 118 p. https://www.orc.govt.nz/media/3809/l-t-g-allocation-study-web.pdf

Rekker J, Houlbrooke C, Gyopari M. 2008. North Otago Volcanic Aquifer study. Dunedin (NZ): Otago Regional Council. 108 p. https://www.orc.govt.nz/media/3815/north-otago-volcanic-aquifer-study.pdf

Stewart MK, Morgenstern U, Gusyev MA, Małoszewski P. 2017. Aggregation effects on tritium-based mean transit times and young water fractions in spatially heterogeneous catchments and groundwater systems. *Hydrology and Earth System Sciences*. 21(9):4615–4627. https://doi.org/10.5194/hess-21-4615-2017

Taylor CB. 1968. A comparison of tritium and strontium-90 fallout in the Southern Hemisphere. *Tellus*. 20(4):559–576. https://doi.org/10.3402/tellusa.v20i4.10038

van der Raaij RW. 2003. Age-dating of New Zealand groundwaters using sulphur hexafluoride [MSc thesis]. Wellington (NZ): Victoria University of Wellington. 122 p.

Ward JH. 1963. Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association*. 58(301):236–244. https://doi.org/10.1080/01621459.1963.10500845

White PA, Moreau M, Mourot F, Rawlinson ZJ. 2019. New Zealand Groundwater Atlas: hydrogeological-unit map of New Zealand. Wairakei (NZ): GNS Science. 88 p. Consultancy Report 2019/144. Prepared for Ministry for the Environment.

Wilson S. 2012. Hawea Basin Groundwater Review. Dunedin (NZ): Otago Regional Council. 57 p.

Wilson S, Lu X. 2011. Rainfall recharge assessment for Otago groundwater basins. Dunedin (NZ): Otago Regional Council. 42 p. https://www.orc.govt.nz/media/3806/land-surface-recharge-report-december-2011-web.pdf

Zuber A, Witczak S, Różański K, Śliwka I, Opoka M, Mochalski P, Kuc T, Karlikowska J, Kania J, Jackowicz-Korczyński M, et al. 2005. Groundwater dating with $^{3}H$ and $SF_6$ in relation to mixing patterns, transport modelling and hydrochemistry. *Hydrological Processes*. 19(11):2247–2275. https://doi.org/10.1002/hyp.5669

# APPENDICES

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## APPENDIX 1 HYDROGEOLOGICAL SYSTEMS IN THE OTAGO REGION AND CORRESPONDING AQUIFER NAMES AND/OR GROUNDWATER MANAGEMENT ZONES

| HS Type | HS Name | Aquifer Name or Groundwater Management Zone Name |
|---|---|---|
| Coastal Basin | Dunedin | South Dunedin Coastal Aquifer[4] |
| | Inch Clutha | Lower Clutha Plain[1]; Inch Clutha[2], Inch Clutha Gravel Aquifer[3] |
| | Oamaru | Kakanui-Kauru Alluvium[1], Kakanui-Kauru Alluvial Ribbon[2]<br>Lower Waitaki Alluvium[1], Lower Waitaki Plains Aquifer[2, 3]; Papakaio Formation[1], Papakaio Aquifer[2, 3]<br>Waiareka and Deborah Volcanics[1], North Otago Volcanics Aquifer[2, 3] |
| | Palmerston | Shag Alluvium[1], Shag Alluvium Aquifer[2, 3] |
| | Taieri Coastal | - |
| Coastal Volcanic | Oamaru Volcanic | - |
| | Otago Peninsula | - |
| Inland Basin | Brother | - |
| | Ettrick | Ettrick Basin[1], Ettrick Basin Aquifer[3] |
| | Ida | Ida Valley Aquifer[3] |
| | Lower Nevis | - |
| | Maniototo | Maniototo Basin[1], Maniototo Tertiary Aquifer[2, 3] |
| | Manuherikia | Dunstan Flats Zone A[1], Dunstan Flats Zone B[1], Dunstan Flats Aquifer[2, 3]<br>Earnscleugh Terrace[1], Earnscleugh Terrace Aquifer[2]; Manuherikia Alluvium Springvale Terrace[1], Manuherekia Alluvium Aquifer[2,3], Manuherekia Claybound Aquifer[2,3], Manuherekia Groundwater Management Zone[3] |
| | Middlemarch | Strath Taieri Basin[1, 2]; Strath Taieri Aquifer[3] |
| | Onslow | - |
| | Paerau | - |
| | Pigroot | - |
| | Roxburgh | Roxburgh East[1], Coal Creek[1], Roxburgh Basin Aquifer[2], Roxburgh East Aquifer[3], Roxburgh West Aquifer[3] |
| | Taieri | Lower Taeri Plain – East[1], Lower Taeri Plain – West[1], Lower Taieri Aquifer[2, 3]; Henley Aquifer[3]; Mosgiel-Momona Confined Aquifer[3]<br>Tokomairiro Basin[1], Tokomairiro Groundwater Management Zone[3] |
| | Tiroiti | - |
| | Tuapeka | Kuriwao Basin[1], Kuriwao Basin Aquifer[2, 3];<br>Clydevale-Wairuna Basin Aquifer[3] |
| | Upper Clutha | Hawea Basin[1, 3], Hawea Flat[2], Hawea Flat Aquifer[3]<br>Lindis Valley[1], Lindis Alluvial Ribbon Aquifer[2, 3]; Ardgour Valley Allocation Zone[2]<br>Lowburn Valley[1], Lowburn Alluvial Ribbon Aquifer[2]<br>Maungawera Valley[1], Maungawera Valley Aquifer[2]<br>Wanaka Basin[1],Wanaka Cardrona Gravel Aquifer[2], Cardrona Gravel Aquifer[2],Cardrona Alluvial Ribbon Aquifer[3]<br>Upper Clutha Valley[1]<br>Pisa Terrace[1], Luggate, Queensberry and Pisa groundwater management zones[3]<br>Bendigo Allocation Zone[2]; Cromwell Terrace Aquifer[2, 3]<br>Lower Tarras Allocation Zone[2], Lower Tarras Aquifer[3] |
| | Upper Nevis | - |
| | Waikaka | Pomahaka Basin[1], Pomahaka Basin Aquifer[2, 3], Pomahaka Alluvial Ribbon Aquifer[3] |
| | Waipahi | Clydevale-Wairuna Basin Aquifer[3] |
| | Wakatipu | Glenorchy[1], Glenorchy Groundwater Management Zone[3]; Kingston[1]; Kingston groundwater Management Zone[3]<br>Wakatipu Basin[1, 3], Wakatipu Basin Aquifer[2]; Frankton Flats Aquifer[3]; Upper Mill Creek Aquifer[3], Mid-Mill Creek Aquifer[3], Ladies Mile Aquifer (formerly known as Windemeer)[3]; Morven aquifer[3]. |
| Inland River Valley | Otago | Shag Alluvium[1], Shag Alluvium Aquifer[2, 3] |
| Basement Hard Rock | Basement Hard Rock | Kuriwao Basin[1], Kuriwao Basin Aquifer[2] Kuriwao Basin[3]; Clydevale-Wairuna Basin Aquifer[3] |

Sources: [1] Heller 2001; [2] Lovett and Cameron 2015; [3] Levy et al. 2021; [4] Rekker 2012


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