Waituna Catchment Groundwater Resource

Technical Report

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1. Executive Summary

As part of a wider response to concerns over the ecological health of the Waituna Lagoon, an intensive groundwater resource characterisation study was undertaken by Environment Southland in the Waituna catchment during 2011/12. The characterisation study builds on an earlier technical comment (Wilson, 2011b) that highlighted a critical lack of data surrounding the groundwater resource of the Waituna catchment. From this report, it emerged that the only evolved data set surrounded geological data associated with the lignite exploration programs of the 1970s and 1980s. A recommended approach to addressing key data gaps in an effort to characterise the role of the groundwater resource over the water quality of the Waituna Lagoon was developed with input from groundwater experts at the Environment Southland hosted Waituna 'Think Tank' Science Workshop in July 2011.

The fundamental groundwater question explored during the Waituna Science Workshop was:

What role, if any, does groundwater play in nutrient loadings to the Waituna Lagoon?

In order to answer the above question, two dominant groundwater discharge mechanisms needed to be explored, namely: groundwater discharge via the surface water network and groundwater discharge as direct seepage into the lagoon. In order to assess the role of each discharge mechanism on lagoon health, Environment Southland embarked on a physical and chemical characterisation study of the Waituna groundwater resource, including:

- an assessment of the spatial and temporal variability in the groundwater hydrological and geochemical response;
- the relationship between land use, hydrogeology and groundwater quality in the catchment, and;
- the relationship between the Waituna Lagoon and groundwater resources.

In order to characterise groundwater resources within the Waituna catchment, a network of bores were selected for groundwater level and water quality sampling. A lack of bores in the unconfined aquifer adjacent to the fringes of the lagoon was identified early resulting in Environment Southland installing five piezometres in mid-2011 around the landward side of the lagoon. Existing domestic and farming bores were added to the monitoring network through engagement with the Waituna catchment community with preference given to those bores occurring within the shallow unconfined aquifer system. The network of bores chosen sought to maximise spatial coverage across the catchment including the margins of the Waituna Lagoon.

In addition to the monthly groundwater quality and level baseline monitoring programme, additional groundwater investigations were undertaken to improve characterisation of the overall aquifer water balance including:

- installation of real-time groundwater level, electrical conductivity and water temperature data loggers at five sites throughout the catchment;
- a catchment wide groundwater level (piezometric) survey undertaken utilising more than 70 bores and 30 surface water sites;
- a concurrent gauging and water quality survey of Waituna Creek completed under low flow (baseflow) conditions during the summer of 2011/12, and;
- two groundwater seepage trials undertaken at the eastern and western portions of the Waituna Lagoon.

Groundwater quality investigations included the setup of a monthly Waituna groundwater quality run and two "one-off" characterisation surveys. Characterisation surveys sought to provide a spatial snapshot of the shallow (unconfined) groundwater quality throughout the catchment. A significant southerly storm (rainfall) event in mid-July 2011 triggered the artificial opening of the Waituna Lagoon. During this period high-resolution groundwater sampling was undertaken on a selection of wells around the lagoon margin in an attempt to capture temporal behaviour in groundwater level and groundwater quality associated with the artificial opening of the lagoon.

In addition to groundwater sampling, snowmelt, tile and open drain, soil water and surface water samples (Waituna, Moffat and Carran Creeks) were collected throughout the catchment. Soil water, tile drain waters and bulk soil samples were collected from grazed pastures and winter grazed forage crops in the north and south of the catchment. Bulk soil samples and soil water (using a teflon suction cup) were also collected from the Waituna Lagoon Reserve and wetland soils adjacent to the Waituna Lagoon. A drive point piezometre (miniature portable well) was deployed to sample groundwaters in mixed peat-quartz gravel aquifers adjacent to the Waituna Lagoon.

The results of the characterisation program are best summarised through the segregation of the Waituna catchment into three zones according to areas of distinct hydrogeological (physical and chemical) properties, specifically:

1. ***Northern Waituna Zone***

   The northern section of the Waituna Creek catchment (north of Mokotua) has relatively good groundwater quality compared to regional norms due to a combination of factors including the presence of thick, stone less, mineral brown soils. The soils buffer groundwater in this area from the effects of intensive land use due to cation exchange and chemical sorption processes which are aided by a long mean residence times (months) within the unsaturated zone (soil and unsaturated sediments above the water table). Excluding tile drainage, which is elevated in nutrients, shallow aquifers across this zone show little impact from intensive land use;

2. ***Mokotua Infiltration Zone***

   A zone of rapid infiltration in the Waituna Creek catchment between Mokotua and Caesar Road, associated with the reworking of soil and aquifer materials during a former sea level highstand during the last interglacial period (approximately 70,000–100,000 years ago). Across this area, groundwater quality is poor due to the rapid infiltration of soil water with little or no attenuation of soil zone contaminants from intensive land use. The movement of water through the unconfined aquifer within the Mokotua Infiltration Zone (MIZ) is rapid (1-2 week mean residence time) and appears to contribute to the deterioration in the water quality of Waituna Creek south of Mokotua.

3. ***Southern Waituna Zone***

   The southern, predominately wetland portion of the catchment, extends south of Caesar Road to the Waituna Lagoon and includes both the Moffat and Carran Creek catchments. This area is dominated by reducing groundwater conditions due the abundance of organic carbon associated with wetland peat deposits and to a lesser extent lignite measures.

Recharge to shallow groundwater systems in this zone occurs relatively rapidly via the soil profile.

Although naturally reducing conditions prevent assimilation and contamination in nitrate (NO_3-N)[1], median phosphorus (phosphate) concentrations in reduced southern groundwaters are up to 50 times higher than oxic redox state groundwaters occurring in the north. The elevated phosphate within these groundwaters likely reflects both the leakiness of phosphate from organic soils, the naturally higher solubility and mobility of phosphate under reducing conditions and a potentially significant phosphate input from the underlying lignite measure aquifers. Although there is some evidence for anthropogenic phosphate contamination of southern groundwaters due to diffuse soil leaching and localised septic inputs, further work is required to ascertain the magnitude of anthropogenic sources in this sector of the catchment.

4. *Direct groundwater seepage into Waituna Lagoon*

Direct groundwater seepage into the Waituna Lagoon was estimated at between 340 to 460 litres per second (L/s). While seepage measurements indicate a relatively significant volume of groundwater seepage inflow into Waituna Lagoon, the relative contribution of discharge from the unconfined aquifer versus diffuse leakage from the underlying lignite measure aquifers is unknown. From median nutrient values[2], it is estimated that groundwater contributes between 28 and 48 tonnes of TN to Waituna Lagoon per year, of which approximately 30 to 40 percent is derived from base flow in the MIZ. The TP input from groundwater is estimated at approximately 1,434 to 2,389 kg/year of which around 40 to 60 percent is sourced from direct groundwater seepage into the lagoon.

Collectively, the findings of this report indicate that groundwater plays a minor, albeit important role, in the transport of nutrient loads into the Waituna Lagoon. When compared to estimated surface water nutrient loadings (Diffuse Sources and NIWA, 2012) groundwater inputs may contribute approximately 11 to 18 percent of the cumulative TN and 10 to 15 percent of the cumulative TP loadings to Waituna Creek.

The work completed to date has identified a number of areas requiring further investigation. These include:

- the overall magnitude of key components of the catchment water balance including groundwater recharge, base flow and direct seepage to Waituna Lagoon;
- the physical extent of the MIZ (e.g. whether it extends into the upper portion of the Moffat Creek catchment) and its significance with respect to surface water quality and NO_3-N loads to Waituna Creek;
- the source of elevated phosphate in southern groundwaters including the possibility that winter grazing on organic soils and septic tank outfalls play an important role in the elevated phosphate concentrations in southern groundwaters and ultimately the Waituna Lagoon;

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[1] The median NO_3-N concentration of <0.03 mg/L for southern groundwaters falls far below the natural background for Southland of approximately 1 mg/L.

[2] It is acknowledged that the relative contribution from the confined aquifer system to direct seepage is currently unknown. However, median P concentrations for both the unconfined and confined aquifer systems are similar.

- whether discharge of low TN groundwaters from the southern and northern zones of the catchment plays an important role in diluting NO_3-N rich inputs to the Waituna Lagoon from the surface water network;

- the role of seasonality (recharge events) in soil zone contaminant loss to groundwater across the MIZ and other sectors of the catchment;

- the origins of direct groundwater seepage into the lagoon (i.e. from the unconfined or confined aquifer system). This has significance as to the source of phosphate and ultimately how phosphate may best be managed; and,

- additional monitoring on the effect artificial opening of the lagoon has over groundwater inflows (and associated nutrient loading) as direct seepage and stream base flow.

Bearing in mind the above uncertainties, the general findings of this report allows some assessment of how to most effectively target catchment management in order to limit or reduce nutrient loads to the Waituna Lagoon. Catchment management should recognise different parts of the catchment behave differently and therefore we recommend management responses are targeted to higher risk areas, specifically:

- current land use activities across the MIZ may constitute a relatively high risk to water quality in Waituna Creek and appropriate intervention within this zone may yield a disproportional improvement in the surface water quality of Waituna Creek and ultimately the Waituna Lagoon;

- phosphorus is both prone to leaching and of higher mobility within the southern Waituna zone due to a combination of the presence of organic soils and the low oxygen (reducing) conditions. Accordingly, the implementation of phosphate loss management strategies across this portion of the catchment may be of value, and;

- groundwater base flow to Waituna Creek in the northern zone of the catchment likely maintains relatively good water quality in Waituna Creek, due to the thick mineral brown soils, except for during heavy rainfall events when surface runoff and artificial drainage is significant. The most effective land management response will therefore relate to potential contamination from overland flow and artificial drainage.

2. Introduction

Figure 1 shows the location of Waituna Lagoon along the southern coast of New Zealand approximately 10 kilometres east of Invercargill. The Waituna Lagoon is one of the best remaining examples of a natural coastal lagoon in New Zealand and forms a unique, highly valued feature of the Southland environment.

Figure 1: Key topographical features of the Waituna catchment and surrounds

The Waituna Lagoon is a large, brackish coastal lagoon that drains to the sea via an artificially managed opening. The catchment draining into the lagoon comprises three main tributaries (Waituna Creek, Moffat Creek and Carran Creek), which have a combined catchment area of 20,255 ha.

Historically, the Waituna Lagoon was surrounded by peat bog wetland, the drainage from which gave the lagoon its characteristic clear brown stain, low nutrient status, and low pH. It had high ecological habitat diversity, a unique seagrass community (*Ruppia* dominated), internationally important birdlife and large areas of relatively unmodified wetland and terrestrial vegetation. In addition it is highly valued for its aesthetic appeal, its rich biodiversity, duck shooting, fishing (for brown trout primarily), boating, walking, and scientific appeal. The Waituna Lagoon is part of the internationally recognised Awarua Wetlands, which became a Ramsar[3] site in 1976. The cultural significance to the local Ngai Tahu people was recognised under a Statutory Acknowledgement with the Ngai Tahu Claims Settlement Act 1998.

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[3] In 1971, international concern for the increasing loss of wetlands worldwide brought a global gathering to Ramsar, Iran. The meeting resulted in the Ramsar Convention for the Protection of Wetlands which developed criteria to identify wetlands of international importance.

The Waituna Lagoon sits at the bottom of a small, intensively farmed catchment. Over recent years, land use in this area catchment has undergone significant changes including drainage of wetland areas, clearance of indigenous vegetation and an overall increase in the intensity of agricultural production. These factors are considered as likely contributors to the water quality issues observed in the lagoon over recent years. Potential water quality impacts are exacerbated by the lack of a permanent opening to the sea, which limits the amount of flushing through the lagoon system. As a consequence, nutrient inputs tend to accumulate within the lagoon environment increasing the potential for eutrophication to occur.

Environmental monitoring shows that the water quality both in contributing catchments and the lagoon itself have deteriorated over recent years, particularly in terms of nitrogen and phosphorus. As illustrated in Figure 2, the increase in nutrient concentrations has resulted in a marked decline in ecosystem health in the Waituna Lagoon, particularly since 2009.

At the current time, indicators suggest the lagoon ecosystem is being stressed and may be at imminent risk of 'flipping'. This process occurs when nutrient concentrations increase beyond a critical threshold and would likely result in a change from clear water and an aquatic environment dominated by seagrass (*Ruppia*) to turbid, murky water dominated by algal slime. Any such change would likely result in major adverse changes both to the physical appearance of the lagoon as well as the overall lagoon ecosystem.

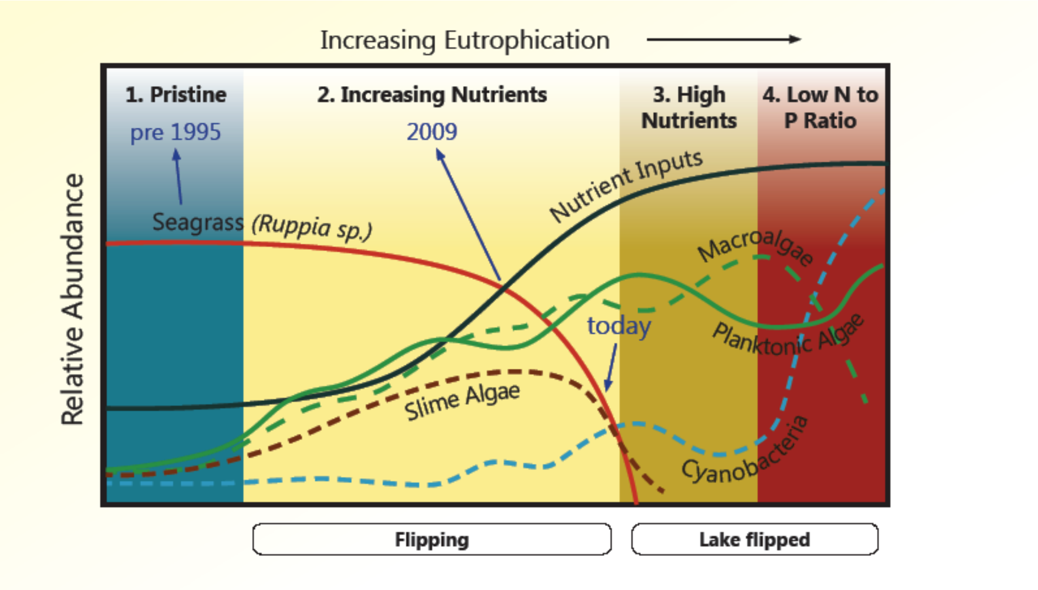

Figure 2: Schematic diagram of the rapid decline in ecosystem health in the Waituna Lagoon

Environment Southland is leading a multi-agency response to address the decline in water quality and to prevent the lagoon from flipping. Agencies involved in this process include the Department of Conservation, DairyNZ, Fonterra, Federated Farmers, Beef and Lamb, Southland District and Invercargill City Councils, Fish and Game Southland, several community groups involved in the catchment, Iwi, local farmers and residents.

In July 2011, Environment Southland hosted a Waituna 'Think Tank' Science Workshop inviting eminent scientists from across the country to review available environmental monitoring data and to identify key research gaps and priorities. As part of this workshop, a recommended groundwater research approach to address key data gaps in an effort to characterise the role of the groundwater resource over the water quality of the Waituna Lagoon was developed with input from groundwater experts. Since this workshop, Environment Southland has undertaken an intensive groundwater monitoring program in order to address the following fundamental question: *what role, if any, does groundwater play in nutrient loadings to the Waituna Lagoon?*

2.1 Objectives

The purpose of this report is to document the current state of knowledge of groundwater resources in the Waituna catchment in order to characterise the role and influence of groundwater on overall water quality in the Waituna Lagoon. The findings from this report will be used to support the Waituna Lagoon technical response and to assess where future groundwater monitoring and investigations should be focused to best address emerging issues or information gaps. This report builds on previous reports (i.e. Wilson, 2011) and will be updated as additional information becomes available.

2.2 Physical Environment

2.2.1 Climate

The Waituna catchment is located in a climate best described as cool-temperate. **Figure** 3 shows a plot of mean monthly rainfall for three monitoring sites near the Waituna Lagoon catchment based on at least 30 years of data. All locations show a consistent seasonal rainfall pattern with the highest totals occurring during summer and autumn and the lowest totals during winter and spring. On an annual basis, the maximum observed rainfall variation between the sites is approximately 230 mm or 21 percentage of the average annual total of 1,070 mm.

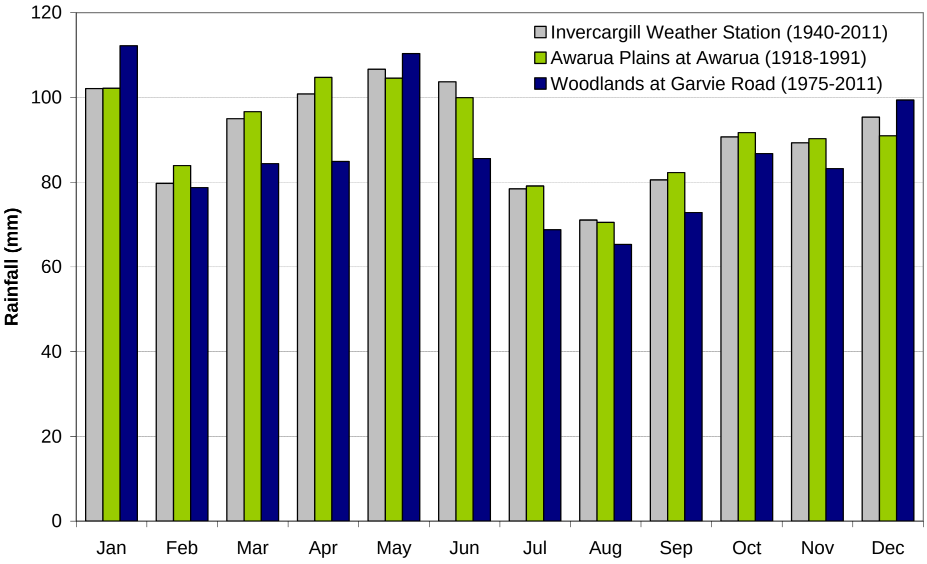

Figure 3: Mean monthly rainfall recorded near the Waituna catchment[4]

Figure 4 shows a simple water balance (rainfall minus potential evapotranspiration) to illustrate potential seasonal water deficits in the Waituna catchment during an "average" year and under more extreme "wet" and "drought" conditions (represented by the 10 and

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[4] Invercargill weather station and Awarua Plains rainfall data was sourced from NIWA's Cliflo database (www.cliflo.niwa.co.nz/)

90 percentiles for rainfall and potential evapotranspiration (PET) using the Invercargill weather station data). Under 'average' climate conditions the figure shows a seasonal water surplus of approximately 450 mm between March to October with rainfall and PET relatively even (i.e. a surplus/deficit close to 0 mm). However, under "drought" conditions (i.e. high PET/low rainfall) monthly water deficits may approach 75 mm during the November to January period with a potential seasonal water deficit exceeding 250 mm during extended periods of low rainfall. Conversely, during "wet" conditions (i.e. high rainfall/low PET) monthly water surpluses may exceed 100 mm throughout the summer period. These figures illustrate the considerable climate variability that may occur in the Waituna catchment, particularly during the summer period.

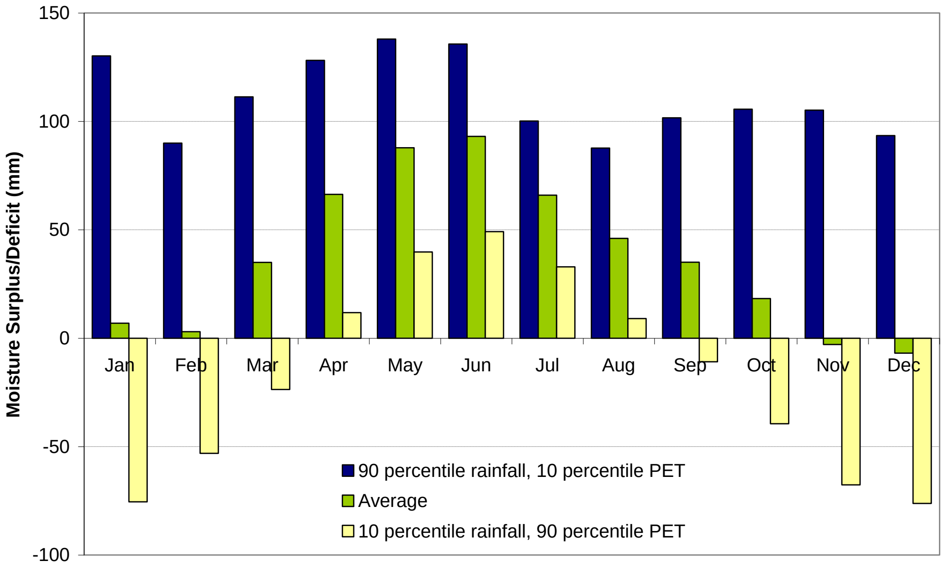

Figure 4: Monthly water balance using Invercargill weather station data under "wet", "average" and "drought" conditions

Long-term changes in rainfall patterns across coastal Southland are illustrated in **Figure** 5 using the cumulative monthly rainfall departure from the long-term average for Invercargill. Between 1940 and 1980, the data shows rainfall was below average (shown as a *downward* trending line) compared to 1980 to 2007 where conditions were wetter than normal (shown as an *upward* trending line). Similar long-term cyclical wet/dry phases have been observed in rainfall, river flow and lake level data from elsewhere in Southland (e.g. McKerchar and Henderson, 2003). This climate variability has been interpreted to reflect the cumulative effect of large-scale changes in inter-annual (i.e. el Niño/la Niña) and interdecadal (i.e. Interdecadal Pacific Oscillation) atmospheric circulation patterns across the Pacific region.

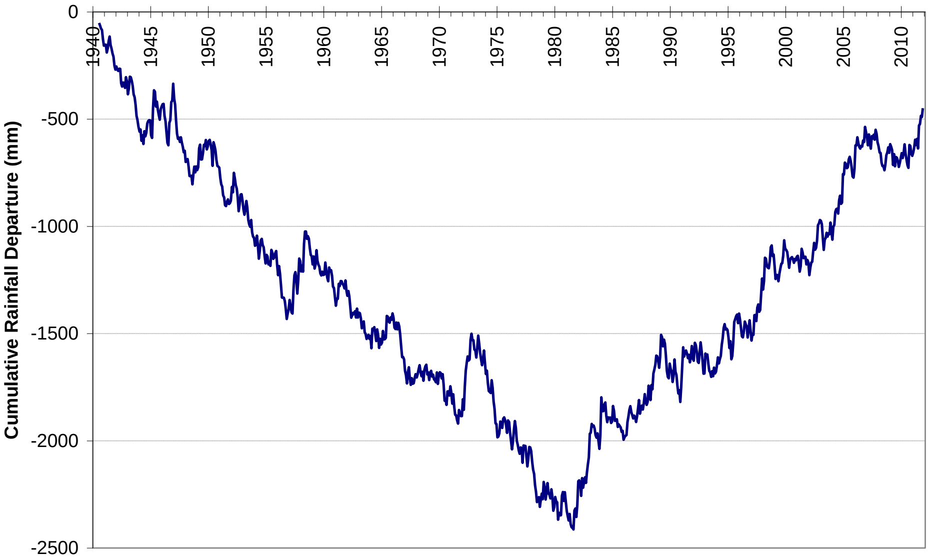

Figure 5: Cumulative monthly rainfall departure for Invercargill, 1940 to 2011

2.2.2 Geology

The geology underlying the Waituna catchment consists of a relatively thin layer of poorly sorted Quaternary clay-bound gravels overlying a thick sequence of fine-grained sediments of the Tertiary East Southland Group, which in turn overlie the Mesozoic basement rocks of the Murihiku and Brook Street Terranes. A schematic cross-section (not drawn to scale) of the geology underlying the Waituna catchment is shown in **Figure 6**.

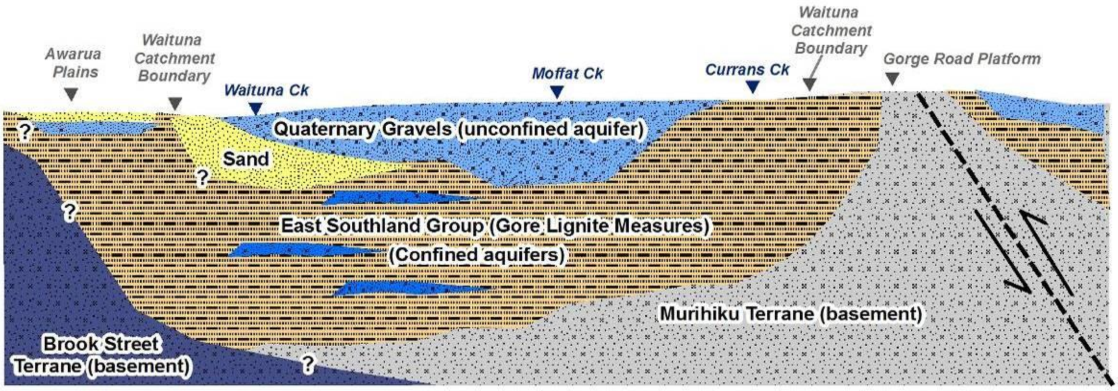

Figure 6: Schematic hydrogeological cross-section of the Waituna catchment from Gorge Road towards Awarua Bay

The basement rocks of the Brook Street Terrane are Permian in age (between 290 to 260 million years old) and are comprised of a distinctive collection of volcanic lavas and ashes possible associated with deposition along a string of island arc volcanoes that marked a subduction zone. The sediments were originally deposited under the sea as sub-horizontal beds with a measured thickness of 14 kilometres. Over the subsequent period these rocks have been extensively deformed with some tilted near vertically to form the Takitimu Mountains and Longwood Ranges in central and northern Southland.

The basement rocks of the Murihiku Terrane are about 250 to 170 million years old and were formed in a collision zone between an oceanic plate and a continent. These meta-sedimentary rocks underlie much of eastern Southland and have been folded on a regional scale by the Southland Syncline to form the Hokonui Hills, a prominent strike ridge that can be traced from Nugget Point in the east to Mossburn in the west.

The basement rocks are overlain by the marine and terrestrial sediments of the East Southland Group, which were deposited from between 65 to 2 million years ago. During this period, a combination of tectonic subsidence and variation in relative sea levels resulted in the inundation of low-lying areas of Southland forming a shallow sea. On-going deposition in this developing sedimentary basin resulted in the accumulation of a thick sequence of shallow marine (limestone and calcareous sandstone) sediments.

During the early to mid-Miocene Period (approximately 23 to 15 million years ago) sea levels gradually declined resulting in the accumulation of a thick, alternating sequence of shallow marine (sand), marginal marine (mudstone and lignite) and terrestrial (gravel) sediments which form a unit referred to as the Gore Lignite Measures. These sediments occur at shallow depths (generally less than 40 metres below ground level) across a large area of eastern and northern Southland, exhibiting a general dip of between 1 to 2º to the south-west reflecting deposition on an extensive, low-lying alluvial delta.

Between 2 million to 10,000 years ago the climate entered an era which saw large variations in climatic conditions between successive glacial and interglacial periods. During glacial periods accelerated rates of erosion resulted in the accumulation of extensive moraine and fluvioglacial outwash gravel deposits in inland area. During subsequent interglacial periods the major river systems down cut into these glacial materials transporting large volumes of sediment downstream to form broad alluvial plains. The resulting Quaternary gravel deposits mantle the Southland Plains and in lowland areas these sediments (shown in **Figure 7**) have been dissected by first and second order streams to form the gently undulating topography seen today

Over time, the Quaternary gravel deposits have weathered leading to the transformation of primary clay minerals to kaolin minerals. An "onion-skin" layering of weathering rinds on the lithic gravel/cobble grains has also led to secondary clay formation particularly for rock types with low resistance to alternation on exposure to water such as lithified siltstone (associated with the Southland Syncline). Gravel deposits which are dominated by weathering-resistant quartz, such as those shown in **Figure 7** tend to be much less weathered than lithic rock types (Rekker, 1996).

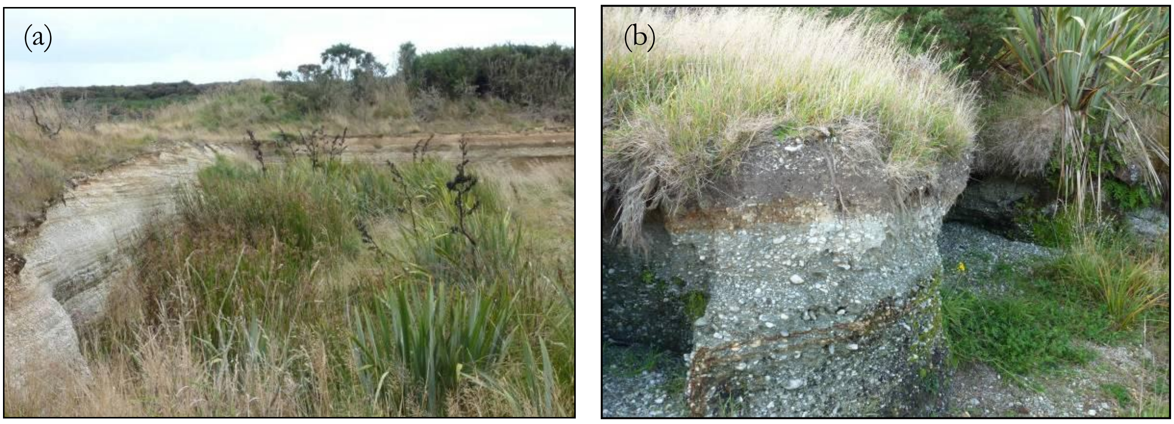

Figure 7: Photograph of the underlying Quaternary gravels exposed in (a) a gravel pit along Hanson Road and (b) terrace riser near Waituna Lagoon Road
[Source: K Wilson, March/April 2011]

During the late Quaternary Period relative sea levels rose and fell during successive glacial and interglacial cycles. During interglacial periods rising sea levels resulted in the land-water retreat of the coastline resulting in the reworking of the alluvial materials in a shallow marine environment. In the Waituna catchment a terrace running roughly east-west approximately 3 kilometres south of Mokotua marks the inland extent of sea level transgression during the current Kaihinuan interglacial period (approximately 70,000 to 120,000 years ago). During subsequent progradation of the shoreline, the Quaternary gravel sediments have been reworked resulting in the accumulation of more resistant quartz-rich gravel deposits evident in this area today with extensive wetland areas (including Waituna Lagoon) forming on these flat-lying, relatively low permeability marine gravel deposits.

The geological map illustrated in **Figure 8** shows the presence of relatively extensive ("peat") wetland systems around the margins of the Waituna Lagoon; the Quaternary gravel layer across the Southland plains ("gravel"); the Tertiary Gore Lignite Measures of the East Southland Group sediments ("sandstone" and "mudstone") and the Mesozoic basement rocks of the Murihiku Terrane ("siltstone") which are evident at the surface near Gorge Road.

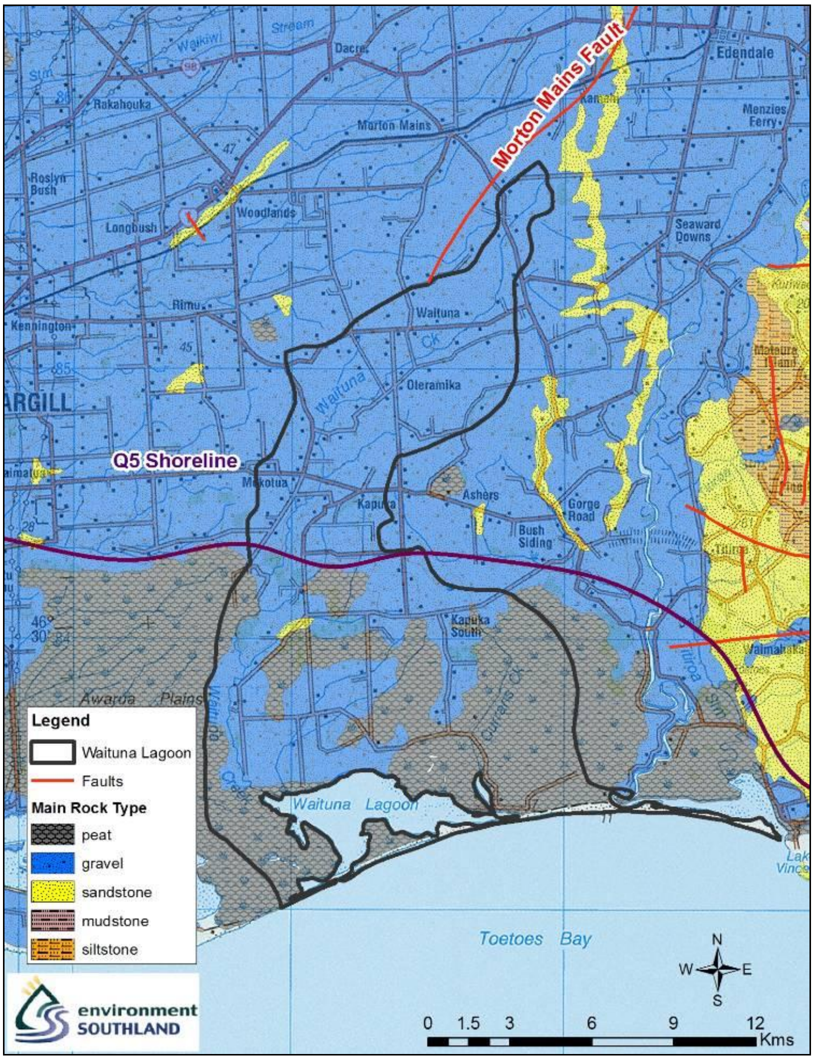

Figure 8: Surface geology of the Waituna catchment and interpolated shoreline approximately 70,000 to 130,000 years ago

[Source: GNS Science, 2003]

Figure 9 shows a 270-metre deep bore log from Hanson Road near the northern boundary of the Waituna Lagoon. The stratigraphic sequence shows recent marine deposits to 4 metres depth overlying a 2.3 metre thickness of Quaternary alluvial gravels which in turn overlies 264 metres of Gore Lignite Measure sediments. The episodic marine transgression and regression is shown in this bore log through the thick layers of mudstone (marine transgression) interspersed with lignite and gravel layers (marginal marine and terrestrial deposits).

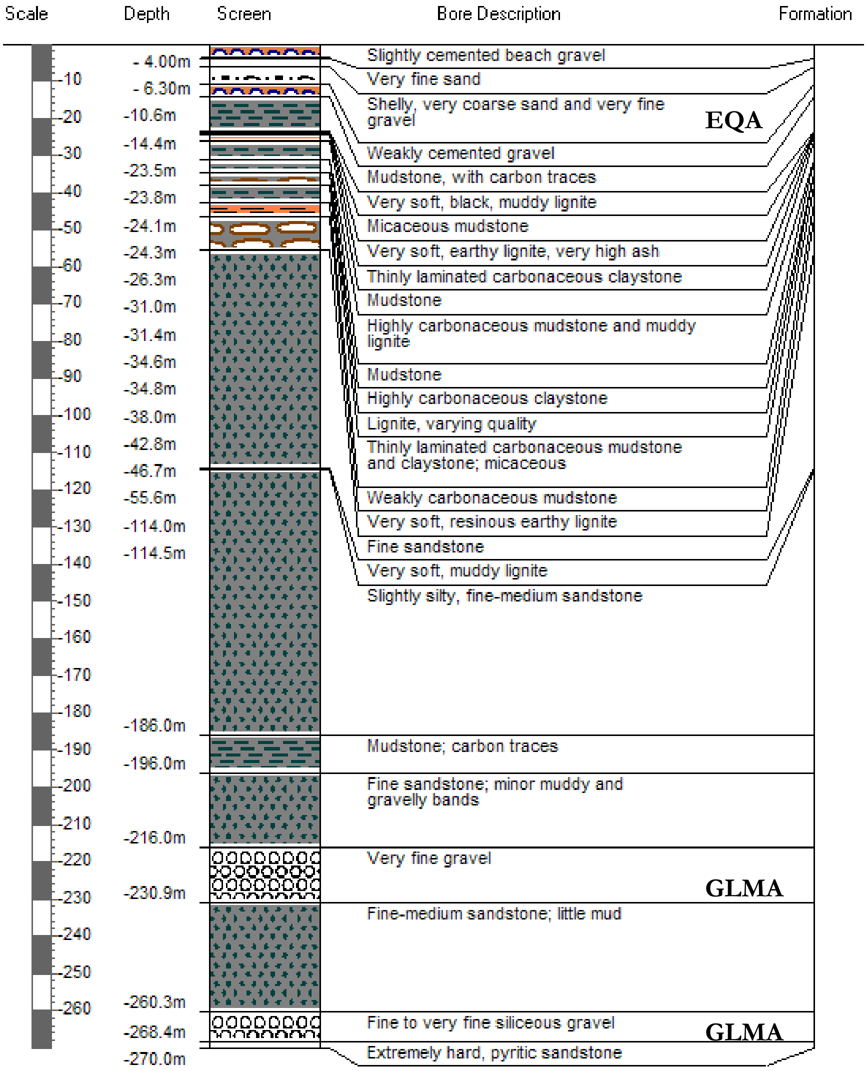

Figure 9: Bore log of F47/009 showing the Gore Lignite Measure Aquifers and unconfined aquifer . [5]

[Note: EQA = Early Quaternary Aquifer or the unconfined aquifer while GLMA = Gore Lignite Measure Aquifers or the confined aquifers.]

2.2.3 Soils

Figure 10 shows the major soil orders in the Waituna catchment are brown, gley, podzolic and organic soils. The organic soils are peat soils formed in slowly decomposing organic material. Typically, they occur as raised bogs (up to 6 metres deep) overlying gravels and have very poor drainage. The podzolic soils developed on alluvial and old marine terraces in coastal areas east of Invercargill. These soils formed in shallow to

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[5] Source: Eastern Southland Coal Project bore log 1147 (1977) at E: 2172855 N: 5397753

moderately deep loess deposits and generally overlie gravel resulting in imperfectly drained soils. Gley soils formed on the floodplains of small streams into fine alluvium from rewashed gravels and loess. These soils are poorly drained due to the silty texture. Brown soils developed on the high terraces and old marine terraces of the southern plains and formed in deep wind-deposited loess. As a result, these soils are typically well to imperfectly drained[6].

Overall, the soils in the Waituna catchment tend to be imperfectly to poorly drained due to the dominance of fine sediment (e.g. clays and silts) in the soil matrix which reflects the accumulation of loess deposits along with the mudstone, siltstone and claybound gravel sediments of the underlying geology. Because of the soil type and the relatively low-lying topography, developed land in the Waituna catchment includes extensive artificial drainage (mole, tile and surface drains) resulting in significant modification of the natural hydrology. Originally, groundwater and extensive wetland areas (like the Awarua Plains) stored and slowly released excess rainfall to surface water ways and in a sense acted like a natural water quality filter. However, with the onset of artificial drainage, water now flows much more rapidly to streams thereby reducing summer stream flows and reducing the opportunity for natural biochemical processes to improve water quality.

An interesting feature of **Figure 10** is how clearly the southern extent of the brown soils shows the last interglacial shoreline from 70,000 to 130,000 years ago (Q5 shoreline shown in **Figure 8**) as interpreted from geological data (GNS, 2003). The key difference in soil characteristics across this boundary is drainage whereby the brown soils are generally more well drained compared to the organic, gley and podzolic soils which are all poorly drained and can often be waterlogged due to impermeable lenses or pans within the soil, impermeable underlying geology and the low topographical gradient. As the Waituna Lagoon fills, the relatively flat nature of the old marine terrace that marks the lower half the catchment causes drainage water to bank upstream, which also waterlogs the surrounding soils.

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[6] The soil descriptions are sourced from Crops for Southland (2002)

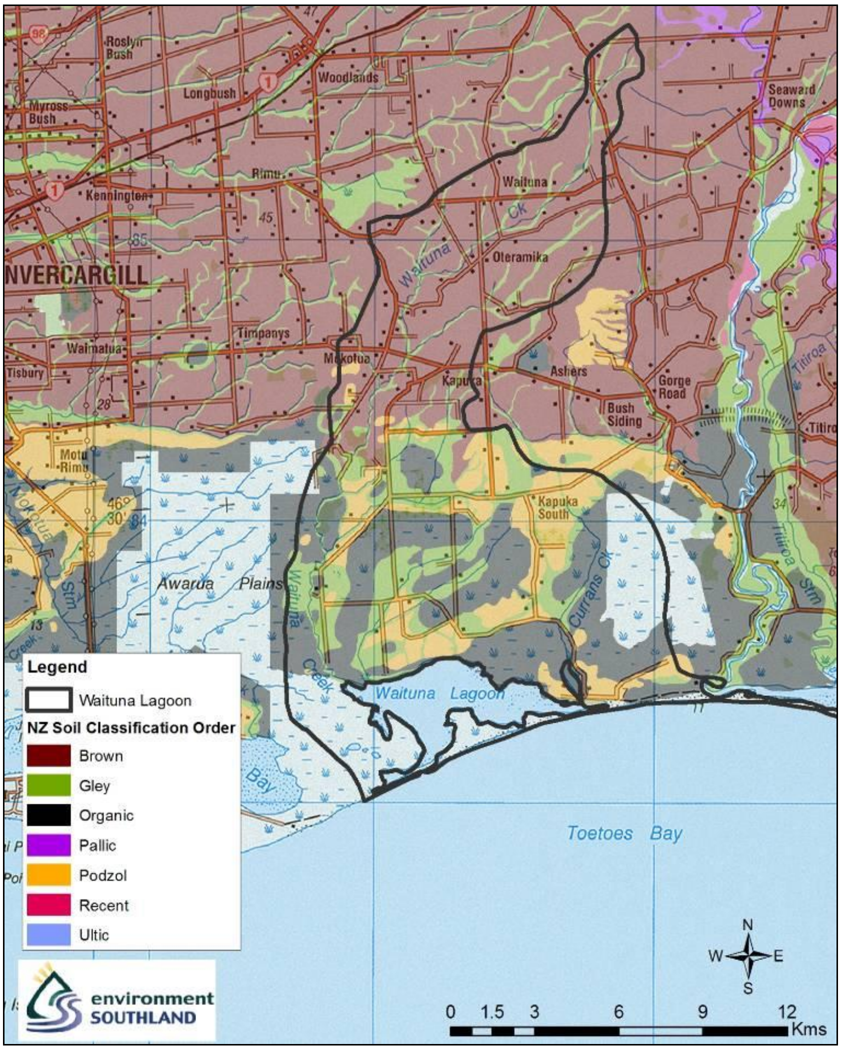

Figure 10: Soil classification in the Waituna catchment.
[Note: the southern boundary of the brown soils matches the Q5 (old marine) shoreline (shown in Figure 8)]

2.3 Hydrogeology

Groundwater occurs throughout the Quaternary gravels and underlying Gore Lignite Measure sediments throughout the Waituna catchment.

The Quaternary gravels host a shallow, unconfined aquifer system, which forms part of the Waihopai groundwater zone defined in the Regional Water Plan for Southland (RWP). This aquifer system is classified as a Lowland aquifer type. This aquifer type is typically hosted in remnants of the original Quaternary gravel outwash surface locally dissected by first and second-order streams to form the gently undulating topography characteristic of large areas of eastern and central Southland. The alluvial materials hosting Lowland aquifers generally exhibit moderate to low permeability due to the high concentration of silt and fine sand in the gravel matrix (resulting from both the mode of deposition and subsequent weathering).

Figure 11 shows a conceptual model of a typical Lowland aquifer system. The diagram shows two primary components of groundwater flow in Lowland aquifers. The major component is local comprises drainage of rainfall recharge from the higher terrace areas to local rivers and streams. The second component is the deeper, sub-regional circulation of groundwater, which follows overall catchment drainage. The vertical boundary between the localised and sub-regional flow components is generally indistinct.

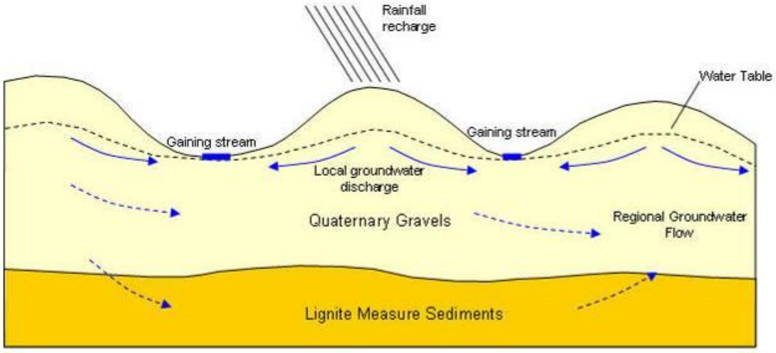

Figure 11: Schematic cross-section of groundwater flow in a lowland aquifer

An extensive groundwater resource also occurs within the Gore Lignite Measure sequence that is in excess of 200 metres thick throughout the Waituna catchment. Although containing appreciable quantities of groundwater, the fine-grained texture (predominantly mudstone and lignite) of a majority of sediments comprising the stratigraphic sequence exhibit low to very low permeability (and thus are best considered as forming “aquitards”[7]). Significant water-bearing strata are generally restricted to thin, laterally discontinuous layers of sand and gravel. Due to the abundance of fine-grained materials the primary water-bearing units in the lignite measure sequence are considered relatively well confined with limited groundwater circulation occurring through the intervening aquitard materials. Artesian pressures are observed in some water-bearing horizons toward the south coast.

Durie (2001) identified the presence of three distinct water-bearing horizons within the lignite measure sequence in the Morton Mains-Kapuka area (nominally termed GLMA-1, GLMA-2 and GLMA-3). However, extrapolation of lithologies between individual bore logs (particularly in areas with significant geological information such as the Ashers-Waituna basin) suggest these “aquifers” represent multiple, discrete water-bearing intervals hosted in lensoidal deposits of sand and gravel at similar depths within the stratigraphic sequence, possibly representing channelized alluvial deposits formed during periods of sea level transgression when much of the area was covered by a prograding delta system. Available hydrogeological and groundwater level data suggest a moderate to low degree of hydraulic connection between individual water-bearing intervals within the Lignite measure sequence.

Figure 12 (a) and **12(b)** show a geological cross-section through the Waituna catchment based on available drill log information with lithologies simplified in order to show coarse changes in stratigraphy. **Figure 12(a)** shows the cross-section A-A’ is oriented east to west and is oblique to the groundwater flow direction (which generally follows the SSW topographic gradient). The following points are illustrated on **Figure 12(b)**:

- the Quaternary gravels range in thickness from less than 1 metre in the eastern extent of the catchment (Carran’s Creek) to 20 metres below ground level in the Moffat Creek catchment. None of the bore logs available intercept basement rock which must be present at a depth greater than 240 metres below the surface. The Tertiary age East Southland Group sediments (which includes the Gore Lignite Measures) are therefore

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[7] An aquitard is defined as a geological unit which stores groundwater but which, due to low permeability, acts to restrict groundwater flow

at least 220 metres thick. Overall sediment texture within the lignite measure deposits changes from predominately sand in the east to silt in the west;

- on the western side of Waituna Creek the bore logs show extensive sand and sandstone layers which may indicate a change from marginal marine lignite, mudstone and siltstone to a shallow marine depositional environment. Alternatively, it could reflect deposits which are aeolian in origin (e.g. paleo-sand dunes formed beyond the prograding delta where lignite measures were deposited);

- confined aquifers in the Gore Lignite Measures sequence are present in the cross-section in the western part of the Waituna catchment and probably reflect relatively thin, localised lenses of water-bearing gravel layers within the thicker layers of sandstone, siltstone and mudstone sediments.

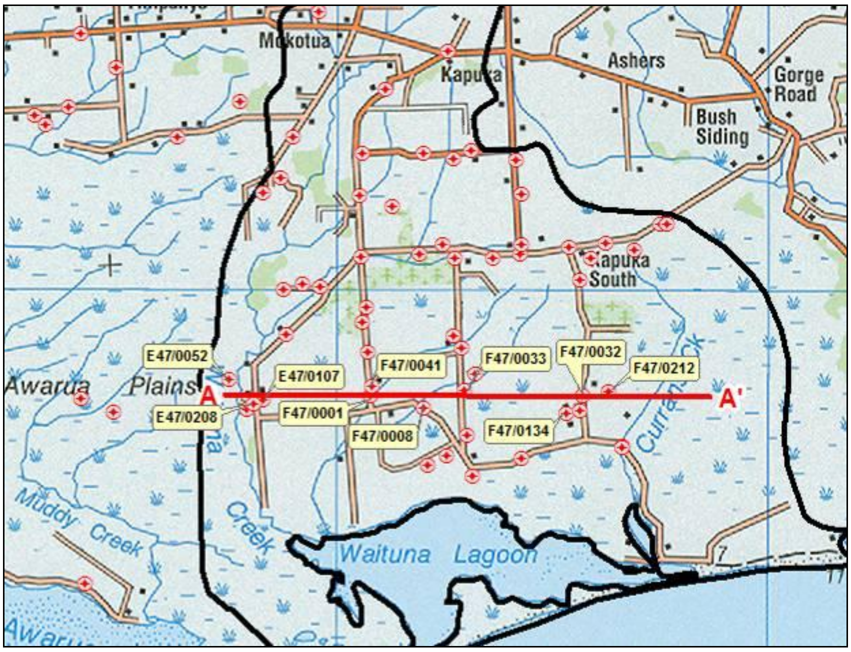

Figure 12 (a): Location of bores used in cross-section A-A'

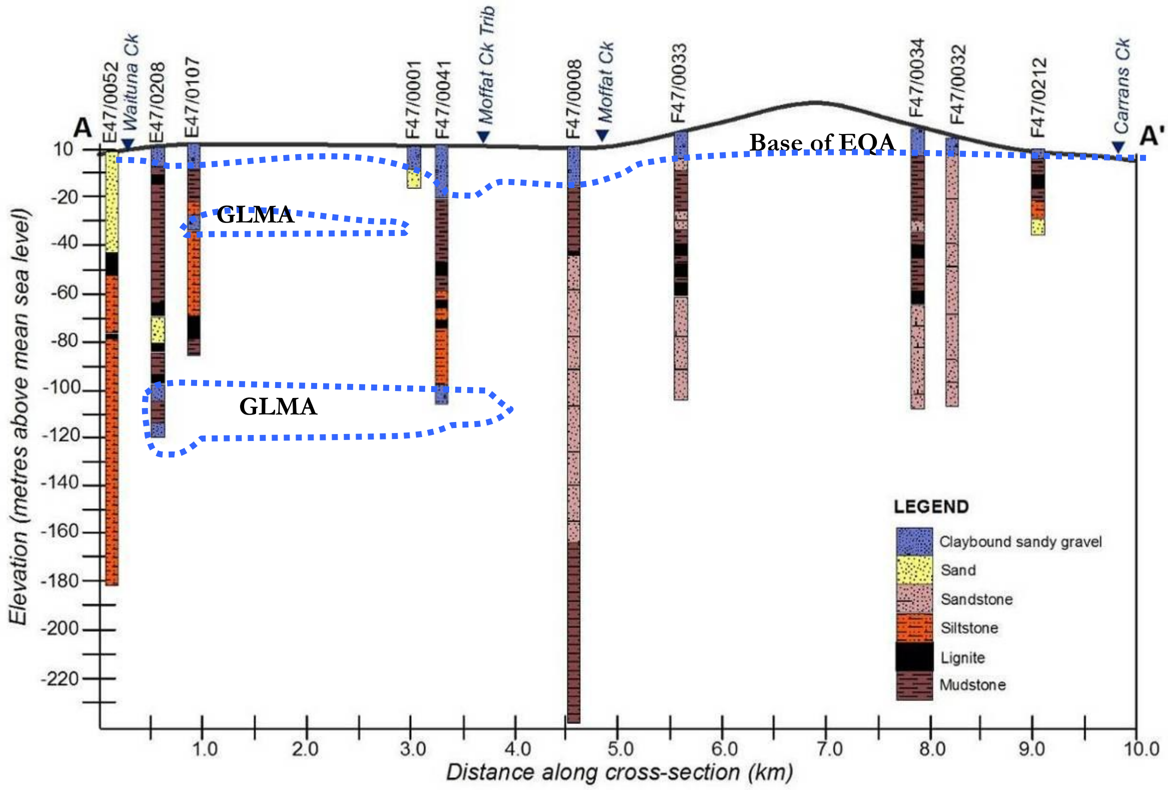

Figure 12 (b): Cross-section of the geology of A-A' based on bore log data with a vertical exaggeration of 1:23 and an interpolated base of the unconfined aquifer (EQA) and Gore Lignite Measure Aquifers (GLMA)

The interpolated thickness of the Quaternary gravel sediments is shown in Figure . From these data it is interpreted that:

- the limited gravel thickness (generally less than 5 metres) in the northern third of the Waituna catchment reflects the influence of the Gorge Road platform (where the Tertiary and basement sediments are present near the surface as shown in **Figure 6**);

- the gravel thickness appears to be deepest under the Moffat Creek catchment which may reflect a paleochannel or geological structure aligned in a southwest direction. This follows the dip of the underlying Tertiary sediments and is consistent with current surface water drainage however does not align with the topographical gradient;

- the gravel thickness in the Waituna Creek catchment is variable, generally ranging from less than 5 metres thick in the upper part of the catchment (**Figure 13**), to between 10 to 20 metres across the middle reaches before thinning again in the lower reaches to less than 10 metres;

- the limited thickness of Quaternary gravels present in the Carran's Creek catchment is likely to limit the extent of the unconfined aquifer in this area resulting in the formation of an extensive wetland complex;

- the catchment drainage, geology and possible paleochannels in the lignite measures and gravels are orientated in a predominately southwest direction. This does not exactly mirror surface topography and does not match the overall catchment boundary orientation, which is largely north-south. This indicates groundwater and surface water catchments may not entirely align and that catchment hydrology may be influenced by the underlying geology.

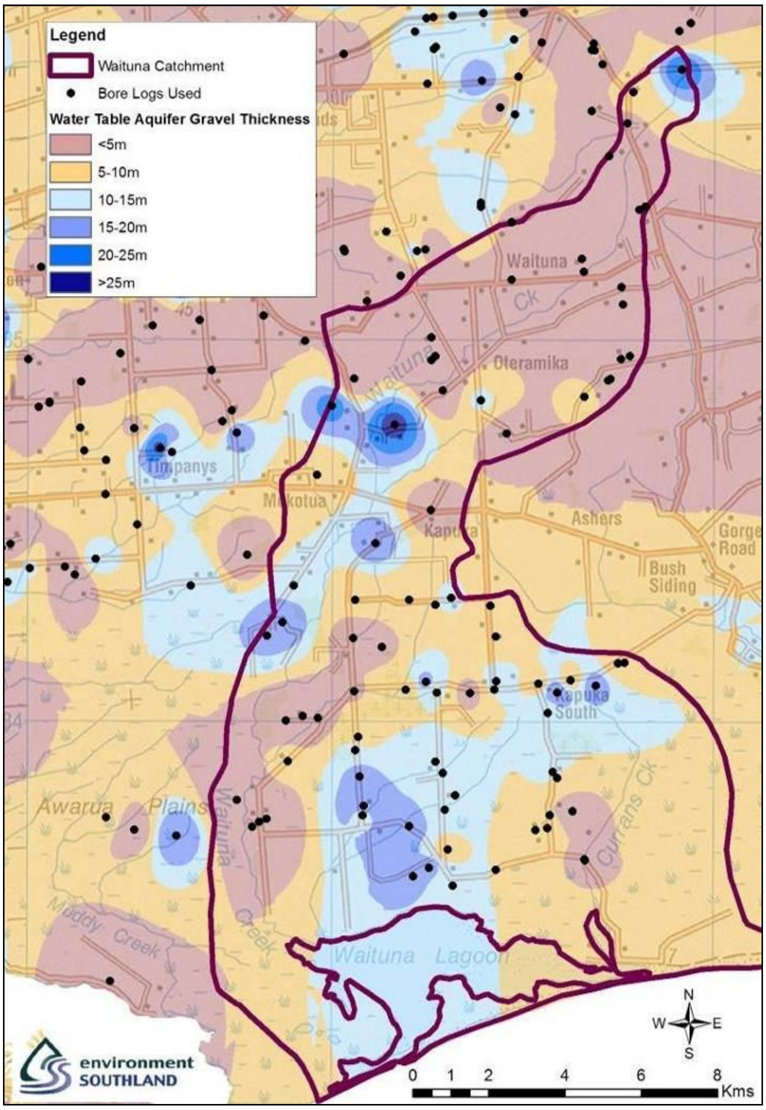

Figure 13: Interpolated unconfined aquifer gravel thickness using an inverse distance weighting method

No aquifer tests are available for the unconfined aquifer in the Waituna Creek catchment. However data from available bore logs indicate specific capacity values in the order of 1 to 55 m^3/day/m (with an average[8] of 20 m^3/day/m) indicating the relatively low permeability of the gravel materials. By comparison, the specific capacity values from bores in the confined lignite measure aquifers ranges between 1 to 400 m^3/day/m (with an average of 42 m^3/day/m). As a consequence of the higher yield and greater available drawdown, confined aquifers in the lignite measure sequence are generally preferred for establishing stock and dairy supplies in the Waituna catchment (although their use for potable supply is often limited by the occurrence of elevated iron concentrations).

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[8] Average specific capacity of bores with a depth less than 20 metres is 20 m^3/day/m. Average specific capacity of bores with a depth 20 metres or greater is 42 m^3/day/m.

3. Groundwater Quantity

The following section utilises existing meteorological and hydrological data to provide a water balance for the Waituna catchment. A summary of available groundwater level and flow gauging data in the Waituna catchment is included to provide an overall view of the physical hydrology of the Waituna catchment.

Figure 14: Photograph showing groundwater levels being measured in bore F47/0153
[Source: K Wilson, March 2011]

Water Balance

Figure 15 shows a schematic illustration of the primary components of the aquifer water balance in the Waituna catchment. The figure shows infiltration of local rainfall is the primary source of recharge with some inflow also possible from aquifer systems (particularly within the lignite measure sequence) external to the Waituna catchment. Groundwater discharge primarily occurs as base flow discharge to the Waituna, Moffat and Carran Creek catchments, direct inflow (seepage) into Waituna Lagoon and discharge direct to the coast or further offshore. A small component of groundwater outflow may also occur via evapotranspirative losses in areas where the water table is shallow and can either be accessed directly by plant roots.

The following section attempts to characterise the primary components of the overall aquifer water balance in the Waituna catchment. While preliminary estimates are provided, it is acknowledged that due to the limited data available, uncertainties remain in the calculation of the key components of the water balance. Given the importance of these figures in terms of understanding both water quantity and water quality interactions within the Waituna catchment, further monitoring and investigations may be required to improve definition of these components including groundwater recharge, base flow and lagoon (seepage) inflows.

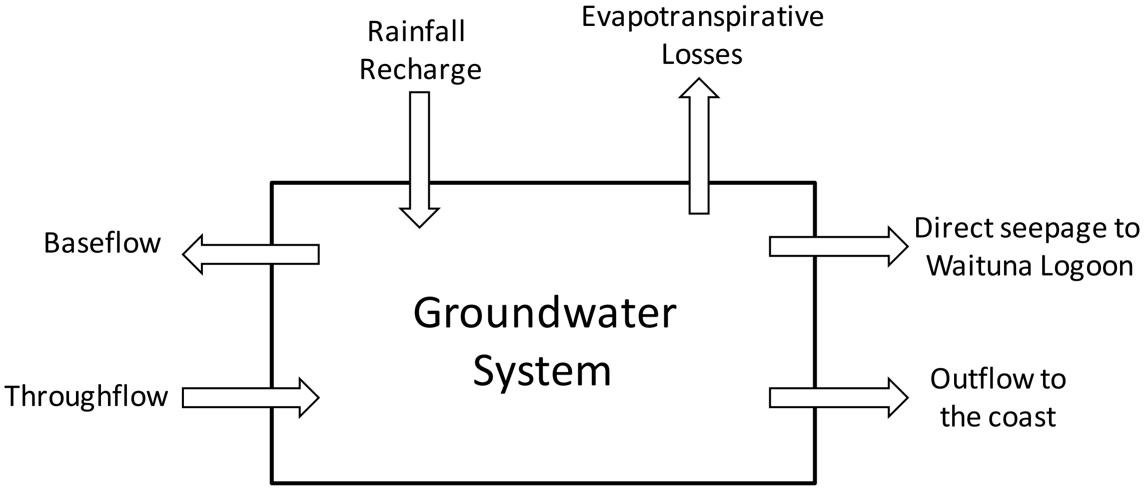

Figure 15: Schematic water balance for the Waituna catchment groundwater system

Rainfall recharge

The unconfined aquifer in the Waituna catchment is predominately recharged from direct rainfall infiltration. LVL and MWH (2003) calculated the average annual rainfall recharge for the Waihopai groundwater zone to be approximately 521 mm per year which equates to approximately 48 percent of the total mean annual rainfall of between 1,080 and 1,100 mm in the Waituna catchment (C Jenkins *pers comms*). Over the Waituna catchment area of 20,255 hectares this equates to approximately 100 million m^3 per year of rainfall recharge to the unconfined aquifer system.

The volume of recharge to the Gore Lignite Measure Aquifers within the Waituna catchment is difficult to quantify due to the lack of data to define overall aquifer hydrogeology. A preliminary estimate of 8.8 million m^3 per year is calculated using Figure 9-2 and Tables 9-5 and 9-6 in LVL and MWH (2003), possibly accounting for approximately 10 percent of the rainfall recharge to the unconfined aquifer system.

Groundwater throughflow

As described in **Section 2**, due to the nature of the topography and underlying geology available data suggest the spatial extent of the surface water and groundwater catchments draining to Waituna Lagoon may not be entirely coincident, especially in the area between Kapuka South and Gorge Road. In particular, due to their lateral continuity and south-western dip, it is possible that water-bearing intervals within the lignite measure sediments are recharged in areas external to the Waituna Lagoon surface water catchment. The volume of this groundwater throughflow is unknown due to the paucity of information available to characterise the hydrogeology of the lignite measure aquifers to the north of the Ashers-Waituna lignite deposit.

Base flow discharge

Available data indicate the hydrology of the Moffat Creek and Waituna Creek are very similar to that observed in the Waihopai River, possibly reflecting overall similarities in landform, geology and rainfall patterns (C Jenkins, *pers comms*). For example, **Figure 16** shows that flow gaugings in the Waihopai River, Moffat Creek and Waituna Creek taken on the same day are strongly correlated (R^2 greater than 0.96). This figure also indicates that Moffat Creek carries a discharge of approximately 10 to 20 percent of that occurring in Waituna Creek.

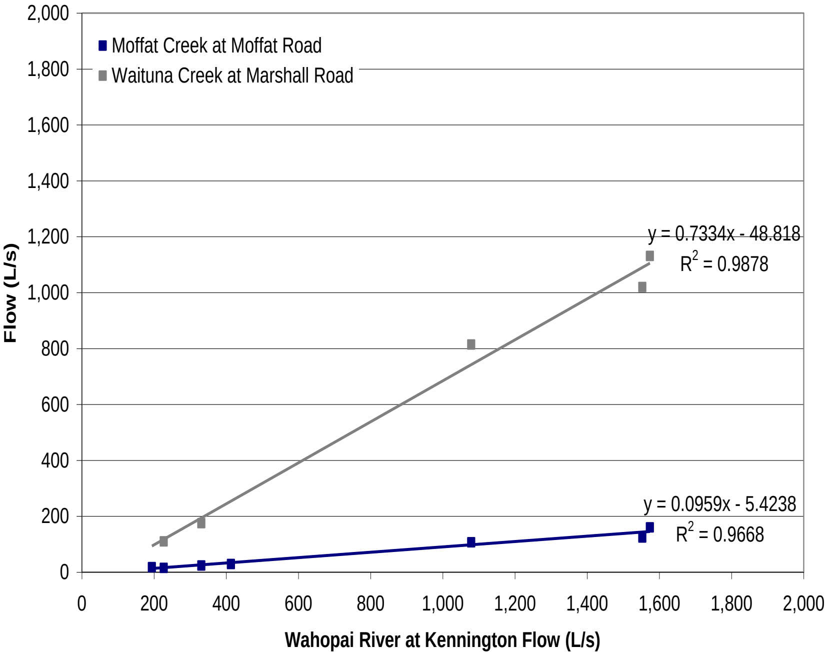

Figure 16: Linear regression correlation with gaugings in the Waihopai River against gaugings in Moffat Creek and Waituna Creek taken on the same day

Table 1 presents base flow analysis of several Southland catchments undertaken using Basejumper (SKM, 2007), a program with performs base flow separation of daily stream flow records using the digital recursive filter technique developed by Nathan and McMahon (1990)[9].

Table 1: Base flow analysis for selected Southland catchments

Catchment	Period	Base Flow Index	Catchment Area (km²)	Mean Annual Stream Flow mm/year	
				Total	Base Flow
Waimea Stream at Mandeville	1990-2011	0.43	398	269	115
Waihopai River at Kennington	1990-2011	0.44	154	547	241
Waikaka Stream at Willowbank	1990-2011	0.49	318	323	159
Mokoreta at McKays Road	1990-2011	0.55	418	730	400
Mataura River at Parawa	1990-2011	0.63	801	709	443
Makarewa River at Counsell Road	1990-2011	0.45	991	478	218
Waituna Creek at Marshall Road	2001-2011	0.48	108	493	237

Overall the data indicate a base flow contribution of between 0.43 and 0.63 (or 43 to 63 percent of total discharge) in the catchments analysed reflecting the relatively high contribution of base flow to stream discharge across the Southland region. In the Waituna catchment the analysis indicates a base flow contribution of 0.48 which is toward the lower end of the range of calculated values. Given a median discharge of 910 L/s in Waituna Creek at Marshall Road, this

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[9] Analysis for all catchments except Waituna Creek undertaken over a standard time period (1990-2011) to ensure direct comparison. Analysis of Waituna Creek undertaken using all available data

analysis indicates a base flow discharge of approximately 440 L/s (approximately 38,000 m^3/day or 13.8 ml/year) across the 108 km^2 catchment for this site, equivalent to a specific discharge of 4.1 L/s/km^2.

Overall, the analysis suggests that groundwater discharge is likely to contribute in the order of 40 to 50 percent of total discharge in the Moffat and Waituna Creek catchments. This suggests groundwater is likely to be a significant component of surface hydrology and, as such, exert a significant influence on overall water quality.

Direct inflow (seepage) to Waituna Lagoon

As outlined in **Appendix 1**, groundwater seepage measurements were undertaken by Environment Southland at two locations in the Waituna Lagoon. Results of these measurements yielded an average seepage inflow rate of 0.00017 m^3/day/m^2 near the eastern end of the lagoon and 0.00401 m^3/day/m^2 near Moffat Road. The order of magnitude difference is interpreted to reflect differences in the texture of the fine sediment "clogging layer" accumulated on the lagoon bed at the two sites.

The effect of the "clogging layer" in retarding the flow of groundwater into the lagoon is illustrated by the piezometric head measured in shallow piezometres installed at both sites which showed underlying groundwater levels were between 0.85 (eastern site) and 0.78 (Moffat Road site) metres higher than lagoon stage. Based on the recorded seepage inflow and observed head difference, the hydraulic conductivity of the bed materials were calculated as 0.005 m/d (eastern site near Waghorns Road) and 0.124 m/day (western site near Moffat Road).

While seepage measurements clearly show groundwater seepage through the lagoon bed, estimation of a representative inflow is dependent on the proportion of the lagoon bed assumed for the two representative seepage values. In reality, the bed materials are likely to be heterogeneous reflecting the complex interaction between currents and wave action, which influence sedimentation within the lagoon. However, anecdotal observations suggest that between half and three quarters of the lagoon bed have coarser sediment similar to that observed at the Moffat Road site, with the occurrence of finer bed sediment more prevalent in the narrow eastern end of the lagoon.

A representative range for seepage inflow to Waituna Lagoon was estimated at between 340 to 460 L/s assuming a ratio of between 50:50 to 70:30 for the higher to lower permeability bed materials. This calculation is based on a lagoon bed area of 14 square kilometres (approximate lagoon area at a stage height of 1.3 metres above sea level) and relates to the combination of lagoon level (slightly above median) and groundwater level (close to seasonal minimum) occurring in April 2012.

While seepage measurements indicate a relatively significant volume of groundwater seepage inflow into Waituna Lagoon, the relative contribution of discharge from the unconfined aquifer versus diffuse leakage from the underlying lignite measure aquifers is unknown. Future water quality investigations may assist determination of the relative contribution from these sources.

Outflow to the coast

The piezometric gradient within both the Quaternary gravel aquifer and the underlying Gore Lignite measures indicates flow toward the south coast. Any water flowing through these aquifers, which does not discharge to the lagoon itself or its immediate surrounds, will ultimately discharge into the sea off the south coast. The quantity of this aquifer throughflow is unknown at the present time but will determine the relative position of the saline interface (the transition between fresh water and saline water) within water-bearing intervals which extend offshore, particularly within the lignite measure sequence.

Evapotranspirative losses

Evapotranspirative losses from the groundwater system include direct evaporation from ponded areas where the water table intersects the land surface and water removed by overlying vegetation in areas where the water table is shallow. While, in the context of the overall catchment water balance evapotranspirative losses are likely to be relatively minor, during extended periods of low rainfall they can be sufficient to result in observable diurnal fluctuations in both stream flow and groundwater levels in the Waituna catchment.

3.1 Groundwater Levels

The Waituna Lagoon is located at the southern boundary of the Waihopai groundwater zone. As previously described, the hydrogeological setting in this area comprises a thin layer of Quaternary gravels (typically less than 20 metres) which host a laterally extensive unconfined aquifer system. This unconfined aquifer overlies a thick sequence of lignite measure sediments, which contain multiple water bearing intervals forming a relatively complex confined aquifer system.

In 2000, Environment Southland initiated a regional State of Environment (SOE) groundwater level monitoring programme which included a number of bores distributed across the Waihopai groundwater zone (generally screened in the unconfined Quaternary gravel aquifer). Over the subsequent period, this monitoring programme has continued with the number and location of sites monitored evolving to enable characterisation of temporal groundwater level variations at a regional-scale.

Prior to 2011, the SOE groundwater level-monitoring programme included two bores located in the Waituna catchment:

- F46/0391 a 15 metre deep bore screen in the unconfined aquifer at Oteramika; and
- F47/0053 a 131 metre bore screened in lignite measure sediments at two intervals (60 to 73 metres below ground and 90 to 121 metres below ground) located on Hodgson Road, approximately 5.5 kilometres north of Waituna Lagoon.

In response to the emerging water quality issues associated with the Waituna Lagoon, an additional 10 monitoring bores (in the unconfined aquifer) were added to the baseline programme in mid-2011.

Since 2008, a significant amount of groundwater level data has also been collected in the Waituna Lagoon catchment as part of ongoing investigations by L&M as part of investigations to characterise the hydrogeology of the Ashers-Waituna lignite resource. Much of this data has been collected from a network of piezometres installed during investigations undertaken by the Liquid Fuels Trust Board (LFTB) during the 1970s and early 1980s[10].

The current groundwater level monitoring network in the Waituna catchment (including bores monitored by L&M) is shown in **Figure 17.** This figure identifies the location of individual

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[10] Unfortunately, much of the hydrogeological information collected during this original phase of investigations has been lost. L&M is thanked for making data collected over recent years freely available to this study

monitoring bores (including multi-level piezometre installations) as well as the current measurement frequency.

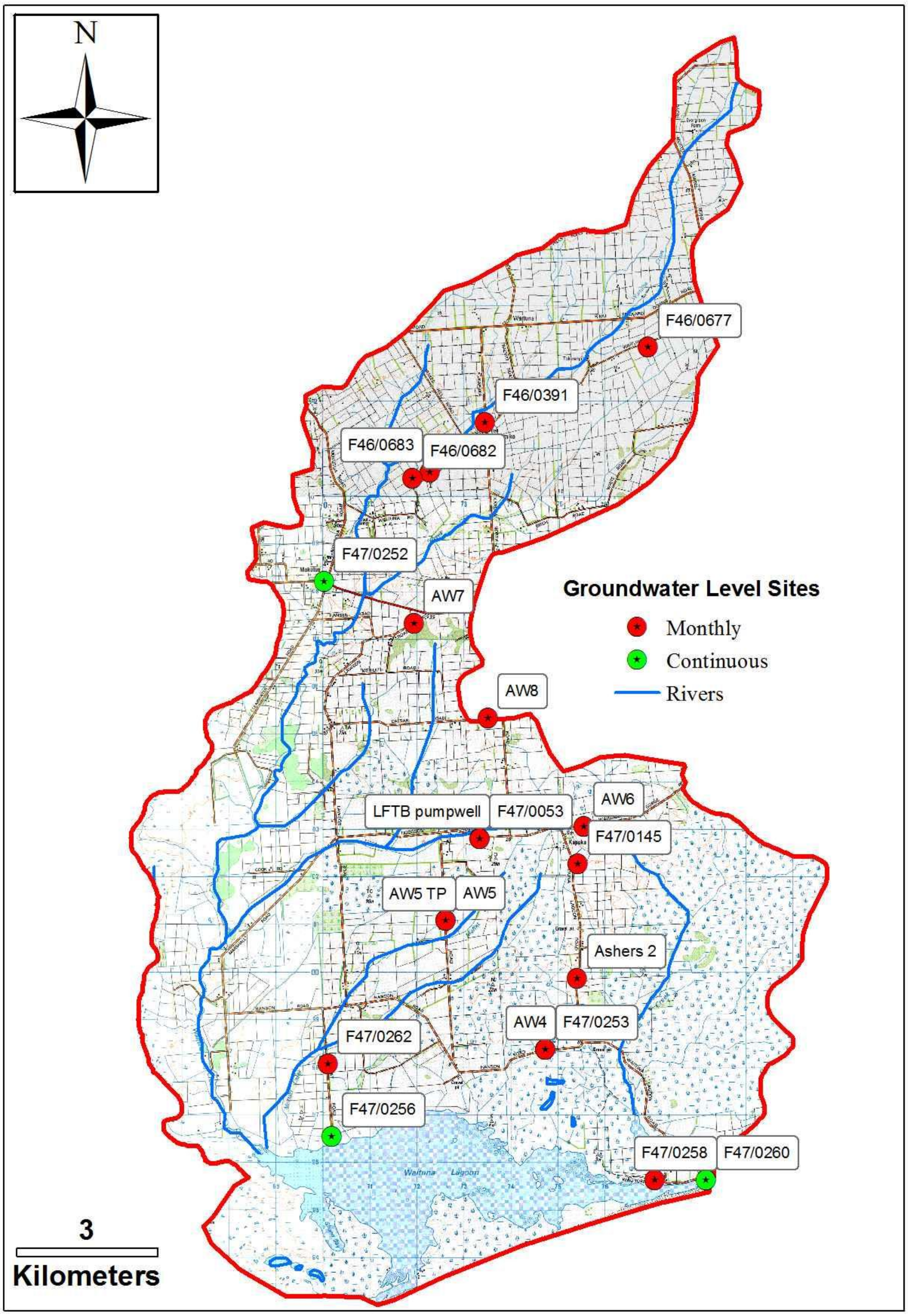

Figure 17: ES groundwater level monitoring sites in the Waituna catchment

The following section provides a review of existing groundwater level monitoring data available in the Waituna catchment, from the regional-scale down to localised groundwater level response around the margins of Waituna Lagoon.

Regional groundwater levels

Figure 18 shows a plot of groundwater levels recorded in the Quaternary gravel aquifer in the Waihopai groundwater zone at Morton Mains (F46/0189), Invercargill (E46/0102) and Dacre (E46/0103). All three sites exhibit a similar pattern of seasonal variation with minimum groundwater levels typically occurring during autumn (March to May) and maximum levels during late winter/spring reflecting temporal variations in rainfall recharge. The amplitude of the observed seasonal variation ranges from 1 to 4 metres depending on seasonal recharge conditions and local hydrogeological characteristics of the Quaternary gravels (e.g. permeability, specific storage and hydraulic connection to surface water). As illustrated on **Figure 18**, the sites exhibit a general upward (linear) trend in groundwater levels over the past 10 years of between 20 to 100 millimetres per year. This overall increase in groundwater storage is interpreted to reflect the extended period of generally above average rainfall over the past decade described in **Section 2.2**

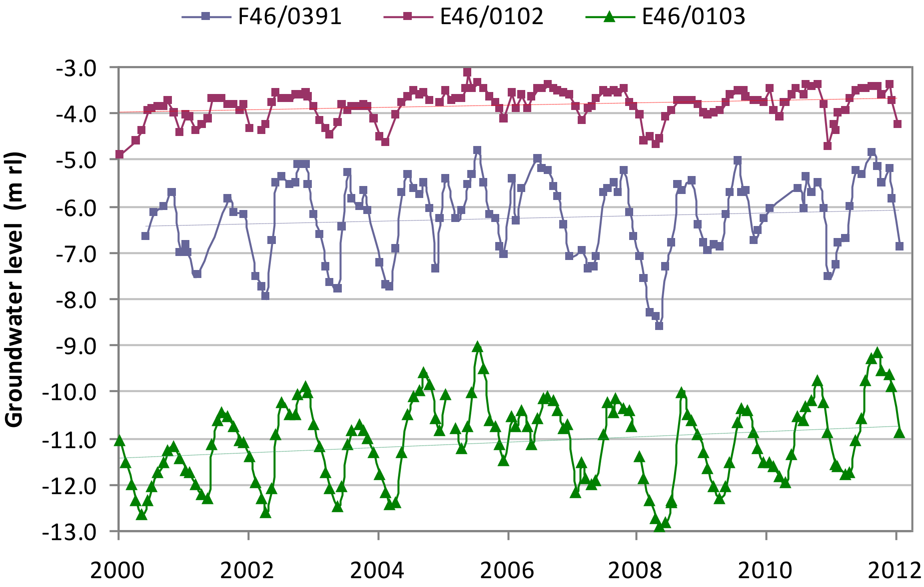

Figure 18: Groundwater level recorded in the Quaternary gravel (unconfined) aquifer in the Waihopai groundwater zone, 2000-2012
[Note: dotted lines represent a linear trend fitted for each data set]

Limited data is available to characterise long-term groundwater level variations within the Tertiary lignite measure sediments underlying the Quaternary gravels. **Figure 19** shows a plot of groundwater levels recorded in two bores screened in separate water-bearing intervals within the lignite measure sediments.

E47/0057 is a 70 metre bore located approximately 13 kilometres north-west of the Waituna Lagoon. Data from this site show a relatively regular seasonal variation of the order of 0.4 to 0.6 metres, which follow similar seasonal variations observed in the overlying Quaternary gravel aquifer. F47/0053 is a 131 metre deep piezometre located within the Waituna catchment approximately 5.5 kilometres north of the Waituna Lagoon. This bore shows a dampened seasonal variation likely to reflect a degree of hydraulic separation from shallow water-bearing intervals receiving seasonal recharge input. Both sites appear to exhibit a similar decline in groundwater levels post-2006, following a period of relatively stable levels over the preceding seven years of monitoring record. The reason for the apparent reduction in piezometric head

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within the lignite measure sediments is uncertain, particularly given the increasing groundwater level trend observed in the overlying unconfined aquifer.

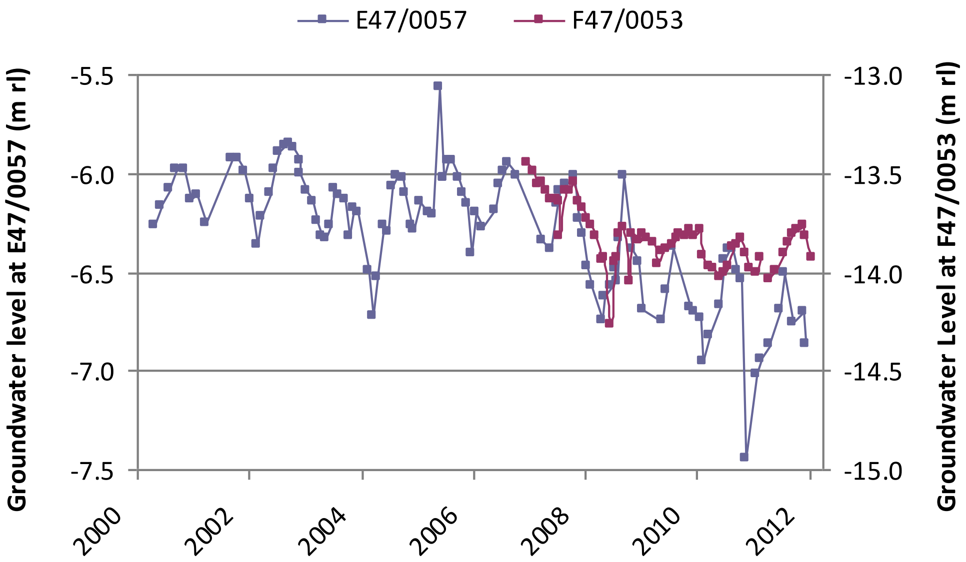

Figure 19: Long-term groundwater levels recorded in lignite measure aquifers in the Waihopai groundwater zone, 2000-2012
[Note: E47/0053 refers to right hand graph axis]

Groundwater levels in the Waituna catchment

As described in **Section 3**, the primary recharge input to the Waituna catchment groundwater system occurs via the infiltration of local rainfall. Significant groundwater discharge occurs via base flow in streams draining into the Waituna Lagoon, with a component of outflow directly into the lagoon or offshore. Observed temporal groundwater level response across the catchment reflects the local influence of these recharge and discharge processes.

Quaternary gravel (unconfined) aquifer

Figure 20 shows a plot of groundwater levels recorded in two automatic groundwater level monitoring sites (Ashers 1 shallow and F47/0252) screened in the unconfined aquifer inland of the ancient (Q5) shoreline[11]. Although there is limited overlap between the respective monitoring records, both sites show a comparable pattern of groundwater level response to significant rainfall events and exhibit a similar recession during periods of low rainfall.

The sharp peaks in the hydrograph reflect relatively rapid recharge of the shallow water table following rainfall events. The resulting increase in groundwater storage is relatively transitory with levels declining rapidly as groundwater discharges to the local drainage network. Due to the relatively high degree of hydraulic connection with local waterways, groundwater recession occurs rapidly during periods of low rainfall as water is progressively drained from the aquifer system. This type of hydrograph inferred to reflect a significant degree of interaction between surface water and groundwater in the shallow unconfined aquifer along the riparian margin of

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[11] The Ashers 1 shallow piezometer is screened at a depth of 8.9 metres along Ashers Road. This bore is located approximately 10 kilometres from Waituna Lagoon and lies within a small un-named catchment which drains eastward into the lower reaches of the Mataura River

Waituna Stream and suggests a relatively short residence time for recharge flux to this section of the unconfined aquifer.

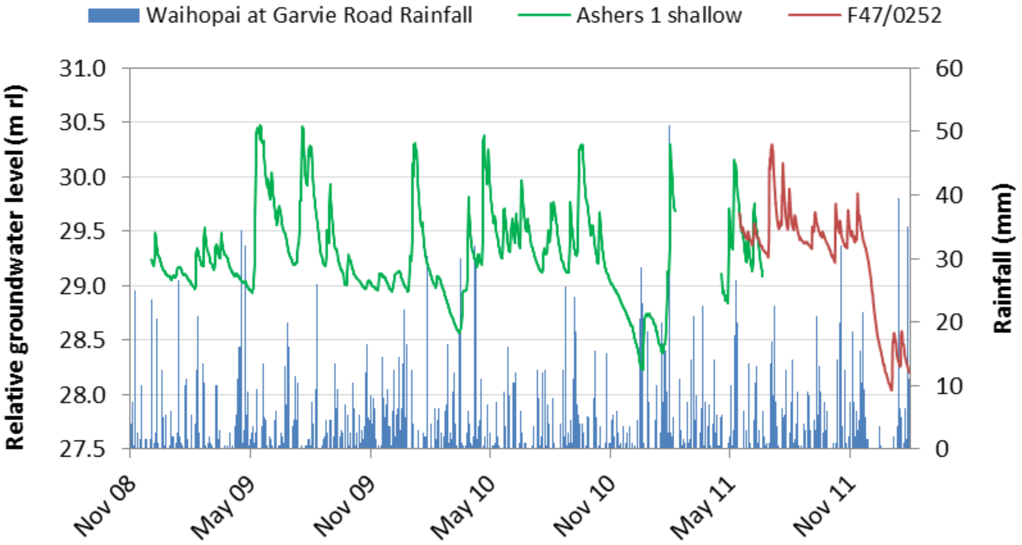

Figure 20: Groundwater levels recorded in the Quaternary gravel aquifer in the Waituna catchment, 2008-2012

Figure 21 shows the short-term hydrograph response in F47/0252. This bore is a 7 metre deep piezometre located adjacent to Gorge Road-Invercargill Highway at Mokotua. The bore is situated approximately 900 metres west of the main stem of Waituna Creek and approximately 850 metres east of a smaller tributary. As illustrated, groundwater levels at this site respond rapidly to rainfall events with the groundwater hydrograph closely matching (or preceding) temporal stage height variations in Waituna Creek. Of note is the large drop in groundwater levels observed during the December 2011. During this period groundwater levels declined by approximately 1.8 metres (an average decline of approximately 35 millimetres per day). This rapid decline is interpreted to reflect the significant contribution of groundwater to base flow in adjacent reach of Waituna Creek.

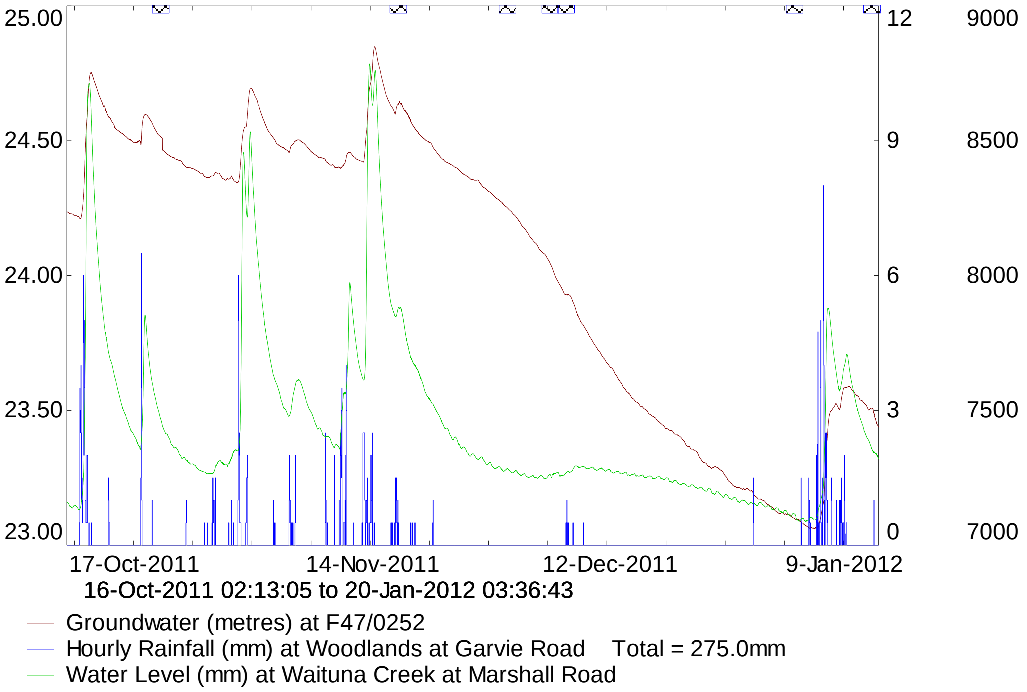

Figure 21: Short-term hydrograph response in F47/0252, October 2011 to January 2012. [Note: vertical axes from far left to right are: Groundwater Level (m), Hourly Rainfall (mm) and Water Level at Waituna Creek (mm)].

However, elsewhere in the unconfined aquifer temporal groundwater levels appear to follow a pattern of seasonal variation more characteristic of that observed across the wider Waihopai groundwater zone (as illustrated in **Figure 20**). **Figure 22** shows a plot of temporal groundwater level variations observed at F46/0391 located in the mid to upper reaches of the Waituna Stream catchment and in the 15 metre deep Ashers 2 piezometre located adjacent to Waituna Lagoon Road, approximately 3.5 kilometres from the lagoon margin. Both sites exhibit a roughly equivalent pattern of seasonal variation with an amplitude of between 2 and 2.5 metres. Compared to F47/0252 and the Ashers 1 piezometre, the more regular seasonal groundwater level variations observed at these sites may be more characteristic of deeper levels of the unconfined aquifer (both bores are screened approximately 15 metres below ground level, near the base of the Quaternary alluvium) which exhibit low permeability and a less direct hydraulic connection to adjacent surface water bodies.

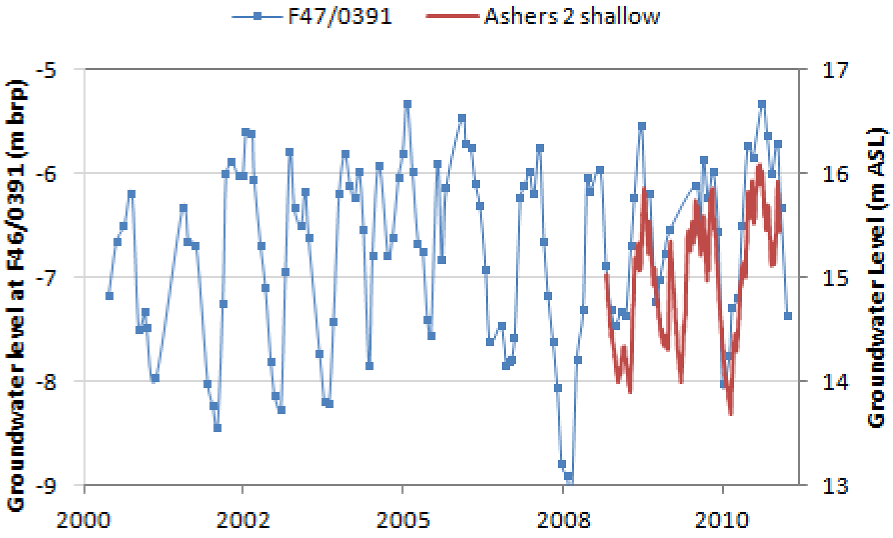

Figure 22: Groundwater levels in the unconfined aquifer at F46/0391 and the Ashers 2 piezometre

Overall, monitoring data from Waituna catchment show groundwater levels in the unconfined aquifer exhibit similar temporal trends to those observed elsewhere in the Waihopai groundwater zone. Groundwater at shallow depths (less than 10 metres) along the riparian margin of the Waituna Creek in the mid to lower catchment typically exhibit hydrographs matching those recorded in nearby streams suggesting rapid recharge to the water table following rainfall events followed by equally rapid base flow discharge. Bores screened at deeper levels of the unconfined aquifer and in the upper reaches of the Waituna Creek catchment typically exhibit a more regular pattern of seasonal water level variation, suggesting lower aquifer permeability and more limited hydraulic connection to surface water.

Lignite Measure Aquifers

Although a significant amount of groundwater level data has been collected from bores screened in water-bearing intervals associated with the Ashers-Waituna lignite deposit, characterisation of the spatial and depth variation in piezometric levels in the lignite measure deposits is complicated by the complex geological setting which consists of multiple, laterally restricted water bearing intervals of uncertain extent. Overall, relative piezometric levels within the lignite measure sediments decline towards the coast (i.e. the vicinity of the Waituna Lagoon) reflecting both the topographic gradient and south-westerly dip of the lignite measure sediments.

Comparison of relative groundwater levels recorded at similar depths across the L&M Ashers-Waituna piezometre array suggest an approximate head difference of 25 metres between the Gorge Road area and the south coast (equating to a piezometric gradient of the order of 0.002). As an example, **Figure 23** shows a map of median piezometric levels recorded in piezometres screened between 35 to 60 metres below ground (typically encompassing the "A100" seam in the Ashers-Waituna lignite deposit). While these data show the general decline in piezometric head toward the south coast, they also illustrate a degree of spatial variability that reflects the complex geological setting.

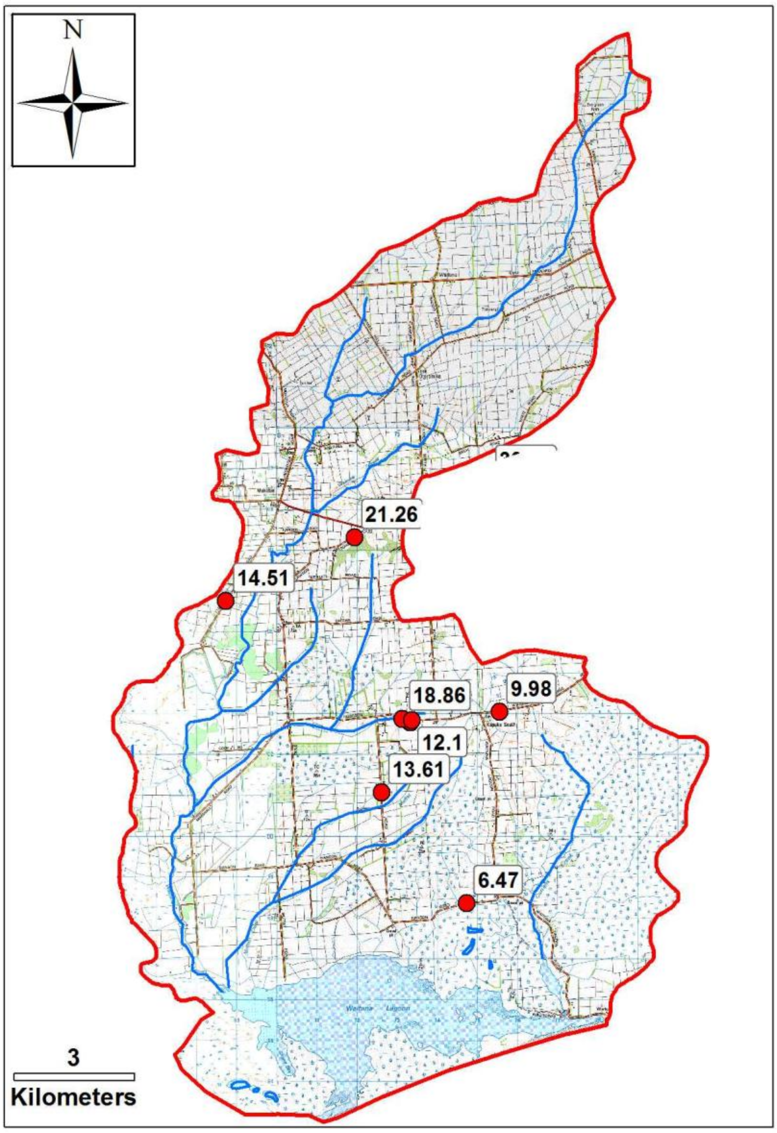

Figure 23: Map of median piezometric levels (in metres below ground level for 2009-2010) recorded in piezometres screened between 35 to 60 metres below ground in the Ashers-Waituna lignite deposit

On the basis of the available data it is noted that the piezometric gradient within the lignite measure sediments may not necessarily correspond to that occurring within surface catchments and associated unconfined aquifer. As a consequence, the groundwater flow system within the lignite measures may extend beyond the defined extent of the surface catchments draining to the Waituna Lagoon.

Many of the bores utilised for monitoring groundwater levels in the lignite measure aquifers contain multiple piezometres screened at varying depths. Data from these piezometres is useful to characterise vertical hydraulic gradients in the lignite measure sediments. **Table 2** provides a listing of median groundwater level derived from monitoring undertaken since late 2008 at nested piezometres in the Ashers-Waituna lignite deposit. Overall, the data show a downward hydraulic gradient is present across the entire area with the difference in relative piezometric head between individual piezometres varying according to screen depth and spatial location.

Table 2: Relative groundwater levels recorded in nested piezometres in the Ashers-Waituna lignite deposits

Borehole	Piezometre	Collar_RL (m ASL)	Depth (m)	Median groundwater level (m ASL)
Ashers 1	Piezo 1	31.3	8.89	29.23
	Piezo 2		23.3	14.98
Ashers 2	Piezo 1	18.12	15.1	15.04
	Piezo 2		137.5	5.19
AW4	Piezo B	9.66	7.35	6.71
	Piezo D		28.85	6.56
	Piezo C		46.8	6.47
	Piezo A		77.3	5.45
AW5	AW5TP	18.72	?	13.88
	Piezo A	18.58	52.1	13.61
AW6	Piezo B	23.64	29.3	15.75
	Piezo A	23.65	60.5	9.98
AW7	Piezo B	31.95	40.69	21.26
	Piezo A		75.1	17.59
AW8	Piezo B	32.1	69.5	10.82
	Piezo A	32.09	99.6	11.01
LFTB P2	Piezo 2	19.59	1.68	19.26
	Piezo 1		13.9	19.26
	Piezo 3		43.2	18.86
LFTB P3	Piezo 1	25.8	45.4	16.72
	Piezo 2	25.84	68.85	12.23
	Piezo 3	25.84	96.64	10.21
LFTB P4	Piezo 1	24.95	17.47	22.24
	Piezo 2		96.64	17.38

Figure 24 shows a plot of reduced groundwater levels recorded in the LFTB pumpwell installation situated along Hodgson Road, approximately 5.5 kilometres north of Waituna Lagoon. This installation consists of a large diameter bore and three nested piezometres (with a total of 9 separate screened intervals) installed during investigations into the Ashers-Waituna lignite resource during the 1970s. The data suggest the presence of at least four separate water-bearing layers with a relatively significant vertical hydraulic gradient of the order of 0.14 metres per metre.

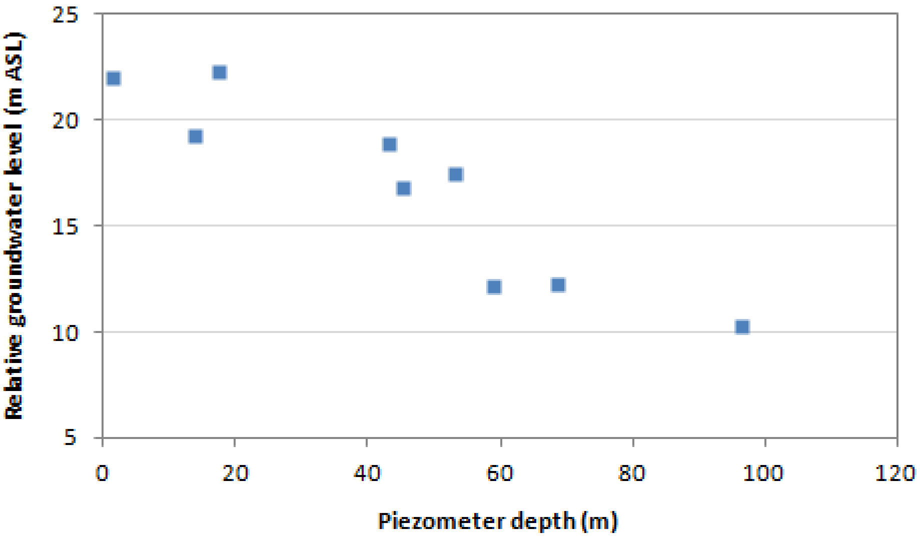

Figure 24: Variation in groundwater level with piezometre depth at the LFTB pumpwell installation on Hodgson Road

Figure 25 shows a plot of groundwater levels recorded in a nested piezometre (LFTB P3) at the pumpwell installation. These data show the significant vertical gradient between the respective piezometres in this bore. Also of note is the greater magnitude of seasonal variation observed in the two deeper piezometres (Piezo 2 and Piezo 3) compared to the shallower Piezometre 1 (45 metres). Levels in the two deeper piezometres also appear to exhibit the long-term seasonal decline observed elsewhere in the deeper lignite measure aquifers in the Waihopai groundwater zone (see **Figure 19**).

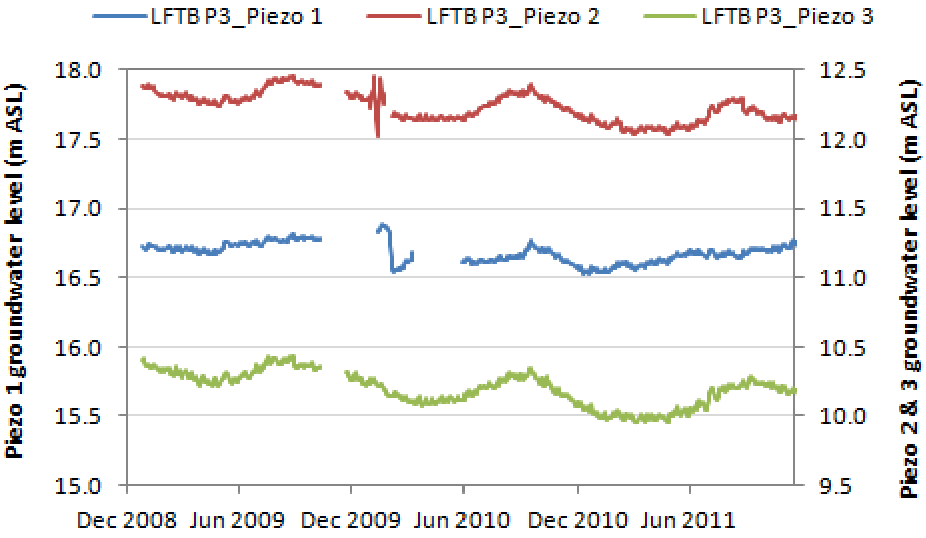

Figure 25: Temporal groundwater levels recorded in three piezometres installed in the LFTB P3 bore
[Note: relative levels for Piezo 2 and Piezo 3 relate to the right hand graph axis]

Despite the downward hydraulic gradient the potential exists for artesian heads to develop (particularly in shallow water-bearing intervals) toward the coastal margin as relative piezometric levels rise above the topographic surface. The presence of artesian head in this area is illustrated by the presence of an artesian bore (F47/0015) located near Carrans Creek adjacent to Waituna Lagoon Road. While this is one of only a few known artesian bores recorded in the Waituna catchment, the distribution of artesian heads is poorly constrained by the lack of deeper bores along the coastal margin.

The observed southerly piezometric gradient in the lignite measure aquifers infers an appreciable throughflow of water within this aquifer system in a southerly direction. Discharge of water via diffuse (artesian) leakage along the coastal margin is one possible mechanism to account for this hydraulic gradient. Such leakage is also one possible explanation for the apparent depressurisation in shallower water bearing layers observed in AW4 compared to relative levels recorded at similar depths near Hansen Road (both shallow and deep piezometres in this installation exhibit relative groundwater levels between 5.5 and 6.5 m ASL). **Section 3** reviews physical measurement of seepage rates into the bed of Waituna Lagoon, which may be, at least in part, associated with, discharge from aquifers within the underlying lignite measure sequence.

Groundwater level variation around the Waituna Lagoon margin

During 2011 Environment Southland installed a series of shallow piezometres around the margin of Waituna Lagoon to investigate local-scale variation in groundwater levels and groundwater quality around the lagoon margin.

F46/0256 is a 6 metre deep piezometre located at the south end of Moffat Road, approximately 150 metres from the northern margin of Waituna Lagoon. **Figure 26** shows a plot of groundwater levels in this bore over the September 2011 to February 2012 period along with Waituna Lagoon water levels and Woodlands rainfall. The data show groundwater level recovery between September to December 2011 tracking the ongoing rise in lagoon water levels with relatively minor response to individual rainfall events. Of particular interest is the virtually identical recession in lagoon and surrounding groundwater levels during the December 2011 to January 2012 period when little rainfall was recorded in the catchment. The similarity in hydrographs between Waituna Lagoon and F47/0256 indicates a significant degree of interaction between the Lagoon and shallow groundwater around this section of the north-western lagoon margin.

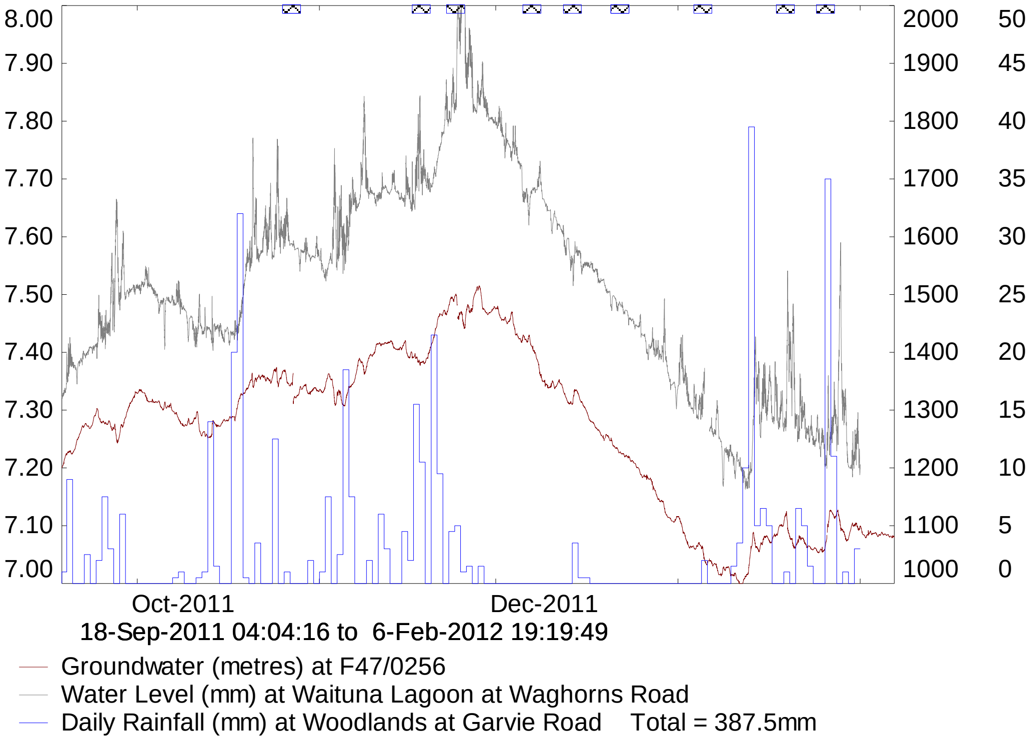

Figure 26: Stage height in Waituna Lagoon, rainfall at Woodlands and piezometric levels recorded in F47/0256, September 2011 to February 2012.
[Note: vertical axes from far left to right are: Groundwater Level (m), Waituna Lagoon water level (mm) and Daily Rainfall (mm)].

F47/0260 is a 6 metre deep piezometre located near the eastern extent of Waituna Lagoon. This bore is situated approximately 250 metres inland from the coast, 75 metres from the lagoon margin and 1,000 metres east of the Carrans Creek outlet. As illustrated in **Figure 27**, groundwater levels at this site appear to closely follow the temporal rainfall pattern with little evidence of water level variations associated with changes in lagoon stage. Although exhibiting a similar temporal response, it is noted the amplitude of piezometric level variations at this site is significantly reduced compared to that observed in shallow piezometres elsewhere in the Waituna catchment (e.g. **Figure 21**)

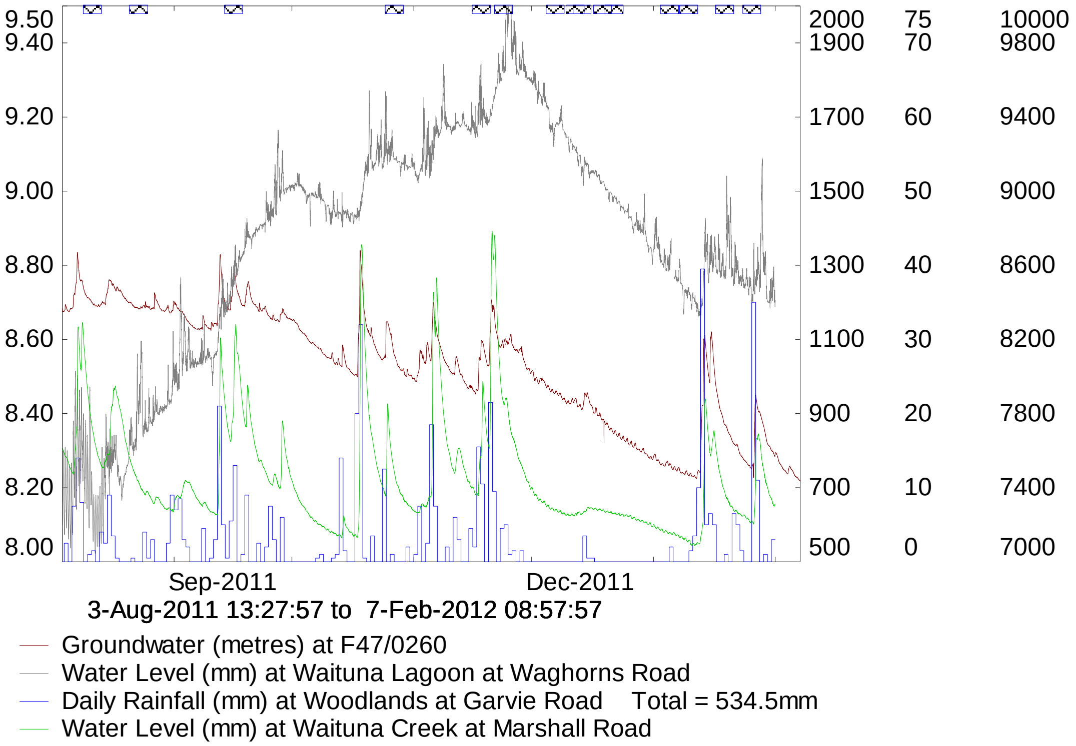

Figure 27: Graph of water levels in Waituna Lagoon, stream stage in Waituna Creek, rainfall at Woodlands and piezometric levels in F47/0260, August 2011 to February 2012. [Note: vertical axes from far left to right are: Groundwater Level (m), Waituna Lagoon water level (mm), Daily Rainfall (mm) and Water Level (mm) at Waituna Creek].

Both the limited tidal variation and high relative groundwater level suggest a poor hydraulic connection between the unconfined aquifer in the vicinity of F47/0260 and the marine environment. This observation is interpreted to reflect the low permeability of the barrier beach sediments (as evidenced by the water levels in the Waituna Lagoon).

As illustrated in **Figure 28**, the small semi-regular groundwater level variation observed in F47/0260 during the December 2011 to January 2012 recession was observed to be out of phase with the local tide and more closely correlated with similar variations in stream stage observed in Waituna Creek. This phenomena is commonly observed in stream flow records from elsewhere in the Southland region during periods of low rainfall and is assumed reflect diurnal variations in evapotranspiration within the catchment. Given the shallow water table in the local area, this observed variation in F47/0260 may result from temporal variations in evapotranspiration from surrounding phreatophytic vegetation.

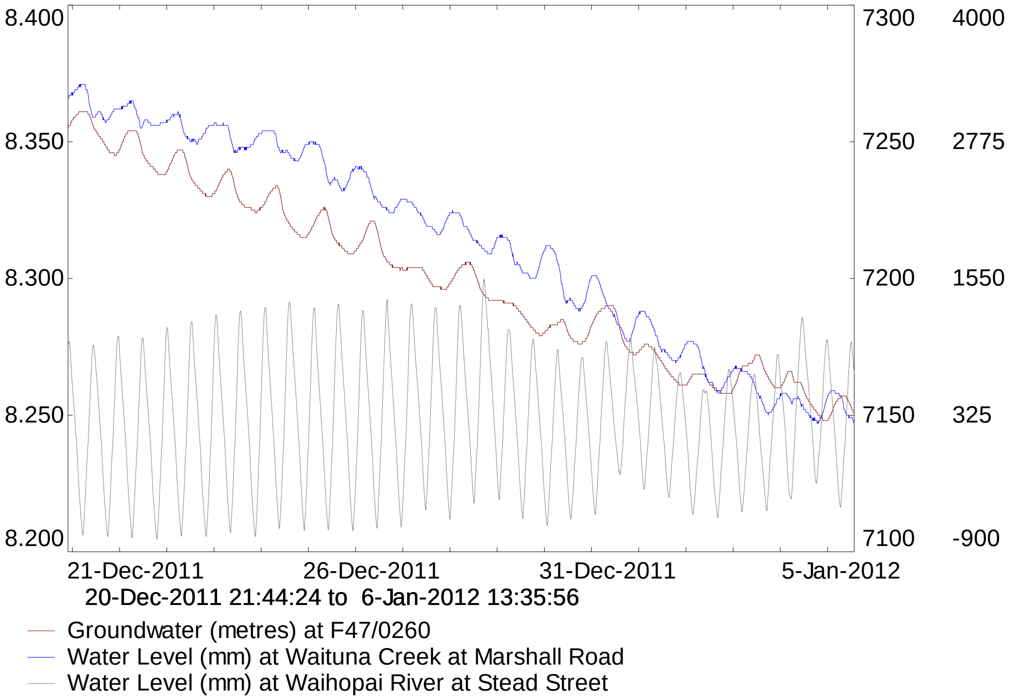

Figure 28: Diurnal variation in piezometric level in F47/0260 compared to stage height in Waituna Creek and tidal stage in the lower Waihopai River.
[Note: vertical axes from far left to right are: Groundwater Level (m), Water Level (mm) at Waituna Creek and Water Level (mm) at Waihopai River].

Recent monitoring data from F47/0258 (January to February 2012) located adjacent to the Carrans Creek outlet show a similar pattern of temporal groundwater level response to that observed in F46/0260 indicating similar hydrogeological conditions along this section of the lagoon margin.

F47/0253 is a 7.5 metre deep piezometre situated adjacent to Hanson Road, approximately 2 kilometres north of the lagoon margin and approximately 150 metres from a tributary of Carrans Creek. **Figure 29** shows a plot of groundwater levels recorded in F47/0253 over the period July 2011 to February 2012. The data show a relatively steady decline in groundwater levels over the period of record, punctuated by a relatively short period of water level recovery during mid to late-September. Overall, groundwater levels at this site show little discernible response to rainfall events, Waituna Creek stage or variations in lagoon level.

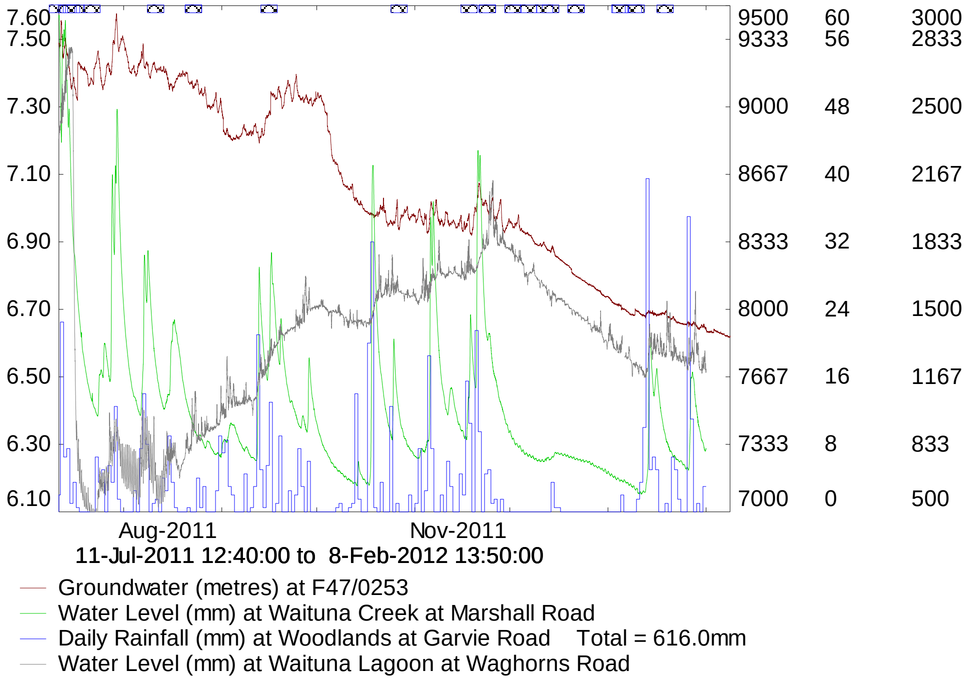

Figure 29: Piezometric levels at F47/0253 compared to water level in Waituna Lagoon, stage height in Waituna Creek and rainfall at Woodlands.
[Note: vertical axes from far left to right are: Groundwater Level (m), Water Level (mm) at Waituna Creek, Daily Rainfall (mm), Water Level at Waituna Lagoon (mm)].

While interpretation of the hydrograph from F47/0253 is limited by the short monitoring record available, comparison with piezometric levels at F47/0260 (**Figure 30** suggests groundwater levels at this site track the long-term pattern of rainfall recharge. It is therefore concluded that collection of additional data from this site will yield a hydrograph similar in nature to that recorded in F47/0391 and the Ashers 2 (shallow) piezometre (see **Figure 22**).

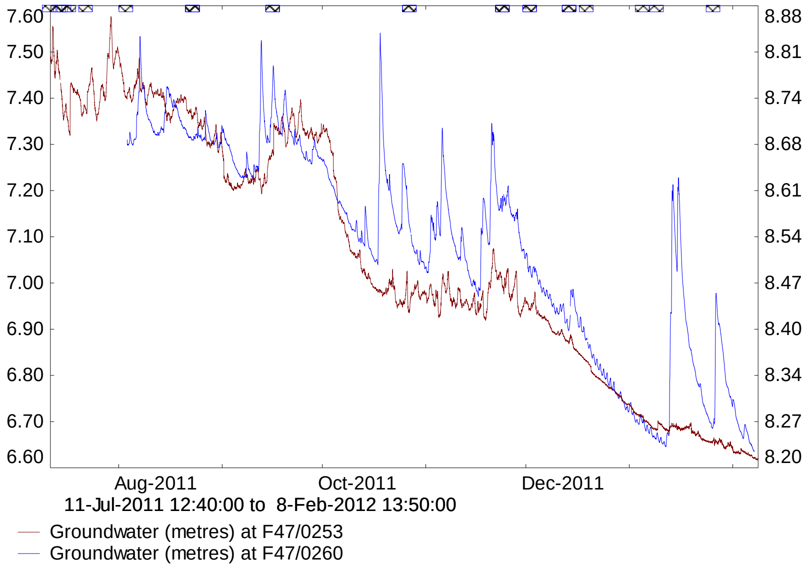

Figure 30: Piezometric levels in F47/0253 (left hand vertical axis) and F47/0260 (right hand vertical axis), July 2011 to February 2012.

Overall, shallow groundwater levels recorded around the margin of the Waituna Lagoon exhibit a wide range of temporal variability. Along the north-western margin groundwater levels appear to be significantly influenced by lagoon levels indicating a significant degree of hydraulic connection between Waituna Lagoon and the surrounding unconfined aquifer. In contrast, groundwater levels at the eastern margin of Waituna Lagoon appear to be largely influenced by rainfall recharge with little evidence of direct hydraulic connection to the lagoon or the marine environment. To the north of the Waituna Lagoon, shallow groundwater levels appear to track the seasonal pattern of rainfall recharge suggesting a relatively moderate hydraulic connection to nearby surface water bodies (including local drainage and the Waituna Lagoon).

The reasons for the observed differences in hydrograph response around the margin of the Waituna Lagoon are uncertain but may possibly relate to local geological conditions including permeability of the Quaternary gravel sediments and recent marine deposits as well as the accumulation of "clogging layers" on the bed of the lagoon and surrounding surface waterways. **Section 3** reviews the physical measurement of seepage rates into the bed of Waituna.

3.2 Groundwater – Surface Water Interaction

3.2.1 Waituna Creek

In early December 2011 Environment Southland commenced a concurrent gauging programme in the Waituna Creek in order to characterise flow variability across the catchment. This gauging programme involved measurement of flow and water quality at nine sites on the main stem of Waituna Creek and at a further nine sites in significant tributaries within a restricted time period (typically on the same day). **Figure 31** shows the location of gauging sites along with measured flows for the four sets of gaugings undertaken between December 2011 and February 2012.

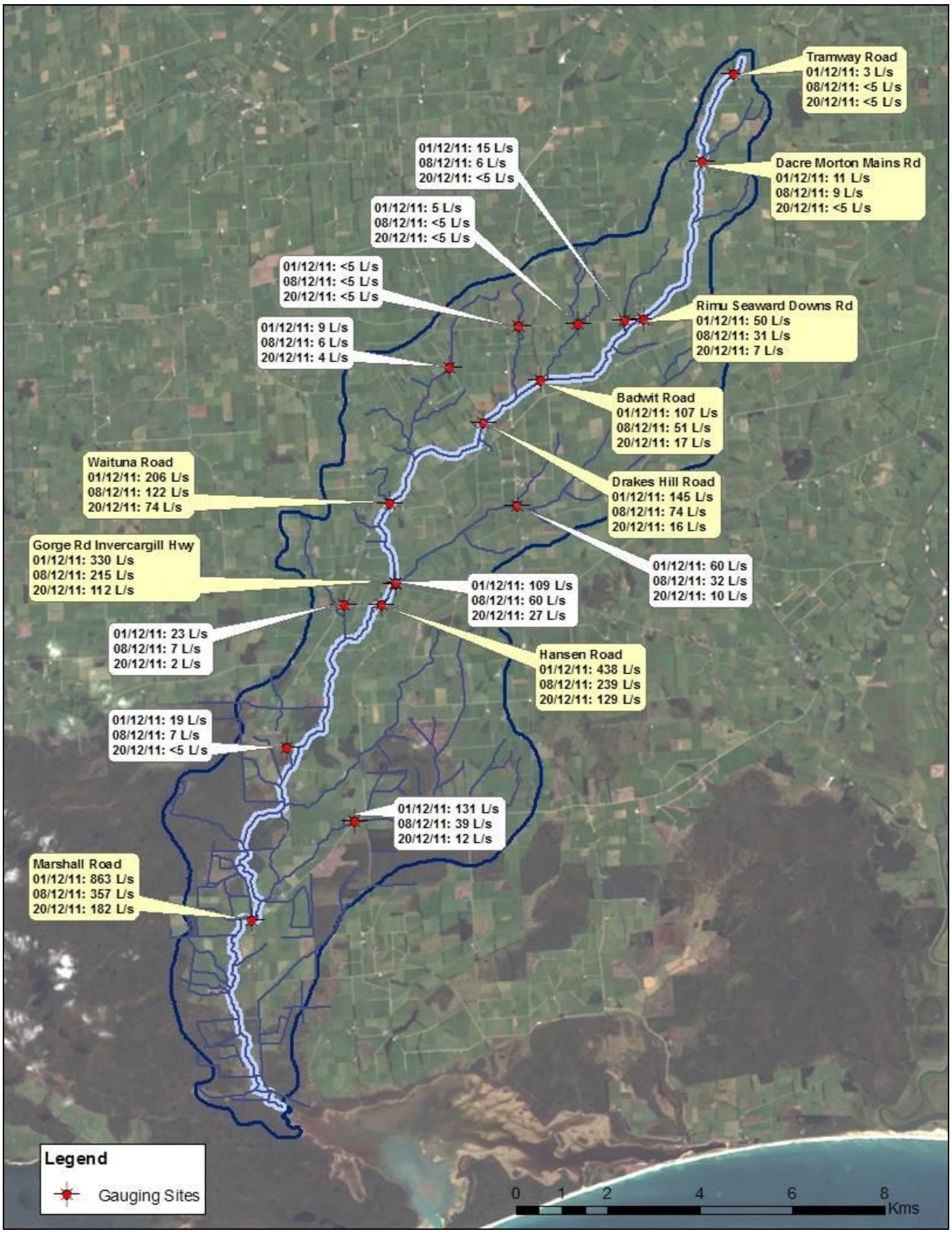

Figure 31: Flows in the Waituna Creek catchment during the December 2011 recession
[Note: Waituna Creek has yellow labels; its tributaries have white labels]

Concurrent gaugings undertaken during a period of stable flow recession during December 2011 provide useful information to characterise base flow discharge across the catchment. As shown in **Figure 32**, gauging results show a progressive increase in flow down the catchment indicating that the Waituna Creek gains flow across its entire length. The data show an appreciable increase in discharge across the lower catchment (downstream of Hansen Road) in early December 2011 shortly following the onset of a period of stable recession. Flows measured subsequently during December 2011 show a progressive decline in discharge across the entire catchment, particularly in this lower section with flows in the upper catchment upstream of Drakes Hill Road) declining to very low levels (less than 20 L/s).

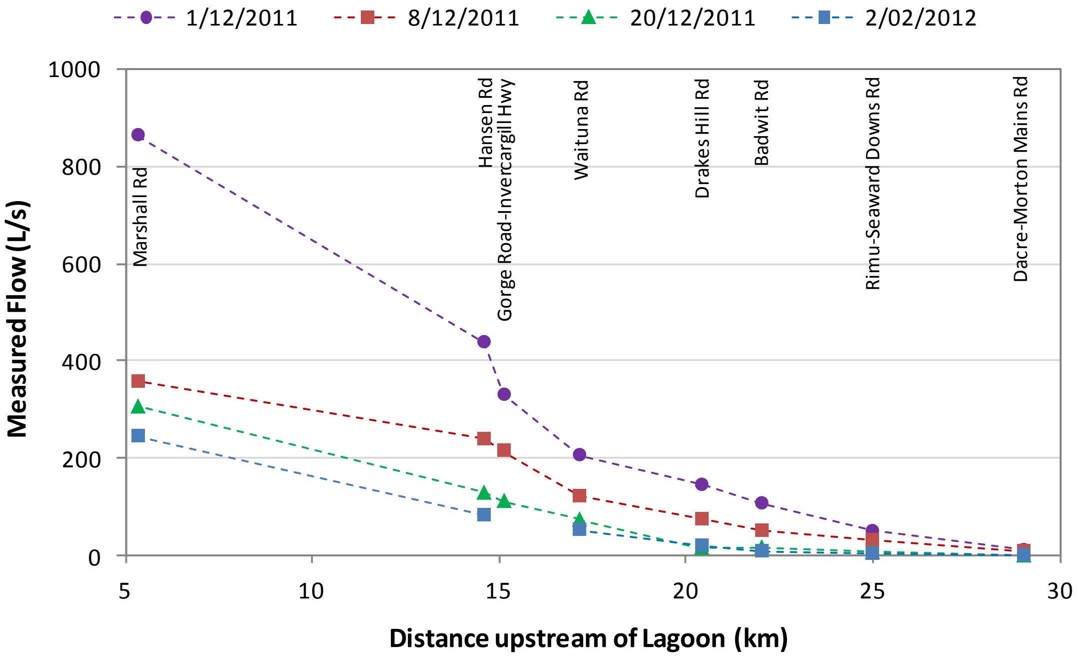

Figure 32: Results of concurrent gaugings from Waituna Creek

Figure 32 shows a plot of catchment yield (discharge divided by catchment area) for each of the concurrent gauging runs undertaken. These data show a marked increase in yield downstream of Waituna Road. This change is inferred to reflect an increase in base flow discharge across the lower section of the catchment. This change in the nature of groundwater/surface water interaction matches the observed difference in groundwater level hydrographs from the regular seasonal variations measured in F46/0391 on Drakes Hill Road to the more temporally variable levels recorded at F47/0252 near Mokotua (see **Figures 21** and **22**)[12].

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[12] Particularly given that F46/0391 is located approximately 300 metres from Waituna Creek compared to 900 metres for F47/0252

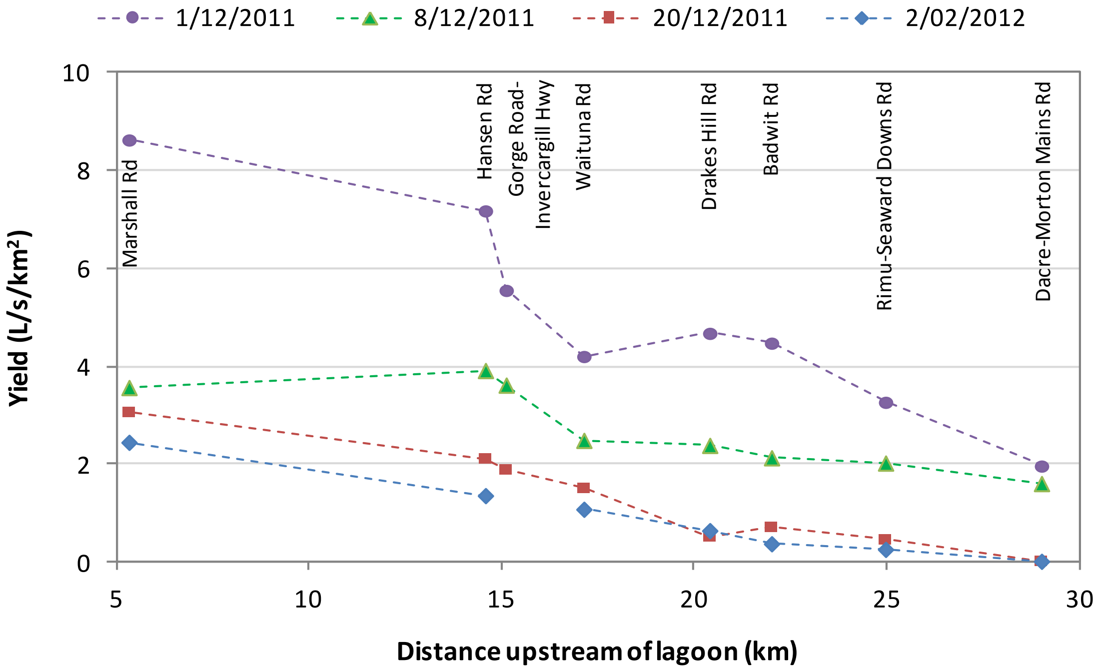

Figure 33: Calculated catchment yield along the main stem of Waituna Creek

In terms of base flow discharge, **Figure 34** illustrates the spatial variation of observed flow gain/loss in the main stem of Waituna Creek. This data is adjusted to account for measured tributary inflows and show a comparatively low average flow gain of the order of 5 L/s/km upstream of Drakes Hill Road, which increases, to around 20 L/s downstream of Waituna Road. It is noted that gauging data from the Waituna Creek tributary between Gorge Road-Invercargill Highway and Kapuka North Road indicate a flow gain across this reach approximately half that observed in the corresponding section of the Waituna Creek main stem. This difference in the rate of base flow discharge may reflect differences in the physical character of the respective reaches particularly in terms of channel form, sediment as well as the hydraulic characteristics of the surrounding unconfined aquifer.

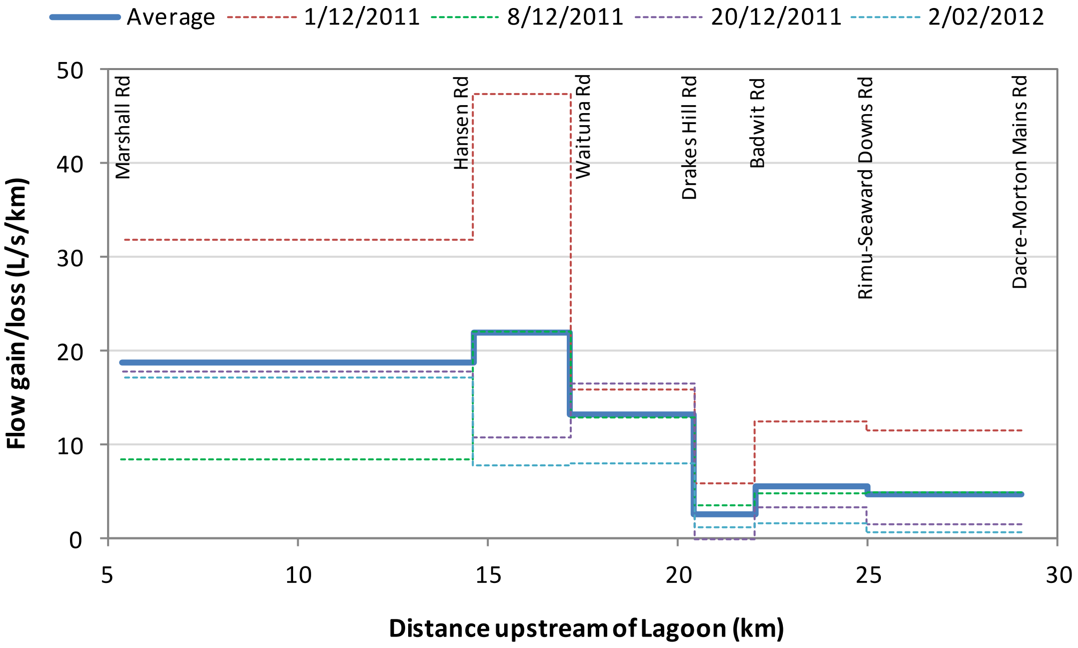

Figure 34: Spatial variation in observed flow gain/loss in the main stem of Waituna Creek

Waituna Stream is the largest tributary of Waituna Lagoon with a total catchment area of approximately 106 square kilometres. Concurrent gaugings undertaken in Waituna Stream indicate the stream gains flow from the surrounding unconfined aquifer across its entire length, with the rate of base flow discharge increasing appreciably in the lower catchment (downstream of Waituna Road).

3.2.2 Moffat Creek and Carran Creek

Moffat Creek and Carran Creek are two smaller catchments that drain into Waituna Lagoon. Moffat Creek drains a catchment area of approximately 14.7 square kilometres encompassing the area south of Hodgson Road between the western end of Hanson Road and Waituna Gorge Road. Carran Creek drains a catchment of approximately 38.6 square kilometres east of Waituna Lagoon Road extending approximately two kilometres north of Waituna Gorge Road.

Limited data is available to characterize the spatial or temporal variability of discharge within these catchments. In general, available gauging data suggest flows of less than 20 L/s across both catchments suggesting the mid to upper reaches of these streams (limited data is available from the lower reaches) make a relatively minor contribution to the overall water balance within the Waituna Lagoon catchment.

4. Water Abstraction

Water is an extremely valuable resource for the Southland region and is integral to the economic, social, cultural and environmental wellbeing of the community. In order to sustainably manage water resources, a balance needs to be struck between the desire of humans to use water and requirements to maintain environmental values at or above nominated thresholds. To successfully achieve this balance, many different elements need to be considered including the potential connection between water bodies (e.g. groundwater and surface water), the capacity of water to support abstraction without adversely impacting on ecosystem health or long-term yields, climate change and climatic variability, reliability of supply for water users and management of competing environmental, social, cultural and economic values.

Environment Southland is responsible for the governance and management of Southland's water resources. The objectives for sustainable freshwater management in the Southland region are specified in the Regional Policy Statement and the Regional Water Plan for Southland. The Regional Water Plan also details community expectations, standards and targets for water management. As an alternative for setting maximum sustainable allocation limits for individual aquifer and surface water systems, the Regional Water Plan outlines a management framework for water abstraction based on the concept of adaptive management whereby the level of information and assessment to support additional abstraction escalates and allocation increases. This allows water resources to be managed sustainability in the absence of the high level of knowledge of an individual water resource required to reliably define fixed maximum allocation limits.

4.1 Allocation

Allocation refers to the volume of water authorised to be taken from a particular water body for consumptive and non-consumptive use. Under the Resource Management Act 1991, individuals are able to access water for reasonable stock and domestic use without the need for a resource consent provided there are no more than minor effects on the environment. This type of allocation is referred to as "*non-consented allocation*" in this report. The Regional Water Plan makes further provision for small-scale non-consented allocation by allowing up to 20 m^3/day/landholding of groundwater and 10 m^3/day/landholding of surface water to be taken for any purpose, subject to minimal adverse effect criteria. Any water takes in excess of these volumes require a resource consent from Environment Southland (termed "*consented allocation*") in order to ensure the effects of abstraction or no more than minor and to manage overall cumulative effects.

Non-consented allocation

Because individuals are permitted to take water for reasonable domestic and stock use without needing to obtain a resource consent, there is no register of non-consented water takes in Southland.

However, Environment Southland's WELLS database can be used to provide an indication of the level of non-consented groundwater takes. Information stored in the WELLS database comes from a variety of sources including;

- geological exploration surveys (e.g. the Liquid Fuels Trust Board survey in the 1970s and 1980s);

- door-knocking surveys in parts of northern and eastern Southland (including the Waituna catchment in 2011);
- between 2000 and 2005 some local drilling firms voluntarily supplied Environment Southland with drill logs; and
- since 2005, all drilling activity in Southland has required a resource consent which includes a condition requiring all drill logs to be supplied to Environment Southland.

At the current time the Environment Southland database contains records of a total of 225 bores or wells which have been drilled in the Waituna catchment. **Figure 35** shows the majority of bores have been drilled for investigation or monitoring purposes (83 bores), primarily as part of the Liquid Fuel Trust Board exploration programme during the 1970s and 1980s. At the current time there are at total of 76 bores in the Waituna catchment known to be used for non-consented abstraction (i.e. stock and domestic supplies) and a further 48 bores used for dairy-shed and stock supply. There are 21 bores recorded as being unused or decommissioned (classified as "other") and 24 bores whose use is unknown.

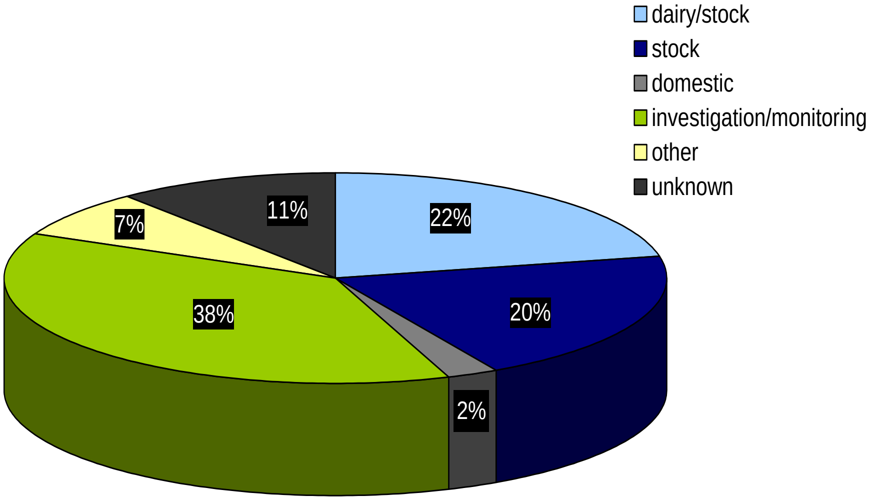

Figure 35: Use of bores in the Waituna catchment[13]

Figure 36 shows a plot of the distribution of bore depths recorded in the Waituna catchment. The figure shows that of bores currently utilised for water supply approximately 50 percent are screened at depths of less than 25 metres, with a relatively even distribution of the remainder between depths of 25 and 200 metres. The figure also shows a significant number of bores (approximately 45) deeper than 100 metres in the Waituna catchment, of which only 10 are recorded as currently being used. The remaining unused deep bores are generally investigation bores installed in and around the Ashers-Waituna lignite deposit, of which approximately one-third remain as active single or nested piezometre installations.

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[13] "Investigation/monitoring" includes all bores drilled during the 1970's and 1980's as part of the lignite exploration as it is unknown how many of these bores may still exist today.

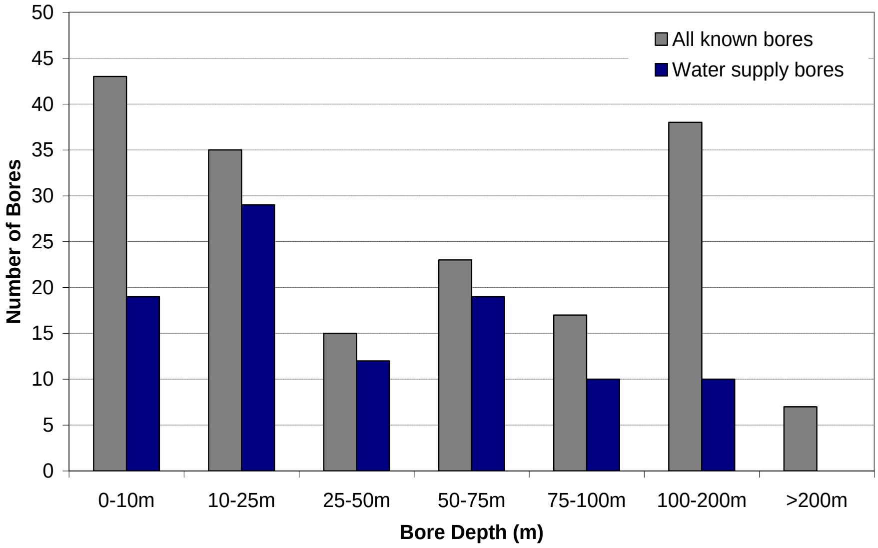

Figure 36: Reported bore depths for all known bores and active water supply bores in the Waituna catchment

Consented allocation

At the current time consented groundwater allocation (including applications) in the Waituna catchment totals 2,639 m^3/day (or approximately 770,500 m^3/year). This allocation includes a total of 32 dairy takes (typically comprising dairy shed supply, wash-down and stock water) with an average daily volume of 80 m^3/day. The current consents are divided between the Moffat Creek (2 consents, 10 percent of total allocation), Carran Creek (2 consents, 9 percent of allocation) and Waituna Creek catchments (27 consents, 81 percent of allocation).

Of the total allocation in the Waituna catchment, approximately 59 percent (1,560 m^3/day) is sourced from bores screened in the Gore Lignite Measure sequence, 25 percent from shallow bores screened in the Quaternary gravels with the remaining 16 percent from bores for which insufficient information is available to determine the source aquifer.

Figure **37** provides a summary of the source and volume of groundwater allocation in the three main catchments of Waituna Lagoon.

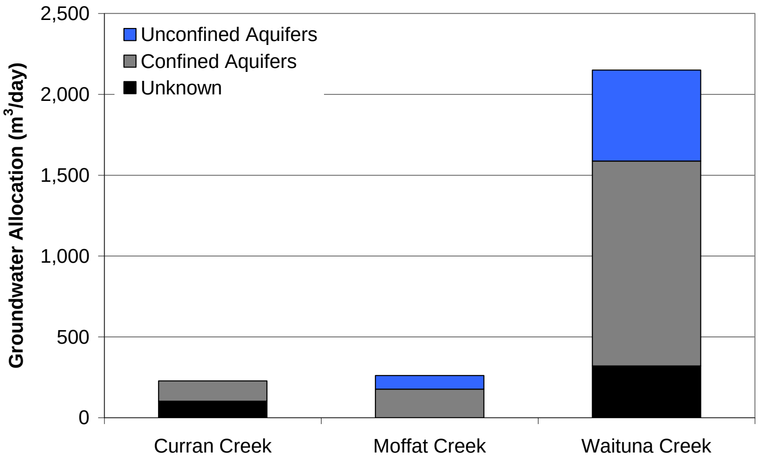

Figure 37: Consented daily groundwater allocation for the Waituna catchment[14]

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[14] Aquifer classification has been determined, where possible, using bore log information

5. Groundwater Quality

All water contains dissolved constituents and of all freshwater sources, groundwater generally contains the largest amount of dissolved solids. The range and relative concentration of the dissolved constituents reflect a range of factors including the nature and source of aquifer recharge, the rate and characteristics of groundwater flow through the aquifer system as well as geochemical processes resulting from the interaction between groundwater and the physical environment. Anthropogenic (or human) influences on groundwater quality include the introduction of contaminants associated with land use activities and wastewater discharges as well as alterations to the natural flow of groundwater as a result of abstraction (Cherry and Freeze, 1979; Mather, 1997; Wilson, 2010b).

5.1 Groundwater Quality Monitoring

Sampling

Of the 225 bores and wells within the Waituna catchment, 63 have some form of hydrochemical data. The earliest available data is from 1998 with only four wells (F47/0221, F46/0501, F46/0277 and F46/0694) having long-term data records (e.g. greater than 5 years). The long-term records are associated with compliance monitoring and contain only nitrate (NO_3-N), *E.coli* and electrical conductivity (EC) data. Electrical conductivity is an indirect measure of the dissolved ion concentration of a groundwater and includes a correction for temperature. Bores with one-off samples that pre-date 2011 also typically contain only NO_3-N, *E.coli* and EC data.

Due to the paucity of hydrochemical data, Environment Southland embarked on a catchment wide groundwater quality survey starting in May of 2011. The groundwater quality survey included the setup of a bi-monthly Waituna groundwater quality run and two 'one-off' characterisation surveys. Characterisation surveys sought to provide a snapshot of the shallow (unconfined) groundwater quality throughout the catchment. The first characterisation survey was conducted in August 2011 and the second in January 2012. For the monthly groundwater quality run and both characterisation surveys preference was given to shallow bores tapping the unconfined aquifer systems (n = 30; mean depth = 10.0 m) although a few deeper bores (n = 3; mean depth = 60.0 m) occurring within the confined aquifer system were also sampled. L&M also provided hydrochemical data for the 2010 and 2011 calendar years, from lignite exploration bores within the catchment. A lack of shallow bores adjacent to the fringes of the lagoon was identified early on and as a result five shallow piezometres (or monitoring bores) were drilled by Environment Southland in mid-2011. Three of these bores were then included in the monthly Waituna groundwater quality sampling run. Including the snapshot surveys, a total network of 31 bores have been sampled, the majority more than twice, over the 2011/12 period (**Figure 38**).

In addition to groundwater quality samples, snowmelt, tile and open drain, soil water and surface water samples (Waituna, Moffat and Carran Creeks) were collected throughout the catchment. Soil water, bulk soil and tile drain samples were collected from grazed pastures and winter grazed forage crops in the north and south of the catchment. Bulk soil samples and soil water (using a teflon suction cup) were also collected from the Waituna Lagoon Reserve and wetland soils adjacent to the Waituna Lagoon. A drive point piezometre (miniature portable well) was deployed to sample groundwaters in mixed peat-quartz gravel aquifers adjacent to the Waituna Lagoon.

For bores sampled more than once, the median concentration was calculated for each analyte prior to graphical and statistical processing. For graphical and water type classification, mass units (mg L^{-1}) were converted to milli-equivalents per litre for the most abundant ions (e.g. Na^+, K^+, Mg^{2+}, Ca^{2+}, Fe^{2+}, Cl^-, SO_4^{2-}, NO_3^{2-}, NH_4^+, HCO_3^-)[15]. All chemical data and relevant conversions, graphical plots and mineral saturation indices were computed using Geochemist Workbench, V. 8.01. Statistics and Principal Component Analysis (PCA) was under taken with the Unistat Software Package, V 6.0.

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[15] Median values and statistics calculated after removal of a septic tank contaminated sample with an exceptionally elevated TDS (4,206 mg/L).

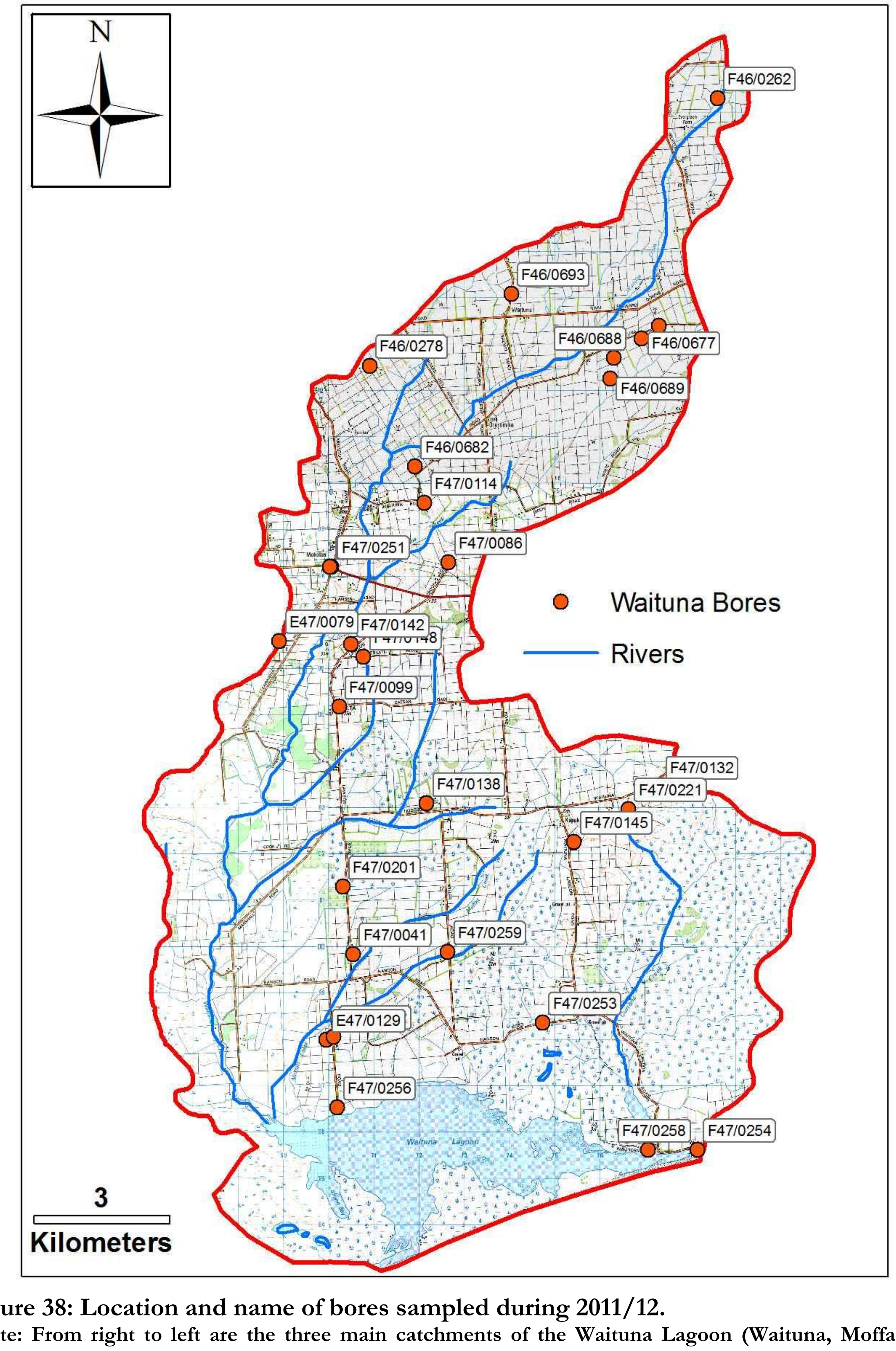

Figure 38: Location and name of bores sampled during 2011/12.

[Note: From right to left are the three main catchments of the Waituna Lagoon (Waituna, Moffat and Carran Creeks)]

5.2 Groundwater Hydrochemistry

Nearly all groundwater originates as rain or snowmelt that infiltrates through the soil and unsaturated zone (Cherry and Freeze, 1979; Matthess, 1982; Mather, 1997). Consequently, much of the chemical character of groundwater is established prior to reaching the underlying water table. However, once within an aquifer the extent to which a groundwater undergoes chemical change is dependent on the degree of water-rock interaction that takes place. The type and magnitude of these water-rock interactions are determined by:

(i) the chemical potential/reactivity of the infiltrating soil and unsaturated zone water;
(ii) the reactivity and composition of aquifer lithologies; and
(iii) groundwater residence time/age.

In coastal settings with highly weathered soils and inert lithologies, such as the Waituna catchment, dissolved ions come mainly from rainfall and dry deposition of marine salts, especially Na (sodium), Cl (chloride) and SO_4 (sulphate) (Mather, 1997; Rosen, 2001). Under these settings, marine aerosolic inputs of Na, Cl and SO_4 may exceed natural Ca (calcium), Mg (magnesium) and HCO_3 (bicarbonate) inputs from chemical reactions between infiltrating precipitation, soils and aquifer materials (Matthess, 1982). Snow samples collected during August of 2011 are dilute (<100 mg/L TDS) Na-Cl type waters with minor Mg > SO_4 > Ca >> HCO_3, and minute concentrations of nitrogen (**Table 3**). All snow samples fall along the Seawater Dilution Line (SWDL) for molar Na and Cl, supporting a dominant marine origin (**Figure 40**).

Table 3: Composite snowmelt composition for regional Southland, on a milliequivalent percent basis – August, 2011 snowfall event

[Note: the dominance of Na and Cl ions, followed by Mg, SO_4 and Ca. The remaining ions constitute ≤ 1% of the total ion content. The composition of this snowfall is typical of that analysed for relatively pristine coastal areas from around the world (Cherry and Freeze, 1979; Matthess, 1982; Mather, 1997)]

Composite Snowmelt Composition, Southland (Milliequivalent Percent)										
Sample ID	Fe++	SO4--	NH4+	NO3-	HPO4--	Na+	K+	Ca++	Mg++	Cl-
Snow Sample 1	0.03	5.0	0.08	0.004	<0.001	38.3	0.9	1.7	8.9	45.1
Snow Sample 2	0.04	7.1	0.15	0.001	<0.001	37.4	0.9	1.8	8.6	44.0
Snow Sample 3	0.02	5.7	0.04	0.002	<0.001	36.9	0.8	1.7	8.7	46.2
Snow Sample 4	0.06	5.8	0.06	0.007	<0.001	39.4	0.9	2.1	9.0	42.7

Dissolved salts include all the major anions (negatively charged ions) and cations (positively charged ions) and nutrients (nitrogen and phosphorus nutrients). Dissolved salts are otherwise known as solutes and in pre-human groundwaters come from precipitation (dry deposition (dust), rain and snow) and from reaction of infiltrating water with soil and aquifer materials. However, with modern colonisation and land development anthropogenic inputs to the land surface have become an important component of the dissolved solute load of young groundwaters that are hydrologically connected to the soil zone (Böhlke, 2002; Morgenstern et al., 2012). Therefore, young hydrologically connected groundwaters, such as those occurring throughout much of Southland, invariably contain some degree of human sourced contamination where the degree of contamination and the type of contaminant(s) is strongly dependant on the soil type, land use activity and intensity, drainage and climate.

Natural sources of dissolved salts typically vary within specific ranges. For Southland, the natural background for NO_3-N is ≤1 mg/L, Dissolved Reactive Phosphorus (DRP) ≤0.03 mg/L, SO_4

≤17 mg/L, Na ≤20 mg/L, Cl ≤30 mg/L, Ca ≤10 mg/L, Mg ≤10 mg/L and K ≤1 mg/L[16]. These values represent the thresholds beyond which human sourced contamination becomes increasingly likely (Panno et al., 2006; Morgenstern et al., 2012). Each threshold value is derived by plotting groundwater data on log cumulative probability plots according the methods of Reimann et al., (2005) and Panno et al., (2006). The data from which thresholds were derived includes up to 1,300 individual bores and up to 6,000 samples from throughout the Southland region. The magnitude of the reported thresholds for the individual species are in accord with groundwater geochemical data reported for New Zealand (Rosen, 2001; Morgenstern et al., 2012) and provide an important baseline for the groundwater quality of the Waituna catchment.

The most common signature of anthropogenic inputs include the various forms of nitrogen along with elevated levels of the more soluble and less reactive ions such as Na and Cl (Böhlke, 2002; Panno et al., 2006; Morgenstern et al., 2012). Nitrogen salts such as nitrate (NO_3) are relatively rare in pristine environments, primarily because the nitrogen concentrations in rainfall and snowmelt (**Table 3**), rocks and soils are extremely low. Further, few living species are able to fix nitrogen from the atmosphere[17]. For Southland and New Zealand, the pre-human range of NO_3-N (nitrate as nitrogen) was below 1 mg/L (Rissmann et al., 2011a; Morgenstern et al., 2012). Similarly, phosphate in natural settings is often low and derived primarily from the weathering of soil and rock, much of which is naturally low in phosphate[18]. Consequently, most natural systems are incapable of sustaining the production rates required for modern day agricultural and horticultural practices without the addition of large quantities of nutrients as fertiliser and/or manure.

In addition to nitrogen and phosphate nutrients, fertilisers and animal manures contain variable, but commonly large, quantities of soluble salts (**Table 4**). These salts include the major ions of Na, K, Mg, Ca, NH_4 (ammonium), SO_4 and Cl. Some of these salts are removed or stored, at least temporarily, due to reactions within the soil zone or uptake by plants. However, the natural ability of a soil to remove or sequester dissolved salts is highly variable and dependant on the soil type and associated mineralogy, soil structure, climate and vegetation type. Whatever the soil type the natural capacity of soils to absorb or aid in the removal of fertiliser or manure inputs is finite. Indeed, research shows increased leaching losses of all ions, not just nutrients, under modern day intensive land use practices (Böhlke, 2002; Magesan et al. 1999; Kraft et al., 2007 and references therein).

In strongly contaminated groundwaters, most major ions are significantly elevated above regional norms with elevated concentrations of NO_3, Na, Cl, K, SO_4 and Mg especially common (Rosen, 2001; Panno et al., 2006; Morgenstern et al., 2012). Of the two main nutrients, phosphate is typically poorly mobile in most soils and groundwaters due to natural chemical reactions, which sequester or sorb DRP onto/into specific minerals, removing it from solution. However, phosphate mobility is enhanced where mineral surfaces are absent or of low abundance, such as in organic soils, and where chemically reducing (low oxygen) conditions exist within the soil zone or aquifer. The leaching of animal and fertiliser phosphate can therefore contribute significantly to the phosphate concentration of aquifers in wetland areas where a greater abundance of organic soils occur and reducing conditions are more common.

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[16] For redox sensitive species, NO_3 and SO_4, reduced groundwaters were excluded. For DRP reduced groundwaters were included.

[17] In New Zealand significant use is made of rye grass/clover pasture to utilise the fixation of atmospheric N_2 by clover.

[18] Elevated P concentrations are associated with the regional occurrence of lignite measures, which may contribute a significant fraction of the dissolved P concentration in regional groundwaters. Note this source for P does not originate within the soil zone.

Therefore, the dissolved salt load of young hydrologically connected groundwaters comes from three main sources:

- Rainfall, snowmelt and atmospheric dust (“precipitation”)
- Natural water-soil and water-rock interactions, and;
- Human (anthropogenic inputs) associated with intensive land use (rural and urban).

Table 4: Major ions and nutrient fractions (mg/L) from tile drains, open drains, soil water, dairy cow manure and urine in the Waituna catchment

[Note: Where EC = Electrical Conductivity (µS/cm); TN = Total Nitrogen; DKN = Dissolved Kjeldahl Nitrogen; TAM = Total Ammoniacal Nitrogen; TDN = Total Dissolved Nitrogen; TKN = Total Kjeldahl Nitrogen; TP = Total Phosphorus; TDP = Total Dissolved Phosphorus; DRP = Dissolved Reactive Phosphorus]

Sample Type and Location	Date	pH	EC	Na	K	Mg	Ca	Cl	SO_4	HCO_3	TN	NO_3-N	DKN	TAM	TDN	TKN	TP	TDP	DRP
Tile Drain - Mokotua	23/09/2011	6.2	313	27	4.5	4.4	24	45	25	33	5.3	4.6	0.61	0.056	5.2	0.63	0.032		
Tile Drain - Marshall Rd	6/07/2011	5.4	177	18	1.12	5.9	5.5	29	26	8.5	1.25	0.077	.	0.16	.	1.17	0.49	0.45	0.46
Tile Drain 1 - Waituna Road at Oteramika	24/08/2011	6.5	180	15.6	0.25	2.8	12.7	28	12.4	16.4	1.52	1.05	0.36	0.024	.	0.46	0.015	0.002	0.002
Tile Drain 2 - Waituna Road at Oteramika	24/08/2011	6.2	180	12.7	1.07	2.5	13.9	24	14.5	19.8	2.5	1.95	0.56	0.026		0.6	0.013	0.002	0.002
Tile Drain - Badwit Rd at Oteramika	27/10/2011	6.3	208	15.5	0.87	3.5	18.8	22	30	26	3.4	3	0.24	0.018	.	0.35	0.004	0.002	0.002
Drain on left bank Moffat Road	24/08/2011	4.7	210	32	4.8	5.8	9.9	67	26	2	1.47	0.052	1.25	0.005	1.31	1.42	0.163	0.137	0.04
Drain on left bank Moffat Road	16/09/2011	5.2	192	19.4	3.2	4	8	38	15.9	4.9	1.85	0.23	1.43	0.028	1.66	1.61	0.23	0.164	0.13
Soil Water - Winter Cropping Paddock (Kapuka)	23/09/2011		636	35	34	3.2	18.8	80	40	137	86	0.033	32	29	32	86	14	.	.
Soil Water - Winter Cropping Paddock (Oteramika)	23/09/2011	6.8	1408	87	97	14.6	75	184	116	184	59	0.009	31	24	31	59	8.4	.	.
Soil Water - Old Winter Cropping Paddock (Lagoon Edge)	23/09/2011		474	65	28	5.3	14.3	91	0.6	81	13.3	0.072	10.6		10.7	13.2	1.33	.	.
Soil Water - Waituna at DOC Reserve	28/09/2011	5.7	490	67	2.2	10.2	5.4	94	.	10	.	.	.	.	.	.	0.051	.	.
Waituna, Composite Dairy Cow Manure	28/09/2011	7.3		57	55	16	28	108	18	.	41	0.024	40	.	40	41	17.7	11.1	10.5
Waituna, Composite Dairy Cow Urine 1	28/09/2011	7.3	29400	780	10000	200	280	6400	105	3293.5	5400	0.78	7800	62	7800	5400	5	1.65	0.02
Waituna, Composite Dairy Cow Urine 2	28/09/2011	7.1	28000	770	9700	122	250	5700	510	2696.9	8000	0.58	8100	112	8100	8000	4.9	1.68	0.12
Waituna, Composite Dairy Cow Urine 3	28/09/2011	7.0	21500	320	6300	125	131	4800	320	1798.2	5200	0.48	4800	88	4800	5200	5	1.5	0.12

5.3 Groundwater Type

Broadly, groundwaters of the Waituna catchment are characterised as dilute, slightly acidic groundwaters with low electrical conductivity (EC) and correspondingly low Total Dissolved Solid (TDS) concentrations (**Table 5**). Within this general characterisation, there is considerable variation in the concentration and dominance of specific ions that indicates differing processes and origins for the sampled groundwaters. One way of representing the different water types or "geochemical" facies is via a Piper plot of the major ions. A Piper plot of the major ion concentration of groundwaters from within the Waituna catchment is presented in **Figure 39**.

Table 5: Summary statistics of Waituna groundwater chemistry
[Note: Statistics calculated from median values for wells with more than one sample. Groundwaters contamination by a septic outfall have been excluded as they represent an extreme outlier in the data set. Where HPO_4^{--} = DRP]

Variable/Analyte	Valid Cases	Mean	Median	Standard Deviation	Lower Quartile	Upper Quartile	Interquartile Range	Coefficient of Variation
Temperature	26	15.0	11.0	19.4	10.7	11.6	0.9	1.3
Electrical conductivity	28	262	240	79	212	295	84	0.3
pH	26	6.5	6.4	0.6	6.0	6.5	0.5	0.1
O2	21	2.1	1.2	2.4	0.4	3.1	2.7	1.1
Nitrate Nitrite Nitrogen	30	1.50	0.09	3.18	0.02	1.13	1.11	2.12
Mn++	26	0.13	0.07	0.16	0.01	0.20	0.19	1.27
Fe++	30	5.52	1.94	8.30	0.03	7.20	7.17	1.50
SO4--	30	8.9	6.7	7.7	4.7	10.4	5.7	0.9
NH4+	30	0.16	0.03	0.38	0.01	0.12	0.11	2.38
Total Nitrogen	28	2.01	0.69	3.34	0.25	2.20	1.95	1.66
TP	28	0.10	0.07	0.15	0.01	0.11	0.09	1.50
HPO4--	30	0.029	0.009	0.048	0.002	0.040	0.038	1.687
Na+	26	27.3	24.0	10.6	22.0	28.0	6.0	0.4
K+	26	3.4	1.2	5.2	1.1	2.0	0.9	1.5
Ca++	26	14.0	11.7	10.2	6.9	16.4	9.5	0.7
Mg++	26	5.1	5.1	2.2	3.4	6.6	3.2	0.4
Cl-	30	43.5	35.8	22.6	28.0	51.0	23.0	0.5
I-	24	0.010	0.005	0.011	0.003	0.015	0.013	1.089
Br-	24	0.2	0.1	0.2	0.1	0.2	0.1	0.8
Total Alkalinity	26	45.0	43.5	25.8	28.5	56.0	27.5	0.6
Carbonate alkalinity	16	<1	<1	.	.	.	.	.
HCO3-	26	45.0	43.5	25.8	28.5	56.0	27.5	0.6
Dissolved Organic Carbon	15	4.0	2.6	3.3	1.3	7.4	6.1	0.8
Total Organic Carbon	5	5.8	3.8	4.7	3.2	8.2	5.0	0.8
Total Dissolved solids	26	138.3	129.2	51.3	114.5	153.0	38.5	0.4

An alternative method used to define the water type is to convert the concentrations of major ions to milliequivalents per litre (a milliequivalent takes into account the molecular weight and ionic charge of each ion) of the major cations and anions (after Rosen, 2001). Milliequivalents are then converted to percentage values and the water type expression is formed by listing the ions with concentrations greater than 10 percent in decreasing order (the cations are listed first). The value of defining groundwater types is that groundwaters of the same "type" commonly share a similar evolution and/or origin, which makes water 'typing' very useful in understanding the dynamics of groundwater systems (**Table 6**). The assignment of groundwater types via both Piper plots and the milliequivalent-ranking method forms the basis for the interpretation of the source and evolution of Waituna groundwaters.

Further resolution over the origin and evolution of Waituna groundwaters is provided by application of Principal Component Analysis (PCA) to the Waituna groundwater quality data set. Principal Component Analysis is a multivariate statistical method for identifying the relationships between chemical parameters. When combined with traditional methods (i.e., graphical and water typing methods) PCA is a powerful tool for understanding the factors governing the chemistry of a groundwater (Güler et al. 2002; Daughney et al. 2011; Raiber et al. 2012). Therefore, the following discussion makes use of groundwater chemistry, graphical and statistical methods to define the nature of Waituna groundwaters.

5.4 Interpretation of the Hydrochemistry of Waituna Groundwaters

Hydrochemically, the low dissolved solute load (median TDS of 129 mg/L) and the prevalence of Na-Cl type groundwaters indicates minor soil zone or water-rock interaction with infiltrating coastal precipitation (**Tables 5 and 6**; **Figures 39 and 40**). The predominance of Na-Cl type waters is interpreted to reflect the moderate to highly weathered soils (acidic brown, acid-gley, podzolic and organic soils of low base status) and relatively inert aquifer lithologies (quartz and sandstone gravels) in the Waituna catchment that allow the dominantly marine aerosolic signature to dominate over that of the soil zone.

The dominant marine precipitation influence over groundwater composition is evident in the prevalence of Na and Cl as the most abundant ions (~54% of waters; **Table 6**) within Waituna groundwaters (with or without Fe, Ca, Mg and HCO_3). Further, as shown in **Figure 40**, the majority of the wells sampled plot close to the Seawater Dilution Line (SWDL) supporting a marine aerosolic origin. In some instances, ion exchange reactions with clays may increase the concentration of Na relative to Cl as is seen for a number of bores within the northern half of the catchment where soil types and aquifer materials are comparatively clay rich (**Figure 41**).

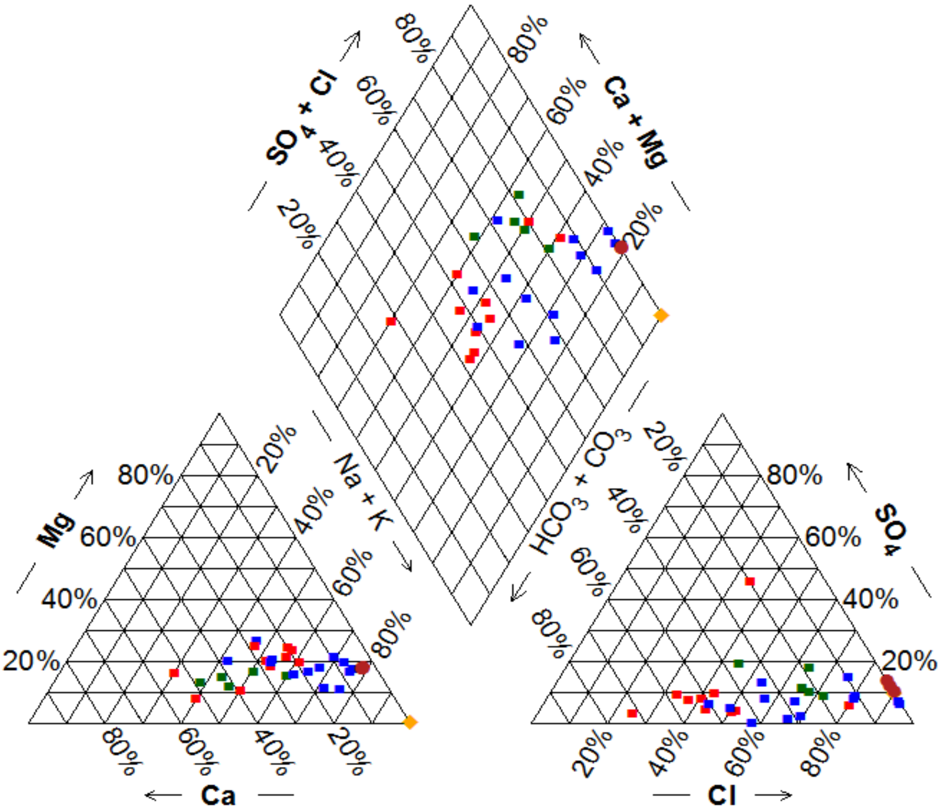

Figure 39: Major ion composition of shallow Waituna groundwaters
[Note: Groundwaters are dominantly of the Na-Cl type with greater proportions of Ca-Cl and Ca-HCO_3 types for northern groundwaters (red and green) relative to southern groundwaters (blue). Where, brown circles are snowmelt samples collected from Southland and yellow diamonds are surface waters from the Waituna Lagoon. Groundwaters can be seen to evolve from snowmelt/rainfall gaining varying quantities of major ions, depending on their locality and the redox potential of the respective aquifer.]

Table 6: Groundwater types of the Waituna catchment

[Note: Units for individual ions are expressed as milliequivalent percent abundances. The water type expression is formed by listing the ions with concentrations >10% in decreasing order (the cations are listed first)]

Sample ID	Fe++	NO3-	Na+	Ca++	Mg++	Cl-	HCO3-	SO4--	Water type
F47/0148	0.0	2.9	19.0	24.5	8.8	29.8	8.5	8.3	Ca-Na-Cl
F47/0086	0.0	1.5	20.3	28.2	7.5	22.2	18.1	9.4	Ca-Na-Cl-HCO3
F47/0142	0.0	2.4	21.0	24.1	6.9	29.1	10.6	5.0	Ca-Na-Cl-HCO3
F46/0278	0.0	0.0	15.8	28.7	8.6	12.0	34.3	1.5	Ca-Na-HCO3-Cl
F46/0693	0.0	0.6	21.4	28.9	4.4	21.0	23.0	4.6	Ca-Na-HCO3-Cl
F46/0682	0.0	3.2	20.7	26.6	7.0	18.5	10.7	24.6	Ca-Na-SO4-Cl-HCO3
F47/0259	19.5	0.0	17.4	15.9	8.4	26.7	11.3	2.9	Fe-Na-Ca-Cl-HCO3
F47/0201	24.9	0.0	24.5	4.3	3.6	27.2	13.2	0.5	Fe-Na-Cl-HCO3
F47/0251	0.2	0.5	29.7	12.5	7.7	38.5	10.1	4.7	Na-Ca-Cl-HCO3
F47/0252	0.0	1.4	27.2	18.3	9.2	32.1	10.6	4.8	Na-Ca-Cl-HCO3
F47/0253	4.1	0.0	30.0	11.4	7.9	27.9	17.2	6.8	Na-Ca-Cl-HCO3
F47/0114	6.4	0.0	25.3	12.5	9.8	20.9	24.3	3.0	Na-Ca-HCO3-Cl
E46/0096	5.0	0.0	26.2	14.3	10.4	23.3	20.0	1.8	Na-Ca-Mg-Cl-HCO3
E47/0079	6.2	0.0	22.3	13.2	12.9	23.2	21.3	2.2	Na-Ca-Mg-Cl-HCO3
F47/0145	0.2	0.1	27.4	14.2	10.4	28.9	17.7	3.9	Na-Ca-Mg-Cl-HCO3
F46/0689	0.6	0.0	30.5	12.0	11.5	16.2	27.9	4.5	Na-Ca-Mg-HCO3-Cl
F46/0262	0.0	0.4	28.3	14.7	10.0	20.1	25.7	3.9	Na-Ca-Mg-HCO3-Cl
F46/0688	6.9	0.2	22.8	14.2	12.4	19.3	23.1	1.9	Na-Ca-Mg-HCO3-Cl
E47/0129	1.6	0.3	31.8	9.8	8.8	39.7	5.3	4.2	Na-Cl
F47/0254	0.1	0.8	40.8	4.1	9.2	38.8	5.2	7.5	Na-Cl
F47/0257	0.3	0.0	36.2	3.1	8.4	51.0	0.4	3.2	Na-Cl
F47/0262	2.5	0.0	34.8	3.7	9.4	49.0	0.3	3.6	Na-Cl
F47/0138	6.3	0.0	34.2	8.4	5.6	31.3	12.9	1.0	Na-Cl-HCO3
F47/0256	16.7	0.0	23.2	5.2	6.2	26.3	19.3	0.1	Na-Fe-Cl-HCO3
F46/0677	11.4	0.0	26.6	9.1	11.2	16.5	24.4	3.4	Na-Fe-Mg-HCO3-Cl
F46/0759	0.0	0.0	31.9	10.4	10.8	38.4	6.8	2.6	Na-Mg-Ca-Cl
F47/0258	0.1	0.0	34.3	4.8	11.0	42.3	6.1	4.1	Na-Mg-Cl
E46/0098	5.2	0.0	26.3	9.8	11.8	24.2	21.8	1.6	Na-Mg-Cl-HCO3

Second in abundance are Ca-Cl/HCO_3 type groundwaters that comprise 21 percent. Bores displaying this groundwater type are restricted to the northern portion of the catchment where brown soils (acidic-mottled orthic and mottled firm brown soils) are developed in windblown loess overlying mid-Quaternary gravels of the Kamahi Formation (**Figure 42**). These thick mineral soils range from moderate to low base saturation and contain appreciable reserves of Ca (low Mg, K and Na) relative to the acid-gley, podzolic and organic soils that dominate to the south (Crops of Southland, 2002). The inference being that the higher base saturation and Ca concentration of these soils results in the enrichment of the Ca concentration of infiltrating rainwater and ultimately shallow groundwaters beneath these soils.

Significantly, a transition from Ca-Na dominated to Na-Ca dominated groundwaters occurs in the northeast of the catchment in conjunction with a change to orthic brown soils (mottled-acidic orthic brown) of lower base saturation and Ca concentration (**Figure 42**). Again, it is likely that the lower base saturation and Ca content of these soils allow the predominantly marine aerosolic signature to overwhelm that of the soil in this locality.

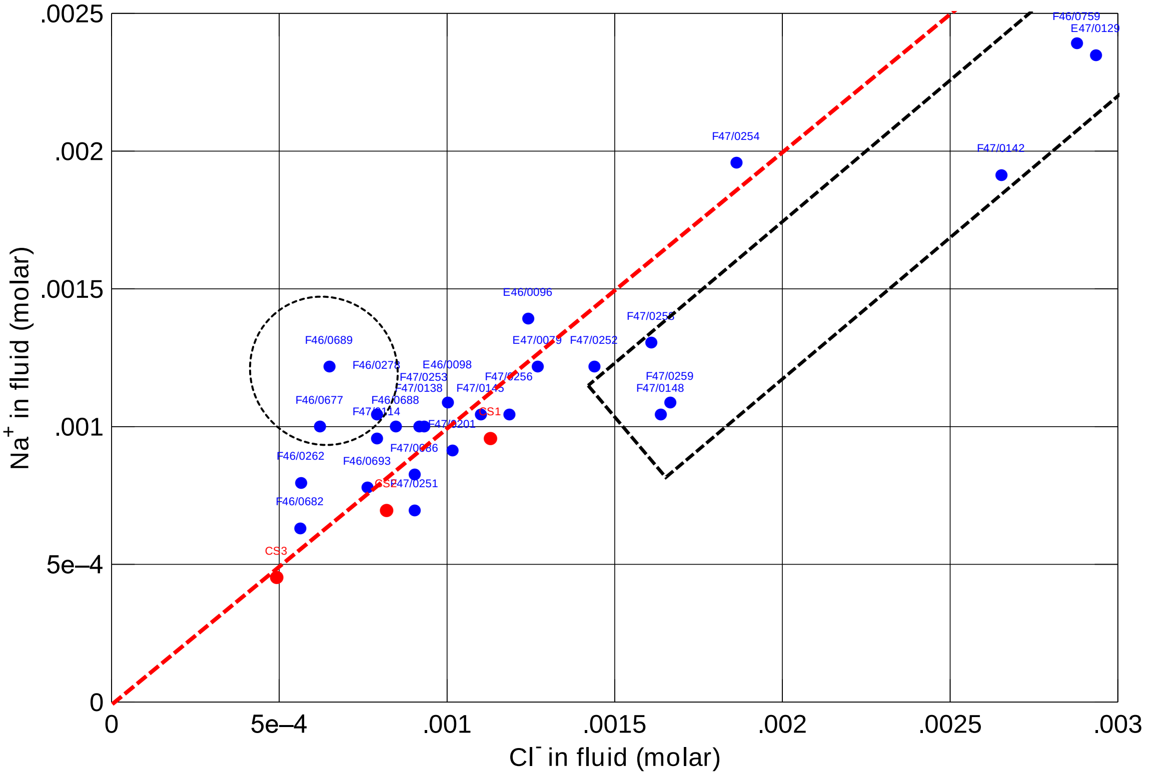

Figure 40: Molar Sodium (Na) versus Chloride (Cl) plot for Waituna groundwaters (blue) and composite snowmelt samples (red)

[Notes:

1. **How the majority of groundwaters plot close to the Seawater Dilution Line indicating a dominantly marine aerosolic source for Na and Cl.**
2. **Also:**
   - **(i) the enrichment of Cl relative to Na for a number of groundwaters with elevated TDS (dashed rectangle) all of which show evidence of impact by intensive land use (elevated K and SO_4/NO_3-N concentrations; see Section 5.2); and**
   - **(ii) Na enrichment relative to Cl, for a number of the northern wells, due to possible ion exchange (dashed-ellipse) with clay rich soils and aquifer sediments.]**

The HCO_3 ion, although subordinate to Cl in most Waituna groundwaters, occurs as a significant (i.e. greater than or equal to 10 percent) constituent of approximately 75 percent of the bores sampled. The prevalence of HCO_3 is not surprising, given it is produced during the interaction of rainwater with atmospheric and soil zone CO_2 and via the dissolution of carbonate minerals such as calcite ($CaCO_3$). The majority of Waituna groundwaters lie below the calcite dissolution line (1:1 on a milliequivalent basis) indicating a greater proportion of HCO_3, relative to Ca, which suggests that additional CO_2 is dissolved during infiltration through the soil zone (**Figure 42**).

Of the six groundwaters waters that plot close to the calcite dissolution line, only two are known to be hosted in beach gravels (F47/0254 and F47/0258) where shell fragments are common. However, well F46/0278, on the extreme north-eastern margin of the catchment, contains elevated Ca and HCO_3 and, falls close to the calcite dissolution line in **Figure 42**. This bore exhibits the only groundwaters within the unconfined aquifer that are saturated with respects to calcite and dolomite (log Q/K = $+0.14_{\text{calcite}}$ and $+0.60_{\text{dolomite}}$). A review of available bore log information suggests the possibility of a shallow outcrop of calcareous mudstone (Oligocene Winton Hill Formation) at this locality as the primary source of calcite and dolomite enrichment.

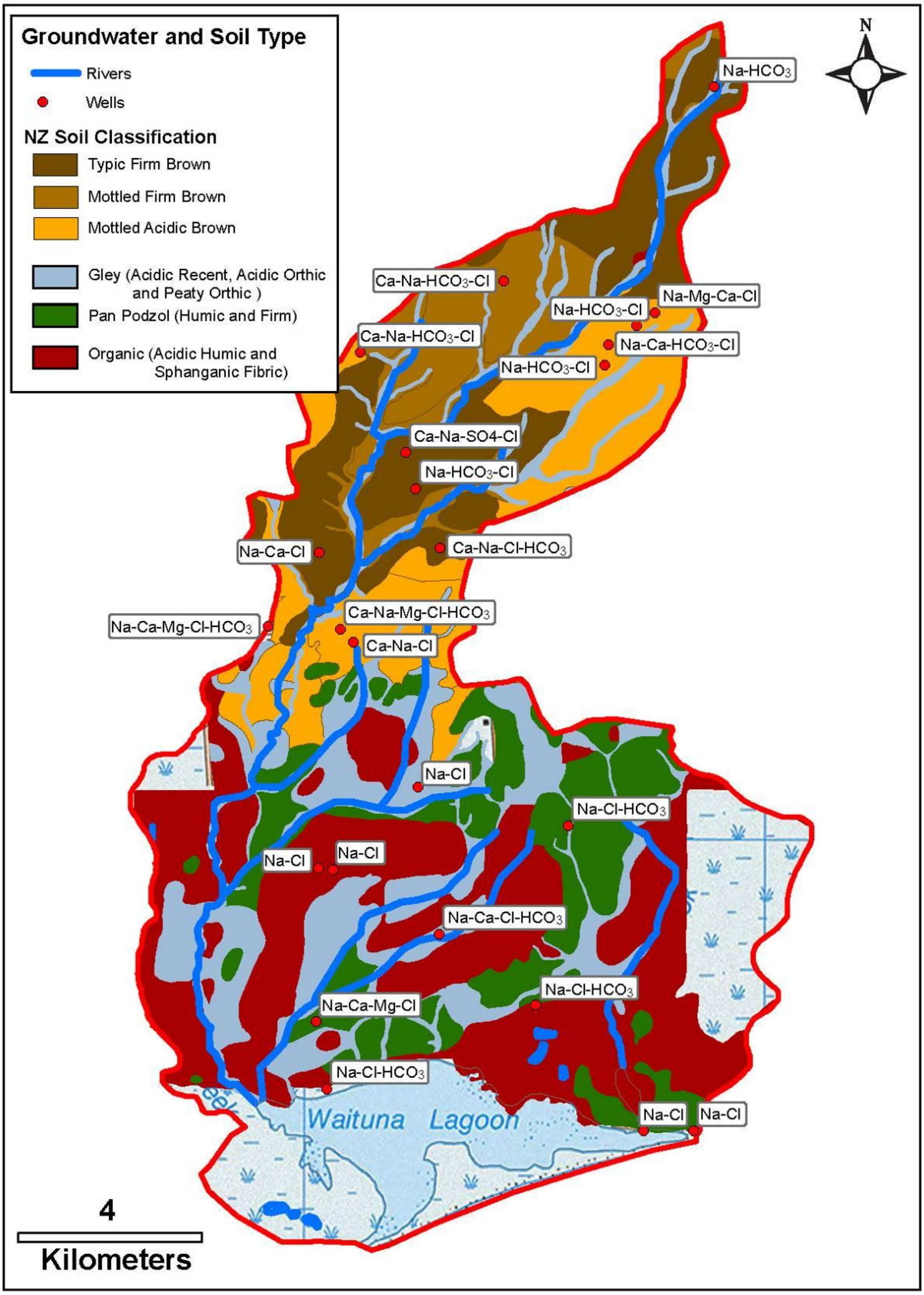

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Figure 41: **Groundwater type and soil types of the Waituna catchment**

[Notes:

1. **The greater abundance of Ca-type groundwaters in the north in association with thick mineral brown soils.**
2. **Dominance of Na-Cl type waters in the south in accord with the transition to wetland soil types of comparatively low base saturation and Ca concentrations.]**

Another potentially important source of HCO_3 to Waituna groundwaters likely from bacterially mediated oxidation of organic matter under reducing conditions, especially during SO_4 reduction (see **Section 5.8: *Redox***). Oxidation of organic matter produces large quantities of HCO_3, which may account for the large number of reducing groundwaters plotting well below the calcite dissolution line in **Figure 42**.

Also in **Figure 42** it is notable that a number of groundwaters plot above the calcite dissolution line, with the Ca enrichment of bores F47/0142 and F47/0148, attributed to possible contamination of these groundwaters with animal wastes which are high in Ca (and other major ions) (**Table 4**). Bores F47/0148 and F47/0142 contain Ca concentrations that exceed the natural background for Southland by between 2 and 4 times, respectively. It is noted that these bores also exhibit elevated NO_3-N (9.8 – 13.8 mg/L NO_3-N) and K (13.8 and 21 mg/L) and *E.coli* counts (more than 90 MPN; *E.coli* measured for F47/0142 only) that are indicative of some form of localised contamination.

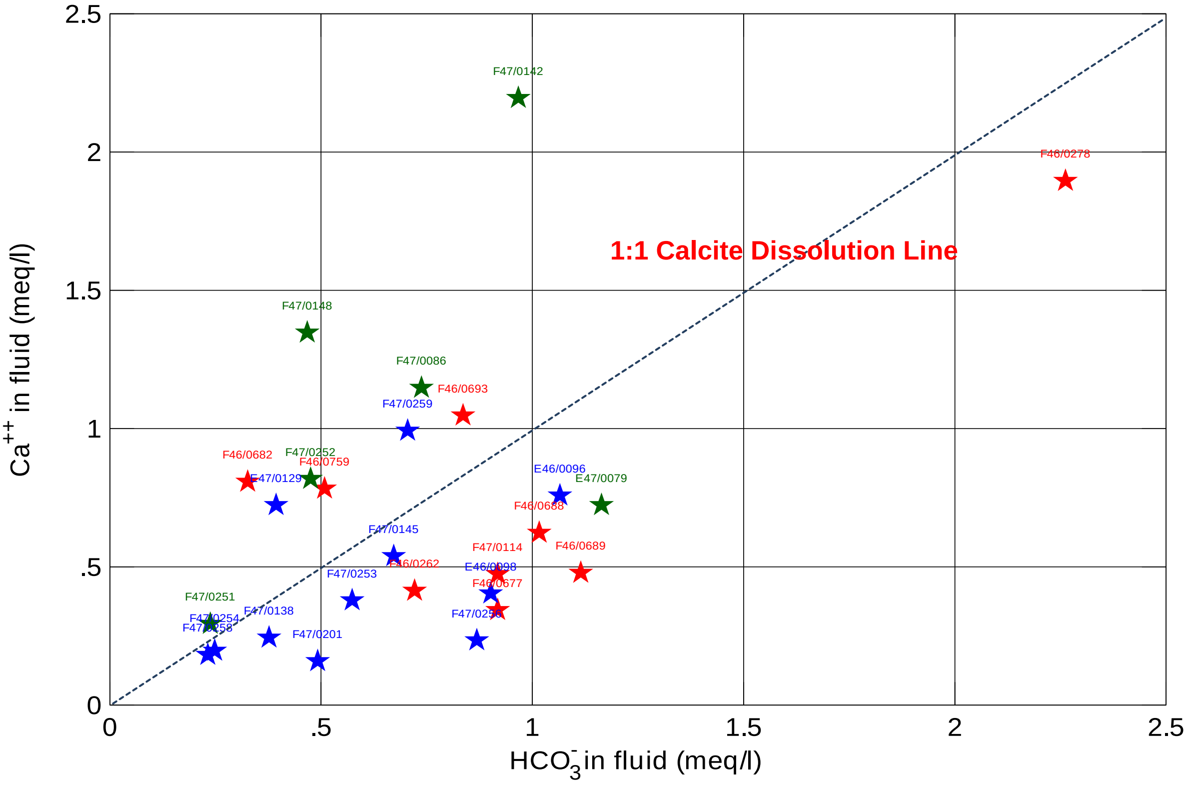

Figure 42: Median Ca plotted against median HCO_3 as milliequivalents

[Note: Calcium dominated aquifers tend to plot on the 1:1 line for calcite dissolution. All of the wells plotting beneath the calcite dissolution line are reducing in nature, suggesting a significant contribution of HCO_3 to these groundwaters from the oxidation of organic matter. The large enrichment in Ca for wells F47/0142, F47/0148 reflects contamination of these groundwaters by animal wastes.]

Iron is the dominant cation at two sites where reducing conditions occur. These same sites exhibit low SO_4 concentrations due presumably to reduction to H_2S. The role of redox potential over the geochemical evolution of Waituna groundwaters is discussed in detail in **Section 5.8.**

Only one site, occurring within a heavily grazed winter cropping paddock, showed SO_4 as the dominant anion (F46/0682) (**Figure 39**). Soil water samples from this paddock returned highly elevated Na (87 mg/L), Cl (184 mg/L), SO_4 (114 mg/L), K (97 mg/L) and NH_4 (24 mg/L) concentrations consistent with the high loads of animal wastes encountered within the paddock at the time of sampling (Oteramika soil water sample in **Table 4**). The enrichment in soil water solute loads also coincides with elevated concentrations of NO_3-N (6.8 mg/L) and K (15.1 mg/L) that exceed the natural background threshold for Southland by 6.8 and 15.1 times, respectively.

There were no occurrences of NO_3 as the dominant anion in any of the groundwaters sampled. However, at sites of oxidising groundwater influenced by intensive land use NO_3 constitutes up to 3.2 percent of the total ion load on a milli-equivalent basis. This relates to localised enrichments of NO_3-N of up to 13.8 times the natural background for Southland and New Zealand.

5.5 Recharge Mechanisms

Comparing the composition of rain and snowmelt, soil water, surface water and groundwater is a useful way of understanding the chemical changes occurring as water moves through the vadose zone (soil and unsaturated zone beneath the soil) to an underlying aquifer. Comparing the composition of water from these different domains enables factors such as water residence time (within the vadose zone), specific chemical reactions and the mode of recharge to be inferred. When comparing the major ion composition of all Waituna waters clear evolutionary and spatial differences are evident. **Figure 43** depicts the major ion composition of snowmelt, soil water, surface water and groundwaters collected from within the Waituna catchment.

Northern Portion of Catchment

North of Mokotua, away from the main axial flow path of Waituna Creek, tile drain waters exhibit large increases in $Ca>HCO_3>SO_4$ and NO_3, relative to snowmelt, indicating the interaction of infiltrating precipitation with the soil zone including the leaching of $Ca + SO_4$ and an increase in HCO_3 due to solvation of soil zone CO_2 (**Figure 43**). The significant increase in Ca and SO_4 is thought to reflect the proportionately greater reserves of Ca and subsoil SO_4 associated with the thick mineral brown soils that predominate in the northern portion of the catchment (Crops of Southland, 2002).

Relative to tile drain water, northern groundwaters exhibit similar TDS loads, moderate increases in HCO_3 concentration and a significant decrease in both $SO_4 + NO_3$. These changes suggest sufficient residence times for the evolution of SO_4 reducing conditions in the unsaturated zone, prior to infiltration to the unconfined aquifer according to the following reaction[19]:

$$SO_4^{2-} + 2CH_2O \text{ (organic matter)} \Rightarrow 2HCO_3^- + H_2S$$

The efficacy of thick mineral brown soils in removing anthropogenic contaminants also extends to K and DRP, which are very low beneath these soil types due to the high mineral clay content (layer silicates and amorphous iron oxides) which results in the removal of these ions via cation exchange and chemical sorption processes, respectively.

Mid-catchment

Mid-catchment, around the paleo-shoreline south from Mokotua/Kapuka to Caesar Rd (**Figure 8**), shallow groundwaters (F47/0252, F46/0086, F47/0142 and F47/0148; dark green

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[19] As conditions evolve towards SO_4 reduction NO_3 is also removed from solution via the process of denitrification.

stars in **Figure 43**) show little difference to tile drain waters draining grazed brown-soil pastures. This similarity in water type may reflect rapid infiltration of soil water with little attenuation of K, SO_4 or NO_3 either within the soil zone or during transport through the aquifer. Minor attenuation of contaminants is this locality is supported by the occurrence of the poorest groundwater quality within this area, including the highest median NO_3-N, SO_4 and K concentrations and the highest incidence of *E.coli* contamination. As above, the association of NO_3-N, K and SO_4 is consistent with an anthropogenic signature possibly associated with contamination by animal wastes (see **Section 5.6**).

Waituna Creek waters are very similar to groundwater composition across the middle section of the catchment (**Figure 43**). This similarity is consistent with a significant contribution of groundwater to base flow across this zone of high permeability. Importantly, a significant deterioration in the water quality in Waituna Creek is evident immediately downstream of Mokotua, raising the possibility that groundwater plays in important role over the deterioration of surface water quality in this part of the catchment. Collectively, the above information supports the concept of rapid through flow, negligible attenuation of contaminants (both within the soil zone and during transport through the aquifer) and minimal groundwater residence times in this area of the catchment. (Hereafter this portion of the Waituna catchment is referred to as the Mokotua Infiltration Zone (MIZ)).

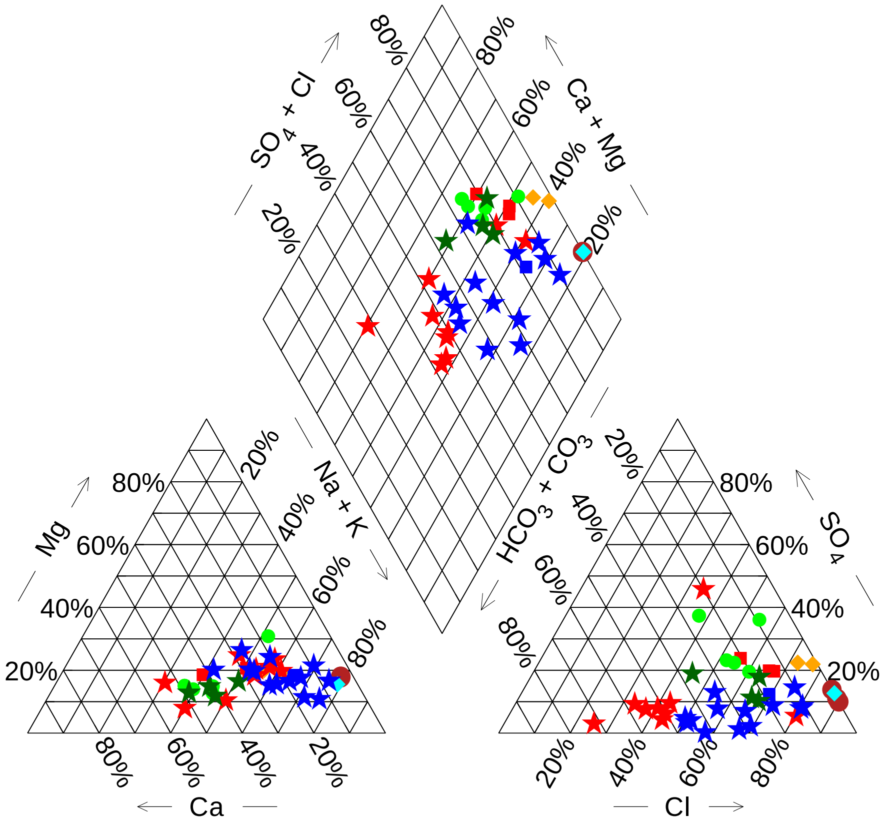

Figure 43: Major ion composition of shallow Waituna groundwaters, drainage waters, soil water, snowmelt and surface waters

[Note: Where: red (northern catchment), dark green (mid-catchment MIZ) and blue (southern catchment) stars represent Waituna groundwaters; light green circles = northern tile drain waters; orange diamonds = southern drains (open and tile); aqua diamonds = soil water DOC reserve; burgundy circles = Southland snowmelt, and; red squares are surface waters from Waituna, Moffat and Carran creeks. Snowmelt can be seen to evolve from a Na-Cl type fluid gaining varying quantities of SO_4, HCO_3, Ca, Mg and HCO_3 within the soil zone according to soil type and residence time. Soil waters tend to evolve through the reduction of NO_3 and SO_4 and the addition of HCO_3 as they percolate to the underlying aquifer.]

Southern Catchment

Relative to rainfall, drainage water from grazed pastures throughout the southern portion of the catchment exhibits significant gains in SO_4>Mg>K, with variable loads of Fe, HCO_3 and NO_3 (**Figure 43**). By comparison, soil water collected from 'pristine' conservation land within the Waituna Lagoon Conservation Reserve is compositionally similar to rainwater/snowmelt with low dissolved loads of NO_3-N, SO_4 and K (**Tables 3 & 4**). The significant gains in SO_4 and variable quantities of K are suggestive of the leaching of fertiliser and animal effluent during infiltration of rainfall as is evident from event sampling of groundwaters within the southern portion of the catchment (**Figure 44** and **Table 4**).

Relative to drain water, groundwaters in this section of the catchment exhibit similar proportions of conservative ions (Na and Cl) and some minor variance in Mg and Ca (**Figure 43**). The major differences in chemical compositions compared to upstream sections of the catchment include variable (according to redox potential) decreases in the concentrations of reducible ions (SO_4 and NO_3) and large increases in reduced species such as Fe^{2+} and NH_4. As described in **Section 5.8** these changes are consistent with the predominantly reducing conditions encountered within aquifers south of the MIZ.

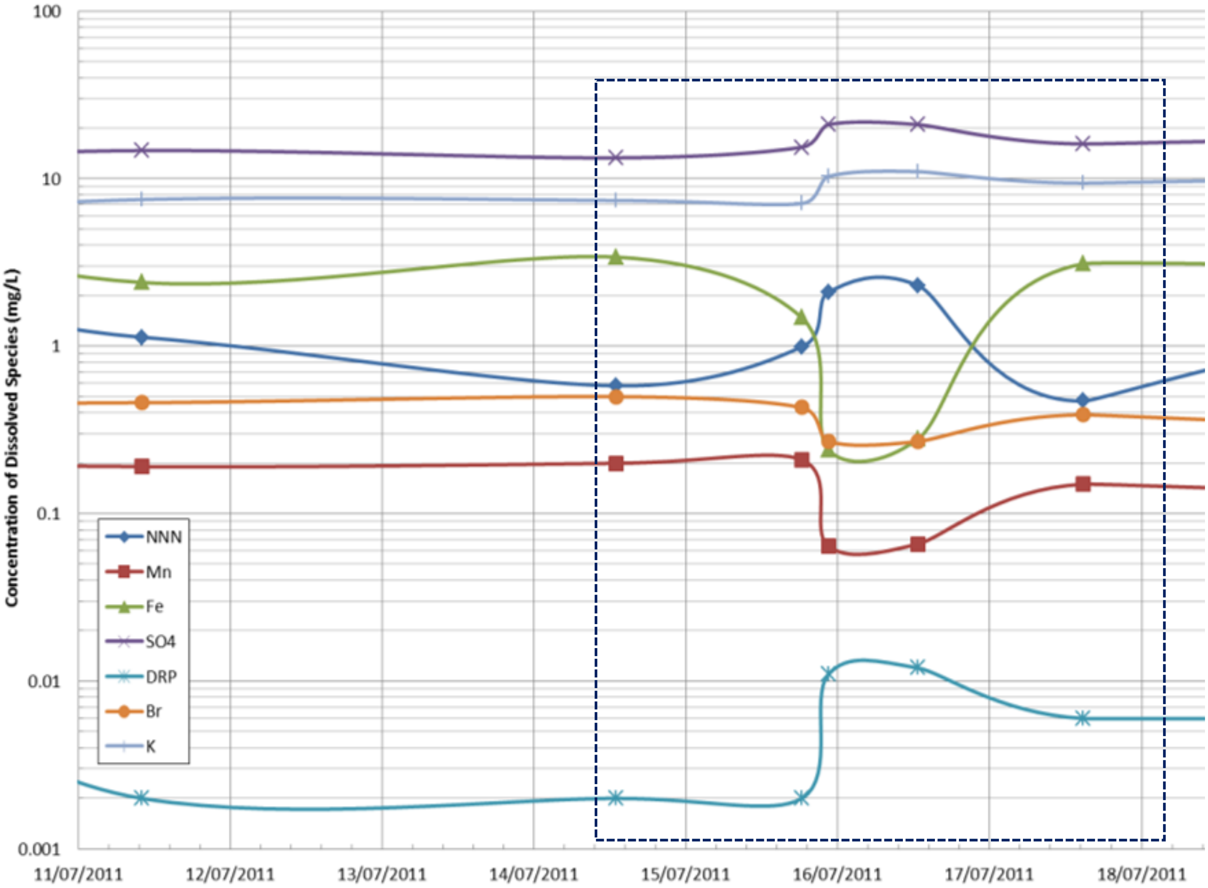

Figure 44: Soil zone recharge during event sampling in the southern half of the Waituna catchment (hashed outline).

[Note: The above chemical infiltration pattern for well E47/0129 coincides with spikes in soil moisture (to saturation) and groundwater level data in response to the passage of a storm event (8 – 15th of July, 2011; >50 mm in 24 hours), which triggered the artificial opening of the Waituna Lagoon.]

Evidence for the rapid infiltration of soil water to the unconfined aquifer in the southern section of Waituna catchment comes from high-resolution sampling (4, 12 and 24 return periods) undertaken during a major southerly storm (rainfall) event in mid-July of 2011. This event was associated with rainfall totals of more than 50 mm in 24 hours, which resulted in a major flood event triggering the artificial opening of the Waituna Lagoon. As shown in **Figure 44** shallow groundwaters in the vicinity of Waituna Creek exhibit rapid increases in the concentration of oxidisable species NNN (nitrate-nitrite-nitrogen) and SO_4 with a simultaneous decrease in reduced species (Mn, Fe and NH_4) following this event. The data show a positive spike in NO_3, SO_4, K and DRP concentrations supporting a soil dominated, anthropogenic signature for the infiltration event. A soil zone source is also supported by the inverse correlation between DRP and dissolved Fe concentration. It is significant to subsequent discussion that following this recharge event DRP from the soil zone increased in concentration in the unconfined aquifer by at least an order of magnitude.

Following the recharge event, redox sensitive species appear to rapidly readjusted to pre-event levels. The return period over which the redox state reverts to its original state is difficult to assess due to the small number of bores with high temporal resolution data (i.e. event sampling). However, for bores E47/0129, F47/0253 and F47/0256 a rapid shift from a mixed (oxic-anoxic) redox state back to the dominant anoxic redox state is observed within approximately 14 hours of the cessation of the main recharge event, suggesting a relatively rapid consumption of reducible species. The above observations support the concept of rapid (days - week) infiltration of rainfall through the soil zone in the southern sector of the Waituna catchment.

5.6 Statistical Modelling and Anthropogenic Signatures

Application of Principal Component Analysis (PCA), following the methods of Güler et al. (2002) and Daughney et al. (2011), provides additional insight to the general interpretation of the major element hydrogeochemistry of Waituna groundwaters. Specifically, PCA identifies three significant components that are cumulatively able to describe approximately 76 percent of the variability in Waituna groundwater quality data set (**Table 7**)[20]. Component 1 explains approximately 35 percent, Component 2, approximately 25 percent and Component 3, approximately 15 percent of the variance in the data.

The importance of redox potential is illustrated by the weightings of D.O., NO_3-N and SO_4 in Component 1, which oppose those of Fe, Mn and NH_4-N. As noted in other New Zealand studies (Daughney et al., 2011; Raiber et al., 2012) this pattern indicates a distinction between oxic waters, in which NO_3 and SO_4 are present but Fe, Mn and NH_4 are absent, compared to anoxic waters, which display the opposite pattern. The negative weighting of DRP in Component 1 probably reflects the greater solubility of DRP under reducing conditions due to the dissolution of Mn and Fe oxy hydroxides (see **Section 5.8**).

Also of note is that K is the only cation with a strong positive weighting in Component 1 and that this positive weighting coincides with those for NO_3 and SO_4 (**Table 7**). This association suggests a likely anthropogenic source for NO_3, SO_4 and K as is supported by:

- soil zone recharge events in the southern part of the catchment (**Figure 44**);
- the occurrence of these three species in groundwaters at concentrations that greatly exceed the natural background for Southland (see **Section 5**), and;

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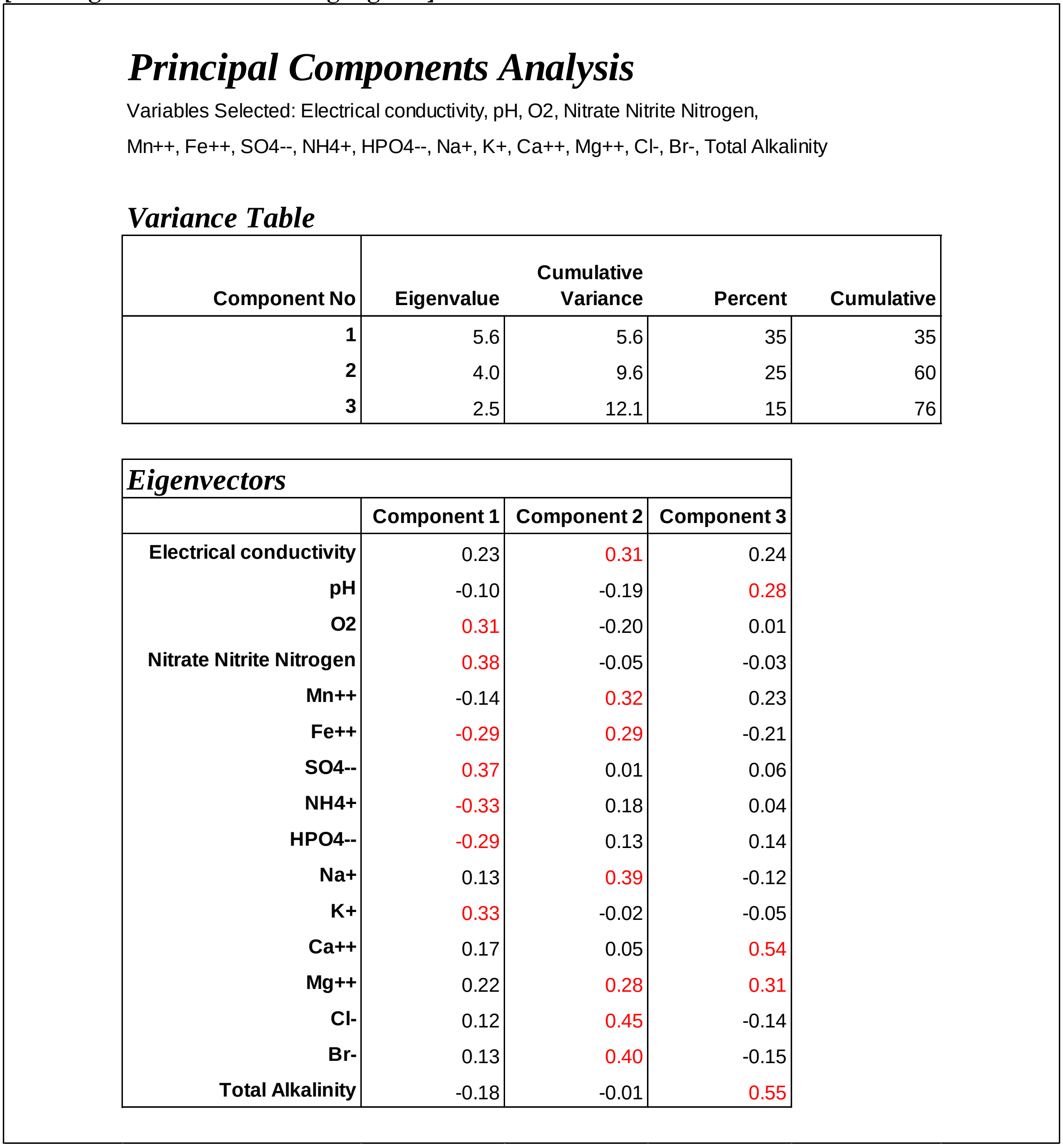
[20] Eigenvalues >1; each defining ≥ 10% of the variance.

- ➢ the higher concentrations of these three constituents in soil waters, tile drain leachate and groundwaters collected from paddocks under heavily grazed winter crops (**Table 4**).

Table 7: Principal component analysis of Waituna groundwaters
[Values greater than 0.25 are highlighted]



Principal Components Analysis

Variables Selected: Electrical conductivity, pH, O2, Nitrate Nitrite Nitrogen,
Mn++, Fe++, SO4--, NH4+, HPO4--, Na+, K+, Ca++, Mg++, Cl-, Br-, Total Alkalinity

Variance Table

Component No	Eigenvalue	Cumulative Variance	Percent	Cumulative
1	5.6	5.6	35	35
2	4.0	9.6	25	60
3	2.5	12.1	15	76

Eigenvectors

	Component 1	Component 2	Component 3
Electrical conductivity	0.23	0.31	0.24
pH	-0.10	-0.19	0.28
O2	0.31	-0.20	0.01
Nitrate Nitrite Nitrogen	0.38	-0.05	-0.03
Mn++	-0.14	0.32	0.23
Fe++	-0.29	0.29	-0.21
SO4--	0.37	0.01	0.06
NH4+	-0.33	0.18	0.04
HPO4--	-0.29	0.13	0.14
Na+	0.13	0.39	-0.12
K+	0.33	-0.02	-0.05
Ca++	0.17	0.05	0.54
Mg++	0.22	0.28	0.31
Cl-	0.12	0.45	-0.14
Br-	0.13	0.40	-0.15
Total Alkalinity	-0.18	-0.01	0.55

The presence of K in high concentrations suggests the capacity of the soil to remove K via ion exchange has been locally overwhelmed (Rosen, 2001). Potassium is especially high in dairy cow urine (**Table 4**) and in potash (KCl) super. Both SO_4 and NO_3 are known to be highly mobile ions within the soil zone and tend to accumulate under oxidising conditions. Using NO_3, K and SO_4, a graphical display of the degree of human impact on Waituna groundwaters is provided in **Figure 45**. The fields in **Figure 45** outlining possible anthropogenically affected groundwaters are defined according to natural background thresholds determined for NO_3-N (≤1 mg/L), K (≤1 mg/L) and SO_4 (≤17 mg/L) for the Southland region. From **Figure 45** and comparisons against regional threshold values for the relevant species, it is evident that approximately 50 percent of Waituna groundwaters show significant anthropogenic contamination.

Importantly, oxidised groundwaters within the Mokotua infiltration zone (green squares) display the greatest degree of contamination. Strongly reducing groundwaters exhibit low SO_4 and NO_3-N but retain a signature of elevated K. Impacted reduced groundwaters also exhibit DRP concentrations that are between 2 - 8 times higher than the regional background threshold of less than or equal to 0.03 mg/L for Southland. The elevated DRP concentrations of impacted southern groundwaters may reflect the enhanced solubility of phosphate in reduced groundwaters and the possibility that fertiliser and effluent phosphate is more prone to leaching under organic soils (**Figure 45**; R. McDowell, *pers. comm,* 2012) although the latter is the subject of further research.

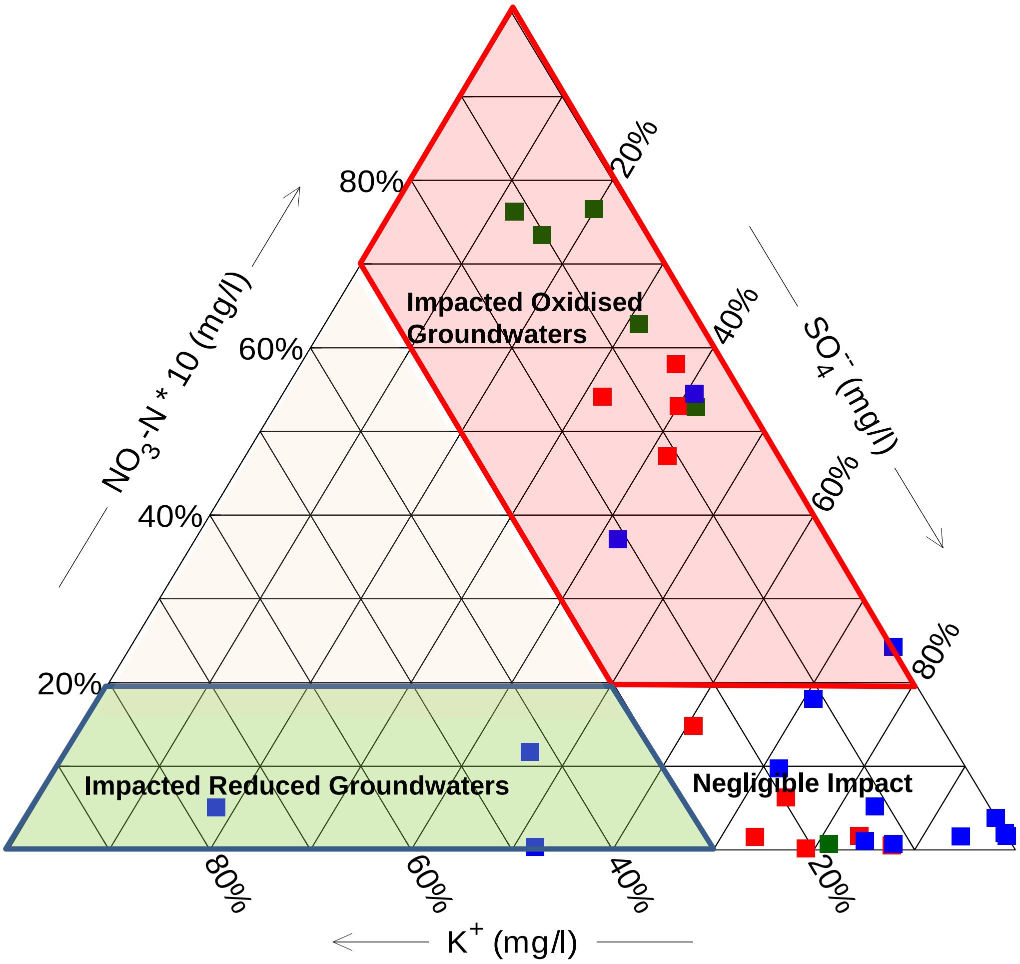


Figure 45: Ternary diagram of Waituna groundwaters displaying the impact of land use [Note: Anthropogenic fields are assigned according to natural background for NO_3-N (≤1 mg/L), K (≤1 mg/L) and SO_4 (≤17 mg/L) based on interpretation of log cumulative probability plots of regional data (n = 1300 – 6000 samples). Oxidised groundwaters within the Mokotua infiltration zone (green squares) display a high degree of contamination. Strongly reducing groundwaters exhibit low SO_4 and NO_3-N but retain a signature of elevated K.]

Component 2 (approximately 26 percent of variability) shows the strongest positive weightings for Na, Cl, Br and EC with less positive weightings for Mg. The type of analytes and the magnitude of weightings associated with Component 2 supports the important role of marine aerosolic inputs (Na, Mg, Cl (Br)) from rainfall over the dissolved solute load of Waituna groundwaters. This interpretation is supported by an increase in the loadings of Component 2 for individual groundwaters with proximity to the coastline. Another process, which may also explain some of the variance in Component 2, is the enhanced leakiness of wetland soils to animal effluents and fertilisers. The latter is consistent with the greatest weightings for

Component 2 associated with southern groundwaters that also show elevated, possibly anthropogenic, K concentrations. Component 2 may therefore represent the combination of both marine derived and anthropogenic salts to Waituna groundwaters. The positive weighting of Fe and Mn within Component 2 indicates a positive association with reducing groundwaters that predominate in the southern half of the catchment. The only negative weightings for Component 2 are associated with pH and total alkalinity (HCO_3) which support the infiltration of naturally acidic rainfall that is naturally low in alkalinity when contrast with evolved soil zone waters or groundwaters (**Table 3**).

An alternative hypothesis to explain that data pattern within Component 2 is that of connate waters (ancient seawater trapped in pore fluids of marine deposited sediments) contributing to the dominantly marine solute signature. However, only deep wells (greater than 30 metres) that tap the confined aquifers (F46/0759) show elevated TDS (greater than 250 mg/L) values consistent with a possible connate origin for dissolved Na and Cl[21]. The remaining shallow bores have a median TDS of less than 130 mg/L that is only slightly elevated above the median value of 105 mg/L for tile and open drain waters of the catchment making a connate origin unlikely.

Component 3 only accounts for 13 percent of the variance within the data but shows particularly strong positive weightings for pH, Ca and HCO_3 which coincide spatially with shallow groundwaters evolved beneath thick mineral brown soils, of higher base saturation and bulk Ca concentrations, in the north of the catchment (**Table 7**). Therefore, the weightings of chemical species in Component 3 are suggestive of a distinction between Ca–HCO_3 type waters and Na–Cl type waters, which coincides with a shift from thick mineral brown soils of moderate to high base saturation to acidic wetland soils of low to very low base saturation in the south. An alternative or contemporaneous process contributing to the evolution of northern, Ca-HCO_3 type groundwaters, is calcite (and perhaps dolomite) dissolution due to water rock interaction. However, only one bore (F46/0278) shows a strong association with carbonate bearing aquifer rocks and exhibits saturation with respects to both calcite and dolomite.

5.7 Waituna Groundwater Hydrochemistry Summary

Analysis of the major ion chemistry of shallow Waituna groundwaters supports the presence of predominantly dilute groundwaters that evolve from coastal rainfall according to the soil type, residence time within the unsaturated zone and redox status of the underlying aquifer. Overall, Waituna groundwaters waters can be defined as 'surface-dominated' according to the criteria of Freeze and Cherry (1979).

However, some important spatial variations in groundwater composition are observed, namely (**Figure 46**):

- geochemically the most evolved groundwaters in the Waituna catchment occur north of Mokotua/Kapuka, suggesting longer residence times within the unsaturated zone in this area and/or a greater degree of water-rock interaction along the flow path. Groundwaters in this region of the catchment show little evidence of impact from intensive land use;

- a region of rapid infiltration of soil zone water in an area associated with the paleo-shoreline (Q5) in the vicinity of Mokotua/Kapuka, with minimal attenuation of contaminants and no evident evolution of groundwater chemistry. These groundwaters show the greatest impact from intensive land use and may be partially responsible for the

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[21] After removal of one groundwater sample that is heavily contaminated by a septic tank outfall.

deterioration in the water quality in Waituna Creek south of Mokotua. Hereafter this zone will be referred to as the Mokotua Infiltration Zone (MIZ); and

- a southern region of dominantly Na-Cl groundwaters that respond rapidly to rainfall recharge and evolve chemically in response to reducing conditions. These waters are low in NO_3-N but show elevated concentrations of TP and DRP, which may be associated with anthropogenic inputs.

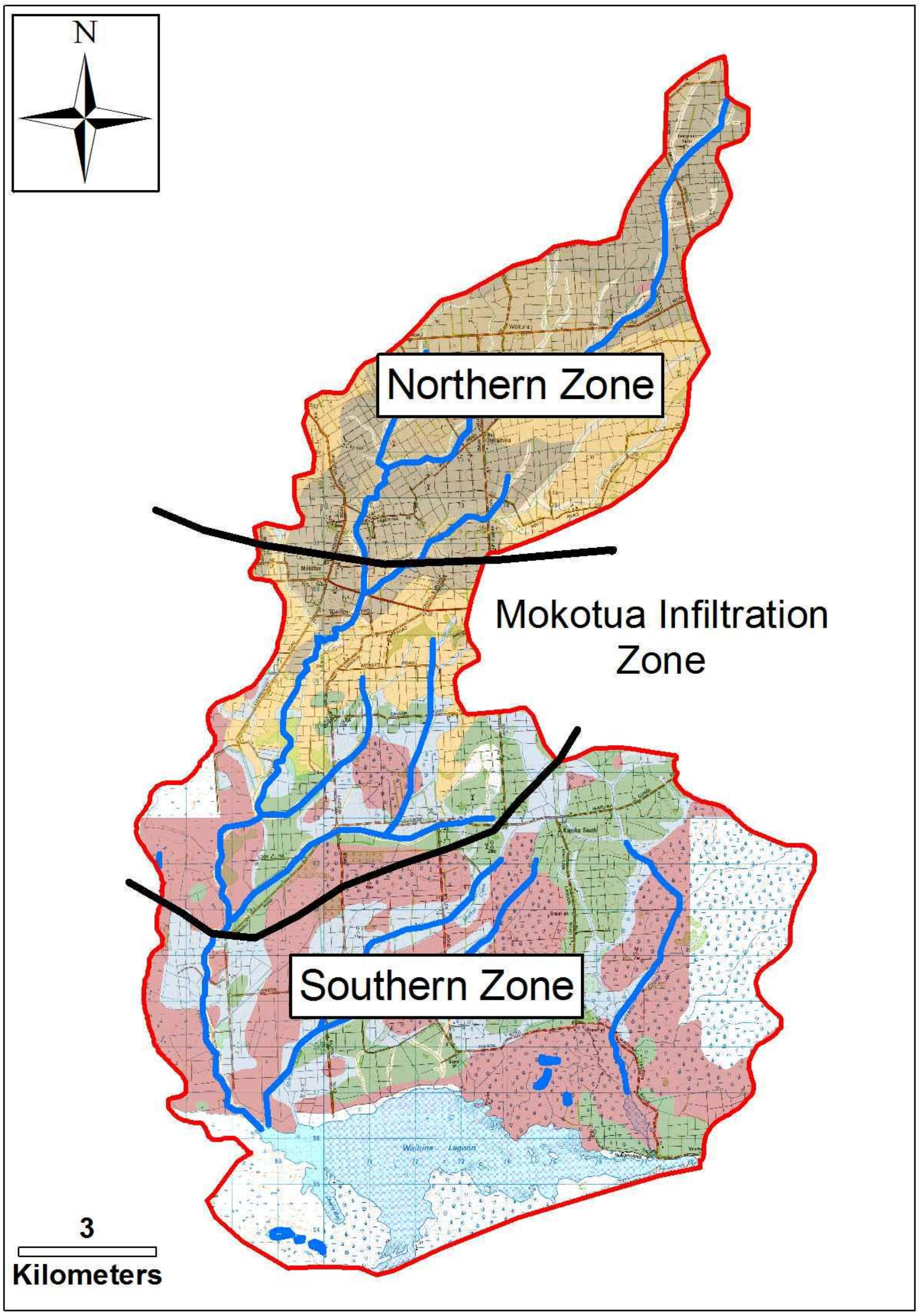

Figure 46: Groundwater quality zones of the Waituna catchment as defined by natural variation in hydrogeological properties, soil and aquifer types and hydrochemical variation.

[Note: Changes in colour, from north to south, of solid contours reflects the change from thick mineral brown soils in the north to wetland soil types in the south.]

5.8 Groundwater Redox

Although the influence of redox conditions over water composition to overall groundwater composition has already been noted, the following section provides an analysis of redox in terms of key water quality parameters including the nutrients nitrogen and phosphorus.

5.8.1 Redox Background

The amount of oxygen dissolved in groundwater is very important to the overall water quality of a given aquifer or groundwater zone. For this reason, scientists classify groundwater according to oxygen status or more correctly "redox status" (reduction-oxidation status). A redox reaction is defined by the transfer of electrons from one chemical species to another. Therefore, for a redox reaction to proceed there must be an electron donor and an electron acceptor.

The most common electron donor in groundwater systems is dissolved and particulate organic carbon (organic matter from plant material and low rank coal measures (i.e. lignite and brown coal)) although in some instances minerals such as pyrite (FeS_2) and/or glauconite (iron rich clays) may act as electron donors. The most common electron acceptors include dissolved oxygen (O_2), nitrate (NO_3^-), manganese (Mn^{4+}), ferric iron (Fe^{3+}), sulphate (SO_4^{2-}) and carbon dioxide (CO_2) (**Figure 47**).

In groundwater, redox reactions are largely driven (catalysed) by bacteria, which gain energy by facilitating the transfer of electrons from organic matter to an electron acceptor. This process results in the breakdown of organic matter into its constituent elements (carbon, oxygen, nitrogen, phosphorus and some minor trace elements), the consumption of the electron acceptor, and a net energy release for the micro-organism.

Because micro-organisms gain energy by catalysing the transfer of electrons from donor (almost always organic matter) to an electron acceptor they tend to favour the acceptor that supplies them with the most amount of energy (**Figure 47**). Of the possible terminal electron acceptors, oxygen provides the greatest amount of energy and for this reason it is preferentially used by microorganisms. However, because groundwater can be isolated from the atmosphere oxygen tends to be consumed as groundwater moves through an aquifer.

Once oxygen has been consumed bacteria move onto the next most energetically favourable electron acceptor, nitrate (NO_3^-), followed by manganese (Mn^{4+}), ferric iron (Fe^{3+}), sulfate (SO_4^{2-}) and eventually carbon dioxide (CO_2). This order of preferential electron acceptor utilisation - $O_2 > NO_3 > Mn > Fe > SO_4 > CO_2$ – is referred to as the ecological succession of terminal electron-accepting processes (**Figure 47**). Therefore, once oxygen has been depleted from groundwater the decay of organic matter continues through a succession of reactions that represent a progressively lower tendency of the groundwater to remove electrons from organic matter. All electron acceptors (oxidising agents) are themselves reduced when they gain electrons. Therefore, during the ecological succession of terminal electron accepting reactions groundwater becomes increasingly reduced.

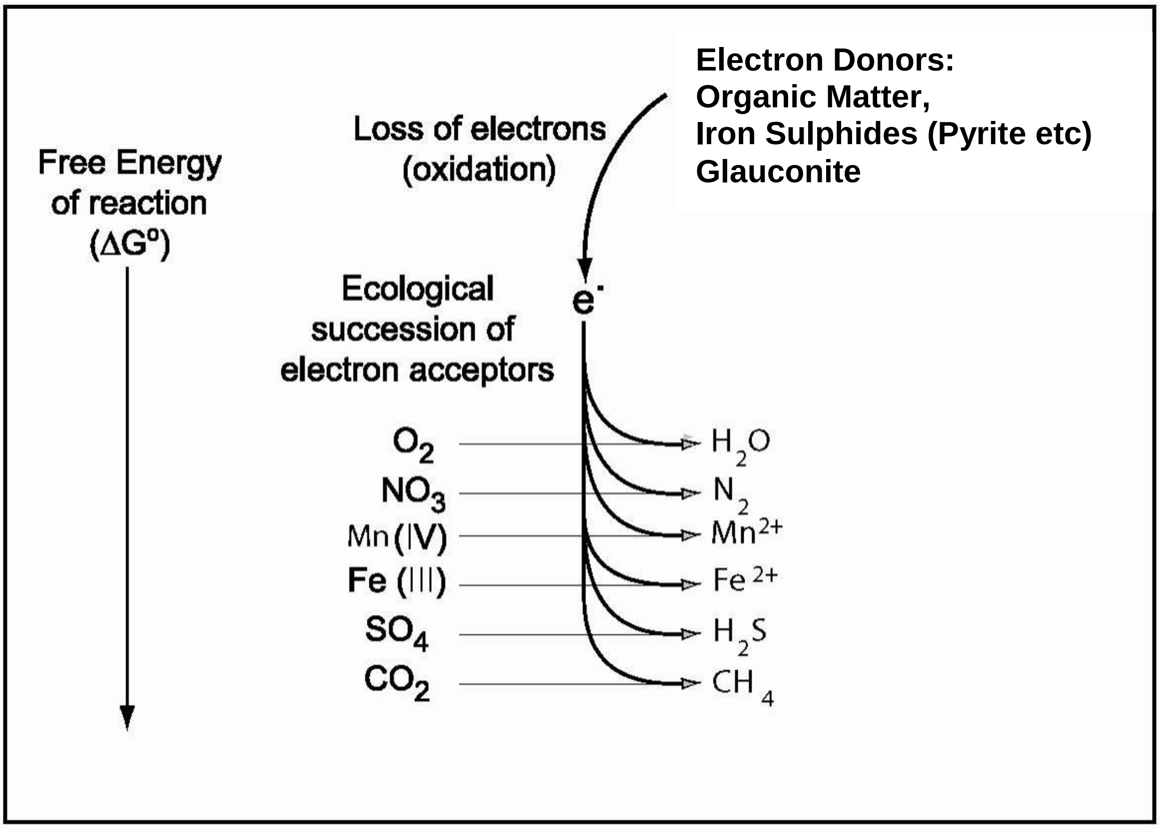

Figure 47: Ecological succession of electron-accepting processes and sequential production of final products in groundwater
[Note: A decrease in free energy available to microbes occurs as each successive electron acceptor is consumed. Typically organic matter (organic carbon) is by far the most common electron donor in groundwater but iron sulphides and glauconite may be locally significant (modified from McMahon and Chappelle, 2008)]

5.8.2 Importance of Groundwater Redox State

Understanding the redox status of a shallow groundwater aquifer is critical to issues of groundwater quality. In particular, the redox status determines such factors as:

- whether nitrate will accumulate or be attenuated by denitrification;
- the solubility and mobility of phosphorus;
- the solubility of toxic metals such as arsenic (As);
- the presence of nuisance chemicals that degrade water quality such as dissolved iron (Fe^{2+}), manganese (Mn^{2+}) and hydrogen sulphide (H_2S) with its distinctive rotten-egg smell.

The controls over the redox status of groundwater are determined by the materials that comprise an aquifer, the relative rates of introduction of oxidants (i.e. O_2, NO_3-N, Mn and SO_4) and the consumption of these oxidants by bacterially catalysed decomposition of organic matter. The most important variables governing the redox status of groundwater include (Drever, 2002; McMahon and Chappelle, 2008):

1. **Distribution and reactivity of organic matter and other potential reductants in the aquifer**
   Aquifers vary greatly in the amount of organic matter present, and more importantly, the reactivity of that organic matter. Organic material locked up in sedimentary rocks (mud-, silt- and sandstone etc.) tends to be both poorly available and indigestible to microbes as a food source. Conversely, peats and weakly metamorphosed coal measures (lignite and brown coal) along with marine and estuarine sediments have an abundance of freely available and readily oxidisable organic matter. The mass of easily oxidisable organic matter is one factor critical to the evolution of the redox status of a groundwater from oxidising through to reducing conditions. Aquifers with an abundant supply of electron donators tend to rapidly consume oxygen and progress quickly through the ecological succession of terminal electron accepting species (**Figure 47**) (rarely, electron donors other than organic matter play an important role as electron donors and include iron sulphides and glauconite).

2. **Distribution of inorganic terminal electron acceptors in an aquifer**
   The mass of the inorganic terminal electron acceptors, specifically the oxides of iron and manganese, within groundwater aquifers is commonly large. Consequently, these oxides provide a large reservoir of oxidising materials. Due to the large mass of manganese and iron oxides, commonly shallow groundwater does not evolve beyond Fe reducing conditions.

3. **Oxygen content of recharge water**
   Recharge water may enter an aquifer through fractures in bare rock, or it may percolate through a soil rich in organic matter. In the first case, the recharge water will be high in oxygen so microbes within the groundwater reservoir will have an abundant supply of a powerful oxidant for organic matter decomposition. In the second case, oxygen, and perhaps nitrate, may be consumed within the soil profile before infiltrating to the aquifer. In this instance, the infiltrating water will be reducing before reaching the groundwater zone and bring with it a low capacity to oxidise organic matter.

4. **Circulation rate of groundwater**
   Because the bacterial catalysis of organic matter is typically slow, the redox status of a particular groundwater system depends very much on the residence time of the water in the aquifer. The residence time depends on both the velocity of the water and the "length" of the aquifer system from recharge to discharge points. In general, the longer the residence time the more advanced groundwater is along the ecological succession of terminal electron accepting processes (**Figure 47**).

5.8.3 Redox and Nutrients

If an energetically more favourable electron acceptor is introduced to a chemically reducing groundwater, bacteria will quickly switch to using this compound to breakdown organic matter. An important example is the leaching of NO_3, a relatively high-energy electron acceptor, into reduced groundwater. In these circumstances, microbes will quickly utilise the introduced NO_3 converting it to nitrous oxides (intermediate form) and ultimately nitrogen gas. Nitrogen gas and nitrous oxides are poorly soluble in water and will tend to migrate as they bubble towards the atmosphere resulting in a net loss of nitrogen from the groundwater. This process, called denitrification, effectively removes NO_3 from groundwater and may prevent the accumulation of NO_3 and the degradation of water quality. However, if the groundwater is not reducing (i.e. containing abundant oxygen) NO_3 will accumulate.

Whereas the removal of NO_3 via denitrification is favoured by reducing conditions, phosphorus in its dissolved reactive form (DRP) tends to be both more soluble and more mobile. Under oxic conditions, Fe and Mn oxides exist as poorly structured minerals with a large surface area that has a strong affinity for DRP. Therefore, DRP entering an oxygen rich soil or aquifer is rapidly removed from solution by chemical sorption onto Fe and Mn oxides. However, as groundwaters evolve beyond NO_3 reducing conditions, Mn and Fe oxides dissolve as bacteria use each as a terminal electron acceptor (**Figure 47**). As Mn and Fe are dissolved any DRP that has been sorbed is released back into solution. For systems already at Fe or SO_4 reducing conditions, with only minor concentrations of Fe and Mn oxides remaining, introduced DRP tends to remain in solution. Therefore, anthropogenic phosphate introduced via the soil zone to a reduced aquifer is more likely to accumulate to high levels than in oxidised groundwater systems.

Further, organic soils, which typically have lower Fe and Mn oxide contents, are also less effective at removing phosphate from solution and consequently are more prone to phosphate losses. Significantly, both organic soils and reducing conditions tend to occur together due to the abundance of organic carbon supplied by peat, which results in the rapid consumption of high-energy terminal electron acceptors as per **Figure 47**.

5.8.4 Redox Assignment

Redox status and the Terminal Electron Accepting Process (TEAP) of groundwaters were assigned from median values of redox sensitive species for 31 shallow (less than 20 metres) bores within the Waituna catchment using the methods of McMahon and Chapelle (2008) and the Excel Workbook for Identifying Redox Processes in Groundwaters provided by the USGS (Jurgens et al., 2009; **Table 8** and **Table 9**). Because redox reactions are usually not at chemical equilibrium[22] within low temperature groundwaters, the redox assignment framework predicts the redox state according to the widely observed ecological succession of electron-accepting processes (as described **Sections 5.8.1 – 5.8.3** and in **Figure 47**). Redox assignments are therefore made according to the relative concentration of the key terminal electron acceptors as per **Table 8**[23]**.**

Redox assignments for each groundwater sample includes identification of the dominant redox state (i.e., oxic, suboxic, and mixed (oxic-anoxic)) and the principal TEAP operating within that groundwater (**Table 9**; **Figure 47**). Iron reducing conditions are differentiated from SO_4 reducing conditions by measuring the mass ratio of Fe^{2+} to total sulphide (see Chapelle et al., 2009).

Of the 31 bores only 7 (approximately 23 percent) exhibit oxic conditions where O_2 reduction is the principal TEAP. Of the remaining bores, 12 exhibit anoxic conditions (approximately 36 percent) and 13 (approximately 42 percent) have a mixed (oxic-anoxic) redox state (**Table 9**). By comparison more than 80 percent (n = 61) of regional groundwaters, from outside the Waituna catchment, have an oxic redox status. McMahon

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[22] Chemical equilibrium is the state in which both reactants and products in a reaction are present at concentrations which have no further tendency to change with time.

[23] Each of the threshold values defined for the key terminal electron accepting processes are based on laboratory trials, field studies and published literature on groundwater redox conditions (see McMahon and Chapelle, 2008; Chapelle et al., 2009; Jurgens et al., 2009).

and Chapelle (2008) report a similar proportion of oxic groundwaters (75 – 90 percent) for the principal aquifer systems of the United States.

The dominance of anoxic and mixed redox state groundwaters (approximately 78 percent) reflects the local abundance of organic carbon (from peat and to a lesser degree lignite) within Waituna aquifers – especially in the south. The oversupply of organic carbon results in the rapid consumption of high energy terminal electron acceptors (e.g., NO_3), introduced during recharge events, and the progression towards Fe(III), SO_4 and even CO_2 reducing conditions.

The few measurements (n = 5) of Total Organic Carbon (TOC) for Waituna groundwaters range between 0.9 – 12.8 mg/L with a median of 3.8 mg/L. Measurement of the Dissolved Organic Carbon (DOC; n = 15) fraction ranged between 0.3 – 10.2 mg/L with a median of 2.6 mg/L[24]. Values of DOC in excess of 2.0 mg/L are typical of wetland aquifers whereas outside of these areas elevated DOC concentrations typically reflect anthropogenic inputs (Chomycia et al., 2008 and references therein).

North of the MIZ groundwater DOC is generally low (median of 1.5 mg/L) and increases markedly to a median value of 7.4 mg/L in the south in response to the transition from mineral soils to organic carbon rich wetland soils (**Figure 41**). Across the MIZ, DOC concentrations in groundwater are also elevated (median = 4.4 mg/L) despite the absence of wetland soil types and in conjunction with the poor water quality of this area of the catchment may reflect an anthropogenic DOC input.

As expected, the small proportion of bores (7 of 31) with an oxic redox status all occur north of paleo-shoreline where aquifer materials transition to terrace gravels and sands with little if any inclusions of peat (Rissmann, 2011b). The predominance of weathered chemically inert materials (gravel, sand and silt) results in a lack of electron donors (organic carbon) limiting the ecological succession of terminal electron-accepting processes, within an aquifer, towards reducing conditions. However, only those groundwaters within the MIZ exhibit significant NO_3-N concentrations due primarily to the short residence times within the unsaturated zone and underlying aquifers (see **Section 3**). North of the MIZ, thick mineral brown soils appear to result in an extended residence time within the unsaturated zone, prior to infiltrating to groundwater, during which redox conditions remove excess NO_3 during evolution of SO_4 reducing conditions.

Of the anoxic groundwaters, the majority (9 out of 11) exhibit either Fe(III) or SO_4 reduction as the principal TEAP (**Table 9**). By measuring the concentration of total sulfide for some of these groundwaters it was possible to discriminate Fe(III) from SO_4 reduction as the principal TEAP for the majority of anoxic groundwaters. The predominance of Fe(III) as the principal TEAP within anoxic groundwaters is consistent with buffering by the large mass of ferric hydroxides or oxyhydroxides ($Fe(OH)_3$ and Fe_2O_3) is typical of aquifer materials. Despite dominance by Fe(III) reduction the odour of H_2S was extremely common within anoxic groundwaters with significantly lower median SO_4 concentrations for anoxic groundwaters indicating that SO_4 reducing conditions occur at the same time as Fe(III) reduction. The occurrence of one or more redox process is not uncommon in aquifers where electron-donors (i.e., organic carbon and ferrous iron) are not limiting (Vroblesky and Chapelle, 1994).

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[24] Dissolved Organic Carbon is that fraction able to pass through a 0.45 μM filter.

The proportion (approximately 42 percent) of groundwaters with a mixed redox state (i.e., both oxic and anoxic with O_2 and Fe(III) reducing conditions, respectively) is unusually large when contrast with the regional groundwater redox data set (e.g., only 6 percent; n = 61) for Southland. McMahon and Chapelle (2008) report a similar proportion of mixed redox status groundwaters (1.1 – 8.1 percent) within the principal aquifer systems of the United States, with the exception of aquifers in coastal lowlands. The high proportion of mixed-redox state groundwaters probably reflects the inherent small-scale heterogeneity of aquifer materials encountered within the Waituna catchment. In particular, the interbedding of peat with chemically inert sands and gravels and/or the proximity of lignite measures, which results in reducing conditions developing in one part of the aquifer but not elsewhere (Rissmann, 2011b).

Mixed redox state conditions commonly occur where the scale of sampling is larger than the scale of redox heterogeneity in the rock or sediment. For example, a screened or open bore that simultaneously draws water from a sequence of interbedded peat and quartz gravel may supply both reduced groundwater from the peat and oxidising groundwaters from the gravel. Groundwaters sampled from aquifers characterised by small scale redox heterogeneity commonly exhibit mixed-redox states and such aquifers are especially common in coastal lowlands due to the tendency of organic carbon to accumulate under high water tables (Krantz and Powars, 2002; McMahon and Chapelle, 2008).

Interbedding of peat and gravel within the southern portion of the catchment is evident from drill logs, from field experience of point driven bores and in exposed gravel scarps/terraces along the edge of the Waituna Lagoon. Incremental depth measurements (0.5 m increments) of groundwater D.O. in a quartz gravel aquifer adjacent to Waituna Lagoon vary between oxic (more than 2 mg/L), suboxic (1 - 2 mg/L) and anoxic (less than 0.5 mg/L) over the 3.4 metre sampling depth. Although an initial general decline in D.O. occurred with depth, a significant increase in median D.O. to 4.0 mg/L at 3.0 metres followed by a subsequent decline to less than 2.0 mg/L demonstrates the small scale variability in redox potential within this coastal aquifer (**Figure 48**)[25]. Groundwaters from bores F47/0258 and F47/0254, flanking the Waituna Lagoon, are screened within the same mixed quartz gravel-peat aquifer and both exhibit mixed redox states where O_2-Fe and O_2-Mn are the dual TEAPs, respectively.

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[25] Organic rich layers were identified by a rich reddish brown staining of pumped groundwaters and the presence of particulate carbon in the sampled waters.

Table 8: Redox assignment criteria used for Waituna groundwaters based on the ecological succession of terminal electron accepting process commonly encountered in cold groundwaters.

[Modified from McMahon and Chapelle, (2008). Redox process: O_2, oxygen reduction; NO_3, nitrate reduction; Mn(IV), manganese reduction; Fe(III), iron reduction; SO_4, sulfate reduction; CH_4gen, methanogenesis. Chemical species: O_2, dissolved oxygen; NO_3^-, dissolved nitrate; MnO_2(s), manganese oxide with manganese in 4+ oxidation state; $Fe(OH)_{3(s)}$, iron hydroxide with iron in 3+ oxidation state; $FeOOH_{(s)}$, iron oxyhydroxide with iron in 3+ oxidation state; SO_4^{2-}, dissolved sulfate; $CO_{2(g)}$, carbon dioxide gas; $CH_{4(g)}$, methane gas. Abbreviations: mg/L, milligram per litre; —, criteria do not apply because the species concentration is not affected by the redox process; ≤, less than or equal to; ≥, greater than or equal to; <, less than; >, greater than. At times D.O. measurements at low D.O. concentrations can be inaccurate. However, field trails of the accuracy of Galvanic D.O. probes indicate that probes regularly calibration against a zero D.O. solution have no problem in accurately measuring D.O. concentrations down to concentrations of 0.5 mg/L.]

			Criteria for inferring process from water-quality data					
Redox category	**Redox process**	**Electron acceptor (reduction) half-reaction**	**Dissolved oxygen (mg/L)**	**Nitrate, as Nitrogen (mg/L)**	**Manganese (mg/L)**	**Iron (mg/L)**	**Sulfate (mg/L)**	**Iron/sulfide (mass ratio)**
Oxic	O2	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	≥0.5	—	<0.05	<0.1	—	
Suboxic	Suboxic	Low O2; additional data needed to define redox process	<0.5	<0.5	<0.05	<0.1	—	
Anoxic	NO3	$2NO_3^- + 12H^+ + 10e^- \rightarrow N_{2(g)} + 6\ H_2O$; $NO_3^- + 10H^+ + 8e^- \rightarrow NH_4^+ + 3H_2O$	<0.5	≥0.5	<0.05	<0.1	—	
Anoxic	Mn(IV)	$MnO_{2(s)} + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O$	<0.5	<0.5	≥0.05	<0.1	—	
Anoxic	Fe(III)/SO4	Fe(III) and (or) $SO4^{2-}$ reactions as described in individual element half reactions	<0.5	<0.5	—	≥0.1	≥0.5	no data
Anoxic	Fe(III)	$Fe(OH)_{3(s)} + H^+ + e^- \rightarrow Fe^{2+} + H_2O$; $FeOOH_{(s)} + 3H^+ + e^- \rightarrow Fe^{2+} + 2H_2O$	<0.5	<0.5	—	≥0.1	≥0.5	>10
Mixed(anoxic)	Fe(III)-SO4	Fe(III) and $SO4^{2-}$ reactions as described in individual element half reactions	<0.5	<0.5	—	≥0.1	≥0.5	≥0.3, ≤10
Anoxic	SO4	$SO_4^{2-} + 9H^+ + 8e^- \rightarrow HS^- + 4H_2O$	<0.5	<0.5	—	≥0.1	≥0.5	<0.3
Anoxic	CH4gen	$CO_{2(g)} + 8H^+ + 8e^- \rightarrow CH_{4(g)} + 2H_2O$	<0.5	<0.5	—	≥0.1	<0.5	

Table 9: Redox assignment output for Waituna bores.

[Redox assignments are based on median values for the 5 main redox species. Threshold values are set according to McMahon and Chapelle, (2008). Where: Redox Process is the principal terminal electron accepting process operating within this groundwater. This assignment does not account for other electron accepting process that may be occurring simultaneously. Where upper GLM denotes some influence from the upper Gore Lignite Measures. Dissolved oxygen (D.O.) concentrations were measured in the field using a Galvanic D.O. probed that was routinely calibrated against a zero D.O. solution and atmospheric pressure].

Sample ID	*Dissolved O_2*	*NO_3^- (as Nitrogen)*	*Mn^{2+}*	*Fe^{2+}*	*SO_4^{2-}*	*Sulfide (sum of H_2S, HS^-, S^{2-})*	**Redox Assignment**		
	0.5	**0.5**	**0.05**	**0.1**	**0.5**	**none**	**General Redox Category**	**Redox Process**	**Fe2+/ Sulfide, ratio**
E47/0079	0.01	0.005	0.22	9.5	5.9		Anoxic	Fe(III)/SO4	
F46/0677	0.45	0.012	0.089	12	6.1		Anoxic	Fe(III)/SO4	
F46/0688	0.42	0.46	0.3	8.5	4.1		Anoxic	Fe(III)/SO4	
F46/0759 (upper GLM)	0.1	0.23	0.4	0.09	9.4		Anoxic	Mn(IV)	
F47/0114	0.48	0.007	0.106	6.8	5.4		Anoxic	Fe(III)/SO4	
F47/0201	0.01	0.023	0.078	26	0.9		Anoxic	Fe(III)/SO4	
F47/0253	0.41	0.067	0.142	3.8	10.8	0.345	Anoxic	Fe(III)	11.01
F47/0256	0.34	0.007	0.069	21	0.25	0.017	Anoxic	CH4gen	
F47/0259	0.01	0.015	0.64	34	8.6		Anoxic	Fe(III)/SO4	
F47/0262 (septic 1)	0.12	0.027	1.35	99	250		Anoxic	Fe(III)/SO4	
F47/0257 (Septic 2)	0.21	0.062	0.56	3.5	76	0.0025	Anoxic	Fe(III)	1400.00
Driven Peizo Waituna East Beach 2 - (3.8 m)	0.25	0.008	0.108	0.05	260		Anoxic	Mn(IV)	
E46/0096 (upper GLM)	0.85	0.001	0.24	7.4	4.7		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
E46/0098 (upper GLM)	2.7	0.007	0.142	5.95	3.25		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
E47/0129	2.3	1.33	0.2	3.25	15.05	0.0185	Mixed(oxic-anoxic)	O2-Fe(III)	175.68
F46/0278	1.2	0.039	0.061	0.01	4.6		Mixed(oxic-anoxic)	O2-Mn(IV)	
F46/0689	3.1	0.005	0.078	0.62	8.6		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0041	3.49	0.001	0.007	7.2	0.25		Mixed(oxic-anoxic)	O2-CH4gen	
F47/0132	0.8	0.01	0.45	6.4	4.8		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0138	2.25	0.001	0.008	5.165	1.425		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0145	0.53	0.183	0.48	0.17	7.2		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0221 (upper GLM)	3.39	0.01	0.09	7.2	6		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0251	4.02	0.67	0.0044	0.13	5.3		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0254	4.945	2.3	0.0097	0.12	17.25		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
F47/0258	2.505	0.1025	0.0042	0.105	7.55		Mixed(oxic-anoxic)	O2-Fe(III)/SO4	
Driven Peizo Waituna East Beach 1 - (0.5 m)	0.65	0.006	0.141	0.05	270		Mixed(oxic-anoxic)	O2-Mn(IV)	
F46/0262	9.9	0.7	0.0169	0.01	5.3		Oxic	O2	
F46/0682	4.5	6.1	0.0023	0.01	36		Oxic	O2	
F46/0693	4.25	1.26	0.0013	0.01	8.1		Oxic	O2	
F47/0086	1.1	3.7	0.0012	0.01	18.4		Oxic	O2	
F47/0142	4.5	13.8	0.026	0.01	22		Oxic	O2	
F47/0148	4.89	9.9	0.039	0.03	22	0.0135	Oxic	O2	
F47/0252	4.06	4	0.023	0.03	10.4		Oxic	O2	

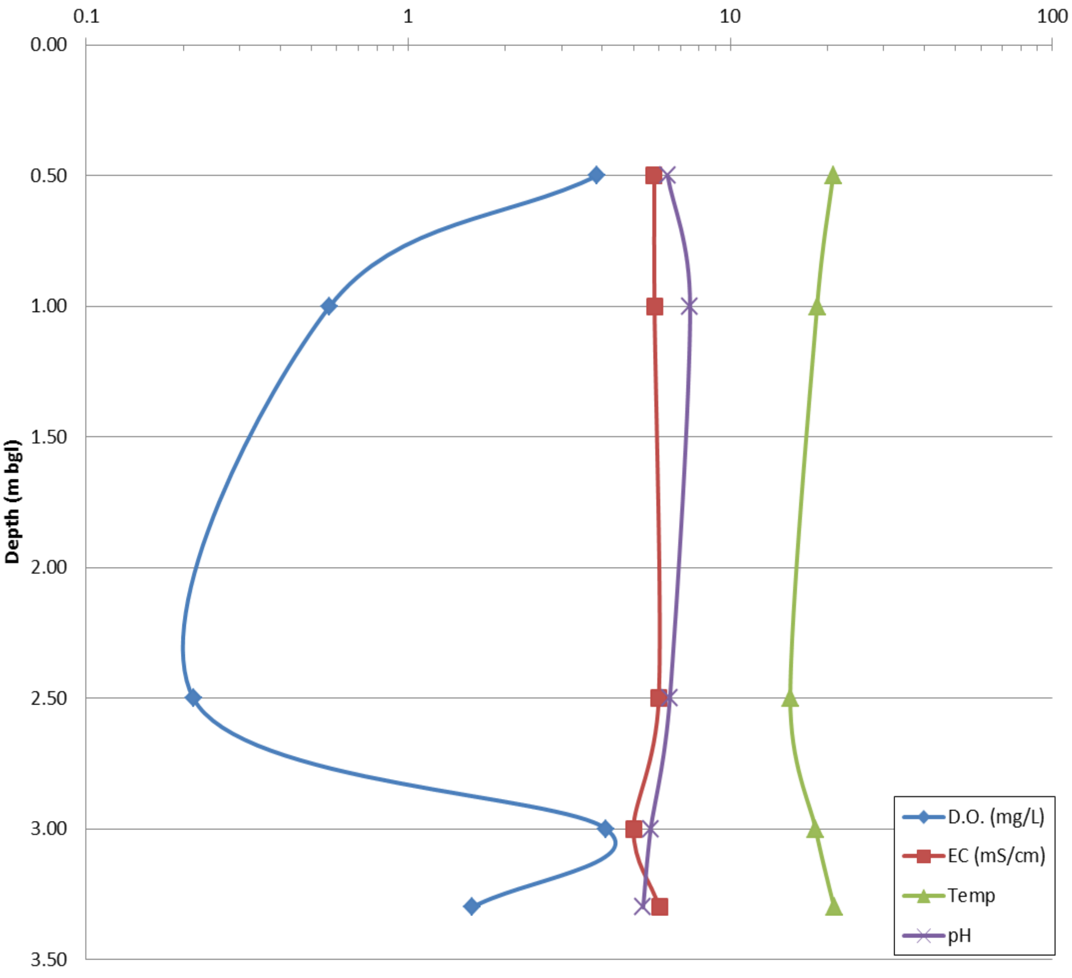

Figure 48: Driven piezometre profile of dissolved oxygen (D.O.) concentration, electrical conductivity (E.C.), water temperature (°C) and pH within a quartz gravel-peat aquifer fringing Waituna Lagoon
[Notes:
1. **Where the horizontal axis is log scaled.**
2. **The large variability in D.O. concentrations with depth.]**

5.9 Drinking Water Standards

Groundwater quality within the Waituna catchment is assessed against the New Zealand Drinking Water Standards (NZDWS). Nitrate (NO_3-N) and *E.coli* (faecal bacteria) pose the greatest risk to human health whereas low pH groundwaters pose a secondary health risk by dissolving toxic metals (copper and lead) from plumbing fixtures and piping. The range of iron (Fe) and manganese (Mn) concentrations typically encountered in groundwaters constitute more of an aesthetic concern (i.e., staining of ceramics (baths, vanities and toilets) and/or laundry and imparting unpleasant taste to the water). Similarly, hydrogen sulphide (H_2S) my impart an unpleasant odour/taste but is not typically a health risk.

Although not normally a drinking water quality issue the concentrations of phosphorous (orthophosphate (PO_4^{-3}), organic and particulate) and ammonium (NH_4-N) are relevant to the ecological concerns surrounding the lagoon.

Of the above contaminants, all but *E.coli* are either redox sensitivity (NO_3, NH_4, Fe, Mn and H_2S) or indirectly influenced by the redox state (PO_4^{-3}). Therefore, in the following a particular emphasis is placed on the effect of redox status on the quality of Waituna groundwaters.

Nitrate (NO_3-N)

Nitrate as nitrogen has a NZDWS limit of 11.3 mg/L. The mean, median and standard deviation for all samples (n = 98) was 1.3, 0.06 and 3.40 mg/L NO_3-N. Proportionately, approximately 82 percent of the groundwaters fell below 1 mg/L NO_3-N which has been assigned as modern day 'background' for Southland groundwaters[26].

Only one bore (F47/0148) exceeded the NZDWS with a NO_3-N value of 13.8 mg/L. Four other bores, sampled between 2011 – 2012, have groundwater NO_3-N values greater than 3.0 mg/L (3.1 – 10.7 mg/L NO_3-N) and are all oxic in nature (D.O. > 2.0 mg/L). Overall, the low NO_3-N concentration of Waituna groundwaters reflects the predominance of reducing conditions within the catchment. Under low oxygen conditions, NO_3 is typically removed via the process of denitrification, a microbially mediated reaction in which NO_3 reduction is coupled to the oxidation of organic carbon and produces N_2 gas and bicarbonate:

$$4NO_3^- + 5CH_2O \rightarrow 2N_{2(g)} + 5HCO_3^-$$

where CH_2O is organic matter and $N_{2(g)}$ is gaseous nitrogen. Groundwater microbes find it difficult to metabolise N_2 gas, which is both relatively inert (non-reactive) and commonly lost from groundwater systems via degassing to the atmosphere. From **Table 10** NO_3-N is approximately 130 (0.03 mg/L) times lower in anoxic and mixed redox state groundwaters relative to oxic (4.0 mg/L) groundwaters. The large difference in NO_3-N concentrations provides strong evidence for the removal of NO_3 under the anoxic and mixed redox state conditions.

The D.O. concentration threshold required for the onset of denitrification has been reported at approximately 2 mg/L but may be even higher in settings with high electron donor availability such as Waituna (Vroblesky and Chapelle, 1994). Mixed redox state groundwaters have a median D.O. concentration of 2.5 mg/L, which falls slightly above the reported threshold but these groundwaters still show evidence for active removal of NO_3. The latter may reflect the onset of denitrification at D.O. concentrations above the 2.0 mg/L threshold, as noted above, and/or periodic redox excursions towards more reducing conditions. Whatever the case, the high proportion (71 percent) of anoxic and mixed redox state groundwaters within the Waituna catchment play an important role in the maintenance of the generally low NO_3-N concentrations via the process of denitrification.

The differences in median concentrations of Total Nitrogen (TN), 0.4 mg/L (anoxic), 0.3 mg/L (mixed) and 5.9 mg/L (oxic), between the three redox categories, also supports the active removal of nitrogen via denitrification within both anoxic and mixed redox state groundwaters (**Table 10**). However, relative to NO_3-N the magnitude of difference between TN concentrations suggests an additional N fraction, for anoxic and mixed redox state groundwaters, likely associated with the generation of NH_4 during the ammonification of buried organic matter (see *Ammonium*).

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[26] Modern day background for NO_3-N of ≤ 1.0 mg/L is typical of 'pristine' sites with no/or little history of intensive land use. These sites include Conservation Estate Reserves, National Parks and forested areas.

In summary, the majority (greater than 90 percent) of Waituna groundwaters exhibit median NO_3-N concentrations far below the NZDWS and ANZECC 95 percent protection trigger value for freshwater of 0.7 mg/L. The low NO_3-N and moderately low TN concentrations reflect the electron donor rich environment (peat, lignite and reduce iron) which favours denitrification and prevents the accumulation of NO_3 and TN to high levels. The groundwaters with the most elevated NO_3-N values occur in groundwaters within the MIZ.

Table 10: Summary statistics of groundwater analytes by redox status for bores less than 20 metres deep.

[Note: EC as specific conductance measured in µs/cm; analyte units in mg/L. Where DIN = Dissolved Inorganic Nitrogen; DON = Dissolved Organic Nitrogen; TDN = Total Dissolved Nitrogen; TP = Total Phosphorus; DRP = Dissolved Reactive Phosphorus; TDP = Total Dissolved Phosphorus; DOP = Dissolved Organic Phosphorous; PP = Particulate Phosphorus. These assignments include four bores influenced by the upper Gore Lignite Measures.]

	Anoxic (n = 9)			Mixed (n = 13)			Oxic (n = 7)		
	Mean	Median	Stdev	Mean	Median	Stdev	Mean	Median	Stdev
Electrical conductivity	258	215	98	270	252	78	259	251	72
pH	6.3	6.3	0.3	6.7	6.5	0.9	6.4	6.2	0.3
Dissolved O_2	0.2	0.3	0.2	2.5	2.5	1.3	4.7	4.5	2.6
Dissolved Mn	0.23	0.14	0.19	0.14	0.08	0.16	0.02	0.02	0.01
Dissolved Fe	13.52	9.50	11.15	3.36	3.25	3.23	0.02	0.01	0.01
Dissolved SO_4	5.72	5.90	3.60	6.61	5.30	4.84	17.46	18.40	10.58
Total Nitrogen	0.74	0.41	0.77	0.70	0.30	0.89	5.90	4.20	4.97
NO_3-N	0.10	0.03	0.16	0.35	0.03	0.68	5.60	4.00	4.70
NH_4-N	0.41	0.12	0.64	0.08	0.04	0.10	0.01	0.01	0.01
DIN	0.50	0.13	0.63	0.43	0.17	0.66	5.61	4.02	4.70
DON	0.24	0.18	0.25	0.18	0.08	0.24	0.29	0.18	0.29
TP	0.12	0.10	0.09	0.15	0.10	0.22	0.02	<0.004	0.03
DRP	0.043	0.013	0.078	0.031	0.021	0.032	0.008	<0.004	0.014
TDP	0.070	0.056	0.079	0.014	0.010	0.019	0.009	<0.004	0.017
DOP	0.021	.	0.033	0.002	.	0.003	0.001	.	0.002
PP	0.052	0.032	0.055	0.165	0.042	0.280	0.010	.	0.017
Na+	27.1	23.0	10.6	30.1	26.5	11.3	23.7	19.0	10.0
K+	1.3	1.1	1.0	1.9	1.2	2.0	8.3	3.5	8.4
Ca++	10.5	9.5	5.5	11.5	8.9	10.2	22.3	21.0	11.3
Mg++	5.5	5.1	2.6	5.2	5.5	1.9	4.3	3.7	2.0
Cl-	44.1	36.0	24.3	44.3	39.0	21.7	43.1	32.0	26.9
I-	0.015	0.006	0.013	0.011	0.006	0.011	0.004	0.002	0.006
Br-	0.21	0.16	0.18	0.19	0.13	0.11	0.23	0.14	0.23
Total Alkalinity	48.6	53.0	14.5	45.8	32.5	38.6	39.5	44.0	14.0
HCO_3 Alkalinity	48.6	53.0	14.5	45.8	32.5	38.6	39.5	44.0	14.0
Dissolved Organic Carbon	9.8	9.8	.	3.3	2.3	3.2	3.2	2.7	1.9

Ammonium (NH_4-N)

Nitrogen in the form of NH_4 is readily converted to NO_3 in the presence of oxygen and is therefore a risk to both human and environmental health (Rosen, 2001). Within the groundwaters of the Waituna catchment, significant median NH_4-N concentrations (i.e. more than 0.1 mg/L) occur in 34 percent of the bores sampled with a maximum median NH_4-N concentration of 1.85 mg/L. The source of the NH_4 has not previously been assessed for the Waituna catchment but likely reflects the ammonification of organic matter under reducing conditions within peat and lignite aquifers. Ammonification of buried organic matter is typical of peat wetland aquifers (Rosen et al., 1998; Eser and Rosen, 1999) and has been noted as a dominant process responsible for the elevated NH_4 of groundwaters within the confined Tertiary lignite aquifers of the region (Rekker, 1994; 1996). As expected, all of the bores with elevated NH_4 exhibit either mixed or anoxic redox states.

Another pathway by which NH_4 may accumulate is via dissimilatory nitrate reduction (DNRA) where NO_3 is converted to NH_4 under reducing conditions. However, DNRA is a rare process within groundwater systems (McMahon and Chapelle, 2008). If DNRA was to constitute a significant pathway the conversion of NO_3 to NH_4 should result in the conservation of nitrogen within the aquifer. Therefore, if DNRA were a significant process occurring within Waituna groundwaters we would not expect to see the significant decrease in TN that occurs within anoxic and mixed redox state groundwaters.

E.Coli

Only three bores exceeded the NZDWS (less than 1 MPN) for faecal bacteria (*E.coli*) and only one bore (F47/0148) had an elevated NO_3-N concentration. The other two bores containing elevated *E.coli* counts exhibit anoxic or mixed redox state conditions, which as observed above are sufficiently reducing for NO_3 to be removed via the process of denitrification. Of the *E.coli* contaminated bores, all were of a diameter of 300 mm or greater. Rekker (1998) in a study of the Oteramika Catchment, Southland, noted a similar relationship between larger diameter wells and both faecal and nitrogen contamination. On this basis, exclusion of contaminants infiltrating to depth may be remedied by better wellhead protection.

Iron and Manganese

The NZDWS place aesthetic limits of 0.2 and 0.05 mg/L for iron (Fe) and manganese (Mn), respectively. When assessed against the NZDWS approximately 71 percent and 68 percent of Waituna groundwaters exceed the guideline values for Fe and Mn, respectively. The high levels of both Fe (up to 34 mg/L) and Mn (up to 0.64 mg/L) reflect the predominance of anoxic and mixed redox conditions under which Fe and Mn are highly soluble. The range of Fe and Mn concentrations do not pose a health risk but do constitute an aesthetic issue. Dairy sheds within the catchment utilise either a sand bed aeration filter system to firstly precipitate and then filter out Fe. Other systems precipitate out excess Fe by chemical dosing prior to filtration.

By redox category, the median Fe concentrations are approximately 950 (anoxic) and 325 (mixed) times higher than oxic groundwaters. A less extreme pattern is evident for median Mn concentrations, with anoxic and mixed groundwaters approximately 8 and 3 times greater than equivalent oxic groundwaters. The similarity in median Mn concentration between anoxic and mixed redox state groundwaters reflects the higher free energy associated with Mn(IV) reduction relative to Fe(III) reduction, and results in the onset of Mn(IV) reduction under less reducing conditions (**Figure 47**).

Again, although Fe(III) reduction is the principal TEAP, elevated median Mn concentrations indicate simultaneous Mn(IV) reduction is also occurring. A progression towards more reducing conditions where SO_4 or CO_2 are the TEAP appears to be buffered by the large mass of iron oxides and oxy hydroxides associated with aquifer materials.

Phosphorus

After removal of a septic tank contaminated groundwater sample (TP and DRP of 610 and 590 mg/L, respectively) the median Total Phosphorus (TP), Total Dissolved Phosphorus (TDP) and DRP concentrations for all samples and all bores are 0.069, 0.011 and 0.009 mg/L, respectively.

Importantly, for TP approximately 65 percent of sample medians exceed the ANZECC 95 percent protection trigger value for freshwater of 0.033 mg/L. Dissolved Organic Phosphorus (DOP = TDP – DRP) and the Particulate Phosphorus (PP = TP – TDP) fractions were calculated for each groundwater sample. From the calculations, DOP constitutes only a very minor fraction (mean of less than 0.001 mg/L) with only one groundwater exhibiting an elevated value of 0.08 mg/L. Conversely, PP returns a median concentration for Waituna groundwaters of 0.04 mg/L and constitutes approximately 50 percent of the phosphorus loads within Waituna groundwaters.

Although DRP is naturally more soluble under reducing conditions it is difficult to assign the elevated concentrations of DRP and TP to solely natural or anthropogenic sources. For instance, groundwaters from the confined Gore Lignite Measures contain naturally elevated phosphate concentrations (**Table 11**) and may contribute to the elevated concentrations within the overlying unconfined aquifer system. For example, bores F46/0688 and F46/0689 within the northern groundwater zone occur in close proximity to the Gore Lignite Measures and exhibit elevated TP concentrations but relatively low DRP concentrations. A similar phosphate pattern for groundwaters influenced by the Gore Lignite Measures is evident in **Table 11**. Therefore, regionally TP may be elevated due to contributions from lignite measures.

However, evidence exists for diffuse and point source anthropogenic phosphate inputs from the soil zone to unconfined aquifers within the southern portion of the catchment. A point source input of phosphate from a septic system was detected during the sampling of bore F47/0262, within 15 metres of the septic disposal trenches, returned a record DRP value of 59,000 times (590 mg/L) the ANZECC guidelines for Lowland Streams (i.e., 0.01 mg/L DRP) (**Table 12**). Bore F47/0262 is screened at a depth of 8.9 metres suggesting that effluent phosphate has migrated a considerable distance from the outfall trench/soak pit.

Table 11: Summary statistics of nutrients with the Gore Lignite Measures bores (n = 9).
[Note: Nutrients reported as mg/L. Bores have a median depth of 49 m]

Summary Statistics	Mean	Median	Standard Deviation	Minimum	Maximum	Range
Total Nitrogen	0.36	0.05	0.51	0.05	1.23	1.18
Nitrate Nitrite Nitrogen	0.05	0.01	0.08	0.01	0.23	0.23
NO3-	0.04	0.01	0.08	<0.01	0.23	0.23
NH4+	0.07	0.06	0.08	0.01	0.23	0.23
Mn++	0.33	0.24	0.20	0.14	0.64	0.50
Fe++	10.1	7.2	10.9	0.1	34.0	33.9
SO4--	6.1	5.9	2.2	3.3	9.4	6.2
TP	0.11	0.10	0.03	0.08	0.15	0.08
DRP	0.05	0.04	0.04	<0.004	0.09	0.09

Enhanced phosphate mobility is an important feature of anoxic Fe/Mn-rich groundwaters with many researchers noting the development of groundwater phosphorus plumes (as ferrous or manganous phosphate colloids) within reducing groundwaters beneath septic disposal systems (Gschwend and Reynolds, 1987; Robertson et al., 1998; Robertson, 2008). Therefore, under reducing conditions where elevated Fe and/or Mn concentration occur, phosphate is both more soluble and mobile than under typical oxic conditions. Mineral saturation indices calculated for septic outfall contaminated groundwaters within the Waituna catchment show saturation with respects to $MnHPO_4$(c) (log Q/K = 0.294 to -0.024) but were under saturated with respects to iron phosphate minerals (vivianite type: $Fe_3(PO_4)_2 \bullet 8(H_2O)$; log Q/K = -2.773 to -4.469).

Table 12: Summary statistics (n = 6 samples) of septic tank groundwater from well F47/0262.

[Note: dissolved organic carbon was only measured once. Where HPO$_4^{--}$ = DRP]

	Mean	Median	Standard Deviation	Minimum	Maximum
Electrical conductivity	7000	6820	823	6230	8420
pH	5.3	5.8	1.6	2.1	6.4
O2	0.2	0.1	0.1	0.0	0.5
Total Nitrogen	5.2	1.1	9.2	1.0	24.0
Nitrate Nitrite Nitrogen	0.15	0.13	0.11	0.06	0.35
NO3-	0.03	0.03	0.02	0.00	0.06
NH4+	0.07	0.02	0.11	0.01	0.30
TP	104	2	248	1	610
HPO4--	98.3	0.002	241	0.002	590.0
Mn++	1.5	1.3	0.6	1.1	2.6
Fe++	151	103	143	52	440
Na+	1082	1155	216	670	1260
K+	10	11	1	8	11
Ca++	102	110	18	67	115
Mg++	160	166	30	108	189
Cl-	2370	2550	490	1520	2900
SO4--	318	225	213	187	740
HCO3-	34	27	31	1	82
I-	0.014	0.011	0.009	0.010	0.032
Br-	7.0	7.5	1.9	3.7	9.0
Total Alkalinity	34	27	31	1	82
Carbonate Alkalinity	<1	<1	.	.	.
Dissolved Organic Carbon	19	19			
Dissolved solids	4331	4351	333	3828	4817

The direct leaching of soil zone DRP to groundwaters was also noted during event sampling and raises the possibility of widespread diffuse phosphate inputs from fertiliser and effluent derived phosphate inputs (**Figure 44**). This preliminary data from the Waituna catchment supports the general view that organic soils are poorly able to retain mineral phosphate inputs from animal wastes and fertiliser-phosphate and that phosphate is far more mobile under the reducing conditions that predominate within unconfined southern aquifers.

Therefore, elevated phosphate concentrations within Waituna groundwaters are likely derived from two sources:

- soil zone anthropogenic inputs from animal and human effluent and fertiliser phosphate, and;
- naturally occurring phosphate inputs from lignite measure aquifers.

In terms of nutrient loads, the recognition that organic soils are particularly leaky with respects to phosphate and that phosphate mobility is enhanced within reducing groundwaters has important implications for the Waituna catchment. Further work is required to ascertain the magnitude of anthropogenic, soil zone inputs to the elevated phosphate loads of southern groundwaters.

pH

The NZDWS specify a desirable pH range of 7.0 – 8.5 for potable groundwaters. Of the Waituna groundwaters only 8 percent fall within this range, the vast majority exhibiting pH (field and laboratory) values below 7.0 (range of: 5.4 – 8.5 pH units) with 65 percent falling below a pH of 6.5[27]. The prevalence of slightly acidic groundwaters is consistent with young groundwaters recharged by naturally acidic rainwater, high organic carbon concentrations (weak organic acids) and low acid buffering capacity of weather soils and relatively inert lithologies.

If used as a potable water source the acidic nature of Waituna groundwaters may cause the leaching of metal ions such as: copper, lead, and zinc from plumbing fixtures. Low pH values also enhance the solubility of Fe and Mn within groundwater aquifers along with toxic metals such as arsenic (As). The limited As data for the Waituna catchment indicates minimal risk.

5.10 Groundwater Quality Summary

As a whole, the groundwater quality of the Waituna catchment is of good quality with respects to regional norms and natural background thresholds for NO_3-N but of poor quality with respects to phosphate. Spatially, groundwater quality transitions from nitrogen poor in the north to nitrogen-enriched around the MIZ (**Figure 46**). South of Mokotua groundwaters revert to nitrogen poor but are phosphate enriched possibly due to the leakiness of organic soils to fertiliser, animal and human effluent phosphate as well as naturally elevated concentrations from lignite measures.

Table 13: Summary statistics of nutrients by catchment zone
[Note: Nutrients reported as mg/L. Where MIZ = Mokotua Infiltration Zone; Std.Dev = Standard Deviation. Statistics calculated after exclusion of lignite bores and septic tank outliers.]

Nutrient Forms	Northern			MIZ			Southern		
	Mean	Median	Std.Dev	Mean	Median	Std.Dev	Mean	Median	Std.Dev
Total Nitrogen	1.5	0.5	2.5	5.7	4.0	5.5	1.2	0.9	1.1
Nitrate Nitrite Nitrogen	1.4	0.4	2.4	5.4	3.9	5.4	0.5	0.1	0.8
NO3-	1.4	0.4	2.4	5.3	3.9	5.3	0.5	0.1	0.9
NH4+	0.03	0.01	0.05	0.02	0.02	0.01	0.41	0.08	0.69
TP	0.05	0.05	0.05	0.03	0.02	0.03	0.10	0.05	0.13
DRP	0.011	<0.004	0.022	0.011	0.007	0.014	0.039	0.012	0.081

NO_3-N concentrations are particularly low, however this reflects the unusually high proportion of reducing groundwaters within the catchment due to an abundance of organic carbon associated with wetland soils, interbedded peat and gravel aquifers and to a lesser extent shallow outcrops of lignite measures. Due to the abundance of reducing conditions, NO_3-N infiltrating from the soil zone, is quickly removed via denitrification, which prevents the accumulation to high levels within the majority of Waituna aquifers.

However, across the MIZ where groundwaters are not reducing and/or where soils are particularly permeable, the impact of intensive land use is evident in concentrations of NO_3-N that exceed the modern day background for the Southland region by up to 13.8 times. Of particular note, are the elevated NO_3-N concentrations that occur within oxidised groundwaters beneath the MIZ. Here, soil zone waters infiltrate rapidly with little if any attenuation of contaminants before they discharge as base flow to the Waituna Creek.

Although reducing conditions favour the active removal of NO_3-N in the majority of Waituna groundwaters, the same conditions favour the accumulation of phosphate to high

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[27] The normal range for pH in groundwater systems is 6.5 to 8.5.

concentrations. This paradox is well illustrated by median TP concentrations for shallow (less than 20 metres) groundwaters that are 50 - 30 times higher for reducing (anoxic and mixed redox state groundwaters) groundwaters relative to their oxidised counterparts.

The limited phosphate-retention of organic soils and reducing conditions within the majority of Waituna aquifers raises the possibility that southern groundwaters are particularly susceptible to contamination by soil zone phosphate. Groundwater sampling shows some evidence for phosphate contamination by both intensive land use and domestic septic systems. However, further work is required to both discriminate between anthropogenic and natural sourced phosphate inputs (lignite measures).

6. Mass Flows and Nutrient Loads

Within this section the relative significance of groundwater mass flows (volume of water) occurring as base flow to Waituna Creek and as direct seepage to the lagoon is assessed. From these physical estimates nutrient loadings from groundwater occurring as base flow and direct seepage to the lagoon are calculated. Groundwater nutrient loads are then contrasted with estimates made for surface water inputs.

Groundwater nutrient inputs to the Waituna Lagoon catchment occur via two primary pathways; base flow to Waituna Creek and direct seepage inflow to Waituna Lagoon.

Base flow nutrient loadings

As described in **Section 5**, groundwater quality varies across the Waituna catchment reflecting a combination of soil types, geology and geochemical factors. The following section provides a basic assessment of potential groundwater nutrient inputs to Waituna Stream via base flow discharge in the three water quality zones described in **Section 5.7**.

In order to estimate groundwater nutrient loadings to Waituna Stream, the relative base flow contribution from the northern groundwater zone, the MIZ and the southern groundwater zone were estimated from the available concurrent gauging data. These data were collected during December 2011 and February 2012 during periods of stable flow recession when virtually all catchment discharge was derived from base flow[28]. The relative base flow contribution from each zone was estimated by comparing the measured change in discharge across each zone[29] with flow recorded at the Marshall Road recorder site, averaged over the four concurrent gauging runs. Annual base flow discharge in each zone was then calculated by multiplying the median discharge at Marshall Road by the calculated base flow index of 0.48 and the relative base flow contribution for each zone.

Table 14: Estimated groundwater nutrient loadings to Waituna Creek.
[Note: MIZ = Mokotua Infiltration Zone. The reported ranges are based on the measured median and mean groundwater nutrient concentrations reported in Table 13. Where the mean and median value are the same only one value is reported.][30]

Zone	Base flow Contribution (%)	Base flow (ML/ year)	Total Nitrogen (kg/year)	Nitrate (kg/year)	Ammonia (kg/year)	Total Phosphorus (kg/year)	DRP (kg/year)
Northern	37	5.10	2,548 – 7,650	2,039 – 7,140	51 - 153	255	10 - 56
MIZ	20	2.75	11,020 – 15,390	10,744 -14,580	55	55 - 83	19 - 30
Southern	43	5.92	5,331- 7,104	592 – 2,960	474 – 2,427	296 - 592	71 - 231
Total	100	13.77	18,899 – 30,144	13,375 – 24,680	580 – 2,635	606 - 930	101 - 317

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[28] Analysis using the *Basejumper* program (see **Section 4.1**) indicates >95 percent of stream flow was derived from base flow when the gaugings were undertaken

[29] Nominally Northern Zone = cumulative discharge upstream of Waituna Road/Kapuka North Road
MIZ = change in discharge between Waituna Road/Kapuka North Road and Hansen Road
Southern Zone = change in discharge between Hansen Road and Marshall Road

[30] It is important to also note that the median TP concentrations calculated for both the unconfined and confined aquifers are similar.

For annual load calculations, the use of mean groundwater concentrations were considered most appropriate as it is the sum of all the nutrient that will enter the lagoon or stream over a year that is required. However, for sake of conservatism both median and mean groundwater nutrient concentrations were used in the calculations of estimated groundwater nutrient loadings in **Table 14**.

Overall, analysis of base flow discharge indicates significant inputs of TN to Waituna Creek, particularly through the middle reaches of the catchment (Mokotua Infiltration Zone). Ammonia loadings are generally low but increase significantly in the vicinity of Waituna Lagoon reflecting the shift from generally oxidising groundwater in the northern groundwater zone and MIZ to reducing groundwaters in the southern groundwater zone. In terms of phosphorus loadings, TP and DRP inputs are higher in the southern groundwater zone, perhaps reflecting both the general leakiness of organic soils to fertiliser and effluent phosphorus and its enhanced mobility under reducing conditions as well as contributions of TP from lignite measure aquifers.

However, further resolution over the source of seepage, unconfined aquifer or confined lignite measures, is required before the origins of phosphorus loads can be confidently assigned. If phosphorus is derived primarily from the lignite measures there is very little that can be done to remedy the situation. If on the other hand direct seepage from the lagoon contains an appreciable phosphorus component from the confined aquifer then land use management practices may be important to reducing the overall input of phosphorus to the lagoon.

Groundwater seepage nutrient loadings

Seepage measurements described in **Appendix 1** indicate direct groundwater inflow (seepage) to Waituna Lagoon is a relatively significant component of the overall lagoon water balance. Estimates of the overall groundwater seepage rate range between 340 to 460 L/s, an unknown (but assumed to be relatively significant) quantity of which is assumed to represent upward (diffuse) leakage from confined aquifers hosted within the Gore Lignite Measures.

Table 15 provides an estimate of nutrient loadings to Waituna Lagoon occurring via direct groundwater (seepage) inflows. This assessment assumes that overall nutrient concentrations in the confined aquifers are similar to those observed in the southern groundwater zone. Again, median and mean nutrient concentrations were used for southern groundwaters according to **Table 13**. Future estimates of nutrient contribution to Waituna Lagoon will be further refined by analysis of seepage water quality.

Table 15: Groundwater nutrient loadings to Waituna Lagoon via seepage inflow cumulative groundwater nutrient loadings

[Where the reported ranges for low and high seepage estimates are based on the median – mean nutrient concentrations, respectively for southern groundwaters reported in Table 13.]

Seepage Estimate	Inflow (ML/year)	Total Nitrogen (kg/year)	Nitrate (kg/year)	Ammonia (kg/year)	Total Phosphorus (kg/year)	DRP (kg/year)
Low	10.67	9,606 – 12,804	1,067 – 5,335	854 – 4,375	534 – 1,067	128 - 416
High	14.59	13,132 – 17,508	1,459 – 7,295	1,267 – 5,982	730 – 1,459	175 - 569

Table 16 provides an estimate of the cumulative groundwater nutrient contribution to Waituna Lagoon (based on the mean seepage value). These figures indicate that groundwater contributes between 28 and 48 tonnes of TN to Waituna Lagoon per year, of which approximately 30 to 40 percent is derived from base flow in the MIZ. The TP input from

groundwater is estimated at approximately 1,434 to 2,389 kg/year of which around 40 to 60 percent is sourced from direct groundwater seepage into the lagoon.

When compared to estimated surface water nutrient loadings (Diffuse Sources and NIWA, 2012), the figures in **Table 16** suggest that groundwater inputs may contribute between approximately 11 to 18 percent of the cumulative TN and 10 to 15 percent of the cumulative TP loadings to Waituna Creek.

Table 16: Estimated total groundwater nutrient contribution to Waituna Lagoon[31]

Source	**Total Nitrogen (kg/year)**	**Nitrate (kg/year)**	**Ammonia (kg/year)**	**Total Phosphorus (kg/year)**	**DRP (kg/year)**
Base flow Waituna Ck.	18,899 – 30,144	13,375 – 24,680	580 – 2,635	606 - 930	101 - 317
Seepage (low)	9,606 – 12,804	1,067 – 5,335	854 – 4,375	534 – 1,067	128 – 416
Seepage (high)	13,132 – 17,508	1,459 – 7,295	1,267 – 5,982	730 – 1,459	175 - 569
Totals (lowest – highest)	**28,505 – 47,652**	**14,442 – 31,975**	**1,434 – 8,617**	**1,140 – 2,389**	**229 - 886**

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[31] It is important to note that the above nutrient ranges reflect a realist estimate based on currently available data. As such, some of the uncertainties inherent in current estimates include the magnitude of baseflow and seepage flux as well as representativeness of groundwater quality data.

7. Uncertainties

The work completed to date has identified a number of uncertainties, which provide a basis for identifying areas requiring further investigation. These include:

- the overall magnitude of key components of the catchment water balance including groundwater recharge, base flow and direct seepage to Waituna Lagoon;
- the physical extent of the MIZ and its significance with respects to surface water quality and NO_3-N loads to Waituna Creek;
- the source of elevated phosphate in southern groundwaters including the possibility that winter grazing on organic soils and septic tank outfalls play an important role in the elevated phosphate concentrations in southern groundwaters and ultimately the Waituna Lagoon;
- whether discharge of low TN groundwaters from the southern sector of the catchment plays an important role in diluting NO_3-N rich inputs to the Waituna Lagoon from the surface water network;
- the role of seasonality (recharge events) in soil zone contaminant loss to groundwater across the MIZ and other sectors of the catchment;
- the origins of direct groundwater seepage into the lagoon (i.e. from the unconfined or confined aquifer system). The latter has significance as to the source of phosphate from direct seepage to the lagoon and ultimately how phosphate may best be managed; and
- additional monitoring of the role artificial opening of the lagoon has over groundwater inflows (and associated nutrient loading) as direct seepage and stream base flow.

8. Summary and Recommendations

The Waituna Lagoon and sea are the receiving environments for both groundwater and surface water inflows. This report has examined the groundwater relationships of the Waituna catchment including the physical and chemical hydrology of the groundwater resource to the lagoon and surface water network. From these relationships, an estimate of the contribution of nutrients sourced from groundwater has been provided. The focus has been on Waituna Creek as the relatively minor role (less than 20 percent) of both Moffat Creek and Carran Creek in nutrient loading into the lagoon. However, the findings of this report and the following recommendations have potential implications for the water quality of both of these small tributaries.

The results of the characterisation program are best summarised through the segregation of the Waituna catchment into three groundwater zones according to areas of distinct soil and aquifer types and hydrogeological (physical and chemical) properties, specifically:

1. ***Northern Waituna Zone***

   The northern section of the Waituna Creek catchment (north of Mokotua) has relatively good groundwater quality compared to regional norms due to a combination of factors including the presence of thick, stone less, mineral brown soils. The soils buffer groundwater in this area from the effects of intensive land use due to cation exchange and chemical sorption processes which are aided by a long mean residence times (months) within the unsaturated zone (soil and unsaturated sediments above the water table). Excluding tile drainage, which is elevated in nutrients, shallow aquifers across this zone show little impact from intensive land use;

2. ***Mokotua Infiltration Zone***

   A zone of rapid infiltration in the Waituna Creek catchment between Mokotua and Caesar Road, associated with the reworking of soil and aquifer materials during a former sea level high stand during the last interglacial period (~70,000–100,000 years ago). Across this area, groundwater quality is poor due to the rapid infiltration of soil water with little or no attenuation of soil zone contaminants from intensive land use. The movement of water through the unconfined aquifer within the Mokotua Infiltration Zone (MIZ) is rapid (1-2 week mean residence time) and appears to contribute to the deterioration in the water quality of Waituna Creek south of Mokotua.

3. ***Southern Waituna Zone***

   The southern, predominately wetland portion of the catchment, extends south of Caesar Road to the Waituna Lagoon and includes both the Moffat and Carran Creek catchments. This area is dominated by reducing groundwater conditions due the abundance of organic carbon associated with wetland peat deposits and to a lesser extent lignite measures. Recharge to shallow groundwater systems in this zone occurs relatively rapidly via the soil profile.

Although naturally reducing conditions prevent the build-up of nitrate (NO_3-N)[32], median TP concentrations in reduced southern groundwaters are up to 50 times higher than oxic redox state groundwaters occurring in the north. The elevated phosphate within these groundwaters likely reflects both the leakiness of phosphate from organic soils, the naturally higher solubility and mobility of phosphate under reducing conditions and a potentially significant phosphate input from the underlying lignite measure aquifers. Although there is some evidence for anthropogenic phosphate contamination of southern groundwaters due to diffuse soil leaching and localised septic inputs, further work is required to ascertain the magnitude of anthropogenic sources in this sector of the catchment.

4. ***Direct groundwater seepage into Waituna Lagoon***

Direct groundwater seepage into the Waituna Lagoon was estimated at between 340 to 460 litres per second (L/s). While seepage measurements indicate a relatively significant volume of groundwater seepage inflow into Waituna Lagoon, the relative contribution of discharge from the unconfined aquifer versus diffuse leakage from the underlying lignite measure aquifers is unknown. From median nutrient values[33], it is estimated that groundwater contributes between 28 and 48 tonnes of TN to Waituna Lagoon per year, of which approximately 30 to 40 percent is derived from base flow in the MIZ. The TP input from groundwater is estimated at approximately 1,434 to 2,389 kg/year of which around 40 to 60 percent is sourced from direct groundwater seepage into the lagoon.

Collectively, the findings of this report indicate that groundwater plays a minor, albeit important role, in the transport of nutrient loads into the Waituna Lagoon. When compared to estimated surface water nutrient loadings (Diffuse Sources and NIWA, 2012)[34] groundwater inputs may contribute approximately 11 to 18 percent of the cumulative TN and 10 to 15 percent of the cumulative TP loadings to Waituna Creek.

Implications of management of nutrients to the Waituna Lagoon

Bearing in mind the above uncertainties (**Section 8**), the general findings of this report allows some assessment of how to most effectively target catchment management in order to limit or reduce nutrient loads to the Waituna Lagoon. Catchment management should recognise different parts of the catchment behave differently and therefore we recommend management responses are targeted to higher risk areas, specifically:

- current land use activities across the MIZ may constitute a relatively high risk to water quality in Waituna Creek and appropriate intervention within this zone may yield a disproportional improvement in the surface water quality of Waituna Creek and ultimately the Waituna Lagoon;

- phosphorus is both prone to leaching and of higher mobility within the southern Waituna zone due to a combination of the presence of organic soils and the low oxygen (reducing)

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[32] The median NO_3-N concentration of <0.03 mg/L for southern groundwaters falls far below the natural background for Southland of ~1 mg/L.

[33] It is acknowledged that the relative contribution from the confined aquifer system to direct seepage is currently unknown. However, median TP concentrations for both the unconfined and confined aquifer systems are similar.

[34] Calculation of the groundwater baseload contribution to Waituna Creek is based on median values given in Table 8.2 within the Diffuse Sources and NIWA (2012) report.

conditions. Accordingly, the implementation of phosphate loss management strategies across this portion of the catchment may be of value, and;

- groundwater base flow to Waituna Creek in the northern zone of the catchment likely maintains relatively good water quality in Waituna Creek, due to the thick mineral brown soils, except for during heavy rainfall events when surface runoff and artificial drainage is significant. The most effective land management response will therefore relate to potential contamination from overland flow and artificial drainage.

Future research priorities

The information included within this report will inform the Waituna Lagoon management response and will provide important groundwater information for the Waituna Catchment Technical Group whose role includes identifying scientific research priorities for the wider Waituna catchment. Notwithstanding this, the authors of this report consider the understanding of groundwater and its role in over nutrient loading to the Waituna Lagoon would benefit from additional investigation into the following:

1. ongoing monitoring of the groundwater resource to improve characterisation of the spatial and temporal variability of key water balance and water quality inputs;

2. further work to understand the links between the confined and unconfined aquifer systems in terms of the contribution of each to nutrient loads occurring as direct seepage and base flow;

3. an assessment of the role of land based application of phosphate over the elevated phosphate concentrations in southern groundwaters and ultimately phosphate loads to the Waituna Lagoon;

4. refinement of the nature and extent of the high permeability MIZ along with the recharge frequency, contaminant range and magnitude of groundwater nutrient inputs from the MIZ to Waituna Creek;

5. further seepage monitoring under winter time conditions to assess the role of relative groundwater head over direct groundwater seepage rates and nutrient fluxes to the lagoon.

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Appendices

Appendix 1: Benthic Flux Chambers Methodology

Flux Chambers

The benthic flux chambers utilised in this study consisted of a galvanised steel cylinder, shown in Figure A1. The cylinder was open at one end and the other capped with a shallow cone to which a threaded tube was welded. The footprint of each chamber is 0.2826 m^2.

A commercially available brass two-way tap was subsequently screwed onto the threaded tube. An alkathene 25mm to 10mm reduced pipe fitting was then attached to one side of the tap via a short length of plastic tubing. The larger end of the pipe fitting was wrapped in amalgamation tape so as to increase the width and create a smooth surface to which a condom could be attached and a water tight seal created.

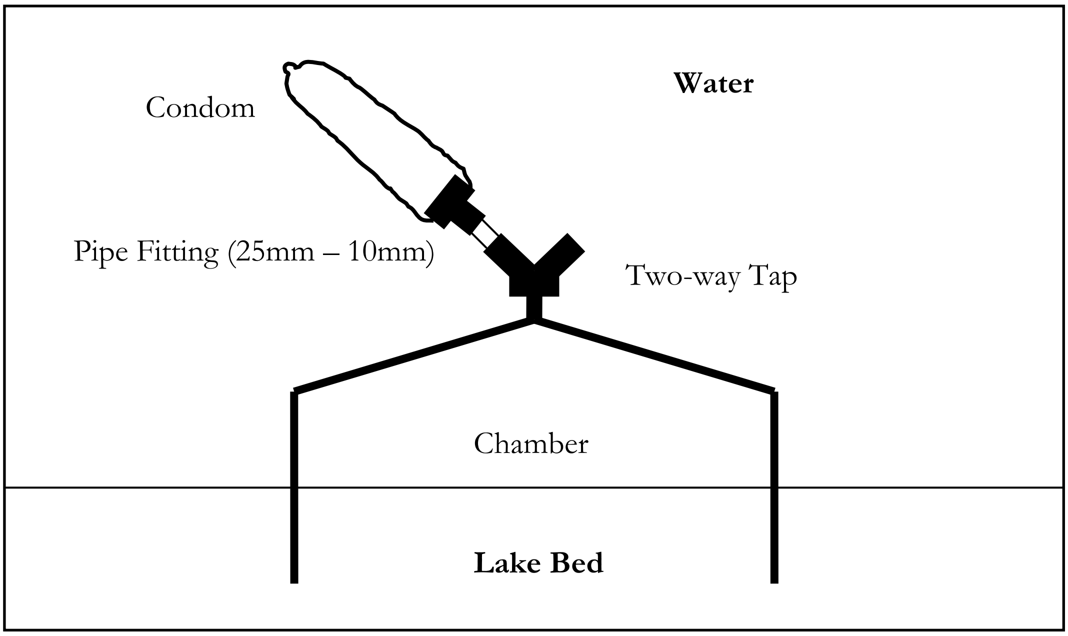

Figure A1: Benthic flux chamber

Condoms were used as they are cheap, easy to apply and relatively small. This was an important feature in an effort to keep the collection bag (condom) fully submerged so as not to alter the piezometric head in the chamber and surface water; especially in the shallow margins of the lagoon where the chambers were deployed.

Installation and seepage measurement

The benthic flux chambers were deployed at two sites in Waituna Lagoon, one at the eastern end and the other near the western end. The sites were selected based on differences in lake bed composition and the recorded sensitivity of groundwater level to lake level fluctuations from piezos located near each site. The western end showed relatively high sensitivity in comparison to the eastern end of the lagoon.

The chambers were first deployed at the eastern end in a cluster of 10. The chambers were set out in three offset lines roughly 10 metres apart with each chamber 10 metres from the next as shown in Figure A2. The first chamber was installed close to 20m offshore where sufficient depth was attained. At the western site a cluster of 9 chambers was deployed. The chambers were set out in two offset lines following the same 10 m spacing as the eastern site with the first chamber set 10 m offshore.

Installation of the chambers involved a mixture of digging and pressing the chambers into the lake bed using a turning and rocking motion with the taps removed or opened. At both sites the chambers were left to equalise and settle for a minimum period of 24 hrs in order for installation effects to subside and pressures both in and outside of the chambers to equilibrate.

Once the chambers were in place and equalised, measurements were then collected. Condoms were placed over the end of the pipe fitting and the air was subsequently drawn out and the tap closed sealing the space within the pipe fitting and condom. The opposing tap was left on whilst the tap was attached to the chamber. Once all the chambers were set this way they were then turned on by first closing the open tap and then opening the tap with the condom attached, the time of opening was recorded.

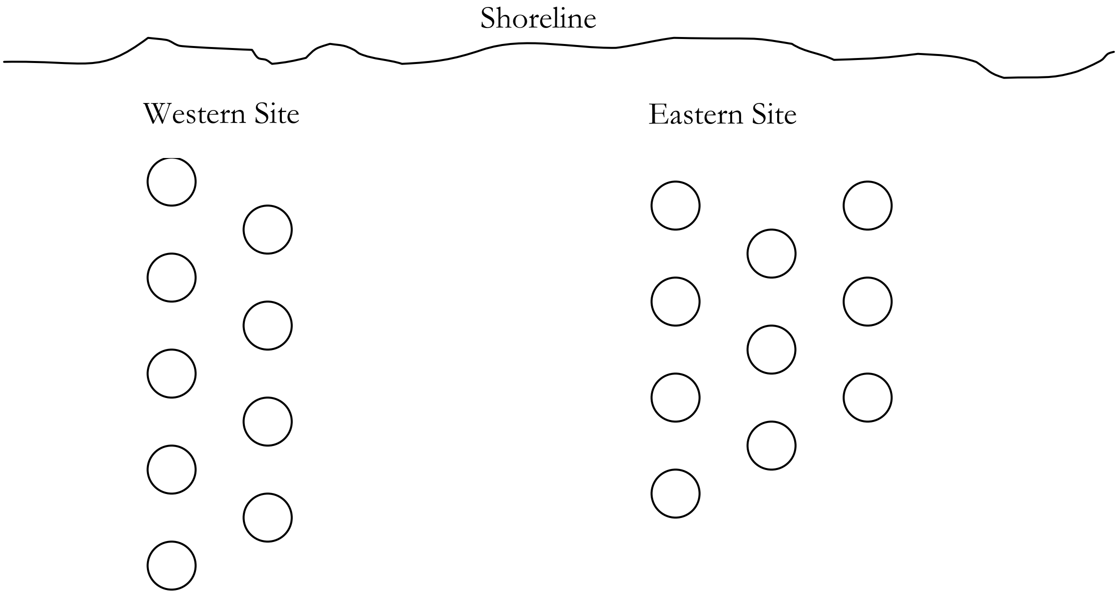

Figure A2: Chamber set out at western and eastern sites. Approximate spacing of 10 m using GPS coordinates.

The seepage rates at the eastern site were low as a result measurements were collected at roughly 24 hr periods. In contrast the western site produce relatively high seepage rates and measurements were collected at periods ranging from 3 hours to 50 minutes.

In order to collect the seepage measurements the tap connected to the condom was turned off and the entire unit removed from the chamber. The water contained inside the condom and pipe fitting was then transferred into a plastic bottle using a purpose built pipe and fitting in order to avoid spillage.

The time at which the tap was turned off was recorded on the plastic bottle along with the chamber number. An effort was made to collect 6 'good' measurements from each chamber at each site. Once collected the measurements where then filtered and weighed and the weight of the plastic bottle subtracted. This weight was subsequently used in conjunction with the time period and footprint of the chambers to calculate a seepage rate per m^2.

Note:

One problem associated with using condoms is their resistance to inflation once their slack volume has been filled. It is unlikely that the pressure generated by seepage into the chambers would be enough to overcome this even in the slightest sense. Because of this it was important to monitor the time it took to fill the slack volume of the condoms. At the eastern site this was not an issue as the seepage rates were slow enough that the slack volume was not filled on any occasion over the time periods they were sampled. At the western site however, we began with sample periods of 3 hours which proved to be too long and some of the condoms were reaching capacity. The time was reduced to 50 minutes to avoid this, however one or two chambers still managed to reach capacity. This may result in a slight underestimation of groundwater seepage into the lagoon.