Physiographics of Southland
Part 1:
Delineation of key drivers of regional hydrochemistry and water quality

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Technical Report

June 2016

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Physiographics of Southland
Part 1:
Delineation of key drivers of regional hydrochemistry and water quality

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Technical Chapter 2:
Discrimination of Recharge Mechanisms and Vulnerability to Bypass Flow

June 2016

Beyer, M., Rissmann, C., Rodway, E., Marapara, T. R., Hodgetts, J.

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TC2 Discrimination of Recharge Mechanisms and Vulnerability to Bypass Flow

TC2.1 Introduction

In the preceding chapter (TC 1) we demonstrated that surface and groundwater composition, specifically the concentrations of Cl and Na, are largely driven by precipitation source, i.e. coastal, inland and alpine precipitation. In this chapter, we identify recharge mechanisms of regional ground and surface water on the basis of hydrochemistry indicators and explore the impact of recharge mechanisms on freshwater composition. Since it is often hard to separate the two drivers, recharge mechanism and precipitation source, when assessing the impact on freshwater chemistry, we consider and discuss both drivers where appropriate in this chapter.

Generally, surface and groundwaters are recharged by a range of mechanisms or pathways. Recharge can be local or distal, from a source far away, and reach ground or surface water bodies through rapid or slow flow paths. Across Southland we define these recharge mechanisms according to the domain in which the water originates (Figure 2-1):

- Local recharge is where the water source (precipitation) and the resultant recharge area occur within the same recharge domain and the recharge does not move large distances outside of the recharge domain. Hereafter, we refer to local recharge as 'Land Surface Recharge.'

- Distal recharge is where the water source (precipitation) and the resultant recharge area(s) occur in different domains. The water has moved a long distance from its point of origin. Hereafter, we refer to distal recharge as 'River or Riverine Recharge'. Driven by its unique topography, major stem rivers in Southland originate in alpine and bedrock areas and travel into lowland areas. Hereafter we refer to these distal recharge sources of regional freshwater as 'Alpine River Recharge' and 'Bedrock River Recharge'.

- Generally, recharge of freshwater consists of varying portions of both distal and local recharge. In fact, pure distal recharge is unlikely to exist, given that local recharge will to some extent always be present at any given site in the region except for confined freshwater bodies, which are not considered in this study. As such, regional freshwaters will to some degree carry signatures of both distal and local recharge.

In addition to local or distal recharge mechanisms, there are also rapid and slow flow pathways along which recharge moves (Figure 2-1). Overland flow is an example of a rapid flow path and is most common in steep areas with thin soils or areas where soils are slowly permeable. Slower flow paths are normally associated with deep percolation of recharge waters to underlying aquifers and eventual discharge through the surface water network as baseflow (Figure 2-1). Typically, Alpine or Bedrock/Hill Country catchments do not have significant aquifer systems for slower transport of meaningful volumes of water so rapid flow paths predominate. In this chapter we identify both the recharge domains and mechanisms, including natural bypass flow, across Southland on the basis of hydrochemistry indicators and explore the impact of these on freshwater composition.

Rapid flow is also associated with artificial subsoil drainage or soil drainage facilitated by open drains[1]. Rapid flow is also associated with natural structures such as vertical cracks or pedogenic structures within soils that rapidly conduct recharge to either a poorly permeable subsoil layer or in some instances, an aquifer.

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[1] Flow of water through preferred pathways in the soil e.g. large continuous cracks or a series of intermittent and somewhat connected soil cracks or channels with a large pore space can result in the bypass of a large proportion of the soil matrix

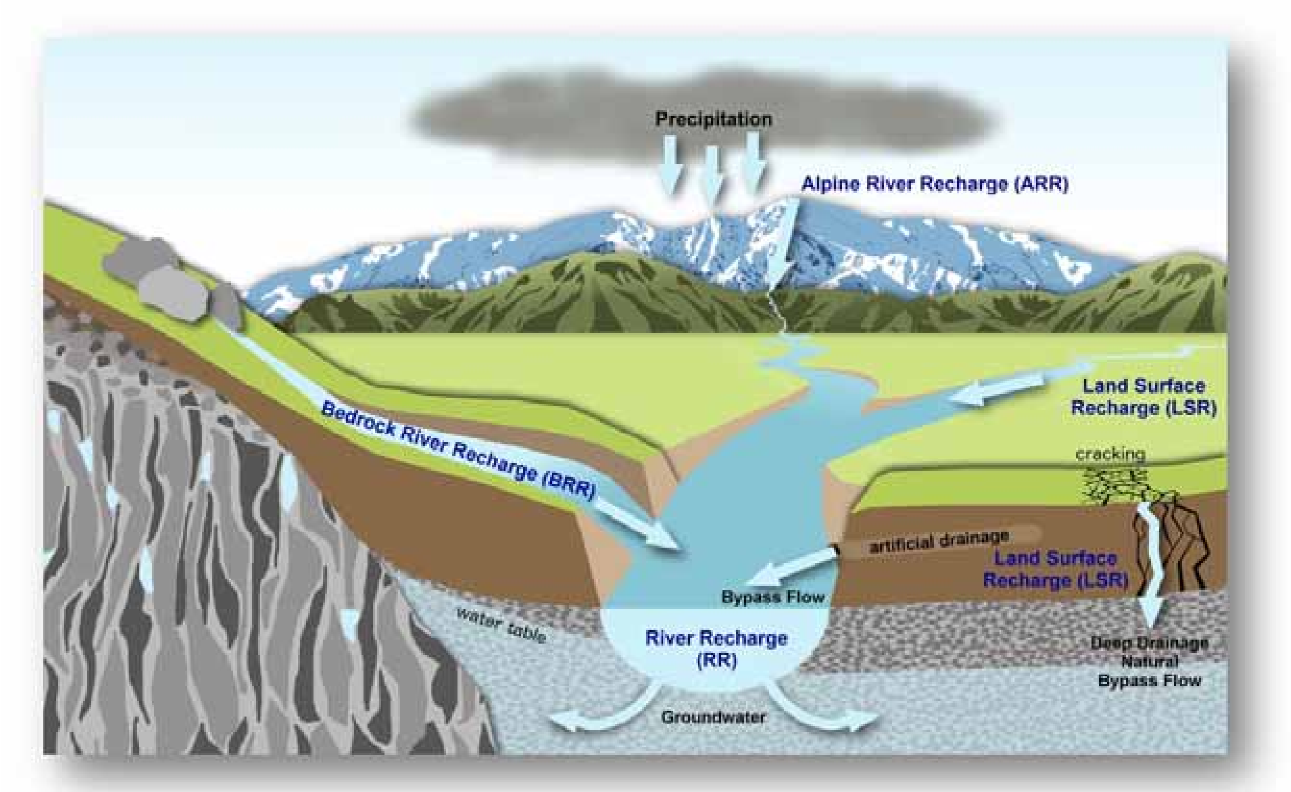

Figure 2-1: principal recharge mechanisms of ground and surface water.

In addition to identifying recharge mechanisms in this study, we considered it important to distinguish between shallow artificial, shallow natural, and deep natural bypass flow to assess the combined and separate effects of those on regional freshwater hydrochemistry. Therefore we aimed to establish a detailed bypass flow map of the Southland Region that distinguishes between shallow and deep bypass flow vulnerability due to artificial drainage and natural soil properties described in the following sections. In this chapter, we present a map of regional recharge mechanisms, recharge source and vulnerability to vertical bypass flow of surface and shallow groundwater. In addition, we applied a simplified hydromorphic approach to constraining hydrogeological characteristics for regional groundwater wells to account for various pathways and sources of recharge.

(Hillel, 1998). This phenomenon is referred to as bypass or preferential flow. Generally, bypass flow can lead to high concentrations of contaminants and pathogens that are otherwise partially retained or retarded in the soil zone. In particular, the concentrations of redox sensitive species are affected by bypass flow. Studies that assessed the effect of bypass flow on pathogen and contaminant concentrations in New Zealand include McLeod et al. (1998), Aislabie et al. (2001), McLeod et al. (2003), Houlbrooke et al. (2004), Monaghan and Smith (2004), McLeod et al. (2004), Houlbrooke et al.(2006), Houlbrooke et al. (2008) and McLeod et al. (2008).

Conditions for bypass flow are commonly caused by earthworms, plant roots, freeze-thaw processes, or wetting and drying cycles, particularly in very fine textured soils with a drainage impediment (Hillel, 1998, McLeod et al., 2008). Soil structure also has an influence on preferential flow processes where soils with coarser prismatic or large blocky structures and firm clay coated peds can inhibit micropore flow (Wells ,1973, Magesan et al., 1999, McLeod et al., 2004, McLeod et al., 2008). In the following, we refer to bypass flow that has natural causes as 'natural bypass flow'.

Conditions for bypass flow can also be created artificially, e.g. through installation of drainage such as mole pipes. Soil cracking, mediated by natural bypass, is a separate question/proposition to bypass mediated by artificial drainage. In contrast to natural bypass, artificial drainage bypass is often shallow and does not progress into the deeper subsurface or aquifer. Therefore artificial drainage is not expected to impact groundwater quality directly, whereas deeper, natural bypass is expected to impact on both groundwater and surface quality. To understand and predict regional ground and surface water quality in Southland, a better understanding of potential bypass flow in regional soils is important in addition to the understanding of recharge mechanism and recharge source.

For our analysis we used a total of 2,546 groundwater samples at 403 sites, and a total of 19,097 surface water samples at 339 sites that have been collected since 1986 and 1975 respectively. In addition, we used bypass vulnerability, predicted in previous studies (McLeod et al., 2008 and later Webb et al., 2010) and information on soil properties, such as hydraulic properties, to help better define bypass flow vulnerability.

TC2.2 Assessment of recharge mechanism

TC2.2.1 Methods

TC2.2.1.1 Hydrochemistry indicators and HCA

To assess whether we can distinguish the recharge mechanism of ground- and surface water in Southland based on hydrochemical indicators, Hierarchal Cluster Analysis (HCA) was carried out on normalised, z-scored Cl, Na, and EC data, using Wards algorithm for linkage, and squared Euclidean distance (E^2) as a measure of distance. Cl was used because it is conservative and exhibits clear patterns in the Southland Region, which can explain two main recharge sources (Type 1 and Type 2 precipitation, in combination with and $\delta^{18}O\text{-}H_2O$ values, as demonstrated in TC1).

In addition, EC and Na were used because both are strongly correlated with Cl as noted in TC 1 and both show similar spatial patterns to Cl and $\delta^{18}O\text{-}H_2O$. Other hydrochemical parameters, such as $\delta^{13}C$-DIC and $\delta^{18}O\text{-}H_2O$ values, the concentration of sulphate (SO_4) and alkalinity, as well as F_c Na values (Na enrichment factor relative to seawater), calcite saturation indices, and Na:$\delta^{18}O\text{-}H_2O$ ratios are expected to be good indicators for recharge mechanism, although they were not included in the HCA[2]. These parameters were used to support the HCA interpretation, and to identify dominant recharge sources and mechanisms of Southland's ground and surface waters.

HCA was carried out on southern and northern samples separately, because these exhibit significantly different Cl, Na, EC, and $\delta^{18}O\text{-}H_2O$ signatures, as demonstrated in TC 1. Clustering of both northern and southern samples together revealed weaker and less meaningful relationships or patterns than the ones obtained when considering these separately. Similarly, surface and groundwaters were assessed separately.

TC2.2.1.2 Surface water hydrology and regolith hydrogeology

To support the identified recharge mechanisms of Southland's surface and groundwater based on hydrochemical signatures, we assessed surface water hydrology. For example, we assessed impermeable bedrock or permeable soil features of alpine derived rivers and regolith hydrogeology using QMAP information. In locations with an insignificant soil layer, such as in alpine and hill country bedrock outcrop, we would expect predominately surface water or river water recharge. In contrast, in locations with a developed soil layer, predominantly in lower altitude areas and valleys, we would expect Land Surface Recharge (LSR) to dominate. In addition, in lowland areas in close proximity to major stem rivers we would expect a mix of LSR and River Recharge (RR).

TC2.2.2 Results

The HCA on regional surface water samples identified 2, 3 and 4 clusters at the 2800, 500 and 400 phenon lines respectively, for Southland's northern surface water samples.2, 3 and 4 clusters were also identified at the 6500, 2500 and 2000 phenon lines respectively, for Southland's southern surface water samples (Figure 2-2). HCA on Southland's groundwater samples identified 2, 3 and 4 clusters at the 2500, 1000, 400 and 520 phenon lines respectively, for Southland's northern groundwater samples, and at the 4800, 2800 and 2000 phenon lines, respectively for Southland's southern groundwater samples (Figure 2-3).

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[2] Sulphate was not included since it may have other (anthropogenic) sources and the rate of sulphate removal in soil (i.e. during Land Surface Recharge) is dependent on the soil chemistry; Fc Na and Na:^{18}O are already represented in the HCA through inclusion of Na and δ $^{18}O\text{-}H_2O$, respectively. $\delta^{13}C$-DIC values were only available for a limited number of sites, which would have reduced the dataset to < 25%.

As summarised in Table 2-1 and Table 2-2 and illustrated in Figure 2-2, Figure 2-3, Figure 2-4, and Figure 2-5, the identified surface and groundwater clusters exhibit significantly different Cl, EC, Na, and δ^{18}O-H_2O signatures, allowing for discrimination between recharge sources, i.e. Type 1 vs. Type 2 precipitation. For example, the higher concentrations of Cl and Na in combination with more positive δ^{18}O-H_2O values are indicative of coastal precipitation. Electric conductivity exhibits greater scatter than Cl due to contribution from solutes from sources other than marine aerosols. Sodium concentrations exhibit a similar relationship to EC and Cl in ground and surface water, but as noted in TC1, Na enrichment relative to the SWDL is a feature of the rainout of marine aerosols with altitude and reflects the expression of an endogenous soil or water-rock derived Na weathering source.

In addition, the concentration of Na in relation to Cl (or Fc Na), δ^{13}C-DIC, SO_3, pH, alkalinity, and calcite saturation differ significantly for each cluster (Table 2-1 and Table 2-2) allowing for discrimination of recharge mechanisms (i.e. LSR vs. RR). For example, generally higher concentrations of Na (relative to Cl), a higher alkalinity and more negative δ^{13}C-DIC i.e. soil respired, are indicative of LSR, as opposed to RR. However, in some instances it is difficult to identify the recharge mechanism purely based on hydrochemistry, because the hydrochemical signature of ground and surface water is affected by recharge mechanism, soil chemistry, and hydrology, as well as recharge source, which in some cases can lead to similar hydrochemical signatures for water recharged through different mechanisms.

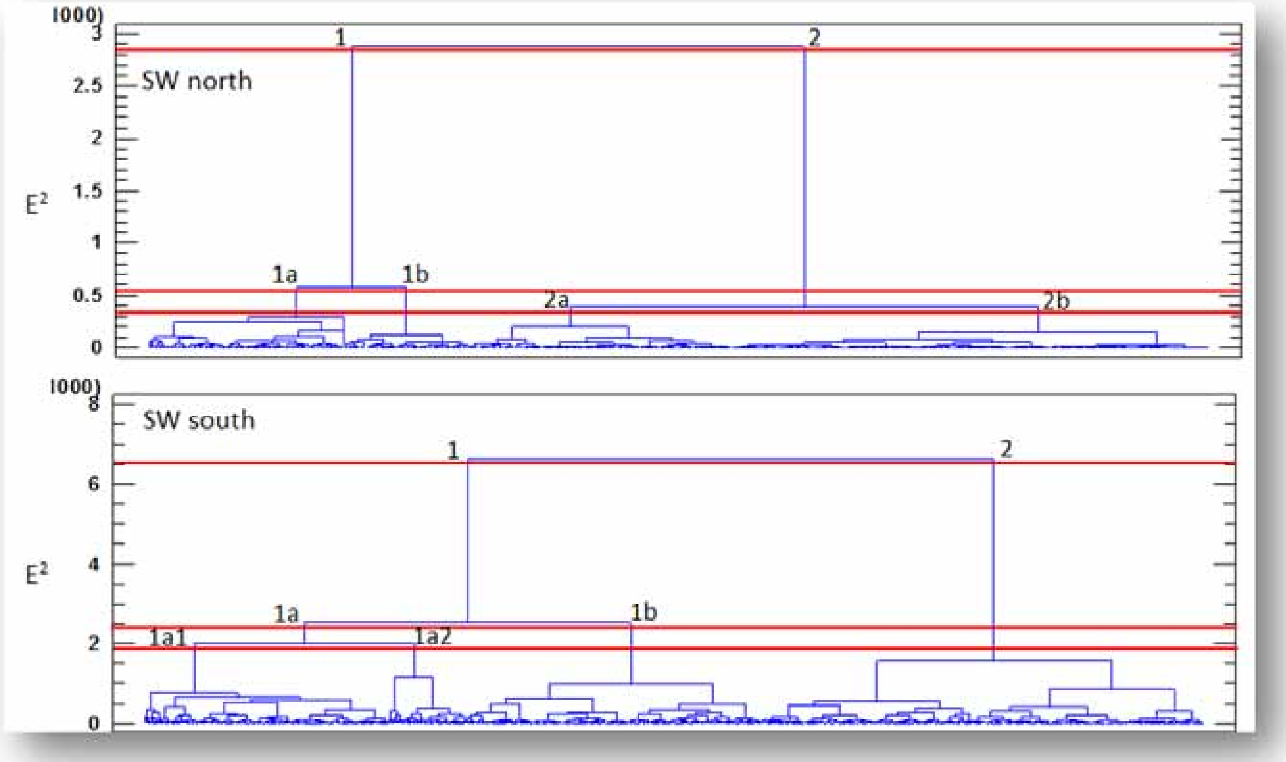

Figure 2-2: Dendrogram of northern and southern Southland surface water samples identifying clusters at 3 different phenon (red lines); HCA was carried out on normalised, z-scored Na, Cl, EC data, using Wards algorithm for linkage and squared Euclidean distance (E^2) as a measure of distance.

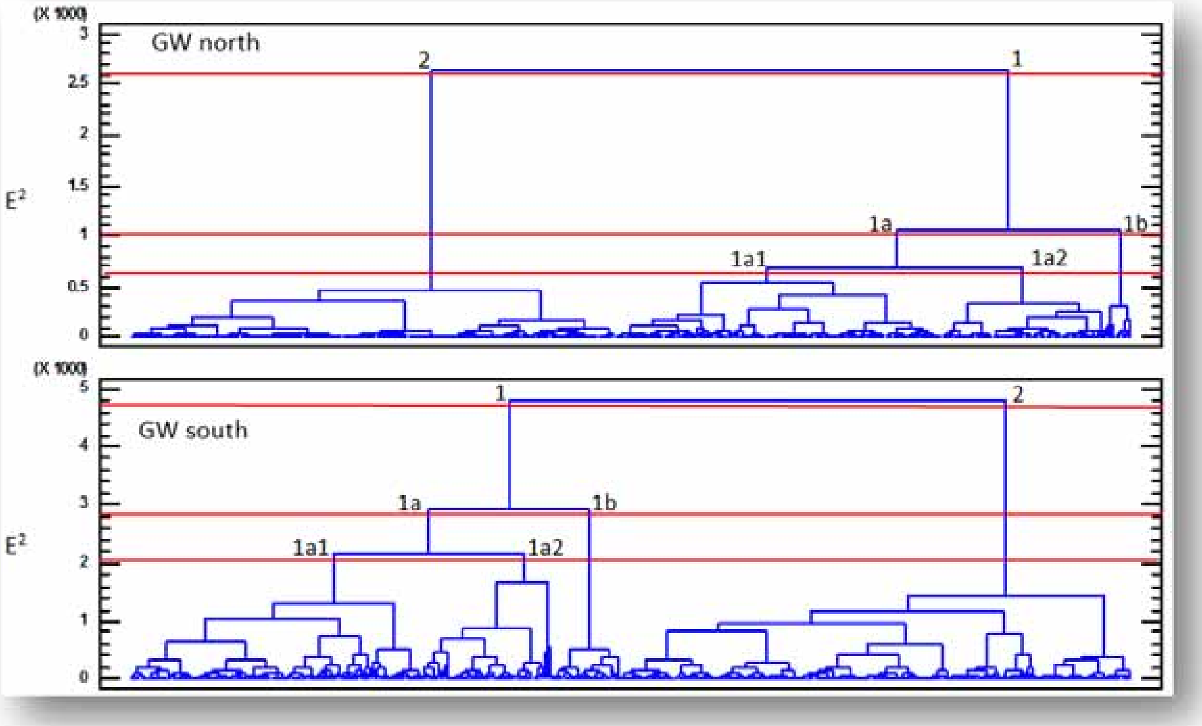

Figure 2-3: Dendrogram of Southland northern and southern groundwater samples identifying clusters at the 3 different phenon red lines; HCA was carried out on normalized, z-scored Na, Cl, EC data, using Wards algorithm for linkage and squared Euclidean distance (E^2) as a measure of distance.

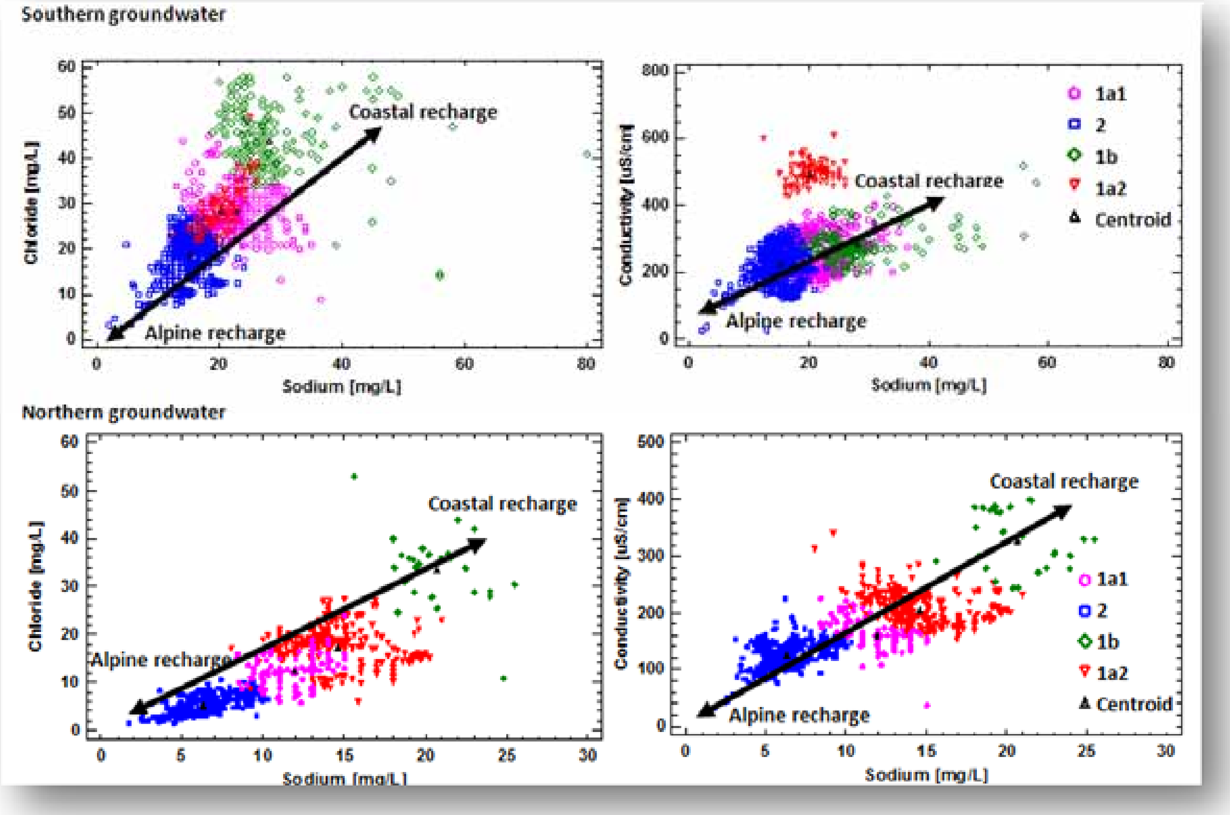

Figure 2-4: Relationship between Sodium and Chloride and Sodium and Electrical Conductivity for Southland groundwaters.

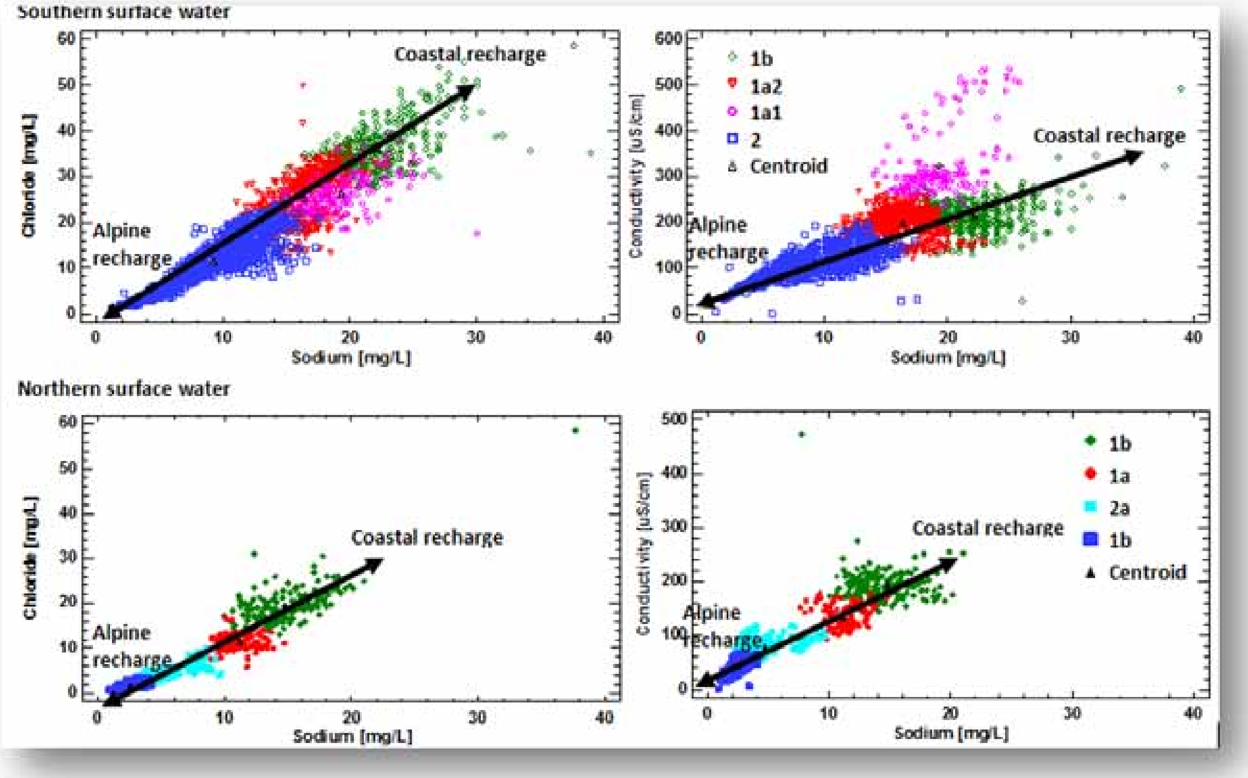

Figure 2-5: Relationship between Sodium and Chloride and Sodium and Electrical Conductivity for Southland surface waters.

Error! Reference source not found. illustrates the geographic location of the southern and northern groundwater clusters on a simplified hydrogeological map (showing areas with expected LSR and RR) as indicated by the presence or lack of a significant soil layer. Figure 2-6 illustrates the geographic location of the southern and northern surface water clusters and the river network (REC class >2), colour coded according to their source, i.e. alpine or lowland. Generally, the chemical signature of ground and surface water clusters follow a dilution continuum of 2 >>1a2 > 1a1 > 1b in order of most dilute to most concentrated, suggesting Cluster 2 waters are dominantly alpine river recharged, 1a1 and 1a2 are predominantly LSR in mid to low altitudes, but may have a secondary alpine recharge source. 1b are exclusively coastal Land Surface Recharged.

Specifically, groundwater associated with Cluster 2 and surface water associated with Cluster 2a and 2b are located in alpine areas > 800m (Figure 2-4 and Figure 2-5). These waters exhibit the lowest Cl and Na concentrations, lowest EC and most negative δ^{18}O-H$_2$O values similar to those of precipitation Cluster 2, see TC 1. This suggests groundwater associated with Cluster 2 and surface water associated with Cluster 2a and 2b receive recharge from alpine, high altitude sources being Type 2 precipitation, (Table 2-1 and Table 2-2).

Since these waters receive very dilute precipitation, the influence of soil zone is significant as indicated by relatively high Fc Na values and Na/Cl ratios and elevated EC and Na concentrations compared to alpine precipitation (Cluster 2 waters, TC 1). By comparison, in close proximity to the coast weathering derived Na is swamped by very high Na and Cl concentrations in precipitation (see Cluster 1b waters described subsequently).

Importantly, Southland's main stem rivers in the northern headwater catchments retain the signature of alpine waters (Type 2 precipitation) as far south as their middle reaches, i.e. Mataura River to Mataura, Aparima River to Otautau and Oreti River to Wallacetown.

Cluster 2 ground and surface waters across southern Southland are overwhelmingly associated with main stem rivers and their floodplain (**Error! Reference source not found.** and Figure 2-6). These waters have slightly higher EC, Cl, Na and more positive $\delta^{18}O-H_2O$ signatures than their northern counterparts and on the basis of tabulated $\delta^{18}O-H_2O$ values suggest c. 20% of the water by volume is derived from low altitude drainage. Given groundwater in such aquifers typically retains a relatively negative $\delta^{18}O-H_2O$ signature, the elevated EC and Cl values often observed in these groundwaters suggests that a relatively small proportion of concentrated soil zone recharge has a significant influence on the chemistry of groundwater within these aquifer systems (further discussed in TC 3 and 8). As with northern cluster 2 waters, the influence of soil zone is evident through relatively high Fc Na values and Na/Cl ratios and in addition, very negative $\delta^{13}C$-DIC values.

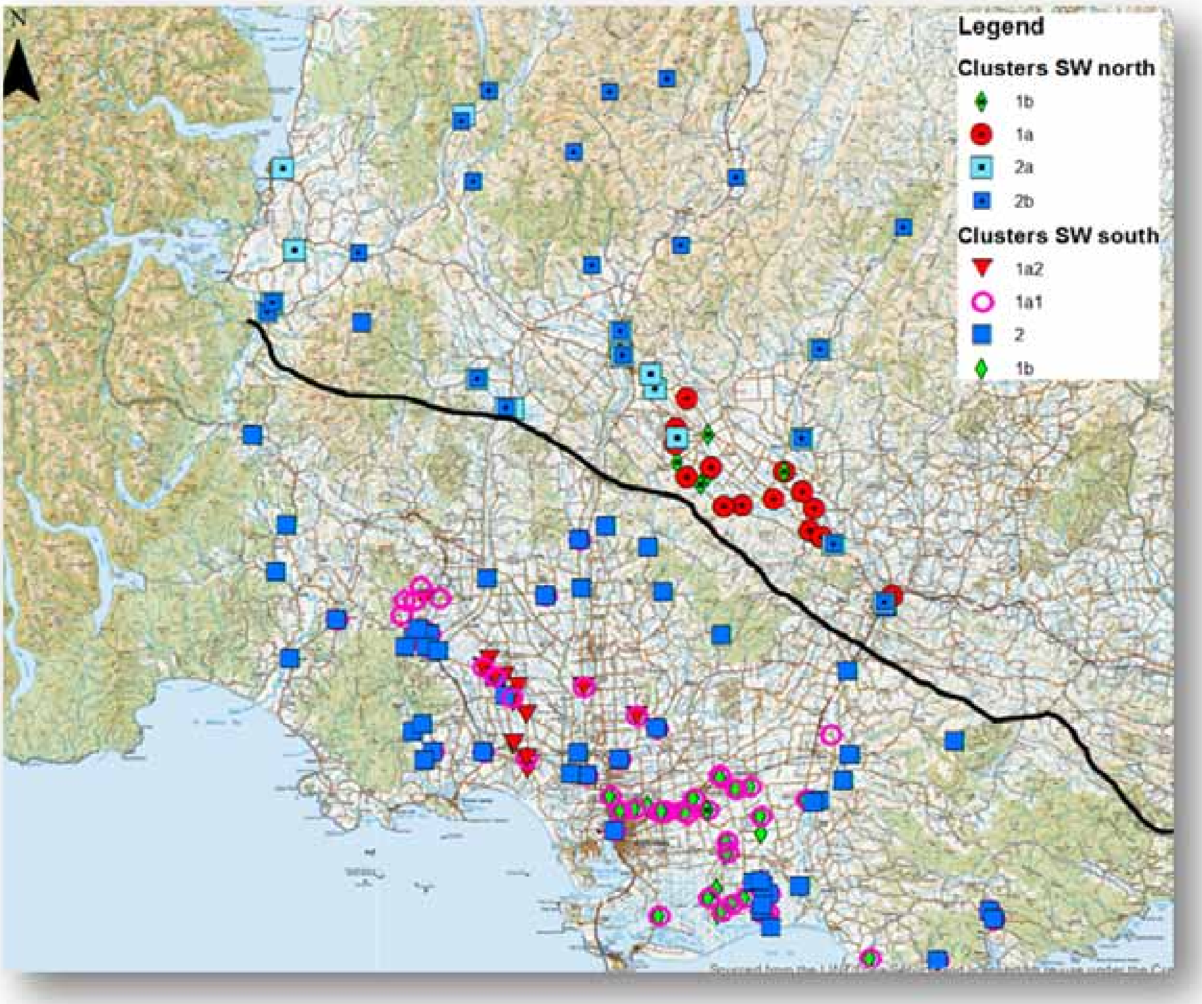

Figure 2-6: Geographical location of surface water clusters, river network highlighted according to their source (alpine and bedrock vs. low altitude). Line symbolizes border between northern and southern Southland

Southern ground and surface waters associated with Cluster 1b are located in the coastal areas where we expect LSR and an insignificant effect of alpine RR (**Error! Reference source not found.** and Figure 2-6). These waters exhibit the highest concentration of Na and Cl and the most positive $\delta^{18}O-H_2O$ values which are close to that of coastal precipitation (see Cluster 2 b in TC 1), confirming a large marine aerosolic Na and Cl load associated with recharge by coastal precipitation (Type 1). Relative to Cl, EC is not always elevated for Cluster 1b waters indicating recharge through weathered soils of low BS% and pH that equate to Ca, Mg and K poor recharge and low alkalinity (Table 2-1 and Table 2-2, see also TC 3). These waters exhibit slight enrichment in Fc Na values (although lower than for alpine cluster 2, swamped signal) and the lowest pH in all clusters.

Northern ground and surface waters associated with Cluster 1b are notable by their association with the low-lying Balfour aquifer and the hydrologically connected lowland reaches of the Waimea Stream as well as elevated parts of the Knapdale aquifer (**Error! Reference source not found.** and Figure 2-6). These are areas where we expect LSR. These waters are characterised by the most isotopically positive $\delta^{18}O-H_2O$ values and highest Na and Cl concentrations of all waters in northern Southland, reflecting low altitude inland recharge (Type 1). These low-lying areas receive the highest marine Na and Cl load of northern Southland and show little evidence of high altitude riverine inputs (Type 2 precipitation).

1a2 groundwaters in northern Southland are located in areas where we would expect predominately LSR. These waters are very dilute and exhibit a relatively negative $\delta^{18}O$ signature, suggesting that they are recharged primarily by spill over from alpine mountains. A soil respired $\delta^{13}C$-DIC signature and slightly elevated alkalinity (compared to cluster 2 waters) in conjunction with strongly elevated NO_3-N support LSR as the dominant recharge mechanism. These waters are not hydrologically connected to high altitude recharge sites rather they are recharged by dilute alpine precipitation. A classic example is the Wendonside Terrace, which receives spill over recharge from the Garvie Mountains. This rain shadow effect of $\delta^{18}O-H_2O$ signatures is noted in much of the frontal ranges of the Southern Alps (Scott, 2015).

1a1 ground and 2a surface waters in northern Southland occur in close proximity to riverine areas where we expect a mix of LSR and RR. These waters exhibit slightly elevated Cl, EC and Na concentrations compared to cluster 2 (southern) waters. 1a1 groundwaters appear to be a mix of high and low altitude recharge sources - more specifically, a mixed precipitation source - high altitude RR and low altitude LSR. There is also evidence for a predominantly hill country contribution with some 2a surface water sites associated with inflows from the northern flank of the Hokonui Hills and the headwaters of the Waimea Stream also falling within this cluster.

Switching between Cluster 1a2 and 2 surface waters occurs in response to flow with 1a2 waters dominating low flow and Cluster 2 at high flows derived from snowmelt or orographic rainfall (apparent in **Error! Reference source not found.**). This suggests that water composition of hill country fed streams is significantly influenced by connectedness/disconnectedness to alpine sources. Generally, alpine derived streams carry their ‘alpine signature’ all the way down into the lowland. Hill country derived streams that are connected to alpine areas show more of an alpine signature than hill country derived streams that do not receive significant amounts of alpine recharge, e.g. the Hokonui Hills, but also at the foot of alpine areas. This suggests that it is important to distinguish between recharge in the bedrock domain that is connected to the alpine recharge domain, in the following referred to as bedrock 1 domain and recharge in the bedrock domain that is not connected to the alpine domain, in the following referred to as bedrock 2 domain.

In southern Southland, Cluster 1a1 ground and surface waters are located in low altitude areas that occur in close proximity to hill country (**Error! Reference source not found.** and Figure 2-6). Cluster 1a1 groundwater generally exhibit elevated alkalinity, EC and pH, although all show a very large range indicating LSR and differing soil zone processes. Cl, Na and $\delta^{18}O-H_2O$ and $\delta^{13}C$-DIC values are relatively low (Table 2-1) compared to more coastal and other low elevation clusters indicating a mix of relatively dilute hill country precipitation LSR and hill country RR for cluster 1a1 groundwater in southern Southland. Calcite saturation indices exhibit a large range with some waters close to calcite saturation (S.I.>-0.5), consistent with the presence of carbonate rocks and outcrop for some of these waters.

1a1 waters exhibit the highest alkalinity (and highest pH) of all groundwater suggesting the significant alkalinity generation is driven by water-soil-rock interaction within the soil and the shallow groundwater system (see TC 3 on Dunsdale soils). Cluster 1a surface waters are significantly more dilute with more negative $\delta^{18}O-H_2O$ values when contrasted with southern 1a1 surface waters, which are exclusively associated with hill country fed streams such as those draining the Hokonui Hills, Catlins and Coastal Longwoods.

Cluster 1a2 groundwater in southern Southland is located in lowland areas (**Error! Reference source not found.**) and exhibits Cl, Na and $\delta^{18}O-H_2O$ values that are similar to Cluster 1a1 but pH, alkalinity and EC are significantly lower than for cluster 1a1 waters, indicating lesser water-soil-rock interaction and resultant acid buffering with no evidence of high altitude RR. Similar to cluster 1a1, cluster 1a2 waters exhibit a large range of calcite saturation indices with some waters close to calcite saturation (S.I.>-0.5) suggesting this cluster includes some waters influenced by carbonate rock.

Table 2-1: HCA clusters and associated mean concentrations and SD of selected hydrochemistry parameters in Southlands northern and southern groundwater

	Key Characteristic	Detailed Characteristics		Cl [mg/L]	EC [μS/cm]	Na [mg/L]	$Na:O^{18}$ ratio	S.I. (calcite)	$\delta^{18}O-H_2O$ [ppt VSMOW]	Alkal. tot. [mg/L]	Fc Na	Na: Cl ratio	SO_4 [mg/L]	pH	$\delta^{13}C$-DIC [ppt, VPDB]
2 north	Alpine (type 2) RR	Cluster 2 north groundwater occur in close proximity to alpine and hill country areas, lowest Cl and Na concentrations, lowest EC and most negative $\delta^{18}O-H_2O$ values indicating **recharge from alpine, high altitude sources (Type 2 precipitation),** highest Fc Na and Na/Cl ratio of all waters – indicating large influence of weathering	Mean	5.67	128.4	6.55	-0.66	-2.05	-9.15	36.49	2.28	1.27	5.66	6.91	-19.01
			SD	3.34	27.36	2.47	0.23	0.83	0.65	12.33	0.63	0.35	3.91	0.52	3.69
2 south	Alpine RR (main stem rivers with alpine head catchments), small proportion of LSR	Cluster 2 south groundwater can be overwhelmingly associated with **main stem rivers and their floodplain**; waters have slightly higher EC, Cl, Na and more positive $\delta^{18}O-H_2O$ signatures than their northern counterparts and on the basis of $\delta^{18}O-H_2O$ values suggest c. 20% of the water by volume is derived from low altitude drainage. Given groundwater in such aquifers typically retains a relatively negative $\delta^{18}O-H_2O$ signature, the elevated EC and Cl values often observed in these groundwater suggests that **a relatively small proportion of concentrated soil zone recharge** has a significant influence on the chemistry of groundwater within in these aquifer systems (further discussed in TC 4)	Mean	19.5	228.6	15.46	-2.06	-1.85	-7.66	56.92	1.53	0.85	11.4	6.67	-19.48
			SD	5.51	53.84	3.37	0.75	1.35	0.72	30.50	0.51	0.28	8.96	0.57	3.68
1a1 north	Mix of high alt RR and low altitude LSR	Cluster 1a1 north groundwater occur in close proximity to riverine areas, slightly elevated Cl, EC and Na concentrations compared to cluster 2 (south) waters, appear to be a **mix of high and low altitude recharge sources**. More specifically, a mixed precipitation source - high alt RR and low altitude LSR.	Mean	13.0	168.6	12.15	-1.51	-2.45	-8.44	27.83	1.81	1.01	5.72	6.59	-18.12
			SD	4.70	34.85	2.83	0.56	0.97	0.46	12.35	0.49	0.27	6.44	0.41	4.98
1a1	Mix of hill	Cluster 1a1 south groundwater are located in low	Mean	28.6	491.4	20.25	-2.86	-2.02	-7.33	189.2	1.28	0.71	7.77	7.60	-14.92

	Key Characteristic	**Detailed Characteristics**		**Cl [mg/L]**	**EC [μS/cm]**	**Na [mg/L]**	**Na:O^{18} ratio**	**S.I. (calcite)**	**$\delta^{18}O$-H_2O [ppt VSMOW]**	**Alkal. tot. [mg/L]**	**Fc Na**	**Na: Cl ratio**	**SO_4 [mg/L]**	**pH**	**$\delta^{13}C$-DIC [ppt, VPDB]**
south	country spill over LSR and/or hill country RR	altitude areas close proximity to hill country, generally elevated alkalinity, EC and pH, although all show a very large range indicating **differing soil zone processes**; Cl, Na and $\delta^{18}O$-H_2O and $\delta^{13}C$-DIC values are relatively low compared to more coastal and other low elevation clusters indicating a **mix of** relatively **dilute hill country spill over LSR and hill country RR**; large range of calcite saturation indices, some close to 0 indicate this cluster includes **some waters located in carbonate catchments and aquifers,** these waters show the highest alkalinity generation (and highest pH) of all groundwater, driven by the low pH of hill country recharge	SD	4.75	42.88	2.68	0.34	2.64	0.34	35.08	0.15	0.08	8.07	0.39	3.33
1a2 north	LSR dominated, spill over from alpine mountains	Cluster 1a2 north groundwater are **LSR dominated** systems that are recharged primarily from **spill over from alpine mountains** –why they are relatively dilute and $\delta^{18}O$ are relatively positive. They do **not necessarily have a high altitude RR source** but the ppt that falls is relatively dilute. Classic example is the **Wendonside Tce** that receives **spill over** recharge from the **Garvie Mountains** and a significant number of groundwater throughout the Waimea Plain. This rain shadow effect is noted in much of the frontal ranges of the Southern Alps (Scott, 2015)	Mean	16.9	200.1	14.36	-1.82	-2.45	-7.88	30.49	1.64	0.91	10.9	6.41	-19.45
			SD	4.43	34.95	2.64	0.38	1.08	0.51	15.85	0.57	0.32	9.47	0.35	3.92
1a2 south	Low altitude LSR, no evidence of high altitude RR	Cluster 1a2 south groundwater exhibit Cl, Na and $\delta^{18}O$-H_2O values are similar to cluster1a1, but alkalinity and EC are significantly lower than for clusters 1a1waters indicating a **low altitude recharge source (of higher pH)**; again a large	Mean	27.9	249.4	22.89	-3.09	-1.85	-7.23	56.14	1.53	0.85	9.67	6.65	-18.63
			SD	5.88	59.01	4.55	0.76	1.19	0.59	28.65	0.53	0.29	8.52	0.45	3.25

	Key Characteristic	**Detailed Characteristics**		**Cl [mg/L]**	**EC [μ S/cm]**	**Na [mg/L]**	**Na:O^{18} ratio**	**S.I. (calcite)**	**δ^{18}O-H_2O [ppt VSMOW]**	**Alkal. tot. [mg/L]**	**Fc Na**	**Na: Cl ratio**	**SO_4 [mg/L]**	**pH**	**δ^{13}C-DIC [ppt, VPDB]**
		range of calcite saturation indices, some close to 0 indicates the cluster also **includes waters affected from carbonate catchments and aquifers**													
1b north	Low altitude inland LSR, little evidence of high altitude RR	Cluster 1b north groundwater are located in low-lying areas associated with **the low-lying Balfour aquifers** and the **hydrologically connected lowland reaches of the Waimea Stream** as well as elevated parts of the **Knapdale aquifer.** These waters are characterised by the isotopically most positive δ^{18}O-H_2O values (although relatively large SD) and highest EC, Na and Cl concentrations and largest range of alkalinity, sulphate and ^{13}C-DIC values of all waters in northern Southland, **reflecting low altitude inland LSR through differing soils**. These waters receive the highest marine Na and Cl load of northern Southland and show **little evidence of high altitude riverine inputs (Type 2 precipitation)**	Mean	29.3	303.2	18.56	-2.30	-1.87	-7.88	41.40	1.33	0.74	18.4	6.56	-17.20
			SD	11.4	85.92	4.47	0.78	0.85	0.71	33.33	0.68	0.38	15.3	0.60	7.75
1b south	Coastal LSR	Cluster 1b south groundwater exhibits the highest concentration of Na and Cl and the most positive δ^{18}O-H_2O values (although relatively large SD) indicating a large marine aerosolic Na and Cl load associated with **recharge by coastal precipitation (Type 1)**. Relative to Cl, EC is not always elevated for Cluster 1b waters indicating **recharge through weathered soils of low BS% and pH** that equate to Ca, Mg and K poor recharge and of low alkalinity; Chloride concentrations in coastal precipitation (see TC 1, cluster 1b) and 1b south GW cluster 1b compares very well, although Na and EC are significantly elevated in GW indicating a significant	Mean	42.5	275.8	26.80	-3.81	-2.09	-7.14	43.46	1.21	0.67	8.25	6.32	-18.22
			SD	8.98	50.74	7.60	1.17	1.31	0.58	29.34	0.67	0.37	7.50	0.50	4.16

	Key Characteristic	Detailed Characteristics		Cl [mg/L]	EC [µS/cm]	Na [mg/L]	Na:O^{18} ratio	S.I. (calcite)	δ^{18}O-H$_2$O [ppt VSMOW]	Alkal. tot. [mg/L]	Fc Na	Na: Cl ratio	SO$_4$ [mg/L]	pH	δ^{13}C-DIC [ppt, VPDB]
		effect of weathering on the composition of GW.													

Table 2-2: HCA clusters and associated median concentrations (SD) of selected hydrochemistry parameters in Southlands northern and southern surface water

	Summary Charact.	Characteristics		Alkal. Tot [mg/L]	Ca [mg/L]	Cl [mg/L]	EC [µS/cm]	Fc Na	δ^{13}C-DIC	Na/ Cl	Na/ O^{18}	δ^{18}O-H$_2$O [ppt VSMOW]	Na [mg/L]	SO$_4$ [mg/L]	pH	SI(Calcite)
2 b north	High altitude RR (main stem rivers within northern headwater catch-ments)	Exhibits lowest Cl and Na concentrations, lowest EC and most negative δ^{18}O-H$_2$O values indicating recharge from alpine, **high altitude sources (Type 2 precipitation); main stem rivers within northern headwater catchments** retain the signature of alpine waters, Type 2 ppt, as far south as their middle reaches i.e., Mataura River to Mataura, Aparima River to Otautau and Oreti River to Wallacetown.	Mean	18.39	4.09	1.70	42.37	2.93	-13.64	1.63	-0.25	-9.78	2.54	1.59	7.25	-3.06
			SD	5.23	1.17	0.68	12.90	0.91	4.42	0.50	0.08	0.81	0.72	0.77	0.21	2.10
2 south	Mix of high altitude RR (main stem rivers) and c. 20% low altitude drainage.	Overwhelmingly associated with **main stem rivers** and their floodplain. These waters have slightly higher EC, Cl, Na and more positive δ^{18}O-H$_2$O signatures than their northern counterparts. On the basis of tabulated δ^{18}O-H$_2$O values suggest c. **20% of the water by volume is derived from low altitude drainage**.	Mean	28.54	8.37	11.70	110.6	1.55	-12.97	0.86	-1.17	-8.01	9.22	5.47	7.40	-1.71
			SD	10.57	3.23	5.48	31.11	0.39	5.47	0.22	0.56	0.95	3.43	2.80	0.27	1.24
1a north	Dominantly Hill Country RR	1a1 ground and surface waters are restricted to the **Waimea Basin**. There is evidence for a **dominantly Hill Country contribution** with some 1a1 surface water sites associated with **inflows from the northern flank of the Hokonui Hills** with the **headwaters of the Waimea Stream** also falling within this cluster	Mean	38.19	10.52	11.47	135.2	1.80	-14.90	1.00	-1.47	-7.82	11.21	7.26	7.50	-1.21
			SD	12.11	2.88	1.90	21.99	0.38	3.45	0.21	0.18	0.65	1.37	4.15	0.26	0.58

	Summary Charact.	**Characteristics**		**Alkal. Tot [mg/L]**	**Ca [mg/L]**	**Cl [mg/L]**	**EC [µS/cm]**	**Fc Na**	**δ^{13}C-DIC**	**Na/ Cl**	**Na/ O^{18}**	**δ^{18}O-H_2O [ppt VSMOW]**	**Na [mg/L]**	**SO_4 [mg/L]**	**pH**	**SI(Cal-cite)**
1a1 south	LSR in carbonate catchments	Are associated with **carbonate catchments** with higher alkalinity and calcite saturation; Cl, Na and δ^{18}O-H_2O values are not significantly different between the Cluster 2a1 and 1a2 a indicating similar recharge source.	Mean	37.45	14.69	25.40	199.6	1.19	-16.95	0.66	-2.43	-6.99	16.34	13.1	7.22	-1.59
			SD	21.02	4.72	5.31	28.54	0.24	2.13	0.13	0.42	0.81	2.09	5.38	0.51	1.70
2a north	Primarily high altitude spill over LSR.	These SWs are of a similar origin as GW, recharged **primarily by high altitude spill over**. Switching between Cluster 1a2 and 2 SWs occurs in response to flow. 1a2 SWs dominate low flow and Cluster 2 high flows derived from snowmelt or orographic rainfall (**Error! Reference source not found.**)	Mean	28.08	6.83	3.89	79.31	2.31	-14.68	1.29	-0.59	-9.02	4.70	3.89	7.39	-1.62
			SD	9.09	1.46	1.71	14.89	0.57	3.00	0.32	0.25	0.63	1.77	1.67	0.24	0.79
1a2 south	Hill country RR	Are significantly more dilute with more negative δ^{18}O-H_2O values when contrasted with southern 1a1 surface waters and are **exclusively associated with hill country fed streams such as those draining the Hokonui Hills, Catlins, Coastal Longwoods**	Mean	104.33	36.72	26.44	326.7	1.33	-17.43	0.74	-2.54	-7.27	19.31	14.0	7.88	-0.85
			SD	44.57	18.14	3.85	75.43	0.23	1.60	0.13	0.34	0.49	2.62	5.57	0.35	2.03
1b north	Low altitude inland LSR, little evidence of high altitude RR	Associated with the **low-lying Balfour aquifers and the hydrologically connected lowland reaches of the Waimea Stream** and elevated parts of the **Knapdale aquifer.** These waters are characterised by the isotopically most positive δ^{18}O-H_2O values and highest Na and Cl of all waters in northern SL, reflecting **low altitude inland recharge (Type 1)**. These low-lying areas receive the highest marine Na and Cl load of northern SL and show **little evidence of high altitude riverine inputs (Type 2 ppt)**	Mean	42.73	14.50	19.24	194.7	1.39	-16.49	0.77	-2.07	-7.50	14.63	11.0	7.62	-1.04
			SD	10.48	3.12	3.31	30.23	0.21	1.75	0.11	0.37	0.71	2.32	5.80	0.34	0.57

	Summary Charact.	Characteristics		Alkal. Tot [mg/L]	Ca [mg/L]	Cl [mg/L]	EC [μS/cm]	Fc Na	δ^{13}C-DIC	Na/ Cl	Na/ O^{18}	$\delta^{18}O-H_2O$ [ppt VSMOW]	Na [mg/L]	SO_4 [mg/L]	pH	SI(Cal-cite)
1b south	Coastal LSR	Exhibits the highest concentration of Na and Cl and the most positive $\delta^{18}O-H_2O$ values indicating a large marine aerosolic Na and Cl load associated with **recharge by coastal precipitation (Type 1)**. Relative to Cl, EC is not always elevated for Cluster 1b waters indicating **recharge through weathered soils of low BS% and pH** that equate to Ca, Mg and K poor recharge and of low alkalinity	Mean	24.93	11.52	36.11	213.2	1.11	-16.47	0.62	-3.73	-6.09	22.13	14.4	6.88	-2.65
			SD	12.59	4.77	4.90	34.44	0.14	3.17	0.08	0.61	0.57	2.77	7.52	0.82	2.69

TC2.3 Bypass Flow

TC2.3.1 Introduction

Pearson (2015) has developed a map depicting artificial subsurface drainage density in Southland (Figure 2-7). The map was established based on land cover information, to identify agricultural production areas where artificial drainage is likely occurring, and soil drainage class and permeability to estimate drainage density.

McLeod et al. (2008) and later Webb et al. (2010) established a map of natural bypass flow in New Zealand. These studies ranked bypass in soil based on data obtained in microbial breakthrough curve experiments and related this data to soil classification and soil characteristics (after Hewitt, 1993). Confirmation of their bypass flow rankings through bypass measurements in field and lab is still on-going work, e.g. Aislabie (2011) confirmed the bypass ranking of two soil types through additional experiments. Figure 2-8 illustrates McLeod et al.'s (2008) natural bypass flow ranking for the Southland Region.

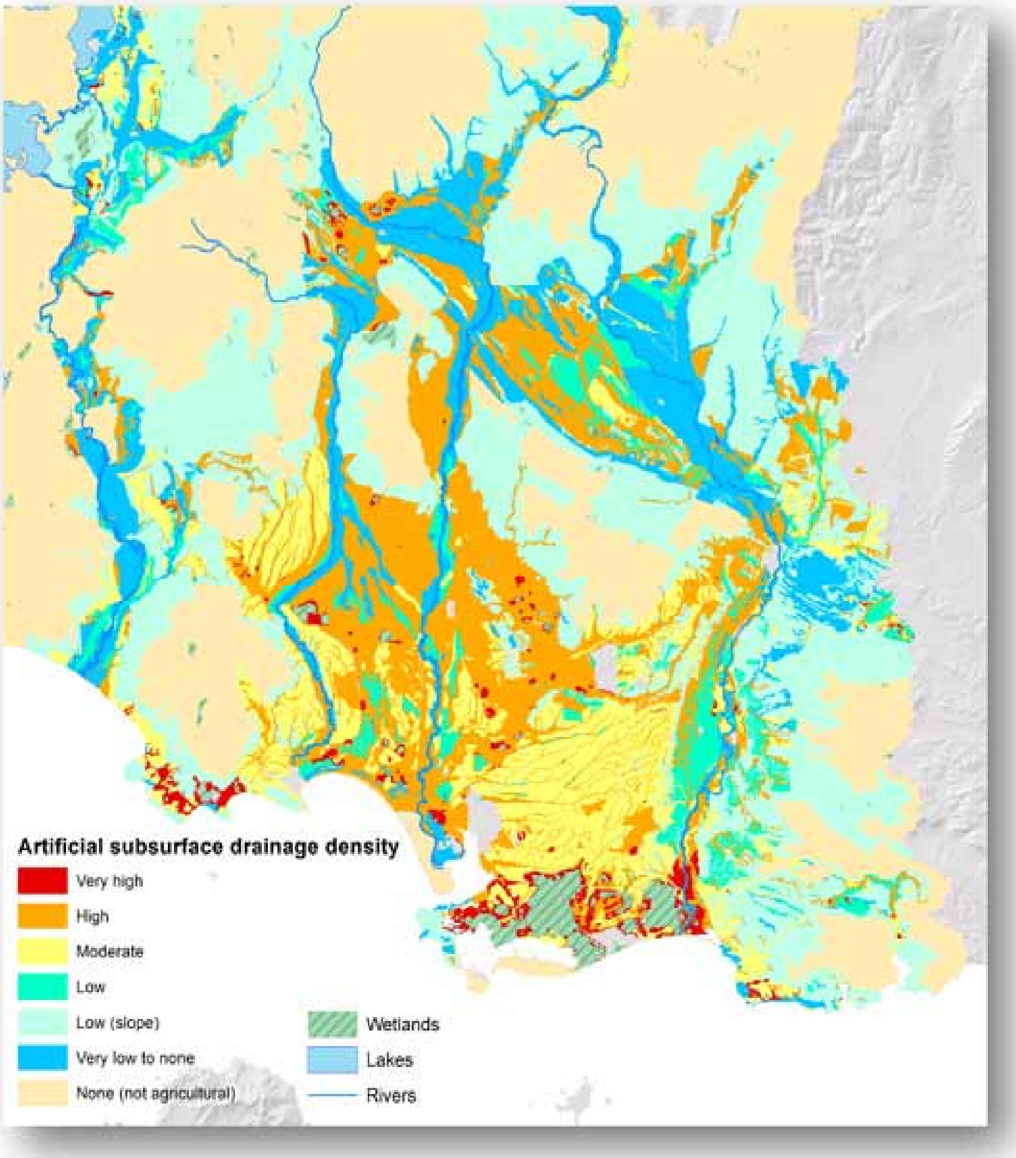

Figure 2-7: Approximate subsurface drainage densities across the Southland region (Pearson, 2015).

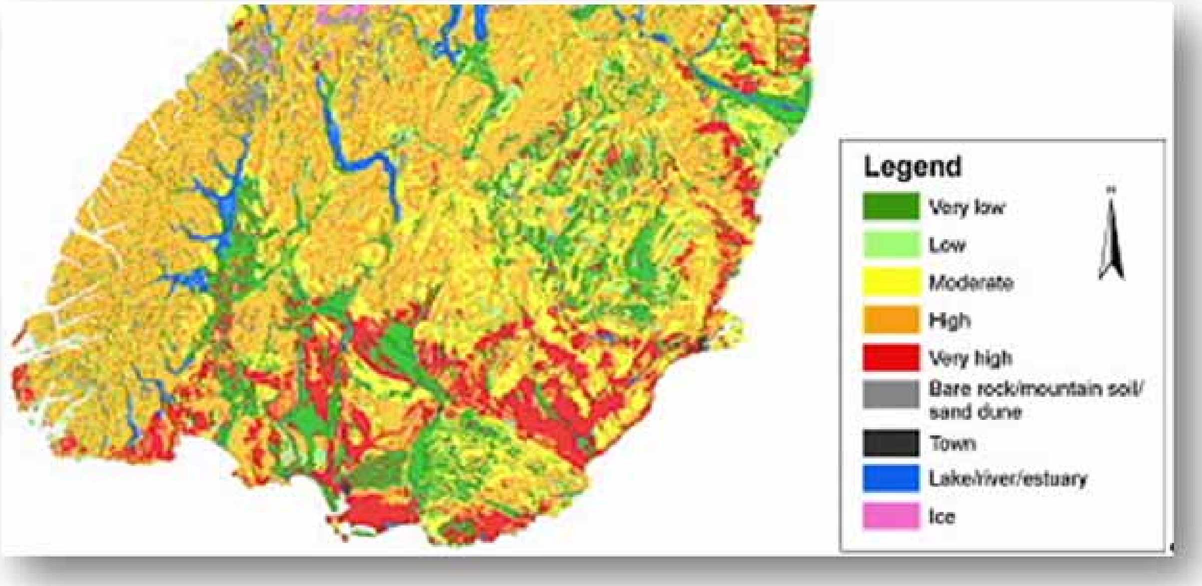

Figure 2-8: Likelihood of transport of microbes through soil by bypass flow on flat to rolling land in the Southland Region from McLeod et al. (2008).

A more recent study by Webb et al. (2010) refined the rankings of McLeod et al. (2008). Specifically, vulnerability to bypass flow was based on the presence of flood irrigation and drainage (not well documented how this has been established) and presence of macropores/cracks in the soil based on soil properties (Webb et al., 2010 and Lilburne et al., 2014). As such Webb et al.'s (2010) bypass flow map includes vulnerability to both artificial and natural bypass flow. Figure 2-9 illustrates Webb et al.'s (2010) bypass flow ranking for the Southland Region which has been included in S-map. Differences between Webb et al.'s (2010) (S-map) and McLeod et al.'s (2008) bypass flow ranking (Figure 2-8 and Figure 2-9) are particularly notable in intensely farmed areas, such as the Central Plains, a higher bypass flow ranking in S-map can be attributed to the presence of artificial drainage. Webb et al.'s (2010) bypass flow map does not differentiate between natural and artificial bypass flow.

TC2.3.2 Development of a regional shallow bypass flow map

We used the more recently established map developed by McLeod et al. (2008) to define shallow natural bypass flow vulnerability in Southland. We then combined it with the drainage density layer developed by Pearson (2015) to define shallow artificial bypass flow vulnerability based on drainage density. Specifically, Table 2-3 summarizes the bypass flow ranking that was defined on the basis of the bypass flow map Webb et al. (2010), S-map and the drainage density map by Pearson (2015) in this study. For example, areas with high S-map bypass flow and low artificial drainage were defined as high in natural bypass flow. Vice versa, areas with high S-map bypass flow and high drainage were defined as high in artificial bypass flow.

We note that neither Webb et al.'s (2010) nor McLeod et al.'s (2008) bypass flow map fully cover the entire region, e.g. bypass in alpine and bedrock areas were not defined (Figure 2-9). Since these areas are not used for agricultural cultivation, due to their steep slopes and/or very thin to non-existing soil layer, we assume that artificial bypass flow in these areas is low to none (as also suggested by Pearson, 2015). Similarly, we assume that natural bypass flow is also low, because groundwater resources in bedrock areas is negligible and the steep sloped terrain of alpine areas supports the presence of overland flow as main water path.

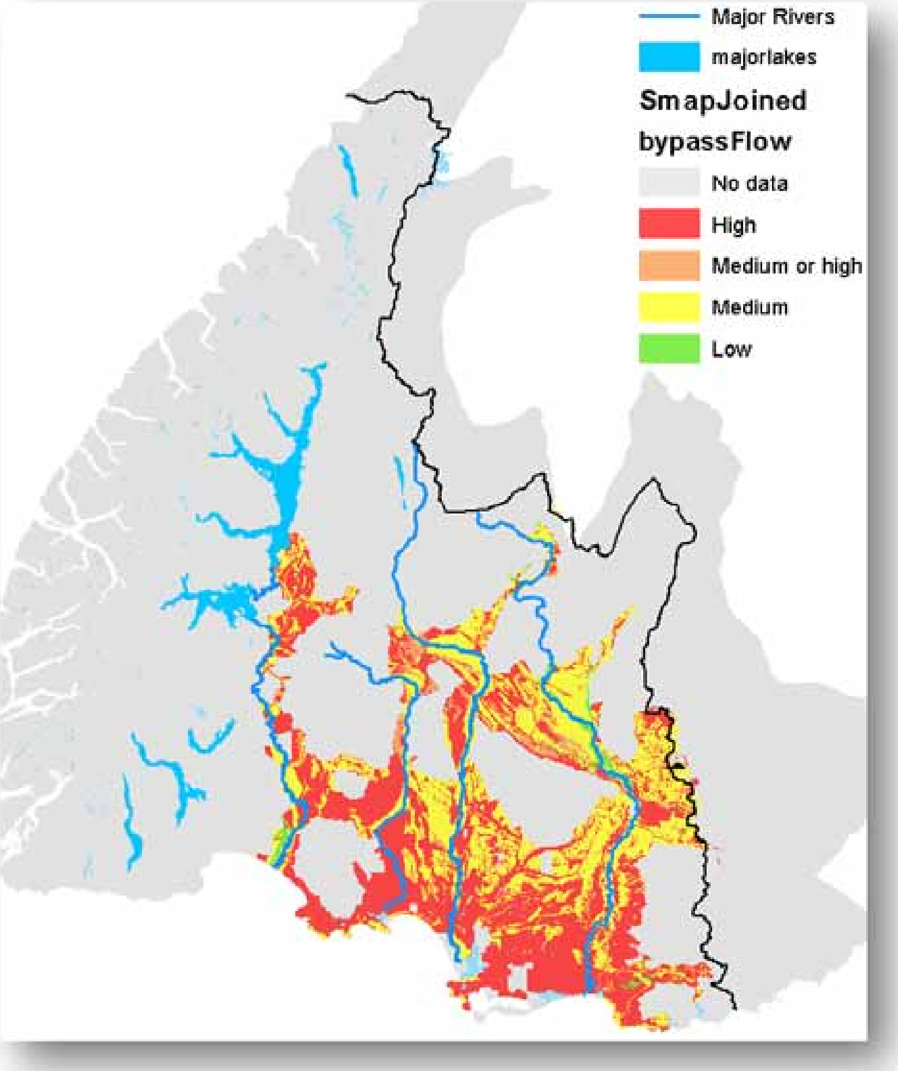

Figure 2-9: S-map soil bypass flow ranking for the Southland Region.

The map was further refined by adjusting natural bypass flow rankings for certain soils on the basis of detailed field data by Greenwood (1999). Specifically, Greenwood (1999) showed that Makarewa, Aparima, Dacre, Pukemutu and Waikoikoi soil series are prone to natural bypass flow, either seasonally due to drying and cracking of the soil, or all year round due to the soils macroporosity conditions. For only 1 out of 2,340 S-map soil polygons associated with these soils, the S-map bypass flow ranking was defined as ‘Low’. For this particular soil polygon, we corrected the S-map bypass ranking to ‘Medium or high’.

Figure 2-10 illustrates the final bypass layer ranking map of Southland combining all above information on bypass from the different sources. We will show in TC 6 and Chapter 3 that the established map supports observed groundwater and surface quality, in particular the concentration of redox sensitive species and consequent the redox status of regional groundwaters.

Table 2-3: Shallow bypass flow ranking for this study was defined on the basis of the bypass flow map Webb et al. (2010) S-map and the drainage density map by Pearson (2015).

Bypass flow ranking (Webb et al., 2010; S-map)	Drainage density (Pearson, 2015)	Bypass flow ranking for this study
low	Low	Natural bypass - low
	low (slope)	
	none (not agricultural)	
	very low to none	
	moderate	Artificial bypass - medium
	High	Artificial bypass - high
	very high	
	n/a	Natural bypass – low, no drainage data
medium	Low	Natural bypass - medium
	low (slope)	
	none (not agricultural)	
	very low to none	
	moderate	Artificial bypass - medium
	High	Artificial bypass - high
	very high	
	n/a	Natural bypass – medium, no drainage data
medium or high	Low	Natural bypass - moderate or high
	low (slope)	
	none (not agricultural)	
	very low to none	
	moderate	Artificial bypass - medium
	High	Artificial bypass - high
	very high	
	n/a	Natural bypass – medium or high, no drainage data
high	Low	Natural bypass - high
	low (slope)	
	none (not agricultural)	
	very low to none	
	moderate	Mix artificial and natural bypass- high
	high	Artificial bypass - high
	very high	
	n/a	Natural bypass –high, no drainage data
n/a	low	Artificial bypass – low, no S-map data
	low (slope)	
	none (not agricultural)	
	very low to none	
	moderate	Artificial bypass – medium, no S-map data
	high	Artificial bypass – high, no S-map data
	very high	

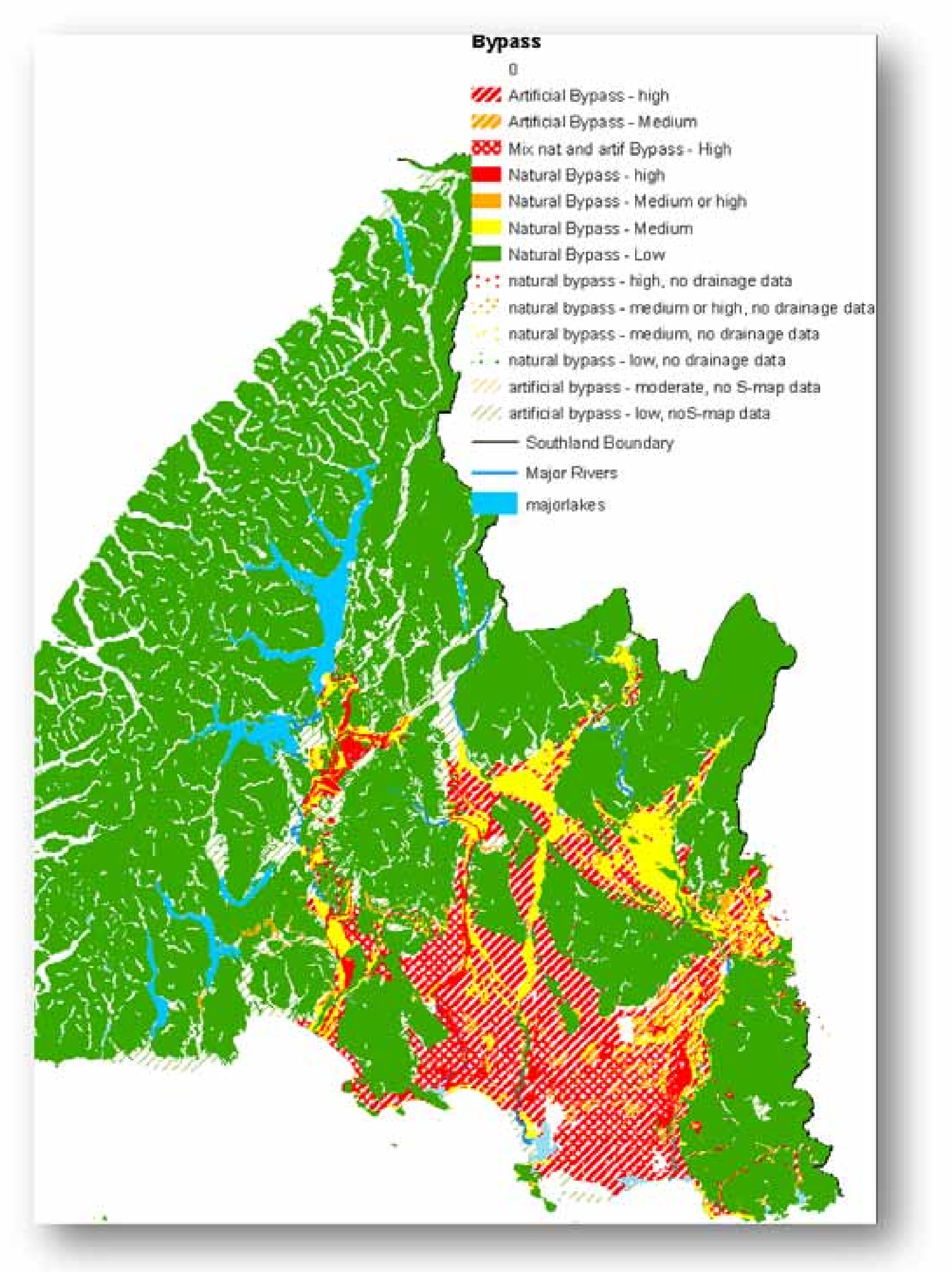

Figure 2-10: Established shallow bypass flow map for the Southland Region illustrating the vulnerability of Southland soils to artificial and natural bypass flow. The map was established on the basis of bypass flow vulnerability estimates given in S-map and drainage density estimates predicted by Pearson (2015). Definition of categories is given in Table 2-3.

TC2.3.3 Deep bypass flow map based on soil properties

In some areas of Southland, such as the Central Plains, natural conditions for deep bypass flow may evolve under unusual, e.g. extremely dry or wet, conditions. For example, deep cracks may open in the soil layer creating conditions for deep bypass flow for soils that are not normally vulnerable to deep bypass flow. Evidence for this soil behaviour at Heddon Bush in the Central Plains is provided by hydrograph data showing temporal variability in rainfall, soil moisture and underlying groundwater level (Figure 2-11). Figure 2-11 illustrates that the groundwater level at Heddon Bush responded rapidly to rainfall events during the months of May to July in 2013, which can be linked to deep drainage, deep bypass or deep macropore flow. During the remaining months, the groundwater level is less responsive to rainfall events indicating the absence of deep drainage or bypass flow.

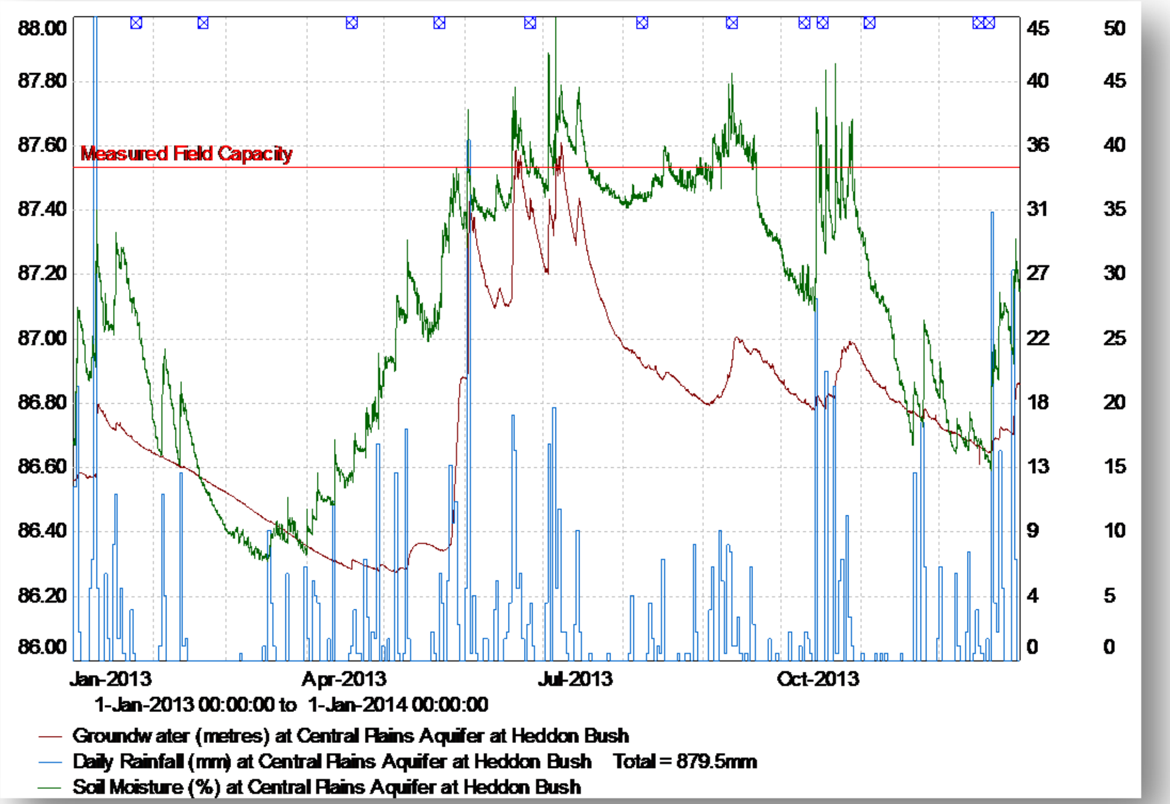

Figure 2-11: Temporal variation in rainfall, soil moisture and groundwater level at Heddon Bush, 2013.

During the summer and early autumn, soil moisture remained well below field capacity and groundwater levels show limited response to individual rainfall events, indicating limited deep drainage. However, during late autumn, soil moisture progressively increased due to regular rainfall and lower evapotranspiration. Field capacity was reached in early May. At this point groundwater levels exhibit a rapid rise of around 1 meter indicating the occurrence of rapid deep drainage. Over the subsequent winter and early spring groundwater levels showed a more muted response to rainfall when soil moisture reaches field capacity. The difference in the magnitude of groundwater level response to rainfall of a similar magnitude between late autumn and the subsequent winter period is attributed, at least in part, to the hydraulic properties of the soils in this area.

This behavior in the Central Plains is linked at least in part, to the hydraulic properties of the soils in this area. Due to weathering of mafic parent material, soils in this area contain a relatively high proportion of clay minerals, principally montmorillonite, which are subject to shrink/swell behavior. As soil moisture is reduced during the summer these minerals shrink, opening cracks within the otherwise slowly permeable soil matrix. During late autumn this cracking enables rapid bypass flow through the soil matrix. However, as the clay minerals rehydrate, the macropore structures close and the soils revert to being slowly permeable, resulting in a reduced volume of deep drainage in response to rainfall events during the winter period.

Figure 2-12 shows that (shallow) bypass flow vulnerability based on McLeod et al. (2008) and Pearson (2015) in the Heddon Bush area is mapped as ‘high natural bypass’, ‘medium natural bypass’ or ‘high artificial bypass’ suggesting that our established map of shallow bypass flow vulnerability gives reasonable bypass vulnerability estimates for this area. Unfortunately, information such as hydrograph data are rare, which make it extremely difficult to identify deep bypass flow of soils that may behave differently to that indicated on a map (with regards to shallow bypass flow illustrated in Figure 2-12).

We used soil properties to better define vulnerability towards deep bypass flow. Specifically, we assumed that soils that have similar properties to those of the Central Plains, where we observe deep soil cracking during dry periods, are expected to be vulnerable to deep natural bypass flow during dry periods. As mentioned earlier, the properties of the Central Plains soils that can be linked to the shrink swell behaviour of the soils causing deep soil cracking include:

- Pukemutu soil series
- Fragic Pallic, Fragic Gley, or typic gley soils

Figure 2-13 illustrates the area identified as being highly vulnerable to deep soil cracking/bypass flow on the basis of the above remaining soil properties[3]. This gives a liberal, potential estimate of possible deep natural bypass in the region. Assessment of the concentration of redox sensitive species in shallow groundwaters in these areas confirms that the reduction of infiltrating water does not occur, despite the reducing soils demonstrated below (see also TC 6).

Specifically, boxplots of the concentrations of redox sensitivity in areas vulnerable to deep bypass flow (as defined in Figure 2-13) vs. areas with reducing soils (further detailed in TC 6) that are not vulnerable to bypass flow, suggest significantly different redox conditions in bypass flow environments. For example, Fe(II) and Mn(II) are lower while D.O. and NO_3-N are higher in areas with potential deep bypass flow. ANOVA testing on normalized data[4] confirmed Fe(II), Mn(II) and NO_3-N are significantly different for the ‘bypass’ and ‘non-bypass’ group. Assessment of nitrate hotspots over reduction potential of soil and geology in TC 6 (Figure 6-15 and Figure 6-16) further demonstrates reduction of nitrate in shallow groundwater does not occur, despite reducing soils.

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[3] Using query definition in ArcGIS: (FamilyName = 'Pukemutu' OR (NZSCDescri LIKE '%Fragic%' AND NZSCDescri LIKE '%Gley%') OR (NZSCDescri LIKE '%Fragic%' AND NZSCDescri LIKE '%Pallic%') OR (NZSCDescri LIKE '%Typic%' AND NZSCDescri LIKE '%Gley%'))

[4] inverse of D.O.; Mn(II), Fe(II), NO_3-N no transformation required

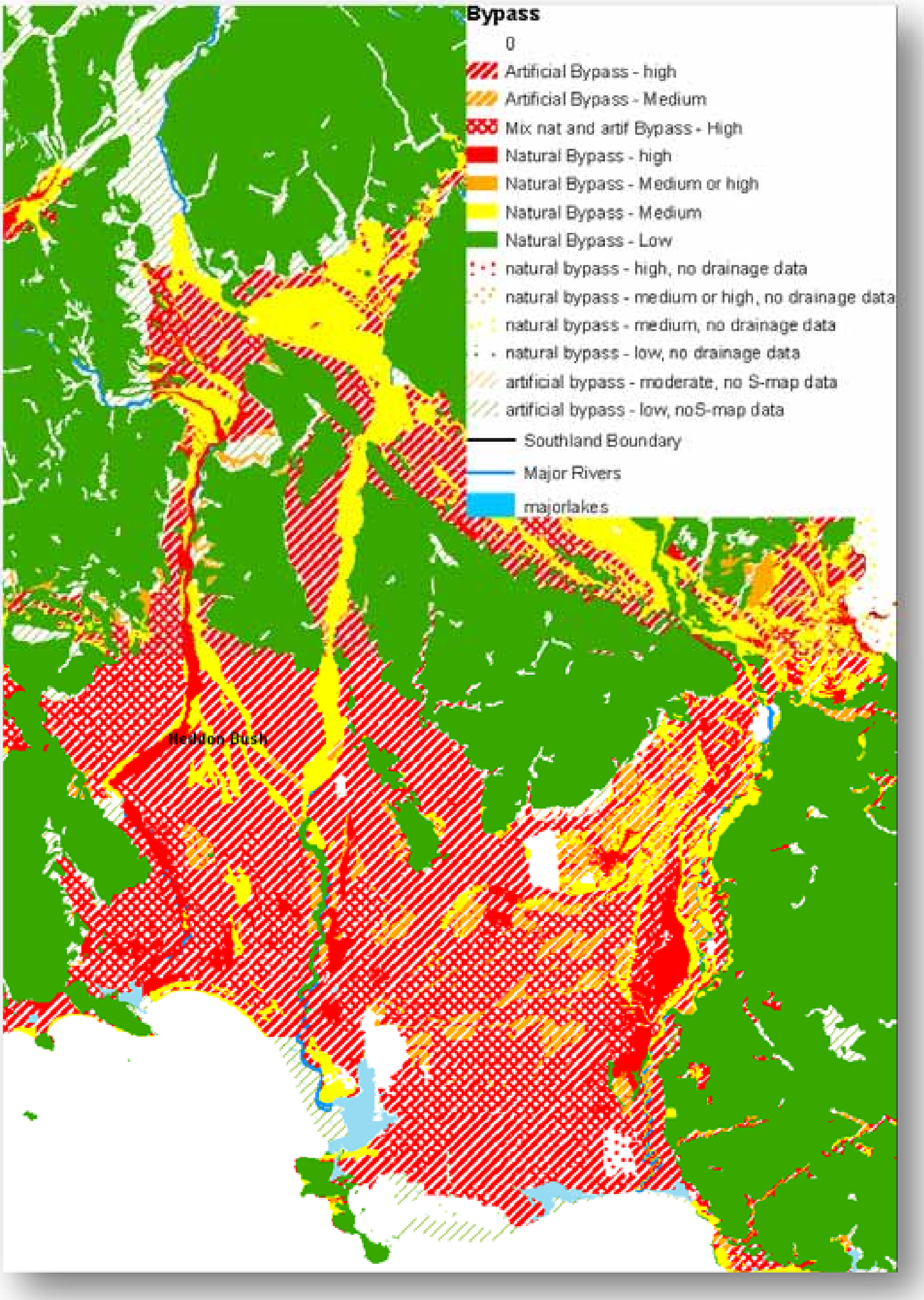

Figure 2-12: Close-up of bypass vulnerability map (given in Figure 2-10), highlighting the location of Heddon Bush, where field data suggest high risk of bypass flow during some parts of the year.

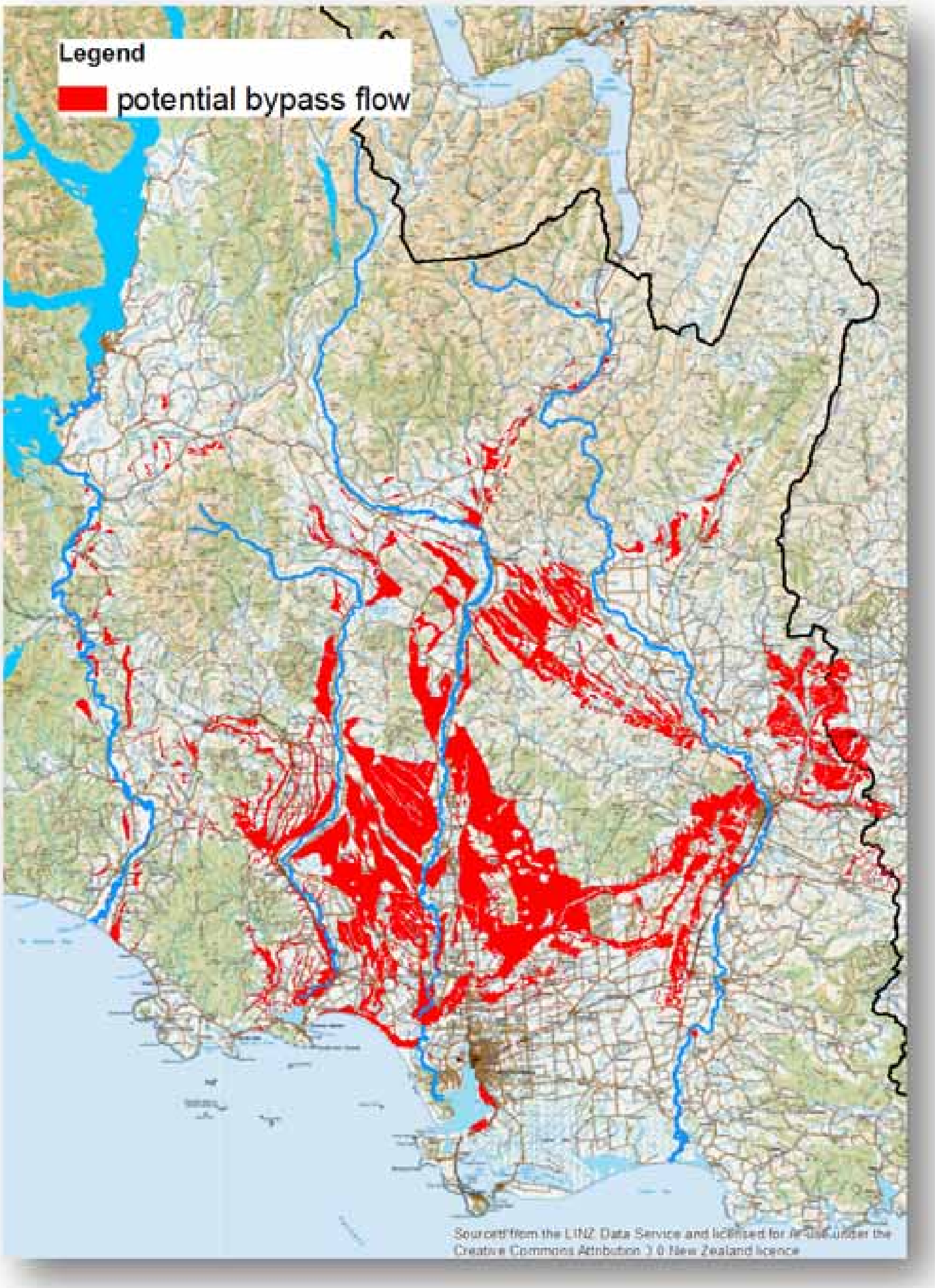

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Figure 2-13: Potential (deep, natural) bypass flow based on soil properties, i.e. similar properties to soils in the Central Plains that showed evidence of deep soil cracking during dry periods.

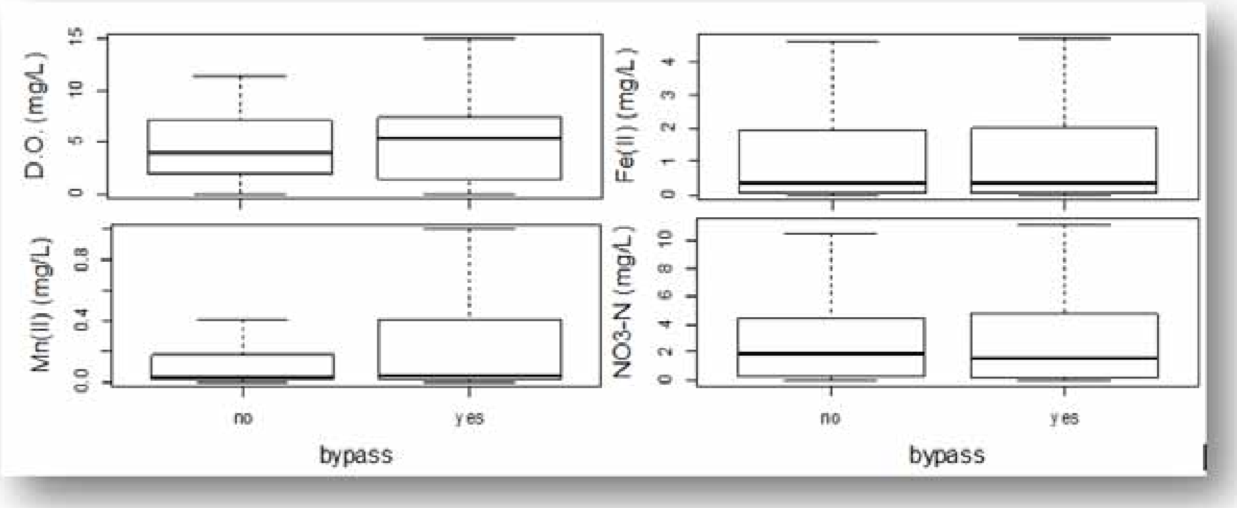

Figure 2-14: Boxplots of redox sensitive species in bypass and non-bypass areas that have reducing soils.

TC2.4 Groundwater hydrodynamic zones

Generally a groundwater sample is a collection of waters from different sources, we therefore need to account for various pathways and sources of recharge for better estimation of groundwater chemistry. Hence, in addition to considering recharge domain and bypass vulnerability at each groundwater site based on the developed maps, we applied a simplified hydromorphic approach to constraining hydrogeological characteristics for regional groundwater wells. This included an assessment of the hydrodynamic setting of each well as defined by groundwater hydrogeological data associated with regional groundwater hydrodynamic zones (after Hughes, 2003 and 2016). Factors or categories defining the settings include:

1. Aquifer Type (i.e., lowland, terrace, riparian)
2. Degree of River Influence (High or Low)
3. River Connectivity (Low or High/Low)
4. Vertical Bypass (Low or High/Low)

Collectively, these relatively simplistic hydrogeological characteristics allow us to constrain what appears to be the most important drivers of groundwater and validate our conceptual model. High/Low designations recognise the high degree of heterogeneity in hydraulic connectivity to main stem rivers due to alluvial architecture. Similarly, vertical bypass of the soil zone is also heterogeneous as it is a function of soil properties.

Table 2-4: Groundwater zone information on river influence, connectivity, and type. The locations of the groundwater zones are illustrated in Figure 2-15.

GW Zone	Aquifer Type	River Influence	Connectivity	Bypass-Redox	K_H [m/d]
Castlerock	Terrace	Low	Low	Low	30
Central Plains	Lowland	Low	Low	High/Low	15
Edendale	Terrace	Low	Low	Low	100
Five Rivers	Riparian	High	High/Low	Low	50
Knapdale	Lowland	Low	Low	Low	25
Lower Aparima	Terrace	High	Low	High/Low	30
Lower Mataura	Lowland	High	Low	High/Low	50
Lower Oreti	Lowland	High	Low	High/Low	15
Lower Waiau	Terrace	Low	Low	Low	40

GW Zone	Aquifer Type	River Influence	Connectivity	Bypass-Redox	K_H [m/d]
Makarewa	Lowland	Low	Low	Low	10
Riversdale	Riparian	High	High/Low	Low	200
Te Anau	Terrace	High	High	Low	50
Upper Aparima	Terrace	High	High/Low	High/Low	50
Upper Mataura	Riparian	High	High/Low	High/Low	100
Waihopai	Lowland	Low	Low	Low	15
Waikaia	Riparian	High	High/Low	Low	
Waimatuku	Lowland	Low	Low	High/Low	20
Waimea Plain	Lowland	Low	Low	High/Low	30
Waipounamu	Riparian	High	Low	Low	250
Wendonside	Terrace	Low	Low	Low	15

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Figure 2-15: Southland groundwater zones.

TC2.5 Summary

In summary, assessment of the relationship between $\delta^{18}O\text{-}H_2O$ and both Cl and EC in Southland's ground and surface waters showed distinct patterns of Na, Cl, EC and/or $\delta^{18}O\text{-}H_2O$ signatures that can be linked to three principal precipitation sources, (coastal, inland low altitude and alpine precipitation), as described in TC1 and three recharge mechanisms/domains (River Recharge (RR), Land Surface Recharge (LSR) and mixed recharge). We also developed a map of natural deep bypass flow. Both the deep natural bypass flow map and the recharge domain and recharge mechanism maps are used in the Conceptual Model (Chapter 3) in combination with other driver maps to predict regional freshwater quality and composition.

Specifically, we found that in alpine and hill country areas, surface waters are recharged proximally through overland flow. Significant groundwater resources in these areas do not exist. In lower altitude areas such as the northern and southern inland plains, most ground- and surface waters are recharged proximally through LSR. The remaining groundwater occurs across the inland (low altitude) plains in close proximity to major stem rivers receiving mixed recharge of alpine and bedrock sourced rivers and LSR from riparian groundwater systems.

We summarised and translated precipitation source, marine aerosol load and recharge mechanisms into four main recharge domains:

a) Alpine River Recharge – originating from high altitude (>800m RSL) areas;

b) Bedrock River Recharge – originating from mid to high altitude (<800m RSL) bedrock catchments both coastal and inland. We observed that bedrock derived streams that are disconnected to alpine areas carry a different signature than bedrock derived streams that receive a small alpine input, often switching between the alpine and bedrock signatures occurs in response to the presence or absence of alpine input. This suggests that in Southland we can distinguish between pure bedrock RR that is disconnected from alpine areas, referred to as 'bedrock 2' and bedrock RR that receives some proportion of alpine RR, referred to this as 'bedrock 1'.

    a. Bedrock 1: pure bedrock RR that does not receive an alpine input

    b. Bedrock 2: bedrock RR that receives an alpine input

c) Land Surface Recharge coastal and inland – precipitation percolating through lowland soils (<500m RSL), and;

d) Mixed recharge - i.e. distal = hill country or alpine RR in addition to proximal LSR (inland and coastal) across the low altitude plains in close proximity to major stem rivers.

To discriminate between these recharge domains and precipitation sources, threshold values of conservative tracers Na, Cl, EC, and elevation can be used (summarized in Table 2-5). In combination with $\delta^{18}O\text{-}H_2O$ and carbonate saturation data, and the degree of alkalinity, it is possible to further discriminate Land Surface Recharge and carbonate influenced recharge, respectively. We note that waters that are characterised as alpine and bedrock /hill country recharge exhibit the lowest variation in chemical composition and are therefore easiest to distinguish from waters that are recharged through LSR or mixed recharge. Waters that are characterised as LSR generally show the highest variability in composition, probably reflecting the heterogeneous chemistry of geology and soil in lowland Southland. In addition, precipitation can range from dilute, in close proximity to high altitude areas, to highly concentrated in Na and Cl in close proximity to the coast.

Distinguishing LSR waters from waters that received mixed recharge, i.e. LSR and RR, is difficult, as even a small amount of LSR can have a large effect on chemistry. For example, see description of groundwater cluster 2 south in Table 2-1. Assuming that mixed recharge is limited to areas with recent fluvial soils, which are very transmissive and in close proximity to major stem rivers which support mixed recharge, we expect to be able to distinguish between groundwaters that receive mixed recharge, from those that receive LSR based on their location and consideration of hydrodynamic zone characteristics.

Table 2-5: Summary of thresholds of indicator species used to discriminate recharge sources and recharge mechanisms of Southland surface and ground water. * we distinguish bedrock 1 (connected to alpine) and bedrock 2 (disconnected to alpine) on the basis of connectedness to alpine areas using REC capture zones.

Indicator Species	Alpine RR	Hill country/ bedrock RR*	Coastal, lowland plains	LSR across inland, lowland plains	Mixed recharge across inland, lowland plains
Electrical Conductivity [µS/cm]	Very Low (<80)	Low (<100)	High (>120)	Mod (80-120)	Mod to low
Cl [mg/L]	Very Low (<8)	Low (<15)	High (>25)	Mod (15-25)	Mod to low (5-15 North; 15-30 South)
Na [mg/L]	Very Low (<5)	Low (<8)	High (>20)	Mod (10-20)	Mod to low (5-15 North, 13-25 South)
δ^{18}O-H_2O [pptv VSMO]	Very Low (<-9.3)	Low (<-7.4)	High (> - 7.4)	Mod (-7-8)	Mod to low
Elevation/ Topography	Mountainous >800 m RSL	Elevated bedrock 500-800 m RSL	<500m RSL, close proximity to coast	<500m RSL	<500m RSL

The recharge domains were subsequently mapped as key drivers for the prediction of regional water chemistry. Specifically, areas > 800m were defined as alpine. Bedrock/rock outcrop areas using Qmap < 800m were defined as bedrock[5]. We then defined bedrock 1 and bedrock 2 areas on the basis of their connection to alpine (>800m) areas. Specifically, we used stream catchments orders 1 – 6, i.e. catchments that contain alpine area(s), bedrock 1, vs. catchments that do not contain alpine area(s), bedrock 2, to distinguish between bedrock 1 from bedrock 2 areas[6]. The remainder of the region with alluvium, using Qmap, was defined as areas with predominantly LSR (Figure 2-16). Areas of recent and raw soils, using Topoclimate, that are connected to a stream with alpine source were defined as mixed recharge domain[7]. To define stream source, we used the REC classification. Specifically, we identified stream origin within alpine, bedrock and lowland areas (Figure 2-17 to Figure 2-19). For groundwaters, we also applied a simplified hydromorphic approach to constraining hydrogeological characteristics for regional groundwater wells. This included an assessment of the hydrodynamic setting of each well as defined by groundwater hydrogeological data associated with regional groundwater hydrodynamic zones.

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[5] Specifically, we used the following mapping rules: Qmap - Map Unit = Bedrock NOT alluvium/colluvium with the exception of Till and Moraine or inferred Till or Moraine (mapped as outwash gravel, Te Anau basin only). AND include any Lignite/Marine Terraces polygons with a slope >7° (DEM)

[6] Specifically, we selected catchments (order 1-6) that contained areas >800m. Then selected all areas of bedrock within these catchments and defined these as bedrock 1. We then removed bedrock areas that are in a lowland setting or not hydraulically connected to alpine areas. The remaining bedrock that did not intersect alpine areas was defined as bedrock1.

[7] Specifically, the following mapping rules were used: TCS - NZSC Order and Group = Recent Fluvial Soils; excluding the 'Waiau' soil Series in the Lower Waiau Catchment. Also excluding recent fluvial soils that are not within an active floodplain, defined by terraces, or do not have an alpine source (> 800 masl) (DEM, REC) AND Qmap - Map Unit = All alluvium hydrologically connected to an alpine source (> 800 masl, DEM, REC) where no soil information exists.

In this chapter we also showed that in addition to recharge mechanism and precipitation source, the presence of bypass flow can also significantly affect freshwater quality. We established a map of the bypass flow vulnerability of soils in the Southland region. The novelty of this map is that we can distinguish between the vulnerability to shallow and deep natural bypass flow, caused by deep soil cracking and shallow natural, caused by shallow soil cracking and shallow artificial bypass flow, caused by artificial drainage.

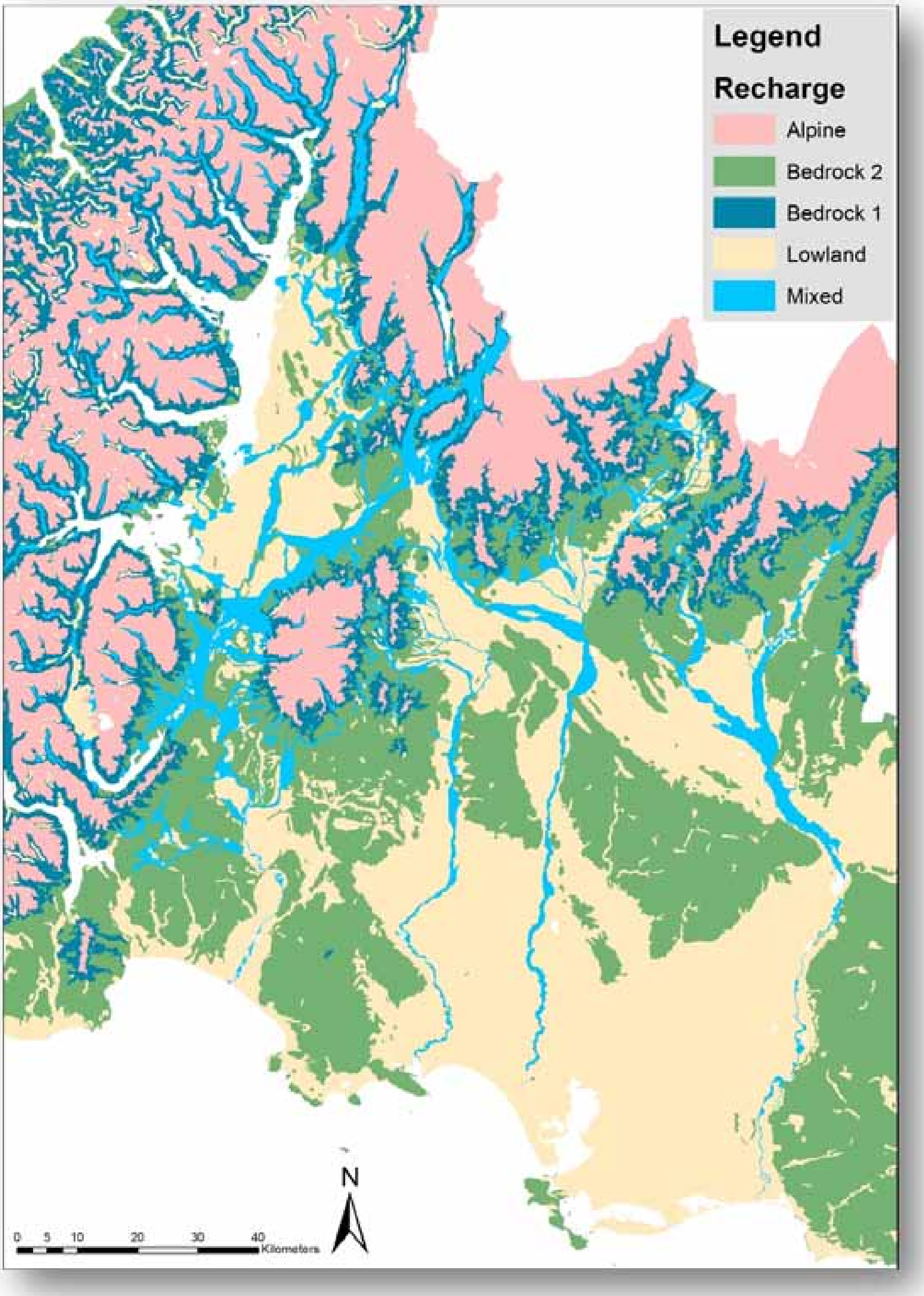

Figure 2-16: Recharge domains (Alpine RR; Bedrock RR; Lowland LSR, and; Mixed Alpine RR and Lowland RR) and bypass.

We added the bypass map to the recharge domain map to establish the conceptual maps showing the recharge mechanism, potential bypass and river source. These provide a spatially explicit picture of water source controls that have been developed on the basis of the above analysis (Figure 2-16 to Figure 2-18). These maps form the basis for interpreting water source and are used in conjunction with precipitation source to stratify the hydrochemical data and build the Conceptual Model (Chapter 3).

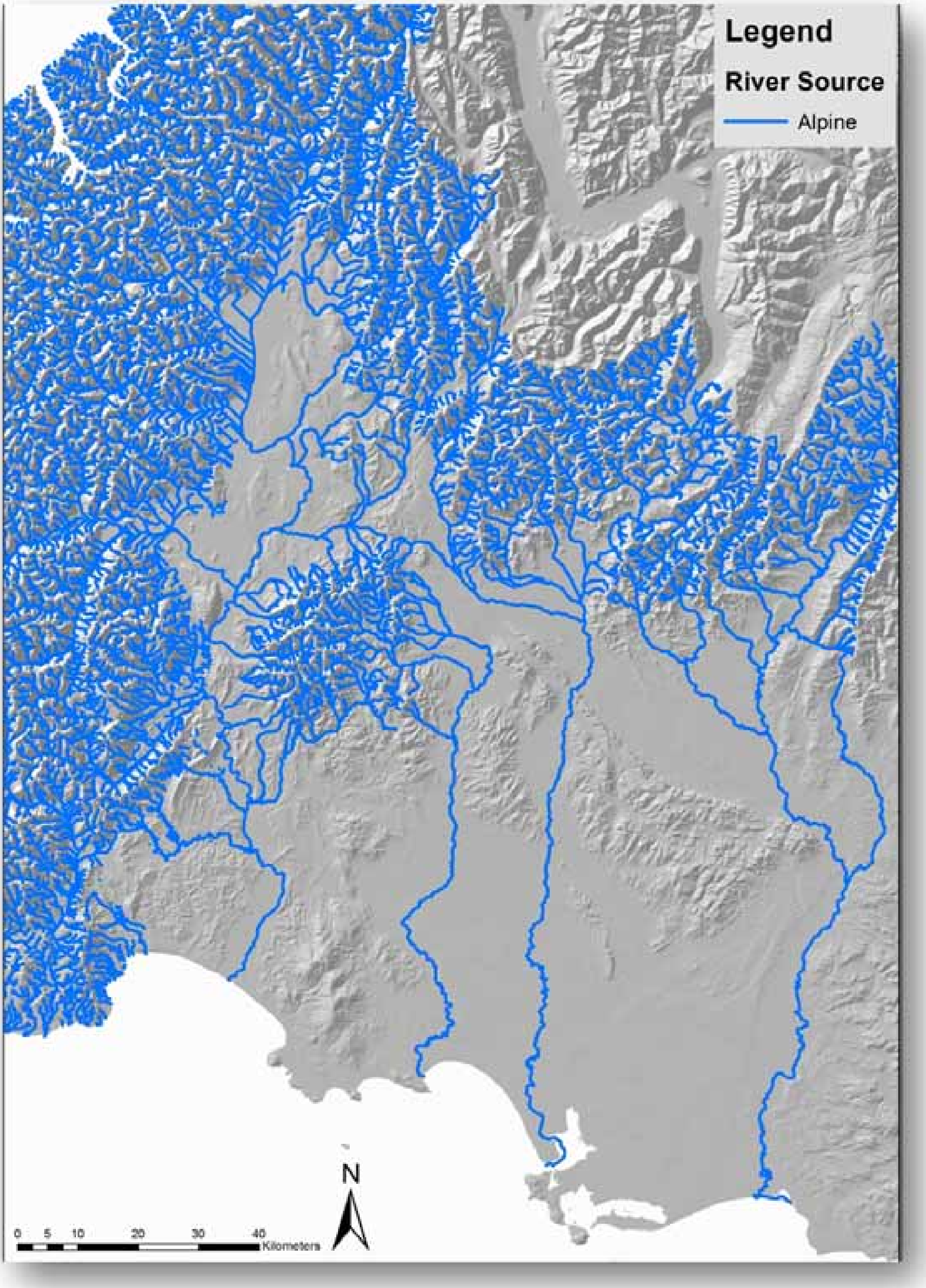

Figure 2-17: Alpine river recharge domain sourced river network from REC.

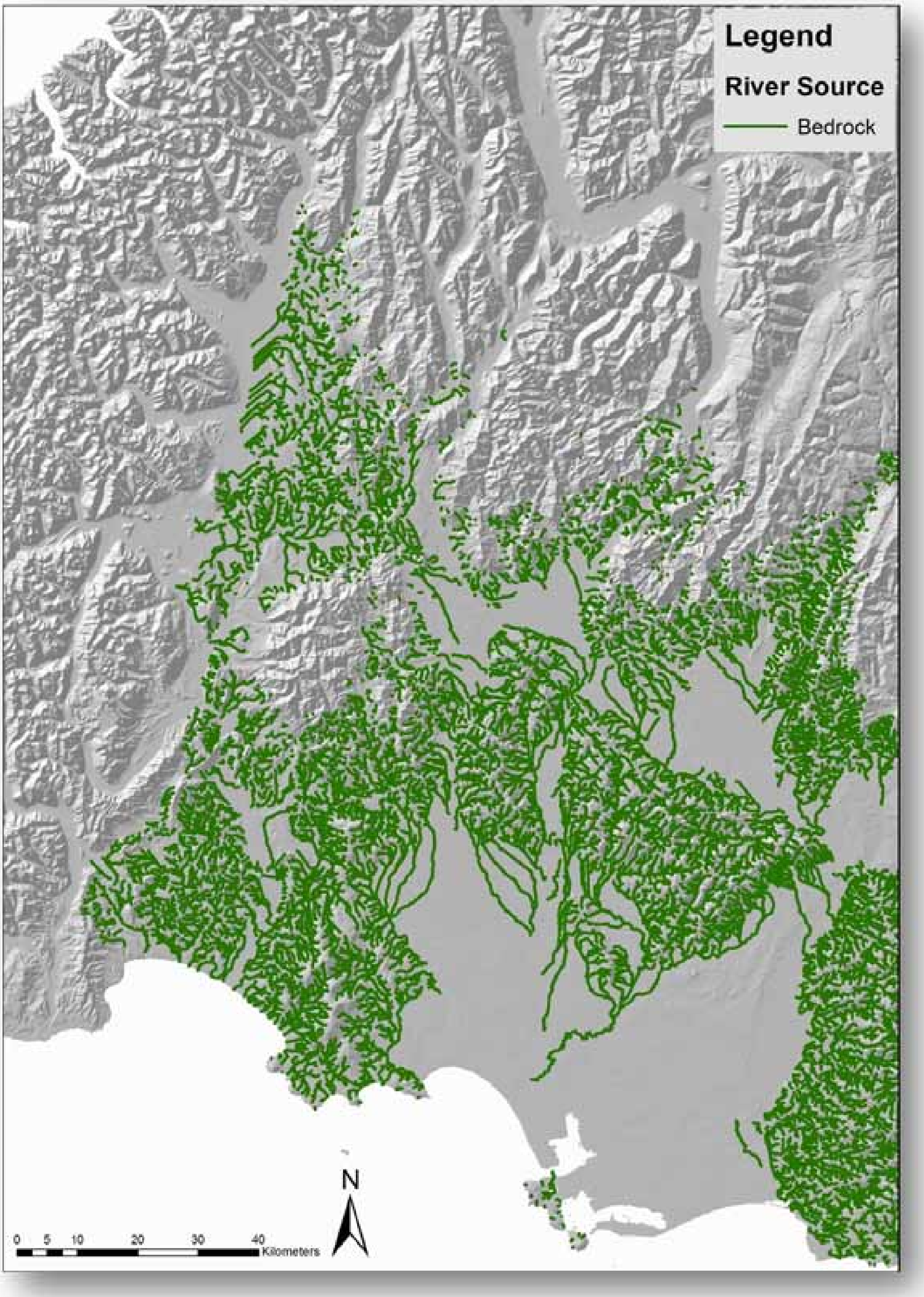

Figure 2-18: bedrock sourced river network from REC.

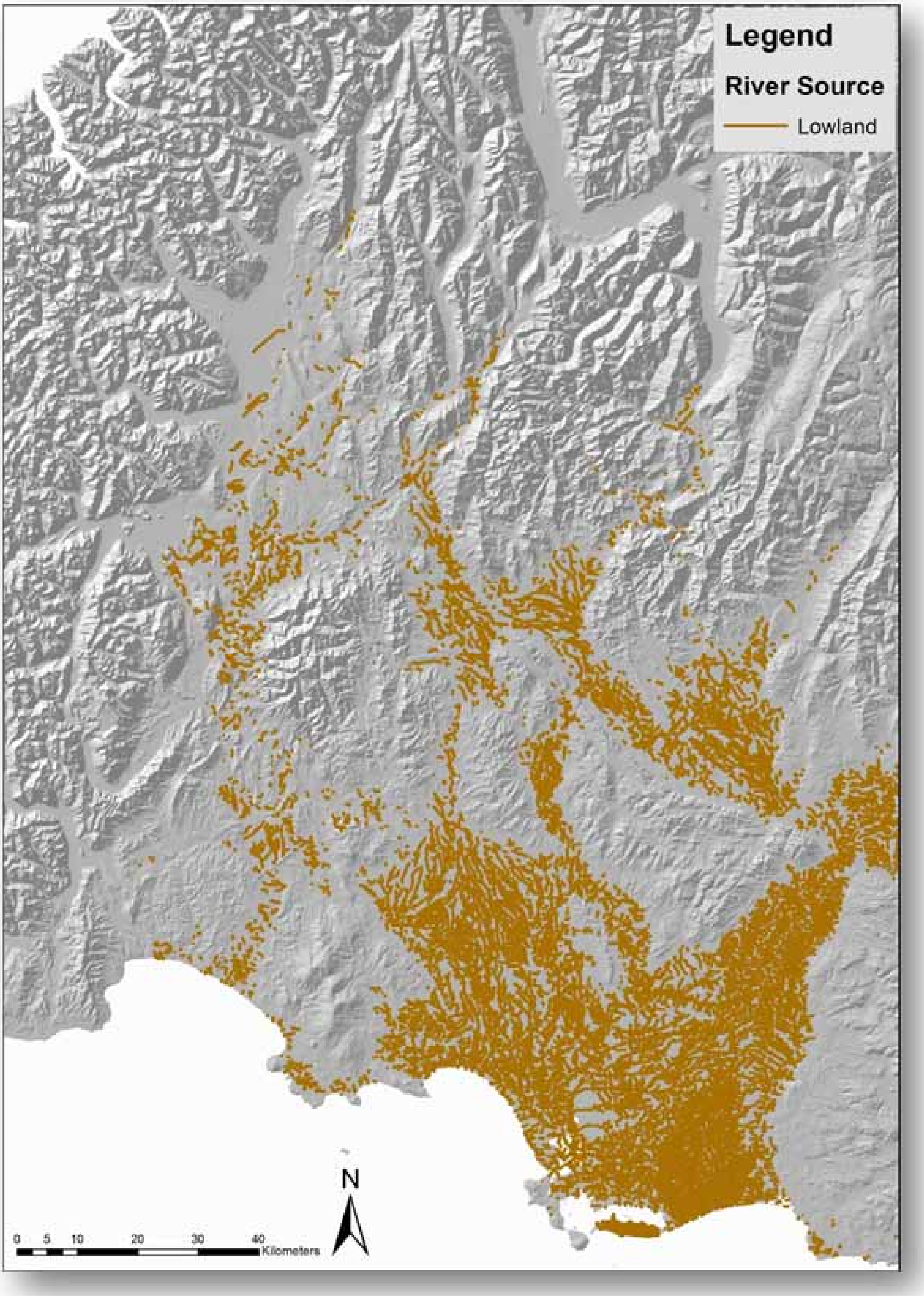

Figure 2-19: LSR sourced river network from REC.