

Physiographics of Southland

Part 1:

Delineation of key drivers of regional hydrochemistry and water quality

Technical Report

June 2016

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Physiographics of Southland

Part 1:

Delineation of key drivers of regional hydrochemistry and water quality


Technical Chapter 8:

Geomorphic Surface Age and Substrate Compositional Influences over Regional Hydrochemistry

June 2016

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TC8 Geomorphic Surface Age and Substrate Compositional Influences over Regional Hydrochemistry

TC8.1 Introduction

As discussed in the preceding TCs, identifying the key drivers of hydrochemistry for a region, and understanding why they vary in space, is critical to explaining variations in freshwater hydrochemistry, and therefore water quality. The main objective of this section is to produce a calibrated map that estimates substrate Ca, Mg and other major cations such as K abundance and pH buffering capacity from spatial frameworks of geomorphic surface age and substrate composition. This map constitutes a key driver layer necessary for explaining spatial variance in Ca, Mg and other major ions, pH and alkalinity of surface waters and soil influenced groundwater. The importance and influence of the recharge domain (hydrology), precipitation and redox as they relate to variation in concentrations and pH of regional freshwaters, is dealt with via a combination of driver layers in Chapter 4 (Validation of the Conceptual Model).

In TC 3 it was shown that the geomorphic surface age, its degree of weathering and substrate composition e.g., mafic, felsic, carbonate and peat are the chief determinants over soil Base Saturation (BS), Ca, and Mg abundance and the pH, buffering capacity of regional soils. Specifically, geomorphic surface age followed by parent material composition determine upwards of 65% of the chemical variability of regional soils, reflecting the joint influence of geomorphic surface age and the initial parent material composition over BS and pH of regional soils.

In TC 4 the important correlation between soil BS, pH and soil water hydrochemical composition was established including a demonstration of how the alkalinity of shallow, soil influenced groundwater can be estimated from soil pH and the partial pressure of soil zone CO₂.

In TC5 the key relationships between soil water hydrochemistry and regional freshwaters were demonstrated, including the observation that there was no statistically significant difference in Ca and alkalinity concentration between soil waters and oxidised, under-saturated, with respects to carbonate minerals, groundwater and surface waters regionally.

Collectively, TC 3 to TC5 demonstrate the coupled relationship between geomorphic surface age and substrate composition over the Ca, Mg, pH and alkalinity profiles of regional soil, soil waters, surface water and soil-influenced groundwaters. TC8 develops the findings of the previous technical chapters to classify spatial frameworks of geomorphic surface age and substrate composition into meaningful categories that govern spatial variance in Ca, Mg, pH and alkalinity profiles of regional soil¹, soil waters, surface water and soil-influenced groundwaters.

This chapter provides detailed background information on the influence of geomorphic surface age and landform/substrate composition on soil properties, in particular soil BS, pH buffering and major ion composition (Ca, Mg, K). It also summarizes existing frameworks to define geomorphic surface age and substrate composition.

¹ Where alkalinity refers to soil alkalinity generating potential.

TC8.2 Background – Context and Existing frameworks for classification of geomorphic surface age and substrate composition

TC8.2.1 Geomorphic Surface Age

Landform ‘types’ may be summarised according to topographic and climatic factors as well as geomorphic characteristics, specifically, ‘erosive’ and ‘constructional’ landforms. Erosive landforms are defined as areas of uplifted or exposed bedrock, subject to higher rates of mechanical weathering due to topographic relief and greater climatic extremes. In this context Southland’s steep alpine mountains and subalpine hill country are classified as erosive. In contrast, constructional or so called ‘depositional’ landforms are the product of sediment transport and deposition from areas of active erosion.

Alpine areas are characterised by predominantly bare rock, incipient soil cover and low organic carbon biomass. Valleys or depositional areas within alpine areas or more stable plateaus may support areas of greater biomass and thicker soil development but overall these areas are minor relative to the area of exposed bare rock.

Subalpine ‘hill country’ across Southland has a long history of thick forest or tussock cover. Due to dense vegetative cover, soils often have a duff or litter layer. Dense vegetative cover reflects less extreme temperature variation relative to alpine areas and abundant precipitation. Windthrow of trees is a significant bioturbation mechanism. Steep slopes are also prone to slips, sheet or rill erosion. Material eroded from alpine and sub-alpine hill country is eventually redeposited across low lying areas.

Constructional or so called ‘depositional’ landforms are the product of sediment transport and deposition from areas of active erosion. Aside from constructional landforms, geological age is not necessarily reflected by soil age (Schmidt et al., 2005). This is due to the spatial variability of erosion in exposing fresh parent materials and influencing soil development.

Across Southland, the dominant constructional landforms are alluvial in nature, reflecting a long history of glacial and fluvioglacial activity and associated reworking and deposition across the Southland Plains (Turnbull and Allibone, 2003). Alluvial landforms such as river terraces and floodplains constitute a relatively thin veneer (c. 30 m) on top of the poorly permeable basement rock of the Southland Plains. Alluvial and fluvioglacial landforms are loess mantled in places, with loess thickness increasing with landform age. Glacial moraines are important in parts of the Te Anau basin and their remnants occur in alpine areas.

A key attribute in understanding the physiographic setting of Southland and other temperate areas across New Zealand is the recognition that active eroding landforms often constitute the youngest geomorphic surfaces, even if the rock or landform is old. Specifically, recent glaciation and high physical erosion rates expose fresh or slightly weathered bedrock, particularly in areas of steep slopes or high altitude, which is subsequently transported by overland flow or mass movement processes to fluvial networks for redistribution downstream. In contrast, stable constructional landforms represent the accumulation of eroded material and represent the geomorphically most stable and consequently the oldest geomorphic surfaces in Southland. The youngest constructional surfaces (Q1) occur adjacent to main stem rivers and correlate with the distribution of eroded material from erosion prone parts of the landscape.

The contrast in mechanical erosion rates or geomorphic age, precipitation volume and temperature range between erosive landforms, alpine and sub-alpine and between erosive and constructional landforms is an important factor governing the hydrochemical evolution of groundwater and surface

waters. The latter reflects the dominant control of temperature, moisture flux and solution gradients over mineral weathering rates, microbiological activity and the accumulation of organic carbon through biomass (Moldan and Cerny, 1994; Lal, 2006).

The degree of weathering influences both pH buffering and the abundance of exchangeable Ca and Mg, as demonstrated in TC 3 (pH buffering capacity, and exchangeable Ca and Mg are well correlated with landform age). Generally, the rate of weathering or water rock interaction and the buffering capacity of stable landforms peaks and then slowly declines as a function of geomorphic age in response to the exhaustion of more reactive minerals or the occlusion by secondary mineral formation as the geomorphic surface weathers (Seyers and Walker, 1969; Seyers et al., 1970; Walker and Seyers, 1976; Crews et al., 1995). Weathering rate is also an important consideration when assessing regional hydrochemistry, as further detailed in TC8.2.2.

Across Southland, soils of elevated base saturation (BS) have high pH values and are associated with young alluvial sediments or parent materials that have a higher proportion of base cations (TC3). A strong correlation between the base cation composition of parent materials and both the BS and pH of Southland soils (TCs 3 and 4) was observed. As demonstrated in TC 4, soils of elevated BS produce waters of higher pH and consequently alkalinity. Due to the relationship between substrate type and pH buffering capacity it is important to recognise the spatial variability in substrate composition across Southland to better understand hydrochemical controls.

TC8.2.2 Landform/substrate composition

The ability of a substrate to buffer pH change is a feature of its composition. Specifically, substrates with high proportions of base cations (or 'Lewis bases') tend to have higher buffering capacities. Table 8-1 summarises the acid buffering capacity of differing substrates, adapted from Giller and Malmqvist (2004). Rock types with a great ability to buffer pH change tend to be carbonate or 'mafic' in composition or at least have relatively higher Ca and Mg contents. Felsic rocks, with lower base cations, have lower acid buffering capacity and organic substrates such as peat have very limited acidic buffering capacity and a high content of organic acids. Ultimately, substrate composition or lithological variance is the main source of pH buffering capacity. However, as demonstrated in TC 4 and TC 5, pH buffering is most commonly mediated through rapid reactions or process such as ion exchange and acid hydrolysis.

Table 8-1 summarises the acid buffering capacity, and Ca and Mg availability of Southland's landforms, as based on substrate composition and soil BS and pH. Readily apparent is the higher contents of Ca and Mg in mafic and ultramafic rock relative to felsic rock and sediment. These substantial compositional differences equate to significant differences in mineral weathering rates, acid buffering potential, the major and trace cation composition of soils, unsaturated zone and the saturated zone materials across Southland (Figure 8-2; see also TC 3 to 7). The spatial variability in the natural chemical characteristics of differing rock and sediment types influences the chemical composition of soil and ultimately the water that interacts with the soil during recharge or runoff. Similarly, large differences in chemical composition and hence reactivity of bedrock exposures, such as an outcrop of limestone within an area of predominantly felsic rock, will strongly influence the chemical composition of water it comes in contact with.

The following describes in further detail the availability of cations (i.e. BS and pH buffering) as a function of rock composition and degree of weathering and reactivity or weathering rates.

Table 8-1: Chemical characteristics of different rock types that drive water chemical variation across Southland (adapted from Giller and Malmqvist, 2004). The listed variables will vary according to the degree of weathering and are therefore a general approximation.

Geology	Composition	pH Buffering Capacity	Ca (Mg) abundance
Erosive Felsic	High siliceous with lower Ca, Mg and Fe than below	Low	Mod. Low
Erosive Mafic	Siliceous with elevated Ca, Mg, Fe	Mod.	High
Erosive Carbonate	Ca-CO ₃ /Mg-CO ₃ + minor felsic detritus	High	Very High
Aeolian/Alluvium Mafic/Ultramafic	Siliceous with elevated Ca, Mg and Fe	Low to High, depending on age of material (young=high, old=low)	High
Aeolian/Alluvium Felsic	High siliceous with lower Ca, Mg and Fe than above	Low	Low
Lignite/Marine Terrace	Felsic-organic	Mod.	Low
Peat	Organic	Very Low	Very Low
Ophiolite Alpine	Siliceous with high Mg relative to Ca	Mod.-High	Ca low (Mg high)

Availability of cations as a function of rock composition

The availability of Ca to water percolating through a substrate, is an important hydrochemical consideration. Calcium abundance within the environment is primarily a feature of rock weathering (TCs 3 and 4). However, with the exception of carbonate rock, Ca concentration in Southland groundwater and surface waters is acquired primarily from the soil zone via ion exchange, sorption and desorption processes (TC4 and 5). Again, parent materials with a high Ca concentration produce soils and secondary minerals with a higher abundance of exchangeable Ca. Magnesium availability mirrors that of Ca but it is most often subordinate to Ca in terms of concentration, with the exception of soils and waters originating from the Dun Mountain Ophiolite Belt where Mg abundance is greater than Ca.

Volcanic rocks are typically divided into four basic types according to the amount of silica (SiO₂) in the rock (Figure 8-1). However, as discussed above, it is the relative abundance of K, Ca, Mg and Fe that make the greatest difference in terms of rock weathering, reactivity and acid buffering potential and the supply of major ions to exchange sites and ultimately water. Naturally, the composition of a sedimentary rock will depend strongly upon the composition (e.g., felsic or mafic) of the detrital material. Accordingly, an output of this analysis is a map of spatial variability in parent material composition, landform type and age across Southland, discriminates between sedimentary rock of varying composition (e.g. felsic, mafic, carbonate, carbonaceous etc.). The provenance of alluvial and glacial, i.e. 'constructional' landforms are also sourced.

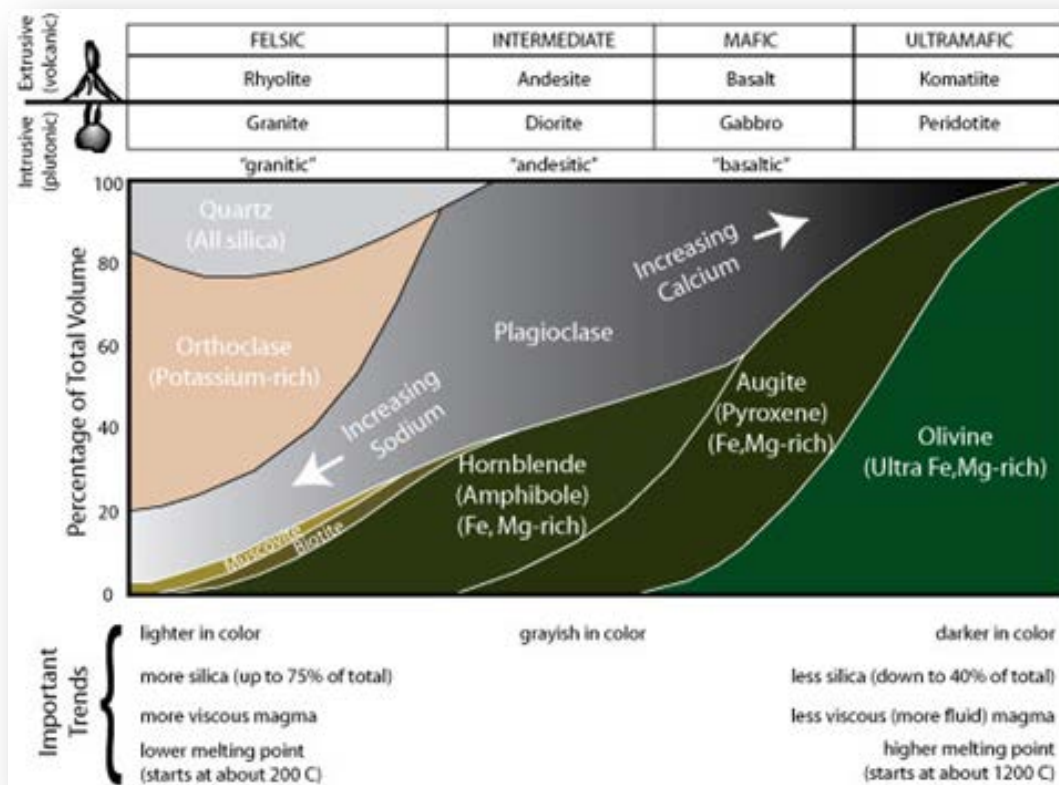


Figure 8-1: Major cation composition of igneous rock (after Hamblin and Christiansen, 2004).

Availability of cations as a function of degree of weathering and reactivity of rock

As mentioned above, the degree of weathering and reactivity also influences both pH buffering and the abundance of exchangeable Ca and Mg, and ultimately acid buffering capacity. Figure 8-2 depicts Goldich's weathering series for silicates and some non-silicates. It indicates that reactivity increases as the proportion of lower valence ions which replace Si within the silica lattice increases. For that reason, Fe, Ca and Mg rich mafic and ultramafic minerals are more reactive and have higher acid buffering potential than felsic minerals and also release larger quantities of Ca, Mg and in some instances Na (Lermand and Meybeck, 1985; Giller and Malmqvist, 2004). Conversely, felsic rocks and sediments contain lower concentrations of Ca, Mg, Na and Fe and yet significantly higher concentrations of Si and often K.

Weathering rates are also an important consideration when assessing regional hydrochemistry. For context, the weathering rates of major silicate minerals is summarised for a standard mineral size for a pH of 5 and a temperature of 25°C in Table 8-2 (after Lasaga, 1984). Immediately apparent is the incredibly slow reaction rates for quartz, feldspars (K-feldspar and albite) and micas (muscovite) that make up a large proportion of Southland's geology². Of these minerals, quartz and muscovite mica are largely insoluble whereas albite (Na-feldspar) is the most reactive. Even so, geological time spans,

² Quartz, muscovite, K-feldspar and albite (Na-feldspar) are the most abundant silicate minerals in Southland's Quaternary aquifers. Enstatite and diopside are ultramafic minerals and exceeding rare constituents of Southland's Quaternary aquifers. Nepheline is often found in mica and schist but is weathered very quickly and unlikely to persist for long enough to be deposited by alluvial processes. Anorthite is a rare compositional variety of feldspar and due to minor abundance and rapid weathering is unlikely to constitute a significant source of cations to local waters. Calcite sits somewhere between diopside and nepheline in terms of weathering rate.

tens of thousands of years, are required for appreciable albite weathering, especially under the cool temperate climate of Southland (Table 8-2).

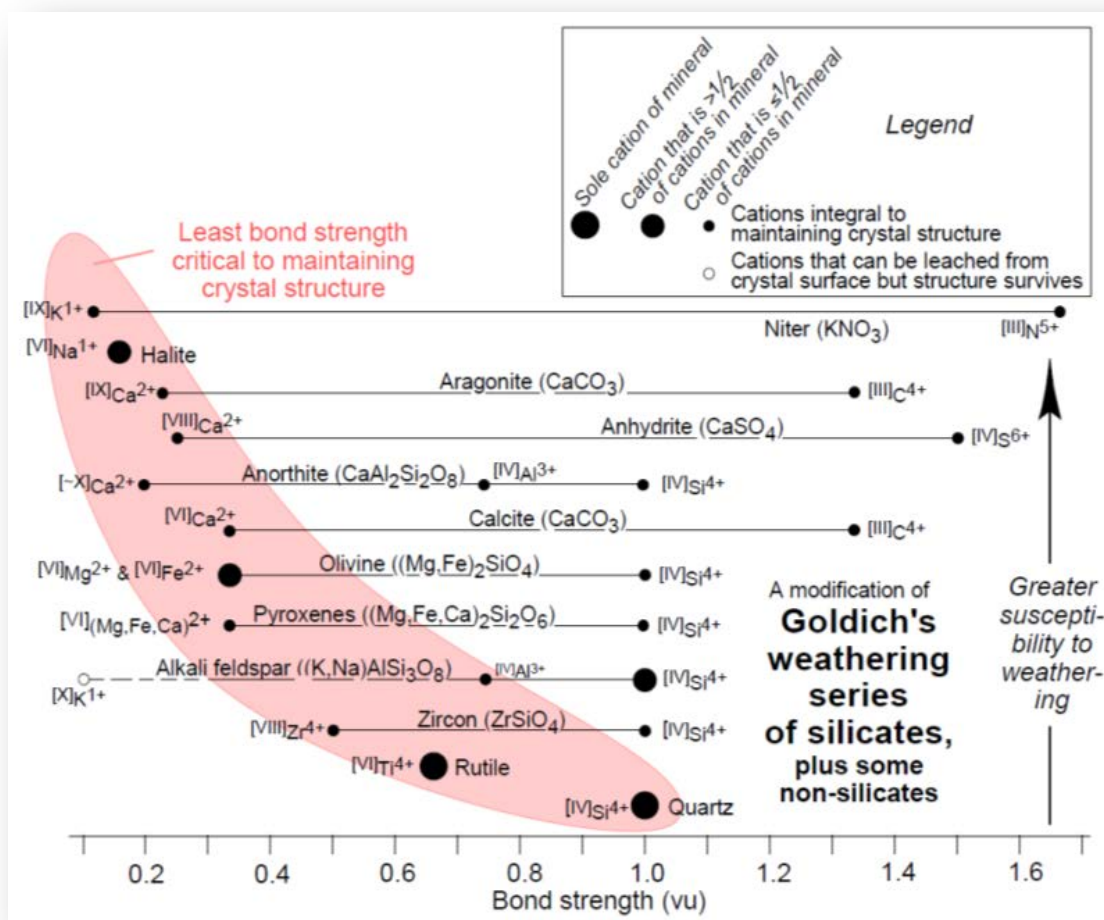


Figure 8-2: Goldich's weathering series according to bond strength. Modified from Railsback (2012).

In addition to the slow weathering rates of the bulk of silicate minerals, infiltrating water moves relatively rapidly through the unsaturated zone and shallow aquifers across Southland (Wilson et al., 2014; Chanut, 2014; Daughney et al., 2015). As a result, the contact time between the infiltrating water and rock minerals is insufficient for any significant instantaneous dissolved load from direct water-rock reaction of silicates to be inherited by the reacting water.

However, as depicted in Figure 8-3, weathering does occur and is the primary source of more labile, water soluble constituents. As silicates gradually weather to clays, a portion of the cations and some anions released from primary silicates migrate to sites of electrostatic charge associated with clay minerals and organic matter. The attraction of ions to solid phase clay and organic matter provides a reservoir of ions ready for rapid exchange with dilute recharge waters. Other, less surface reactive ions, move directly into solution and are flushed from the unsaturated zone to the underlying groundwater table during recharge events.

Table 8-2: Mean Lifetime of a 1-mm³ Crystal predicted from chemical kinetics of water-rock interaction at pH 5 and T = 298 K (Lasaga, 1984).

Mineral	Lifetime
Quartz	34 m.y.
Muscovite	2.7 m.y.
Forsterite	600,000 years
K-feldspar	520,000 years
Albite	80,000 years
Enstatite	8,800 years
Diopside	6,800 years
Nepheline	211 years
Anorthite	112 years

Figure 8-5 presents some of the more important silicate mineral weathering reactions. Each of the reactions described consumes acidity and eventually results in a net release of ions to exchange sites where rapid exchange or solubilisation by infiltrating water occurs. These reactions however, take many thousands of years and it is more often rapid processes such as protolysis, due to soil solution dilution, that result in rapid acid buffering of infiltrating water (Figure 8-4).

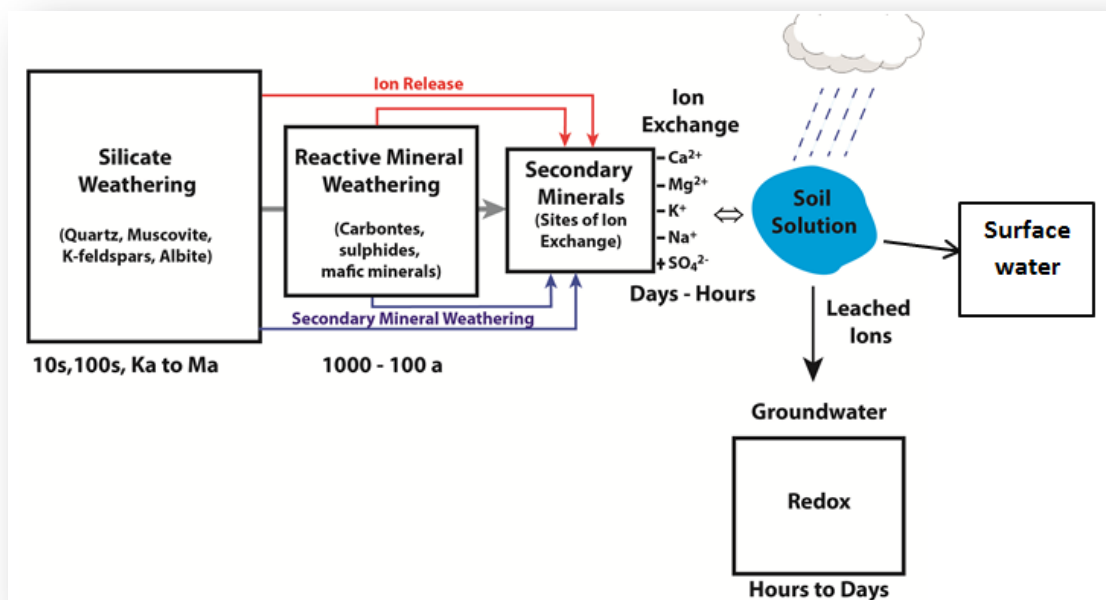


Figure 8-3: Conceptual diagram of the weathering rates and processes in cation production and loss to natural waters.

Acidity is also consumed by: (i) the biological breakdown of proteins; (ii) denitrification and other microbially mediated electron accepting processes; (iii) mineralisation of soil organic matter, and; (iv) ion uptake by roots. Buffering of soil solution pH by pyrolysis or dissociation is largely a factor of soil composition, which in turn relates to how weathered a soil is and ultimately its parent material composition. Therefore, soil age and PM govern the buffering capacity of a soil although the reactions that mediate soil solution composition are distinct and far more rapid than weathering of primary and secondary minerals.

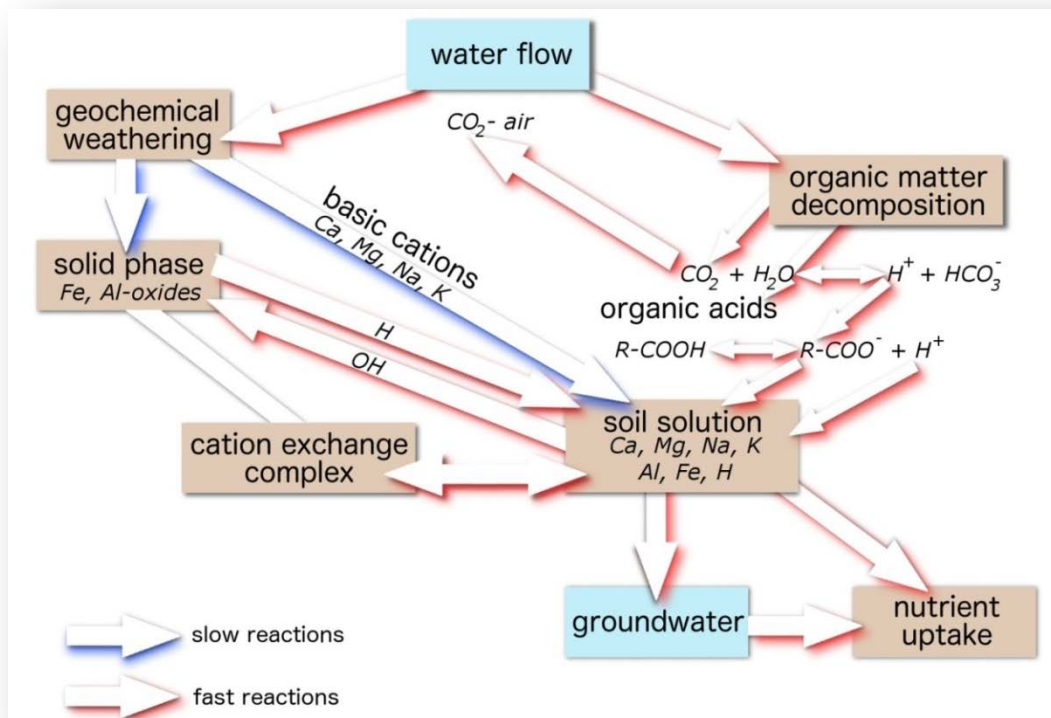


Figure 8-4: Schematic of fast and slow acid buffering reactions of infiltrating water in soils.

For old groundwaters, those that exceed several thousand but more commonly tens of thousands of years, it is not uncommon for a significant component of the dissolved solid load to have been derived from the *in situ* weathering of silicate minerals. However, for young groundwaters, less than 100 years old, such as the majority of Southland waters, the contribution of dissolved solids from direct water-rock interaction between silicate rocks and acidic recharge waters is minimal relative to other sources such as ion exchange within the soil zone (see TC 4 and 5).

In contrast to silicate minerals, carbonate minerals such as calcite and aragonite are highly reactive with weathering rates that are on average 6 orders of magnitude faster than silicate minerals (Lasaga, 1984). Carbonates also have a high, potentially infinite, acid buffering capacity. Further, it only takes a small mass of highly reactive carbonate rock to potentially dominate the composition of natural waters. Waters having interacted with carbonate minerals are characterised by high Ca and sometimes Mg concentrations and elevated pH which leads to high to very high alkalinity in a system that is open to the atmosphere or source of CO₂.

Assessment of the saturation indices for Southland groundwater and surface water revealed that 552 of 6,125 samples (c. 9%) are at equilibrium or super-saturated with respect to carbonate minerals (Figure 5-1 to 5-4 in Section 5). These waters are generally higher in Ca, Mg, alkalinity and conductivity than non-carbonate waters and have the highest pH of all Southland waters (Figure 8-6).

Gibbsite-kaolinite	$\underline{\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}} + 2\text{Si}(\text{OH})_4 = \underline{\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + 5\text{H}_2\text{O}$
Na-montmorillonite-kaolinite	$\underline{\text{Na}_{0.33}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2} + \frac{1}{3}\text{H}^+ + \frac{23}{6}\text{H}_2\text{O} = \underline{\frac{7}{6}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \frac{1}{3}\text{Na}^+ + \frac{4}{3}\text{Si}(\text{OH})_4$
Ca-montmorillonite-kaolinite	$\underline{\text{Ca}_{0.33}\text{Al}_{4.67}\text{Si}_{7.33}\text{O}_{20}(\text{OH})_4} + \frac{2}{3}\text{H}^+ + \frac{23}{2}\text{H}_2\text{O} = \underline{\frac{7}{3}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \frac{1}{3}\text{Ca}^{2+} + \frac{8}{3}\text{Si}(\text{OH})_4$
Illite-kaolinite	$\underline{\text{K}_{0.6}\text{Mg}_{0.25}\text{Al}_{2.30}\text{Si}_{3.5}\text{O}_{10}(\text{OH})_2} + \frac{1}{10}\text{H}^+ + \frac{8}{3}\text{H}_2\text{O} = \underline{\frac{23}{10}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \frac{3}{5}\text{K}^+ + \frac{1}{5}\text{Mg}^{2+} + \frac{6}{5}\text{Si}(\text{OH})_4$
Biotite-kaolinite	$\underline{\text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2} + 7\text{H}^+ + \frac{1}{2}\text{H}_2\text{O} = \underline{\frac{1}{2}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \text{K}^+ + 3\text{Mg}^{2+} + 2\text{Si}(\text{OH})_4$
Albite-kaolinite	$\underline{\text{NaAlSi}_3\text{O}_8} + \text{H}^+ + \frac{9}{2}\text{H}_2\text{O} = \underline{\frac{1}{2}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \text{Na}^+ + 2\text{Si}(\text{OH})_4$
Albite-Na-montmorillonite	$\underline{\text{NaAlSi}_3\text{O}_8} + \frac{6}{7}\text{H}^+ + \frac{20}{7}\text{H}_2\text{O} = \underline{\frac{3}{7}\text{Na}_{0.33}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2} + \frac{6}{7}\text{Na}^+ + \frac{10}{7}\text{Si}(\text{OH})_4$
Microcline-kaolinite	$\underline{\text{KAlSi}_3\text{O}_8} + \text{H}^+ + \frac{9}{2}\text{H}_2\text{O} = \underline{\frac{1}{2}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \text{K}^+ + 2\text{Si}(\text{OH})_4$
Anorthite-kaolinite	$\underline{\text{CaAl}_2\text{Si}_2\text{O}_8} + 2\text{H}^+ + \text{H}_2\text{O} = \underline{\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \text{Ca}^{2+}$
Andesine-kaolinite	$\underline{\text{Na}_{0.5}\text{Ca}_{0.5}\text{Al}_{1.5}\text{Si}_{2.5}\text{O}_8} + \frac{3}{2}\text{H}^+ + \frac{1}{4}\text{H}_2\text{O} = \underline{\frac{3}{4}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4} + \frac{1}{2}\text{Na}^+ + \frac{1}{2}\text{Ca}^{2+} + \text{Si}(\text{OH})_4$

*Solid phases are underlined.

Figure 8-5: Mineral Weathering Reactions (after Freeze and Cherry, 1979).

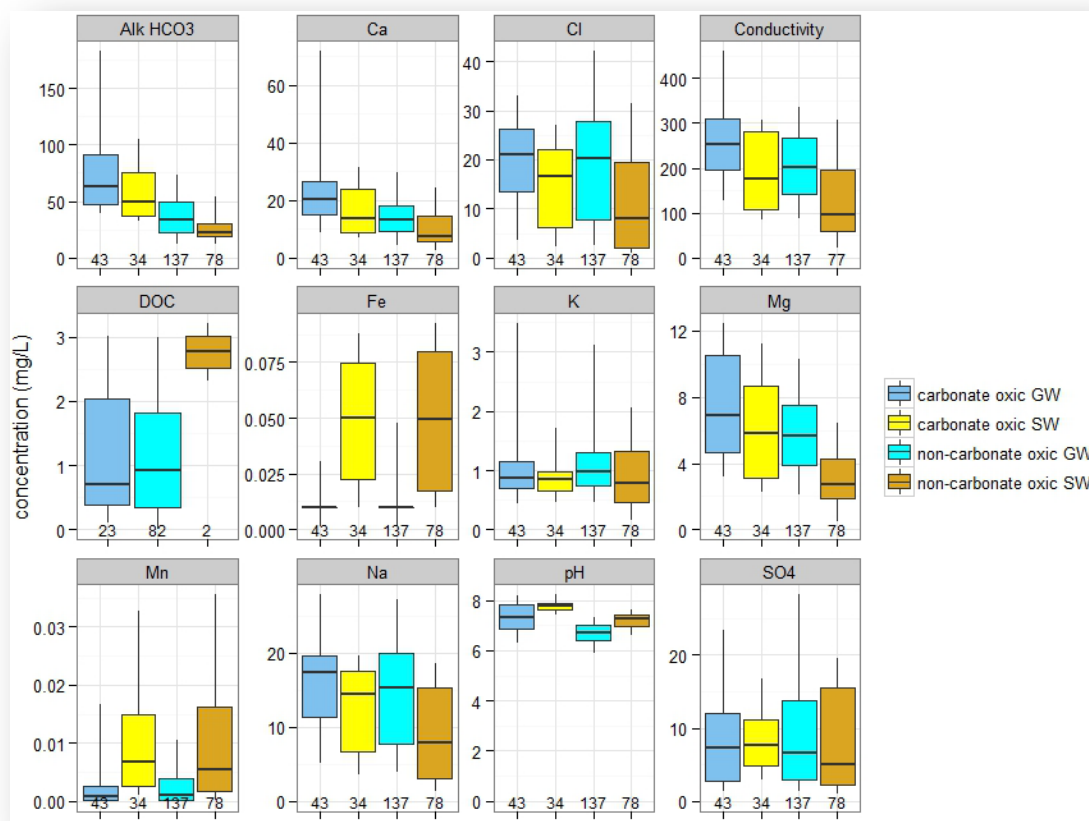


Figure 8-6: Selected parameter boxplot for carbonate and non-carbonate oxic ground and surface waters. The number at the base of the graph indicates the total sample size.

TC8.3 Development of regional geomorphic surface age and substrate composition maps

That both geomorphic surface age and substrate composition affects soil composition is discussed above, in particular major cation composition and pH buffering, which ultimately impact on regional hydrochemistry. In recapping, consideration of how geomorphic surface age and substrate composition influence major ions and pH buffering capacity regionally, is important to understanding the provenance or source of regional freshwaters including major ion hydrochemical facies. Furthermore, pH influences the speciation of major and trace ions as well as heavy metals. We also summarised existing frameworks to define geomorphic surface age and substrate composition above.

In this chapter, we use existing frameworks, i.e., QMAP, Topoclimate and S-Map, to classify geomorphic surface age and substrate composition according to their influence over the hydrochemical variation in Ca and Mg abundances and pH buffering of regional freshwaters. Developing a regional scale map of rock and sediment provenance required a combination of local geological knowledge in addition to existing spatial frameworks. Specifically, the spatial frameworks important to classification of the drivers of hydrochemical variation in Ca and Mg abundance, pH and alkalinity across Southland are the S-Map parent material source layer, QMAP and Topoclimate, where S-Map provides an indication of soil parent material composition. QMAP also provides an estimate of depositional landform age which serves as a proxy for geomorphic surface age.

Specifically, geomorphic domain i.e., Alpine, Bedrock (*senso lato* 'Hill Country'), and Lowlands and associated climatic zones were defined using elevation, a 5m x 5m DEM and QMAP info on rock outcrops (Figure 8-7). Specifically, high altitude areas (>800m RSL) were defined as Alpine, mid to high altitude (<800m RSL) bedrock catchments were defined as Bedrock, and the remaining lowland areas (<500m RSL) associated with constructional landforms (i.e., mainly Quaternary aged alluvial and alluvial/aeolian landforms) were defined as the Lowlands. Discrimination of alpine, bedrock and lowland was also guided by recharge and water source assessment (TC1 and 2).

The absolute max geological age (i.e. Quaternary age classifications Q1, Q2, Q3, ..., Q10, Q11) defined in QMAP was used to define age of constructional landforms (Figure 8-9). QMAP age is based on the classification in White et al. (2012) given in Table 8-3. Ages older than 2.58 Ma was classed as erosional.

For non-depositional, i.e. erosional landforms, alpine and hill country bedrock, rock age, not the geomorphic surface age is provided in QMAP. As discussed above, it is well recognised that the Alpine landforms of Southland and other temperate areas nationally and globally are the youngest surfaces, followed by Hill Country/Bedrock with lowland depositional landforms constituting the oldest land surfaces. We therefore defined alpine and hill country landforms as erosional, youngest landforms (Figure 8-9).

Geological and Soil Composition (i.e. clastic sediment, schist, gneiss, tectonic, metamorphic, chemical sediment) were defined using QMAP available information (Rock class, Rock description, Main Rock, Terrane equivalent and Rock group) (Figure 8-8 and Figure 8-9). More specifically, for definition of subsurface geology and age and surface age, QMAP information was used. QMAP does not provide a compositional type for all depositional landforms, lowland alluvium, moraines or loess mantles. Accordingly, the parent material layer in S-Map is used to augment QMAP.

Table 8-3: Oxygen isotope boundaries as used in QMAP to estimate geologic age, i.e. Quaternary time. The stage boundaries of the listed publications (see references) were considered in deciding upon suitable QMAP ages.

Stage Boundary	Shackleton and Opdyke (1973)	Imbrie et al. (1984)	Bassinot et al. (1994)	Martinson et al. (1987)	QMAP age (thousand years)
1 and 2	13	12	11	12	12
2 and 3	32	24	24	24	24
3 and 4	64	59	57	59	59
4 and 5	75	71	71	74	71
5 and 6	128	128	127	130	128
6 and 7	195	186	186	190	186
7 and 8	251	245	242	244	245
8 and 9	297	303	301		303
9 and 10	347	339	334		339
10 and 11	367	362	364		362
11 and 12	440	423	427		423
12 and 13	172	478	474		478
13 and 14	502	524	528		524
14 and 15	542	565	568		565
15 and 16	592	620	621		620
16 and 17	627	659	659		659
17 and 18	647	689	712		689
18 and 19	688	726	760		726
19 and 20	706	736	787		736
20 and 21	729	763	820		763
21 and 22	782	790	865		790

Composition was considered initially based on the “Rock Class” (QMAP) and “Parent Material” (S-Map) field. This however left 6 compositionally ambiguous classifications for QMAP derived data. Where possible these were assessed using the rock description to assign a classification as either mafic, felsic, carbonaceous, or calcareous limestone. Some rocks could not be classified based on the information available and were defined as “Undifferentiated Clastics”. These classifications are highly approximate in many situations and based on the rock description rather than any quantitative mineralogy.

As a key output of this chapter, maps of key geomorphic and compositional (i.e., rock and biological sediment type) factors were produced that spatially stratifies the region into distinct areas. Figure 8-7 summarises spatially the pattern of surface and subsurface landform type (i.e., erosive or constructional), Figure 8-8 summarizes subsurface composition, Figure 8-9 summarizes surface composition and Figure 8-10 summarizes landform age as key drivers of regional freshwater composition.

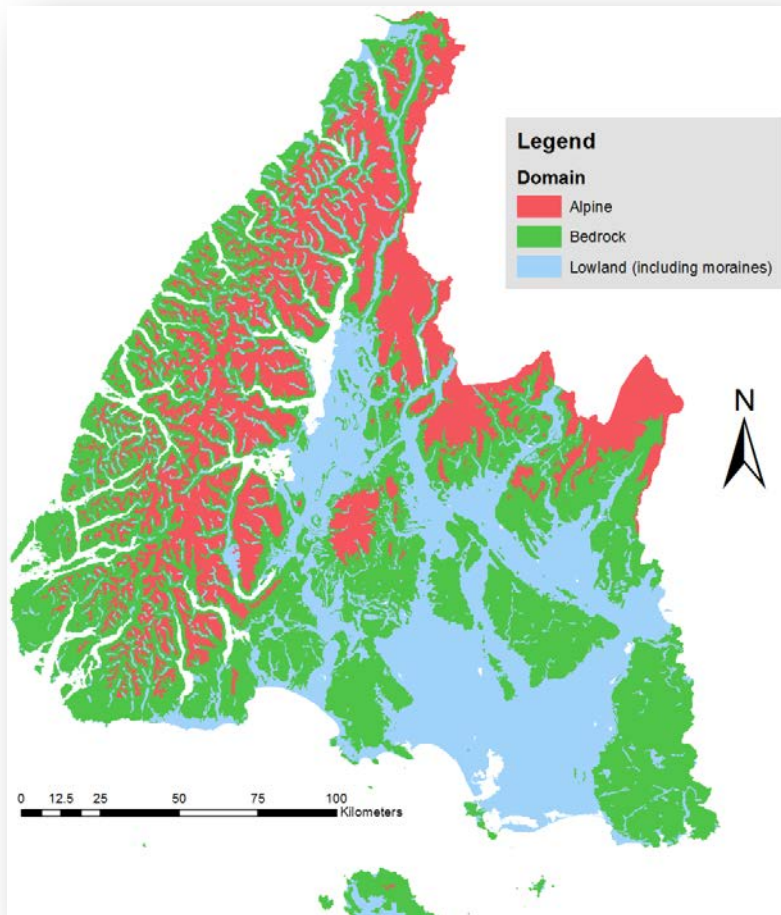


Figure 8-7: spatial distribution of regional landform domain, alpine, bedrock/hill country and lowland

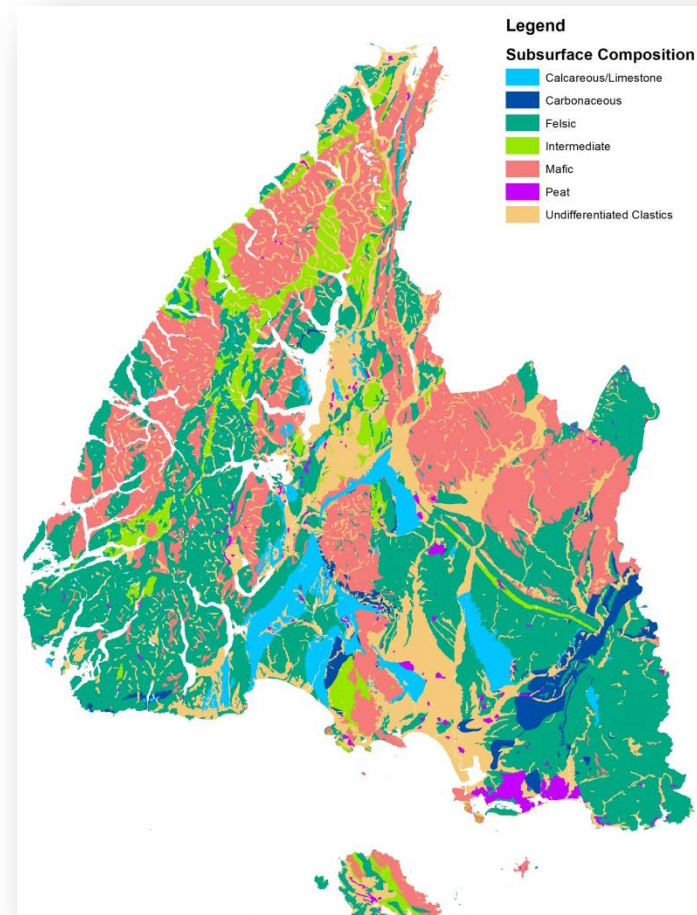


Figure 8-8: spatial distribution of regional subsurface composition

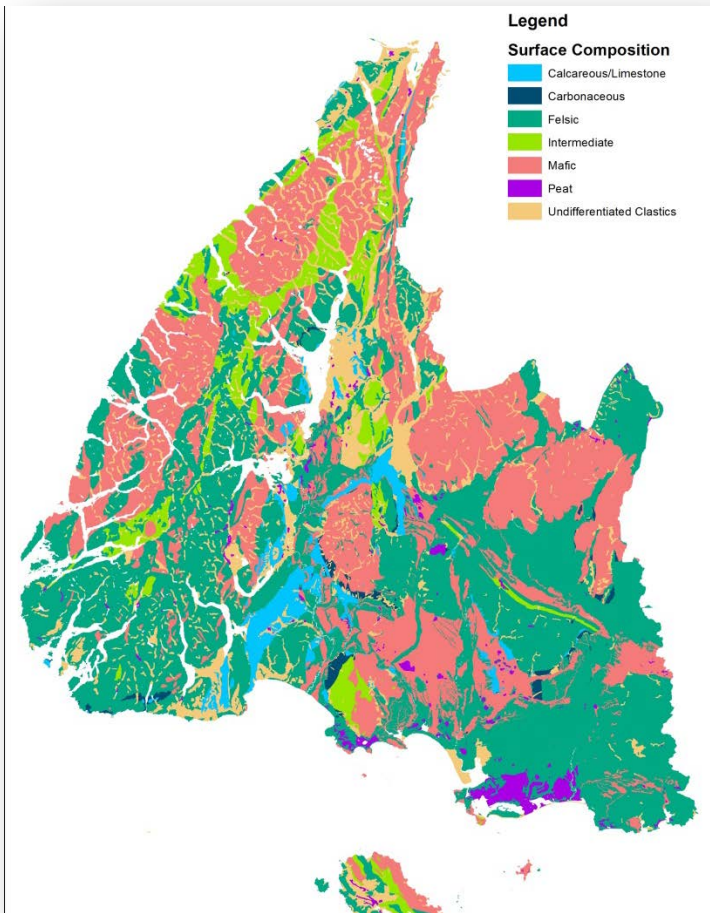


Figure 8-9: spatial distribution of regional surface composition

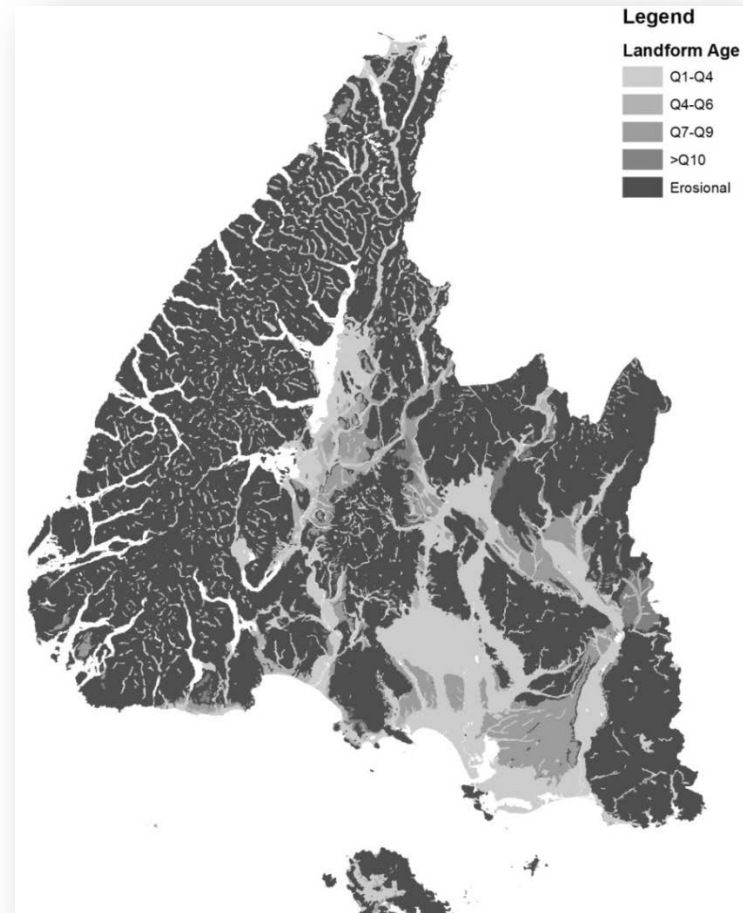


Figure 8-10: spatial distribution of landform age in Southland

As an initial cross-validation of the developed map with 356 soil chemical data sourced from Topoclimate, including depth weighted soil BS, pH, Ca, Mg and K abundance, were intersected with the developed landform age and surface composition maps.

Figure 8-7 suggests that soil BS generally peaks and then slowly declines as a function of geomorphic age. This is in agreement with the general understanding of the relationship between water rock interaction and weathering of stable landforms. It is in response to depletion of more reactive minerals and/or occlusion by secondary mineral formation as the geomorphic surface ages and weathers (Seyers and Walker, 1969; Seyers et al., 1970; Walker and Seyers, 1976; Crews et al., 1995). A similar relationship would be expected between soil pH and landform age, but this is not seen very strongly in the observed data, which may be a reflection of the shallow nature of soil samples (≤ 900 mm; Figure 8-8). Soil Ca, Mg and K content show similar relationships to landform age to that of soil BS whose data is not presented here.

Figure 8-9 and Figure 8-10 suggest that soil BS and soil pH decrease with rock type in the order: calcareous limestone > mafic > felsic > peat. This finding is in agreement with the general understanding of relationships between rock composition and soil (Table 8-1). For example, the higher Ca and Mg contents in mafic and ultramafic relative to felsic rock equate to significant differences in mineral weathering rates, acid buffering potential, and major and trace cation composition of soils, i.e. higher BS and pH of soils derived from mafic rock compared to those soils derived from felsic rock.

Cross-validation of the developed maps in combination with other driver maps, i.e. precipitation source, recharge mechanism and redox control developed in TC 1, TC 2 and TC 6, respectively, with regional surface and groundwater chemistry (in Chapter 4) further support the above findings. More specifically, it is demonstrated that that spatial variability of regional freshwater chemistry can be estimated with a high degree of confidence (Chapter 4).

In summary, a calibrated map is produced which estimates substrate Ca, Mg and other major cations such as K abundance and pH buffering capacity from spatial frameworks of geomorphic surface age and substrate composition. This map constitutes a key driver layer necessary for explaining spatial variance in the Ca, Mg and other major ions, pH and alkalinity of surface waters and soil influenced groundwater.

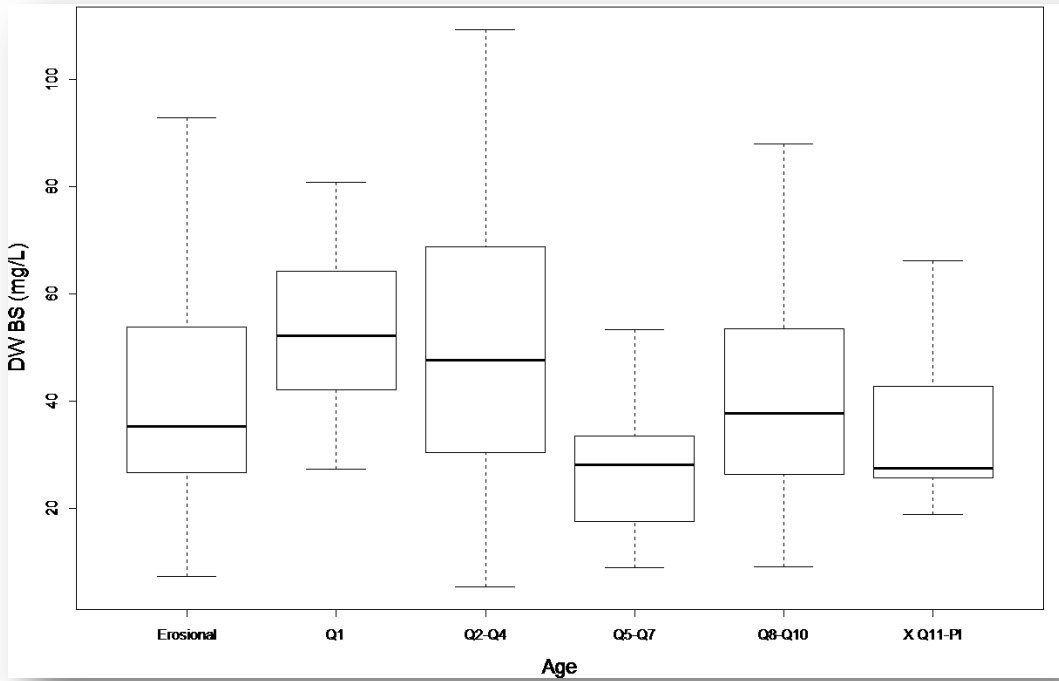


Figure 8-11: depth weighted soil BS as a function of landform age

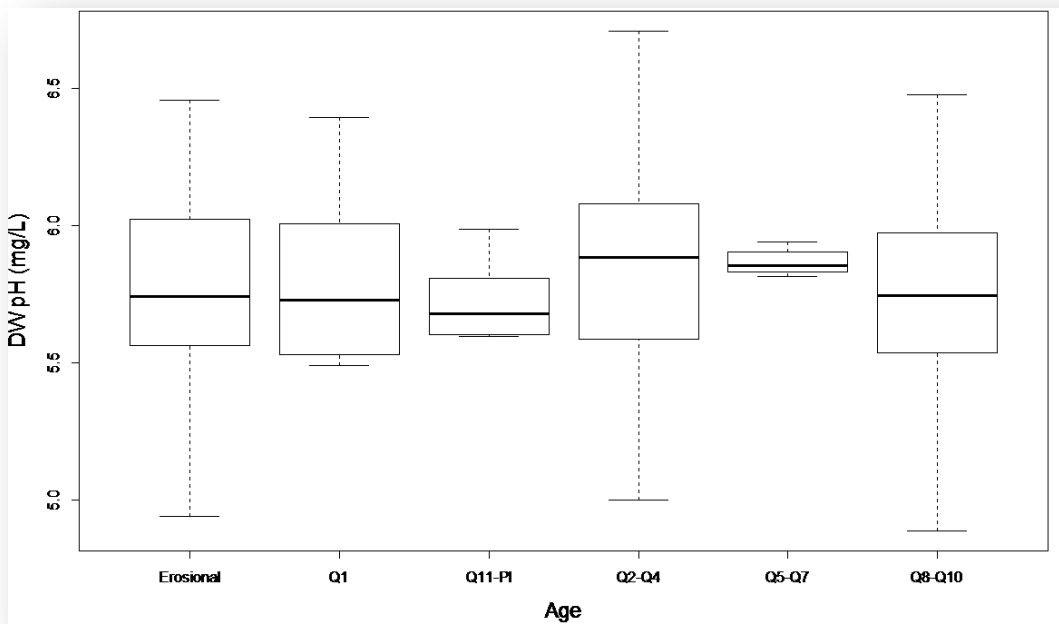


Figure 8-12: depth weighted soil pH as a function of landform age

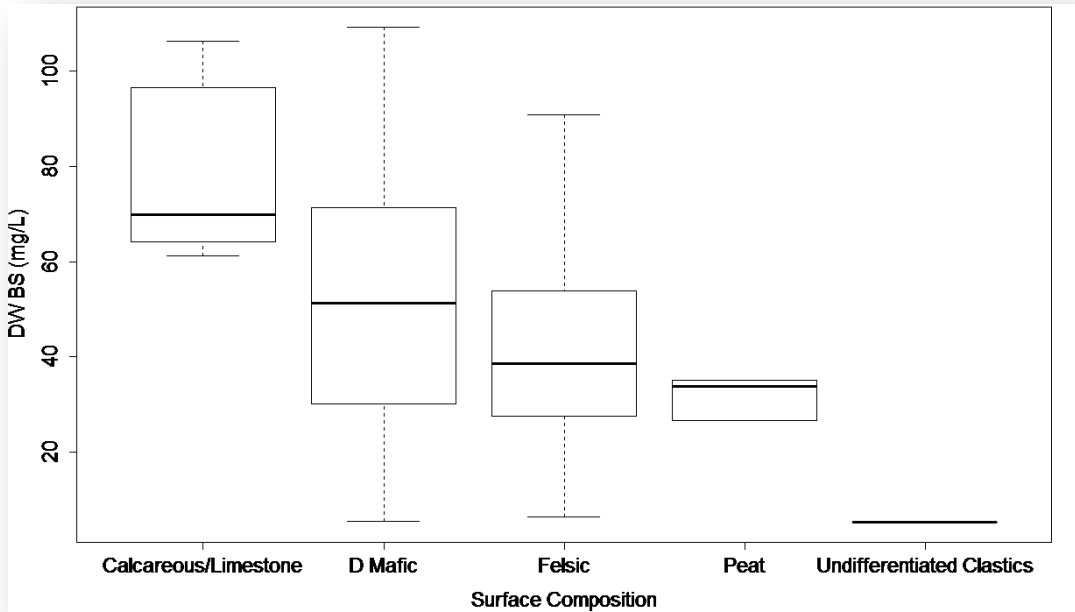


Figure 8-13: depth weighted soil BS as a function of surface composition

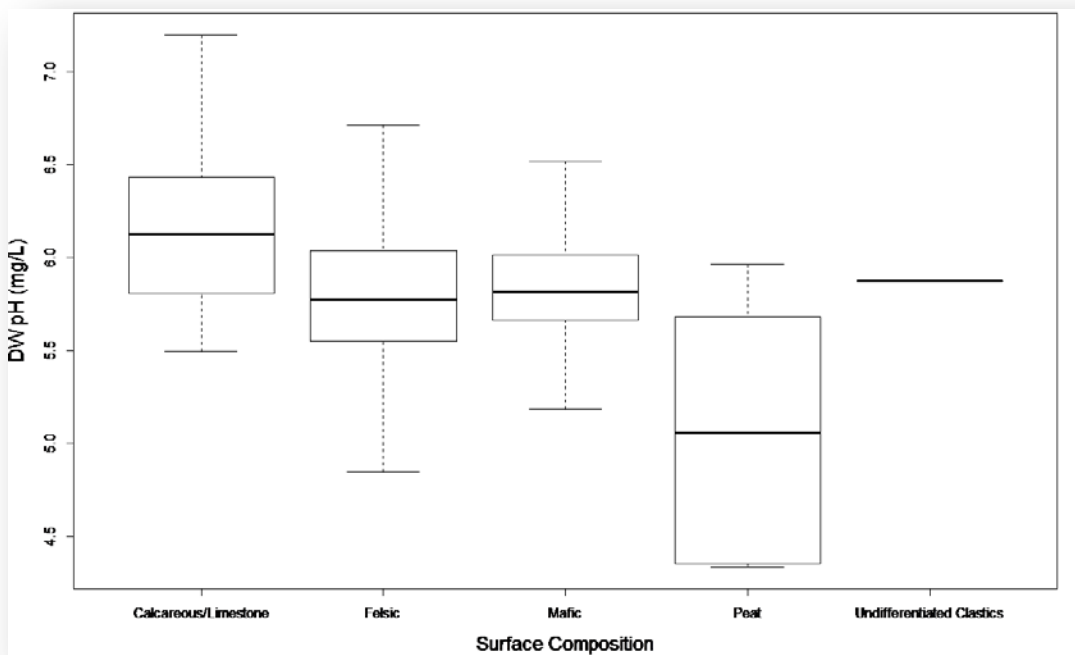


Figure 8-14: depth weighted soil pH as a function of surface composition