Physiographic Environments of New Zealand: Inherent susceptibility of the landscape for contaminant loss

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Community Summary

In the wrong place or at excessive concentrations nutrients (nitrogen and phosphorus) and sediment become contaminants. Along with pathogens (harmful microbes), these contaminants require reduction to improve water quality nationally. Landscape variation has been identified as a driver of significant differences in water quality despite similar land use pressures. Therefore, understanding the role the landscape has in the resulting water quality outcomes can drive better land use decisions.

As part of the Our Land and Water 'Physiographic Environments of New Zealand' project, areas that have similar landscape characteristics based on hydrological, redox (chemical processes), and weathering processes have been classified into Physiographic Environments. Physiographics can be used to explain the 'how' and 'why' water quality varies across a catchment, region, or nationally.

The Physiographic Environments Classification is hierarchical with a basic 10 class *family* classification, and a more technical (28 class) *sibling* classification, which provides more resolution over gradients within the broader *'families'* classification. These Environments each have a defining set of landscape characteristics that affect water quality in a predictable manner and can be used to show contaminant risk to water quality from multiple contaminants. For example, the Environments include classifications that describe the potential of the landscape to physically filter out contaminants, or biogeochemically remove or transform contaminants through redox processes.

In addition to the main classification, variants are used to spatially depict where hydrology has been modified for land use and where climatic seasonality and/or episodic events may result in divergence from the steady-state depiction of the general classification. Specifically, the variants include consideration of likely artificial drainage density (anthropogenic), soil macropore bypass in response to soil moisture deficit (natural) and overland flow risk associated with episodic climatic events all of which may modify the dominant hydrological flow path and contaminants form and quantity exported to water.

The risk to water quality for each Physiographic Environment is provided determined according to the dominant hydrological pathway and contaminant form. A risk matrix is populated according to both the inherent (unmodified) and modified (artificial drainage) characteristics of the landscape and includes consideration of both transport and attenuation of nitrogen as nitrate nitrite nitrogen, ammoniacal nitrogen, and organic nitrogen, phosphorus as particulate phosphorus and dissolved reactive phosphorus, sediment (particulate), and microbial contamination. The risk matrix assumes a maximum source load for all contaminants irrespective of the land cover or enterprise type. Obviously, the actual contribution from an area maybe significantly different depending on the enterprise type and land use pressure (i.e., low for native forest or high for high producing grassland and cropping). In the PENZ classification, risk to water quality for all contaminants is significantly increased when the soil matrix is bypassed in response to macropore flow, artificial drainage and/or overland flow. As such, the classification recognises the important role of anthropogenic modification of soil hydrology, seasonality in soil hydrological behaviour, and episodic runoff in governing water quality outcomes.

The classification has been developed through the integration of nationally available datasets (typically at 1:50,000 to 1:250,000 scale). At this resolution, it is suitable to help inform land use policy options and decision making but does not replace the need for catchment or farm-specific assessments and other due diligence.

Importantly, the Physiographic Environment classification and inherent susceptibility risk assessment presented here is currently preliminary work is being advanced through an Our Land and Water -

Sources to Sink project which aims to refine and improve the classification and quantification of risk. This refinement will provide additional documentation and validation to support the landscape classification. In addition to this, an assessment of attenuation and uncertainty at various spatial scales will also be undertaken. A refined classification is expected to be available for use by June 2022.

1 Introduction

In the wrong place, or at excessive concentrations, nutrients (nitrogen and phosphorus) and sediment become contaminants. Along with pathogens, they require reduction to improve water quality. In the first phase of Our Land and Water National Science Challenge (OLW NSC), Land and Water Science produced the ‘Physiographic Environments of New Zealand’ (PENZ) classification to explain how and why water quality varies across NZ. This classification can be used to assess environmental risk of nitrogen and phosphorus species, sediment, and microbes in our environment and can be used to support the implementation of the National Policy Statement for Freshwater Management (2020).

1.1 Environmental Risk

Environmental risk can be described by the intersection of three factors:

1. the *pressure* from land use and management contributing to contaminant generation
2. the *inherent susceptibility* of the landscape to contaminant mobilisation, and
3. the *vulnerability* of downstream receiving environments to mobilised loads.

The PENZ classification can be used to define the **inherent susceptibility of the landscape** to contaminant mobilisation and support problem identification as part of a multi-contaminant framework considering land use pressure in landscape units (Figure 1). This assessment is currently qualitative, providing a relative susceptibility of contaminant loss that is defined categorically i.e., from low to high for each contaminant.

Instream concentration and load calculations are a function of both land use pressure and the inherent susceptibility of the landscape to contaminant loss. Endogenous loads, those associated with natural sources, are also included in concentration and load assessments. Whereas ecosystem vulnerability (including in-stream, groundwater, lakes, estuaries, and the coastal marine environment) is commonly assessed according to trophic state and ecological health indices. Ecosystem vulnerability identifies if action is needed to reduce land use pressure (as landscape factors are predominantly inherent). The risk framework is modelled on the widely used framework for climate impacts and adaptation (Royal Society of New Zealand, 2016).

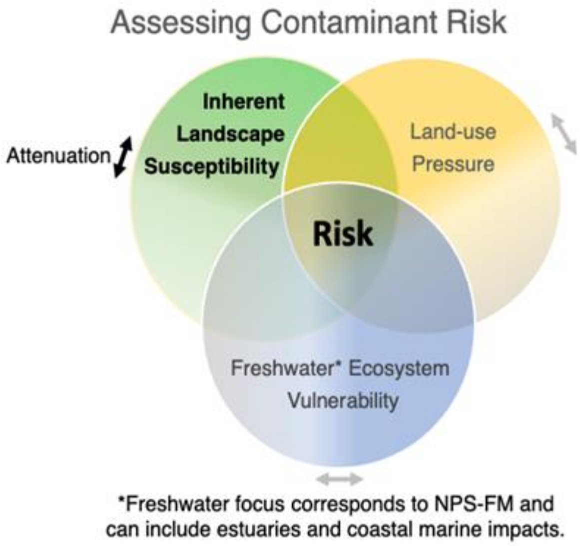


Figure 1. Contaminant risk is the intersection of the pressure from land uses, the inherent susceptibility of the landscape for contaminant loss, and the vulnerability of the receiving environment.

1.2 Report Overview

This report summarises a risk assessment developed from the Physiographic Environments of New Zealand (PENZ). PENZ provides conceptual understanding of the role the landscape has in controlling water quality outcomes and includes the modified hydrological network. Land use pressures are considered separately to the inherent susceptibility of the landscape (Figure 1). Land use activities undertaken on land with a high susceptibility to contaminant loss are likely to have high loss rates if mitigation actions are not undertaken. Conversely, land use activities undertaken on land with a low inherent susceptibility are likely to have low loss rates even if mitigations actions are not undertaken. Low land use intensity and/or the combination of mitigation actions can result in a lower loss of contaminants. Meaningful mitigating losses from land with a high inherent susceptibility may be untenable without a land use change that results in a decrease in land use pressure.

The PENZ classification considers both the hydrological pathway contaminants take and the role the landscape has in minimising the contaminant concentration through dilution, filtration and adsorption, and attenuation of nitrogen (denitrification) and phosphorus (mobility).

This report provides a summary of the environmental contaminants that have been targeted for reduction under the National Policy Statement for Freshwater Management (2020) in Section 2. Under different landscape settings, the forms of nitrogen and phosphorus (dissolved or particulate) differ, and as such their relative loss rates. Sediment and microbial loss also varies as a function of the landscape setting. Accordingly, PENZ can be used to predict the inherent susceptibility of the landscape to contaminant loss enabling those making decisions to be more targeted with reduction strategies.

Section 3 provides background to the physiographic approach, method, and the PENZ classification. The conceptual understanding of the landscape is described for each unit. In addition to the Family and Sibling level classifications, seasonal differences in the hydrological pathway associated with soil macropore bypass (most relevant when seasonally dry) and overland flow (most relevant when seasonally wet) are represented as *'Variants'*. Variants reflect important seasonal variation in hydrological pathways and as such the type, forms and magnitude of contaminant loss from land to water.

Section 4 demonstrates the use of physiographic process gradients to understand how contaminants are reduced in the landscape through filtration and adsorption, attenuation by redox reactions (such as denitrification), resistance to physical disturbance, and dilution. The effect of seasonality and episodic events for contaminant transport are also discussed.

Section 5 presents a multi-contaminant risk matrix for Physiographic Environments through understanding the role of the landscape in reducing contaminants. It discusses the risk to water quality and how multiple factors, including the inherent susceptibility of the landscape, land use intensity, and endogenous loads from natural sources (background conditions) are combined to assess environmental risk.

Lastly a summary of the current and future work is discussed. Including how the physiographic process layers can be utilised to single contaminant risk assessments beyond the current PENZ classification.

2 Environmental Contaminants

2.1 Nitrogen

Nitrogen (chemical symbol N) has three forms in the environment, molecular, organic, and inorganic, and is cycled from one form to another depending on the environmental and biological conditions (Figure 2). Molecular nitrogen is a gas (N_2) and makes up about 78% of the Earth's atmosphere. Nitrogen fixers sequester N_2 from the atmosphere and both nitrous oxide and gaseous ammonia are formed as part of the N-cycle. Both the organic and inorganic forms of nitrogen are ecologically important. Organic nitrogen refers to the diverse range of nitrogen-containing organic molecules in soil, aquifers, and water. Inorganic nitrogen occurs in three forms:

- **Nitrate** (NO_3^-) is the preferred form of nitrogen nutrition for most species of plants. Nitrate is highly soluble and is easily transported through the soil if not used by plants and microorganisms. Sources of nitrate include inorganic fertiliser, animal wastes including farm dairy effluent, septic tanks and sewage systems. Nitrate also occurs as a result of nitrification of organic matter and animal waste by bacteria in the soil but also in stream sediments and saturated sediments including aquitards and aquifers. It is toxic at high concentrations. The majority of nitrate is released through microbial mineralisation processes irrespective of the primary N source.
- **Nitrite** (NO_2^-) is formed during the process of nitrification and is highly toxic even at relative low concentrations. It is an intermediary and metastable molecule that may be converted to N_2O under specific conditions.
- **Ammoniacal nitrogen** ($NH_4^+/NH_{3(g)}$) is represented by ammonia (NH_3) and ammonium (NH_4^+). Which form dominates in water is dependent on pH, ammonia concentrations increase as pH increases. In most natural waters with pH values less than 7.5, ammonium is the dominant form. Ammonia is highly toxic to fish and other aquatic organisms. Ammonium is less mobile than nitrate as it is strongly attracted to negatively charged clay minerals.

The ecologically important organic and inorganic forms of nitrogen are added as nutrients (i.e., fertilisers, composts, manures) to enhance plant growth. Due to their high lability (conversion from one form to another) and potential mobility, nitrogen can easily become an environmental contaminant. In surface water, this can cause nuisance aquatic weeds and algae to flourish. Nitrite and ammoniacal nitrogen both become toxic at high concentrations.

In a farm system, the primary inputs of nitrogen to the soil are effluent from livestock, decomposition of plant materials (organic matter), and synthetic fertiliser. Nitrogen fixing plants may also be an important source of N in some systems, with minor contributions associated with direct deposition from the atmosphere. Of the agricultural inputs, fertiliser and urine inputs are generally in the form of urea ($(NH_2)_2CO$), which is quite rapidly converted to ammonium and ammonia (collectively they are known as ammoniacal nitrogen). Regardless of the source of nitrogen, the processes in the nitrogen cycle always apply (Figure 2).

The two main forms of inorganic nitrogen in the soil are ammonium (NH_4^+) and nitrate (NO_3^-). Ammonium and ammonia co-exist, with the proportion of each dependent on pH, soil temperature, and moisture. Ammonia may be lost to the atmosphere in response to volatilisation. In addition to fertiliser and urine, ammoniacal nitrogen is released during the breakdown of organic matter (which can be dung or dead plant material). In response to breakdown, mineralised nitrogen may be sequestered or released by the microbial biomass into solution. The conversion from ammonium to nitrate (nitrification) is a biologically mediated process (facilitated by microbes) that is subject to soil pH, moisture, and temperature.

Ammonium and nitrate are both available for plant uptake, but there are important differences in their characteristics. Nitrate is highly mobile in soil due to its poor adsorption characteristics, but ammonium is generally less mobile because it tends to adsorb to the soil particles, particularly in soils with a high clay content. Nitrate is subject to denitrification, which is the gaseous loss of nitrogen as both nitrous oxide (N_2O, a harmful greenhouse gas) and nitrogen gas (N_2). If nitrate is not denitrified to gaseous forms, it can be lost to water through leaching. Ammonium is also lost to the atmosphere by volatilisation through the emission of ammonia gas (NH_3). Denitrification and associated nitrous oxide and N_2 generation, along with ammonia volatilisation respond to short-term daily climate and soil factors and can be highly episodic.

In most mineral or non-wetland soil types, the dominant form of nitrogen below the root zone is nitrate nitrogen, with a potentially important contribution from soluble dissolved organic nitrogen forms. Other forms of nitrogen, particulate organic N, larger dissolved organic forms, and ammonium seldom percolate to these depths due to physical exclusion (filtering), and other processes. These forms of nitrogen tend to accumulate at or near the soil surface and are more easily transported with runoff.

For artificially drained soils (mole-pipe drainage type), the potential range of nitrogen forms transported during drainage will vary according to the soil's carbon content, soil water residence time, and the effectiveness of the drainage system.

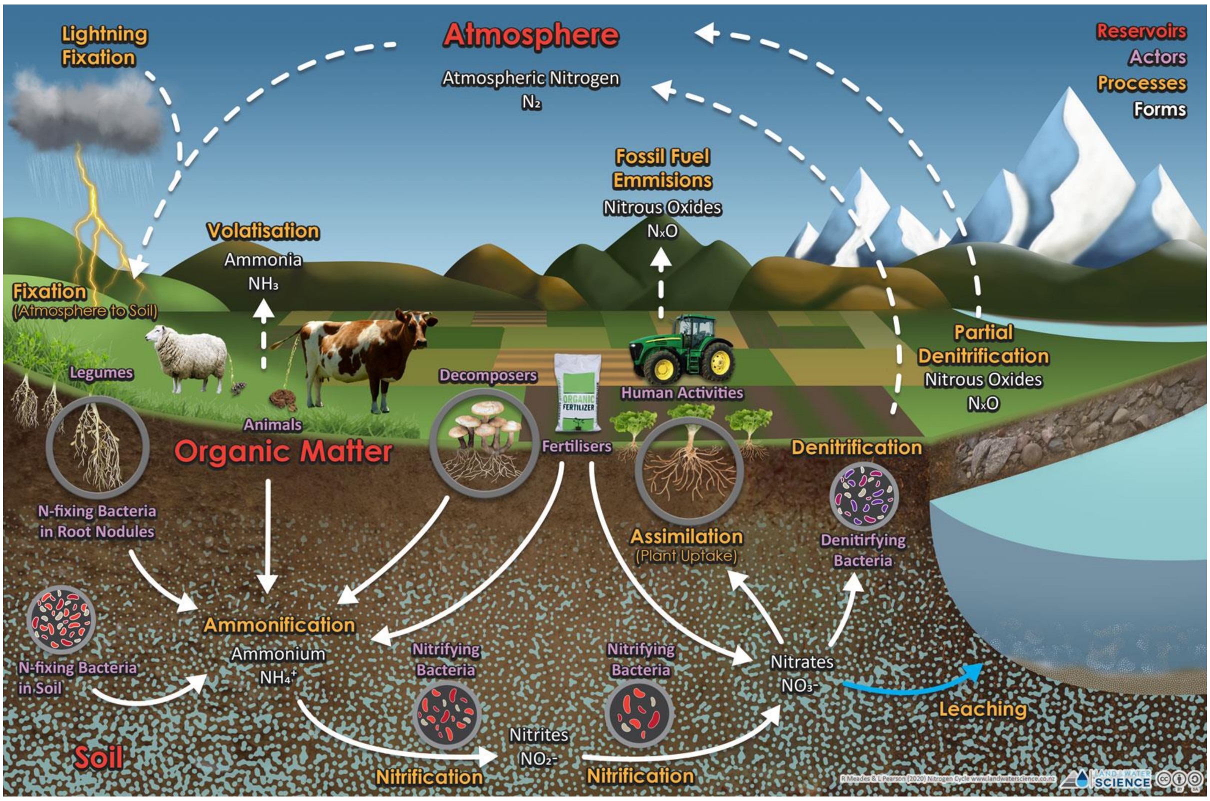


Figure 2. The nitrogen cycle is a complex biogeochemical cycle in which nitrogen is converted from its inert atmospheric molecular form (N_2) into a form that is useful in biological processes. This figure shows the reservoirs of where nitrogen is stored in red, the actors that use it (i.e., us, animals, microorganisms), the processes that nitrogen undergoes (yellow) and the forms of nitrogen in the environment (white).

2.2 Phosphorus

Phosphorus (chemical symbol P) is predominantly found as phosphate-based compounds (solid form) and is cycled through the lithosphere (the rigid outer surface of the earth), hydrosphere (all the water on the earth's surface), and biosphere (the regions of the surface and atmosphere of the earth occupied by living organisms).

In the environment, the weathering of rocks and minerals releases inorganic phosphorus in a soluble form where it is taken up by plants, and subsequently transformed into organic compounds. On a farm, P this is typically added through the use of phosphate fertilisers. Unlike with nitrogen, the atmosphere does not play a significant role in the cycling of phosphorus (Figure 3). Whereas inorganic forms of P dominate early in soil development, organic forms accumulate over time. As soils weather, both organic and inorganic forms of P are often occluded and removed from biogeochemical cycling. Organic phosphate is phosphorus that has been incorporated into plant or animal tissue (e.g., seeds, leaves). In natural waters, phosphorus typically occurs in both inorganic and organic forms.

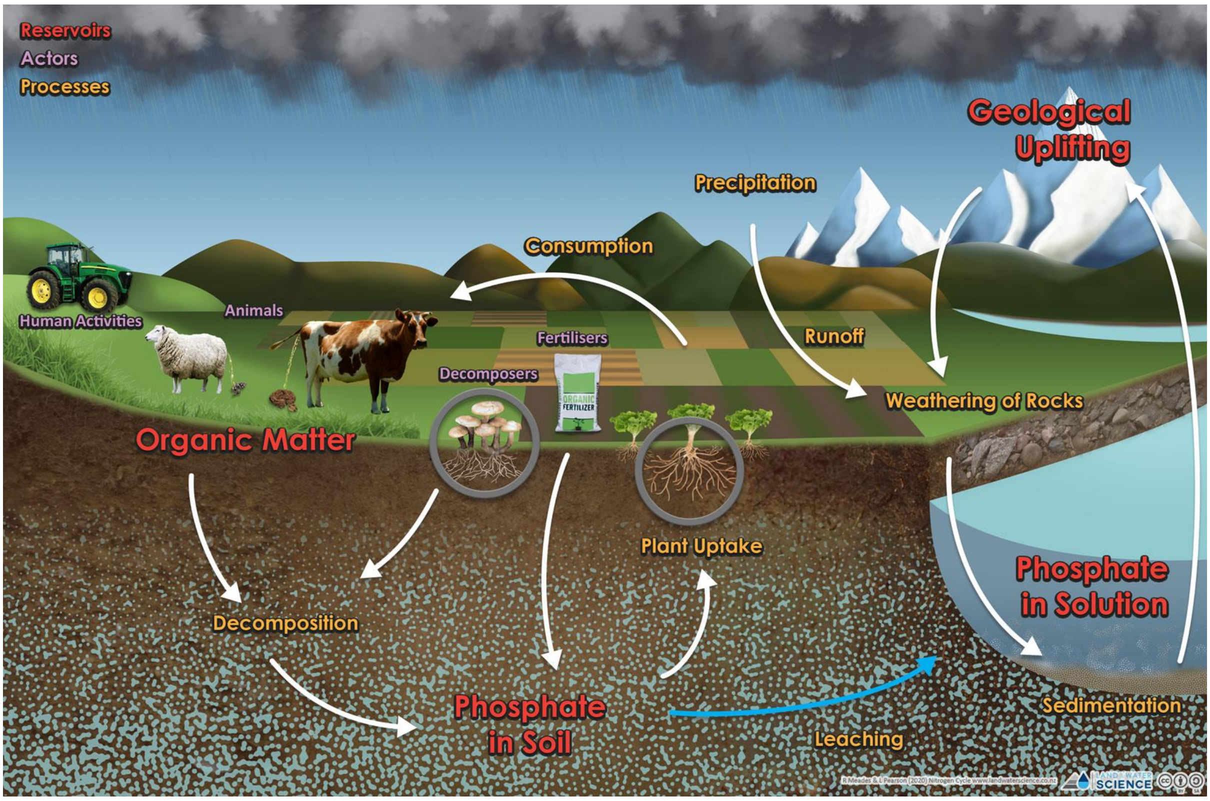


Figure 3. The phosphorus cycle is a slow process which involves the key steps of weathering and erosion, absorption by plants and animals, and return to the environment via decomposition and sedimentation. This figure shows the reservoirs of where phosphorus is stored in red, the actors that use it (i.e., us, animals, microorganisms), and the processes that phosphorus undergoes in the environment (yellow).

In soil, both organic and inorganic forms of phosphate are typically absorbed by iron oxides, aluminium hydroxides, clay surfaces, and organic matter particles, and become incorporated into the soil particle. The bond formed between both organic and inorganic forms of phosphate and soil and sediment is initially electrostatic (a weak bond) but over time a chemical bond forms which can limit the bioavailability. Therefore, when soil is lost by runoff, it carries bound phosphorus with it. In some landscape settings, i.e., peat wetlands or strongly reducing aquifers, P may be highly mobile and behave somewhat like nitrate. In these settings, redox processes influence both the abundance of surfaces for P retention but also the forms of P. The development of colloidal P, nanometre sized and commonly neutrally charged P-organic matter or P-metal complexes, is an important P-form that is highly mobile in aquifers, soils and surface waters. Due to its small size it is analysed as part of the dissolved reactive phosphorus concentration. In wetlands and reducing aquifers colloidal export of P can be an important source of P to waterways.

2.3 Sediment

Sediment is traditionally defined as loose sand, silt, and clay particles that are suspended in a waterway or settled on the bottom of a waterbody. However, sediment also includes organic matter and is more commonly a complex assemblage of inorganic, organic, and biological constituents. Sediment can come from soil erosion or from the decaying (decomposition) of plants and animals. Water, wind, and ice help carry these particles to rivers, streams, lakes, and aquifers. The more intense the rainfall or runoff the more likely sediment will be transported from land to water.

Although sediment is a natural part of a stream, lake, or river, land disturbance by humans is a key driver of sediment export. The type (e.g., colloidal clays vs. sand) and the relative proportion of sediment lost is strongly influenced by the geology of the surrounding area. For example, streams draining an area of weak mudstones tend to be naturally turbid vs. those draining granites or other hard rock types. Even under natural state cover, large differences in sediment export occur as a function of geology and this is manifest in the natural clarity of a stream.

Natural processes that contribute sediment to waterways include mass wasting and erosion. Mass wasting is the movement of soil and rock due to gravity and includes slips, rock avalanches, mudflows, and terracettes. Mass wasting processes are the primary drivers of sediment generation in hill and high country areas across New Zealand. Erosion, on the other hand is the transport of sediment by wind and water. Erosional processes interact with mass wasting to transport sediment from source to depositional areas, such as floodplains. Sediment may take decades or even centuries to reach the ocean or a lake.

Fluvial (water driven) process that transport sediment include scouring of the riverbed and banks, and erosion of sediment from the surrounding catchment from slips and any exposed soils. Sediment can enter streams from alongside a stream reach or from upstream via the many smaller interconnecting streams that form a river network within a catchment area.

As noted above, soil and rock type in the catchment affect the amount of suspended sediment. For example, streams in catchments with clay soils are likely to have naturally poorer water clarity than streams in sandy catchments. In slow-flowing lowland streams where sediment can be very fine, water clarity can be poor for long periods. This is due to the slow rate of flushing and the fact that very fine particles, colloids, are held in suspension almost indefinitely.

While sediment movement is a natural part of a functioning freshwater ecosystem, human activities around a waterway, such deforestation and cultivation of the land, greatly increases the amount of sediment that enters the system. This can have considerable effects on water quality and the plants and animals that live there. The addition of sediment to rivers and streams above normal levels is a serious issue across many parts of New Zealand. As sediment from agricultural lands is also enriched in nitrogen, phosphorus, and microbes, sediment quality is a critical but seldom acknowledged issue for New Zealand waterways. For example, the mass wasting and erosion of agricultural soils with elevated mineralisable N, Olsen P (readily available P), and animal derived microbes may be responsible for a disproportionate component of the anthropogenic contaminant load to rivers, estuaries and harbours. In comparison, although sediment loads may be high from natural state areas they do not tend to have elevated N, P, and microbial content. As such, ignoring the quality of sediment lost to stream is short sighted.

2.4 Microbes

Microbial contaminants are disease-causing organisms. In aquatic environments, microbial contamination is one of the crucial issues with regard to the sanitary state of water bodies used for drinking water supply, recreational activities, and harvesting of food due to a potential contamination by pathogenic bacteria, protozoa or viruses which make us sick.

Common sources of microbial contamination are animal waste, stormwater run-off, and untreated human wastewater discharges. As *E. coli* survives outside the body, it can persist in freshwater environments and is used as an indicator of faecal presence and therefore of disease-causing organisms in a river or lake. Faecal concentrations are typically higher in pastoral streams, but even near-pristine streams are not totally free from *E. coli* because of faecal deposits by birds and wild animals. As many microbes are particle reactive, they are often transported with sediment to waterways. The naturalisation of pathogenic microbes in aquatic sediments is also a recognised phenomenon.

Sediment and microbes are deposited on and eroded from the soil surface and are, therefore, transported predominantly by surficial runoff (overland flow). However, artificial drainage and natural soil bypass (through cracks and joints) can also act as a conduit for sediment and microbes to surface water bodies. Water that infiltrates and percolates through a well sorted soil and or unsaturated zone seldom exhibits microbial contamination.

2.5 Contaminant Transport

Hydrology is the mechanism that transports contaminants, therefore the hydrological flow path is critical to understanding how and why contaminants are transported (Figure 4). Overland flow is the fastest pathway and has the highest risk of contaminant export. It occurs when soils become saturated (saturation-excess overland flow) (Srinivasan et al., 2002), which is most common in low lying areas, or if the rainfall intensity exceeds the soil infiltration rate (infiltration-excess overland flow; Hortonian overland flow) (Horton, 1940), and can be caused by animal treading damage restricting soil permeability. Studies show overland flow from pastures are enriched in P (both dissolved and particulate), sediment, microbes, and nitrogen as ammonium (Smith and Monaghan, 2003; Goldsmith and Ryder, 2013; Orchiston et al., 2013; Curran Cournane et al., 2011; McKergow et al, 2007). Overland flow is likely to originate within gullies and swales due to the natural convergence of rainfall and saturation of the soil. Therefore, the amount, duration, and intensity of the rainfall event, along with the rate that the water can infiltrate the soil and the ability of any artificial drainage system to remove excess water affects how water is transported from the area. Critical source areas are typically located near stream channels or in low infiltration areas and gullies that are connected to the stream channel. On flat land, infiltration excess overland flow will result in surface ponding.

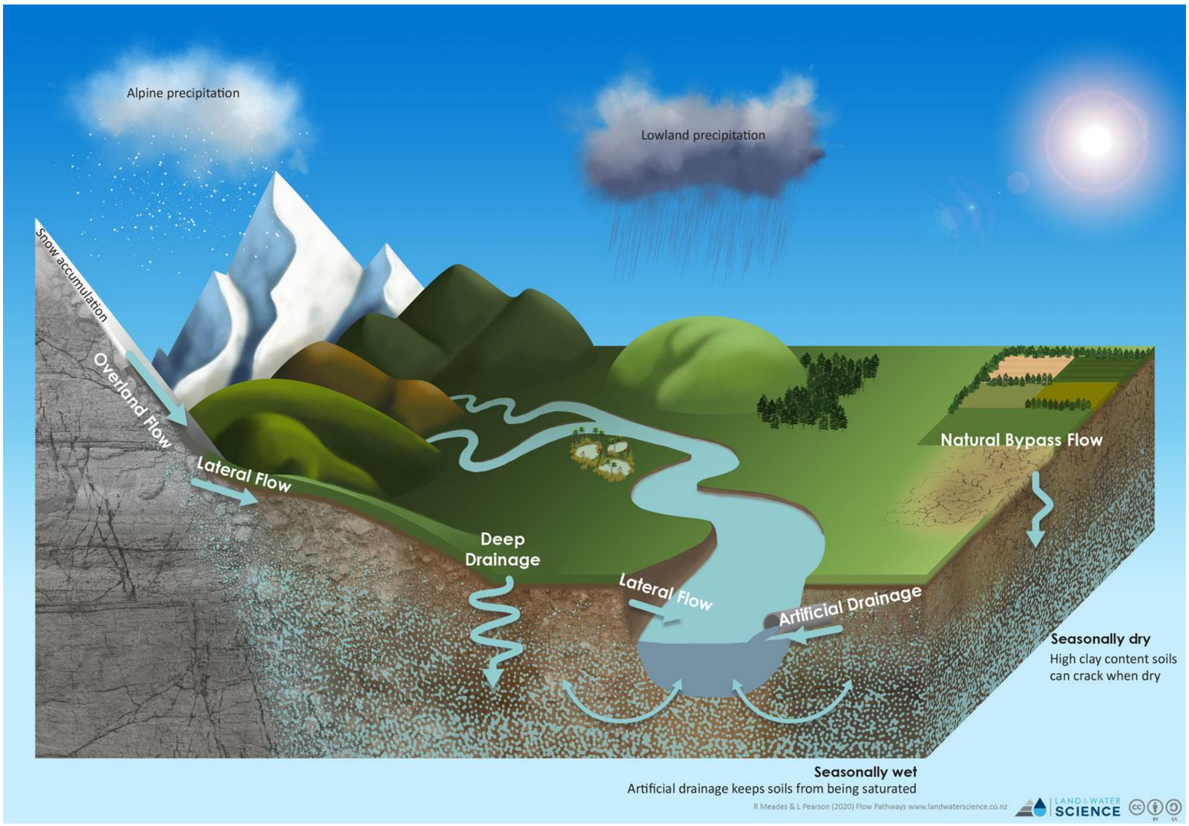


Figure 4. The pathway water takes after rainfall influences contaminant transport.

Deep drainage (or percolation through the soil zone to an underlying aquifer) is the slowest transport pathway and transports predominantly dissolved contaminants to stream (Figure 4). Deep drainage largely transports nitrate nitrogen, and the fate of the nitrate is dependent on the redox condition of the soil and underlying aquifer (see section 4.2.2). In areas where deep drainage is the dominant pathway, overland flow risk is typically low. How fast contaminants are transported to an underlying aquifer will depend on the excess of rainfall (minus evaporation and transpiration), unsaturated zone hydrological characteristics, and the depth to water table.

Lateral flow is the drainage of water laterally through the soil profile. It occurs in areas where slowly permeable soil or rock layers prevent the drainage of water vertically. Lateral flow is common in areas where there is shallow bedrock, such as in hill country. Seeps and springs often occur where lateral drainage flow paths converge with the land surface. Lateral flow also occurs close to waterways. and includes both natural and artificial lateral flow. Contaminants transported in lateral flow will vary depending on the redox setting they originate from. Oxidising areas are most likely to transport nitrate-nitrogen to waterways, while reducing areas are most likely to contribute organic, and ammoniacal nitrogen and dissolved reactive phosphorus. Where lateral flow predominates the volume in the soil for water retention is often limited, and overland flow can occur rapidly in these areas when seasonally wet.

Bypass pathways also facilitate rapid contaminant transport minimising the time water has in contact with the soil zone. Artificial bypass occurs in areas where the land has been drained. Artificial drainage speeds up the lateral flow through the soil and reduces the soil moisture content, thereby increases the amount of air which provides conditions for optimal growth of crops. Artificial drainage includes surface ditches, in addition to subsurface, mole and tile drains. Open ditch drainage is typically used in areas to lower the water table. This pathway dominates over the wetter months and may discontinue over the dryer months (see Section 4).

Natural soil bypass occurs in areas where there are clay rich soils that are prone to cracking when dry. Soils formed in calcium-rich parent materials and magnesium-rich mafic parent materials are most likely to have these shrink-swell clays. As the soil dries out, typically during summer to early autumn, cracks form. Episodic rainfall events occurring at this time leads to drainage water bypassing the soil matrix (Figure 4). Older soils with joints that form between poorly permeable areas are also important bypass pathways for water. Cracks and joints in the soil become a preferential pathway for water to drain through. As the drainage is rapid, there is minimal contaminant removal from the soil zone. High concentrations of microbes, such as *E. coli*, in groundwater is typically from this transport mechanism. In areas where artificial drainage is also present, these cracks can connect to the subsurface drainage network. Contaminants can directly enter a surface water body in these situations.

3 Physiographic Environments of New Zealand

3.1 Background to Physiographic Approach

There are two main factors controlling water quality outcomes – the landscape and us.

In the wrong place or at excessive concentrations, nutrients (nitrogen and phosphorus) and sediment become contaminants. Along with pathogens (harmful microbes), they require reduction to improve water quality nationally. Landscape variation has been identified as a driver of significant differences in water quality despite similar land use pressures. Therefore, understanding the role the landscape has in the resulting water quality outcomes can drive better land use decisions.

For example, overland flow or runoff (a hydrological process) is more common where soils are slowly permeable and imperfectly to poorly drained (Figure 5). Where fine-textured and poorly drained soils dominate a farm or a catchment, the risk of runoff and associated sediment, particulate phosphorus, and microbial loss to waterways is elevated. Where soils are permeable and well-drained, the risk of runoff occurring is lower due to higher rates of filtration and adsorption during the deep drainage of water down through the soil profile.

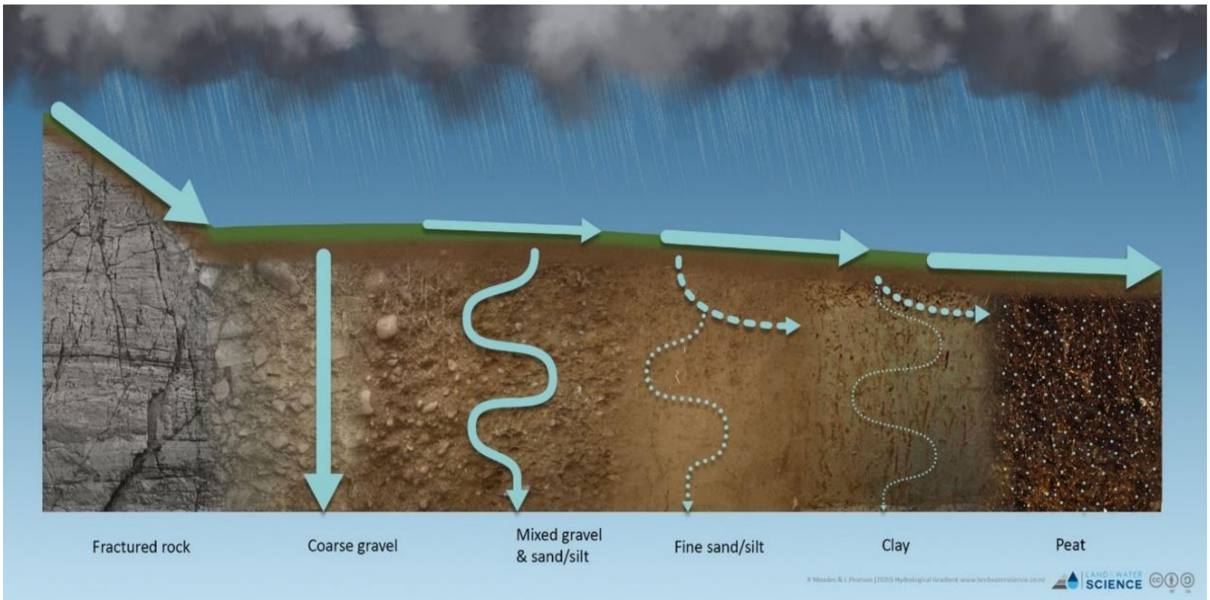


Figure 5. Simplified gradient of the hydrological pathway (response) water takes as slope, soil permeability and drainage class vary.

In another example, chemical processes, specifically oxidation and reduction reactions (redox) control key reactions, such as denitrification (the removal of nitrate to atmospheric nitrogen) but also the solubility and mobility of dissolved phosphorus. If an underlying aquifer is comprised of materials that favour the natural removal of nitrate (classified as reducing), then leached nitrate is likely to be removed before reaching the stream (Figure 6). However, dissolved phosphorus increases in solubility and mobility the more reducing an environment is.

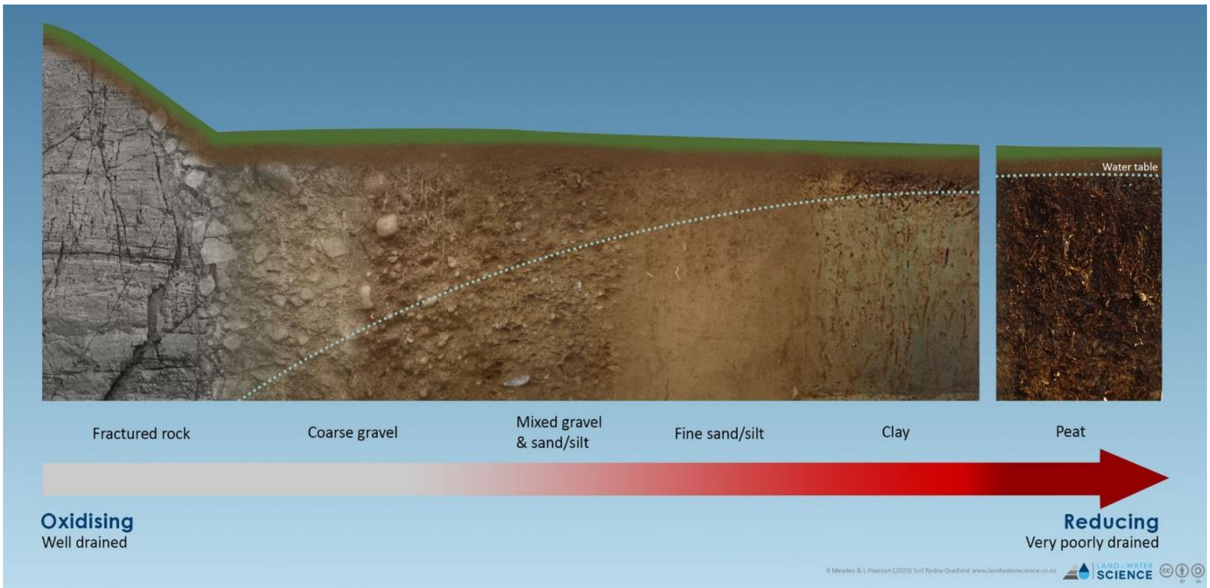


Figure 6. Simplified example of the redox gradients in soil. Reducing environments have a high ability to remove nitrogen whilst oxidising environments have very little.

The dominant processes that control water quality in the landscape, other than land use, are climatic, hydrology, the chemical process of redox, and physical weathering. To understand the main controls for any point in the landscape, we map the dominant processes of hydrology at a broad scale (source and volume) and fine scale (flow pathways), any potential biogeochemical reactions that may take place along the hydrological pathway, and physical weathering processes. Rock type and strength are important controls over sediment supply, with soft sedimentary rock often associated with higher sediment loss than stronger rock types. Weathering leading to sediment generation is therefore highly variable. Combined, these representations of the key processes helps us to understand the inherent susceptibility for contaminant loss from a landscape setting and classify the land into Physiographic Environments. Areas that have the same combination of hydrology, redox, and weathering processes are grouped into Physiographic Environments to provide a multi-contaminant framework for assessing the inherent susceptibility of the landscape for contaminant loss. The process maps can also be used to show variation within a Physiographic Environment for specific contaminants, (i.e., nitrate vs ammoniacal nitrogen).

Hydrochemical tracers (e.g., water source, hydrological pathway, redox) are used to test the performance of the process maps to represent each dominant process before a representation of land use intensity is included and spatial variation in water quality is predicated using a statistical, multivariate approach (Rissmann et al., 2019; submitted). Groundwater hydrochemistry is used to drive the classification of Physiographic Environments, including assessing hydrological connectivity, redox, and chemical weathering. However, most groundwater bores in New Zealand are poorly representative of the shallow, unconfined aquifer system that is directly connected to surface water.

The dominant processes that influence water quality are all controlled by the landscape. Depending on the landscape setting the type of water quality issue and its severity will vary. For this reason, current research suggests that variation in the landscape is often responsible for more than twice the variability in water quality than land use on its own. Therefore, the same farming operation over different landscape environments can have significantly different water quality issues. Knowing the landscape setting is a key way of identifying the water quality risk profile across New Zealand.

A website has been developed to make the background science, interactive maps of the underlying physiographic process layers and the Physiographic Environments of New Zealand Classification at [www.landscapedna.org.](http://www.landscapedna.org)

3.2 Method Summary

The natural gradients in topography (elevation and slope), soil and geological material (physical and chemical composition), and climate (precipitation) have been mapped using a novel landscape classification system, termed Process Attribute Mapping (PoAM). Applied at a national scale to New Zealand, gradients in atmospheric, hydrological, redox, and weathering processes are mapped (Pearson et al., 2018; Rissmann et al., 2018, 2019; submitted; Figure 7). These gradient maps are ultimately combined into the Physiographic Environments of New Zealand classification to explain how and why water quality varies nationally. This work is an extension of Physiographic mapping undertaken by Environment Southland to produce a zone map for policy application (Rissmann et al., 2016; Hughes et al., 2016).

Process gradients are defined according to the landscape attributes that drive variation in the magnitude of process response (Table 1). For example, a soil zone redox potential (“process”) gradient is mapped according to soil drainage class and organic carbon content (“attributes”) (Rissmann et al., 2016; 2018; 2019). Process signals, i.e., redox tracers in soil drainage, ground and surface water were then used to group attributes into classes with a similar redox signature. The resulting output is defined as a process-attribute gradient (PAG).

National application of Process Attribute Mapping (PoAM) utilised twelve pre-existing geospatial datasets (e.g., topography, geology) and >10,000 ground and surface water samples from 2,921 monitoring sites across 8 regions of New Zealand. A total of 16 PAG were defined nationally, 2x climatic, 8x hydrological, 2x redox, 4x weathering, and 1x geothermal (Table 1). Of these 16 PAG the majority were classed according to hydrochemical data. The performance of PAG to replicate process gradients was then tested against tracers of each process (e.g., chloride, bromide, ferrous iron) across the surface water network (cross-validated R^2 of 0.96 to 0.61). Each PAG was also ranked in terms of its sensitivity over the response of each dominant process. This involved hypothesising the likely sensitivity and magnitude of response of each PAG relative to a given hydrochemical tracer (e.g., ferrous iron and dissolved organic carbon for soil zone redox).

The ability of PAG to represent steady-state water quality, as indicated by nitrogen and phosphorus species, sediment, and *E.coli* (a microbial indicator), was assessed by combining an independent dataset of 811 long-term surface water quality monitoring sites and a map representing the gradient in land-use intensity (x-validated R^2 values for total nitrogen of 0.90 - 0.71 (median = 0.78), nitrate-nitrite nitrogen 0.83 - 0.71 (0.79), total phosphorus 0.85 - 0.63 (0.73), dissolved reactive phosphorus 0.76 - 0.57 (0.73), turbidity 0.92 - 0.48 (0.69), clarity 0.89 - 0.50 (0.62) and *E. coli* 0.75 - 0.59 (0.74)). The sensitivity of individual PAG over spatial variation in water quality was evaluated as part of regional modelling of water quality. The modelling identified regional climatic and geological variation as key controls on water quality variation across New Zealand.

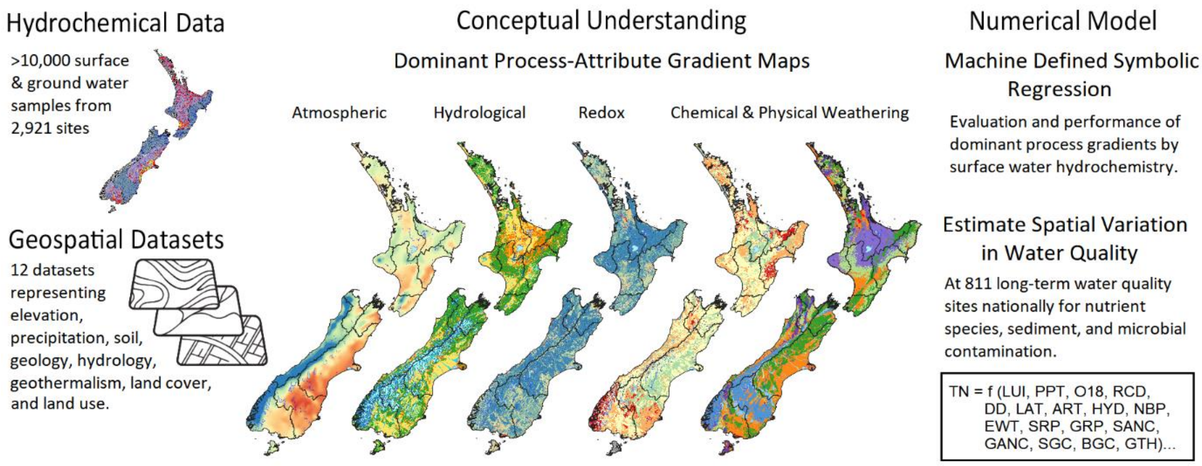


Figure 7. Summary method for process attribute gradient map generation and validating.

Table 1. Summary of the 16 national-scale process-attribute gradients. Relevant datasets are also shown.

Process	PAG	Process attribute gradient	Relevant datasets and scales	Attributes
Atmospheric	O18	Precipitation source	8 m DEM, $\delta^{18}O$-H_2O precipitation isoscape (4 km^2 pixel)	$\delta^{18}O$-H_2O, altitude, distance from the coast
	PPT	Precipitation volume	Annual average rainfall (5 km^2 pixel)	Precipitation volume
Hydrological	RCD	Macroscale recharge domain	Soil surveys (1:50,000), Aquifer type and extent (1:50,000)	Altitude, temperature isotherm, river network, Typic Fluvial Recent soils
	OLF	Overland flow	Soil surveys (1:50,000), 8 m DEM	Soil texture, drainage class, permeability, slope, area of developed land
	DD	Deep drainage (vertical drainage)	Soil surveys (1:50,000)	Drainage class, permeability, depth to slowly permeable horizon
	LAT	Lateral drainage	Soil surveys (1:50,000)	Drainage class, permeability, depth to slowly permeable horizon,
	ART	Artificial drainage	Soil surveys, 8 m DEM, Land Cover (1 ha)	Drainage class, permeability, depth to slowly permeable horizon, slope, agricultural land cover
	HYD	Soil slaking and dispersion as a soil hydrological index	Soil surveys (1:50,000)	Soil texture, drainage class, permeability, area of developed land
	NBP	Soil zone bypass	Soil surveys (1:50,000)	Cation exchange capacity, pH
	EWT	Equilibrium water table and aquifer potential	Water Table Model (0.04 km^2 pixel)	Modelled water table depth
Redox	SRP	Soil reduction potential	Soil surveys (1:50,000); soil chemistry profile points.	Drainage class, carbon content
	GRP	Geological aquifer reduction potential	Geological surveys (1:50,000 - 1:250,000)	Rock type (main and sub rocks)
Weathering	SANC	Soil acid neutralization capacity	Soil surveys (1:50,000); geochemical baseline survey (8 km^2)	Soil pH, cation exchange capacity
	GANC	Geological acid neutralization capacity	Geological surveys (1:50,000 - 1:250,000); geochemical baseline survey (8 km^2)	Rock type
	SGC	Surface/top regolith strength	Geological surveys (1:50,000 - 1:250,000)	Rock type and strength
	BGC	Basal regolith strength	Geological surveys (1:50,000 - 1:250,000)	Rock type and strength
Geothermal	GTH	High enthalpy geothermal (≥180 °C)	Log of resistivity (limited to extent of Taupo Volcanic Zone)	Resistivity

PAG: process attribute-gradient; DEM: digital elevation model

PAG were subsequently combined into Physiographic Environments guided by the performance and the sensitivity of PAG to represent dominant processes controlling water quality. Where each unit, “Physiographic Environment,” is assumed to respond in a similar manner to a broadly equivalent land use pressure. The classification is hierarchical, with a basic 10 environment family classification, and a higher resolution 28 class sibling classification, which provides more resolution over water source and hydrological response, dilution, filtration and absorption, resistance to erosion, and attenuation potential of water quality contaminants. These environments each have a defining set of landscape characteristics that affect water quality in a predictable manner.

Associated with each classification level are variants. Variants provide additional detail where there is modification of the natural hydrology (artificial drainage), seasonal and episodic variation (overland flow and natural soil zone bypass due to cracking soils under soil moisture deficit). Variants change the predicted contaminant profile for the Physiographic Environment.

3.2.1 Assumptions

- Scale of input data is appropriate to represent gradients in macroscale process gradients.

- If PAG can represent the dominant processes governing hydrochemistry, when combined with land use intensity, they are a sound basis for predicting water quality (qualitative and quantitative).
- Includes the use of PAG in combination with land use pressure to estimate steady-state concentrations and yields of contaminants across the digital river network (Rissmann et al., 2019; Rissmann et al., 2020; Pearson and Rissmann, 2020; Rissmann et al., submitted).
- Validated against 7 regions hydrochemistry data (Northland, Auckland, Waikato, Bay of Plenty, Manawatu-Whanganui, Canterbury, Southland). Extrapolated PAG classification to other areas on the basis it was appropriate for regions with hydrochemistry data (Rissmann et al. submitted).
- Surface water, 5-year medians, estimated across 811 sites nationally, using LAWA dataset.

3.2.2 Uncertainty

Uncertainty in the underlying classification is evaluated in a number of ways. Firstly, each PAG is tested to see if it adequately represents dominant process gradients. This phase of testing employs the use of hydrochemical tracers, sampled from surface and ground waters, to test the adequacy with which PAG represents each dominant process. If PAG respond as hypothesised, only then is land use pressure incorporated and water quality models generated.

The multivariate framework for assessing uncertainty, the relative sensitivity, and magnitude of response of hydrochemical tracers and subsequently water quality indicators utilise a hybrid deterministic regression/genetic programming approach that employs symbolism (Rissmann et al., 2019; submitted). This approach generates 'whitebox' models of the relationship between PAG and hydrochemical tracers for each dominant process.

1. The evolutionary nature of the modelling approach, generates billions of models, converging upon the representation that maximises certainty and minimises complexity. Any PAG or mathematical combinations that do not reduce uncertainty and complexity are discarded during the evolutionary process.
2. The PAG retained, their relative sensitivity, and magnitude of response with respect to a dominant process tracer (e.g., hydrological or redox tracer) is defined prior to model development and sensitivity analysis. All PAG are used as input with the machine defined output evaluated against the a priori hypothesis.
3. Cross-validation is used to generate a measure of uncertainty, 90% of the data is used for training and 10% for validation.
4. Only if models respond as hypothesised and achieve performance measures is a representation of land use pressure incorporated and water quality models developed.

Subsequent modelling utilising an ensemble of 7 additional modelling algorithms such as Random Forest, Gradient Boosted Trees, and Support Vector Machines are consistent with the results of the hybrid deterministic regression/genetic programming approach.

3.2.3 Advantages

- Multivariate evaluation shows that process-attribute gradients effectively replicated the dominant process gradients responsible for the generation, storage, attenuation, and transport of water quality contaminants in the environment.
- Dominant process approach and use of whitebox models can be used to explain at a macroscale 'how' and 'why' the type and severity of water quality varies spatially.
- Publicly available and national coverage (www.landscapeDNA.org).

- Objective approach that uses a large national coverage of groundwater quality observations for prediction of redox status (9,100 wells of which 7,535 were used).
- The inclusion of process understanding overcomes the sampling bias associated with purely data-driven modelling approaches.

3.2.4 Disadvantages & Limitations

As with any complex system, the ability to isolate and depict first-order drivers of process response is challenging. Accordingly, as with any model each process-attribute layer can only be considered an approximation of the 'real' macroscale process-attribute gradient. These limitations increase when moving from regional to national scales.

Spatial correlation between landscape attributes may interfere with the machine-driven isolation of primary drivers and limit the ability to identify causation (Rissmann et al., 2019). This is especially true of process-attribute gradients that share similar landscape attributes, such as deep drainage, lateral drainage, and soil reduction potential. Multivariate approaches to limit correlation and maximise causation will be important in future iterations.

Testing bias is associated with the location of surface water monitoring sites for process-attribute gradient performance. These monitoring sites are associated with higher order streams (≥ 3) and larger drainage basin areas for pragmatic reasons. Specifically, of the 730 surface water capture zones with hydrochemical data, the median size is 122 km^2, with only 38 less than 5 km^2 (500 ha).

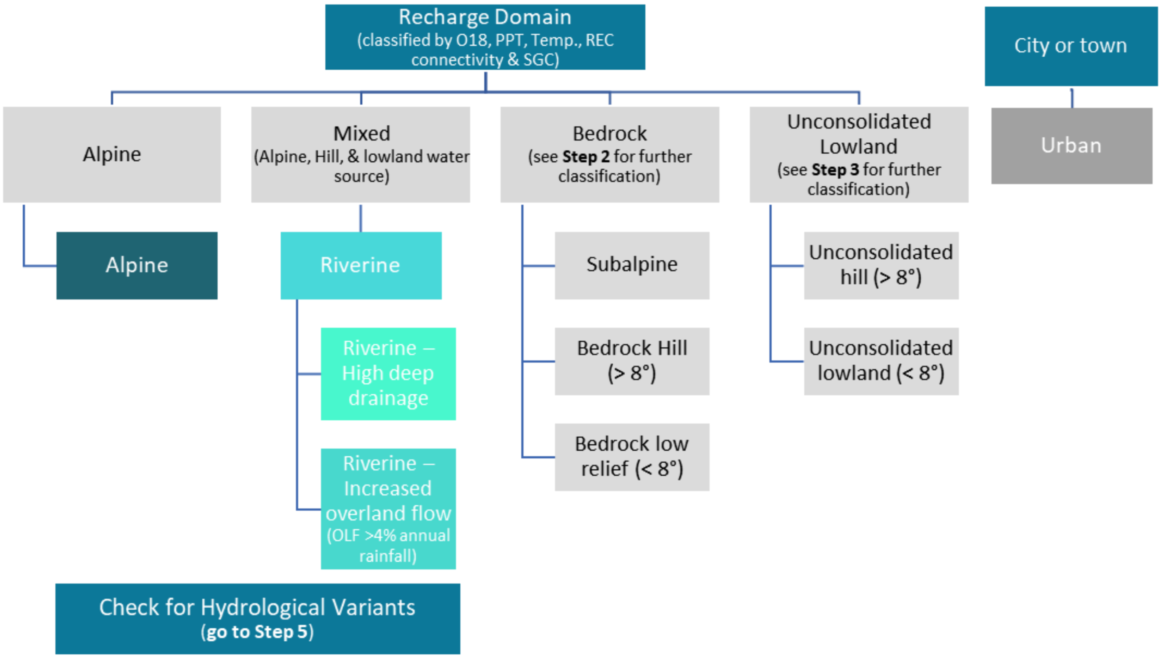
3.3 Physiographic Environments Classification

The Physiographic Environments of New Zealand classification is hierarchical, with a basic 10 Environment **Family Classification**, and a higher-resolution **Sibling Classification**, which provides more information over water source and hydrological response (flow pathway), and the role the landscape has in removing or reducing potential water quality contaminants. These environments each have a defining set of landscape characteristics that affect water quality in a predictable manner.

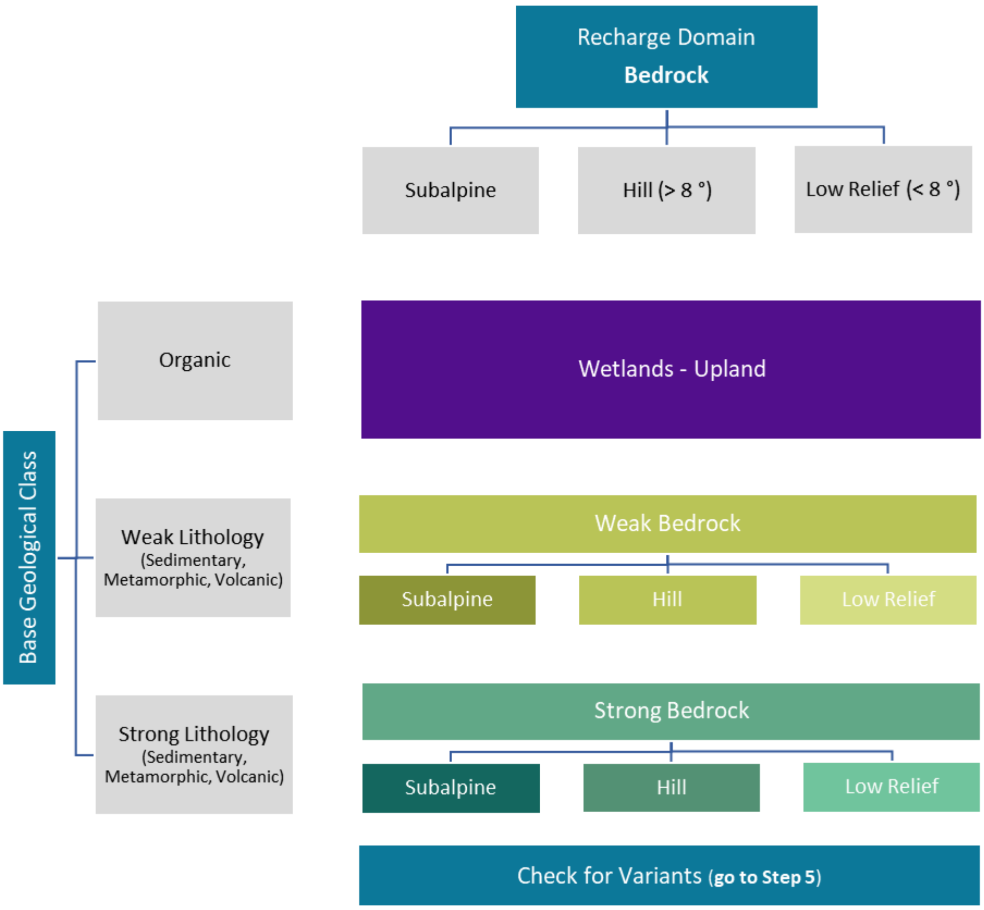
Associated with each classification level are hydrological **variants**. Variants provide additional detail where there is modification of the natural hydrology by artificial drainage, or seasonal and episodic variation in the pathway water takes to leave the land. During heavy rainfall events overland flow may become the dominant pathway or under dry or drought conditions, natural soil zone bypass may occur due to cracking soils. Variants change the predicted contaminant profile for the Physiographic Environment.

Figure 8 shows the classification decision tree from Process-Attribute Gradients (PAG) to the Family and Sibling Classification (Step 1-4) and the identification of variants (Step 5). The classification of an environment is colour coded to match the map legends for the Family class in Figure 9 and Sibling class in Figure 10.

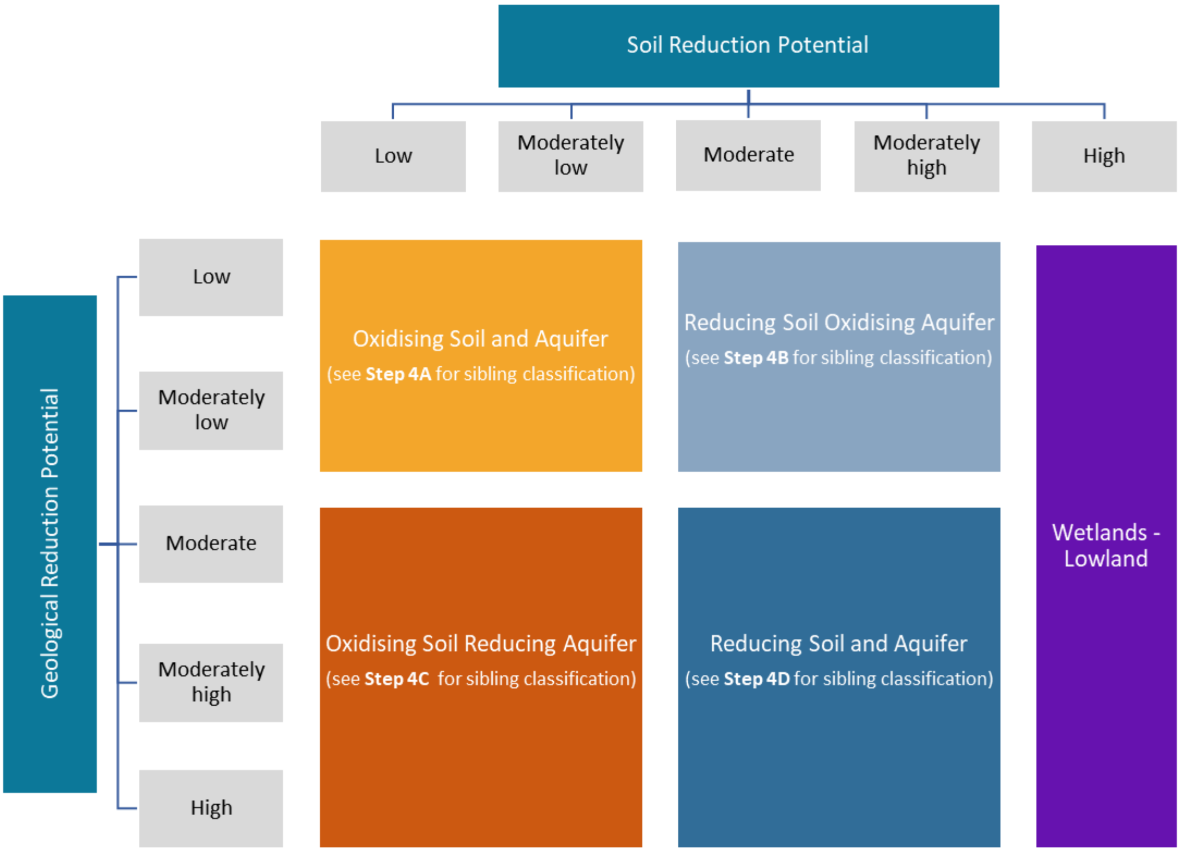
Step 1. Classification of macro scale hydrology (water source and connectivity) and Urban Environment.



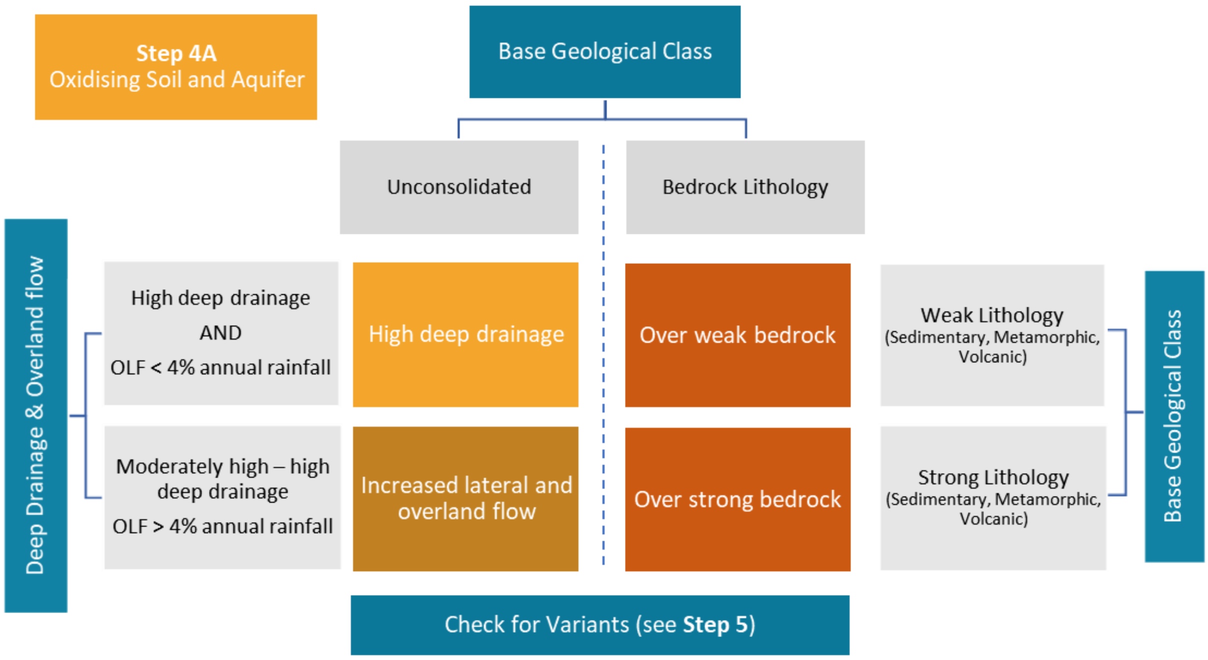
Step 2. Classification of Upland Environments in Bedrock Recharge Domain.

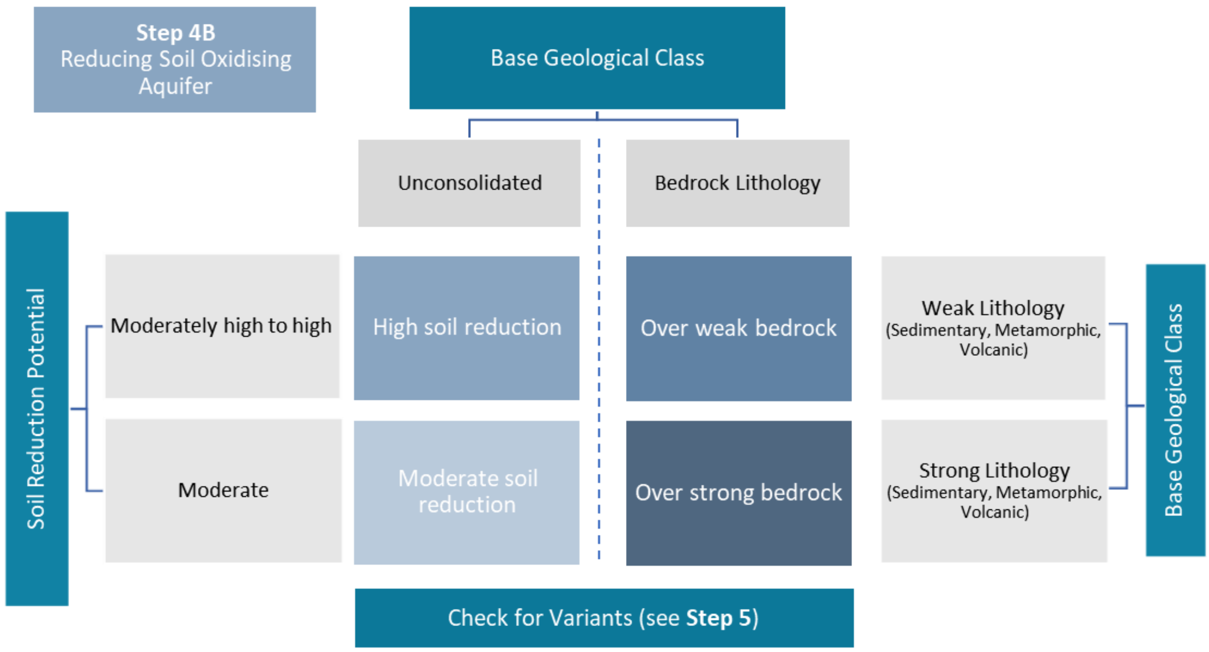


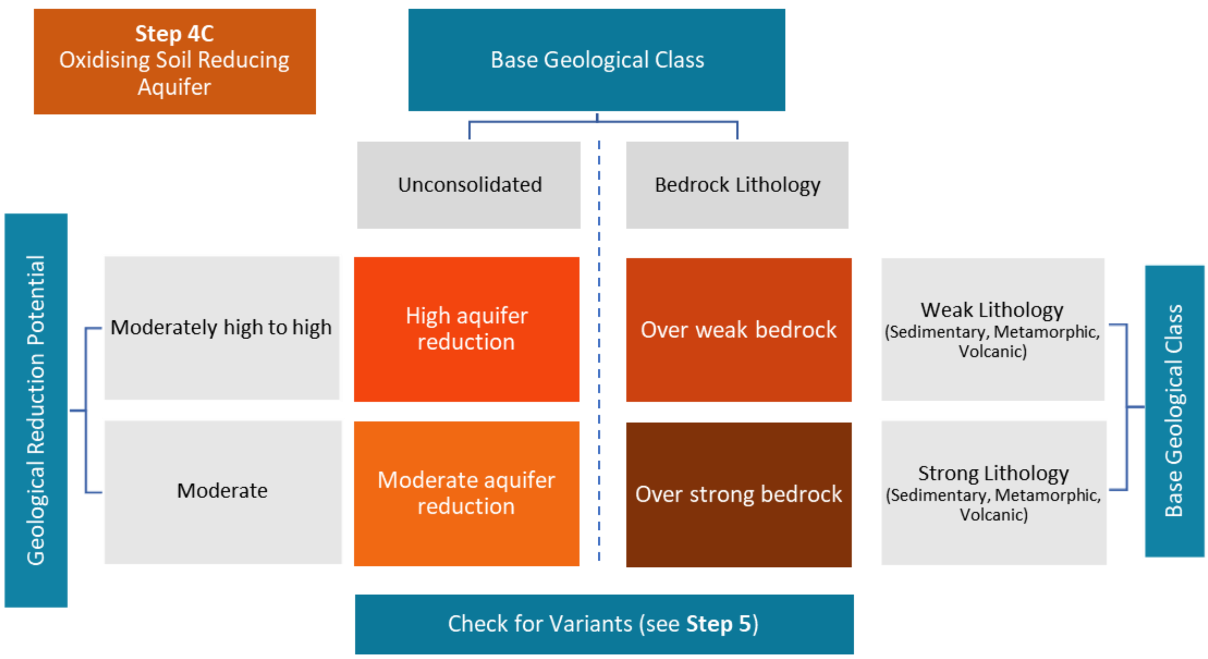
Step 3. Classification of Unconsolidated Lowland Recharge Domain at Family Class. Water source is by land surface recharge only.

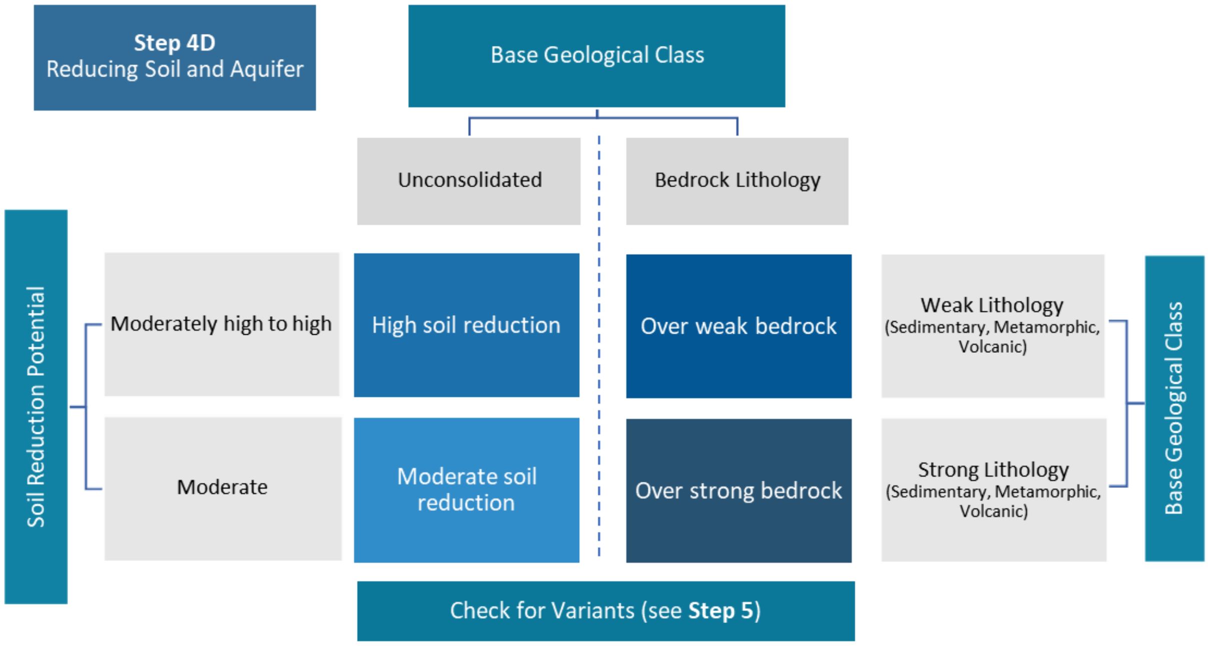


Step 4. Lowland Environments Sibling Classification.




Step 4B
Reducing Soil Oxidising Aquifer
Base Geological Class
Unconsolidated
Bedrock Lithology
Soil Reduction Potential
Moderately high to high
High soil reduction
Over weak bedrock
Weak Lithology
(Sedimentary, Metamorphic, Volcanic)
Moderate
Moderate soil reduction
Over strong bedrock
Strong Lithology
(Sedimentary, Metamorphic, Volcanic)
Base Geological Class
Check for Variants (see Step 5)


Step 4C
Oxidising Soil Reducing Aquifer
Base Geological Class
Unconsolidated
Bedrock Lithology
Geological Reduction Potential
Moderately high to high
High aquifer reduction
Over weak bedrock
Weak Lithology
(Sedimentary, Metamorphic, Volcanic)
Moderate
Moderate aquifer reduction
Over strong bedrock
Strong Lithology
(Sedimentary, Metamorphic, Volcanic)
Base Geological Class
Check for Variants (see Step 5)



Step 5. Hydrological Variants apply in response to episodic rainfall events or seasonal variation and supersede the inherent risk of the Physiographic Environment when the pathway is active.

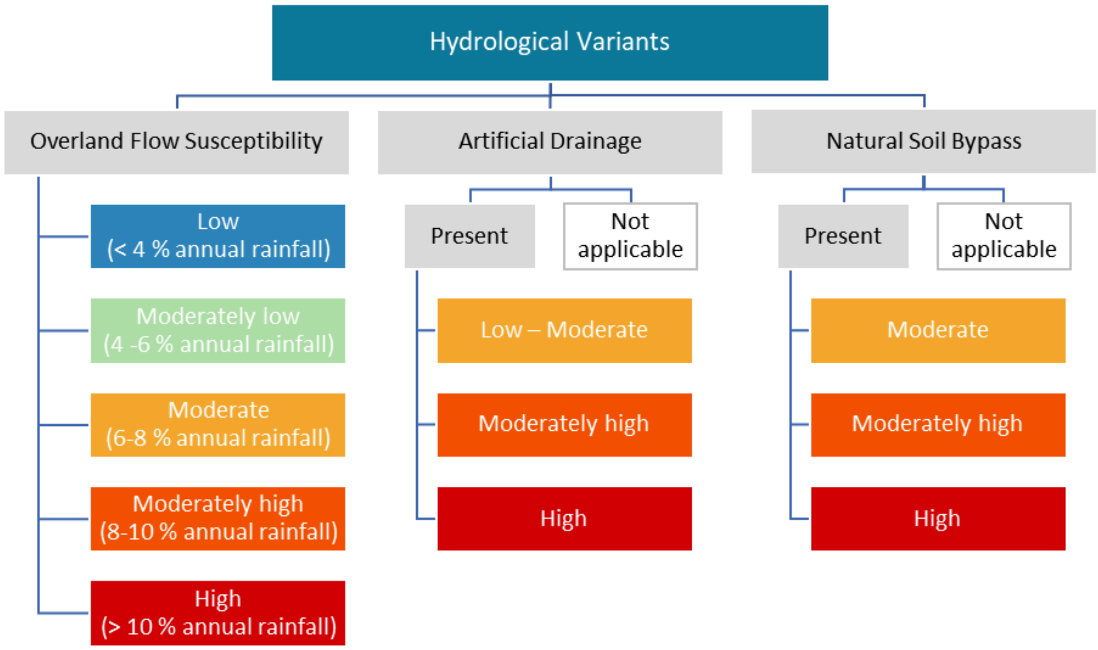


Figure 8. Family and sibling class Physiographic Environment decision tree – steps 1 - 5. Step 1 is the classification of macro scale hydrology (water source and connectivity) and Urban Environment. Step 2 is the classification of upland environments in the bedrock recharge domain. Step 3 is the classification of environments in the unconsolidated lowland recharge domain at the Family level. In Step 4 the lowland Family Environments are classified into siblings. Step 5 is the classification of hydrological variants which overly the Family and Sibling Physiographic Environment Classification. Hydrological Variants apply in response to episodic rainfall events or seasonal variation and supersede the inherent risk of the Physiographic Environment when the pathway is active.

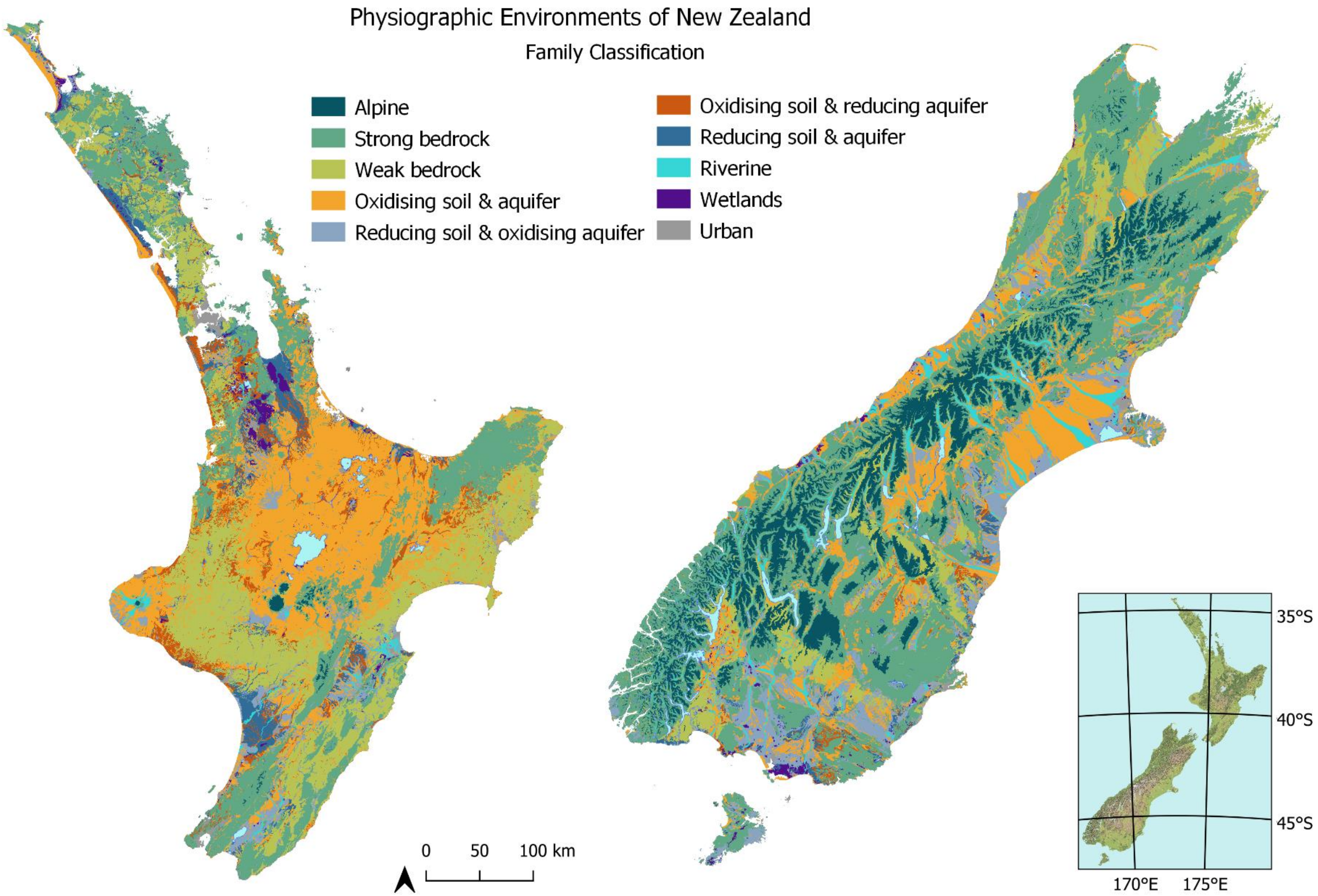


Figure 9. Physiographic Environments of New Zealand – Family classification.

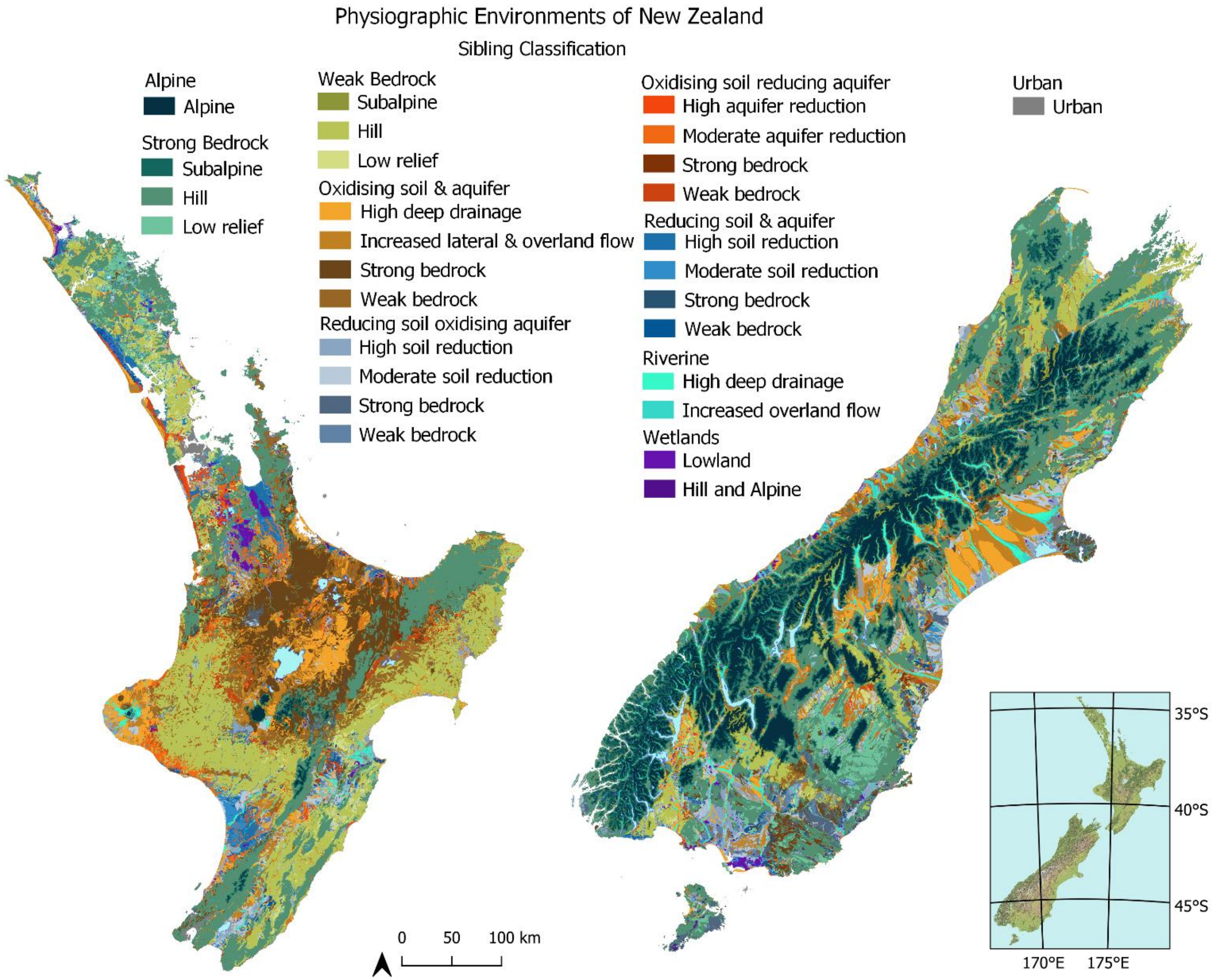


Figure 10. Physiographic Environments of New Zealand – Sibling Classification.

The summary descriptions provided here are for the Family and Sibling Classes of the Physiographic Environments Classification (Figure 9 and 10). Interactive maps and animated videos for each family environment are available through the website https://landscapedna.org. These videos summarise each environment by the key hydrological pathway water takes to leave the land, how our actions have modified natural hydrology through drainage, and the inherent risk of contaminant loss from the land. We show the likely water quality effects in the Physiographic Environment and some best-suited actions to minimise contaminant losses.

Alpine

High (tree line or >800 m) altitude environment, typically with low organic carbon in soil and soil parent material. It will experience snowpack accumulation and high precipitation relative to other environments, and due to short residence times and inert lithologies waters are commonly dilute and strongly oxidising with little evidence for anthropogenic contamination due to little if any land use pressure. Most of the precipitation accumulates as snow over the winter months and seasonal melt water either runs off across bare rock or infiltrates through thin colluvium and moves laterally towards low lying valleys where it forms rivers. This environment is found throughout the Southern Alps of New Zealand (South Island), and the high peaks of the North Island and supplies large volumes of dilute and often pristine water to lowland areas.

There are no siblings within the Alpine Environment.

Strong and Weak Bedrock

Typified by rolling to steep topography where soil and/or colluvium overlies bedrock or glacial till. Historically referred to as 'hill country' the soil mantle is typically thin and well-drained relative to other environments. Most of the precipitation infiltrates and moves laterally at the contact between the soil and underlying bedrock or during periods of wet soils or high-intensity precipitation runs off as overland flow. However, variation in soil hydrology and slope govern moderate to small scale variation in hydrological response. This environment is typically associated with high soil organic carbon content due to a history of forest and native grassland (tussock) cover relative to the Alpine environment and is characterised by elevated precipitation relative to lowland environments. This environment has been subdivided at the family level by **Strong** and **Weak bedrock**, as weak rocks are typically more erosion-prone and contribute larger quantities of sediment to waterways. Fractured rock aquifers are more likely under strong bedrock settings.

Strong and Weak bedrock siblings

- ***Subalpine*** identifies bedrock areas that are hydrologically connected to the Alpine Environment and as a result, have a moderately high dilution potential for downstream receiving environments. This sibling may also have snow accumulation over the winter months. The shallow soils and steeper topography have a greater runoff risk relative to other bedrock areas.
- ***Hill*** identifies areas of shallow soils with rolling topography (greater than 8 degrees). This sibling has a moderate dilution potential for downstream receiving environments. Due to the rolling topography, runoff risk is typically higher relative to the low relief sibling.
- ***Low relief*** maps bedrock areas less than 8 degrees. This sibling has a moderate to low dilution potential for downstream receiving environments. Runoff risk is typically lower than the other bedrock environments.

Oxidising Soil and Aquifer

Related to well-drained oxic soils and oxic aquifers, this environment is poorly connected with Alpine, sub-Alpine, and Bedrock sourced rivers, deriving its recharge from local precipitation. Due to the well-drained soils, most precipitation infiltrates, and percolates to the underlying aquifer before discharging as spring-fed streams that may receive periodic runoff where the land is sloping or where soil infiltration rates are low. This environment is typically associated with moderately well to well-drained soils overlying alluvium. This environment tends to have a low potential for water dilution and is strongly oxidising, allowing nitrate nitrogen to accumulate to high concentrations in the water-table aquifer. Groundwater contributions to baseflow tend to be oxidising and larger than lowland environments characterised by imperfectly to poorly drained soils.

Oxidising soil and aquifer siblings

- ***High deep drainage*** occurs on flat topography where there are minimal impediments to water draining through the soil profile.
- ***Increased lateral and overland flow*** occurs on either undulating topographies or where soils are moderately well-drained resulting in increased lateral or overland flow.
- ***Over strong bedrock*** is a transitional class between the Oxidising Soil and Aquifer Environment and the Strong Bedrock Environment. This sibling identifies where soils occur over strong bedrock which affects how deep water can drain and limits the aquifer potential of the environment. Strong bedrock is more likely to host fractured rock aquifers than weak bedrock.
- ***Over weak bedrock*** is a transitional class between the Oxidising Soil and Aquifer Environment and Weak Bedrock Environment. It identifies where soils occur over weak bedrock which affects how deep water can drain and limits the aquifer potential of the environment.

Oxidising Soil Reducing Aquifer

This environment is characterised by well drained soils overlying carbonaceous (e.g., lignite, peat), terrestrial, or marine-derived sedimentary parent materials. The aquifer underlying these well drained soils contain elevated carbon concentrations (electron donors) relative to other environments and is frequently associated with marine terraces. Due to well drained soils, water infiltrates and percolates to the water table aquifer where microbially mediated redox processes modify the oxic soil recharge. However, if the water table is shallow the poor permeability of the aquifer materials can result in upwelling and lateral discharge via horizon permeable layers or artificial subsoil drainage that has been put in place to supress upwelling of groundwater during the cooler months.

Oxidising soil reducing aquifer siblings

- ***High aquifer reduction*** occurs over areas with either peat, marine terraces, or lignite in the underlying geology.
- ***Moderate aquifer reduction*** typically has mudstones as the underlying geology.
- ***Over strong bedrock*** is a transitional class between the Oxidising Soil Reducing Aquifer Environment and the Strong Bedrock Environment. This sibling identifies where soils occur over strong bedrock which affects how deep water can drain and limits the aquifer potential of the environment. In some instances, strong bedrock is more likely to host fractured rock aquifers than weak bedrock.
- ***Over weak bedrock*** is a transitional class between the Oxidising Soil Reducing Aquifer Environment and Weak Bedrock Environment. It identifies where soils occur over weak

bedrock which affects how deep water can drain and limits the aquifer potential of the environment.

Reducing Soil Oxidising Aquifer

Typically associated with imperfectly to poorly drained mineral soils formed in silt and/or clay-rich parent materials. It also includes minor areas of remanent wetland where extensive drainage has occurred. Most of the water exported from this setting moves laterally via artificial sub-surface drainage in areas of developed land or as overland flow due to the poor internal drainage of the overlying soils. Contribution to groundwater in this environment is low relative to areas with well drained soils. A significant variation from the predicted water quality response is observed in areas where soils, characterised by smectitic clays, are prone to cracking in response to soil moisture deficit, leading to recharge bypassing the soil matrix during autumn recharge and then transitioning to lateral flow when soils rehydrate during the cooler months. This environment exhibits temporal variation in hydrological response and redox signatures due to this shrink-swell soil behavior.

Reducing soil oxidising aquifer siblings

- ***High soil reduction*** occurs where soils are predominantly poorly drained.
- ***Moderate soil reduction*** occurs where soils are imperfectly drained. Soils with imperfect drainage are likely to take on similar characteristics to the oxidizing soil and aquifer during dry periods.
- ***Over strong bedrock*** is a transitional class between the Reducing Soil Oxidising Aquifer Environment and the Strong Bedrock Environment. This sibling identifies where soils occur over strong bedrock which affects how deep water can drain and limits the aquifer potential of the environment. In some instances, strong bedrock is more likely to host fractured rock aquifers than weak bedrock.
- ***Over weak bedrock*** is a transitional class between the Reducing Soil Oxidising Aquifer Environment and Weak Bedrock Environment. It identifies where soils occur over weak bedrock which affects how deep water can drain and limits the aquifer potential of the environment.

Reducing Soil and Aquifer

Associated with imperfectly to poorly drained soils with redoximorphic features, such as mottling and gleying, and aquifer materials with a high-electron donor abundance. This environment often occurs on weathered alluvial terraces or along low Strahler order streams and is associated with silt and/or clay-rich soils and aquifers containing an abundance of electron donors (e.g., organic carbon). It is also associated with peat deposits that have been significantly modified through artificial drainage. It exhibits high soil and aquifer reduction potential and low water dilution potential. Most of the water from this setting moves laterally via artificial sub-surface drainage in areas of developed land or as overland flow due to the poor internal drainage of the overlying soils. Groundwater contributions to baseflow tend to be reducing and of minor volume relative to the Oxidising Soil and Aquifer Environment.

Reducing soil and aquifer siblings

- ***High soil reduction*** occurs where soils are predominantly poorly drained.
- ***Moderate soil reduction*** occurs where soils are imperfectly drained. Soils with imperfect drainage are likely to take on similar characteristics to the oxidizing soils during dry periods

which increases the likely attenuation of phosphorus in the soil and any leached nitrate is likely to be denitrified in the underlying aquifer.

- ***Over strong bedrock*** is a transitional class between the Reducing Soil and Aquifer Environment and the Strong Bedrock Environment. This sibling identifies where soils occur over strong bedrock which affects how deep water can drain and limits the aquifer potential of the environment. In some instances, strong bedrock is more likely to host fractured rock aquifers than weak bedrock.
- ***Over weak bedrock*** is a transitional class between the Reducing Soil Oxidising Aquifer Environment and Weak Bedrock Environment. It identifies where soils occur over weak bedrock which affects how deep water can drain and limits the aquifer potential of the environment.

Riverine

This environment occurs along riparian margins of the upper to mid reaches of Alpine fed rivers. It hydraulically connects the Alpine environment and in areas the Bedrock environment to Lowland environments. Typically, this environment contains recent, well-drained soils and/or alluvium overlying highly permeable aquifers. The water table is strongly influenced by Alpine and Bedrock River discharge with lower volumetric contributions from lowland recharge events. This environment is strongly oxidising, with a high dilution potential. Mixing of large volumes (relative to rainfall) of dilute runoff from alpine headwaters with local rainfall recharge significantly influences water quality in this environment.

Riverine Siblings

- ***High deep drainage*** occurs on areas of flat topography where there are minimal impediments to water draining through the soil profile.
- ***Increased overland flow*** occurs on either sloping topographies or where soils are moderately well-drained, or water tables are very shallow.

Wetlands

The Wetland Environment associated with wetlands and wetland soils rich in organic carbon. This environment is frequently associated with acidic and peaty soils and aquifers, often with low anion exchange capacity that are strongly reducing. Due to the shallow water table and poor internal drainage, this environment is characterised by a strong surficial runoff response and is commonly intensely artificially drained where developed for agricultural use.

Wetland siblings

- ***Lowland*** wetlands are more likely to have deeper peat development and greater extent relative to wetlands located in the upland areas. Peat bogs are the most common wetland type in this sibling.
- ***Upland*** wetlands are often located in gullies and areas where water converges and ponds. They are often smaller and shallower in extent than lowland wetlands. Many of the wetlands located in alpine and subalpine environments are smaller than the scale of the mapping.

Table 3 provides a summary of Physiographic Environments by area. Regional statistics are provided in the Appendix.

Table 2. Physiographic Environments of New Zealand Area Summary.

Physiographic Environment	Sibling	Family Area (ha)	Family Percentage (%)	Sibling Area (ha)	Sibling Percentage (%)
Alpine		2,165,178	8.22	2,165,178	8.22
Strong bedrock		9,045,768	34.34		
	Subalpine			2,071,397	7.86
	Hill			6,331,097	24.04
	Low relief			643,274	2.44
Weak bedrock		4,346,530	16.50		
	Subalpine			293,764	1.12
	Hill			3,608,172	13.70
	Low relief			444,594	1.69
Oxidising soil & aquifer		5,636,510	21.40		
	High deep drainage			1,436,240	5.45
	Increased lateral & overland flow			1,527,673	5.80
	Strong bedrock			1,520,765	5.77
	Weak bedrock			1,151,833	4.37
Reducing soil oxidising aquifer		2,274,644	8.64		
	High soil reduction			698,116	2.65
	Moderate soil reduction			897,764	3.41
	Strong bedrock			358,075	1.36
	Weak bedrock			320,688	1.22
Oxidising soil reducing aquifer		902,592	3.43		
	High aquifer reduction			127,007	0.48
	Moderate aquifer reduction			386,843	1.47
	Strong bedrock			127,472	0.48
	Weak bedrock			261,270	0.99
Reducing soil & aquifer		844,921	3.21		
	High soil reduction			297,992	1.13
	Moderate soil reduction			344,744	1.31
	Strong bedrock			59,744	0.23
	Weak bedrock			142,442	0.54
Riverine		717,536	2.72		
	High deep drainage			403,038	1.53
	Increased overland flow			314,498	1.19
Wetlands		216,815	0.82		
	Lowland			191,542	0.73
	Hill and Alpine			25,273	0.10
Urban		186,700	0.71	186,700	0.71
Quarry		1,056	0.00	1,056	0.00

3.4 Physiographic Variants

In addition to the main classification, variants are used to spatially depict where differences in the hydrological response to land use and episodic events may differ. This occurs where soils have been artificially drained (anthropogenic modification), or through the response of seasonal and episodic rainfall events (overland flow risk - natural seasonal wetness), or where soils crack under soil moisture deficit (natural seasonal dryness) resulting in bypass pathways which can change the predicted contaminant profile for an environment. The maps shown here are depicted according to the process-attribute map, however, are represented by hatching when used as an overlay to the Physiographic Environments in Section 5.3.

Artificial Drainage

Artificial drainage speeds up vertical percolation and lateral flow through the soil (Figure 11, Pearson, 2015a). It facilitates more rapid drainage of the soil and extends the utility of the soil for farming. Artificial drainage includes surface ditches, in addition to subsurface, mole and tile drains. Open ditch drainage is typically used to lower the water table. Open ditches in conjunction with subsurface drainage are used to improve drainage through poorly drained soil and/or locally lower water tables.

Contaminants transported in artificial drainage will vary depending on the redox condition. Oxidising areas are most likely to transport nitrate-nitrogen to waterways, while reducing areas are most likely to contribute ammoniacal nitrogen and dissolved or colloidal forms of phosphorus. Artificial drainage can change the redox potential by increasing the amount of oxygen in the soil. As such, artificial drainage fundamentally changes the biogeochemical properties of a poorly to imperfectly drained soils. Drainage may improve P retention and reduce surface runoff in some settings. However, it also accelerates microbial decomposition of legacy organic matter and subsequently, N and P.

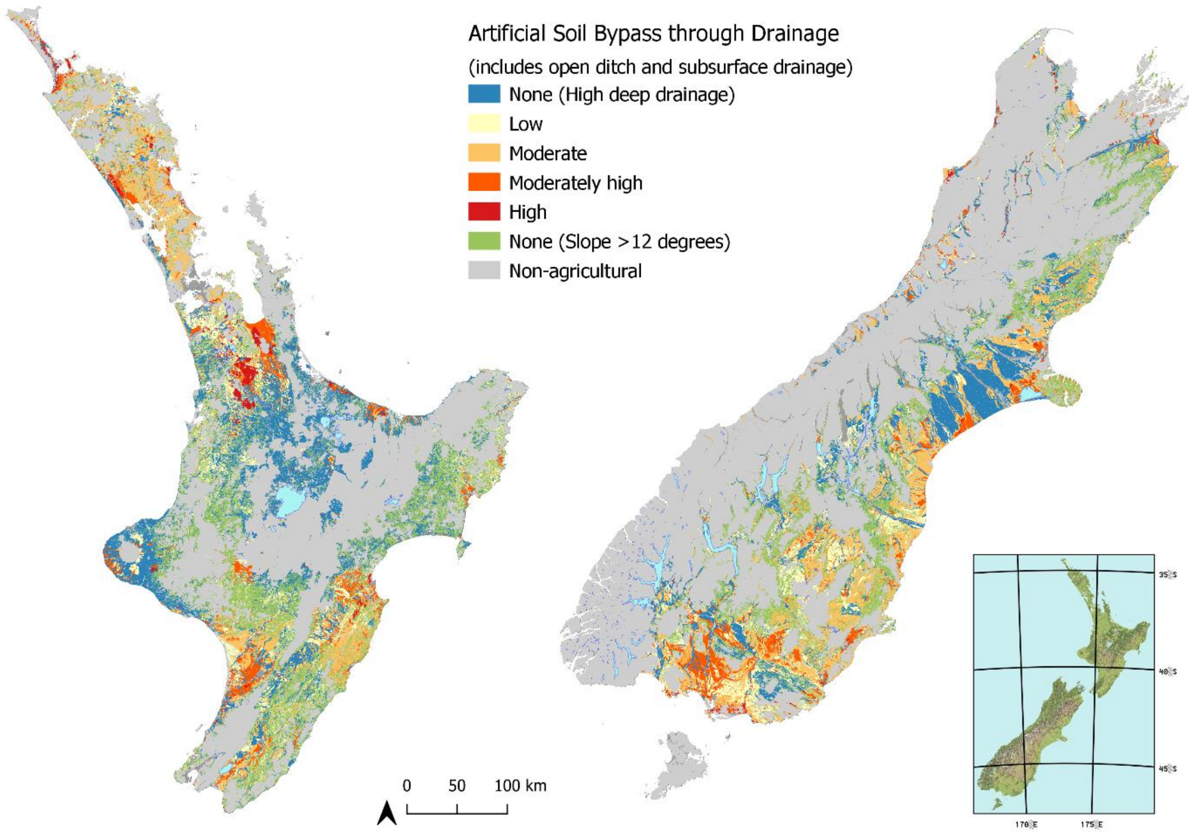


Figure 11. Artificial drainage density across New Zealand. Artificial drainage includes both surface ditch and subsurface (i.e., tile and mole) drainage.

Organic matter content is one of the main factors governing the degree to which drainage modifies soil biogeochemical properties. In imperfectly to poorly drained mineral soils, with low organic carbon content, these formerly reducing soils may start to behave more like oxidised soils, with significant nitrate export. For soils with higher organic carbon contents, nitrate is also likely to be produced, but much of it exhibits denitrification signatures, with the reduced forms of N (organic and ammoniacal) often constituting and important component of the N loss. Phosphorus loss may also be enhanced where organic rich soils are drained due to limited P-retention, mineralisation of P stored in legacy organic matter, and or the export of organic-P colloids. In fact, some of the highest P leaching rates are associated with organic soils. In summary, the effect of artificial drainage over nutrient export varies as a function of soil type.

Overland Flow

Overland flow (surficial runoff) is the contaminant pathway that has highest the risk to water quality. This is because water rapidly discharges picking up contaminants as it runs over the land surface (Figure 12). Water has minimal interaction with the soil zone or geology for any contaminant removal to occur. For overland flow to pose a risk to water quality it requires a contaminant source. Overland flow is estimated by combining two landscape factors – a soil hydrologic index and a slope index and is expressed as a percentage of the annual effective rainfall (McDowell et al., 2005; Pearson, 2015b).

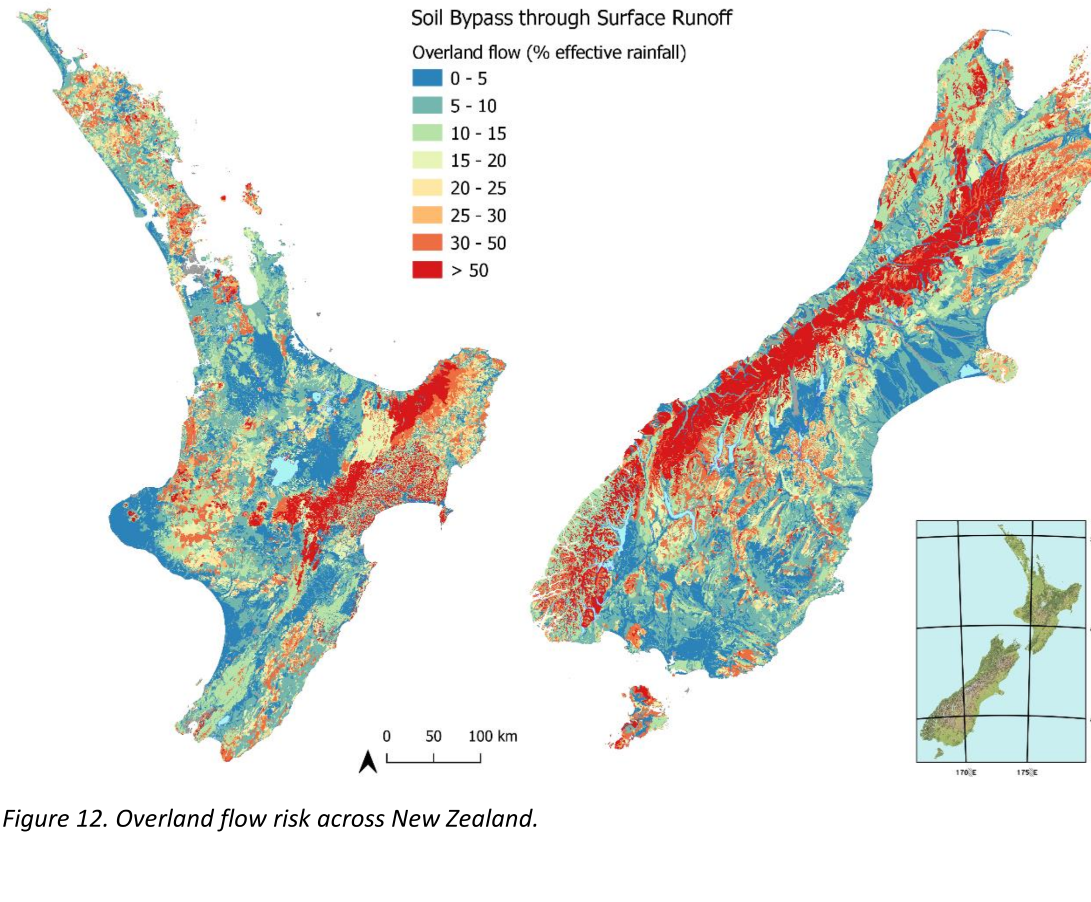


Figure 12. Overland flow risk across New Zealand.

Across lowland areas, the maximum runoff is estimated at 12% of the annual rainfall volume. If these areas are used for intensive farming practices the risk to water quality from overland flow is considered very high. This reflects the likelihood of much higher N, P, and microbial source loads across lowland areas relative to hill and high country settings. As such, overland flow risk is also a function of land use intensity, with runoff from natural state areas unlikely to be associated with an elevated N, P, and microbial load relative to agricultural land.

On rolling to hill country, the likelihood of overland flow occurring is higher. Subalpine and alpine areas have the highest overland flow risk however the source contribution is considered low. While water may runoff, the likely contribution to the contaminant load is low.

Natural Soil Bypass

Natural soil bypass occurs in areas where there are clay rich soils that are prone to cracking when dry or where soil pedogenic structures favour jointing and bypass of drainage water (Figure 13). Soils formed in calcium-rich parent materials and magnesium-rich mafic parent materials are most likely to have these shrink-swell clays. As the soil dries out, typically during summer to early autumn, cracks form leading to drainage water bypassing the soil matrix. Older soils with joints that form between poorly permeable areas are also important bypass pathways for water.

Cracks and joints in the soil become a preferential pathway for water to drain through. As the drainage is rapid, there is minimal contaminant removal from the soil zone. High concentrations of microbes, such as *E. coli*, in groundwater is typically from this transport mechanism. In areas where artificial drainage is also present, these cracks can connect to the subsurface drainage network and result in direct discharge of animal wastes and fertilisers to waterways.

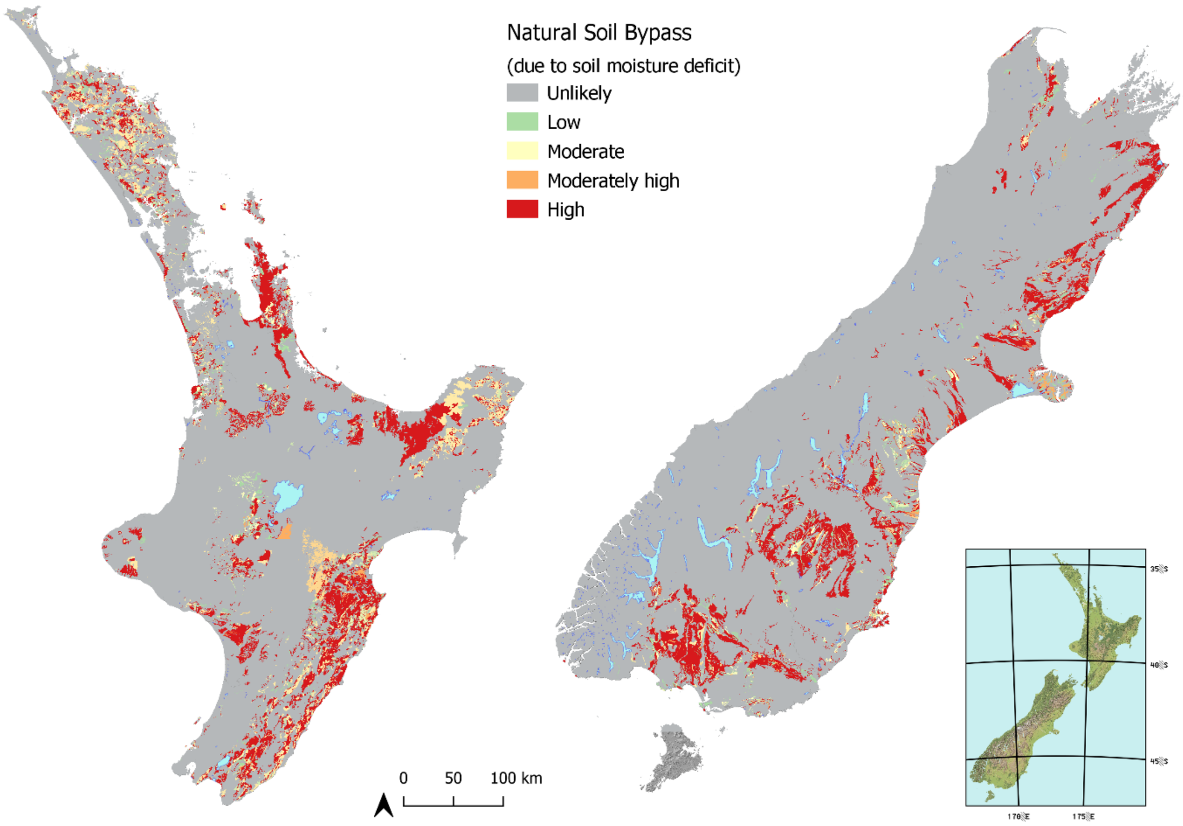


Figure 13. Natural soil bypass under soil moisture deficit for New Zealand.

4 Landscape Inherent Susceptibility

4.1 Seasonality and Episodic Events

As contaminants are all transported by water, the flow path water takes and climatic conditions are important factors in the export of contaminants. Seasonality is a bit like a pendulum, swinging from one extreme (wet) to another (dry) through the seasons. Episodic events however, can occur at any time and the hydrological response to the event is dependent on the antecedent conditions at the time (or the current pendulum position). In terms of contaminant loss, the faster water is transported, the more likely contaminants can be mobilised, relative to slow transport pathways. The longer the length of time between rainfall events, the more time contaminants, such as nutrients and microbes, have to accumulate at the land surface. Temperature is also an important climatic control. During the winter months, especially across southern NZ and higher altitude areas, nutrient uptake slows to practically nothing. When soils reach moisture deficit plant nutrient uptake is also limited. The land activities that are occurring prior to transport events along with the inherent susceptibility of the landscape for loss, dictates the magnitude of contaminant generation.

Table 3 provides a summary of the seasonality for regions around New Zealand (from McDowell et al, 2005). It is these wetter periods when saturation excess overland flow is most likely to occur. Rainfall volume is also a key factor, as the higher the rainfall volume the longer the 'wet' season is (Figure 14).

Table 3. Regional risk months for overland flow (McDowell et al., 2005; derived from New Zealand Meteorological Service, 1989).

Region	Meteorological Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northland	Kaikohe			■	■	■	■	■	■	■	■		
Auckland	Auckland Airport						■	■	■	■			
Waikato/Coromandel	Ruakura					■	■	■	■	■	■		
Bay of Plenty	Whakarewarewa				■	■	■	■	■	■	■		
Central Plateau	Taupo						■	■	■	■	■		
King Country	Rukuhia					■	■	■	■	■	■		
Taranaki	Stratford				■	■	■	■	■	■	■	■	■
East Coast[1]	Gisborne Airport		■	■		■	■	■	■	■			
Manawatu/Whanganui	Grasslands						■	■	■	■			
Wellington	Kelburn					■	■	■	■	■			
Nelson	Nelson Airport					■	■	■	■	■	■		
West Coast	Hokitika Airport	■	■	■	■	■	■	■	■	■	■	■	■
Marlborough	Lake Grassmere												
Canterbury	Lincoln							■	■				
Otago	Dunedin Airport								■				
Southland	Gore					■	■	■	■	■			
High Country[2]	Hermitage Mt Cook	■	■	■	■	■	■	■	■	■	■	■	■
High Country[3]	Omarama												

[1] High risk is allocated to February and March in this region due to the presence of hydrophobic soils.
[2] High Country (>300 m), high rainfall (>700 mm).
[3] High Country (>300 m), low rainfall (< 700 mm).

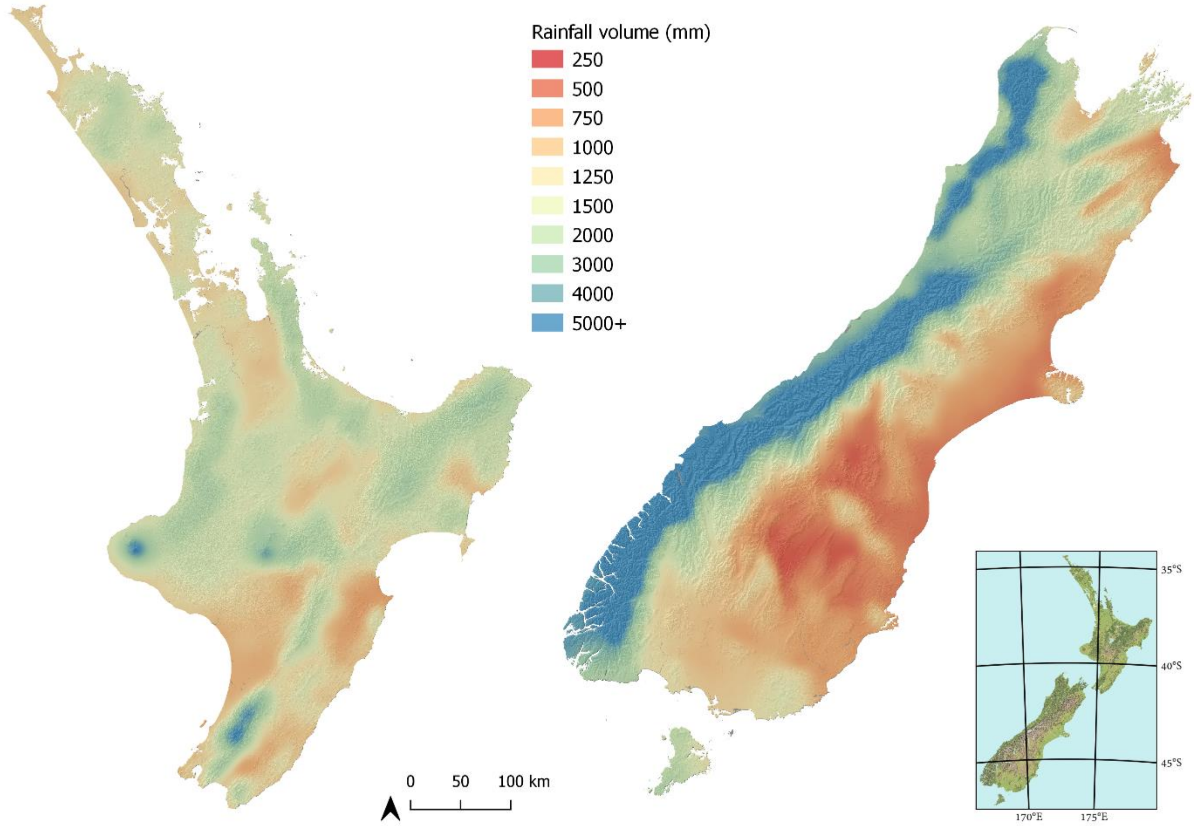


Figure 14. Annual average rainfall volume (1972 – 2016). Data sourced from Ministry for the Environment.

4.2 Role of the Landscape in Reducing Contaminants

Risk to water quality factors both the hydrological pathway contaminants take and the role the landscape has in minimising the contaminant concentration through filtration and adsorption, attenuation by redox reactions, resistance to physical disturbance, and dilution. These processes may also be referred to as regulating ecosystem services.

4.2.1 Filtration and adsorption

Filtration is a physical process where chemicals (inorganic and organic), microbes and particulates, are retained by porous media during the infiltration of and percolation of water. Filtration is primarily a process of physical exclusion. However, there are many chemical and microbial processes that also retard the movement of contaminants through porous media. Chemical species, including nutrients and microbes may be retarded by electrostatic and other processes that retain them at the surface of porous media, removing them from solution. Drainage pathways that involve infiltration of water through a well sorted soil, unsaturated zone, and aquifer matrix result in the removal of many agricultural contaminants (including microbes) between the source and the receiving environment. In such settings, sediments, other forms of N, P and microbes are commonly removed where drainage water infiltrates and percolates through a thick layer of well sorted sediments. The main exception is nitrate, which due to its large hydrated radius and negative charge is repelled by most mineral surfaces. As such, it tends to travel at approximately the same rate as water through any saturated media.

The deep drainage physiographic process map informs where areas are likely to have the highest filtration and retention potential (Figure 15). The equilibrium water table layer of Westerhoff and White (2014) provides an estimate of unsaturated zone thickness, which is an important control over contaminant attenuation. The thicker the unsaturated zone the greater the filtration and retention capability. The deep drainage physiographic process map should be used in conjunction with the equilibrium water table layer of Westerhoff and White (2014) and the hydrogeological units of White et al., (2019) (Figure 16). The presence of artificial drainage will also influence the depth to the water table, however in this case the aquifer may be bypassed as water is routed directly to stream through the artificial drainage network (see Section 3.4; Rissmann et al., submitted).

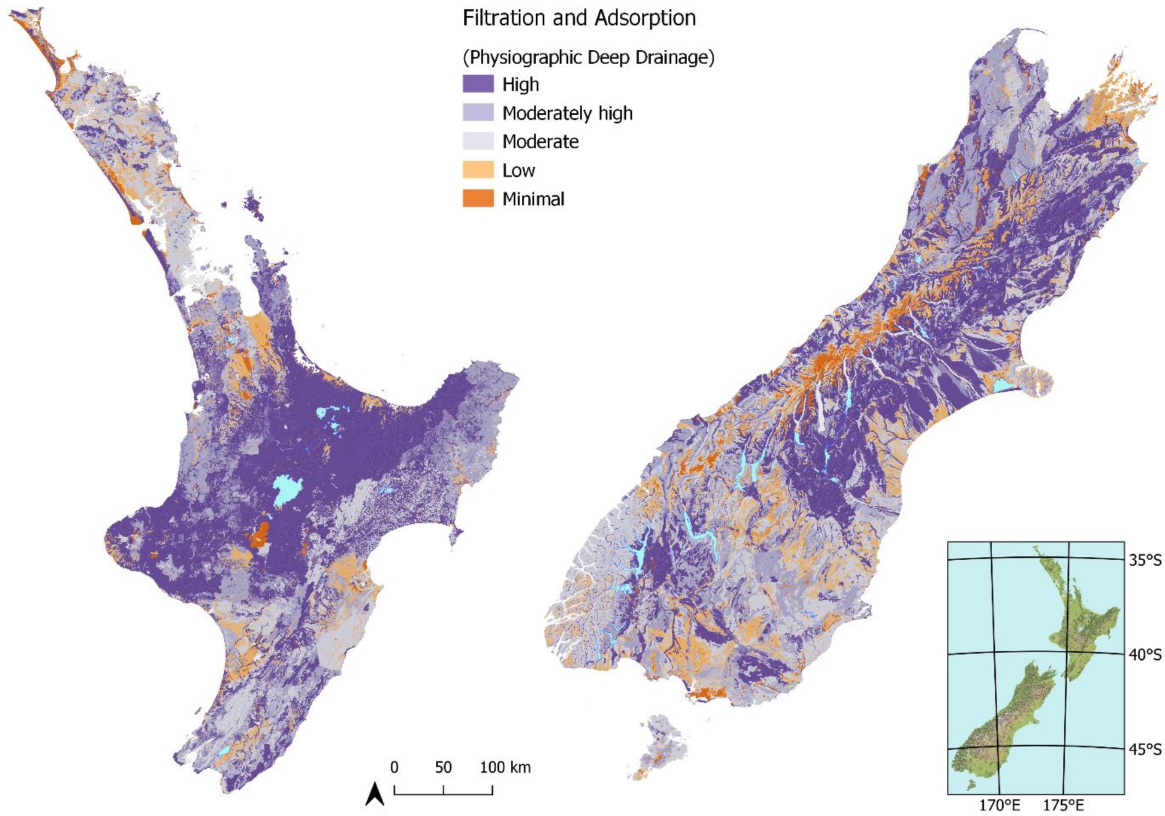


Figure 15. Filtration and retention capacity as indicated by deep drainage physiographic process map. This layer is enhanced when used in combination with the equilibrium water table layer of Westerhoff and White (2014) and the hydrogeological units of White et al., (2019).

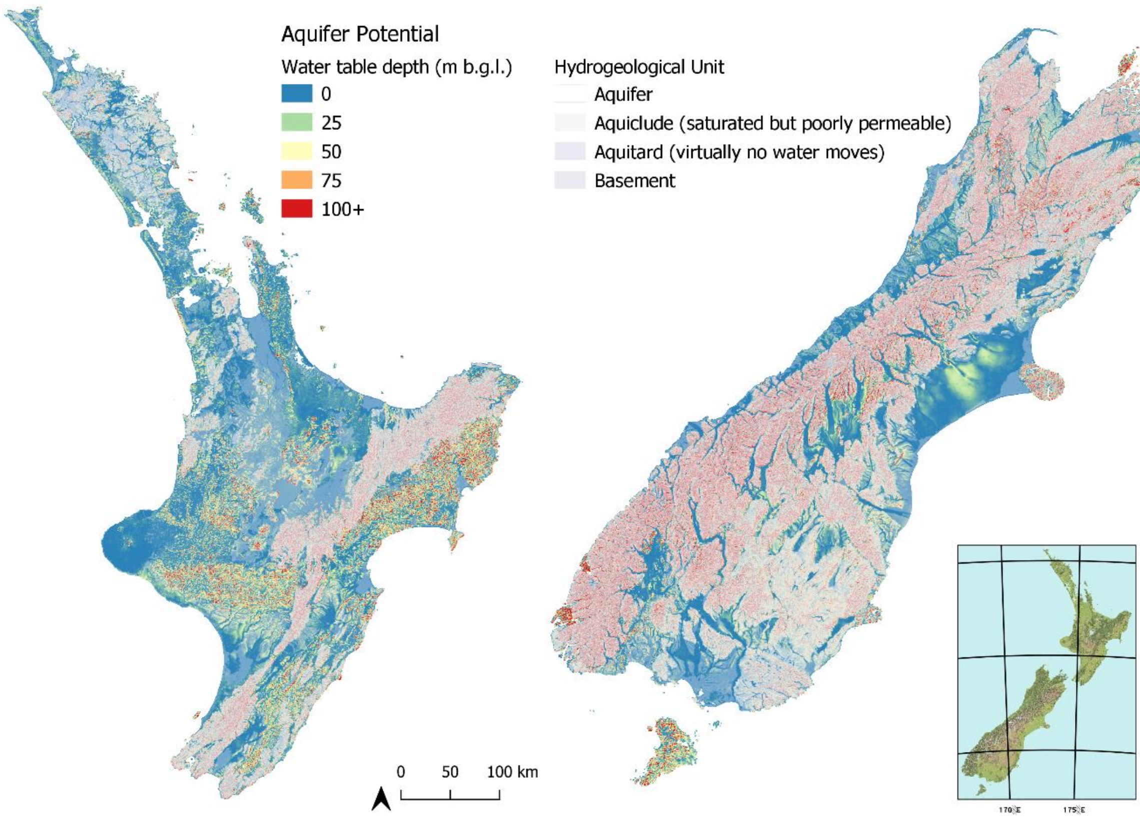


Figure 16. Aquifer potential as informed by equilibrium water table depth (Westerhoff and White, 2014) and hydrogeological units (White et al., 2019).

4.2.2 Attenuation by redox reactions

The physical properties of soil and geology can be used to explain biogeochemical processes occurring in the landscape. Oxidation-reduction (or 'redox' for short) reactions are some of the most important biogeochemical processes influencing water quality. It may sound complex, but redox reactions are part of everyday life. Rusting of metal, electrical energy derived from batteries, cellular respiration are all redox reactions. In the natural environment, redox reactions are driven by microbes (catalysed). In soil and aquifer materials there are trillions of bacteria, many of them specialising in redox reactions from which they derive energy. This myriad of bacteria drives carbon, nitrogen, and phosphorus cycling.

The process of stagnation of a pond or puddle of water is a classic example of redox (Figure 17). The same process occurs in soils, streams, and aquifers. However, as with any reaction process, the strength of stagnation will vary depending on the availability of organic carbon, the main food source for microbes, and subsequently the availability of oxygen, nitrogen, manganese, iron, sulphate, and carbon dioxide. Microbes are highly efficient (lazy), they prefer to expend as little energy as possible. When consuming their preferred food source, organic matter, they must break the chemical bonds between carbon atoms. Breaking bonds requires a lot of energy. To save energy, microbes use oxygen, which has a high affinity for electrons to help break the electron bonds. As the electrons are moved from the organic matter to oxygen, oxygen is consumed and converted to water (Figure 17). If the supply of oxygen runs out, microbes will quickly switch to using nitrate (Figure 17), which has the next highest affinity for electrons. When nitrate gains an electron, it is eventually converted to nitrous oxide gas and under suitable conditions inert nitrogen gas. The nitrate gets removed from the water. Once nitrate has been consumed, microbes then move onto using manganese, then iron, then sulphate. The use of sulphate by microbes as an electron acceptor converts it to hydrogen sulphide, which is characterised by a rotten egg smell typical of stagnant water. Eventually, microbes may end up having to use carbon dioxide dissolved in water as an electron acceptor. In this case, the carbon dioxide is converted to methane. Methane is most commonly produced in wetlands where there is an abundance of organic carbon. If fresh oxygen or nitrate is introduced to the soil or water, microbes will quickly switch back to using these more energy efficient chemicals for accepting electrons.

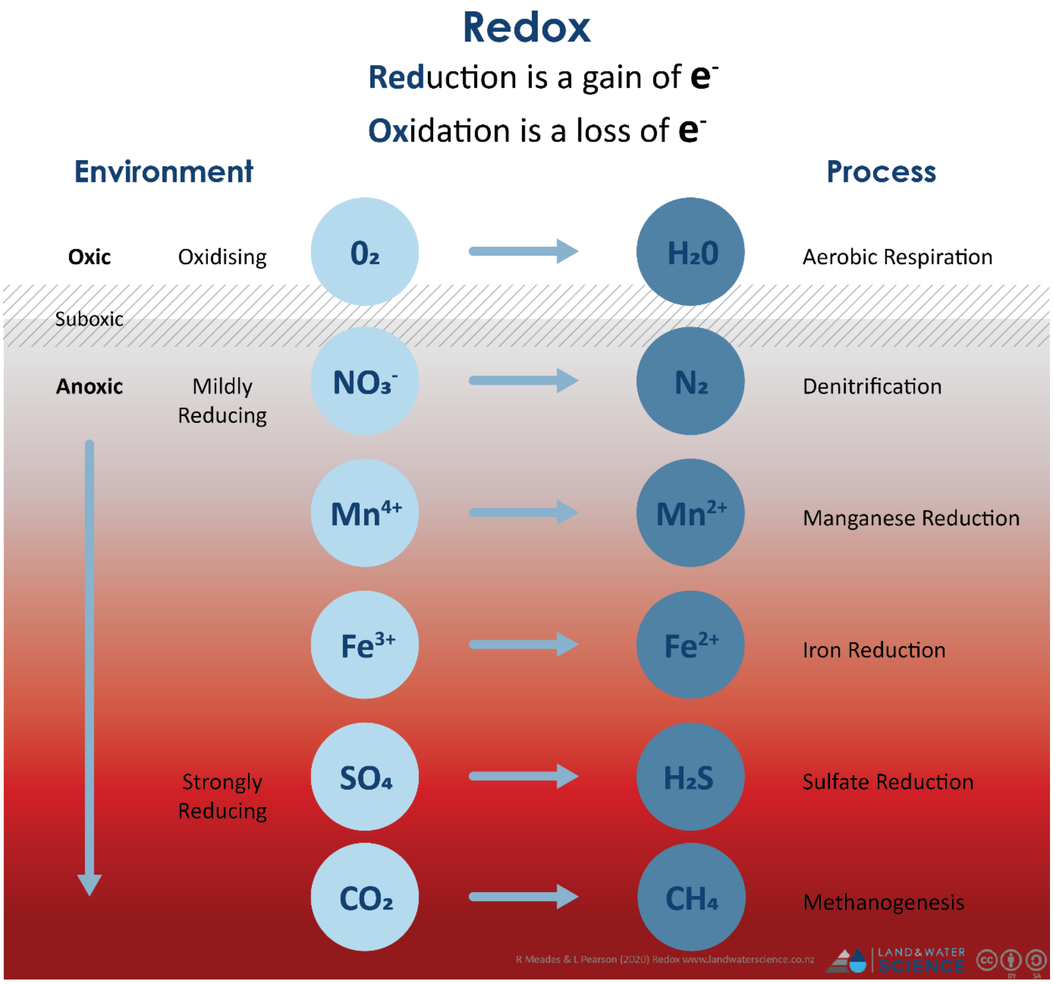


Figure 17. Example of commonly occurring redox processes in the environment and the order they are reduced in.

In very basic terms, the redox state is characterised as the presence of oxygen (oxic) or absence (anoxic) of oxygen. However, as noted it is more accurately described as chemical reactions which involve the transfer of electrons. The chemical species which loses the electron (increase in oxidation state) is oxidised, while the chemical species that gains the electron (decrease in oxidation state) is reduced. The concentrations of oxygen, nitrate, manganese, iron, and sulphate can be used to identify how reducing the water is and they are always reduced in that order (Figure 17). Typically, well drained soils are characterised as oxidising, while poorly drained soils are characterised as reducing.

Redox is important to a range of environmental concerns, including low dissolved oxygen in surface waters, nitrate leaching, denitrification and phosphorus solubility and mobility. Where soils and aquifers have high oxygen, bacteria don't need nor bother to use nitrate as an electron acceptor, as a result it can build up in the environment. When oxygen is restricted, nitrate is commonly removed by bacteria (Figure 18 and 19).

An understanding of redox processes enables an understanding of where shallow groundwater is likely to contain elevated manganese, iron, and arsenic (in areas with arsenic bearing minerals), limiting its potential as a drinking water source. In conjunction with nitrogen load, soil zone redox processes also determine the magnitude of soil zone greenhouse gas emissions (GHG), such as nitrous oxide and methane. When nitrate is used as an electron acceptor in the soil it may convert the nitrate to nitrous oxide, a potent greenhouse gas. The 'A' horizon of most soils is where the highest amount nitrous oxide greenhouse gasses are produced (Figure 18). This only occurs when soils get saturated with water, which temporarily shuts off the supply of oxygen to soil microbes[1]. As the soil drains and oxygen from the atmosphere is once again available, microbes shift to using oxygen as an electron acceptor and the production of nitrous oxide ceases.

The main ingredient for driving redox reactions is organic matter. Oxidising soils and geology typically have a lower abundance of organic matter (electron donors) and oxidising soils are less likely to become saturated. Nitrate lost through the soil in these areas is more likely to accumulate in the groundwater as there is a low potential for reduction from biological removal (denitrification). Reducing soils and geology (high organic matter content) tend to have lower oxygen and may be highly reducing, meaning any electron acceptors e.g., oxygen or nitrate, are rapidly removed.

As redox processes occur in both the soil zone and underlying aquifer, it is important to know the hydrology to establish if the reduction potential is realised. For example, a highly drained mineral soil will have a lower reduction potential than the same soil unmodified by drainage. The contact and time water spends in the soil under saturation are significantly lower.

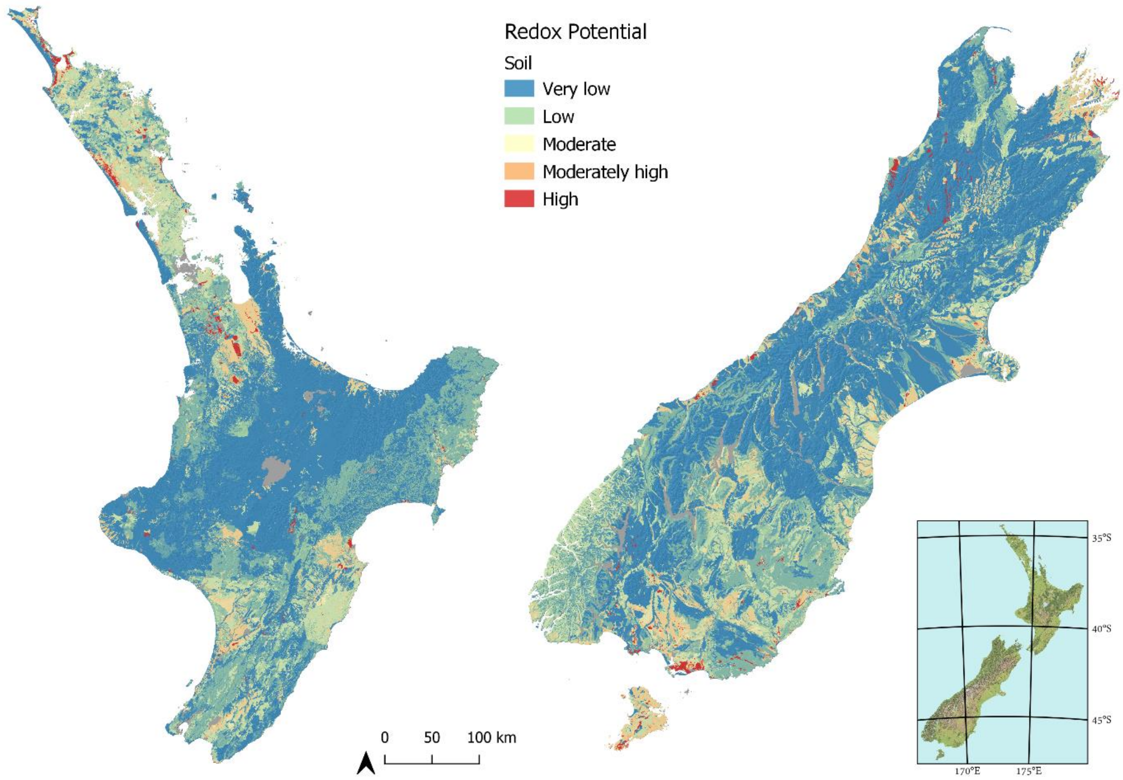


Figure 18. Soil reduction potential predicted by the soil drainage properties and carbon content.

[1] The diffusivity of molecular O_2 is 10,000-fold lower in saturated relative to unsaturated porous media.

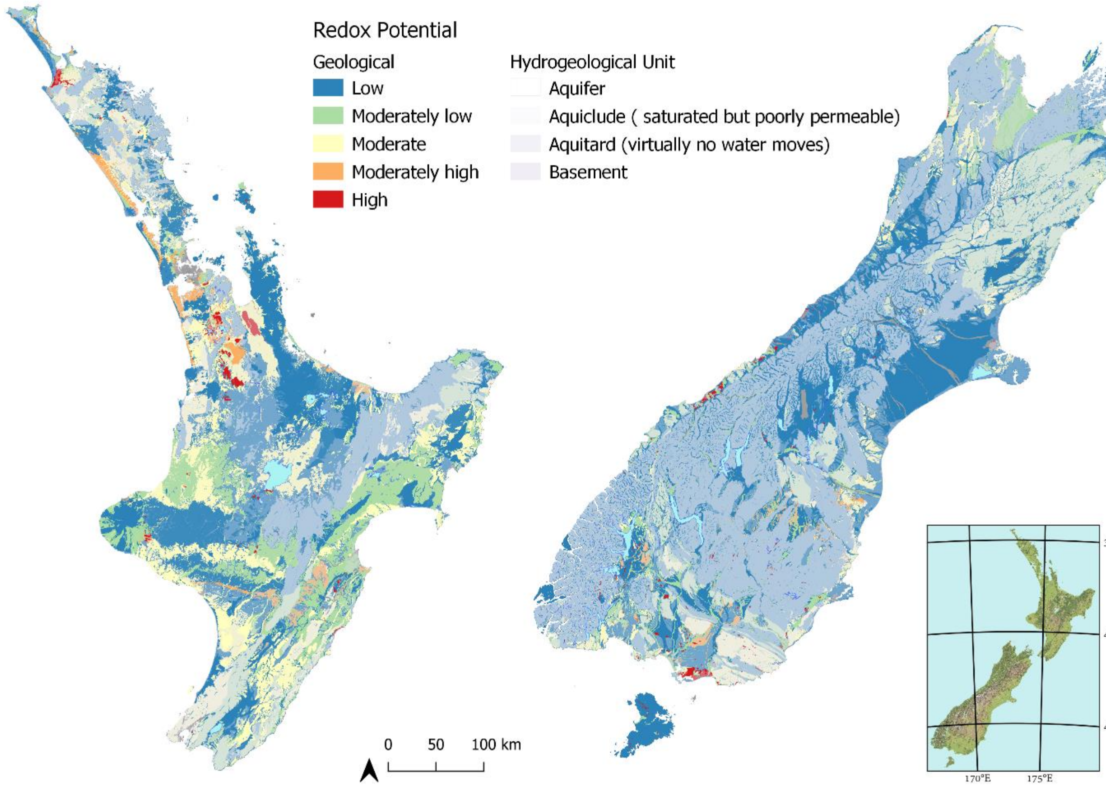


Figure 19. Geological reduction potential predicted by geological composition (Rissmann et al., 2019, submitted). The presence of aquifers is informed by the hydrogeological unit by White et al., 2019.

4.2.3 Resistance to physical disturbance

Resistance to physical disturbance represents the landscapes' inherent susceptibility to mass wasting and erosion. Stronger more resistant rock types weather more slowly and are less likely to succumb to mass wasting and erosion. Traditionally there has been a focus on slope and vegetation cover as an assessment for the erodibility of the land surface. However, while this is generally correct, the underlying geology is commonly the 1st order control over sediment generation rates. Figure 20 shows the general rock strength across New Zealand. Areas that have the largest issues with sediment coincide with weak sedimentary or unconsolidated geologies irrespective of land use.

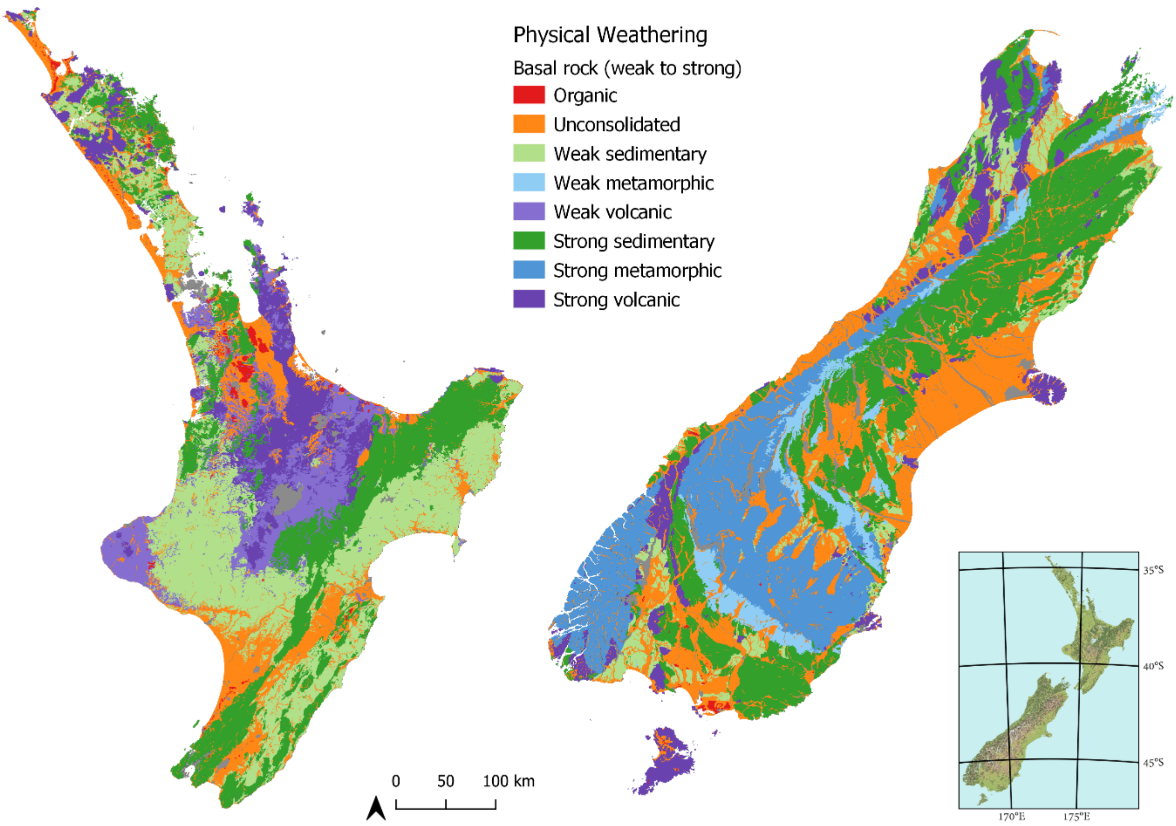


Figure 20. Base rock type and strength. Strong lithologies are more resistant to physical weathering than weak lithologies.

4.2.4 Dilution

Dilution is the process of decreasing the concentration of a contaminant and occurs when a higher volume of water with a low concentration of a given contaminant mixes with a lower volume of water with a higher contaminant concentration. For example, a large volume of rainfall or snowmelt from higher up in a catchment will dilute more concentrated waters that occur at lower elevation. The result is a net reduction in contaminant concentration from the mixing of the different sources of water, e.g., Alpine to lowland. It is important to note that while dilution may alter the concentration of a contaminant in the stream, it is not a true reduction as it does not reduce the total load (amount) of that contaminant to the receiving environment. This means that if the receiving environment is under stress by a contaminant, the only way to improve the condition is by reducing the load it receives.

The recharge domain layer is a macroscale depiction of the hydrological connection between recharge domains (e.g., Hill and Lowland; Figure 21). In addition to identifying the source and routing of water from and between recharge domains it provides an understanding of the dilution potential of a stream.

The Alpine Environment has a high dilution potential due to the large volume of pristine water that is discharged from the environment and low land use pressure. Bedrock Physiographic Environments have a moderate dilution potential due to typically higher rainfall and lower land use intensity, whereas lowland areas have a low dilution potential as water is sourced from local rainfall typically under higher land use pressures. In the Physiographic Environments, the high dilution potential and connectivity to alpine sourced water is used to classify the Riverine Environment. The Riverine

Environment is typified by the large braided streams of the South Island, that originate in the Southern Alps and discharge at the coast.

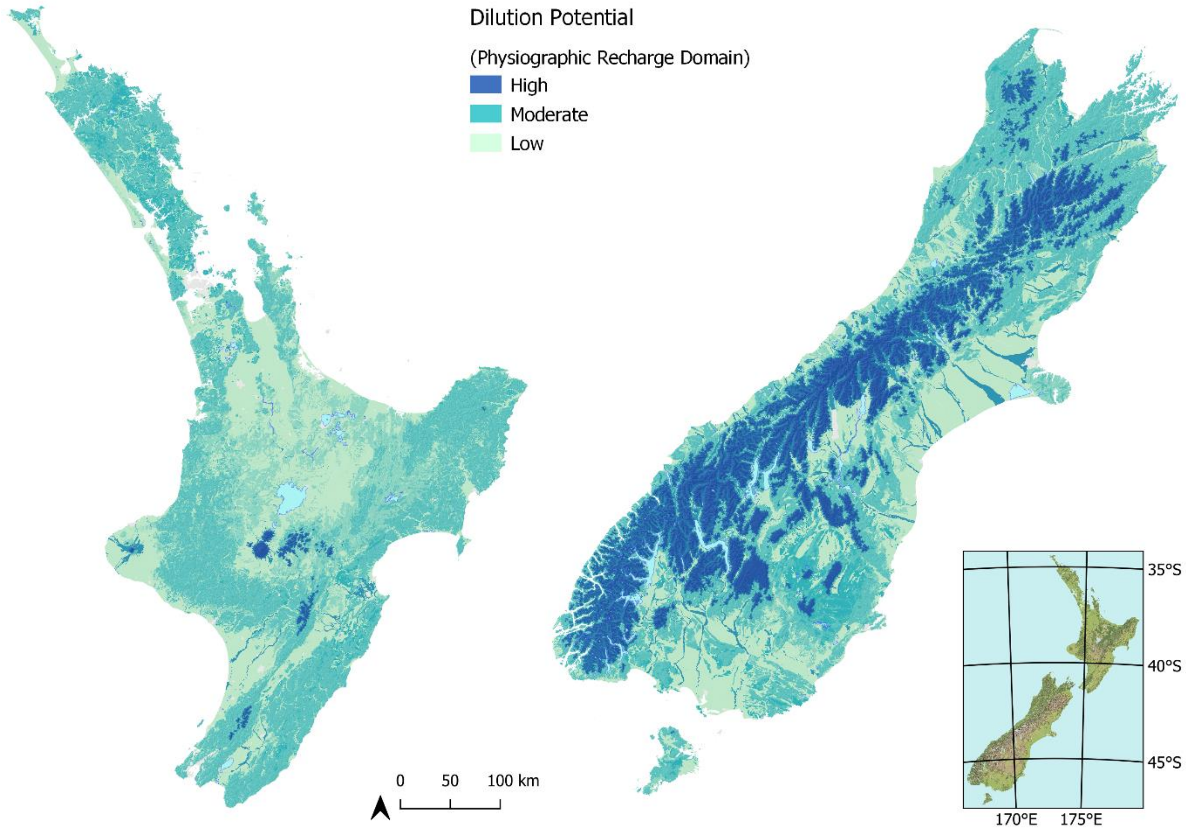


Figure 21. Dilution potential of New Zealand as informed by the physiographic recharge domain class.

5 Risk to Water Quality

For effective use of the Physiographic Environments for decision making, land use context is needed to identify the likely pressure on the landscape as contaminant generation is the product of land use pressure and the inherent susceptibility of the landscape (Figure 1 and 22).

5.1 Land Use Pressure (anthropogenic source)

Contaminants may be generated at the land surface by disturbance of the land and loading by humans, animals, fertiliser, and autogenic processes. The type (e.g., nitrate vs. sediment and/or *E.coli*) and severity of contaminant loss is a factor of anthropogenic influences, inherent landscape properties, and local climatic variability. In the case of nutrients (N & P), the dominant loading is derived from animals and fertiliser application and may vary across space and time as a function of land use and management.

A map layer representing land use intensity was developed for the Physiographic Environments work to provide an estimate of pressure from land use nationally. It was derived by combining the Land Use Capability classification of Lynn et al. (2009), LCDBv5 land cover (Manaaki Whenua Landcare

Research, 2019) and LUCAS land use (Ministry for the Environment, 2019). Land use intensity represents the relative potential for contaminant generation (including nutrients and sediment loss) and was ranked from low (1) to high (5) according to expert judgement based on reported contaminant loss rates (Figure 22; Ledgard, 2012). A separate land use intensity gradient for microbial contaminants was also produced which was ranked in a similar manner for the area of pastoral grazing. These intensity layers remain as separate characterisations as the pressure varies according to the contaminant of interest i.e., cropping has a high pressure for nutrient input and sediment generation and low microbial pressure. Background concentrations in natural state areas were all considered low.

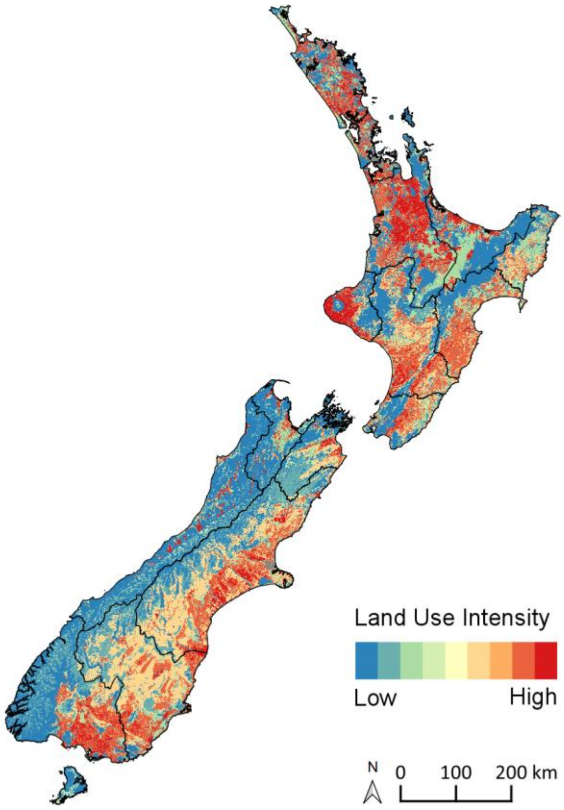


Figure 22. Representation of Land Use Intensity from the Physiographic Environments of New Zealand (Rissmann et al., submitted).

5.2 Landscape Inherent Susceptibility Risk Matrix

Using the concepts of source (or supply) and transport limitation, the pattern(s) of contaminant generation can be predicted by the Physiographic Environment Classification. For example, a wider range of contaminants are likely to be generated from imperfectly to poorly drained agricultural soils during periods peak drainage. This reflects both adequate supply (e.g., land disturbance and contaminant source) and sufficient transport capacity (e.g., artificial drainage/overland flow). Conversely, contaminant generation from well-drained soils with high infiltration rates and equivalent land use pressure are likely to be lower under an equivalent land use pressure and precipitation intensity. In this case, the supply remains the same, but the transport capacity is reduced due to higher soil infiltration rates. In the first setting, the installation of artificial drainage is often used to mitigate the drainage limitation, effectively resulting in a similar outcome to the well-drained soil environment. However, mole-pipe drainage does not facilitate the same level of interaction between water and the soil matrix and as a result contaminants are often elevated in drainage discharges.

Collectively, these landscape factors interact to determine the differential sensitivity and magnitude of discharge of one or more contaminants to water. Therefore, water quality at a catchment-scale represents the outcome of multiple, spatially variable processes which influence the generation, transport, and transformation of contaminants across the contributing catchment.

Inherent landscape susceptibility for contaminant generation considers both the hydrological pathway contaminants take and how the landscape regulates water quality contaminants through dilution, resistance to erosion, filtration and adsorption, and attenuation of both N and P species. Each environment has distinct properties that can be used to predict the susceptibility of a contaminant for loss. Table 4 summarises for each Physiographic Family and Sibling class the hydrological pathway, the role of landscape in regulating contaminants, and the risk to the receiving environment defined as concentration and/or load to surface water, groundwater, or both. Where the landscape has a high regulating capacity it is good at reducing the risk to the receiving environment provided the specified hydrological pathway is active. When there is variation to the predicted hydrological response, variants apply. The ability of the landscape to regulate contaminants when a hydrological variant is active is summarised in Table 5. The variants may apply at different times of the year and modify the ability of the landscape to regulate contaminants. When active, the variant supersedes the predicted response for an environment.

The risk to water quality from agriculture, horticulture, forestry, and urban land uses (here after 'land use') for each Physiographic Environment is provided through a matrix by contaminant and species in Table 6 and for the variants in Table 7. The risk matrix assumes a uniform source (land use pressure) in each environment for assigning risk, while the actual contribution from an area maybe significantly different depending on the actual land use type and intensity (i.e., native forest or high producing exotic grassland). This means for a high risk of loss to be realised, a contaminant source is required. This also applies to the variants where risk to water quality for all contaminants is significantly increased when bypass of the soil zone occurs by either overland flow, artificial drainage, or cracking soils. However, this risk is only realised if there is a contaminant source. For example, overland flow occurring in Alpine or natural state environments may be a relatively large volume of water, but the contaminant source load is low and the nutrient status of the sediment has not been enriched. These contributions to a receiving environment are generally considered background load.

Importantly, the risk assessment presented here is preliminary and subject to refinement through an Our Land and Water, Sources to Sink project which aims to refine and improve the quantification of risk. This refinement will provide additional documentation and validation to support the landscape classification. In addition to this, an assessment of attenuation and uncertainty at various spatial scales will also be undertaken. See section 6 for a summary of future work.

Table 4. The role of landscape in regulating contaminants by Physiographic Environment. If the landscape function is high it is good at reducing the risk to the receiving environment. The risk to the receiving environment is defined as concentration and/or load to surface water, groundwater, or both. For the landscape to perform its regulatory function, the predicted hydrological pathway must be active. See hydrological variants when alternative pathways are active.

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	**Resistance to erosion**	**Filtration and adsorption**	**Attenuation: N-Reduction**	**Attenuation: P-Reduction**	
Alpine	Alpine	Precipitation falls mainly as snow over the winter months and accumulates until spring. Melt water runs over the land surface and converges to form streams. Overland flow is the dominant pathway water takes to leave the land.	High	Low	Low	Low	Low	Load to surface water
Strong Bedrock	Subalpine	Lateral drainage through the soil zone either to stream or a neighbouring lowland environment. Recharge to the underlying aquifer is limited by the permeability of the bedrock. Overland flow is common due to seasonal wetness (see Overland Flow variant when pathway is active).	Moderately high	Low - Moderately low	Moderately low	Moderate	Moderate- low	Load to surface water
	Hill	Lateral drainage along contact with bedrock discharging to stream or neighbouring environment. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Limited aquifer potential unless bedrock is fractured.	Moderate	Moderately low - Moderate	Moderately low - Moderate	Moderately high	Moderately low	Concentration & load to surface water, minor groundwater contribution
	Low relief	Lateral drainage along contact with bedrock discharging to stream or neighbouring environment. Depth to bedrock controls overland flow risk where the shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Limited aquifer potential unless bedrock is fractured.	Moderate - Low	Moderately low - Moderate	Moderately low - Moderate	Moderately high	Moderately low	Concentration & load to surface water, minor groundwater contribution
Weak Bedrock	Subalpine	Lateral drainage through the soil zone either to stream or a neighbouring lowland environment. Recharge to the underlying aquifer is limited by the permeability of the bedrock. Overland flow is common due to seasonal	Moderately high	Low	Moderately low	Moderate	Moderate - low	Load to surface water

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	Resistance to erosion	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
		wetness (see Overland Flow variant when pathway is active).						
	Hill	Lateral drainage along contact with bedrock discharging to stream or neighbouring environment. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Minimal aquifer potential.	Moderate	Low	Moderately low - Moderate	Moderately high	Moderately low	Concentration & load to surface water, minor groundwater contribution
	Low relief	Lateral drainage along contact with bedrock discharging to stream or neighbouring environment. Depth to bedrock controls overland flow risk where the shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Minimal aquifer potential.	Moderate - Low	Low - Moderately low	Moderately low - Moderate	Moderately high	Moderately low	Concentration & load to surface water, minor groundwater contribution
Oxidising Soil and Aquifer	High deep drainage	Deep drainage through the soil zone to an underlying water table aquifer. Water table depth is an important control over attenuation capacity associated with filtration and retention of contaminants, and the occurrence of overland flow (see Overland Flow variant when pathway is active).	Low	High[1]	High[1]	Low	High	Concentration & load to groundwater
	Increased lateral and overland flow	Deep drainage through the soil zone to an underlying water table aquifer with increased lateral and overland flow due to seasonal wetness (see Overland Flow variant when pathway is active). Water table depth is an important control over attenuation capacity associated with filtration and retention of contaminants, and the occurrence of overland flow.	Low	Moderately high – High[1]	Moderately high – High[1]	Low - Moderately low	Moderately high - High	Concentration & load to groundwater, minor surface water contribution

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	Resistance to erosion	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
	Over strong bedrock	Deep drainage until contact with bedrock which transitions to lateral flow. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active).	Low	Moderately high – High	Moderate - High	Low - Moderately high[2]	Moderate[2] - High	Concentration & load to surface water, minor groundwater contribution
	Over weak bedrock	Deep drainage until contact with bedrock which transitions to lateral flow. Slope and soil depth controls overland flow risk where the steeper the slope or shallower the soil the more likely runoff is to occur (see Overland Flow variant when pathway is active).	Low	Moderate - High	Moderate - High	Low - Moderately high[2]	Moderate[2] - High	Concentration & load to surface water, minor groundwater contribution
Oxidising Soil Reducing Aquifer	High aquifer reduction	Deep drainage through the soil zone to an underlying water table aquifer. Water table depth is an important control over attenuation capacity associated with filtration and retention of contaminants.	Low	Moderately high – High	Moderately high - High	High[3]	High[3] (soil zone retention)	Minimal if water drains to groundwater
	Moderate aquifer reduction	Deep drainage through the soil zone to an underlying water table aquifer with increased lateral and overland flow due to seasonal wetness (see Overland Flow variant when pathway is active). Water table depth is an important control over attenuation capacity associated with filtration and retention of contaminants.	Low	Moderately high - High	Moderately high - High	Moderately high - High	Moderately high - High	Minimal if water drains to groundwater
	Over strong bedrock	Deep drainage until contact with bedrock which transitions to lateral flow. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active).	Low	Moderately high – High	Moderately high - High	Moderate - High	Moderate - High	Minimal if water drains through soil to surface water

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	Resistance to erosion	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
	Over weak bedrock	Deep drainage until contact with bedrock which transitions to lateral flow. Slope and soil depth controls overland flow risk where the steeper the slope or shallower the soil the more likely runoff is to occur (see Overland Flow variant when pathway is active).	Low	Moderate - High	Moderate - High	Moderate - High	Moderate - High	Minimal if water drains through soil to surface water
Reducing Soil Oxidising Aquifer	High soil reduction	Lateral drainage through the soil zone either to stream or a neighbouring environment. Recharge to the underlying water table aquifer is limited by soil permeability. Overland flow is common due to seasonal wetness (see Overland Flow variant when pathway is active). Artificial drainage is common under agricultural land uses (see Artificial Drainage variant details if present).	Low	Moderate – Moderately low	Low	High	Low	Concentration & load to surface water, minor groundwater contribution
	Moderate soil reduction	Lateral drainage through the soil zone either to stream or a neighbouring environment. Lateral drainage is likely to become more vertical (deep) during the drier months. Recharge to the underlying aquifer is limited by the soil permeability (likely higher than high soil reduction sibling as soils are imperfectly drained). Overland flow occurs due to seasonal wetness (see Overland Flow variant when pathway is active). Artificial drainage is likely under agricultural land uses (see Artificial Drainage variant details if present).	Low	Moderate	Moderate	Moderately low – Moderately high[4]	Moderately low – Moderately high[4]	Concentration & load to groundwater and surface water
	Over strong bedrock	Lateral drainage along contact with bedrock. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Limited aquifer potential. Artificial drainage may be present under agricultural land uses (see Artificial Drainage variant details if present).	Low	Moderate – Low	Low - Moderate	Moderate - High	Low - Moderate	Concentration & load to surface water, minor groundwater contribution

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	Resistance to erosion	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
	Over weak bedrock	Lateral drainage along contact with bedrock. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Limited aquifer potential. Artificial drainage may be present under agricultural land uses (see Artificial Drainage variant details if present).	Low	Moderate – Low	Low - Moderate	Moderate - High	Low - Moderate	Concentration & load to surface water, minor groundwater contribution
Reducing Soil and Aquifer	High soil reduction	Lateral drainage through the soil zone either to stream or a neighbouring environment. Recharge to the underlying aquifer is limited by the soil permeability. Overland flow is common due to seasonal wetness (see Overland Flow variant when pathway is active). Artificial drainage is common under agricultural land uses (see Artificial Drainage variant details if present).	Low	Moderately low - Low	Low	High	Low	Concentration & load to surface water, minor groundwater contribution
	Moderate soil reduction	Lateral drainage through the soil zone either to stream or a neighbouring environment. Lateral drainage is likely to become more vertical (deep) during the drier months. Recharge to the underlying aquifer is limited by the soil permeability (likely higher than high soil reduction sibling as soils are imperfectly drained). Overland flow occurs due to seasonal wetness (see Overland Flow variant when pathway is active). Artificial drainage is likely under agricultural land uses (see Artificial Drainage variant details if present).	Low	Moderate	Low - Moderate	Moderately high - High	Low – Moderately low	Concentration & load to groundwater and surface water
	Over strong bedrock	Lateral drainage along contact with bedrock. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Limited aquifer potential. Artificial drainage may be present under agricultural land uses (see Artificial Drainage variant details if present).	Low	Low - Moderate	Low - Moderate	Moderate - High	Low - Moderate	Concentration & load to surface water, minor groundwater contribution

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	Resistance to erosion	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
	Over weak bedrock	Lateral drainage along contact with bedrock. Slope and depth to bedrock controls overland flow risk where the steeper the slope or shallower the bedrock the more likely it is to occur (see Overland Flow variant when pathway is active). Limited aquifer potential. Artificial drainage may be present under agricultural land uses (see Artificial Drainage variant details if present).	Low	Low - Moderate	Low - Moderate	Moderate - High	Low - Moderate	Concentration & load to surface water, minor groundwater contribution
Riverine	High deep drainage	Deep drainage through the soil zone to an underlying water table aquifer. Water table depth is an important control over attenuation capacity associated with filtration and retention of contaminants. Water table depth may also govern susceptibility to overland flow.	High	Moderate - High[4]	Moderate - High[4]	Low	Moderate - High[4]	Load to groundwater
Riverine	Increased lateral and overland flow	Deep drainage through the soil zone to an underlying aquifer with increased lateral and overland flow due to slowly permeable soils, seasonal wetness, and sloping land (see Overland Flow variant when pathway is active).	High	Moderately high - High	Moderately high - High	Low - Moderately low	Moderately high - High	Load to groundwater, minor surface water
Wetlands	Lowland	Lateral drainage through the soil zone either to stream or a neighbouring environment. Overland flow occurs more often than other lowland environments due to the shallow water table (see Overland Flow variant when pathway is active). Artificial drainage is common under agricultural land uses (see Artificial Drainage variant details if present).	Low	Low - Moderate	Moderately high – High Filtration (anion exchange Low)	High	Low	Concentration & load to surface water, minor groundwater contribution
Wetlands	Upland	Lateral drainage through the soil zone either to stream or a neighbouring environment. Overland flow occurs due to the limited storage capacity in the soil zone in upland environments and seasonal wetness (see Overland Flow variant when pathway is active). Artificial drainage is likely under agricultural land uses (see Artificial Drainage variant details if present).	Low - High	Low – Moderately low	Moderate – High Filtration (anion exchange Low)	High	Low	Concentration & load to surface water, minor groundwater contribution

Family	Sibling	Contaminant pathway (dominant hydrological pathway)	How the landscape regulates water quality contaminants					Risk to receiving environment
			Dilution	Resistance to erosion	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
Urban	Urban	Overland flow to the stormwater drain. Artificial drainage through the storm water network with discharge typically direct to surface water.	Recharge domain dependent	High	Low	Low	Low	Concentration & load to surface water, minor groundwater contribution where land is pervious.

[1] Depth to water table is an important factor. Shallow water table depths are highly connected to the aquifer and contaminants can enter an aquifer relatively quickly. Deep unsaturated zones may take years to reach groundwater.

[2] Dependent on depth to bedrock and redox state at contact with bedrock.

[3] The stronger the reducing conditions the more likely nitrogen reduction via denitrification will occur, however phosphorus becomes more mobile (reduction is low). In oxidising conditions, phosphorus reduction is high and nitrogen reduction is low.

[4] Dependent on how active the flood plain is, how well sorted the soil and unsaturated zone materials, and the depth to water table. Where the water table is shallow there is a high connectivity for N loss and risk of overland flow is elevated. P loss can be elevated where soils are dominated by large cobbles with little matrix and the water table is shallow.

Table 5. How the ability of the landscape to regulate contaminants is altered hydrological variant pathways are active. Variants apply only when the hydrological pathway is active and supersedes the predicted response for an environment (from Table 4). If the landscape function is high it is good at reducing the risk to the receiving environment. The risk to the receiving environment is defined as concentration and/or load to surface water, groundwater, or both.

Hydrological Variants	**Contaminant pathway (when active only)**	**How the landscape regulates water quality contaminants**					**Risk to receiving environment**
		Dilution	**Resistance to erosion**	**Filtration and adsorption**	**Attenuation: N-Reduction**	**Attenuation: P-Reduction**	
Overland flow	Occurs when soils are saturated and/or infiltration is limited. Pathway is active after prolonged or intense rainfall.	N/A[1]	Low	Low	Low	Low	Concentration & load to surface water
Artificial drainage	Likely where agricultural soils have impeded drainage or a shallow water table. Pathway is most active during the wetter months.	N/A[1]	Moderate – Moderately high	Moderate – Moderately high	Low - Moderate	Moderate – Moderately high	Concentration & load to surface water
Natural soil zone bypass	Occurs when soils are cracked (under soil moisture deficit) or jointed. Pathway is active following extended periods of soil moisture deficit.	N/A[1]	Moderate	Low	Low	Low	Concentration & load to groundwater

[1] Dilution potential is assessed by the Physiographic Environment recharge domain which is indicative of water source and relative volume. This does not change with the hydrological variant.

Table 6. Inherent susceptibility of the landscape for contaminant loss by Physiographic Environment. Nitrogen, phosphorus, and microbes require a source or input for losses to occur. Sediment risk is elevated if nutrient status is also elevated. Where a high susceptibility equals a high risk of loss from agricultural, horticultural, forestry and urban land uses. The contaminants have been colour coded red, orange, and yellow for high, moderately high, and moderate risk respectively. Where the risk is provided as a range, the highest risk is used for the colour. See hydrological variants for contaminant loss when alternative pathways are active.

Family	Sibling	Nitrogen			Phosphorus		Sediment	Microbes
		Nitrate & Nitrite	Ammoniacal	Organic (Dissolved & Particulate)	Particulate	Dissolved Reactive	Particulate	Particulate
Alpine	Alpine	High	High	High	High	High	High	High
Strong Bedrock	Subalpine	Moderately high	Moderately high	Moderately high	Moderately high	Moderately high	Moderately high	Moderately high
	Hill	Low – Moderate	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high
	Low relief	Low – Moderate	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high
Weak Bedrock	Subalpine	Moderately high	Moderately high	Moderately high	Moderately high	Moderately high	High	Moderately high
	Hill	Low – Moderately low	Moderate – High	Moderate – High	Moderately high – High	Moderate – Moderately high	Moderately high – High	Moderately high – High
	Low relief	Low – Moderately low	Moderate – High	Moderate – High	Moderately high – High	Moderate – Moderately high	Moderate - High	Moderately high - High
Oxidising Soil and Aquifer	High deep drainage	High	Low	Low	Low	Low	Low	Low
	Increased lateral and overland flow	Moderately high - High	Low – Moderately low	Low – Moderately low	Low – Moderately low	Low – Moderately low	Low – Moderately low	Low – Moderately low
	Over strong bedrock	Moderately low[1] – Moderate	Low – Moderately high[1]	Low – Moderately high[1]	Low – Moderately low	Low – Moderately high[1]	Low – Moderately low	Low – Moderately low

Family	Sibling	Nitrogen			Phosphorus		Sediment	Microbes
		Nitrate & Nitrite	Ammoniacal	Organic (Dissolved & Particulate)	Particulate	Dissolved Reactive	Particulate	Particulate
	Over weak bedrock	Moderately low – Moderate[1]	Low – Moderately high[1]	Low – Moderately high[1]	Low - Moderate	Low – Moderately high[1]	Low - Moderate	Low - Moderate
Oxidising Soil Reducing Aquifer	High aquifer reduction	Low – Moderately low	Low – Moderately low	Low – Moderately low	Low	Low	Low – Moderately low	Low
Oxidising Soil Reducing Aquifer	Moderate aquifer reduction	Low – Moderately low	Low – Moderately low	Low - Moderately low	Low – Moderately low	Low – Moderately low	Low – Moderately low	Low – Moderately low
Oxidising Soil Reducing Aquifer	Over strong bedrock	Low – Moderately low	Low – Moderate	Low – Moderate	Low – Moderately low	Low – Moderately Low	Low - Moderate	Low - Moderate
Oxidising Soil Reducing Aquifer	Over weak bedrock	Low – Moderately low	Low – Moderate	Low – Moderate	Low - Moderate	Low – Moderately Low	Low - Moderate	Low - Moderate
Reducing Soil Oxidising Aquifer	High soil reduction	Low	High	High	High	Moderately high	High	High
Reducing Soil Oxidising Aquifer	Moderate soil reduction	Low – Moderately low	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderately low - Moderate	Moderate – Moderately high	Moderate – Moderately high
Reducing Soil Oxidising Aquifer	Over strong bedrock	Low – Moderately low	Moderate – High	Moderate – High	Moderate – High	Moderate – Moderately high	Moderate – High	Moderate – High
Reducing Soil Oxidising Aquifer	Over weak bedrock	Low – Moderately low	Moderate – High	Moderate – High	Moderate – High	Moderate – Moderately high	Moderate – High	Moderate – High
Reducing Soil and Aquifer	High soil reduction	Low	High	High	High	Moderately high	High	High
Reducing Soil and Aquifer	Moderate soil reduction	Low – Moderately low	Moderate – Moderately high	Moderate – Moderately high	Moderate – Moderately high	Moderate	Moderate – Moderately high	Moderate – Moderately high

Family	Sibling	Nitrogen			Phosphorus		Sediment	Microbes
		Nitrate & Nitrite	Ammoniacal	Organic (Dissolved & Particulate)	Particulate	Dissolved Reactive	Particulate	Particulate
	Over strong bedrock	Low – Moderately low	Moderate – High	Moderate – High	Moderate – High	Moderate – Moderately high	Moderate – High	Moderate – High
	Over weak bedrock	Low – Moderately low	Moderate – High	Moderate – High	Moderate – High	Moderate – Moderately high	Moderate – High	Moderate – High
Riverine	High deep drainage	High – N load Low – N conc.[2]	Low	Low	Low	Low	Low	Low
	Increased lateral and overland flow	High – N load Low – N conc.[2]	Low - Moderately low	Low - Moderately low	Low - Moderately low	Low - Moderately low	Low - Moderately low	Low - Moderately low
Wetlands	Lowland	Low	High	High	High	Moderately high	Moderate[3] – Moderately high	High
	Upland	Low	High	High	Moderately high - High	Moderate - Moderately high	Moderate[3] – Moderately high	High
Urban	Urban	Variable - High[4]	Variable - High[4]	Variable - High[4]	Variable - High[4]	Variable - High[4]	Variable - High[4]	Variable - High[4]

[1] Dependent on depth to bedrock and if denitrification occurs at contact with bedrock.

[2] Concentration in groundwater does not increase due to high dilution potential.

[3] Sediment is largely organic material.

[4] Urban municipal wastewater has been treated through the wastewater treatment plant however the degree of treatment is variable. The overall risk varies according to the waste composition, degree of treatment and wastewater treatment plant effectiveness including disposal method. Discharges to land have a lower risk as there is potential for further land-based treatment relative to discharges directly to water. Stormwater varies according to source area and degree of treatment. Other contaminants also are present, including but not limited to heavy metals, hydrocarbons (petrol), oils and grease, pesticides, plastics, and microplastics, etc. Risk of loss is considered high as there is no removal of contaminants once they are transported.

Table 7. Inherent susceptibility of the landscape for contaminant loss by seasonal or episodic variants. The risk when these pathways are active supersedes the risk for the environment. Nitrogen, phosphorus, and microbes require a source or input for losses to occur. Sediment risk is elevated if nutrient status is also elevated. Where a high susceptibility equals a high risk of loss from intensive land uses.

Hydrological Variant	**Nitrogen**			**Phosphorus**		**Sediment**	**Microbes**
	Nitrate & Nitrite	**Ammoniacal**	**Organic (Dissolved & Particulate)**	**Particulate**	**Dissolved Reactive**	**Particulate**	**Particulate**
Overland flow	Low	High	High	High	Low	High	High
Artificial drainage	Moderately low - Moderately high	Moderately low - Moderate	Moderately low - Moderate	Moderate	Moderately low	Moderate	Moderate
Natural soil zone bypass	High	High	Moderate	Low	Moderate	Low	High

5.3 Scalability

Improved resolution over the risk to water quality can be provided through the underlying process layers used to generate the Physiographic Environment Classification. Instead of using the classes, which are an amalgamation of the underling values, the full gradient across an area can be represented. This can reduce the range of risk categories assigned to a Physiographic Environment Sibling and is the focus of future work. Rissmann et al. (2019, submitted) provides an example of using symbolic regression models to develop algorithms for a contaminant species which combines several process attribute gradients calibrated to the measured water quality (5-year median) and can be mapped spatially to the land (soil polygon resolution) or river network (REC reach). Using these various layers of detail can help to identify or prioritise high risk areas for management actions, assuming the receiving environment required reduction to meet freshwater objectives (Rissmann and Pearson, 2020).

6 Summary and Future Work

Physiographic Environments of New Zealand is a landscape classification that has been developed for the purpose of understanding how and why water quality varies across New Zealand. The classification has been developed through the integration of nationally available datasets (typically at 1:50,000 to 1:250,000 scale. At this resolution, it is suitable to help inform land use decision making but does not remove the need for site-specific assessments and other due diligence. It can also be used to guide policy development by informing the applicability of policy at various scales.

6.1 Future work

Refinement of a Landscape Classification for Freshwater Management

Land and Water Science will be further developing this work through the Our Land and Water project ‘Mapping Contaminants from Source to Sink’ (S2S). The overall objective of the programme is to produce a national landscape classification for water quality to support contaminant risk assessment for policy option development. The classification units will describe contaminant processes within parcels of land, surface water, and shallow groundwater (hydrologically connected to streams and rivers). The classification, maps and supporting science will inform interchange between policy agencies, science and rural communities, iwi/hapū and industry.

The landscape classification will provide a system for identifying and grouping individual land parcels according to their risk for water quality, considering the substantial diversity of New Zealand’s landscapes. The S2S programme will define the inherent susceptibility of the landscape to contaminant yields matched to the vulnerability of receiving freshwater environments as part of a multi-contaminant framework that considers the risk response of varying land-use pressure in landscape classes. Improvement to PENZ can be made through the incorporation of additional inputs, such as the national groundwater redox map (Wilson et al., 2020), the internationally accepted RUSLE model for soil erosion that has recently been implemented using New Zealand spatial data (Donovan and Monaghan, 2021; Donovan, in press), and microbial pathogen risk. A key focus for this work will be the assessment of attenuation, uncertainties, and information gaps.

Background concentrations (endogenous loads from natural sources)

Land use pressure is not the only source of nutrients, sediment, and microbes in the environment as the landscape also contributes a natural source load. In some places, these loads can be significant and result in locations failing national environment standards for some water quality indicators. If a background source is high, it may account for a significant proportion of the load delivered to stream in addition to anthropogenic contributions. For example, baseflow derived phosphorus in areas of Hawkes Bay (Rissmann and Lovett, 2016) and Northland (Pearson and Rissmann, 2020). Other natural landscape background inputs occur in areas with geothermal inputs, various rock and sediment types such as peat.

An awareness of background contributions (either as a qualitative assessment or export coefficients) is critical for setting appropriate targets for instream concentration and loads. Further work to characterise naturally elevated background contributions within the physiographic landscape classification with the identification would be of significant benefit for resource management processes, including enhancements to catchment accounting methods responding to the National Policy Statement for Freshwater Management (2020).

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Appendix: Regional Statistics

Northland

Table A.1. Summary of Physiographic Environments in Northland Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Strong bedrock		603,525	48.41		
	Hill			440,453	35.33
	Low relief			163,072	13.08
Weak bedrock		293,158	23.51		
	Hill			194,377	15.59
	Low relief			98,781	7.92
Oxidising soil & aquifer		88,167	7.07		
	High deep drainage			25,884	2.08
	Increased lateral & overland flow			55,208	4.43
	Strong bedrock			3,753	0.30
	Weak bedrock			3,322	0.27
Reducing soil oxidising aquifer		66,829	5.36		
	High soil reduction			23,834	1.91
	Moderate soil reduction			33,804	2.71
	Strong bedrock			3,020	0.24
	Weak bedrock			6,172	0.50
Oxidising soil reducing aquifer		35,171	2.82		
	High aquifer reduction			14,364	1.15
	Moderate aquifer reduction			18,167	1.46
	Strong bedrock			207	0.02
	Weak bedrock			2,432	0.20
Reducing soil & aquifer		127,768	10.25		
	High soil reduction			58,165	4.67
	Moderate soil reduction			54,197	4.35
	Strong bedrock			2,812	0.23
	Weak bedrock			12,594	1.01
Wetlands		25,073	2.01		
	Lowland			25,011	2.01
	Hill and Alpine			62	0.00
Urban	Urban	6,954	0.56	6,954	0.56
Quarry	Quarry	112	0.01	112	0.01
Total		1,246,756	100		

Auckland

Table A.2. Summary of Physiographic Environments in Auckland Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Strong bedrock		98,615	20.12		
	Hill			84,783	17.30
	Low relief			13,833	2.82
Weak bedrock		171,517	34.99		
	Hill			105,007	21.42
	Low relief			66,510	13.57
Oxidising soil & aquifer		46,917	9.57		
	High deep drainage			13,209	2.69
	Increased lateral & overland flow			20,957	4.28
	Strong bedrock			1,051	0.21
	Weak bedrock			11,700	2.39
Reducing soil oxidising aquifer		18,872	3.85		
	High soil reduction			3,774	0.77
	Moderate soil reduction			13,465	2.75
	Strong bedrock			411	0.08
	Weak bedrock			1,223	0.25
Oxidising soil reducing aquifer		58,932	12.02		
	High aquifer reduction			35,545	7.25
	Moderate aquifer reduction			9,930	2.03
	Strong bedrock			663	0.14
	Weak bedrock			12,794	2.61
Reducing soil & aquifer		41,506	8.47		
	High soil reduction			12,271	2.50
	Moderate soil reduction			26,722	5.45
	Strong bedrock			97	0.02
	Weak bedrock			2,417	0.49
Wetlands		4,116	0.84		
	Lowland			3,818	0.78
	Hill and Alpine			298	0.06
Urban	Urban	49,505	10.10	49,505	10.10
Quarry	Quarry	192	0.04	192	0.04
Total		490,170	100		

Waikato

Table A.3. Summary of Physiographic Environments in Waikato Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	12,151	0.51	12,151	0.51
Strong bedrock		463,370	19.45		
	Subalpine			9,089	0.38
	Hill			436,201	18.31
	Low relief			18,081	0.76
Weak bedrock		163,609	6.87		
	Subalpine			4,085	0.17
	Hill			140,543	5.90
	Low relief			18,981	0.80
Oxidising soil & aquifer		1,073,936	45.07		
	High deep drainage			188,837	7.93
	Increased lateral & overland flow			243,200	10.21
	Strong bedrock			481,285	20.20
	Weak bedrock			160,615	6.74
Reducing soil oxidising aquifer		103,628	4.35		
	High soil reduction			14,530	0.61
	Moderate soil reduction			51,524	2.16
	Strong bedrock			27,455	1.15
	Weak bedrock			10,119	0.42
Oxidising soil reducing aquifer		254,176	10.67		
	High aquifer reduction			29,342	1.23
	Moderate aquifer reduction			156,184	6.56
	Strong bedrock			22,737	0.95
	Weak bedrock			45,913	1.93
Reducing soil & aquifer		196,505	8.25		
	High soil reduction			99,338	4.17
	Moderate soil reduction			82,027	3.44
	Strong bedrock			4,846	0.20
	Weak bedrock			10,294	0.43
Riverine		5,090	0.21		
	High deep drainage			3,642	0.15
	Increased overland flow			1,448	0.06
Wetlands		91,571	3.84		
	Lowland			84,869	3.56
	Hill and Alpine			6,702	0.28
Urban	Urban	17,918	0.75	17,918	0.75
Quarry	Quarry	705	0.03	705	0.03
		2,382,657	100		

Bay of Plenty

Table A.4. Summary of Physiographic Environments in Bay of Plenty Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Strong bedrock		320,854	26.68		
	Hill			320,060	26.61
	Low relief			795	0.07
Weak bedrock		4,834	0.40		
	Hill			4,831	0.40
	Low relief			3	0.00
Oxidising soil & aquifer		755,516	62.82		
	High deep drainage			158,932	13.22
	Increased lateral & overland flow			67,075	5.58
	Strong bedrock			448,419	37.29
	Weak bedrock			81,090	6.74
Reducing soil oxidising aquifer		16,460	1.37		
	High soil reduction			9,376	0.78
	Moderate soil reduction			4,813	0.40
	Strong bedrock			1,076	0.09
	Weak bedrock			1,195	0.10
Oxidising soil reducing aquifer		61,360	5.10		
	High aquifer reduction			3,345	0.28
	Moderate aquifer reduction			38,015	3.16
	Strong bedrock			15,792	1.31
	Weak bedrock			4,209	0.35
Reducing soil & aquifer		25,667	2.13		
	High soil reduction			18,958	1.58
	Moderate soil reduction			6,296	0.52
	Strong bedrock			137	0.01
	Weak bedrock			276	0.02
Wetlands		6,034	0.50		
	Lowland			1,716	0.14
	Hill and Alpine			4,318	0.36
Urban	Urban	11,867	0.99	11,867	0.99
Total		1,202,591	100		

Gisborne

Table A.5. Summary of Physiographic Environments in Gisborne Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Strong bedrock		217,567	25.96		
	Subalpine			17	0.00
	Hill			791	0.09
	Low relief			216,758	25.86
Weak bedrock		378,139	45.11		
	Subalpine			2,600	0.31
	Hill			89	0.01
	Low relief			375,450	44.79
Oxidising soil & aquifer		82,665	9.86		
	High deep drainage			5,554	0.66
	Increased lateral & overland flow			15,832	1.89
	Strong bedrock			34,035	4.06
	Weak bedrock			27,245	3.25
Reducing soil oxidising aquifer		94,096	11.23		
	High soil reduction			67,916	8.10
	Moderate soil reduction			16,522	1.97
	Strong bedrock			9,574	1.14
	Weak bedrock			84	0.01
Oxidising soil reducing aquifer		23,089	2.75		
	Moderate aquifer reduction			5,644	0.67
	Strong bedrock			6,338	0.76
	Weak bedrock			11,108	1.33
Reducing soil & aquifer		37,859	4.52		
	High soil reduction			35,971	4.29
	Moderate soil reduction			680	0.08
	Strong bedrock			1,191	0.14
	Weak bedrock			17	0.00
Wetlands		2,404	0.29		
	Lowland			2,304	0.27
	Hill and Alpine			100	0.01
Urban	Urban	146	0.02	146	0.02
Quarry	Quarry	2,262	0.27	2,262	0.27
Total		838,225	100		

Taranaki

Table A.6. Summary of Physiographic Environments in Taranaki Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	1640.25	0.23	1,640	0.23
Strong bedrock		3,857	0.53		
	Subalpine			1,624	0.22
	Hill			2,233	0.31
Weak bedrock		327,696	45.20		
	Subalpine			562	0.08
	Hill			324,008	44.69
	Low relief			3,126	0.43
Oxidising soil & aquifer		232,199	32.03		
	High deep drainage			134,948	18.61
	Increased lateral & overland flow			31,868	4.40
	Strong bedrock			4,351	0.60
	Weak bedrock			61,032	8.42
Reducing soil oxidising aquifer		34,390	4.74		
	High soil reduction			19,315	2.66
	Moderate soil reduction			14,169	1.95
	Strong bedrock			688	0.09
	Weak bedrock			219	0.03
Oxidising soil reducing aquifer		80,059	11.04		
	High aquifer reduction			3,414	0.47
	Moderate aquifer reduction			60,271	8.31
	Strong bedrock			35	0.00
	Weak bedrock			16,340	2.25
Reducing soil & aquifer		10,574	1.46		
	High soil reduction			3,644	0.50
	Moderate soil reduction			4,198	0.58
	Weak bedrock			2,733	0.38
Riverine		25,166	3.47		
	High deep drainage			14,431	1.99
	Increased overland flow			10,736	1.48
Wetlands		2,123	0.29		
	Lowland			2,113	0.29
	Hill and Alpine			10	0.00
Urban	Urban	7306	1.01	7,306	1.01
Total		725,009	100		

Manawatu

Table A.7. Summary of Physiographic Environments in Manawatu Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	28,571	1.29	28,571	1.29
Strong bedrock		234,584	10.57		
	Subalpine			41,561	1.87
	Hill			191,947	8.65
	Low relief			1,076	0.05
Weak bedrock		910,527	41.03		
	Subalpine			3,963	0.18
	Hill			875,775	39.46
	Low relief			30,789	1.39
Oxidising soil & aquifer		548,805	24.73		
	High deep drainage			80,406	3.62
	Increased lateral & overland flow			137,564	6.20
	Strong bedrock			105,131	4.74
	Weak bedrock			225,706	10.17
Reducing soil oxidising aquifer		161,452	7.27		
	High soil reduction			45,081	2.03
	Moderate soil reduction			79,303	3.57
	Strong bedrock			3,326	0.15
	Weak bedrock			33,741	1.52
Oxidising soil reducing aquifer		137,286	6.19		
	High aquifer reduction			9,582	0.43
	Moderate aquifer reduction			63,306	2.85
	Strong bedrock			3,906	0.18
	Weak bedrock			60,493	2.73
Reducing soil & aquifer		157,337	7.09		
	High soil reduction			61,595	2.78
	Moderate soil reduction			79,401	3.58
	Strong bedrock			11	0.00
	Weak bedrock			16,331	0.74
Riverine		23,645	1.07		
	High deep drainage			13,983	0.63
	Increased overland flow			9,662	0.44
Wetlands		3,175	0.14		
	Lowland			2,705	0.12
	Hill and Alpine			470	0.02
Urban	Urban	13,888	0.63	13,888	0.63
Total		2,219,269	100		

Hawkes Bay

Table A.8. Summary of Physiographic Environments in Hawkes Bay Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	3,916	0.28	3,916	0.28
Strong bedrock		260,001	18.42		
	Subalpine			17,491	1.24
	Hill			227,826	16.14
	Low relief			14,684	1.04
Weak bedrock		498,347	35.30		
	Subalpine			63	0.00
	Hill			430,155	30.47
	Low relief			68,129	4.83
Oxidising soil & aquifer		377,189	26.72		
	High deep drainage			30,716	2.18
	Increased lateral & overland flow			41,456	2.94
	Strong bedrock			126,085	8.93
	Weak bedrock			178,932	12.68
Reducing soil oxidising aquifer		146,093	10.35		
	High soil reduction			40,597	2.88
	Moderate soil reduction			56,616	4.01
	Strong bedrock			23,904	1.69
	Weak bedrock			24,975	1.77
Oxidising soil reducing aquifer		40,352	2.86		
	High aquifer reduction			4,727	0.33
	Moderate aquifer reduction			3,698	0.26
	Strong bedrock			1,118	0.08
	Weak bedrock			30,809	2.18
Reducing soil & aquifer		40,072	2.84		
	High soil reduction			4,239	0.30
	Moderate soil reduction			16,073	1.14
	Strong bedrock			331	0.02
	Weak bedrock			19,429	1.38
Riverine		31,388	2.22		
	High deep drainage			21,649	1.53
	Increased overland flow			9,739	0.69
Wetlands		7,520	0.53		
	Lowland			5,714	0.40
	Hill and Alpine			1,806	0.13
Urban	Urban	6,768	0.48	6,768	0.48
Total		1,411,644	100		

Wellington

Table A.9. Summary of Physiographic Environments in Wellington Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	4,085	0.51	4,085	0.51
Strong bedrock		407,852	50.86		
	Subalpine			12,341	1.54
	Hill			390,998	48.76
	Low relief			4,513	0.56
Weak bedrock		149,360	18.63		
	Subalpine			1	0.00
	Hill			134,601	16.79
	Low relief			14,758	1.84
Oxidising soil & aquifer		70,057	8.74		
	High deep drainage			17,115	2.13
	Increased lateral & overland flow			39,711	4.95
	Strong bedrock			4,159	0.52
	Weak bedrock			9,073	1.13
Reducing soil oxidising aquifer		90,834	11.33		
	High soil reduction			32,600	4.07
	Moderate soil reduction			47,155	5.88
	Strong bedrock			2,210	0.28
	Weak bedrock			8,869	1.11
Oxidising soil reducing aquifer		20,208	2.52		
	High aquifer reduction			3	0.00
	Moderate aquifer reduction			5,157	0.64
	Strong bedrock			10,482	1.31
	Weak bedrock			4,565	0.57
Reducing soil & aquifer		21,906	2.73		
	High soil reduction			1,658	0.21
	Moderate soil reduction			6,829	0.85
	Strong bedrock			1,656	0.21
	Weak bedrock			11,763	1.47
Riverine		11,387	1.42		
	High deep drainage			3,438	0.43
	Increased overland flow			7,950	0.99
Wetlands		1,785	0.22		
	Lowland			1,771	0.22
	Hill and Alpine			14	0.00
Urban	Urban	24,436	3.05	24,436	3.05
Total		801,908	100		

Tasman

Table A.10. Summary of Physiographic Environments in Tasman Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	70,596	7.35	70,596	7.35
Strong bedrock		511,551	53.26		
	Subalpine			94,285	9.82
	Hill			408,494	42.53
	Low relief			8,773	0.91
Weak bedrock		236,585	24.63		
	Subalpine			20,795	2.17
	Hill			198,846	20.70
	Low relief			16,944	1.76
Oxidising soil & aquifer		87,223	9.08		
	High deep drainage			28,698	2.99
	Increased lateral & overland flow			26,608	2.77
	Strong bedrock			3,643	0.38
	Weak bedrock			28,274	2.94
Reducing soil oxidising aquifer		28,595	2.98		
	High soil reduction			14,040	1.46
	Moderate soil reduction			11,224	1.17
	Strong bedrock			86	0.01
	Weak bedrock			3,245	0.34
Oxidising soil reducing aquifer		2,310	0.24		
	High aquifer reduction			315	0.03
	Moderate aquifer reduction			936	0.10
	Strong bedrock			97	0.01
	Weak bedrock			963	0.10
Reducing soil & aquifer		1,856	0.19		
	High soil reduction			641	0.07
	Moderate soil reduction			847	0.09
	Strong bedrock			2	0.00
	Weak bedrock			367	0.04
Riverine		19,808	2.06		
	High deep drainage			3,007	0.31
	Increased overland flow			16,801	1.75
Wetlands		808	0.08		
	Lowland			600	0.06
	Hill and Alpine			208	0.02
Urban	Urban	1,076	0.11	1,076	0.11
Total		960,407	100		

Nelson

Table A.11. Summary of Physiographic Environments in Nelson Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Strong bedrock		35,984	85.59		
	Hill			35,698	84.91
	Low relief			286	0.68
Weak bedrock		1,288	3.06		
	Hill			1,270	3.02
	Low relief			18	0.04
Oxidising soil & aquifer		1,492	3.55		
	High deep drainage			559	1.33
	Increased lateral & overland flow			854	2.03
	Strong bedrock			6	0.01
	Weak bedrock			73	0.17
Reducing soil oxidising aquifer		859	2.04		
	High soil reduction			333	0.79
	Moderate soil reduction			58	0.14
	Strong bedrock			1	0.00
	Weak bedrock			467	1.11
Oxidising soil reducing aquifer		3	0.01		
	Moderate aquifer reduction			3	0.01
Oxidising soil reducing aquifer	Weak bedrock			1	0.00
Reducing soil & aquifer		317	0.75		
	High soil reduction			316	0.75
	Weak bedrock			0	0.00
Urban	Urban	2,101	5.00	2,101	5.00
Total		42,043	100		

Marlborough

Table A.12. Summary of Physiographic Environments in Marlborough Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	137,431	13.15	137,431	13.15
Strong bedrock		615,662	58.89		
	Subalpine			141,457	13.53
	Hill			471,134	45.07
	Low relief			3,071	0.29
Weak bedrock		136,943	13.10		
	Subalpine			10,444	1.00
	Hill			124,393	11.90
	Low relief			2,106	0.20
Oxidising soil & aquifer		66,213	6.33		
	High deep drainage			29,451	2.82
	Increased lateral & overland flow			15,684	1.50
	Strong bedrock			8,938	0.85
	Weak bedrock			12,141	1.16
Reducing soil oxidising aquifer		53,786	5.14		
	High soil reduction			20,271	1.94
	Moderate soil reduction			13,556	1.30
	Strong bedrock			1,834	0.18
	Weak bedrock			18,125	1.73
Oxidising soil reducing aquifer		135	0.01		
	High aquifer reduction			53	0.01
	Moderate aquifer reduction			2	0.00
	Strong bedrock			63	0.01
	Weak bedrock			18	0.00
Reducing soil & aquifer		305	0.03		
	High soil reduction			26	0.00
	Moderate soil reduction			200	0.02
	Weak bedrock			79	0.01
Riverine		32,692	3.13		
	High deep drainage			15,846	1.52
	Increased overland flow			16,846	1.61
Wetlands	Lowland	11	0.00	11	0.00
Urban	Urban	2,247	0.21	2,247	0.21
Quarry	Quarry	15	0.00	15	0.00
Total		1,045,438	100		

West Coast

Table A.13. Summary of Physiographic Environments in West Coast Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	279,206	12.07	279,206	12.07
Strong bedrock		1,118,902	48.36		
	Subalpine			378,084	16.34
	Hill			730,955	31.60
	Low relief			9,864	0.43
Weak bedrock		228,621	9.88		
	Subalpine			43,445	1.88
	Hill			174,907	7.56
	Low relief			10,269	0.44
Oxidising soil & aquifer		381,119	16.47		
	High deep drainage			103,625	4.48
	Increased lateral & overland flow			127,923	5.53
	Strong bedrock			25,702	1.11
	Weak bedrock			123,870	5.35
Reducing soil oxidising aquifer		182,104	7.87		
	High soil reduction			117,039	5.06
	Moderate soil reduction			56,520	2.44
	Strong bedrock			383	0.02
	Weak bedrock			8,163	0.35
Oxidising soil reducing aquifer		10,010	0.43		
	High aquifer reduction			1,872	0.08
	Moderate aquifer reduction			1,999	0.09
	Strong bedrock			877	0.04
	Weak bedrock			5,262	0.23
Reducing soil & aquifer		10,965	0.47		
	High soil reduction			8,188	0.35
	Moderate soil reduction			1,249	0.05
	Strong bedrock			2	0.00
	Weak bedrock			1,527	0.07
Riverine		85,928	3.71		
	High deep drainage			33,580	1.45
	Increased overland flow			52,348	2.26
Wetlands		14,450	0.62		
	Lowland			13,481	0.58
	Hill and Alpine			969	0.04
Urban	Urban	2,192	0.09	2,192	0.09
Total		2,313,495	100		

Canterbury

Table A.14. Summary of Physiographic Environments in Canterbury Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	682,093	15.38	682,093	15.38
Strong bedrock		1,388,839	31.32		
	Subalpine			481,699	10.86
	Hill			891,320	20.10
	Low relief			15,820	0.36
Weak bedrock		291,913	6.58		
	Subalpine			90,947	2.05
	Hill			180,776	4.08
	Low relief			20,191	0.46
Oxidising soil & aquifer		1,111,424	25.06		
	High deep drainage			455,755	10.28
	Increased lateral & overland flow			436,232	9.84
	Strong bedrock			129,755	2.93
	Weak bedrock			89,682	2.02
Reducing soil oxidising aquifer		534,862	12.06		
	High soil reduction			98,628	2.22
	Moderate soil reduction			294,903	6.65
	Strong bedrock			70,904	1.60
	Weak bedrock			70,427	1.59
Oxidising soil reducing aquifer		34,770	0.78		
	High aquifer reduction			2,546	0.06
	Moderate aquifer reduction			7,871	0.18
	Strong bedrock			10,117	0.23
	Weak bedrock			14,237	0.32
Reducing soil & aquifer		71,361	1.61		
	High soil reduction			4,059	0.09
	Moderate soil reduction			32,522	0.73
	Strong bedrock			12,002	0.27
	Weak bedrock			22,778	0.51
Riverine		293,600	6.62		
	High deep drainage			196,039	4.42
	Increased overland flow			97,561	2.20
Wetlands		3,645	0.08		
	Lowland			3,629	0.08
	Hill and Alpine			15	0.00
Urban	Urban	21,798	0.49	21,798	0.49
Total		4,434,304	100		

Otago

Table A.15. Summary of Physiographic Environments in Otago Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	531,977	17.09	531,977	17.09
Strong bedrock		1,459,649	46.89		
	Subalpine			343,787	11.04
	Hill			808,208	25.96
	Low relief			307,655	9.88
Weak bedrock		250,757	8.05		
	Subalpine			63,620	2.04
	Hill			132,463	4.25
	Low relief			54,674	1.76
Oxidising soil & aquifer		349,656	11.23		
	High deep drainage			35,322	1.13
	Increased lateral & overland flow			155,166	4.98
	Strong bedrock			98,787	3.17
	Weak bedrock			60,382	1.94
Reducing soil oxidising aquifer		336,433	10.81		
	High soil reduction			70,087	2.25
	Moderate soil reduction			83,912	2.70
	Strong bedrock			125,837	4.04
	Weak bedrock			56,598	1.82
Oxidising soil reducing aquifer		55,396	1.78		
	High aquifer reduction			15,232	0.49
	Moderate aquifer reduction			4,490	0.14
	Strong bedrock			18,616	0.60
	Weak bedrock			17,058	0.55
Reducing soil & aquifer		54,137	1.74		
	High soil reduction			5,156	0.17
	Moderate soil reduction			9,938	0.32
	Strong bedrock			19,432	0.62
	Weak bedrock			19,612	0.63
Riverine		57,430	1.84		
	High deep drainage			17,428	0.56
	Increased overland flow			40,003	1.28
Wetlands		7,323	0.24		
	Lowland			5,275	0.17
	Hill and Alpine			2,048	0.07
Urban	Urban	10,398	0.33	10,398	0.33
Total		3,113,155	100		

Southland

Table A.16. Summary of Physiographic Environments in Southland Region.

Family	Sibling	Family Area (ha)	Family Percent (%)	Sibling Area (ha)	Sibling Percent (%)
Alpine	Alpine	413,493	13.29	413,493	13.29
Strong bedrock		1,302,371	41.86		
	Subalpine			549,188	17.65
	Hill			674,030	21.67
	Low relief			79,154	2.54
Weak bedrock		300,284	9.65		
	Subalpine			55,753	1.79
	Hill			210,771	6.77
	Low relief			33,761	1.09
Oxidising soil & aquifer		301,571	9.69		
	High deep drainage			116,952	3.76
	Increased lateral & overland flow			94,135	3.03
	Strong bedrock			52,456	1.69
	Weak bedrock			38,028	1.22
Reducing soil oxidising aquifer		467,624	15.03		
	High soil reduction			172,089	5.53
	Moderate soil reduction			127,169	4.09
	Strong bedrock			96,856	3.11
	Weak bedrock			71,510	2.30
Oxidising soil reducing aquifer		59,011	1.90		
	High aquifer reduction			6,670	0.21
	Moderate aquifer reduction			10,478	0.34
	Strong bedrock			31,656	1.02
	Weak bedrock			10,207	0.33
Reducing soil & aquifer		80,455	2.59		
	High soil reduction			19,061	0.61
	Moderate soil reduction			23,055	0.74
	Strong bedrock			18,400	0.59
	Weak bedrock			19,940	0.64
Riverine		131,403	4.22		
	High deep drainage			79,997	2.57
	Increased overland flow			51,406	1.65
Wetlands		48,939	1.57		
	Lowland			40,731	1.31
	Hill and Alpine			8,208	0.26
Urban	Urban	5,988	0.19	5,988	0.19
Total		3,111,138	100.00		