Arahura Catchment: Physiographic Stocktake

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Land and Water Science Report 2021/11
May 2021

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Document Information
Land and Water Science Report No: 2021/11
Report Date: 28.05.2021
Project Number: 21008

Reviewed by:
Rissmann, C (PhD)
Organisation: Land and Water Science
Position: Director
Review Date: 29.05.2021

Document Status: Final

Citation Advice
Pearson, L., Lawrence, C., and Dang, M. (2021). Arahura Catchment: Physiographic Stocktake. Land and Water Science Report 2021/11. p50.

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Community Summary

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

The Arahura catchment is one of the Department of Conservations priority catchments in the Ngā Awa river restoration programme. This report presents an environmental stocktake and maps for the Arahura Catchment to fulfil the first part of a two-part project. This stocktake comprises Physiographic maps that display the landscape related controls over water quality and land use pressure within the catchment. Physiographic Environments, developed in partnership with the Our Land and Water National Science Challenge, incorporate terrain, catchment hydrological layers, geological, and soil layers to map the processes that, in addition to land use, control water quality.

Physiographic science results in an increased understanding of the landscape processes, which can be used to best guide the implementation of management practices relevant to the characteristics of a farm or catchment. Contextual science forms the basis for more effective and least cost farm decision making, lowering the overall risk of non-compliance and poor investment.

Summary Map

This map shows the Physiographic Environments, digitised stream network and node points where water discharges from a property in the Arahura catchment. Areas that are protected are shown by hatching.

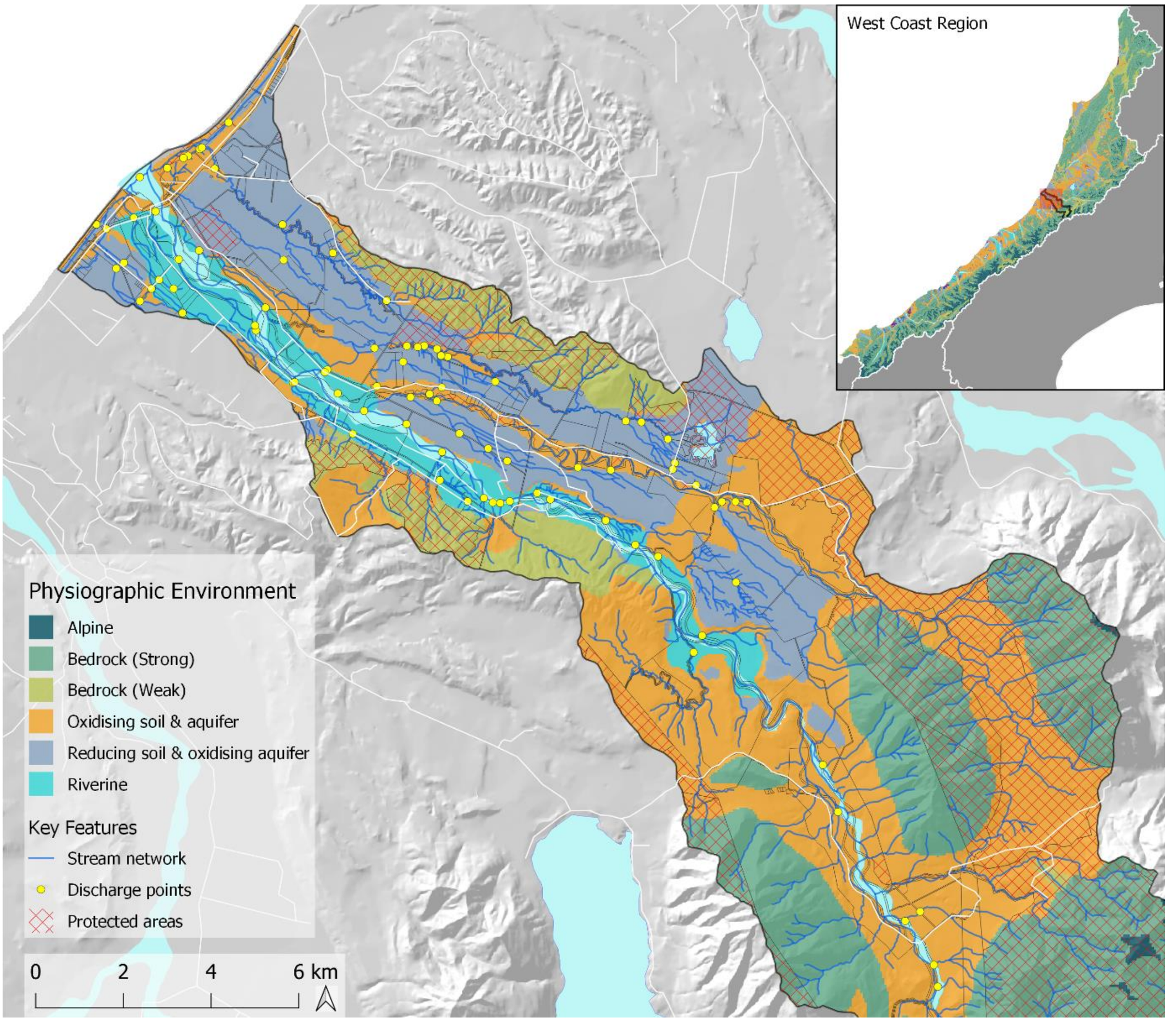

Figure: Arahura Catchment, Physiographic Environments (see https://www.landscapedna.org/). Each Physiographic Environment is associated with a unique set of water quality risks.

Risk to water quality

The risk to water quality from land use for each physiographic environment within the Arahura Catchment is provided via a matrix of dominant hydrological pathway and contaminant type. The risk matrix assumes land use activities are undertaken in each environment, while the actual contribution from land use (i.e., native forest or grassland) is likely to be significantly lower. The risk to water quality for all contaminants is increased substantially when bypass of the soil zone occurs by either overland flow or artificial drainage.

Physiographic Environment	Nitrogen			Phosphorus		Sediment	Microbes
	Oxidised (NO_3^-, NO_2^-)	Reduced (NH_4^+, NH_3)	Organic (Dissolved & Particulate)	Particulate	Dissolved Reactive	Particulate	Particulate
Alpine	High	High	High	High	High	High	High
Bedrock (Strong)	Low	Low	Moderately low	Moderately high	Moderate	Moderatel y high	Moderate
Bedrock (Weak)	Low	Low	Moderate	Moderately high	Moderate	High	Moderate
Riverine	Moderate	Low	Low	Low	Low	Low	Moderately low
Oxidising soil and aquifer	High	Low	Low	Low	Low	Low	Moderately low
Reducing soil oxidising aquifer	Moderately low	Moderate	Moderate	High	Moderately low	Moderatel y high	High

See https://landscapedna.org/ for further information on the Physiographic Environment classification, interactive maps, and actions to help improve water quality efforts.

Future work

Future work in the Arahura catchment involves incorporating higher resolution datasets to refine the physiographic classification for the catchment. This classification will then be used to produce an integrated assessment of risk for all water quality contaminants (nitrogen, phosphorus, sediment, and microbes), including a relative pressure (or source) from the land.

A new stream network will also be developed once LiDAR is available. This work will provide paddock scale resolution over topography, streamflow and associated flowpaths and forms a critical layer for prioritising intervention.

1 Introduction

The Department of Conservation commissioned a high-resolution physiographic stocktake of the Arahura Catchment, one of 14 priority catchments within the winder Ngā Awa river restoration programme. The purpose of this project is to provide the Arahura Catchment stakeholders with data and information to inform their activities in a manner that provides the most environmental benefit. For example, the work involves identifying pressures on the environment from land use across the lower part of the catchment by identifying stream discharge points at property boundaries. By integrating information at property scale, this work seeks to enable the Arahura community to mitigate land use impacts on water quality efficiently and effectively.

This report presents an environmental stocktake and maps for the Arahura Catchment to fulfil the first part of a two-part project. This metadata report provides:

1. A stocktake of existing datasets for the Arahura Catchment
2. A stocktake of new, high-resolution datasets
3. A draft land tenure and land use pressure maps
4. Hydrologically defined discharge or drainage points that represent points of potential contaminant discharge from land to water.
5. A summary of what will be undertaken as part of stage 2 of this project.

This stocktake comprises physiographic maps that display the landscape related controls over water quality. Appendix 1 provides background on the Physiographic Environments, developed in partnership with the National Science Challenge, Our Land and Water, that has been developed, calibrated and tested across New Zealand. Five-year median water quality data from Land Air Water Aotearoa (LAWA) were used to test the performance of the physiographic classification to explain spatial variation in water quality across New Zealand and including the West Coast (Table 1).

Table 1. Median cross-validated performance measures for 811 water quality sites nationally[1].

	TN	NNN	TP	DRP	Turb.	Clarity	*E. coli*
R^2	0.78	0.79	0.73	0.73	0.69	0.62	0.74
Correlation coefficient	0.89	0.89	0.85	0.86	0.83	0.79	0.87
Maximum error	0.59	0.85	0.65	0.58	0.74	0.55	0.90
Mean squared error	0.03	0.10	0.03	0.04	0.05	0.02	0.07
Mean absolute error	0.13	0.21	0.11	0.12	0.15	0.11	0.19
Complexity	33	42	38	38	42	35	35

DRP: Dissolved Reactive Phosphorus; E. Coli: bacterial indicator; NNN: Nitrate-Nitrite Nitrogen; TN: Total Nitrogen; TP: Total Phosphorus; Turb.: Turbidity in Nephelometric Units.

Areas that have similar landscape characteristics are defined as Physiographic Environments. Physiographic Environments respond similarly to land use pressure, resulting in predictable water quality outcomes. A web portal, www.landscapeDNA.org, provides a digital interface to the physiographic science, with complete coverage of the West Coast. The LandscapeDNA portal was developed as part of a Sustainable Farming Fund (SFF) project. When used in conjunction with a land-use context, physiographic outputs can guide investment in improved water quality outcomes.

[1] Performance measures for the West Coast and Tasman are available on request.

Stage two of the Arahura Catchment project will be completed once LiDAR[2] is available and will integrate high-resolution data not currently present in the physiographic classification. The final output will provide property and paddock scale depiction of the landscape factors governing water quality. Input from the Arahura catchment community is essential for refining this project's scientific and land use representations.

1.1 Catchment Location

The Arahura River catchment is located within the West Coast Region, north of Hokitika township. The total area of the catchment is approximately 30,951 hectares (ha). The Arahura River, Newton Creek, Olderog Creek and the Wainihnihi Creek have their headwater sources in the Southern Alps. The other major tributaries feeding into the Arahura have their headwaters west of the Alpine Fault.

The Arahura river passes down through natural tussock, rata-kamahi and other forest. Some plantation forestry occurs in the mid and lower parts of the catchment, and land beside the lower reaches is used for dairy and drystock farming and smaller lifestyle blocks. The Arahura River enters the sea about 8 km north of Hokitika township.

2. Landscape Data Stocktake

The landscape stocktake provides the fundamental landscape information that has been used to develop the Physiographic Environment Classification detailed above. These datasets are predominantly regional to national extent and publicly available. Hydrology was digitised specifically for the Arahura catchment.

2.1. Terrain

2.1.1. Elevation

Elevation was obtained from a NASA Shuttle Radar Topography Mission Digital Elevation Model (DEM). The 27.5 m NASA DEM was smoothed using a gaussian filter and used to create the elevation map, derive slope and developed a Terrain Ruggedness Index (TRI). Elevation data is summarised in Table A.1. NASA's DEM was preferred over the national DEM as it provides far greater resolution across low relief areas.

Data Source: 27.5m DEM from NASA STRM
Pre-processing: Filtering by Simple Gaussian Filter
Output: Raster elevation at 27.5m resolution (Figure A.1).

[2] LiDAR, or light detection and ranging, is a popular remote sensing method used for measuring the exact distance of an object on the earth’s surface. It can be used to produce much higher resolution digital elevation models which intern will produce better hydrological outputs.

Table 2: Area corresponding with each elevation range in the Arahura catchment.

Elevation (m RSL)	Area (ha)	Percent (%)
< 0	8	0.0
From 0 to 100	5200	16.8
From 100 to 200	5973	19.3
From 200 to 400	4761	15.4
From 400 to 600	2768	8.9
From 600 to 800	3057	9.9
From 800 to 1000	2897	9.4
From 1000 to 1500	5167	16.7
From 1500 to 2000	1110	3.6
Total	30941	100

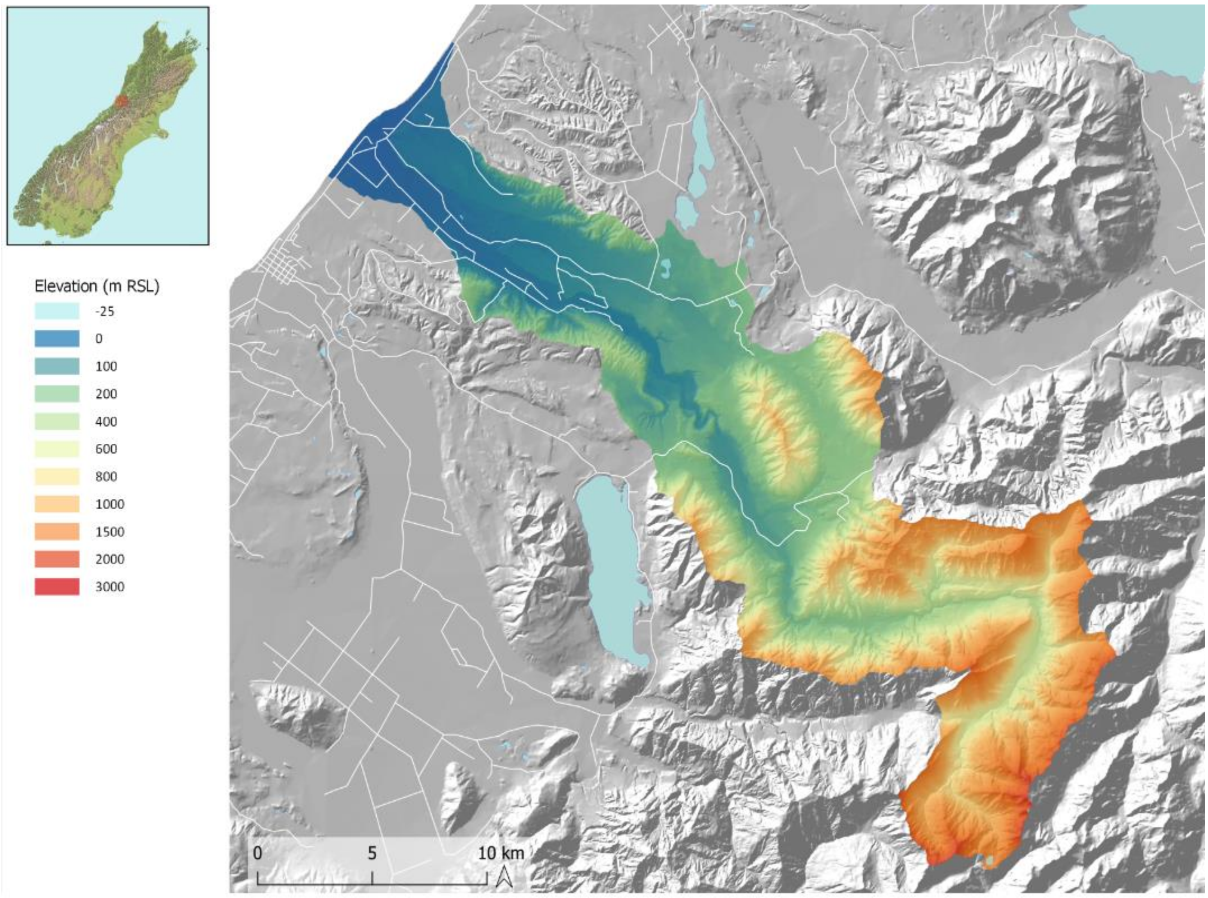

Figure 1. Elevation map of Arahura catchment (metres relative to sea level).

2.1.2. Slope

The slope represents the degree of steepness of the land surface. Table A.2 provides a summary of the slope range in the Arahura catchment. The slope is used for the slope index within the overland flow assessment and informs the likelihood of artificial drainage.

Data Source: 27.5m DEM from NASA.
Pre-processing: Filtering by Simple Gaussian Filter
Processing: QGIS GDAL Geoprocessing tool for slope.

Output: Raster of slope at 27.5m resolution (Figure A.2).

Table 3. Area of slopes ranges in the Arahura catchment.

Slope (^{0})	Area (ha)	Percent (%)
0 to 2	4421	14.5
2 to 4	2956	9.7
4 to 6	1658	5.4
6 to 8	1187	3.9
8 to 10	990	3.2
10 to 15	2268	7.4
15 to 20	2266	7.4
20 to 25	2555	8.4
25 to 30	3076	10.1
> 30	9089	29.8
Total	30,467	100

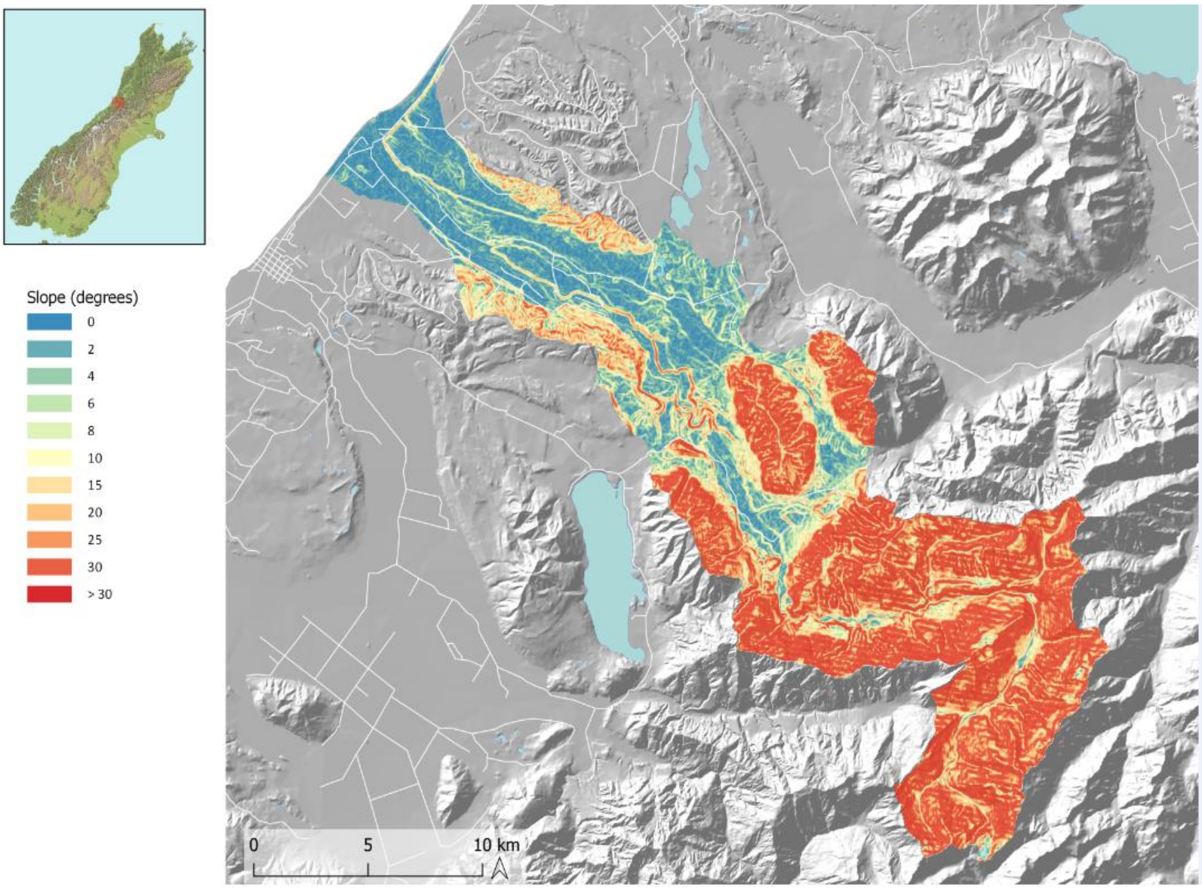

Figure 2. Slope ranges in the Arahura catchment.

2.2. Climate

Climate, particularly temperature and precipitation, profoundly influences the soil-forming processes that occur within a region. The climate largely determines the nature of the weathering processes that will occur and the rates of chemical and physical processes. It directly affects the type of vegetation in an area, which will affect those soil-forming processes related to organisms.

This section of the landscape stocktake has two components: mean annual precipitation and mean air temperature.

2.2.1. Mean Annual Air Temperature

The New Zealand Meteorological Service provides the mean annual air temperature data. Air temperature is provided at a 25 m grid. Mean temperature and elevation were used to determine the alpine recharge domain.

Data Source: Land Resource Information Systems (LRIS) portal hosted by Landcare Research (https://lris.scinfo.org.nz/layer/48094-lenz-mean-annual-temperature/).
Pre-processing: None
Output: Raster layer of annual average air temperature (Figure 3).

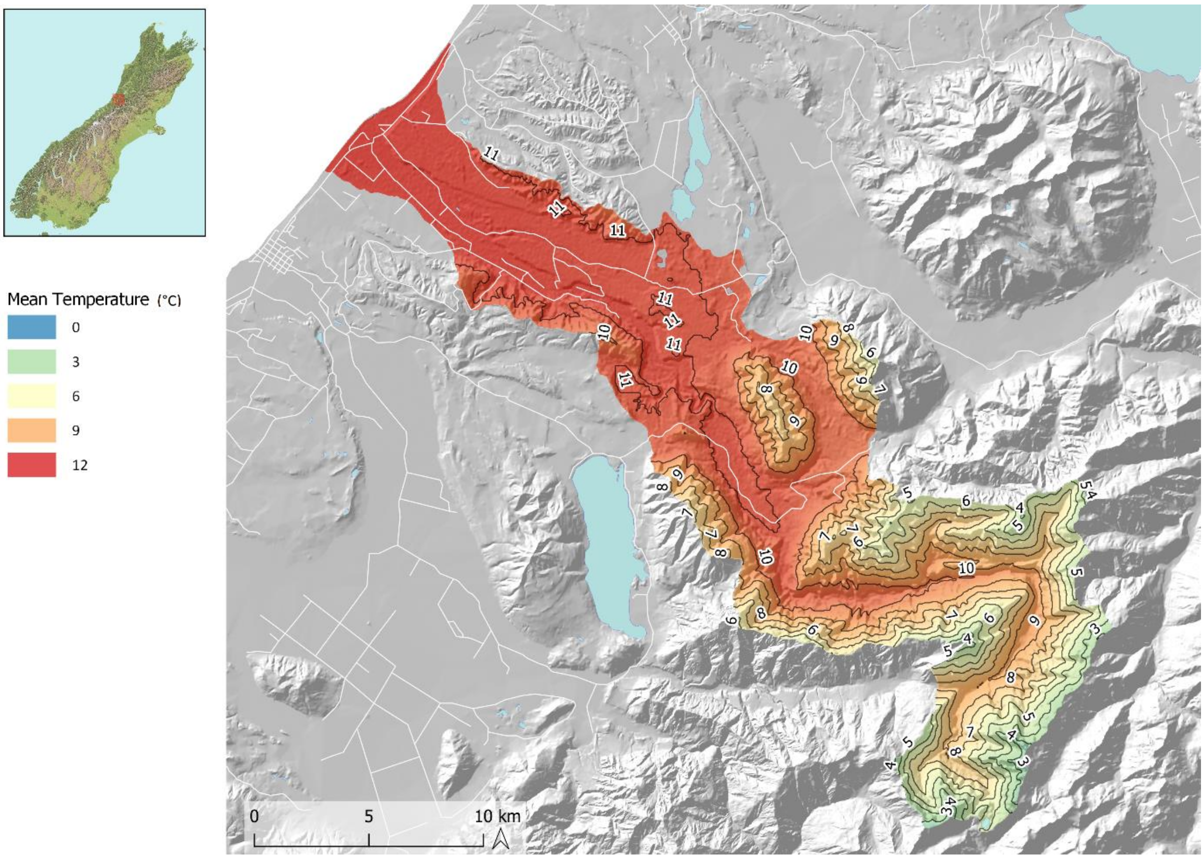

Figure 3. Mean Annual Air Temperature (1972 – 2016) for the Arahura catchment.

2.2.2. Mean Annual Precipitation (1972 – 2016)

The mean annual precipitation data is provided by the National Institute of Water and Atmospheric Research (NIWA) virtual climate network. The volume of precipitation that falls on the land plays a key role in the transport, flushing and dilution of land use derived contaminants.

Data Source: Ministry for the Environment Data Service (https://data.mfe.govt.nz/layer/89421-average-annual-rainfall-19722016/).
Pre-processing: None
Output: Raster layer of mean annual precipitation (Figure 4).

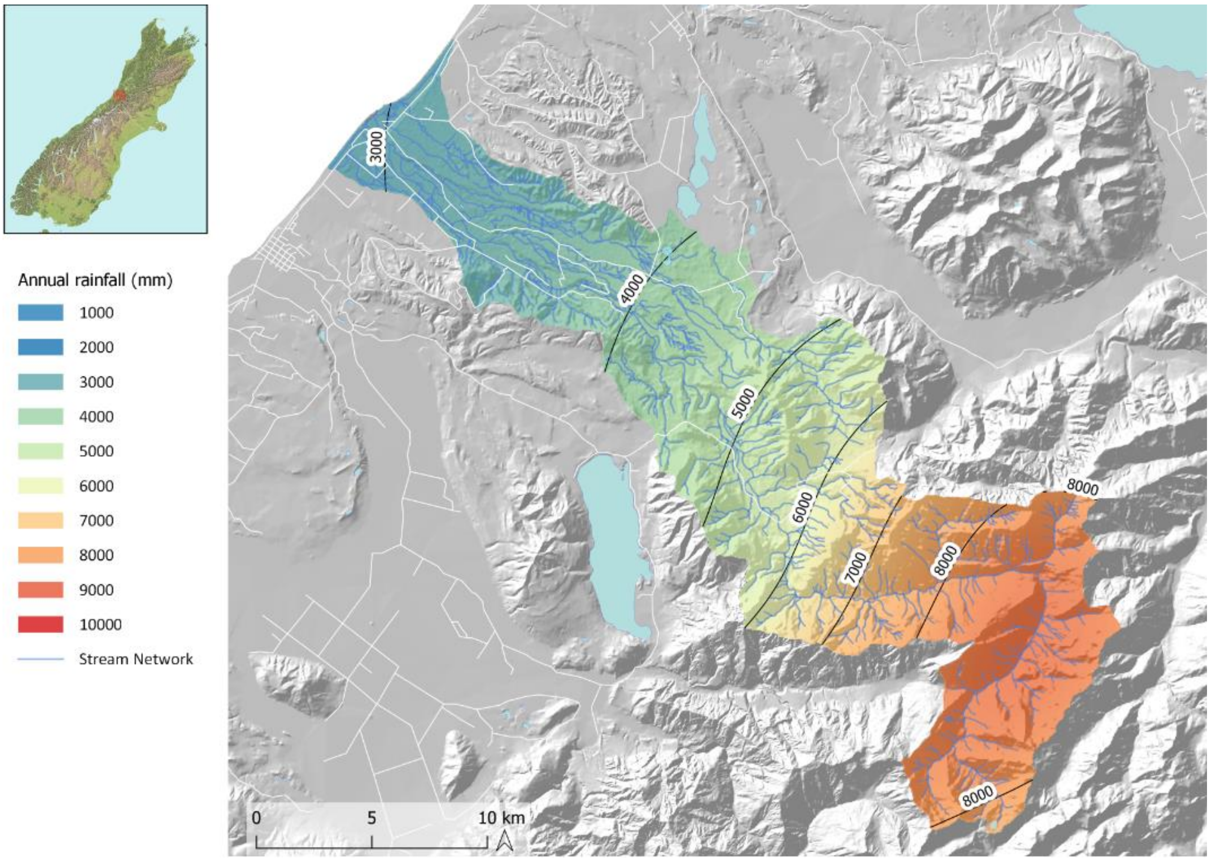

Figure 4. Mean Annual Precipitation (1972 – 2016) for the Arahura catchment. The stream network is shown as a blue line. Although the upper parts of the Arahura catchment above the >7,000 mm isohyet, the volume of water exported from this area is much greater than that of lower elevations.

2.3. Hydrology

The 27.5 m DEM from NASA was tested to create a digital stream network and drainage basin layer using Global Mapper software and was visually compared to aerial and satellite imagery. The outputs were rejected as they failed to define stream channels accurately.

A watershed created from the NZ School of Surveying 8 m DEM and a composite DEM created by Land and Water Science using NASA, Merit, and JAXA DEMs also failed to delineate the stream network effectively.

It is intended that when LiDAR becomes available for the region, the elevation data will be greatly enhanced, and high-resolution elevation, slope, and hydrology layers can be created.

2.3.1. Stream network and Strahler Order

The digitisation of the stream network and sub-catchments was undertaken manually due to the poor resolution of the DEM derived stream network. The combination of aerial photography and the DEM was used to guide the digitisation.

The branching nature of a river and its tributaries can be classified by its Strahler order. This classification is used to indicate the size of a stream based on the hierarchy of the tributaries contributing to it at any location along the network. If two tributaries of the same order combine, the next downstream segment increases by 1 (Figure 5). Following manual digitisation, a script was written and run in Python to automate the assignment of Strahler order to the digital network (Figure 6). When Li-DAR is available the digital stream network, Strahler order, discharge nodes and sub-catchment areas will be upgraded.

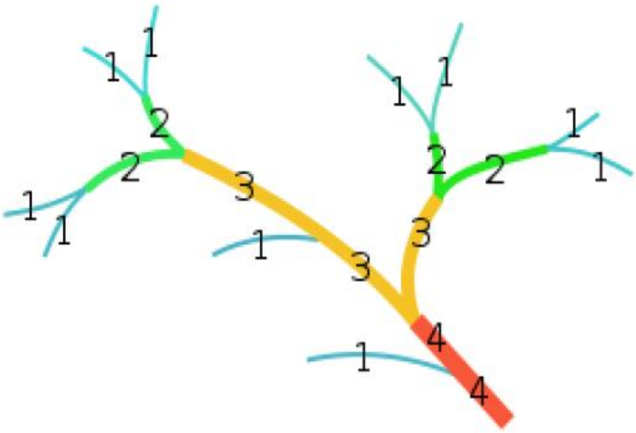

Figure 5. Diagram of the Strahler stream order.

(image from https://en.wikipedia.org/wiki/Strahler_number#/media/File:Flussordnung_(Strahler).svg).

Data Source: Land and Water Science (LWS) manually digitised stream network
Processing: Python script – Strahler assignment
Output: Vector Strahler order (Figure 6).

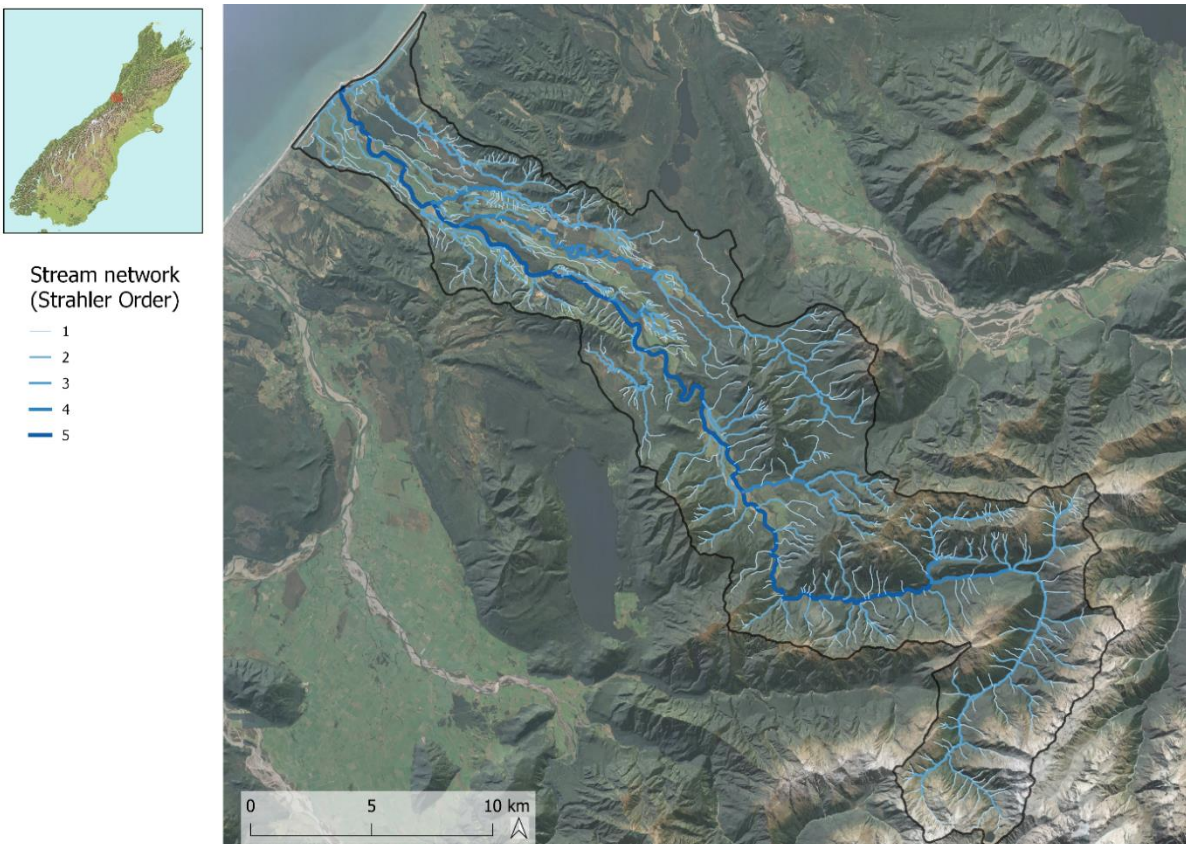

Figure 6. Digital stream network, Strahler order 1 -5, for the Arahura catchment over satellite imagery (Source Google).

2.3.2. Subcatchments

A subcatchment layer was manually created to indicate the source area or watersheds within the Arahura Catchment.

The catchment has been divided into six main sub-catchments, Arahura, Kaiwhaka, Fox Creek, Hatters Creek (a tributary of Flowery Creek), Viaduct Creek, and Red Jacks Creek (Figure 7). The shading used reflects the dominant land use in the sub-catchment. Different river sections are subjective and delineated where a major tributary joins the main stem or land use changes. Stream channels within the area of Red Jacks Creek are not clearly visible and may need refinement. The catchment divide with Four Mile Creek is also unclear and would benefit from local knowledge. For the upper reaches of the main Arahura River, Newton Creek, Olderog, Wainihinihi and the Kaiwhaka watersheds, it was unnecessary to subdivide the watersheds further as the land use is largely still in a natural state.

Data Source: LINZ Topographic Map 1:50,000, LINZ Data Service Aerial Imagery, Google Satellite Imagery, World Imagery, and LWS Stream network
Processing: Manually digitised using a combination of the above sources
Output: Vector Arahura subcatchment (Figure 7).

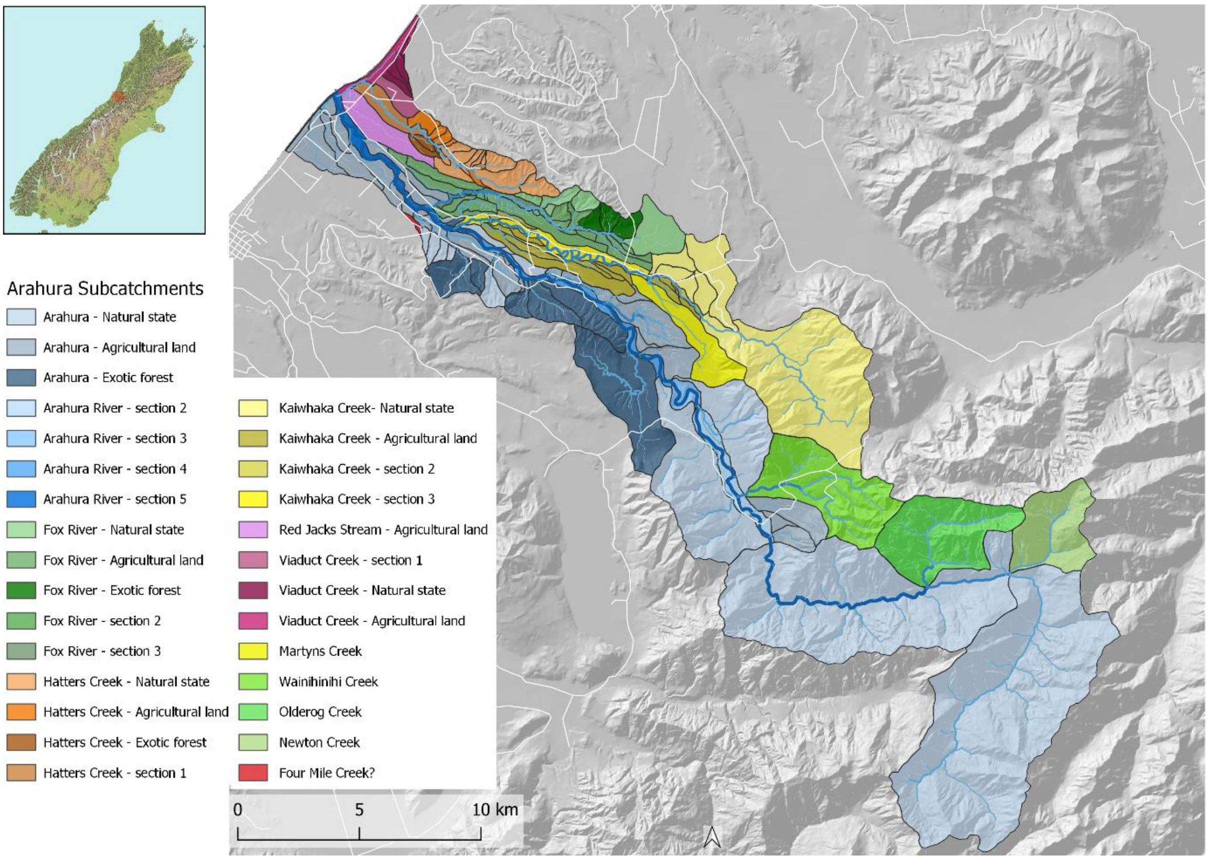

Figure 7. Subcatchments and stream network for the Arahura catchment. The main Arahura watersheds are coloured in various shades of blue. The Kaiwhaka watersheds are shades of yellow; Fox Creek has green shades; Hatters Creek has orange/brown shades; Viaduct Creek has shades of purple, and; Red Jacks is pink. Similar shades indicate similar land use types, e.g., forestry, farming, or natural state.

2.3.3. Water table

The Equilibrium Water Table (EWT) model calculates a long-term average of the water table surface. This model is based on a simplified groundwater flow model and satellite-derived data, including terrain elevation estimates and climate time series across a 200m pixel grid. The EWT model calculates that the water table is generally shallow in New Zealand's alluvial aquifer systems (Westerhoff et al., 2013). Table A.3 shows a summary of the water table depth for the catchment.

Data Source: 200 m Equilibrium Water Table (EWT) by GNS Science
Processing: None
Output: Raster water table (Figure 8).

Table 4. Summary of water table depth in the Arahura catchment.

Range	Area (ha)	Percent (%)
0 to 1	3688	11.9
1 to 2	2224	7.2
2 to 3	1634	5.3
3 to 5	2275	7.4
5 to 10	3752	12.1
10 to 20	3820	12.3
> 20	13552	43.8
Total	30,943	100

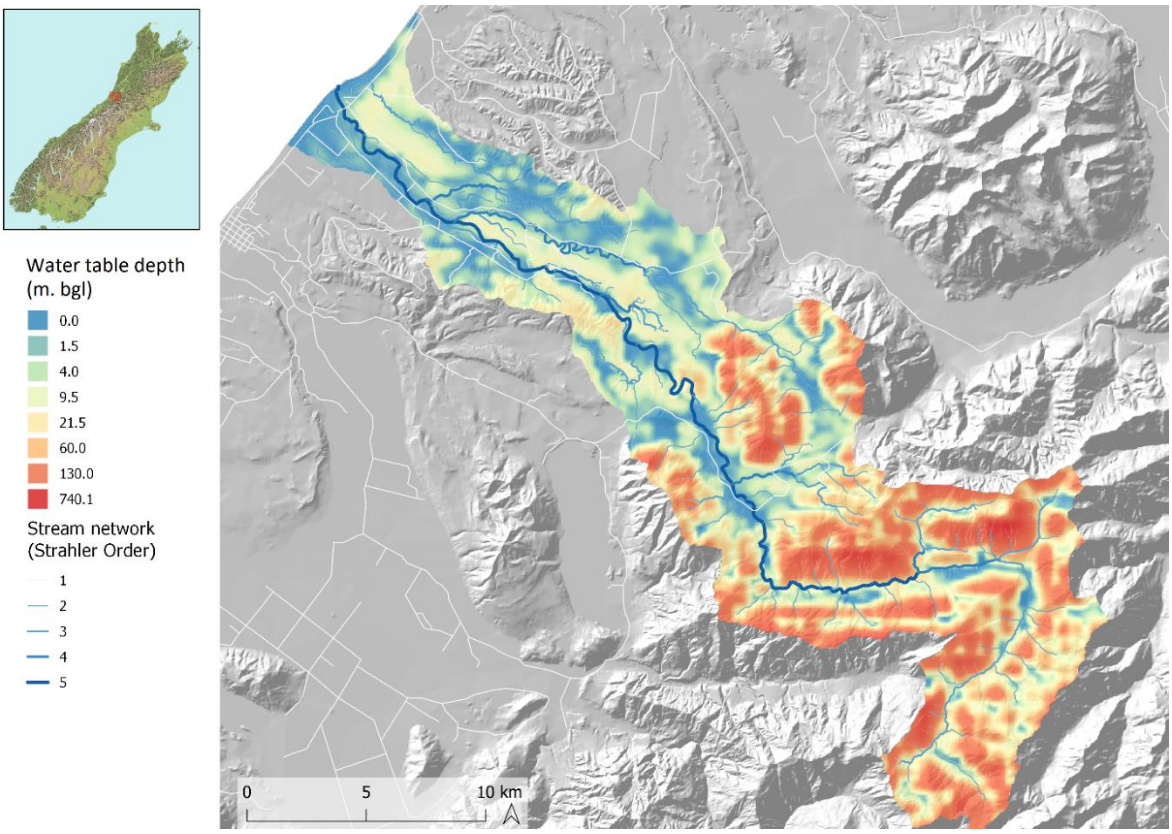

Figure 8. Water table depth in metres below ground level for the Arahura catchment. Symbology is classed using quantiles. This map identifies the likely areas of groundwater accumulation and includes gravel filled valleys in high altitude areas.

2.4. Geology

The geology of a region or catchment is the primary control over elevation, hydrology, soil type and sediment generation. Geology is used to assess weathering processes (mass wasting and erosion), the reduction potential of underlying aquifers, and recharge domain for the physiographic process attribute layers.

2.4.1. QMAP Geology

Geology is sourced from GNS Science QMap 1:250,000 map (Greymouth map series; Nathan et al., 2002, Figure 9). Lithologies east of the Alpine Fault are within the Rakaia Terrane with increasing metamorphic grade and deformation as they near the Alpine Fault. Lithologies west of the Alpine Fault include older Greenland Group metasedimentary rocks and granites of the Buller Terrane. Miocene sandstones and Pliocene gravels are followed by quaternary glacial outwash deposits of various age and depositional processes.

Data Source: NZL_GNS_250K_geologic_units and NZL_GNS_250K_faults by GNS Science (https://www.gns.cri.nz/Home/Our-Science/Land-and-Marine-Geoscience/Regional-Geology/Geological-Maps/1-250-000-Geological-Map-of-New-Zealand-QMAP)
Processing: None
Output: Vector geology and faults (Figure 9)

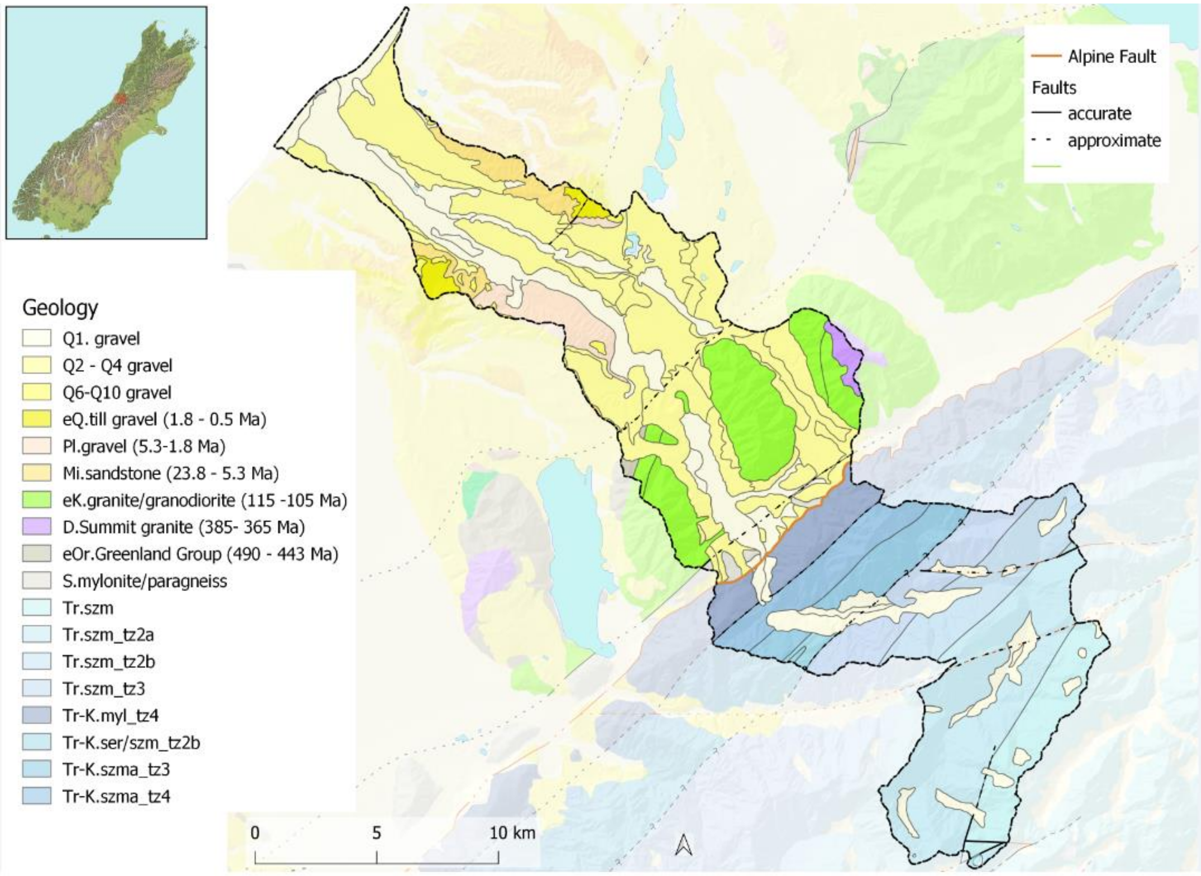

Figure 9. Geology and faults for the Arahura catchment. A detailed explanation of the rock codes is available in the Greymouth map series from Nathan et al., 2002.

QMap also contains several attribute fields relating to the rock type (main, secondary), rock class, terrain, age, and description. Figure 10 shows the geology for the catchment symbolised by main rock. A summary of the main rock area is presented in Table 5.

Table 5. Summary of main rock in the Arahura catchment.

Main rock	Area (ha)	Percent (%)
Gravel	15124.53	48.96
Sandstone	6061.71	19.62
Schist	3515.00	11.38
Granite	2165.04	7.01
Semischist	1641.47	5.31
Mylonite	1233.73	3.99
Granodiorite	732.84	2.37
Sand	310.08	1.00
Paragneiss	61.91	0.20
Silt	29.59	0.10
Serpentinite	14.60	0.05

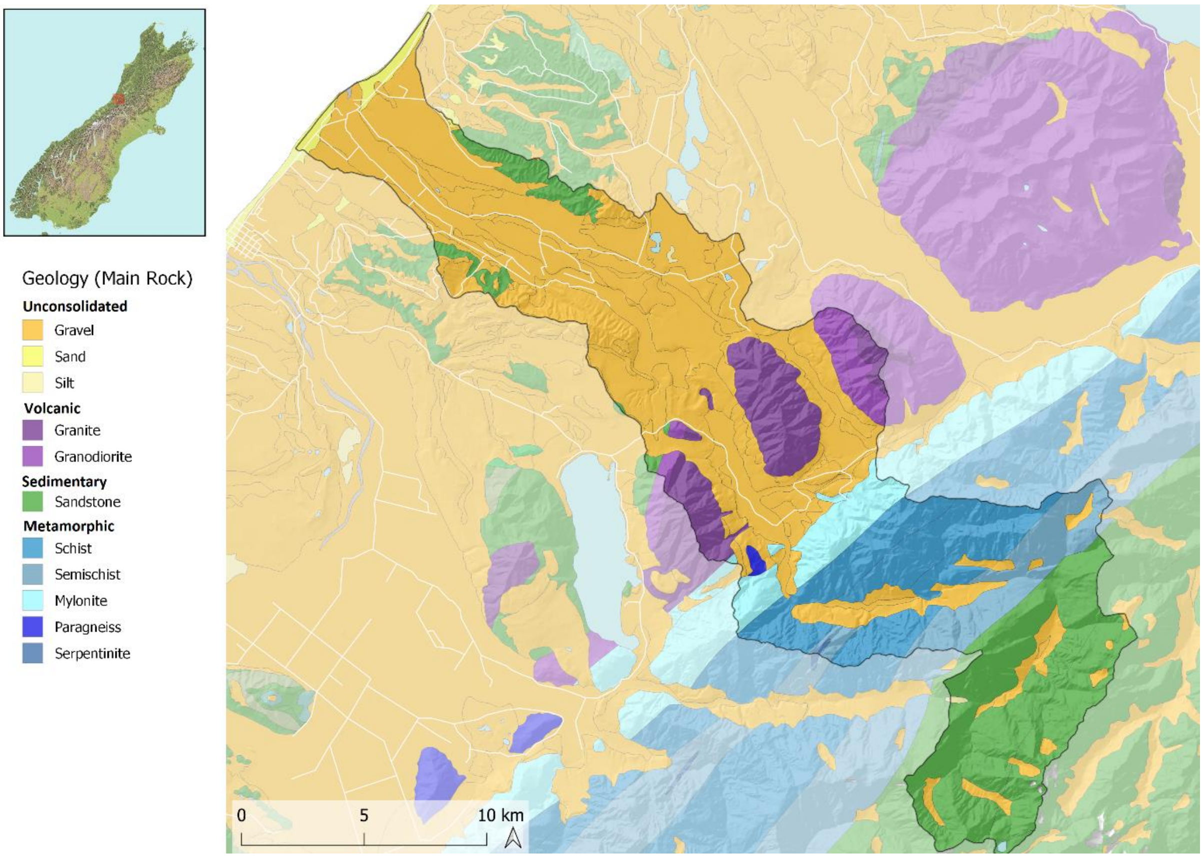

Figure 10. Qmap symbolised on main rock. Main rock is grouped by rock type.

2.5. Soils

2.5.1. Fundamental Soils Layer

Soil data is sourced from Manaaki Whenua Landcare Research and is classified according to the New Zealand Soil Classification (NZSC) and by soil series. Six soil orders are found across the Arahura catchment with a dominance of Brown soil and Podzolic soils (Table 6). Soil information contained within this layer was used to inform hydrological pathways of overland flow, deep drainage, lateral flow, artificial drainage, and the soil reduction potential classification.

Data Source: Fundamental Soil Layers by Landcare Research New Zealand (https://data.mfe.govt.nz/layer/52766-fundamental-soil-layers-new-zealand-soil-classification/)
Pre-processing: None
Output: Vector Soil order and series (Figure 11).

Table 6. Summary of soil by NZSC order and series in the Arahura catchment.

Soil Order	Soil Series	Area (ha)	Percent (%)
Brown Soils	Arahura	4201	13.6
	Ikamatua	1593	5.1
	Kaniere	2682	8.7
	Mahinipua	377	1.2
	Whitcombe	1817	5.9
Recent Soils	Harihari	1373	4.4
	Hokitika	485	1.6
Podozol	Waiuta	2088	6.7
	Hohonu	405	1.3
	McKerrow	1834	5.9
	Okarito	4367	14.1
	Otira	7194	23.2
Gley Soils	Karangarua	190	0.6
Anthropic Soils	Tail & OWork	259	0.8
Raw Soils	Alpine	345	1.1
	Bedrock	1192	3.9

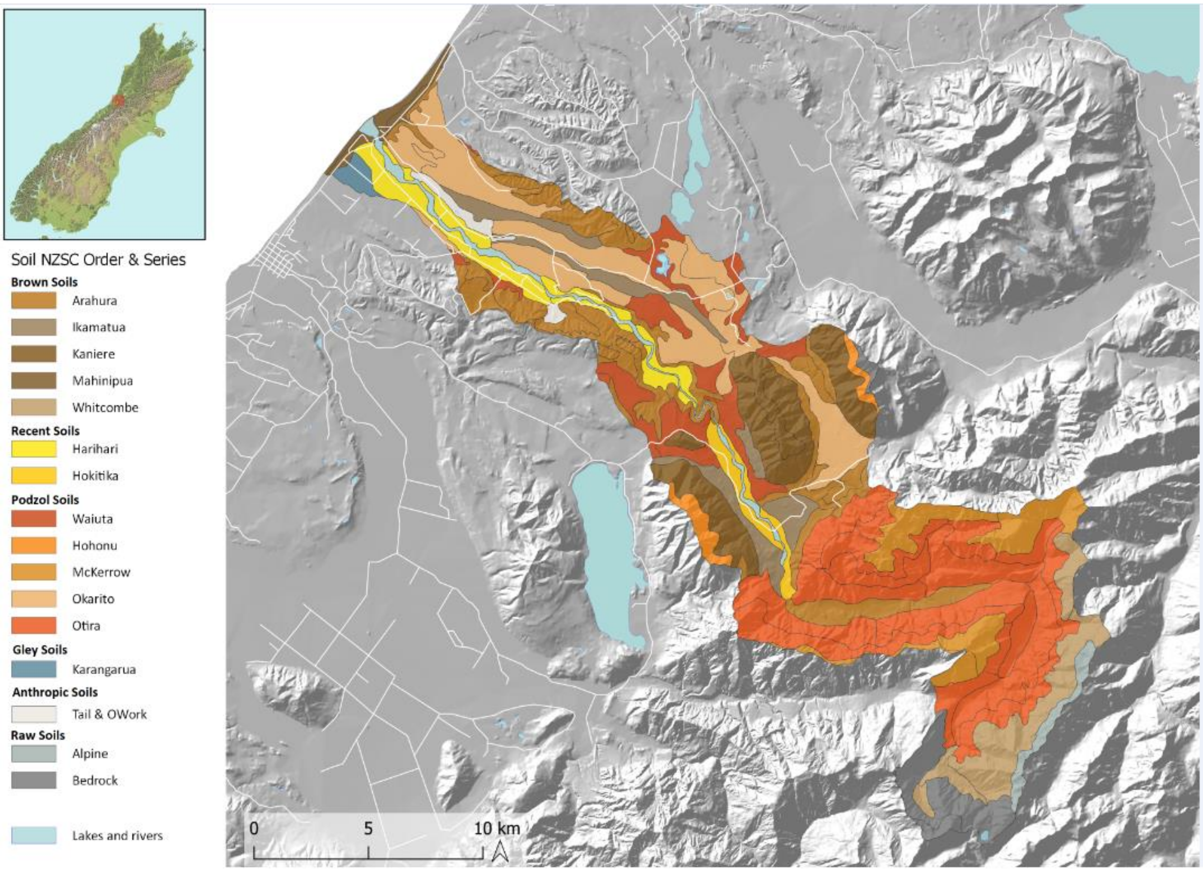

Figure 11. Soil NZSC Order and Series for the Arahura catchment. It is important to note that the existing soil map misses large peat areas, and much of the fine-scale variability in soil significant to environmental outcomes.

3. High-resolution data available for the Arahura Catchment

This section provides a stocktake of datasets that provide higher resolution outputs for the Arahura catchment. Currently, the radiometric derived relative wetness gradient and seasonality of wetness can be used alongside the existing classification to show soil hydrological variation at 50 and 30 m pixel resolution, respectively. These datasets will be integrated into the Physiographic Environment Classification in part 2 of this work programme.

3.1.1. LiDAR

LiDAR, or light detection and ranging, is a popular remote sensing method used for measuring the exact distance of an object on the earth's surface. It can be used to produce much higher resolution digital elevation models, which intern will produce better topographical and hydrological outputs. Figure 12 provides an example of the expected resolution increase between the national 8m DEM, the NASA DEM and LiDAR.

LiDAR is expected to be available for the catchment later in the year.

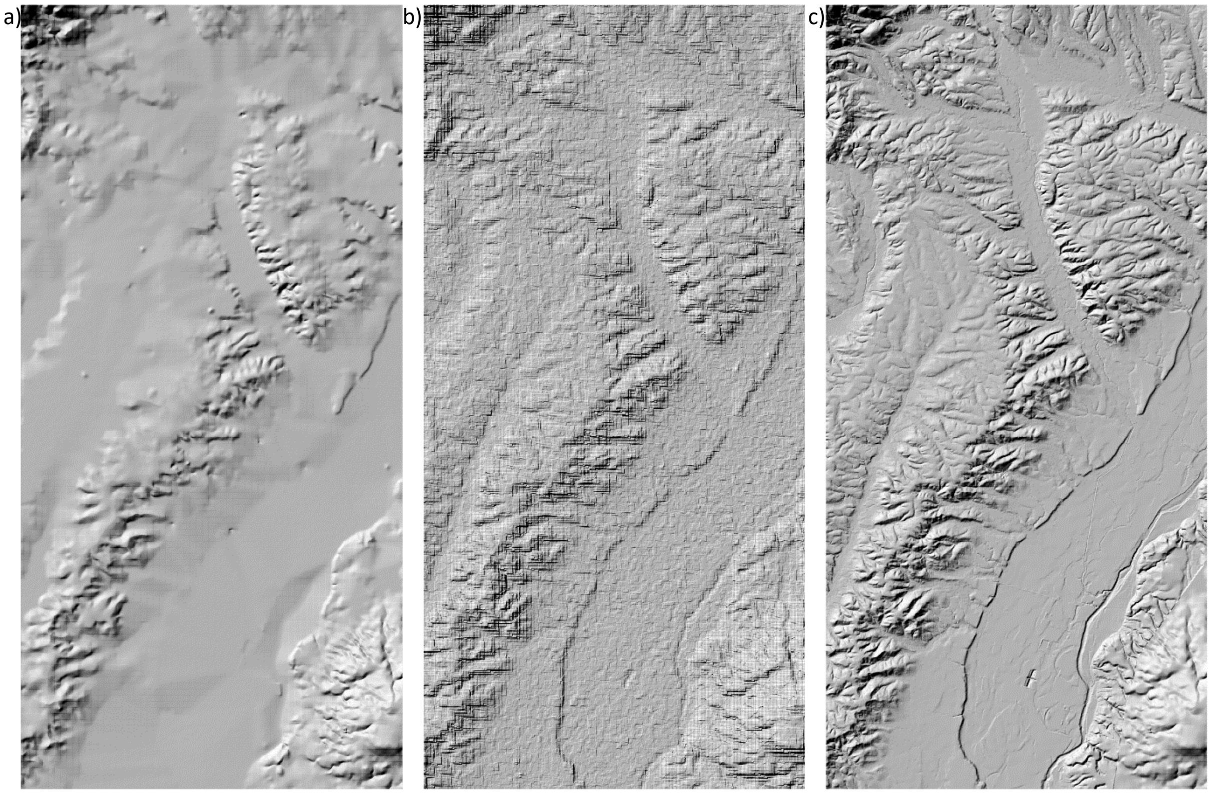

Figure 12. Example of Digital Elevation Models derived from a) National 8m, b) NASA DEM, and c) LiDAR.

3.1.2. Terrain Ruggedness Index (TRI)

Landscape stability gradients are important determinants of soil chemical and physical variation. The Terrain Ruggedness Index (TRI) has been used in various studies to understand the underlying susceptibility of the landscape to large scale mass movement and erosion (Riley et al., 1999; Guzzetti et al., 2012; Różycka et al., 2015; Rissmann et al., 2018). TRI reveals the change of slope and aspect over distances in relief, or in GIS terms, the elevation difference between adjacent cells of a Digital Elevation Model (DEM). Table 7 summarises the TRI for the Arahura catchment, providing an objective scale of the ruggedness of the terrain across the catchment.

Data Source: 27.5m DEM from NASA.
Pre-processing: Filtering by Simple Gaussian Filter
Processing: QGIS GDAL Geoprocessing tool for Terrain Ruggedness Index.
Output: Raster of slope at 27.5m resolution (Figure 13).

Table 7. Summary of proportion area corresponding with Terrain Ruggedness Index.

TRI	Area (ha)	Percent (%)
0 to 2	8384	27.5
2 to 4	2940	9.7
4 to 6	2302	7.6
6 to 8	2231	7.3
8 to 10	2383	7.8
10 to 20	10938	35.9
20 to 30	1246	4.1
30 to 40	41	0.1
40 to 50	2	0.0
Total	30467	100

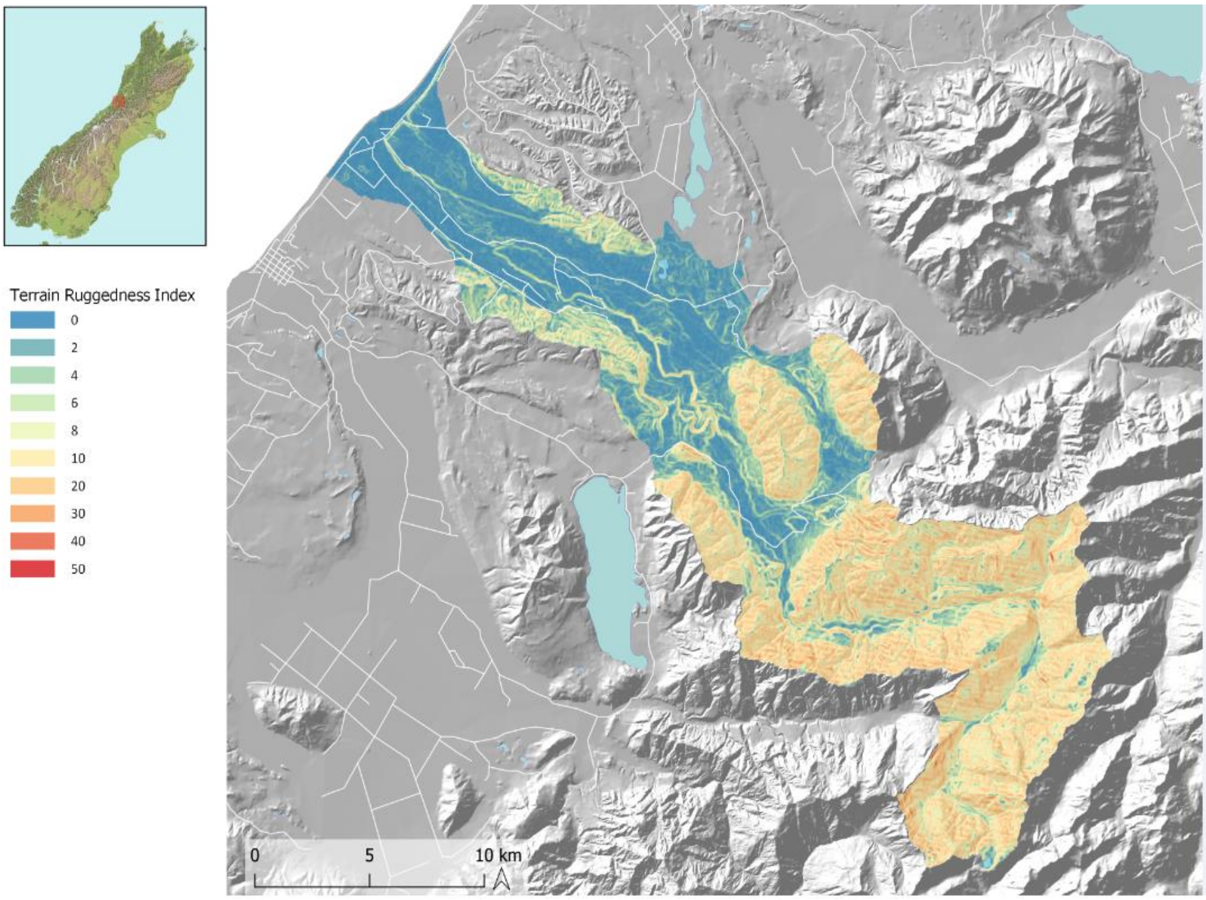

Figure 13. Terrain Ruggedness Index for the Arahura Catchment. The catchment areas with the highest TRI scores are associated with rock outcrops and avalanche areas east of the Alpine Fault.

3.1.3. Radiometric Ternary

Airborne Gamma-Ray Spectroscopy (AGRS) or 'radiometrics' survey layers provide critical information over parent material source and land surface age (and stability), thereby accounting for the soil-forming factors' parent material' and 'time'. AGRS also provides important information as to the role of the water table over the soil environment.

AGRS measures the strength of gamma-radiation emitted from naturally occurring radioisotopes by scintillation counters at the altitudes typically flown by survey aircraft (~50 - 100 m). Most of the gamma radiation emitted to the atmosphere is derived from shallow depths, with approximately 90% coming from the top 300 – 500 mm for dry material with a bulk density of 1.5 g cm^{-3} (Grasty, 1975; Wilford et al., 1997). Radiometric data is typically displayed using a red-green-blue (RGB) ternary, where red is the potassium gamma count, green is the thorium count, and blue is the uranium count (Table 8).

Table 8. Radiometric ternary colours produced by variable mixing of K, eTh and eU.

	Potassium	Thorium	Uranium
Red	High	Low	Low
Green	Low	High	Low
Blue	Low	Low	High
Cyan	Low	High	High
Magenta	High	Low	High
Yellow	High	High	Low
Black	Low	Low	Low
White	High	High	High

Data Source: New Zealand Petroleum and Minerals
Pre-processing: None
Output: Raster Ternary radiometric (Figure 14)

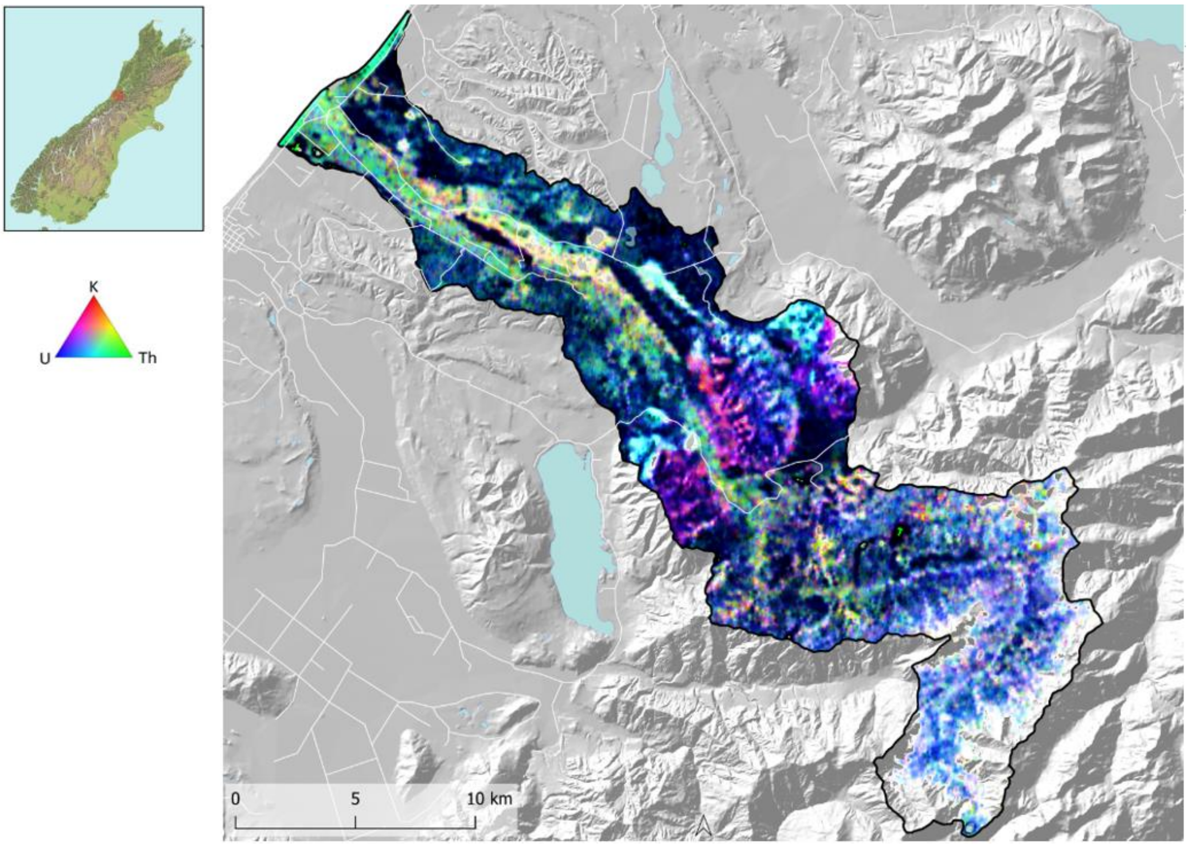

Figure 14. Ternary radiometric, Arahura catchment. Evident in this figure is significant fine-scale variation in rock and soil geochemistry which can be used to identify: 1. Areas of erosion; 2. soil drainage class; 3 wetlands, and 4. the chemical composition of rock and soil. The black areas suggest elevated water table and/or peat deposits across the lowland portion of the catchment. Areas of high terrain ruggedness that are also black are associated with ultramafic rock.

3.1.4. Relative Wetness Gradient

The Relative Wetness Gradient provides a data-driven classification of soil wetness gradients. It was created as a function of gamma-ray attenuation, remote sensors, and topographical indices to define better soil drainage class, wetland extent and seasonal variation in soil moisture. This layer is designed to be used in conjunction with the seasonality of the wetness layer (section 3.1.5). This layer provides a higher resolution depiction of soil drainage class, poorly to well-drained soils, and the presence or absence of peat deposits than provided by the existing soil maps.

Relative Wetness Gradient Classification

There are three families from the wettest, Family 1 (purple), to the driest, Family 3 (blue) along the Relative Wetness Gradient. The RWG has classes defined from wettest to driest (highest to lowest attenuation) within each of the three families. Table 9 provides a summary of the RWG by area. In Figure 15, the RWG is depicted by cool to warm colours to show the relative wetness at a family and class gradient level. The three families have the following characteristics:

- **Family 1** is comprised of RWG classes 1 – 4. There is a strong association between this family and known peat wetlands (LCDBv5 and LUCAS), QMAP geological classification of peat deposits and the New Zealand Soil Classification (NZSC) of Organic and poorly drained wetland soil types (Manaaki Whenua, 2010). Peat thickness and volumetric water content decrease as the class number increases. Also detected were formerly unidentified natural state wetland areas and areas of former peat wetlands that are now associated with productive land cover (e.g., high producing exotic pasture species). The new peat wetlands and organic soil areas identified by the RWG require ground-truthing.
- **Family 2** is comprised of RWG classes 5 – 8. This family commonly surrounds areas of Family 1 land, 'peat wetlands' and is most prevalent across low relief areas, such as valley floors draining hill and rangeland and across lowland floodplains. As such, these classes appear to represent the transition from organic (Family 1) to mixed organic-mineral soils such as Podzols and Gleyed soils (Family 2). There is a strong association between Family 2 and the NZSC of Podzol and Gley soil types (Manaaki Whenua, 2010). According to the NZSC, organic carbon and volumetric water content decrease as the class number increases. This is consistent with a decrease in gamma-ray emission as RWG class increases. Family 2 also occurs on its own, in association with shallow water tables, springs and groundwater seepage. For example, shallow water table controls over Family 2 and 3 RWG were identified at the majority of areas in the Arahura catchment.
- **Family 3** is comprised of RWG classes 9 – 11. This family is most prevalent across the valley floor, and associated floodplain deposits are dominated by imperfectly to poorly drained mineral soils that exhibit tell-tale redoximorphic features (e.g., mottling, low chroma colours etc; Manaaki Whenua, 2010). Overall, there is a strong association between this family and NZSC classification of Gley and poorly drained to imperfectly drained soil types (Manaaki Whenua, 2010). Organic carbon content and drainage class improve as the class number increases (Manaaki Whenua, 2010). The new wetland areas identified by the RWG require ground-truthing.
- **Family 4** is comprised of classes 12 – 23. This family is dominated by better-drained soils across lowland and hill country areas and by rock outcrop and raw geomorphic surfaces (bare earth) across areas of high terrain ruggedness. Across lowland areas, these soils are considered better suited for agriculture but may be associated with higher rates of nitrate leaching.

Data Source: Relative Wetness Gradient (RWG) by Land and Water Science (Rissmann et al., 2020).
Processing: See Rissmann et al., 2020 for methodology
Output: Vector Relative Wetness Gradient (Figure 15).

Table 9. Arahura Relative Wetness Gradient.

RWG	Area (ha)	Percent (%)	Classes
2	1	0.0	Organic/peat wetland
3	35	0.1	
4	302	1.0	
5	609	2.0	Hydric soils (transitional)
6	1238	4.0	
7	2708	8.8	
8	2462	8.0	
9	3668	11.9	Imperfectly drained mineral soils
10	2356	7.6	
11	3191	10.3	
12	10059	32.5	Imperfectly to well-drained mineral soils
13	2459	7.9	
14	1738	5.6	
15	96	0.3	
16	4	0.0	
23	22	0.1	
Total	30948	100	

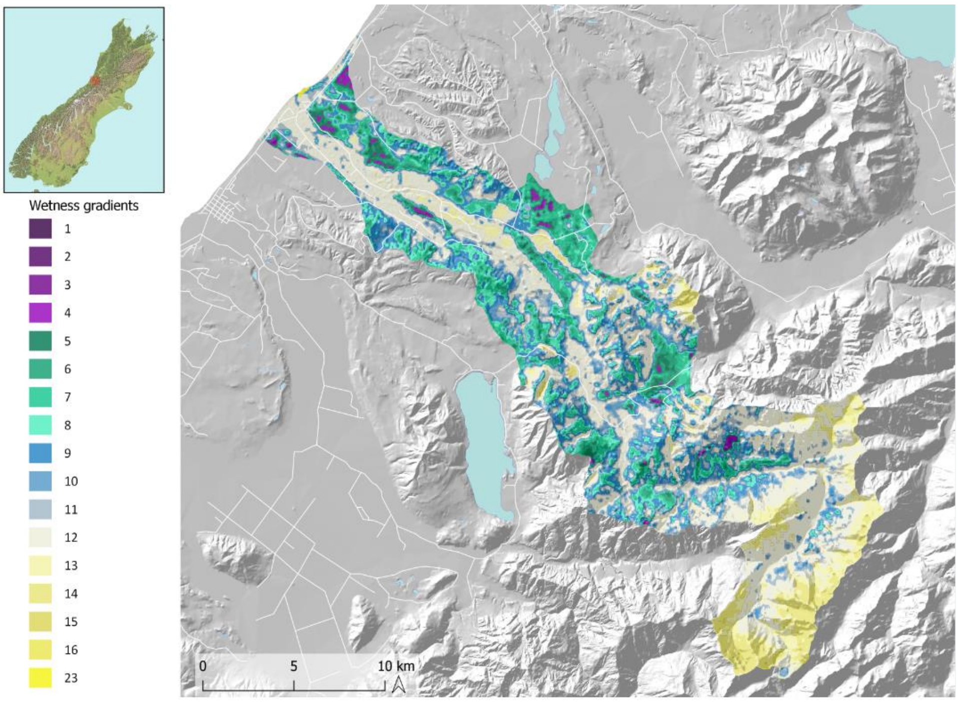

Figure 15. Relative Wetness Gradient (class 2 – 23), Arahura catchment. Yellow (classes 12 – 23) indicate better-drained soils, with classes 14+ associated with rock outcrop and bare ground across alpine areas. This map can be evolved to provide higher resolution over soil drainage class, a critical control over water quality and greenhouse gas generation.

3.1.5. Seasonality of Wetness

The seasonality of wetness (soil wetness) is calculated from European Space Agency Sentinel Imagery sourced from June – August 2018 and Dec – Feb 2018/2019 by applying a Modified Normalised Difference Wetness Index (MNDWI) applied to summer and winter composites (Equation 1).

Bands 8a and 11 of Sentinel-2 were preferred given the established use of both for developing MNDWI for cropland, wetland, and open water body assessment:

$$\text{MNDWI} = \frac{\text{B8a-B11}}{\text{B8a+B11}} \qquad \text{(Eq. 1)}$$

where the closer the index is to 1, the wetter the environment. The resultant MNDWI has a spatial resolution of 10 m. The summer MNDWI scores were subtracted from the winter MNDWI scores to produce a 'difference' layer that depicts seasonal variation in MNDWI scores as a continuum. Hierarchal clustering was then applied to the MNDWI difference layer, for which 25 natural classes were identified. Where the magnitude of difference in MNDWI scores between winter and summer were used to identify:

1. Ephemerally wet land (classes 1 – 6): wetness variation in MNDWI scores significantly influenced by surface and/or ground water table fluctuation and or stream channel migration. Changes in land cover associated with cropping and forest harvesting across productive land overlap with classes 1 - 6. For example, winter forage crops are vegetated in the summer and progressively bare during the winter.
2. Perennially wet land (classes 7 - 14): little difference between winter and summer MNDWI scores. Where the centroid value of class 11 clusters around zero, indicating minimal seasonality between winter and summer. Seasonality increases either side of class 11.
3. Intermittently wet land (classes 14 - 25): medium to large difference in winter and summer MNDWI scores (winter wet and summer dry). Where seasonality, i.e., winter wet and summer dry, increases in magnitude as the class number increases.

The seasonal wetness classification for the Arahura catchment is provided in Table 10 and Figure 16. Green (class 11) areas exhibit little to no seasonality and have the same wetness year-round. Minimal variation is observed in classes 7 - 10 and 12 - 14 and, along with Class 11 have been grouped as perennial. Natural state wetlands exhibit a greater component of perennial wetness or low seasonality relative to better-drained land. Dark blue (class 25) indicates the greatest seasonality (winter wet and summer dry) and is in areas where snowpack accumulates over the winter months. Classes 15 to 25 are grouped as intermittent. Red (class 1) exhibits the greatest seasonality (winter dry summer wet) and occurs in areas where water table fluctuates seasonally or seasonal differences in vegetation cover, such as pasture or crop to bare ground. We have classed these areas (Class 1-6) as ephemeral.

Data Source: Seasonality of wetness by Land and Water Science (Rissmann et al., 2020).
Processing: See Rissmann et al. (2020) for methodology
Output: Seasonality of Wetness MNDWI (Seasonality of Wetness MNDWI.tif) (Figure 16).

Table 10. Summary of Seasonality of Wetness MNDWI

MNDWI	Area (ha)	Percent (%)
Ephemeral		
1 to 2	4	0
3 to 4	136	0.4
5 to 6	154	0.5
Perennial		
7 to 10	14344	46.4
11	4723	15.3
12 to 14	4620	14.9
15 to 19	2403	7.8
Intermittent		
20 to 24	2662	8.6
25	1893	6.1

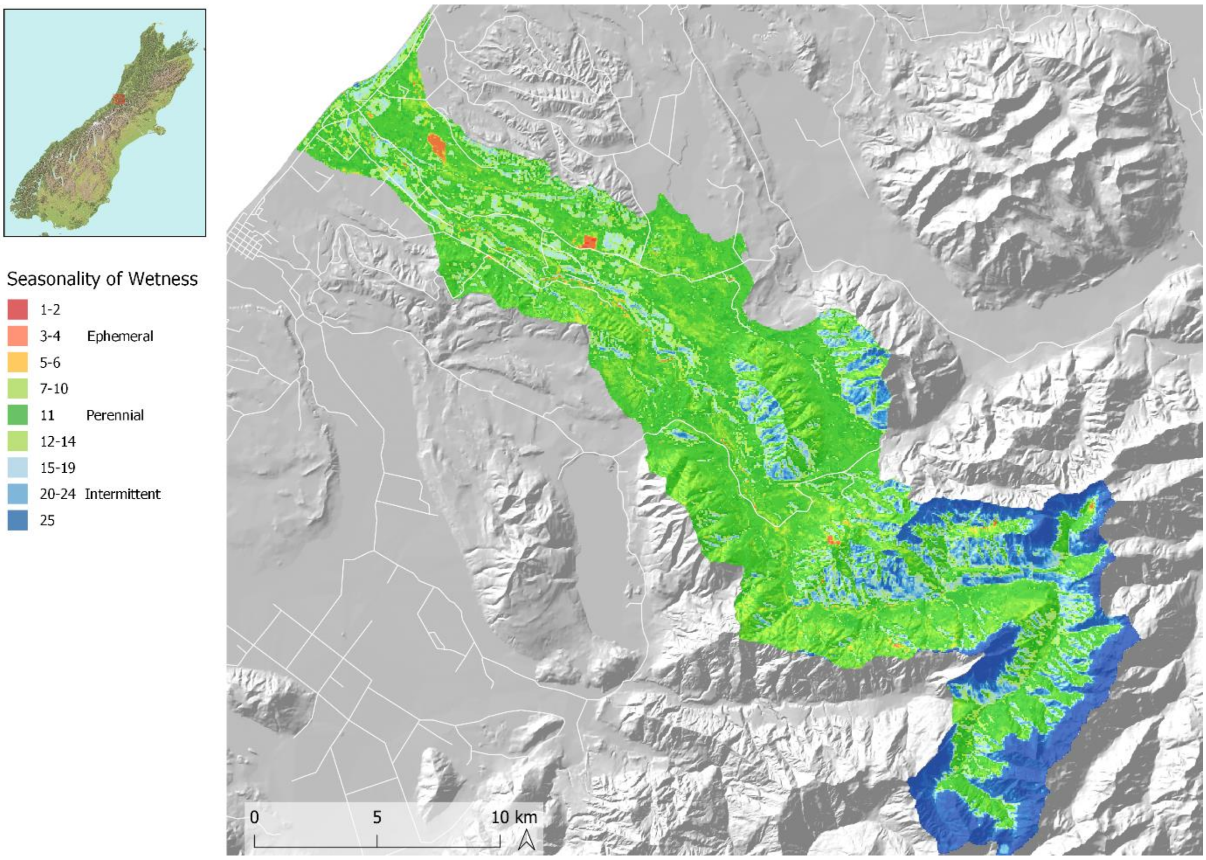

Figure 16. Seasonality of Wetness MNDWI for the Arahura catchment. Light blue areas across lowland show an association with hump and hollow and/or artificially drained land, indicating that these areas exhibit distinct seasonality i.e., winter wet and summer dry. Red patches indicate areas of land cover clearance or disturbance associated with harvesting of exotic forest or cropping. Dark blue, Alpine areas exhibit the greatest component of seasonality, snow in winter followed by bare ground in the summer. The overall green colour of the catchment suggests limited seasonality in wetness.

4. Land Use and Land Pressure

Land use is an important factor for understanding variation in water quality. Poor water quality will only occur in the presence of land use with an intensity higher than the natural ability of the landscape to attenuate or remove contaminants. This section provides a stocktake of the data available to assess land use in the Arahura catchment. Land information can be updated with input from the catchment in part 2 of this work programme.

The data compiled here comprises the land cover database (LCDB v5.0) and a tenure layer generated for the Arahura catchment by Land and Water (LWS) to categorise the land use, land cover, and land tenure.

4.1. Land tenure

A summary map of the landowner status/administrator of property within the catchment is provided in Figure 17. Mawhera Incorporation includes land owned by original ancestral owners transferred to Mawhera Incorporation and freehold land. Maori Landonline was used to categorise land that is Maori Freehold Land, typically with multiple ownership as determined by the Maori Land Court.

Data Source: NZ Primary Land Parcels https://data.linz.govt.nz/layer/50823-nz-primary-land-parcels/; NZ Property Titles including owners (restricted access); Maori Landonline https://www.maorilandonline.govt.nz/gis/map/search.htm; Department of Conservation protected areas are sourced from https://data.linz.govt.nz/layer/53564-protected-areas/

Processing: Compiled and categorised using information from the above sources
Output: Vector layer of land tenure (Figure 17).

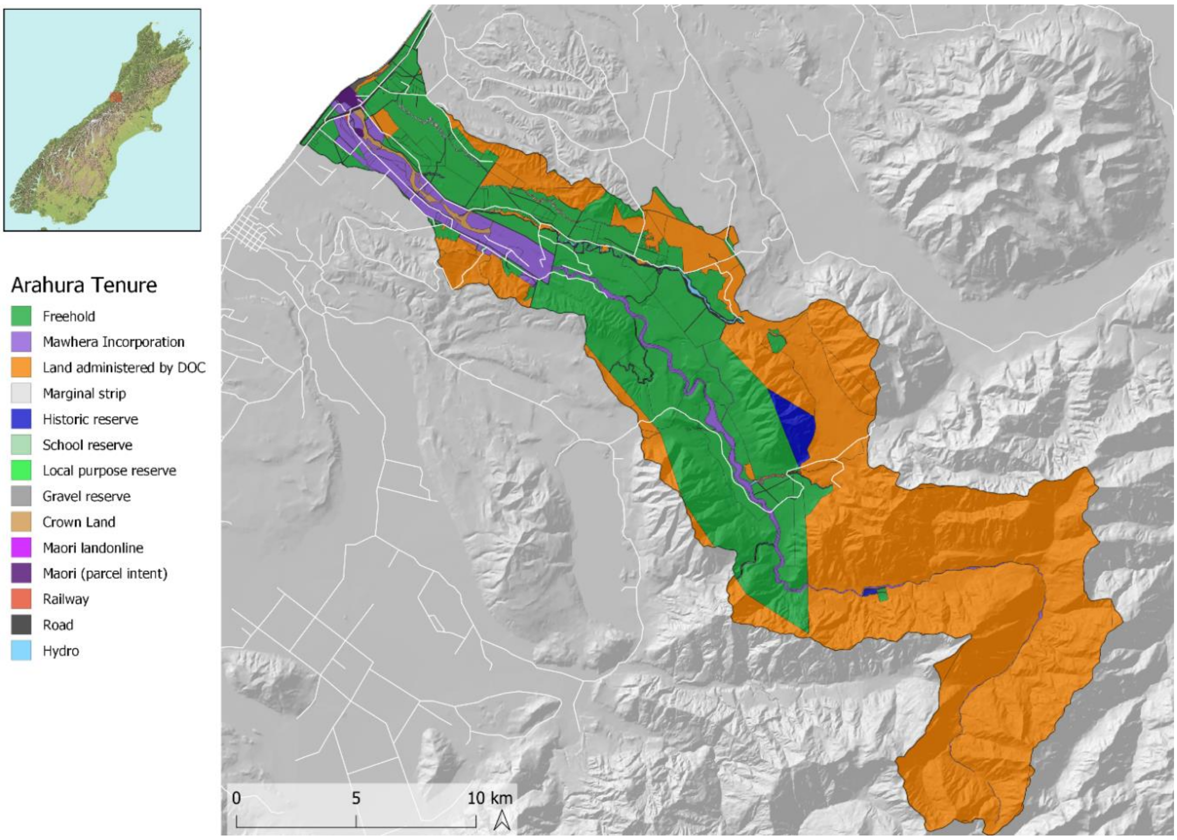

Figure 17. Land tenure in the Arahura catchment.

4.2. Land use and land cover

The West Coast Regional Council Consents Web Map was used to identify where Dairy Shed Consents had been issued to aid the identification of dairy grazing areas.

The protected areas dataset identifies land and marine environments administered by the Department of Conservation (DOC) and is protected by the Conservation, Reserves, National Parks, Marine Mammal and Marine Reserves Acts.

A summary of the land use in the Arahura catchment is provided in Table 11.

Data Source: Arahura tenure by LWS, Land Resource Information Systems (LRIS) portal hosted by Landcare Research (https://lris.scinfo.org.nz/layer/48423-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/). Department of Conservation protected areas are sourced from https://data.linz.govt.nz/layer/53564-protected-areas/.
West Coast Regional Council Consents Online maps
https://gis.westcoast.govt.nz/WestMapsViewer/?map=a167d549ecf04e58b6404e1c45afb305
Processing: Intersect Arahura Tenure with LCDB and categorise by Landuse_Type.
Output: Vector layer of land use pressure (Figure 18).

Table 11. Summary of land use and cover in the Arahura catchment.

	Area (ha)	Percent (%)
Land use		
Dairy grazing	2524	8.2
Forestry	1595	5.2
Low intensity grazing	1374	4.4
Mining	110	0.4
Roads	101	0.3
Land cover		
Indigenous forest	14887	48.1
Sub Alpine Shrubland	4017	13.0
Tall Tussock Grassland	1905	6.2
Alpine Grass/Herbfield	1252	4.0
Scrub – Manuka/ Gorse	1053	3.4
Wetland	945	3.1
Gravel or Rock	643	2.1
Open Water	338	1.1
Low producing grassland	147	0.5
Landslide	35	0.1
Permanent Snow and Ice	9	0.0
Protected area	17,801	38.5
Total	30,934	100.0

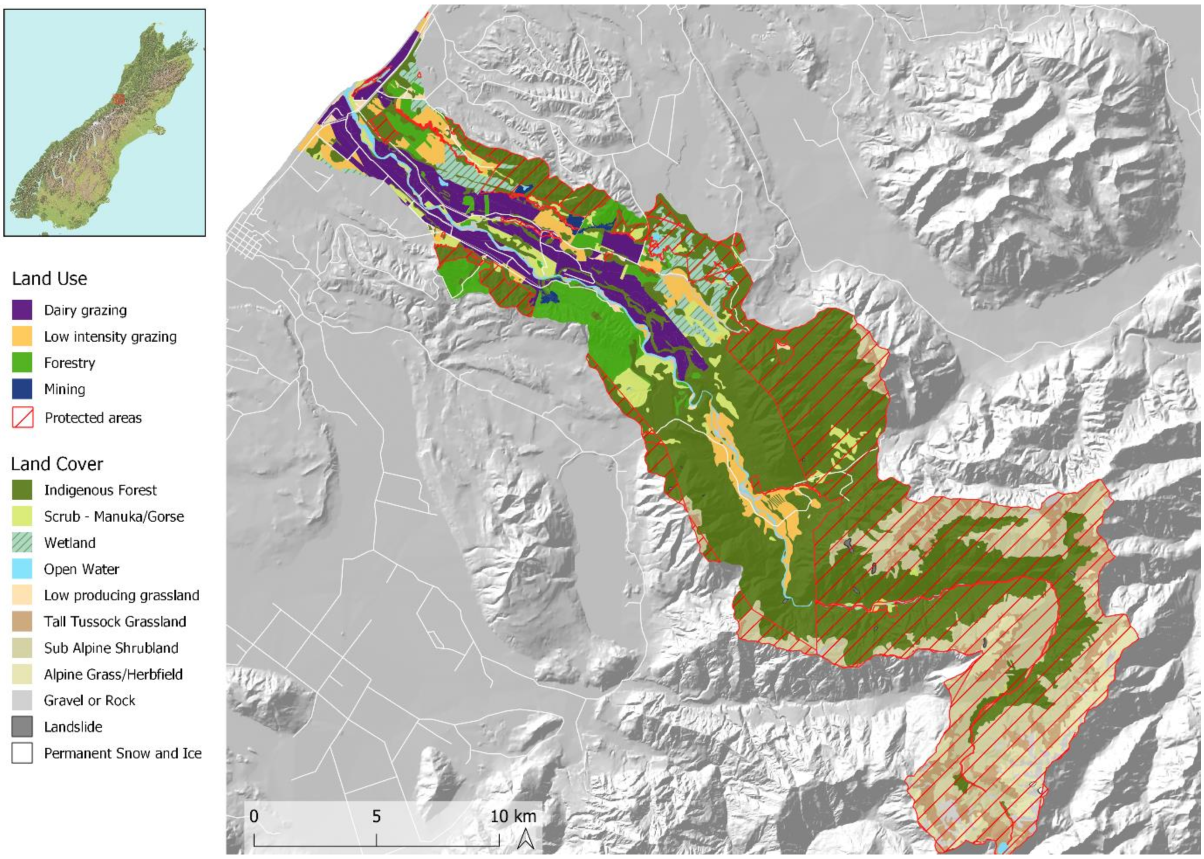

Figure 18. Land use and land cover map for the Arahura catchment. Protected areas are shown with a hatch over the land cover.

4.3. Land use pressure

Land use pressure was assigned as a high, medium, and low category based on the likely risk to water quality from the various land use and cover classes (Table 12). Conservation Estate background concentrations are all considered low as they are part of the natural load to the Arahura river catchment.

Table 12. Land use pressure according to main water quality contaminants.

	Nutrients	Sediment	Microbes
Dairy grazing	High	High (High nutrient status)	High
Forestry	Low	Low (High during harvesting)	Low
Low intensity grazing	Medium	Medium	Medium
Mining	Low	High (High sediment load)	Low
Roads	Low	Low (Unsealed roads - medium)	Low

NB. Nutrients include both nitrogen and phosphorus.

4.4. Discharge points

Discharge points ('nodes') define the location at an ephemeral, intermittent or perennial stream that leaves a farm, forestry, or mining block and enters a neighbouring property or a mainstem river. A total of 78 points were created for the Arahura catchment. These nodes identify a location in the landscape where water leaves a property and are designed to build an awareness of the role of water in transporting contaminants from land to neighbouring properties and, ultimately, a waterway. Often, the majority of discharge from any given land use occurs during a 'surface runoff event' when flowing water picks up and carries nutrients, sediment and microbes and transports them to connected waterways. The contributing area to the node point is typically called a 'capture zone', as precipitation falling on the land surface within the capture area will accumulate at the node. A more sophisticated discharge point layer will be generated when LiDAR becomes available for the catchment.

Data Source: Arahura tenure and stream network by LWS
Processing: Manual identification of intercept point between tenure and stream network
Output: Vector layer of discharge points (Figure 19)

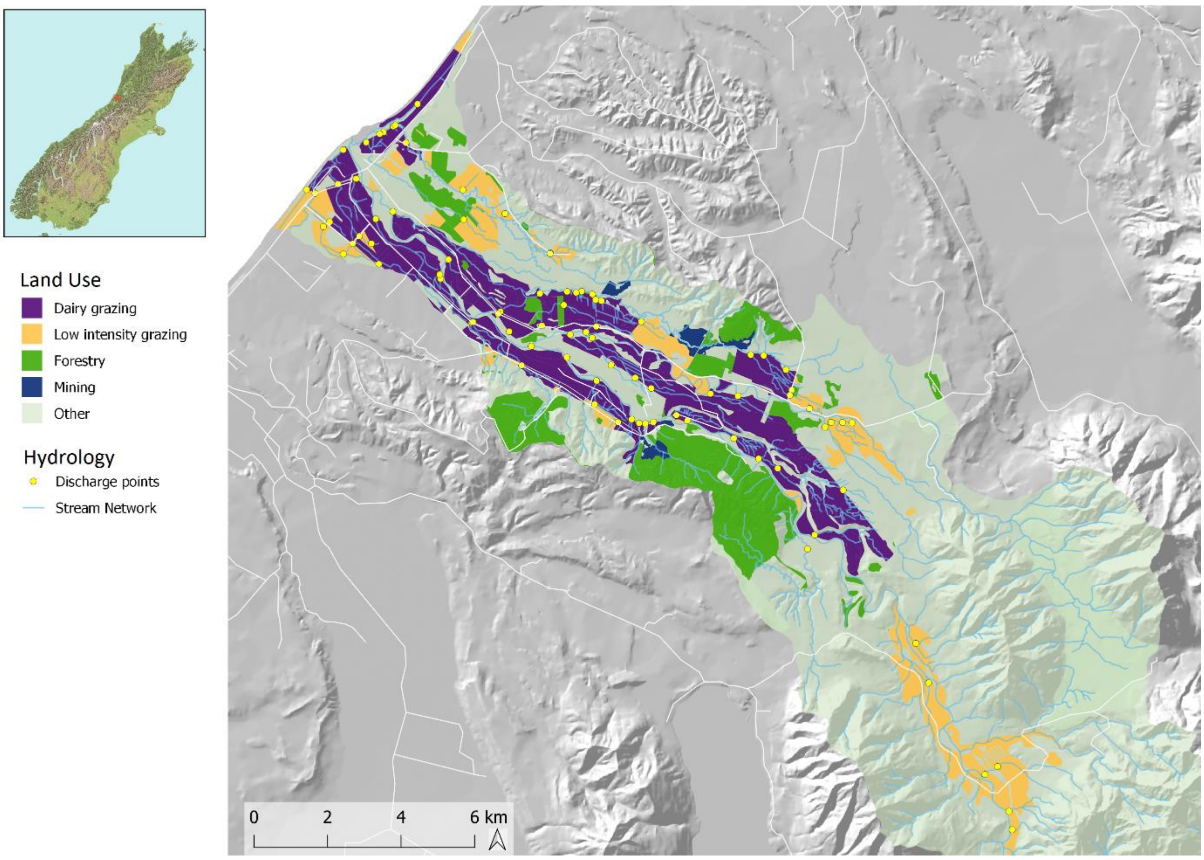

Figure 19. Discharge points from farm, forestry, or mining land use in the Arahura catchment.

5. Summary and Future Work

A stock take of the landscape, hydrological and land use setting of the Arahura Catchment has been completed. The stock take includes a summary of existing and new layers relevant to water quality. Future work in the Arahura catchment involves the incorporation of higher resolution datasets to refine the physiographic classification for the catchment. This classification will then be used to produce an integrated assessment of risk for all water quality contaminants (nitrogen, phosphorus, sediment, and microbes), including a relative pressure (or source) from the land.

A new stream network will also be developed once LiDAR is available. A Li-DAR derived hydrological network will provide an ability to identify and discriminate between ephemeral, intermittent and perennial streams and identify where water leaves a property and enters streams. This work will provide paddock scale resolution over topography, streamflow and associated flowpaths and forms a critical layer for prioritising intervention.

Appendix 1 provides a high-level summary of the Physiographic Environment classification for the Arahura Catchment. The LandscapeDNA web portal (https://landscapedna.org/) includes interactive maps, supporting science (animated videos), and mitigation information. We recommend that the web portal is used in conjunction with the new digital stream network (section 2.3.1), discharge points (4.4) and land use (4.1 – 4.3) layers. The LandscapeDNA website provides the user with a summary of the critical hydrological pathway contaminants take from land to water, how human 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 the best-suited actions to minimise losses.

Appendix 1. Physiographic Environments

1. Background to Physiographic Science

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

Water quality varies in rivers and streams due to land use and variation in landscape characteristics that govern variation in the fundamental process the control variation in water quality. For example, overland flow or runoff (a hydrological process) is more common where soils are slowly permeable and imperfectly to poorly drained (Figure 1). Where fine-textured and poorly drained soils dominate a farm or a catchment, the risk of runoff and associated sediment, 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. Other chemical processes also determine the removal (attenuation) of nitrogen and the solubility and mobility of dissolved phosphorus. For example, if an aquifer is comprised of materials that favour the natural removal of nitrate (denitrification), then leached nitrate is typically removed before reaching the stream (Figure 2). Atmospheric, hydrological, redox (oxidation-reduction reactions), physical and chemical weathering processes are all influenced by landscape characteristics, which interact with land use to determine the type and severity of water quality outcomes. 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 commonly have different water quality issues.

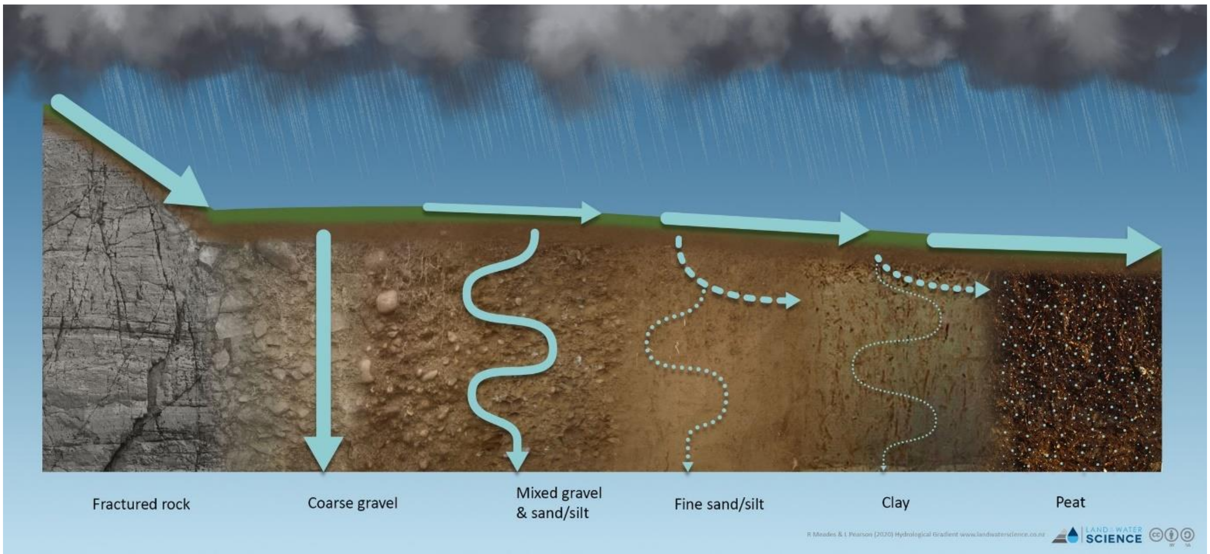

Figure A. 1. Simplified gradient depicting the different hydrological pathway (response) water takes as slope, soil permeability, and drainage class vary.

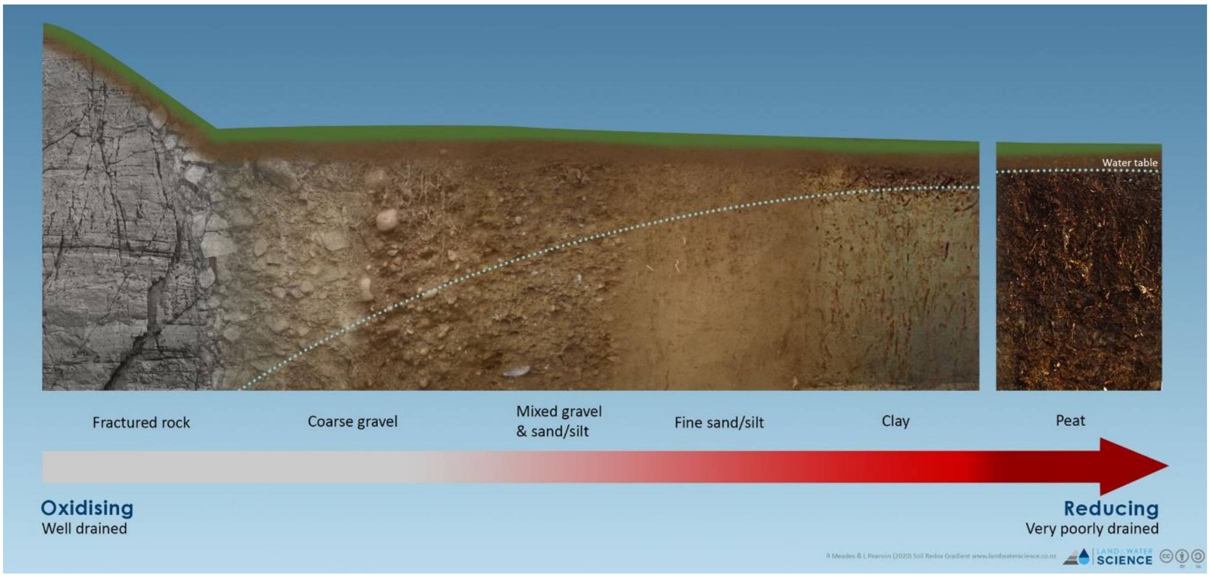

Figure A. 2. Simplified gradient depicting the redox gradients in soil. Reducing environments have a high ability to remove nitrogen, whilst oxidising environments have very little.

To decipher the relationship between landscape characteristics and key processes, physiographic science utilises water chemical and isotopic data to trace the water's journey back through the landscape. National and regional water datasets (hydrochemical and quality) are used, in conjunction with existing geospatial layers to map and numerically model the processes that control the spatial variability of water quality (Rissmann et al., 2019). The method brings together data for climate, topography, geology, soils, and hydrological controls with analytical chemistry at a national scale to produce a water quality specific classification 'Physiographic Environments of New Zealand'.

The uniqueness of the classification is associated with the integration and synthesis of multiple regional and national geospatial information and monitoring datasets (such as water quality data) to provide the only truly integrated picture of landscape factors that govern water quality outcomes across NZ. Physiographic maps enable the relative importance or 'risk' of the various landscape factors (e.g. based on soil type, geology, topography) over water quality outcomes for nitrogen and phosphorus species, sediment, and microbial (*E.coli)* contaminants to be identified.

Physiographic science results in an increased understanding of the landscape processes, which can be used to best guide the implementation of management practices relevant to the characteristics of a farm or catchment. Contextual science forms the basis for more effective and least cost farm decision making, lowering the overall risk of non-compliance and poor investment.

See https://landscapedna.org/ for further information on the Physiographic Environment classification, interactive maps, and actions to help improve water quality efforts.

2. Physiographic Environments of New Zealand

2.1 Physiographic Stocktake

The dominant processes that control water quality in the landscape, other than land use, are hydrology, the chemical process of redox, and weathering. To understand the main controls for any point in the landscape, we first look at the hydrology at a broad scale (source and volume) and fine-scale (flow pathways). Secondly, any potential chemical reactions that may take place along the hydrological pathway. Weathering is an important control over sediment supply. This helps us to understand the inherent susceptibility for contaminant loss from a landscape setting and classify the land into Physiographic Environments.

Underpinning the Physiographic Environments classification are a number of layers, termed process attribute gradients (PAG), representing the key processes that control the variation in water quality (Table A1). These datasets are derived from those identified in the landscape stocktake (Appendix 1) and are presented in the following section for the Arahura catchment.

Table A 1. Summary of the 16 national-scale process-attribute gradients used to classify Physiographic Environments. Relevant datasets and their scale are also shown. Grey highlights the maps included in this stocktake.

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	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)	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 neutralisation capacity	Soil surveys (1:50,000); geochemical baseline survey (8 km^2)	Soil pH, cation exchange capacity
	GANC	Geological acid neutralisation 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	Base regolith strength	Geological surveys (1:50,000 - 1:250,000)	Rock type and strength

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

2.1.2 Hydrological Processes

Water is the mechanism that transports all contaminants from the land. Therefore, the recharge domain and the pathways that water takes from the land to a receiving environment are critical to understanding what contaminants are likely to be mobilised and how to minimise losses. The climate and seasonality of precipitation also plays a critical role as to when contaminants are lost during the year.

Recharge Domain

Recharge domain identifies the water source in the waterway (Figure A3). This also informs the dilution potential and aquifer potential at a location. Dilution is the reduction in contaminant concentration from the mixing of dilute water. Aquifer potential is identifying if there is likely to be a groundwater source and contribution to the waterway.

Alpine: High altitude areas above the tree line. Very high dilution potential. Aquifer potential is very low. Precipitation is stored as snow and ice over the winter months, and when melted, water forms the headwaters of waterways.

Subalpine: Bedrock that connects the alpine domain to hill country. High dilution potential. Minimal aquifer potential. Precipitation is stored as snow and ice over the winter months, and when melted, water forms the headwaters of waterways.

Bedrock hill: Sloping land with shallow bedrock, moderate dilution potential and low aquifer potential (except in areas with fractured rock).

Bedrock low relief: Flatter land with shallow bedrock, moderate dilution potential and low aquifer potential (except in areas with fractured rock). Not present in the catchment.

Mixed: Mixed water source from alpine and subalpine, bedrock, and lowland unconsolidated areas. This area has a high dilution potential due the connectivity with alpine derived water. Unconsolidated material is likely to host local aquifers which contribute groundwater to the stream.

Unconsolidated hill: Sloping land with unconsolidated materials, moderate dilution potential and moderate aquifer potential (higher in areas overlying fractured rock).

Unconsolidated: Typically located in lowland areas. Water is sourced from local rainfall. Dilution potential is low, and aquifer potential is high. Permeability of the unconsolidated material controls whether groundwater is abstractable.

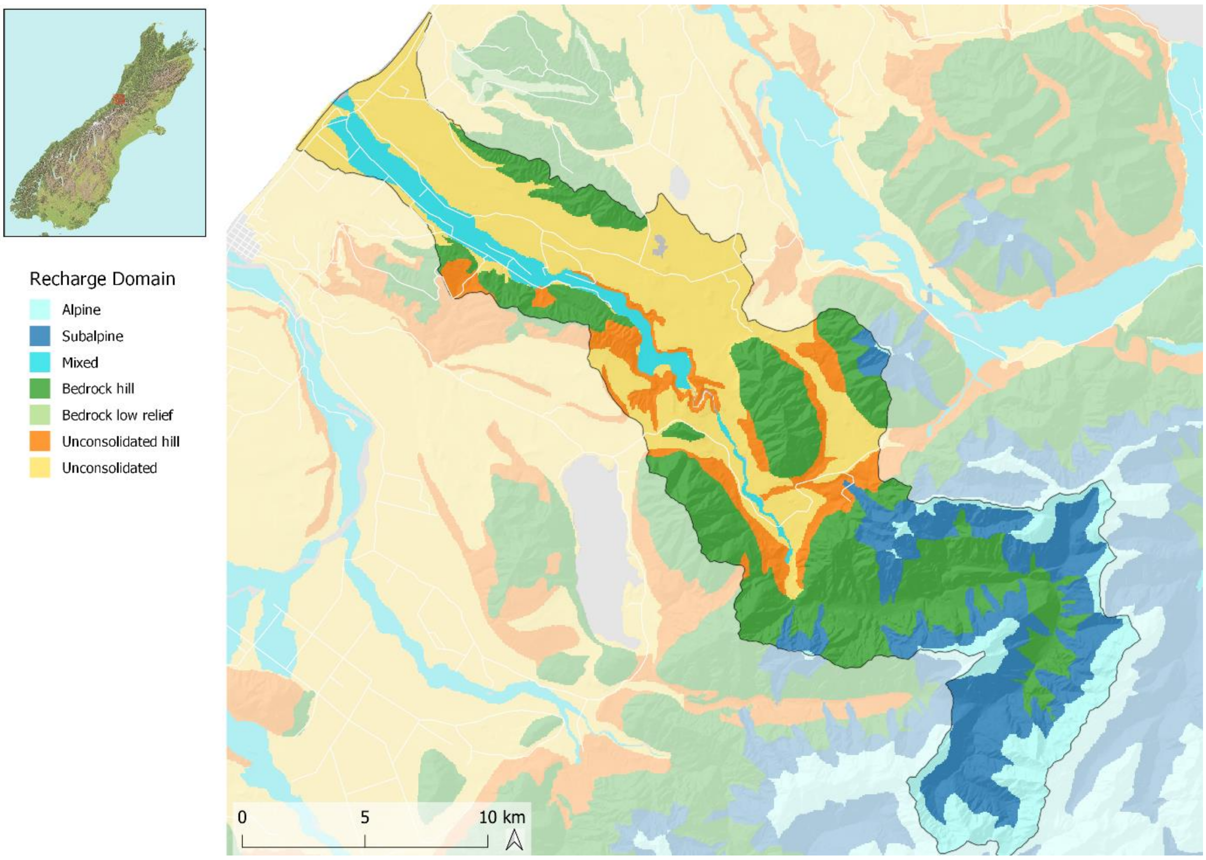

Figure A. 3. Recharge domain for the Arahura catchment.

Flow pathways

The main hydrological flow pathways that water takes to drain from the land are:

- **Deep drainage** through the soil zone into the underlying aquifer (groundwater)
- **Lateral drainage** occurs through the soil along the contact with shallow bedrock or slowly permeable layers in the soil zone
- **Artificial drainage** is used to improve drainage where soils have either poor drainage or slow permeability in agricultural areas
- **Overland flow** via surface runoff
- **Natural bypass flow** when high clay soils are dry and cracked (not present in the Arahura catchment)

Figure A4. shows a conceptual diagram of these pathways.

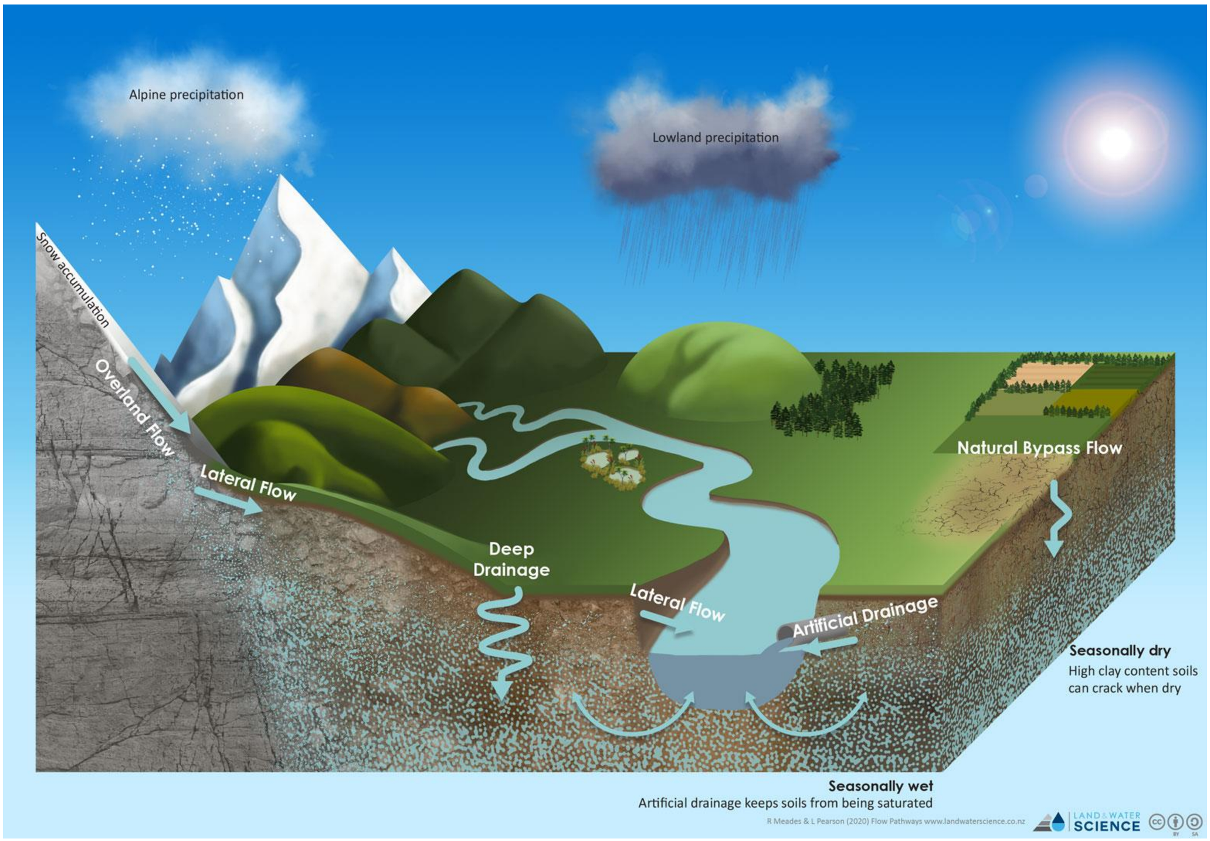

Figure A. 4. Diagram of the main flow pathways water takes to enter a waterway.

Overland Flow

Overland flow (surficial runoff) is the contaminant pathway that has highest the risk to water quality. This is because there is minimal interaction with the soil zone or geology. For this risk to be realised it requires a contaminant source.

Overland flow is estimated by combining two landscape factors – a soil hydrologic index and a slope index. It is mapped for a soil polygon area at 1:50 000 scale and expressed as a percentage of the annual rainfall. The soil index shows how likely runoff will occur due to soil properties such as texture, drainage, permeability, and slaking and dispersion (breakdown of the soil aggregate by water) (Figure A5). The slope index ranks the risk due to slope. Slopes greater than 35 degrees have a very high likelihood of runoff occurring.

In lowland areas with flat to undulating relief, the maximum runoff estimated is 12%. If these areas are used for intensive farming practices, the risk to water quality from overland flow is considered very high. On rolling to hill country, the likelihood of overland flow occurring is higher. Intensive farming practices should be kept to a minimum. 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.

The overland flow risk expressed as a percentage of rainfall is shown in Figure 6 for the Arahura catchment.

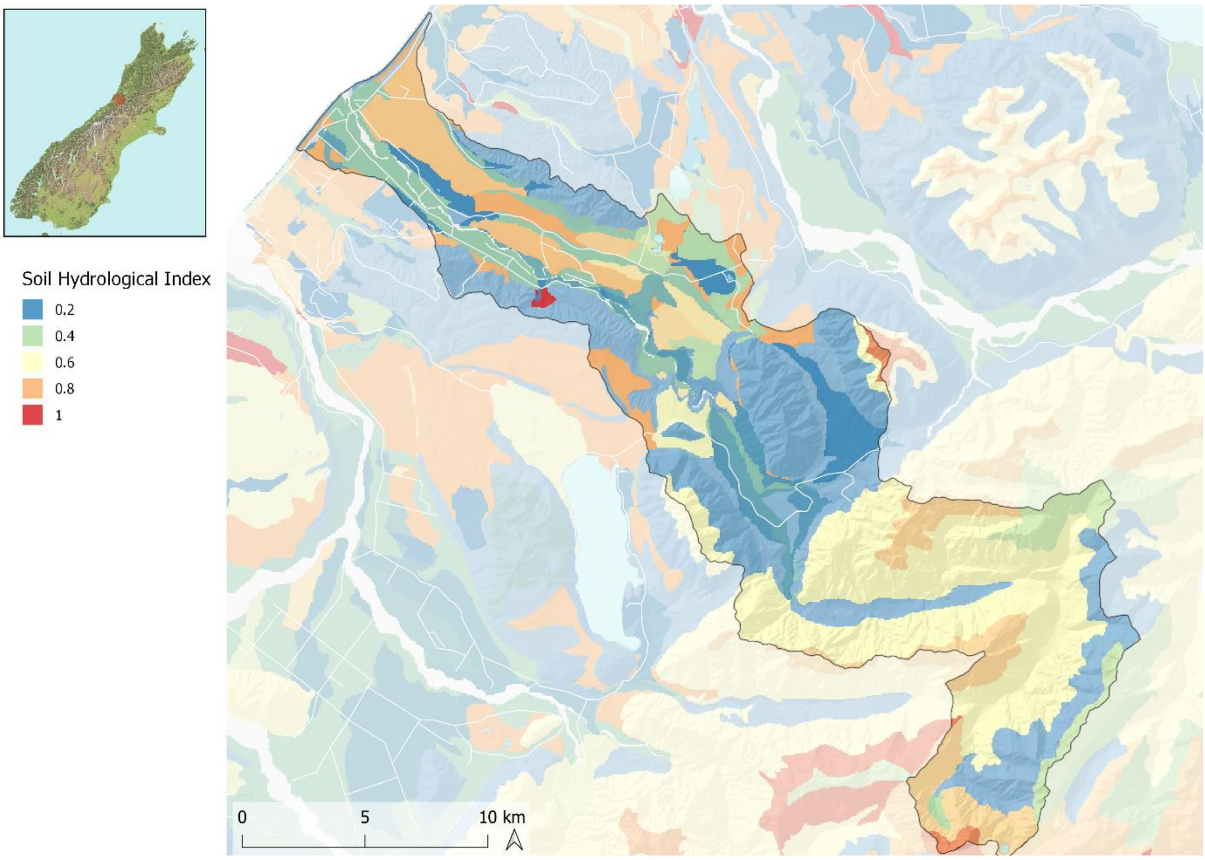

Figure A. 5. Soil hydrological index for the Arahura catchment. The index represents increasing limitations for water infiltrating the soil with less infiltration occurring the higher the index value.

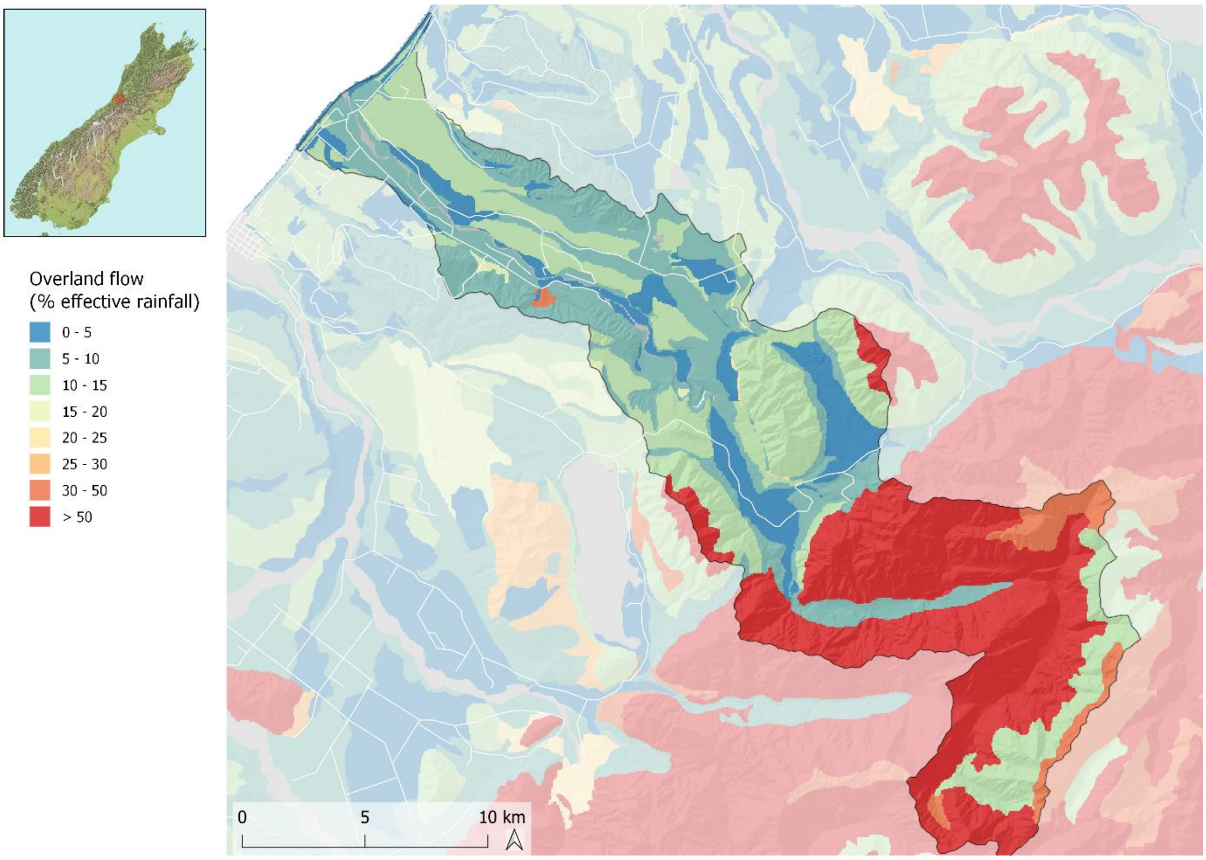

Figure A. 6. Overland flow as a percentage of annual rainfall for the Arahura catchment.

Deep Drainage

Deep drainage occurs where water can infiltrate downward through the soil profile (Figure A7). Deep drainage or groundwater recharge is the primary mechanism water enters an underlying aquifer. It is mapped for a soil polygon area at 1:50 000 scale.

Deep drainage is the primary pathway for nitrate-nitrogen to be loss from the farm system. Deep drainage is highest in areas with well drained soils that have a moderate to rapid permeability. As the drainage becomes more impeded or slowly permeable, we expect to see more lateral flow. Deep drainage is shown in Figure A7 for the Arahura catchment.

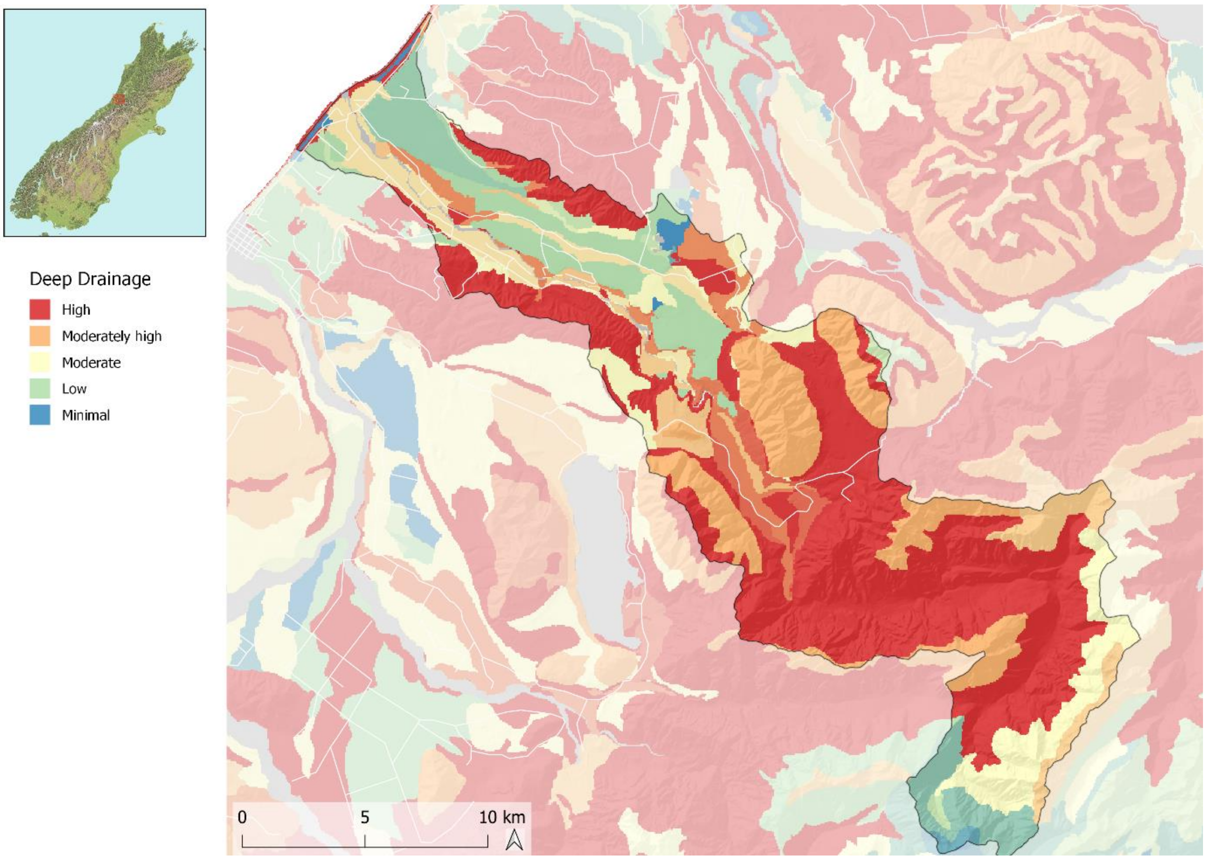

Figure A. 7. Deep drainage the Arahura catchment. Note deep drainage does not account for soil depth therefore, areas with shallow soils are assessed the same as deep soils. The inverse of this map represents lateral drainage.

Lateral Flow

Lateral flow is the drainage of water laterally through the soil profile. It occurs in areas where slowly permeable soil layers prevent the drainage of water vertically. Lateral flow is common in areas where there is shallow bedrock, such as in hill country. We often see seeps and springs occurring 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. Lateral flow is the inverse of deep drainage and is high, where deep drainage is low (Figure A7).

Contaminants transported in lateral flow 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 reactive phosphorus.

Artificial Drainage

Artificial drainage speeds up the lateral flow through the soil. It reduces the moisture in soil and 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 to lower the water table. Open ditches in conjunction with subsurface drainage are used to improve drainage through poorly drained soil. Figure A8 shows the likely artificial drainage density within the Arahura catchment.

Artificial drainage is mapped for a soil polygon area at 1:50 000 scale. It incorporates data from soil maps, topography, and land cover. Artificial drainage is unlikely to be present in areas of high deep drainage, where there are slopes greater than 12 degrees, and areas not under agricultural production.

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 reactive phosphorus. Subsurface artificial drainage can change the redox condition in reducing areas by increasing the amount of oxygen in the soil resulting in the soil acting like an oxidising setting.

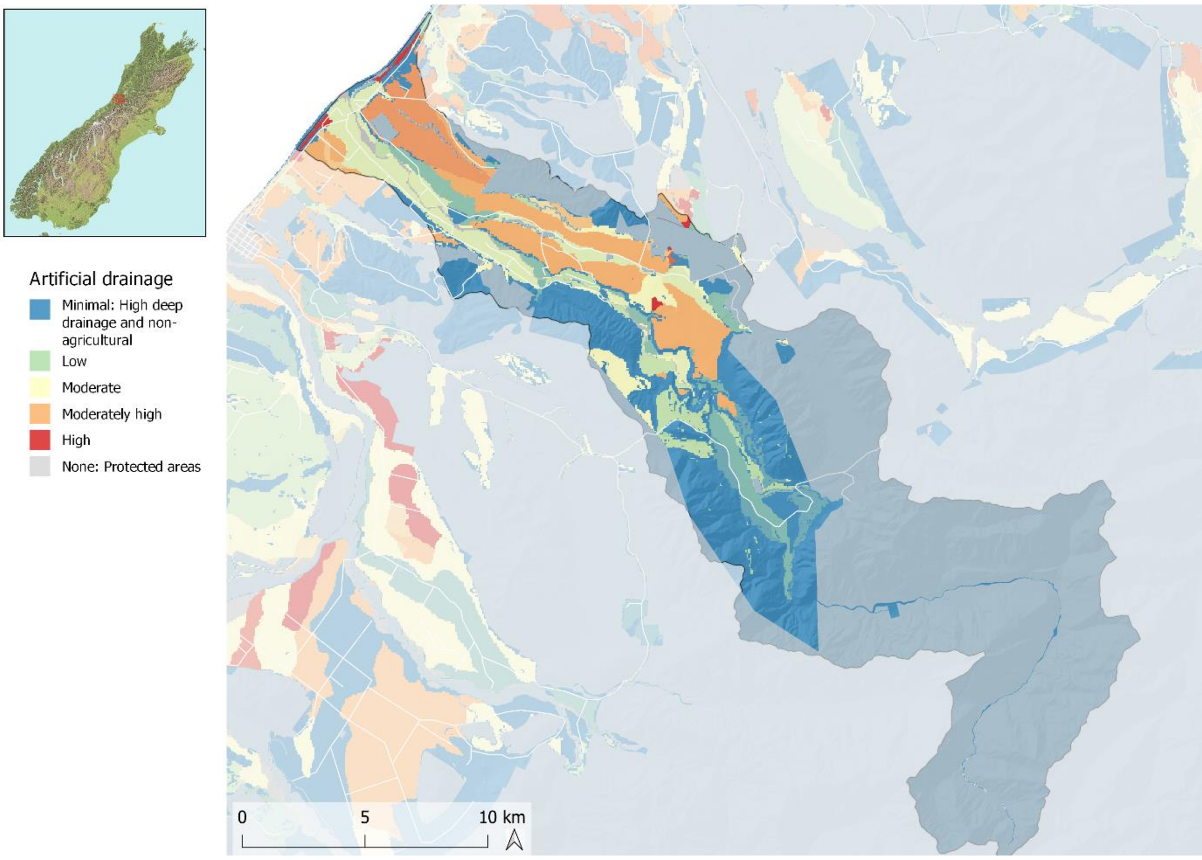

Figure A.8. Artificial drainage the Arahura catchment.

2.1.2. Redox Processes

The physical properties of soil and geology can be used to explain biogeochemical processes occurring in the landscape, as they are important for the oxidation-reduction (**redox)** process. In basic terms, the redox state is characterised as the presence of oxygen (oxic) or absence (anoxic) of oxygen. However, 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 (Figure A9). Typically, well-drained soils are characterised as oxidising, while poorly drained soils are characterised as reducing.

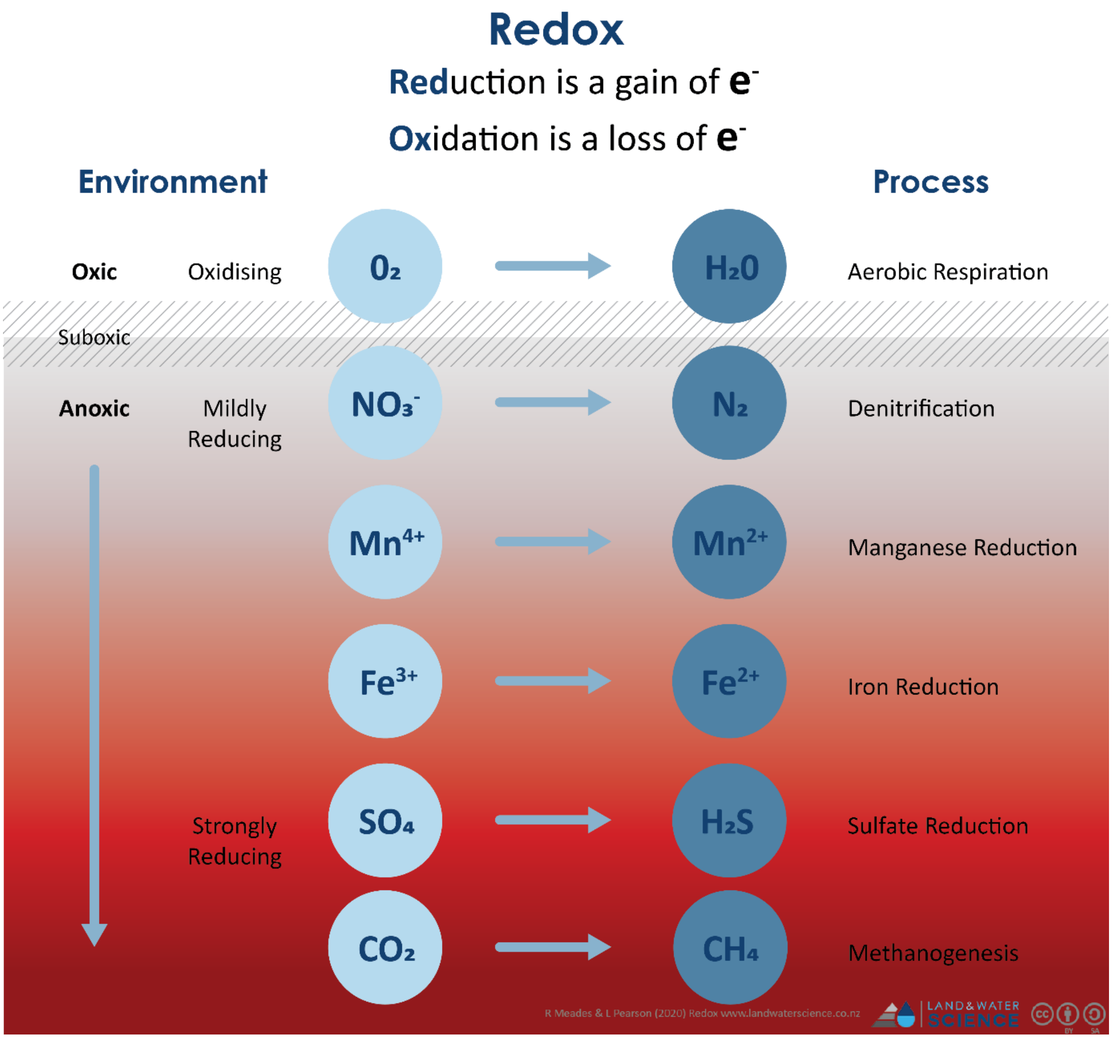

Figure A.9. Example of some commonly occurring redox processes in the environment.

Redox is important to a range of environmental concerns, including low dissolved oxygen in surface waters, where leached nitrate is likely to be removed by denitrification, where phosphorus is likely to be leached and/or be more mobile within soils and aquifers. This information also 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.

Oxidising soils and geology have a low abundance of electron donors and low reduction potential which means they are less reactive. 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).

Organic carbon has a high abundance of electron donors and, therefore, a high reduction potential under anoxic conditions (no oxygen). Any nitrate present in organic soils, such as peat will likely be denitrified to nitrogen gas.

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.

Soil Reduction Potential

Soil redox potential is shown for the Arahura catchment in Figure A10. It is mapped for a soil polygon area at 1:50 000 scale.

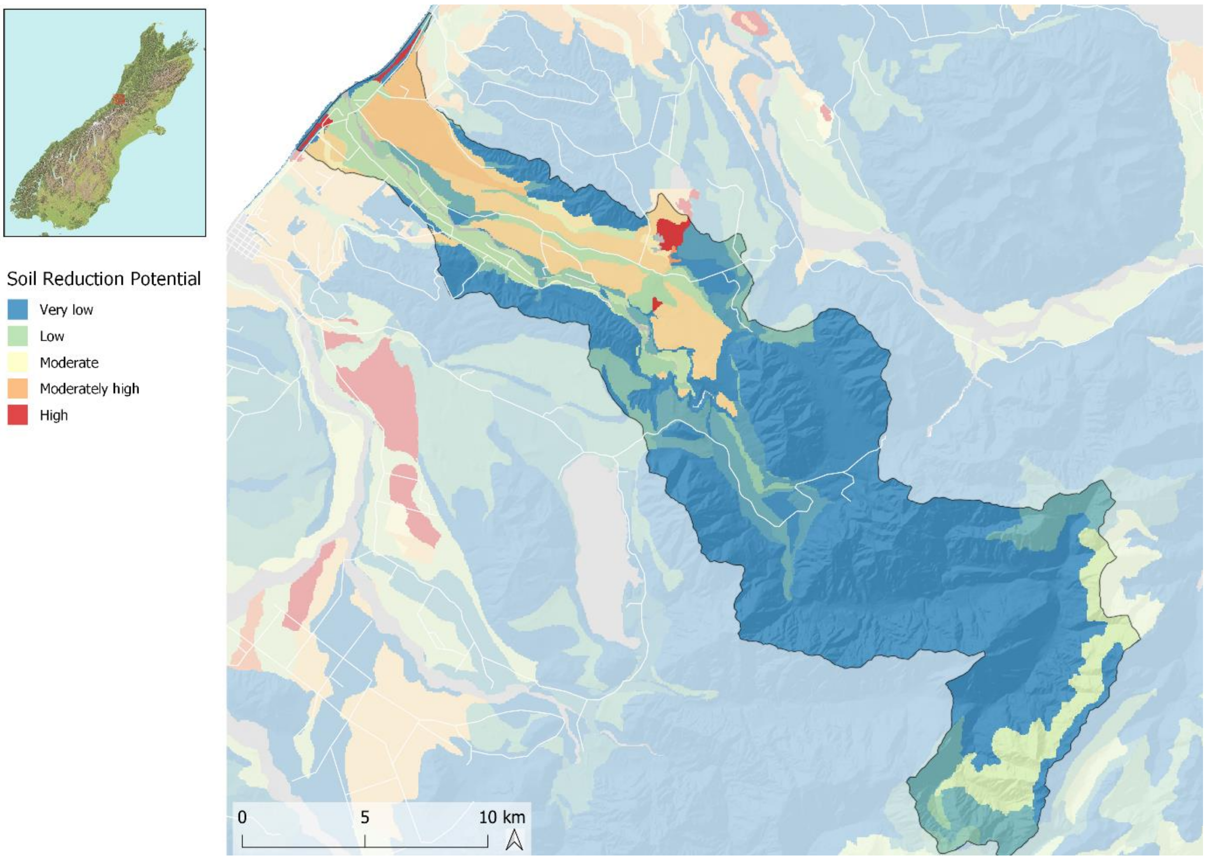

Figure A. 10. Soil reduction potential in the Arahura catchment.

Geological Reduction Potential

Geological reduction potential is shown for the Arahura catchment in Figure A11. It is mapped for a geological polygon at 1:250,000 scale. Geological reduction potential is most important in areas with a high aquifer potential, as indicated by the unconsolidated class in the recharge domain (Figure A3) and shallow water table depth (section 2.3.3). As there is low carbon content in the rocks present in the catchment, the reduction potential is naturally low.

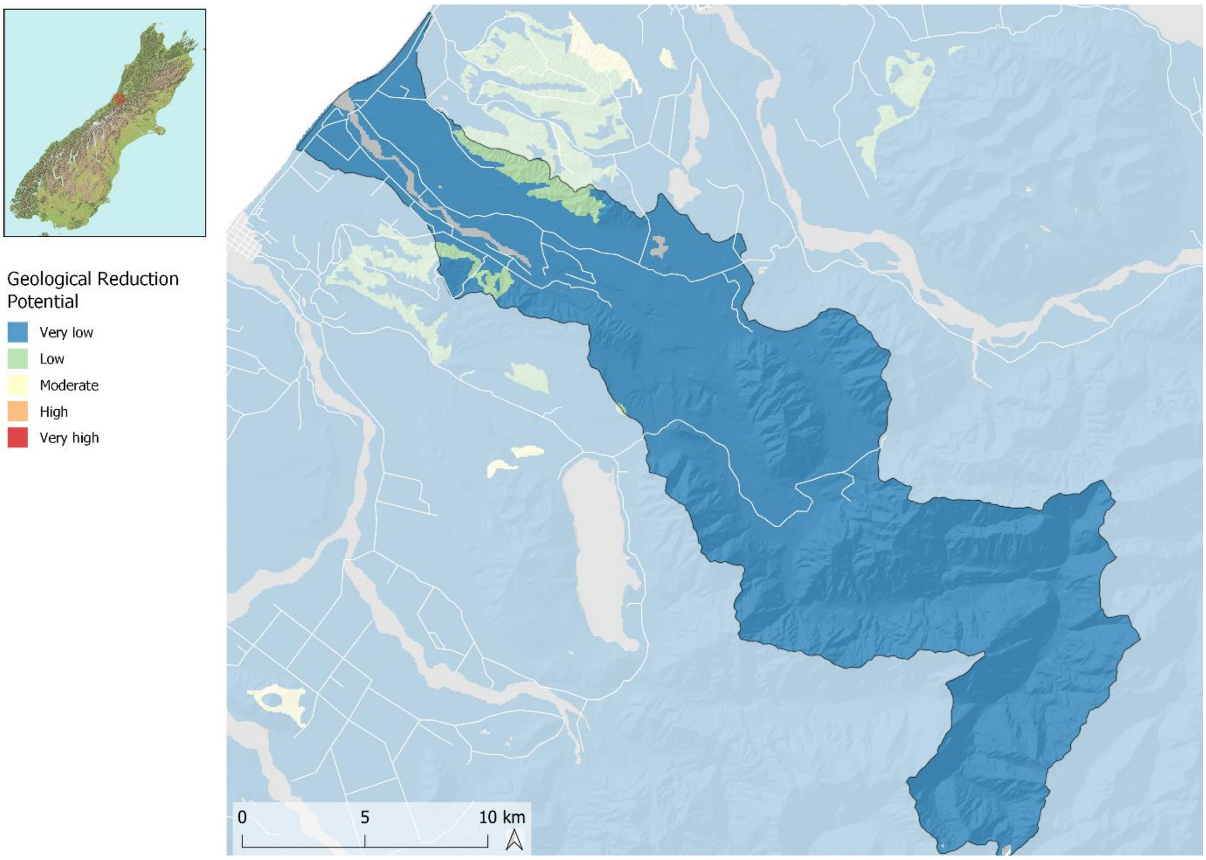

Figure A. 11. Geological reduction potential in the Arahura catchment.

2.1.3. Physical Weathering Process

Rock strength and cohesion is an important factor governing sediment supply to stream. Areas with weaker lithologies (i.e. unconsolidated material or weak sedimentary) are more susceptible to sediment loss. Surficial geological material is shown for the Arahura catchment in Figure A12. It is mapped at soil polygon scale using data from the New Zealand Land Resource Inventory, held by Manaaki Whenua Landcare Research.

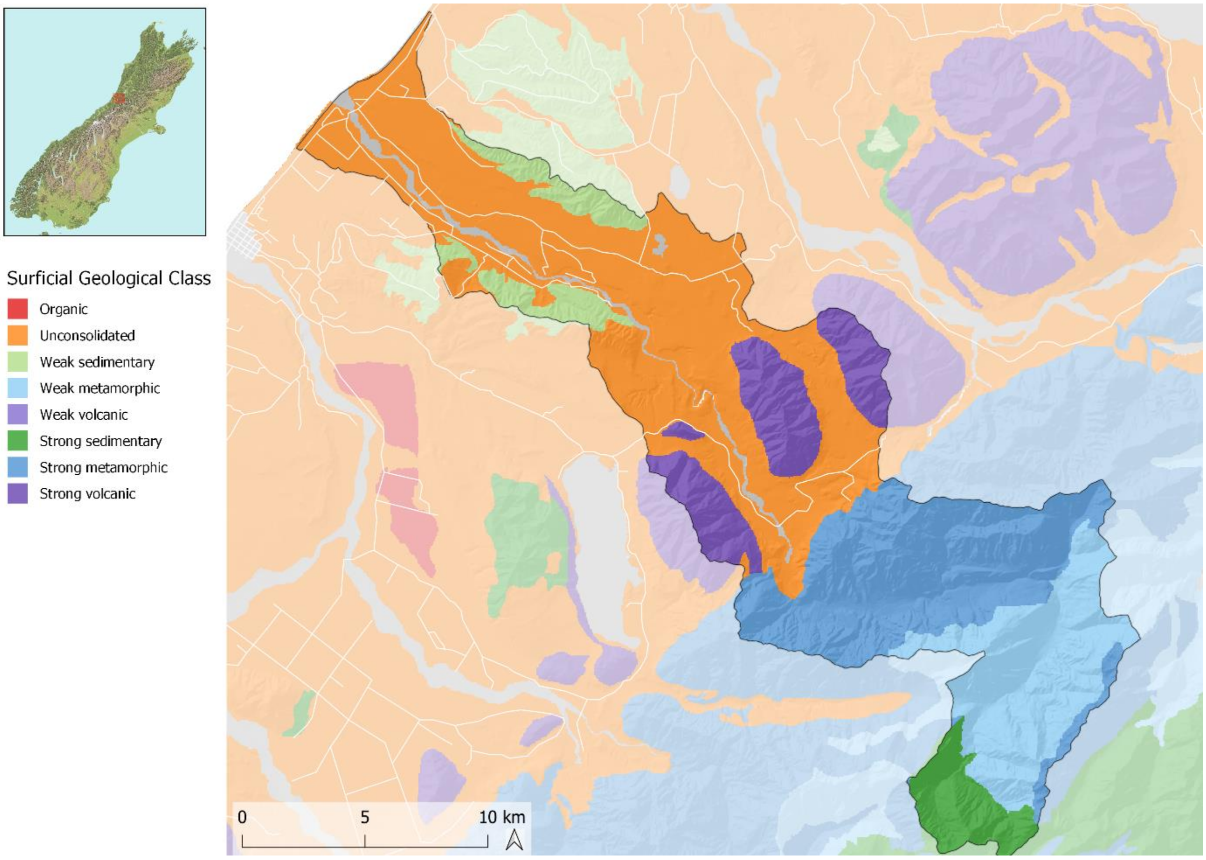

Figure A. 12. Surficial geological class.

2.2. Physiographic Environments Classification

Areas that have similar characteristics and resultant water quality controls have been classified into Physiographic Environments. The classification is hierarchical utilising a family tree to provide more resolution over water source and hydrological response, dilution, filtration and absorption, and attenuation potential of water quality contaminants within each broad family environment. These environments each have a defining set of landscape characteristics that affect water quality in a manner that is predictable. Interactive maps of the Physiographic Environments and underlying process layers are available online at https://landscapedna.org/maps/.

Animated videos for each environment are also available through the website https://landscapedna.org/videos/. These videos take you through 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 the best-suited actions to minimise losses.

2.1.1. Family Class

The summary descriptions provided here are for those environments found within the Arahura catchment (Figure A13 and Table A2). This 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.

Table A13: Summary of physiographic of environment at family scale in the Arahura catchment.

PENZ	Area (ha)	Percent (%)
Alpine	2869	9.3
Bedrock (Strong)	9897	32.2
Bedrock (Weak)	4859	15.8
Riverine	1607	5.2
Oxidising soil & aquifer	7440	24.2
Reducing soil & oxidising aquifer	4025	13.1
Total	30696	100

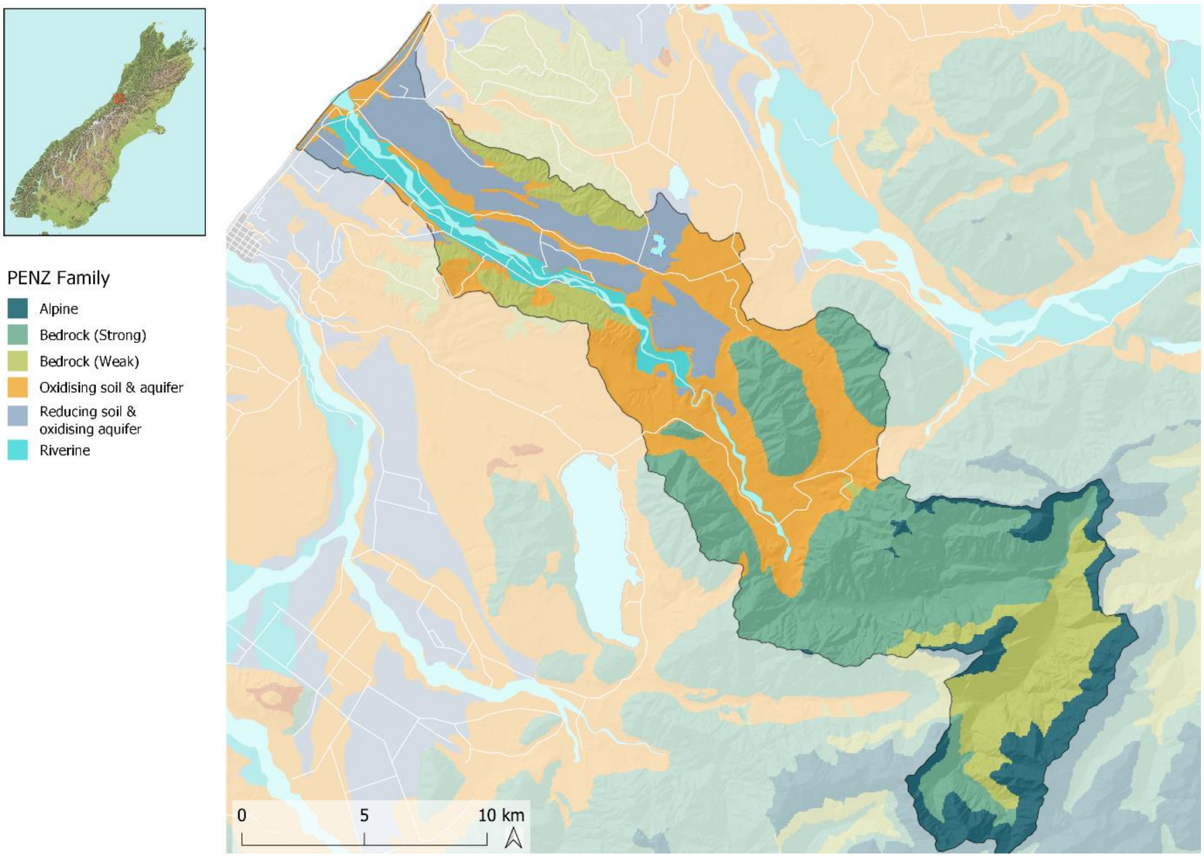

Figure A. 13. Physiographic Environments family class for the Arahura catchment.

Lowland Domain

Oxidising soil and aquifer: Related to well drained oxic soils and oxic aquifers, this environment is poorly connected with Alpine or 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 reducing soils.

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. The majority of water exported from this setting moves laterally via artificial sub-surface drainage in developed land or as overland flow due to the poor internal drainage of the overlying soils.

Mixed Domain

***Riverine*:** This environment occurs along riparian margins of the upper to mid reaches of Alpine fed rivers, predominantly in the South Island. 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 less influence 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.

Upland Domain

***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. 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. The majority of 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.

***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. The majority of 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. Overall the Bedrock Physiographic Environment is the most common environment across New Zealand and supplies large volumes of dilute and often pristine water to lowland areas where natural state vegetative cover remains.

2.1.2. Sibling Class

At a sibling level, the classification provides more resolution over the hydrological and redox gradients that are grouped within a family (Figure A14, Table A3).

***Oxidising soil and aquifer*:** There are three siblings within this environment. 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. Over bedrock identifies where soils occur over bedrock which affects how deep water can drain and the aquifer potential of the environment.

Reducing soil-oxidising aquifer: There are two siblings present in the Arahura catchment. High soil reduction occurs where soils are poorly drained. Moderate soil reduction occurs where soils are imperfectly drained. Soils with imperfect drainage are likely to take on similar characteristics to the oxidising soil and aquifer during dry periods.

Riverine: There are two siblings in this environment. High deep drainage occurs on 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.

Bedrock: There are two siblings present within the strong and weak bedrock environment in the Arahura catchment. Subalpine identifies areas with a direct connection to alpine headwaters, while hill areas don't have a connection to the alpine environment.

Alpine: There are no siblings within the Alpine environment.

Table A14: Summary of Physiographic Environment at sibling scale in the Arahura catchment

Class	Area (ha)	Percent (%)	Type
10	2869	9.3	Alpine
21	2924	9.4	Bedrock (Strong) - Subalpine
23	6974	22.5	Bedrock (Strong) - Hill
31	2669	8.6	Bedrock (Weak) - Subalpine
33	2190	7.1	Bedrock (Weak) - Hill
41	348	1.1	Riverine - High deep drainage
42	1259	4.1	Riverine - Increased overland flow
51	2263	7.3	Oxidising soil & aquifer - High deep drainage
52	4373	14.1	Oxidising soil & aquifer - Increased lateral & overland flow
53	803	2.6	Oxidising soil & aquifer - Over bedrock
81	3700	12	Reducing soil & oxidising aquifer - High soil reduction
82	325	1.1	Reducing soil & oxidising aquifer - Moderate soil reduction
Total	30944	100	

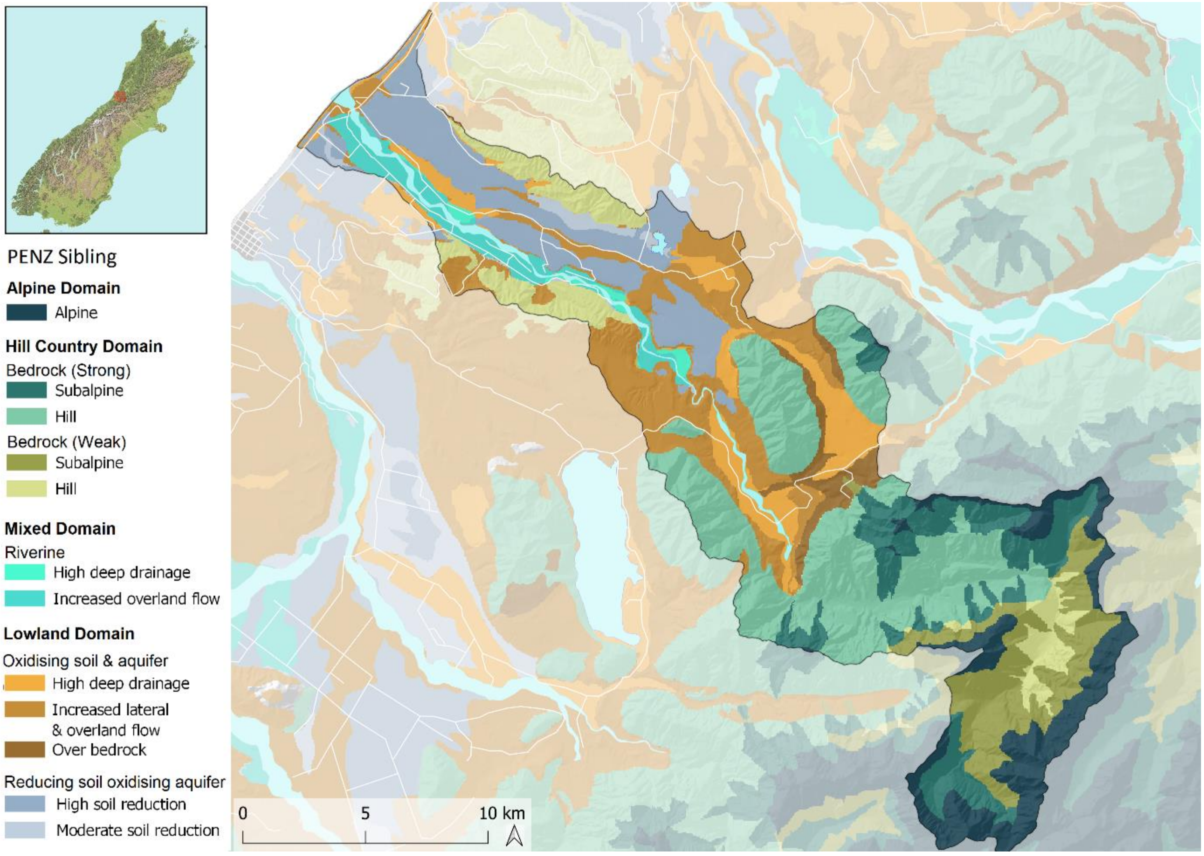

Figure A. 14. Physiographic Environments sibling class for the Arahura catchment.

2.1.3. Inherent Risk to Water Quality in the Arahura Catchment

Risk to water quality needs to consider both the land-use pressure (source, section 4) and the landscape factors (hydrological pathway contaminants take and the role the landscape has in minimising the contaminant concentration through dilution, filtration and adsorption, and attenuation through nitrogen reduction and phosphorus reduction (section 2.0 - 4.4.; Table 1).

Dilution is the process of decreasing the concentration of a contaminant. It occurs when a large volume of relatively dilute water mixes with a lower volume of water with a higher contaminant concentration. It is important to note that while dilution may alter the concentration of a contaminant, it does not reduce the total load of that contaminant to the receiving environment.

Filtration is a physical process where particulates, such as sediment or microbes, are physically removed from water by becoming trapped in the pore spaces between soil and aquifer particles. Particulates can bind to the surface of soil and aquifer particles through adsorption, removing them from solution. Drainage pathways that involve infiltration of water through the soil or aquifer matrix result in the removal of most particulate contaminants (including microbial) between the source and the receiving environment).

Oxidation-reduction chemical reactions or 'redox' processes are important to a range of environmental concerns including low dissolved oxygen in surface waters, where leached nitrate is likely to be removed by denitrification, where phosphorus is likely to be leached and/or more mobile within soils and aquifers. This information also enables an understanding of where shallow groundwater is expected to contain elevated iron and manganese, limiting its potential as a drinking water source.

The risk to water quality from land use for each environment is provided through a matrix by dominant hydrological pathway and contaminant form (Table A4). The risk matrix assumes land use activities are undertaken in each environment, while the actual contribution from actual land use (i.e., native forest or grassland) is likely to be significantly lower. The risk to water quality for all contaminants is increased substantially when bypass of the soil zone occurs by either overland flow or artificial drainage.

Mitigation actions that are matched to the Physiographic Environment, hydrological pathway, or land use type are available at https://landscapedna.org/actions/.

Table A15. Contaminant hydrological pathway, the role of the landscape in removing contaminants and the nutrient risk to receiving environments from a Physiographic Environment.

Physiographic Environment	Contaminant pathway (dominant hydrological pathway under agriculture)	Role of landscape in removing contaminants				Nutrient risk to receiving environment
		Dilution	Filtration and adsorption	Attenuation: N-Reduction	Attenuation: P-Reduction	
Alpine	Overland flow	High	Low	Low	Low	N & P Load
Bedrock (Strong)	Lateral drainage	Moderate	Moderately low	Moderate	Moderate	N & P Load
Bedrock (Weak)	Lateral drainage	Moderate	Moderately low	Moderate	Moderate	N & P Load
Riverine	Deep drainage	High	Moderate	Low	High	N Load
Oxidising soil over oxidising aquifer	Deep drainage	Low	High	Low	High	N toxicity & load
Reducing soil over oxidising aquifer	Artificial drainage	Low	Moderately low	Moderate	Moderate	P load
Hydrological Variants	**Occurrence**					
Artificial drainage	Soils with impeded drainage	Low	Low	Low	Low	Moderately high
Overland flow	High intensity/prolonged rainfall	Low	Low	Low	Low	High

Table A16. Physiographic Environment risk to water quality by contaminant.

Physiographic Environment	Nitrogen			Phosphorus		Sediment	Microbes
	Oxidised (NO_3^-, NO_2^-)	Reduced (NH_4^+, NH_3)	Organic (Dissolved & Particulate)	Particulate	Dissolved Reactive	Particulate	Particulate
Alpine	High	High	High	High	High	High	High
Bedrock (Strong)	Low	Low	Moderately low	Moderately high	Moderate	Moderately high	Moderate
Bedrock (Weak)	Low	Low	Moderate	Moderately high	Moderate	High	Moderate
Riverine	Moderate	Low	Low	Low	Low	Low	Moderately low
Oxidising soil over oxidising aquifer	High	Low	Low	Low	Low	Low	Moderately low
Reducing soil over oxidising aquifer	Moderately low	Moderate	Moderate	High	Moderately low	Moderately high	High
Hydrological variants							
Artificial drainage	Moderately high	Moderately high	Moderately high	Moderately high	Moderately high	Moderately high	High
Overland flow	High	High	High	High	High	High	High

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