



The S-PAL Framework: Technical User Guide for Erosion Susceptibility Assessment and Mitigation

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1. S-PAL v 2.0 USER GUIDE

1.1. Introduction

This User Guide explains how to use the S-PAL v 2.0 Framework to identify land that is prone to erosion across Northland. S-PAL stands for **Sediment–Process Attribute Layers** – a system that combines detailed maps and measurements to show where the land is most likely to erode and shed sediment into waterways.

The guide is designed for anyone who needs to understand erosion risk in Northland, whether you work for a council, manage a farm, advise landowners, or simply want to learn more about how your local landscape behaves.

1.2. How This Guide is Organised

This guide is composed of **five Learning Modules** and an **Appendix**:

Module	What It Covers
Module 1	What regolith is and why it matters for erosion
Module 2	The datasets (LiDAR and radiometrics) that underpin S-PAL
Module 3	How the S-PAL Framework is structured
Module 4	The Source–Pathway–Receptor model for thinking about sediment movement
Module 5	Step-by-step guidance for applying S-PAL in GIS
Appendix	Lookup tables for identifying regolith types

1.3. Where Should I Start?

Modules 4 and 5 are the practical heart of this guide – the engine room for applying S-PAL to identify erosion-prone land and plan mitigation.

Module 4 introduces the **Source–Pathway–Receptor (SPR) model**, which provides a guiding concept for thinking about sediment movement: where it comes from, how it travels, and where it ends up. SPR acts as the frametrails for applying the S-PAL Framework: it tells you not just *what* the landscape is made of, but *what to do about it*.

Module 5 then walks you through **how to use the S-PAL layers in GIS software** to screen for erosion hotspots, validate what you find using aerial imagery, and prioritise areas for action.

If you are keen to get started, you can jump straight to these modules.

However, we strongly recommend reading **Modules 1 through 3 first**.

Here's why: S-PAL is built on some important ideas about how landscapes work – what sits beneath the soil, why some slopes fail while others do not, and how the regolith varies across Northland. Each module builds on the one before, and together they provide the foundation you need to use S-PAL confidently and interpret what you see.

Think of it like learning to drive. You can jump in the car and figure out the pedals, but understanding how the engine works, what the warning lights mean, and why certain roads are more dangerous makes you a much better driver. The same is true here: the more you understand the landscape, the better you will be at reading the S-PAL layers and making good decisions.

1.4. Who is This Guide For?

This guide is written in plain language and assumes no prior knowledge of geology, erosion science, or GIS. Technical terms are explained when they first appear, and the Appendix provides quick-reference tables for examining regolith types.

If you are new to erosion management or GIS, start at the beginning and work through each module in that order. If you already have a background in earth sciences or land management, you may find some sections familiar, but we still recommend skimming the earlier modules to understand how S-PAL defines and organises its information.

1.5. A Note on Data Currency

The S-PAL Framework is built from two main datasets: LiDAR (laser terrain mapping) collected in 2018–2019, and airborne radiometric survey data collected in 2011/12. These datasets reflect the ground conditions at the time they were captured. Any major erosion or mass wasting that has occurred since, for example, slips triggered by Cyclone Gabrielle will not appear in the radiometric layers, although some more recent changes may be visible in the LiDAR data.

This is not a limitation unique to S-PAL. All landscape classifications face the same challenges. Geological maps, Land Use Capability (LUC) assessments, landslide inventories, and erosion susceptibility models are all snapshots in time. The landscape continues to change after a survey is completed, and no classification can accurately predict when or where the next slip will occur.

What matters is understanding what each dataset tells you and what it cannot. S-PAL identifies where the regolith is *susceptible* to erosion based on its physical and chemical properties. For evidence of *recent* erosion events, up-to-date aerial photography provides the clearest and most accessible source, with satellite-based tools available where additional detail or timing information is required.

In short, use S-PAL to understand the underlying susceptibility of the land and use current imagery to see what has actually happened since the surveys were flown.

2. Learning Module 1: The Regolith

2.1. What is Regolith, and Why it Sits at the Heart of S-PAL

Before explaining what S-PAL is, it is important to understand what part of the land S-PAL describes.

Erosion is often discussed only in terms of topsoil, the thin surface layer that can be dug with a spade and managed directly. Although topsoil loss matters, it represents only the uppermost part of the mobile material that can end up in the stream. Beneath the soil lies the regolith, which is the full thickness of loose and weathered material above fresh, solid bedrock (Figure 1).

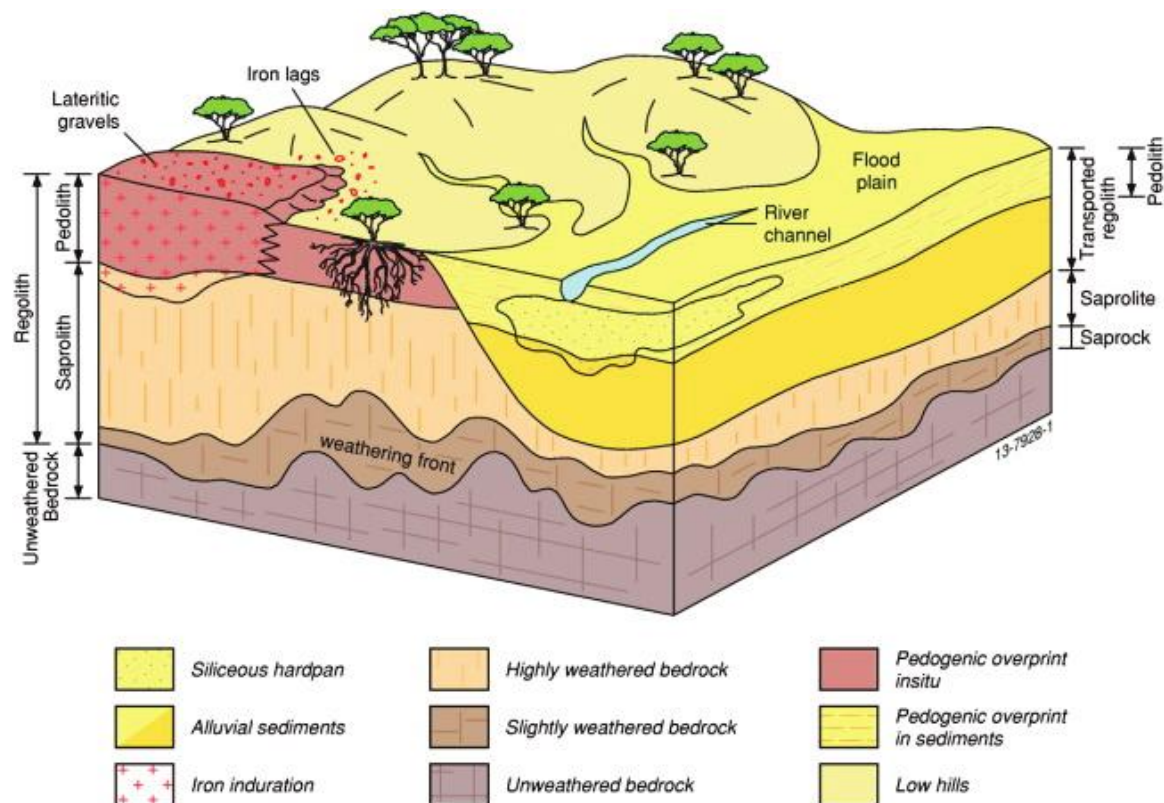


Figure 1. A conceptual diagram of regolith from Wilford et al. (2016)

The regolith is not uniform. It can be described as a series of layers or zones, each with a technical name and distinct role in how the land behaves.

- The uppermost zone is the **pedolith**. This is the soil-dominated part of the regolith and includes the topsoil and subsoil. It is the zone most affected by plants, roots, cultivation, grazing, and surface runoff. When people talk about “soil erosion”, they usually refer to processes acting within the pedolith.
- The **saprolite** lies below the **pedolith**. This is weathered rock that still retains the original structure of the parent rock but has lost much of its strength. To the eye, it may look like a firm clay or rotten rock rather than a solid stone. This zone plays a critical role in slope stability and is a common depth at which slips and slumps are initiated,

particularly when it becomes saturated.

- At the base of the regolith is **weathered or fractured bedrock**, sometimes referred to as a saprock. Although this material was once solid rock, cracking, faulting, or chemical alteration allows water to move through it. From the perspective of erosion and instability, it often behaves more like regolith than intact bedrock.
- Beneath this lies **the fresh, unweathered bedrock** that marks the lower boundary of the regolith system.

In many landscapes, the regolith also includes **transported material** that sits over top of weathered or unweathered bedrock such as river gravels on floodplains, slope colluvium, or older coastal and wetland deposits. These transported deposits may sit on top of or replace parts of the regolith formed in the local bedrock.

The thickness and makeup of the regolith zones vary widely across the landscape. On steep, rugged ridgelines, the regolith may be thin, especially if there has been a recent landslide which exposes fresh, unweathered bedrock. On gently sloping basaltic hills, the regolith can be several meters thick, forming a deep, clay-rich weathered mantle over relatively strong rock. In floodplains, the regolith may be dominated by 1–10s of meters of transported sediments above weathered bedrock. The regolith also hosts aquifers, and water chemically alters bedrock and sediments; therefore, aquifers are part of the regolith system.

2.2. Why the Concept of Regolith Matters for Erosion

Many erosion processes do not start at the soil surface (Figures 2 and 3). Think of this as a building collapsing because of its bad foundation. While the damage is visible on the surface, the actual failure occurs deep underground, where the weakened earth can no longer support the weight above it.



Figure 2. Regolith landslides in soft sedimentary mudstones Manawatu, 2004. While some erosion processes affect the pedolith (the soil zone), such as sheet wash and small rills, many erosion processes begin below the surface.

Examples include (Figure 3):

- slips and slumps, which occur when deeper regolith layers lose strength
- earthflows and downslope creep, which involve slow movement of clay-rich regolith
- tunnel gullying, where water erodes material underground before the surface collapses
- large landslides, where the entire regolith layer can slide over the bedrock.

In these cases, soil is lost, but the loss occurs because a deeper part of the regolith has failed first. In regions such as Northland, the failure of the regolith below the soil zone is a very important mechanism. However, this does not mean that surface runoff is not important; rather, the two processes often interact (see Section. For example, when surface runoff cuts deep channels or gullies into a hill, it can destabilise a slope and trigger a deep landslide. Conversely, after a landslide occurs, it leaves a raw, bare "scar" on the hillside. This exposed earth is completely unprotected, allowing surface rain to easily wash large amounts of sediment into waterways long after the initial slide has stopped.

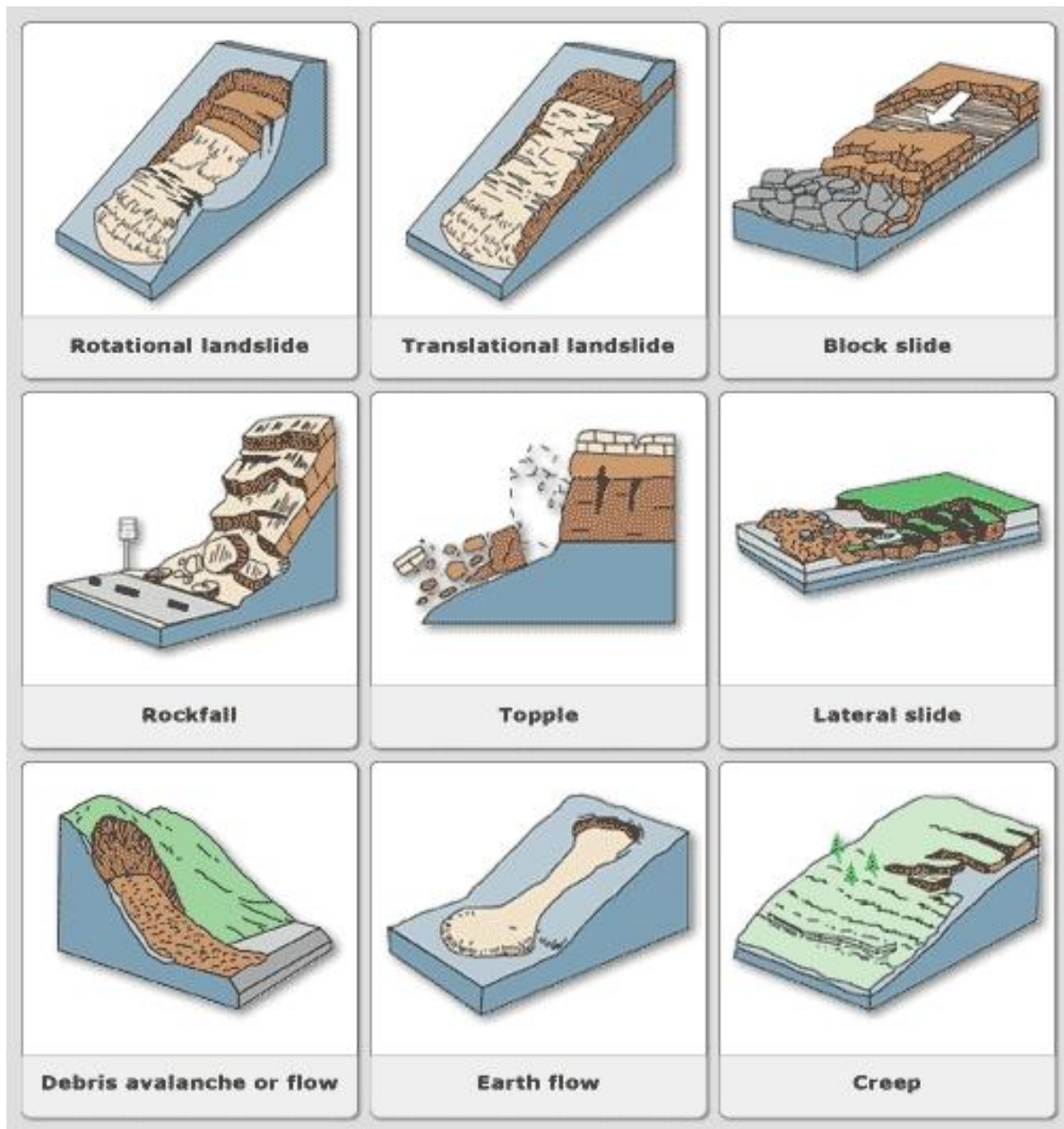


Figure 3. Types of regolith mass wasting. Some mass wasting events are rapid and high-energy (Topple, Rockfall, etc.), while others are slow and low-energy (creep).

2.3. What Triggers Regolith Failure?

Deeper regolith failure usually occurs when water, gravity, and weakened ground conditions occur together. Both climate and human activity influence this process and often interact. Human activities rarely create deep regolith instability on their own. Instead, they tend to modify how water enters, moves through, or is retained within the regolith, increasing the sensitivity to rainfall events rather than acting as the primary cause of failure.

2.3.1 The Role of Land Cover

When native forest is cleared for pastoral farming or plantation forestry, the regolith becomes more susceptible to erosion (Figures 2, 4, 6)¹. Native forests provide continuous, long-term protection in several ways: they intercept heavy rainfall before it reaches the ground, their roots

grow deep into the regolith binding it all together and anchoring the slope, and they transpire water back to the atmosphere, moderating moisture variation in the regolith more effectively than in pastures.

When native forest is removed, the roots begin to decay and lose their strength within a few years. Research following Cyclone Gabrielle found that indigenous forests reduced landslide probability by up to 90% compared to pasture, and that this protection was consistent across different regolith types and slope angles¹.



Figure 4. Due to vegetation clearance on steep slopes, the regolith is prone to failure. Source: New Zealand Herald. The initial failure coincided with the area of soil creep at the top of the landslide.

In contrast, pasture grasses have shallow root systems that provide little reinforcement in the zone of contact between the pedolith and saprolite, the zone where many landslides begin. During Cyclone Gabrielle, over 300,000 landslides occurred across the East Coast, with the vast majority occurring on pastoral land. In Hastings District alone, more than 4% of pastoral hill country failed during the cyclone¹.

Plantation forestry presents a different but related problem. While mature pine forests can reduce landslide probability by 60–80%, this protection is temporary¹. Every 25–30 years, the trees are harvested, and the protective root network begins to decay. Within 3–5 years of harvest, root strength drops significantly, leaving slopes highly vulnerable until the next rotation

¹ McMillan, A., Dymond, J., Jolly, B., Shepherd, J., & Sutherland, A. (2023). Rapid assessment of land damage – Cyclone Gabrielle (Contract Report LC4292). Manaaki Whenua – Landcare Research. Prepared for Ministry for the Environment.

maturing². Cyclone Gabrielle data showed that recently harvested forests had landslide rates as high as, or higher than, pasture. In the Esk catchment, harvested forest had a landslide probability exceeding 4%¹. In areas such as Gisborne, where pine has been grown through multiple harvest cycles, the cumulative effect of repeated disturbance appears to have degraded the regolith structure and reduced its depth, making slopes increasingly prone to failure over time. This helps explain why, in some locations, even mature exotic forests provided little protection during Cyclone Gabrielle, and the legacy of past land use had already compromised the regolith's ability to resist erosion.

2.3.2 Slope: A Critical Factor, But Not Always the Main Driver

Slope angle is an important factor controlling whether a slope will fail. However, slope angle alone does not tell the whole story. Two slopes with the same steepness can behave very differently depending on what the regolith is made of.

The regolith inherits its characteristics from the rock or sediment from which it formed. This "parent material" largely determines how strong the regolith is, how well it drains, and how it responds to rainfall. For example, regolith formed from soft, poorly drained mudstones tends to be clay-rich, weak, and slow to let water pass through. In contrast, regolith formed from hard, free-draining rocks such as the Kerikeri basalts tends to be stronger, coarser, and allows water to soak readily.

Research consistently shows that weak, weathered, or clay-rich materials can fail at much lower slope angles than stronger, more intact materials³. In some cases, regolith properties become more important than slope angle in controlling whether failure occurs. This is especially true for sensitive clays, highly weathered rocks, and layered or fractured materials⁴. In Northland, where much of the regolith has formed from deeply weathered sedimentary rocks and volcanic materials, these inherited properties play a significant role in determining erosion susceptibility.

² Marden, M., & Rowan, D. (1993). Protective value of vegetation on tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. *New Zealand Journal of Forestry Science*, 23(3), 255–263.

Phillips, C., Bloomberg, M., Marden, M., & Lambie, S. (2023). Tree root research in New Zealand: A retrospective review with emphasis on soil reinforcement for soil conservation and wind firmness. *New Zealand Journal of Forestry Science*, 53, Article 6.

³ Stead, D., & Wolter, A. (2015). A critical review of rock slope failure mechanisms: The importance of structural geology. *Journal of Structural Geology*, 74, 1–23. <https://doi.org/10.1016/j.jsg.2015.02.002>

Singh, D., Singh, P., Kainthola, A., Pandey, H., Kumar, S., & Singh, T. (2022). Analysis of failure pattern in cut slopes of bedded sandstone: A case study. *Environmental Earth Sciences*, 81, Article 528. <https://doi.org/10.1007/s12665-022-10528-0>

Pandey, V., & Sharma, M. (2023). Sedimentological characteristics and their relationship with landsliding in the Bhilangana Basin, Garhwal Himalaya, India. *Earth Sciences Research Journal*, 26(4), 331–342. <https://doi.org/10.15446/esrj.v26n4.94720>

⁴ Urlaub, M., Talling, P., Zervos, A., & Masson, D. (2015). What causes large submarine landslides on low gradient (<2°) continental slopes with slow (~0.15 m/kyr) sediment accumulation? *Journal of Geophysical Research: Solid Earth*, 120(10), 6722–6739. <https://doi.org/10.1002/2015jb012347>

Alonso, E., & Pinyol, N. (2015). Slope stability in slightly fissured claystones and marls. *Landslides*, 12, 643–656. <https://doi.org/10.1007/s10346-014-0526-5>

2.3.3 Rainfall, Drainage, and the Trigger for Failure

Rainfall commonly acts as the trigger that tips a marginally stable slope into failure⁵. When a clay-rich, poorly drained regolith gets wet, two things happen at once: it gets heavier and it gets weaker (Figure 5). Water pushes between tiny clay and silt particles, reducing the friction that holds them together and breaks down the regolith structure. Because these soils drain poorly, water builds up inside rather than flowing away. This combination of added weight, reduced strength, and trapped water makes the slopes increasingly unstable.

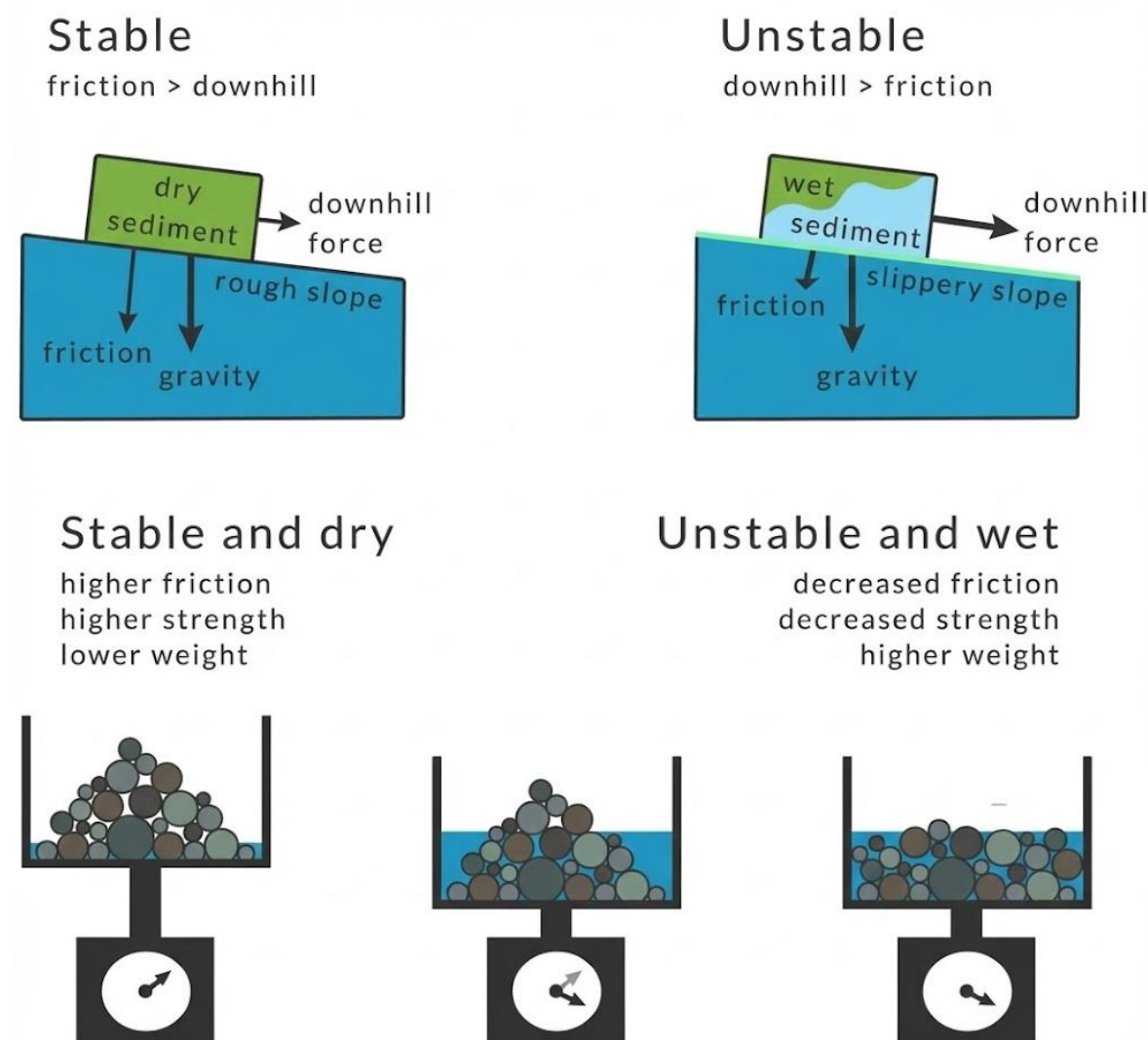


Figure 5. Conceptual illustration of slope stability and landslide processes. Regolith stability is controlled by the balance between downslope gravitational forces and resisting forces, such as friction and internal regolith strength. Source: Scott Elliott (*Landslide 101*).

⁵ Schmidt, J., Turek, G., Clark, M. P., Uddstrom, M., & Dymond, J. R. (2008). Probabilistic forecasting of shallow, rainfall-triggered landslides using real-time numerical weather predictions. *Natural Hazards and Earth System Sciences*, 8(2), 349–357. <https://doi.org/10.5194/nhess-8-349-2008>

Miramontes, E., Garziglia, S., Sultan, N., Jouet, G., & Cattaneo, A. (2018). Morphological control of slope instability in contourites: A geotechnical approach. *Landslides*, 15, 1085–1095.

Drainage also controls how much water runs off across the land surface. On a slope formed in clay-rich, poorly drained regolith, water cannot soak in fast enough during heavy rain. Instead, it runs off across the surface, picking up sediment and driving erosion (Figure 6). On a slope formed in a well-drained regolith, for example silt- and boulder-dominated regolith of the Kerikeri basalts, the same rainfall soaks into the ground rather than running off. These slopes shed less sediment, generate less runoff, and are far less likely to fail, even at the same angle as a clay-rich slope.

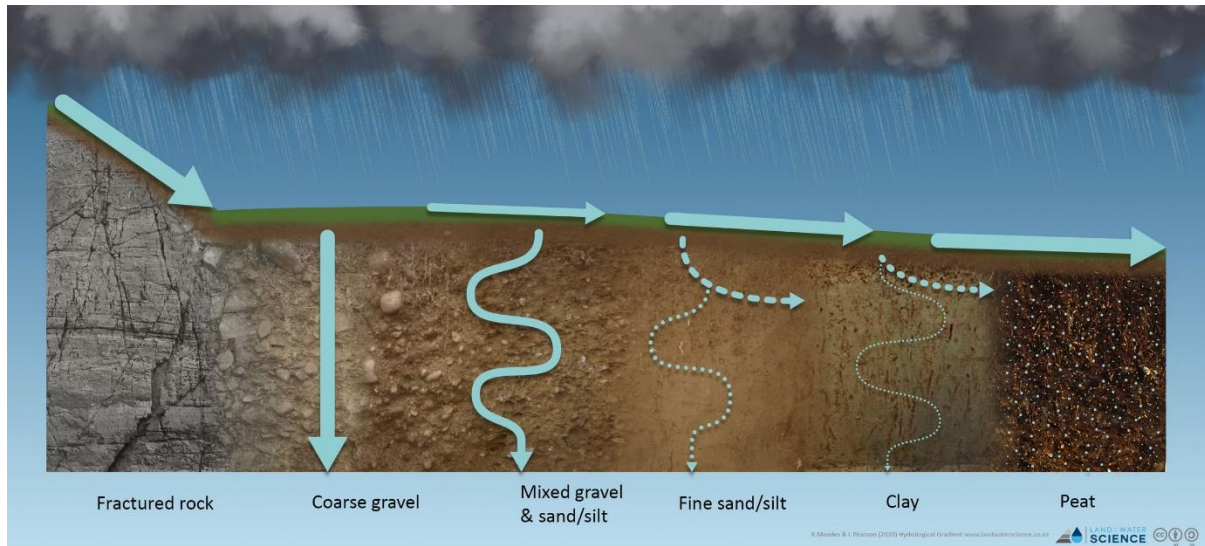


Figure 6. Drainage of the regolith determines the pathway that water takes across the landscape. Regolith characterised by low infiltration rates and poor internal drainage generate more surface runoff for the same slope angle. Source LWS.

This explains why erosion by water, creep, slips, slides, and slumps in Northland tend to cluster in particular geological and regolith units rather than occurring evenly across all steep land. The properties inherited from the parent material, particularly drainage behaviour, clay content, and structure, work alongside the slope angle to control both landslide risk and sediment loss.

2.3.4 How Human Activities Increase Susceptibility

Road and rail infrastructure presents an additional risk where it cuts into the base of slopes (Figure 7). The toe of a slope acts as a natural buttress, providing support that holds the material above in place. When earthworks remove this supporting material, the balance of forces on the slope changes. The weight of the regolith above now pushes against a weakened or absent toe, and the slope becomes more likely to fail. This effect is compounded when construction occurs in deeply weathered regolith that is inherently prone to failure, for example, Brynderwyns. Many of Northland's roads and rail corridors were constructed through hill country decades ago, and the cumulative effect of toe slope removal, altered drainage, and ongoing weathering means that some sections remain marginally stable, requiring only a significant rainfall event to trigger failure.



Figure 7. Another slip on Sate Highway One over the Brynderwyns, 2024. Toe sloep cuts destabilise the already unstable regolith. Image: NZTA.

Pedolith compaction is another important factor that controls regolith erosion (Figure 8). When heavy machinery or livestock trample the ground, they press clay particles tightly together, reducing infiltration capacity⁶. Because water can no longer soak in vertically, it is forced to flow laterally across the surface as overland flow. Where vegetation is sparse or roots are shallow, this overland flow can erode the pedolith and cut into the deeper regolith.

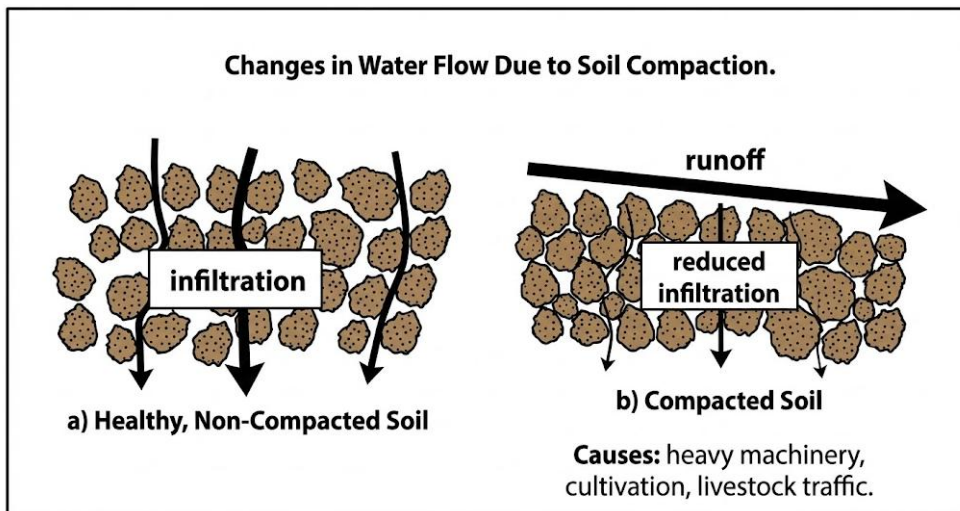


Figure 8. Compaction of the regolith increases runoff (overland flow) and increases susceptibility to erosion by running water.

⁶ Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, 82(2), 121–145.
<https://doi.org/10.1016/j.still.2004.08.009>

On slopes underlain by clay-rich saprolite, a dominant feature of most of Northland's hill country, vegetation clearance (the most common factor), toe slope destabilisation (farm tracks and roading), and compaction (livestock and machinery) increase the susceptibility of the regolith to erosion by water and deeper-seated failure (Figures 2, 4, 6, and 7). While the regolith may remain stable during dry periods, failure becomes more likely during wet phases of the climate cycle, when friction is reduced and material strength is lowest (Figures 2, 4, 5, 7).

2.3.5 The Interaction Between Processes

Surface runoff and mass wasting interact rather than occur in isolation. When surface runoff incises deep gullies, it can destabilise the slope and trigger a deeper slip. Conversely, a landslide leaves an exposed scar on the hillside, leaving the regolith unprotected against future rainfall and erosion caused by overland flow. Mass wasting can also alter natural drainage paths; if displaced soil blocks a stream or ditch, it diverts water onto adjacent land, where the concentrated flow can cut new erosion channels.

Therefore, human activities tend to increase sensitivity to climate rather than acting as the primary cause of deep-seated erosion or landsliding. They influence when and how often instability occurs, but the underlying susceptibility is controlled by the structure and condition of the regolith itself.

2.4. Why Pastoral and Horticultural Regolith Loss Matters for Water Quality

Approximately 44% of the estimated sediment loss that enters waterways across Aotearoa/New Zealand is from pastoral land, according to the Ministry for the Environment's Environment Aotearoa 2019 report.

Understanding how regolith fails and moves downslope is only part of the picture. What ultimately matters is what that mobilised material contains, and what happens when it reaches water. Yes, sediment quality is a real thing.

It is critical to understand that regolith lost from pastoral land typically contains much higher concentrations of phosphorus, organic and ammoniacal nitrogen, and often microbial pathogens than the equivalent mass of regolith lost from conservation land. This reflects long-term fertiliser inputs, livestock excreta, and enhanced biological cycling in productive systems. As a result, sediment loss from pastoral land not only smothers aquatic environments but also drives internal eutrophication, a process where nutrients stored within sediments become a continuing internal source of nutrient supply to the overlying water, fuelling algal growth and oxygen depletion, even if new inputs from the surrounding land are reduced.

Pasture and intensive horticultural soils tend to have much higher total nitrogen and phosphorus concentrations than natural or low-production grasslands, meaning that a kilogram of sediment eroded from high-production land can carry several times the nutrient load of a kilogram eroded from an undisturbed grassland under similar climatic conditions. In contrast, topsoils under natural grasslands typically have lower soil nutrient stocks, with most nitrogen and phosphorus bound in more stable forms and present at lower overall concentrations.

As a consequence, even modest losses of fine, nutrient-rich regolith from pastoral landscapes can deliver a disproportionate nutrient load to streams, creeks, lakes, estuaries, and harbours. Once deposited, these sediments can continue to influence water quality for many years, creating a long-term legacy effect that persists well beyond the original erosion event.

3. Learning Module 2: Understanding the Datasets that Underpin the S-PAL Framework

3.1. The Datasets that Underpin the S-PAL Framework

The S-PAL framework is built on two foundational measurement systems (datasets) that describe different aspects of Northland regolith LiDAR (Light Detection and Ranging) and AGRS (Airborne Gamma Ray Spectroscopy). These two datasets underpin all components of S-PAL, including the Regolith Classification, Regolith Activity Index (RAI), Overland Flow Index (OLF), and Terrain Ruggedness Index (TRI). LiDAR also underpins Northland's Digital River Network (DRN), which plays an important role in assessing the risk of eroded sediment reaching a waterway.

LiDAR describes the physical shape and structure of the regolith, and AGRS describes the natural chemistry (mineralogy) of the regolith. Together, they provide the data for the regolith of Northland to be objectively divided into distinct units that share similar form and chemistry

3.2. Important Geological Context

Northland's landscape is complex because it has been built and reshaped in several major stages over a very long period of time. This geological history has created distinctive and repeatable patterns across the region, which can be detected through careful measurement of both landform shape and regolith chemistry.

One of the most important events was the Northland Allochthon (A-lock-thon), during which younger rocks rafted in from the Pacific Ocean and were forced out of the sea and over the older basement rocks (Eastern Basement) approximately 25–21 million years ago. This process involved intense squeezing, faulting, and folding of the rocks as they were moved and stacked, creating a highly complex geological foundation crisscrossed with faults and folds (Figure 9).

During the allochthon, massive chunks of Tangihua Basalt from the Pacific Ocean were pushed inland, along with an abundance of soft (weak) ocean floor sedimentary mud and sandstones. Softer rocks were warped as they were pushed up against harder rocks, and the ancient basement rock underlying Northland was scoured and exposed across the eastern side of the region (for example, the Bay of Islands and Brynderwyn Hills).

Later, volcanic activity added another layer of complexity. Volcanic eruptions, such as the Waipoua and Kerikeri basalts, spread lava across parts of the region, covering and modifying the earlier land surface rather than creating it from scratch. These basalts erupted through ancient faults in Northland's basement rock and flooded across the surface, burying soft sedimentary mudstones and sandstones.

Together, these events, large-scale rock movement, deformation of the land, and later volcanic activity have shaped Northland's hills, ridges, valleys, terraces, and plains in distinctive and recognisable ways according to the rock or sediment type and its history. Different materials respond differently to erosion and weathering: hard volcanic rock resists erosion and forms steep, rugged slopes, whereas softer sedimentary rocks break down more easily and form

smoother, more rounded landforms. Each material also carries a distinct chemical and mineralogical signature that reflects its origin and subsequent weathering history.

Viewed in this way, the landscape of Northland can be thought of as a giant jigsaw puzzle comprising many distinct pieces. Each piece has both a characteristic shape (morphology) and chemistry. The challenge has always been to consistently identify and map these pieces across a large and complex region.

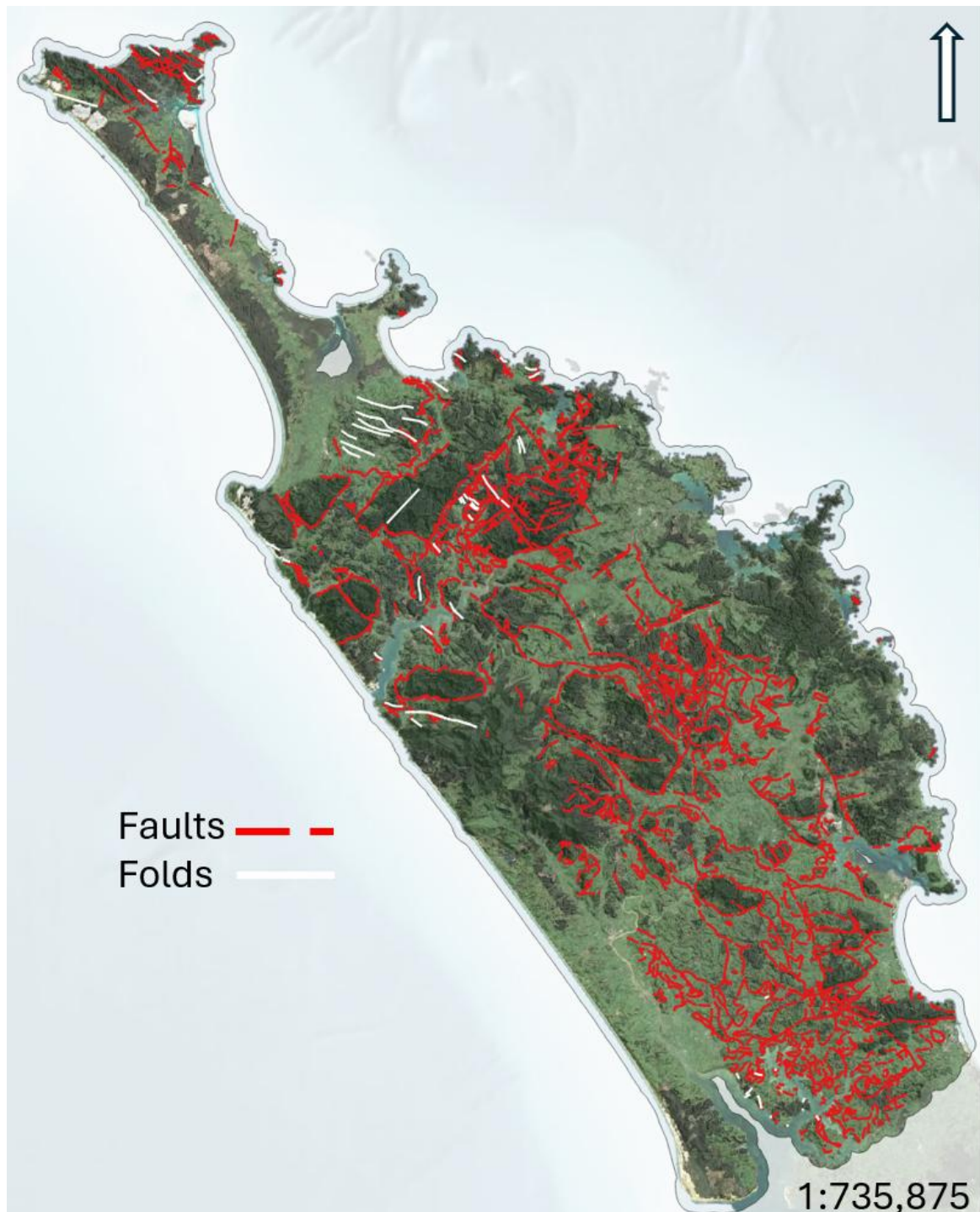


Figure 9. Large areas of Northland are crisscrossed by ancient faults and folds (Q-MAP, GNS Science).

Traditional geological mapping, such as GNS Science's Q-MAP program, was designed to depict the distribution of rock types and geological structures at a regional scale. It serves this purpose well and provides an essential foundation for understanding Northland's geology. However, Q-MAP was not intended to provide high-resolution depiction of the regolith, nor does it reveal the internal variation of rock types within a mapped geological unit, variation that can in places be important for understanding erosion. As most erosional features are sub-paddock scale, subtle differences in regolith properties, drainage, clay content, and depth to bedrock can determine whether the regolith on a farm remains stable or fails in response to climatic events. Mapping at regional scales, although valuable for a broader geological understanding, cannot capture this fine-scale variability.

The two foundational datasets used in S-PAL, LiDAR and Airborne Gamma-Ray Spectrometry (AGRS), provide a way to resolve this complexity at a high resolution across the entire region. Both are measurement-based: LiDAR directly measures the shape of the land surface at one-meter resolution, while AGRS directly measures the radiation emitted by minerals in the regolith. Because they record physical properties rather than relying on interpretation, they provide objective, repeatable, and spatially continuous information that complements and extends traditional geological mapping. When used together, these datasets allow the distinct "pieces" of Northland's geological jigsaw and the variation within them to be identified and mapped at scales relevant to land management, regardless of vegetation cover, access constraints, or observer bias.

3.3 LiDAR – Measuring the Shape of the Land

Light Detection and Ranging (LiDAR) uses laser pulses fired from aircraft to create highly detailed three-dimensional maps of the land surface (Figure 10). The technology has been applied across Northland, providing the physical terrain foundation for the S-PAL framework.



Figure 10. Light Detection and Ranging (LiDAR) survey and inset of Digital Elevation Model. Image LWS.

3.3.1 How LiDAR Data Are Collected

Aircraft fitted with laser scanning equipment fly systematic transects over the region (Figure 10). As the aircraft travels, the scanner emits millions of very short laser pulses toward the ground. Each pulse travels to the land surface, reflects off whatever it strikes, and returns to the aircraft, where sensors record both the precise location and travel time of each return. Because the laser light travels at a known speed, the travel time can be converted to distance, allowing the exact elevation of each reflection point to be calculated.

The result is a dense cloud of elevation points that can be processed into a precise digital elevation model at 1-metre resolution. One of LiDAR's key advantages is its ability to penetrate the vegetation canopy, because many pulses pass between leaves and branches, and the technology can effectively "see through" most but not all forest and scrub cover to measure the actual ground surface beneath.

3.3.2 What LiDAR Measures

LiDAR measures the morphology, that is, the shape and physical structure of the land surface. The primary measurements included elevation (how high or low the land sits), slope (how steep the surface is), terrain roughness (whether the surface is smooth, rolling, or broken), and landform patterns such as ridges, valleys, terraces, and gullies.

From this raw elevation data, many derivative layers can be generated:

- Slope maps showing the steepness of terrain across the region
- Measures of terrain ruggedness that quantify surface irregularity
- Surface flow path models identifying where water concentrates as it moves downslope
- The Digital River Network (DRN), a hydrologically corrected representation of streams, rivers, and catchment boundaries across Northland

These derived layers are essential for identifying landform types, detecting mass-wasting features (slips, slides, slumps, creep) and erosional features (gullying, scour), and assessing regolith activity across the landscape. They also describe how water moves across the land surface and how different landforms are hydrologically connected, information that feeds directly into the Overland Flow Index component of S-PAL.

3.3.3 Why LiDAR is Valuable for S-PAL

LiDAR reveals the shape of the land in extraordinary detail, and that shape is not random. Landforms develop the way they do because of the geological setting, material resistance, and the processes that have acted on them over time. Landforms formed in similar geological settings tend to share similar morphology (shape), which acts like a physical "fingerprint." Just as people of different origins vary in appearance, so too does the land vary according to its geological parentage, for example, think of how distinct the Tangihua Ranges are from the sand dunes of Te Oneroa-a-Tōhē / Ninety Mile Beach.

For S-PAL, this information is used in a practical, classification-focused manner. The S-PAL does not attempt to reconstruct detailed landform history. LiDAR provides the physical shape and structure of the landscape, which reflects the geological setting and long-term erosion

processes; however, it does not identify the chemistry of the regolith directly. This complementary information is obtained from Airborne Gamma-Ray Spectroscopy (AGRS).

3.4. AGRS – Measuring Regolith Chemistry

Airborne Gamma-Ray Spectrometry (AGRS) is a passive sensing method that detects naturally occurring radiation emitted from the regolith. While LiDAR captures the physical form of the landscape, AGRS captures its chemical and mineralogical characteristics.

3.4.1 How AGRS Data Are Collected

Unlike LiDAR, the AGRS sensor beneath an aircraft does not transmit any signals or energy to the ground. Instead, it detects naturally occurring radiation that is continuously emitted from the regolith as the aircraft flies approximately 60 m above ground level (Figure 11).

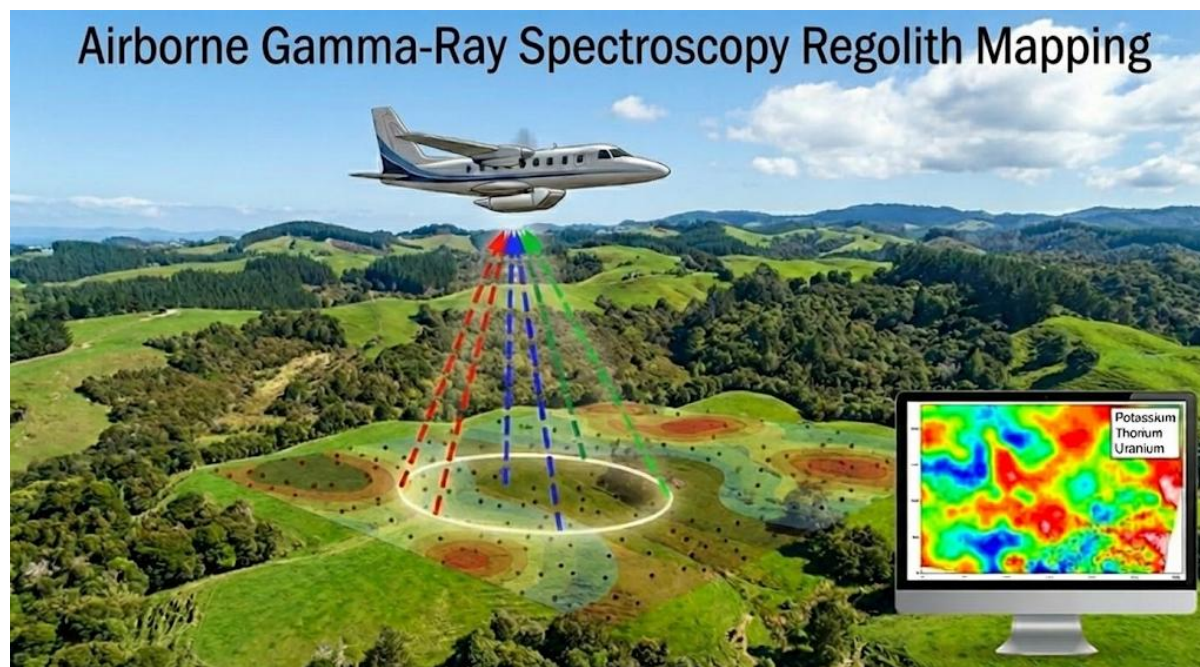


Figure 11. Conceptual illustration of airborne gamma-ray spectroscopy survey methodology. Image LWS.

A helpful way to understand the AGRS is to consider it as a sensitive microphone tuned to hear the natural radiation emitted from the regolith. The type and amount of radiation vary with the chemical (rock and mineral), physical (texture and density), and water contents of the regolith. These variations are recorded by the sensor along continuous flight transects, allowing a map of the natural chemistry of the regolith to be generated (Figure 11).

This radiation is completely natural and harmless and has been present since the Earth formed. All rocks, soils, sediments, and even peat naturally emit small amounts of radiation. Because AGRS does not disturb the land or change it in any way, it simply measures what is already there, the resulting maps provide an objective record of how regolith properties vary spatially across Northland. The depth from which the radiation is emitted varies with the bulk density of the regolith and ranges from several meters (low bulk density regolith such as peat and some tuffs) to 10s of millimetres for bare rock.

3.4.2 What AGRS Measures

Both the type and strength of radiation measured by AGRS vary depending on the parent material from which the regolith is formed, and on how old or weathered that regolith is. Different parent materials, volcanic rocks, sedimentary rocks, or transported deposits (gravel, peat, sand) contain different minerals, which produce distinct radiometric signatures (Figure 12).

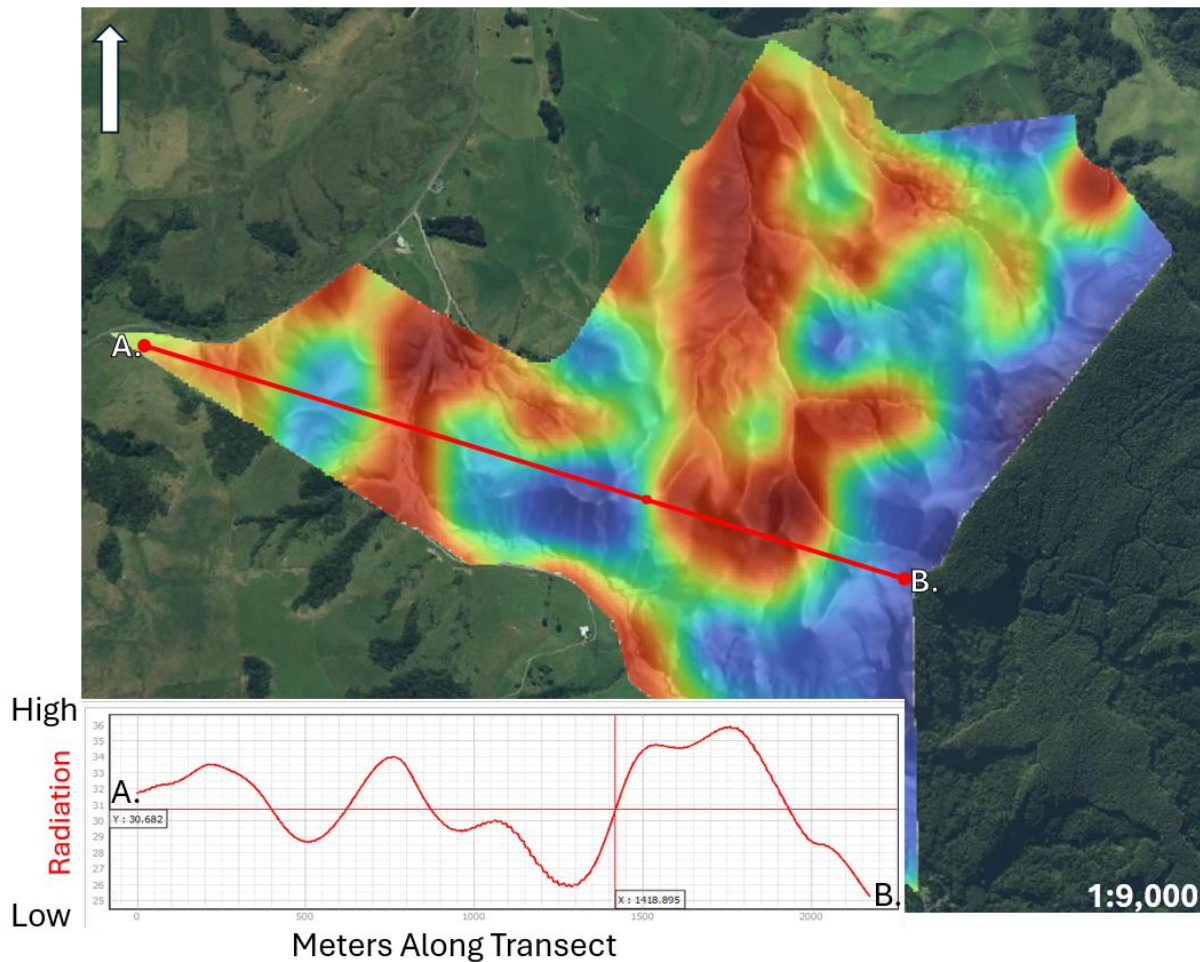


Figure 12. Example of a radiation transect across a hill and high-country property. This pattern is one of six different radiation fingerprints used to provide high-resolution regolith, soil, and erosion mapping. As the regolith varies, so do the fingerprints, with each fingerprint providing crucial information regarding the different properties of the regolith (soil depth, texture, drainage, mineralogy, age, and organic matter abundance).

Over long periods of landscape stability, the regolith slowly loses its radiometric signal as weathering and leaching remove radioactive elements (Figure 13). A helpful way to think about this is like a light bulb connected to a battery that gradually loses its charge. In old, stable regolith, much of the original radiation has been lost, the light bulb has dimmed. When this older material is disturbed by erosion, slips, or landslides, the dim surface layer is partially or wholly stripped away, exposing the fresher material beneath. This newly exposed material retains more of its original radioactive elements and appears radiometrically brighter, the light has been turned back up.

Importantly, AGRS does not respond to chemistry alone. The radiometric signal is also influenced by the physical properties of the regolith, including texture, bulk density, and volumetric water content. Denser materials and those with higher water content attenuate gamma radiation differently, meaning that AGRS captures both chemical and physical variations across the landscape.

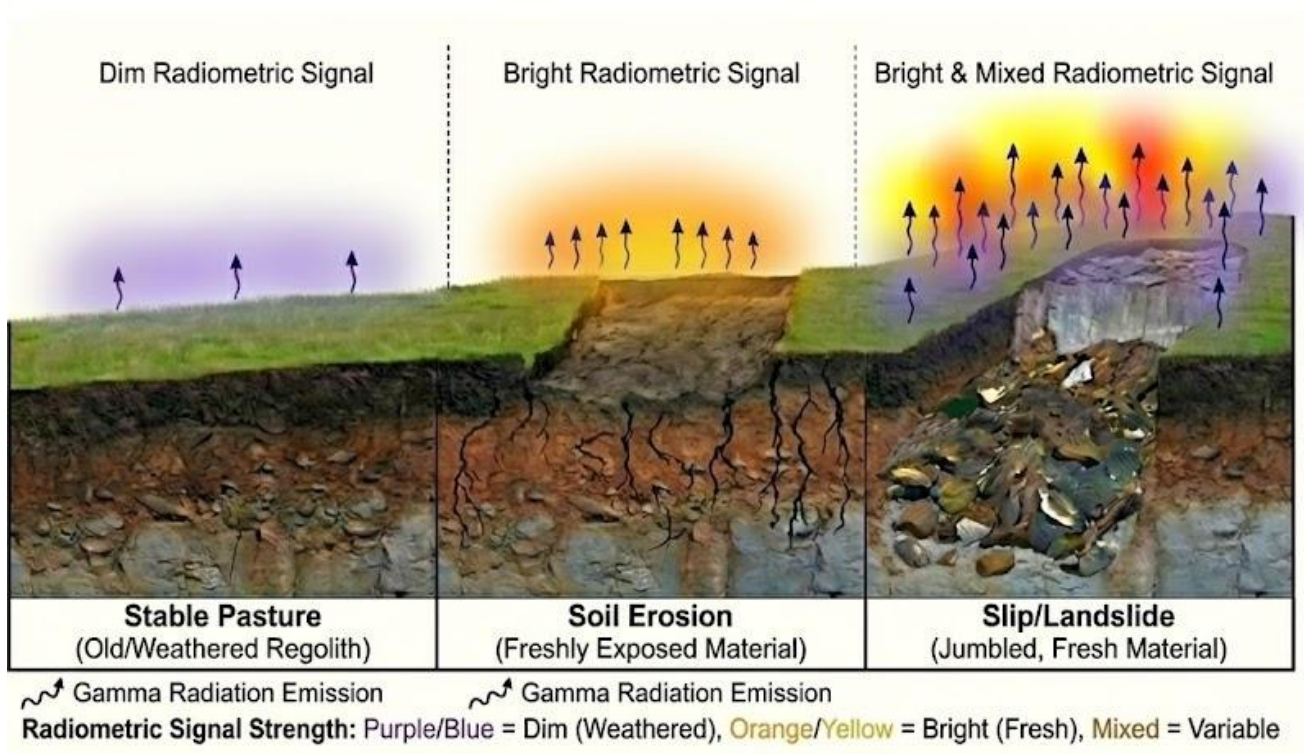


Figure 13. The radiation emitted from the regolith varies with age and exposure. Source: LWS.

In areas affected by repeated slope failure, regolith can become jumbled and mixed (Figures 13 and 14). Regolith materials of different ages are mixed up together, producing a chaotic patchwork of radiometric signals (Figure 14). The AGRS reveals this as a highly variable chemistry and mineralogical expression across short distances. This technology is also sensitive to areas where the entire regolith profile has been stripped by forest clearance or repeated cultivation.

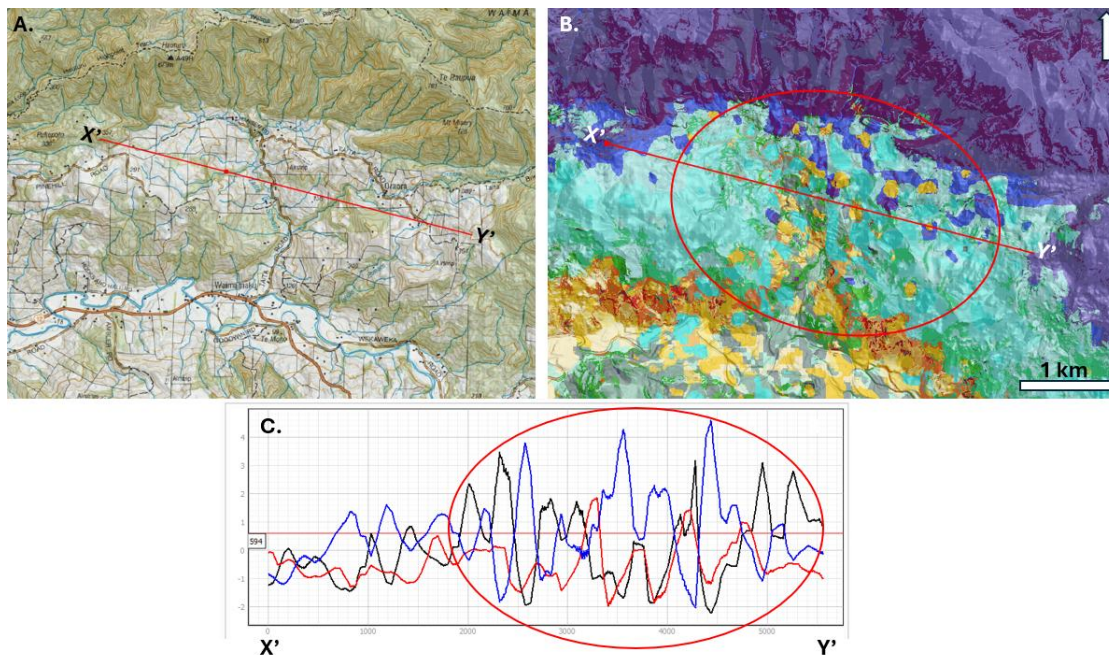


Figure 14. A. Waimamaku Valley and transect $X' - Y'$. B. The S-PAL Regolith Type Classification shows a lot of variability (patchiness) in the type of regolith within the area of recent and ongoing landsliding. C. Jumbling and mixing of radiometric signals across an area of recent landslides.

Despite this local complexity, the overall radiometric pattern still reflects two fundamental controls: the parent material from which the regolith is derived and how weathered or old the regolith is. By capturing both the dimming effect of long-term stability and the brightening caused by fresh exposure and mixing, AGRS provides a powerful window into regolith evolution, age, and stability across the Northland Region.

3.4.3 Why AGRS is Valuable for S-PAL

AGRS reveals aspects of the regolith that cannot be detected from terrain shape alone, including mineralogical expression, degree of weathering, and relative chemical maturity. Just as landforms develop distinctive shapes, regolith develops distinctive chemical fingerprints that reflect mineralogy and long-term surface history.

Even within the same geological unit, regolith can develop in different ways depending on local weathering intensity, erosion history, depositional processes, and time. Regolith that is young or actively reworked often shows a very different radiometric fingerprint from regolith that has remained stable over long periods.

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4. Learning Module 3: What Is S-PAL Framework and How Is It Structured?

4.1. The S-PAL Framework

With a basic understanding of the regolith in place and the datasets used to build S-PAL now introduced, the framework itself can be explained.

S-PAL stands for Sediment–Process Attribute Layers. It is a framework for organising information about the regolith across the landscape in a consistent and spatially explicit way. In other words, the S-PAL is not a single map, a single classification, or a single susceptibility layer. It is a structured system made up of several connected components, each describing a different aspect of the regolith relevant to erosion.

In simple terms, S-PAL identifies:

- the different types of regolith across the region
- indicates its relative stability, and
- whether or not it is likely to generate surface runoff (overland flow).

The underlying principle is straightforward: regolith with a similar physical structure, topographic position, mineralogical expression, and chemical maturity is likely to share similar origins and, importantly, is likely to behave in a similar manner when subjected to land use or storm events.

4.2. A Data-Driven Framework

A defining feature of S-PAL is that it is data-driven.

Rather than starting with assumed landform types, regolith materials, or erosion processes, S-PAL allows the landscape to organise itself based on measurable patterns in terrain shape and geochemical response. These patterns are derived from LiDAR and airborne radiometric survey data.

S-PAL first identifies the spatial patterns. Interpretation of what those patterns represent, in geological, soil, or geomorphic terms, comes later and relies on expert judgement. This separation between objective pattern identification and expert interpretation is deliberate and underpins the framework.

By letting the data reveal the natural "grain" of the regolith across Northland, S-PAL avoids imposing preconceived boundaries or categories. Instead, it captures the actual variation in regolith characteristics as they exist in the landscape, variation that may or may not align with existing geological or soil maps but reflects real differences in how the regolith has formed, weathered, and evolved.

4.3. The Three Core Components of S-PAL

The S-PAL is composed of five core layers. Each of the five layers tells us something different about the landscape, and each draws on different combinations of the foundational datasets:

- The **Regolith Classification** tells us what the regolith is made of and where different types occur. It was built from both LiDAR (terrain shape) and AGRS (regolith chemistry) data.
- The **Regolith Activity Index** tells us how the regolith is behaving—whether it appears stable or active. It is derived primarily from AGRS data.
- The **Overland Flow Index** indicates where water is likely to run off across the surface rather than soak in. It combines LiDAR-derived slope information with AGRS-derived estimates of regolith permeability.
- The **Terrain Ruggedness Index** indicates where the land surface is rough and uneven, and is often a sign of past or ongoing erosion. It was derived entirely from LiDAR.
- The **Erosion Susceptibility Layers** bring these pieces together to show where erosion is most likely to occur.

By keeping these layers separate, we can explain *why* an area has been rated as high or low risk. If a paddock shows high erosion susceptibility, we can look at the individual layers to understand the reason: is it because the regolith is naturally unstable? Because the slope sheds water rather than absorbing it? Is the terrain already showing signs of past landslides? This transparency makes the framework easier to trust, check, and apply in practice.

4.4. Component 1: The Regolith Classification

4.4.1 What the Regolith Classification Identifies

The Regolith Classification describes the structural context of the landscape.

It does not, on its own, identify specific regolith materials or types in a geological or soil-mapping sense. Instead, it identifies areas of the landscape that share similar shapes and chemistry based on measured terrain and radiometric data.

It is assumed that these groupings represent regolith units that are similar in their measurable properties, not units that have been predefined or named based on the assumed material composition or evolutionary history. Despite this, the regolith classes show remarkable spatial coherence with regional geology and pedology.

4.4.2 How Regolith Types Are Interpreted

Understanding what type of regolith a given classification unit represents comes from interpretation.

This interpretation is primarily informed by existing geological information, including mapped geological units, stratigraphy, faults, and structural settings. Soil information also contributes, particularly to understanding the upper part of the regolith, but geology provides the main context for interpreting regolith materials and depth.

Because the Regolith Classification groups areas with similar physical and geochemical characteristics, it is usually straightforward for a trained geologist or pedologist to recognise the geological and soil materials associated with each regolith unit. In most cases, the classification aligns

closely with known geological settings, while also revealing important differences in regolith depth, weathering, and landscape position that are not captured by regional-scale geology or soil maps alone.

In this way, S-PAL separates objective classification from expert interpretation while allowing the two to work together.

4.4.3 The Hierarchical Structure of the Classification

The Regolith Type Classification is organised hierarchically. This means that it is structured in nested levels that move from broad regional patterns to finer local detail.

The classification has three levels:

- **Domains** are the broadest grouping. There are six Domains, representing major regional differences in landscape setting and geological context.
- **Families** sit within Domains and represent major regolith groupings with shared physical and geochemical characteristics. There are 12 families.
- **Siblings** sit within Families and capture finer-scale differences in regolith condition, depth, texture, and landscape position. There are thirty-five Siblings.

Each Sibling belongs to one Family, and each Family belongs to one Domain. This structure works like a family tree in which closely related units share common characteristics and a common origin. The hierarchy reflects the genetic relationships in how regolith forms and evolves across the landscape.

This organisation allows users to work at different scales while retaining context, from broad regional patterns to local detail, without losing the connection between them.

4.5 Layer 1: The Regolith Type Classification

4.5.1 What the Regolith Type Classification Shows

The Regolith Type Classification shows the different types of regolith across Northland and where each type occurs.

It does not name the materials in the way a geological or soil map would. Instead, it groups areas of the landscape that share similar shapes and chemistry based on measurements from LiDAR and AGRS. The assumption is simple: areas that appear alike and have similar chemistries are likely to be made of similar materials and have formed in similar ways.

Although the classification does not start with any preconceived ideas about what should be where, the resulting groups match remarkably well with existing geological and soil maps. This gives us confidence that the classification captures real differences in the regolith.

4.5.2 How We Interpret What Each Class Means

This classification indicates *where* different regolith types occur. Understanding *what* each type is made of comes from interpretation.

This interpretation draws mainly on existing geological maps that show rock types, faults, and how different formations relate to each other. Soil maps are also helpful, particularly for understanding the upper part of the regolith. Because each classification group shares similar physical and chemical characteristics, a trained geologist or soil scientist can usually recognise what materials are present.

In most cases, the classification aligns closely with known geology, but it also reveals important differences in regolith depth, weathering, and landscape position that regional-scale maps do not capture.

In this way, S-PAL keeps the objective classification separate from expert interpretation while allowing the two to work together.

4.5.3 The Three-Level Structure

The Regolith Classification is organised like a family tree, with three nested levels that move from broad regional patterns to finer local detail.

- **Domains** are the broadest level. There are six Domains, representing major regional differences in landscape setting and geological history. Think of them as the main branches of a family tree.
- **Families** sit within Domains. There are 12 families, each representing a major regolith grouping with shared physical and chemical characteristics. These are similar to the smaller branches within each main branch.
- **Siblings** sit within Families. There are thirty-five Siblings, capturing finer-scale differences in regolith condition, depth, texture, and position on the slope. These are similar to the individual members within each family group.

Each Sibling belongs to one Family, and each Family belongs to one Domain. Closely related units share common characteristics and a common origin, just like members of a real family. This structure

allows users to work at different scales, from broad regional patterns to paddock-level details, without losing the connection between them.

4.5.4 How the Classification Was Built

The Regolith Classification was built using a statistical method called hierarchical cluster analysis.

In simple terms, this method groups parts of the landscape based on how similar they are to each other. It works from the bottom up: areas that are most alike in terrain shape and radiometric response are grouped together first. These small groups are then combined into larger groups based on similarity, and so on, until the entire region is organised into a nested structure.

Because of this approach, the classification emerges naturally from the data. It is not drawn by hand and is not forced to match the existing maps. High-resolution measurements are the source of truth; the data reveal the natural grain of Northland's regolith.

4.6. Layer 2: The Regolith Activity Index

The Regolith Activity Index indicates how active or stable the regolith appears to be.

It is derived from radiometric potassium signals (radioactive potassium 40 (^{40}K)). Potassium is one of the elements measured by AGRS, and its concentration in the regolith changes over time as materials weather, erode, mix, or get buried by fresh sediment.

- **Higher values** indicate regolith that appears younger, more recently disturbed, or actively being reworked.
- **Lower values** indicate a regolith that appears older, more weathered, and relatively stable.

The Regolith Activity Index does not map individual slips or erosion scars, assign dates, or identify causes. It provides a broad picture of relative activity across the landscape, highlighting areas where the regolith shows signs of ongoing change versus areas that appear stable.

River channels and floodplains often exhibit high values because they receive regular deposits of fresh sediments. This fresh material has not yet weathered, so it retains higher potassium levels than older, more stable, nearby surfaces.

4.7 Layer 3: The Overland Flow Index

The Overland Flow Index indicates where water is likely to run off across the land surface rather than soak into the ground.

Surface runoff is an important driver of erosion; however, not all runoff causes erosion. Much depends on how well the topsoil holds together and whether it is protected by vegetation. Runoff may sweep up loose material such as dead leaves, animal dung, silt, and clay without cutting into the soil itself. For this reason, the Overland Flow Index should be considered an indicator of erosion potential, not a guaranteed source of erosion.

The index combines several factors:

- **Slope** (from LiDAR) - steeper slopes shed water faster
- **Regolith permeability** (from AGRS and soil data) - how easily water soaks in

- **Long-term rainfall patterns:** how much water the landscape typically receives.

High values indicate areas where runoff is more likely. Low values indicate areas where rainfall is more likely to soak into the ground. This layer captures surface-water behaviour separately from deeper regolith instability.

4.8 Layer 4: The Terrain Ruggedness Index

The Terrain Ruggedness Index indicates where the land surface is rough and uneven.

It is calculated entirely from LiDAR data and measures the extent to which terrain varies over short distances. Rough, irregular terrain often indicates past or ongoing erosion; landslide scars, slump blocks, gullies, and exposed bedrock all create high ruggedness values. Smooth terrain typically indicates stable slopes or areas where sediment has been deposited.

This layer is particularly useful for identifying areas with a history of mass wasting, even where vegetation has regrown and scars are no longer visible on aerial photographs.

4.9 Layer 5: The Erosion Susceptibility Layers

The Erosion Susceptibility Layers bring together information from the other S-PAL layers to show where erosion is most likely to occur.

Susceptibility is not measured directly; it is derived by combining the Regolith Activity Index with the Overland Flow Index to highlight areas of greater susceptibility. Different combinations may be used for different purposes, for example, assessing the risk of shallow landslides versus the risk of surface erosion by runoff.

Because the susceptibility layers are built from the underlying components, we can always trace *why* an area has been rated as high- or low-risk. Transparency is a key strength of the S-PAL framework.

4.10 How the Layers Work Together

Each S-PAL layer describes a different aspect of the same landscape.

- The **Regolith Classification** tells us what types of regolith are present and how they relate to each other.
- The **Regolith Activity Index** indicates whether the regolith appears stable or active.
- The **Overland Flow Index** indicates where water is likely to run off and potentially carry sediment to waterways.
- The **Terrain Ruggedness Index** indicates where the terrain shows signs of past or ongoing erosion.
- The **Erosion Susceptibility Layers** combine these to highlight areas at greatest risk.

By keeping these layers separate, we can explain *why* an area has been rated as it has. If a paddock shows high erosion susceptibility, we can look at the individual layers to understand the reason: is it

because the regolith type is naturally weak? Because the slope sheds water rather than absorbing it? Is the terrain already showing signs of past landslides?

This transparency makes S-PAL easier to trust, check, and apply in practice.

4.11 Why S-PAL Separates Structure from Behaviour

S-PAL is designed to separate *regolith* from *how it behaves*. These are related but different things, and keeping them apart is important for understanding erosion.

- **Regolith structure** refers to the physical makeup of the regolith: what materials are present, how weathered they are, how thick they are, and how they are arranged across the landscape. In S-PAL, regolith structure is captured by the Regolith Type Classification.
- **Regolith behaviour** refers to how the regolith responds to outside influences such as rainfall, wet and dry cycles, and position on the slope. In S-PAL, behaviour is captured by the Regolith Activity Index, and at a hydrological level, by the Overland Flow Index.

Why does this separation matter? This is because, despite being formed in the same rock or sediment type, the regolith can behave very differently in different settings. A clay-rich regolith on a gentle, well-drained slope may have remained stable for several decades. The same material may fail repeatedly on steep slopes with poor drainage. By keeping structure and behaviour separate, S-PAL can capture both the underlying similarity (same regolith type) and the important difference (one is stable, one is not).

This separation also makes S-PAL transparent. When an area is flagged as high susceptibility, we can trace back exactly why, is it because of the regolith type, or because of how that regolith is behaving in that particular location?

4.12 Scale vs Resolution: Why Both Matter

To understand how S-PAL fits alongside existing maps, it helps to understand the difference between scale and resolution:

- **Scale** is about the map's zoom level, the ratio between distance on the map and distance on the ground. Regional geological and soil maps are typically drawn at scales like 1:50,000 or 1:250,000. At these scales, maps are designed to show broad patterns over large areas. Northland's Land Use Capability (LUC) mapping is presented at 1:63,360 scale.
- **Resolution** is about the smallest feature that you can actually see or measure. This depends on how closely spaced the original measurements are or how small the mapped areas are. For example, although the LUC mapping is presented at 1:63,360 scale, the average size of each mapped unit is about 250 hectares. In practical terms, this means that variations in soil or landform smaller than approximately 500 × 500 m are lumped together within larger mapping units.

The S-PAL Framework uses much higher-resolution data:

- **AGRS**: on the ground resolution of 40–50 metres
- **LiDAR**: elevation data captured at 1-metre spacing

This means that S-PAL can detect variation at scales that regional maps cannot down to property level and, in many cases, paddock level.

4.13 How They Work Together

Regional geological and soil maps provide essential context. They explain *why* the landscape behaves as it does and the underlying rock types, faults, and broad soil patterns that control how regolith develops. S-PAL does not replace these maps. Instead, it works alongside them, revealing fine-grained variation *within* broader patterns.

Think of it this way:

Map Type	What it tells you
Geological maps	<i>Why</i> the landscape behaves as it does - rock types and structural controls
LUC mapping	<i>What</i> broad land capability patterns exist
S-PAL	<i>Where</i> within those patterns the critical variations occur that need targeted management

All three are valuable. They answer different questions at different scales.

4.14 What S-PAL Is—and What It Is Not

The S-PAL is:

- A landscape-scale framework
- Built entirely from measurement data (LiDAR and AGRS)
- Designed to identify differences in the character of the regolith and its activity

S-PAL is not:

- An inventory of slips, slides, or erosion scars
- A prediction of erosion rates or sediment loads
- A replacement for soil or geological maps.

S-PAL does not assign blame, prescribe actions, or judge land use. It provides the physical context needed to understand erosion susceptibility and the high-resolution detail needed to target management where it will be most effective.

5. Learning Module 4: The Source–Pathway–Receptor Model

5.1 Introduction

This module introduces the most important concept for putting S-PAL into practice: the **Source–Pathway–Receptor (SPR) model**.

If S-PAL tells you *what* the landscape is made of and *how* it behaves, the SPR model tells you *what to do about it*. It provides a simple, logical way to consider erosion and sediment movement and, more importantly, where to intervene to make a real difference.

The SPR model works at every scale, from an entire Freshwater Management Unit to a single paddock. It applies to whether your goal is to protect water quality, conserve soil, or both. Once this is understood, using the S-PAL framework becomes straightforward.

5.2 Why This Matters

While land use, whether farming, horticulture, forestry, roading, or urban development, is often seen as the main cause of water quality problems, it is important to recognise that the land itself sets the stage for what kinds of issues occur and how severe they are.

Human activities do not create sediment; it exists naturally in landscapes. However, our actions can disturb, release, and redistribute it. Whether sediment reaches a waterway depends heavily on the natural features of the land: regolith type, slope, drainage, and how well connected a source area is to the stream network.

This has critical implications for management; *similar activities can lead to very different outcomes depending on where they take place*. Some areas are naturally more susceptible to sediment loss, whereas others are more resilient. A hillslope on clay-rich Mangakahia mudstone may fail repeatedly, while a neighbouring slope on Kerikeri basalt remains stable under identical rainfall and land use.

Understanding this helps us work *with* the landscape rather than against it. Instead of applying the same management everywhere, we can target the right solutions in the right places, focusing on effort and investment where it will make the most difference.

This was the origin of the SPR model. It answers two essential questions:

- 1. Where should we act?** — Identify which source areas are connected to waterways and which pathways carry the most risk.
- 2. Why should we act there?** — A well-connected source, even a small one, can contribute more sediment to waterways than a larger source with no clear pathway. Prioritisation based on connectivity ensures that limited resources are directed where they will have the greatest impact.

However, the SPR model does not replace good land management. It sharpens it, helping landowners, advisors, and councils focus on the parts of the landscape where action will deliver real results.

5.3 What is the Source-Pathway-Receptor Model?

Think of it like tracking a parcel through the postal system (Figure 15).

 SOURCE Where does sediment originate? Erosion and Mass Wasting Areas	 PATHWAY How does it get there? The pathway runoff (water is the vehicle) + sediment takes to an intermittent or perennial waterway.	 RECEPTOR (RECEIVING ENVIRONMENT) Where does it end up? Ditch drain, small creek, stream, river, lake, estuaries, harbour.
		

Figure 15: The three components of the Source–Pathway–Receptor model. Source: LWS.

The first step is to identify source areas (critical source areas) which may include areas of active cultivation or intensive grazing, in addition to erosion. Second, trace where water will leave the source area, follow the likely pathway, and see if it reaches an intermittent or perennial stream (Figure 16).

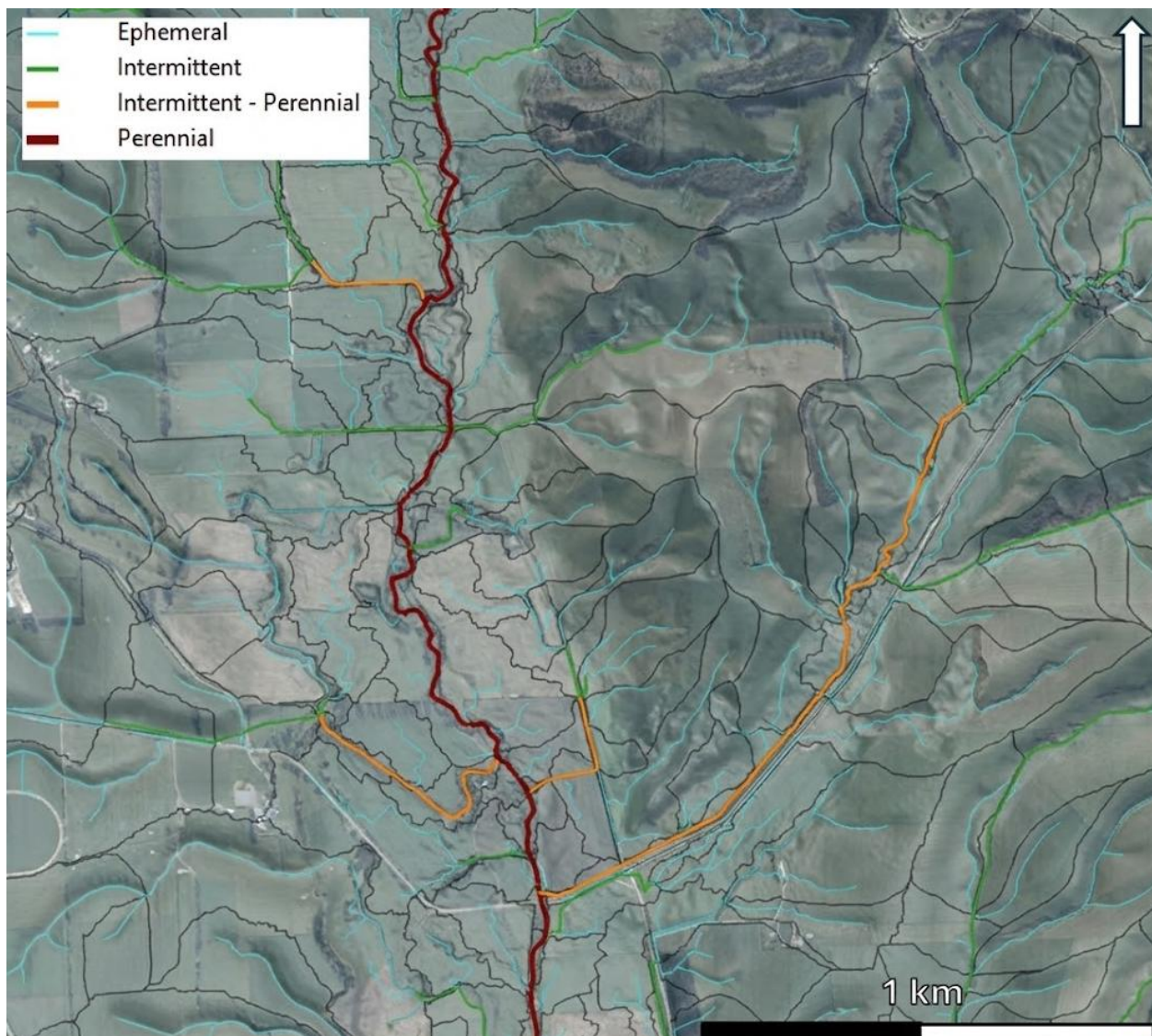


Figure 16. There are three stream types: ephemeral, intermittent, and perennial.

Of the three different stream types, an ephemeral stream typically flows only under wet weather, a handful of times a year. These are the key pathways to intersect runoff, either by slowing down the flow or by trapping and treating the runoff. An intermittent stream has water in it for several months of the year, and open ditches are often intermittent. They tend to flow in the winter and dry up during the summer months. A perennial stream is one that flows year-round, except during a major drought.



Figure 17. An example of interception of runoff along an ephemeral pathway (swale) in a paddock. Here, a daisy chain (there are three of these structures in a row, one is hidden from view) of boulder check dams was placed within an ephemeral pathway. Jack Russel for scale (courtesy of Chris and Andrea Bullied, Waimea Catchment Group).

The idea is to slow the water down along the ephemeral flow path (Figure 17). Once runoff has entered an intermittent or perennial stream, it is too late.

5.4 Why Does This Matter?

5.4.1. The Critical Insight

Finding an erosion-prone area (**Source**) is only part of the picture.

An eroding hillslope that drains onto a flat terrace may have a limited downstream impact—the sediment is deposited before it reaches a waterway. However, the same erosion may still be a concern from a soil conservation perspective because productive soil is being lost.

A minor or moderate source directly connected to an intermittent or perennial waterway may contribute far more sediment than a larger source with no clear pathway. This is especially true when land use is intensive. This connection matters as much as the source itself.

Bottom line: Prioritisation depends on the connection between all three components, not just how erosion-prone an area appears to be.

- For **water quality**, the focus should be placed on sources that are well connected to waterways.
- For **soil conservation**, focus should be placed on stabilising source areas, regardless of connectivity.
- For **best results**, do both stabilise sources and intercept pathways.

5.4.2. Key Action: Mitigate Along the Ephemeral Pathway

If you can do only one thing, do this: *intervene along the ephemeral pathway before the runoff reaches an intermittent or perennial waterway.*

Why? Once sediment-laden water enters a permanent or seasonal waterway, it is too late.

However, if you slow water down while it is still on an ephemeral pathway, a swale, a hollow, a paddock gully, sediment drops out. Vegetation filters it. Ponds trap it. Every small series of small interventions along a flow path reduces what reaches the stream.

6. Learning Module 5: Applying the S-PAL Framework

6.1. Identifying Erosion Prone Land and Mitigation

The previous modules explained what the S-PAL layers were and what they revealed about the landscape. This module shows how to apply that knowledge to identify erosion-prone land and plan effective mitigation.

The application of the S-PAL Framework is guided by the Source–Pathway–Receptor (SPR) model.

Think of it this way:

- **S-PAL tells you what the regolith is and how it is likely to behave**
- **SPR provides a way of addressing what you find**

When combined, they provide a systematic approach to erosion management that works at any scale, from a single paddock to an entire Freshwater Management Unit.

6.2 The Bottom Line

The S-PAL framework can indicate where regolith is active, where runoff is likely, and where the terrain shows signs of past erosion. However, information alone does not reduce sediment in waterways. What matters is how information is applied, where you look, what you look for, and how you decide what to do next. The SPR structures every step of the workflow that follows.

6.3 What You Need Before You Start

Before beginning your assessment, make sure you have the following data layers loaded into your GIS:

Data Layer Checklist

Base Layers

- ☐ **Hillshade Model** (for visual interpretation)
- ☐ **Recent (c. 12 months), high resolution aerial imagery** (for identifying visible erosion and mass wasting features)
- ☐ **DRN Watersheds at 2 ha** (for identifying sediment catchment)
- ☐ **Digital River Network (DRN) river lines** (for tracing pathways) - ideally discriminating ephemeral, intermittent, and perennial streams.
- ☐ **Q-Map v3 Geological Layer** (rock and sediment type, age, etc.) - optional

Boundary Layers (as needed)

- ☐ **FMU boundaries** (if working at regional scale)
- ☐ **Subcatchment boundaries** (if working at catchment scale)
- ☐ **Property boundaries** (if working at farm scale)

S-PAL Framework

- ☐ **DRN Watershed Susceptibility Layer** (50:50 RAI + OLF - for screening)
- ☐ **Regolith Activity Index (RAI)** (regolith activity status)
- ☐ **Overland Flow Index (OLF)** (surface runoff - hydrological)
- ☐ **Regolith Classification** (Domain–Family–Sibling - understand the setting)

- ☐ **Distance to Faults and Folds raster** (major structural features that influence regolith stability) - optional
- ☐ **LiDAR derived Terrain Ruggedness Index** (highly correlated with mass wasting features) - optional

 **Tip:** To focus on your area of interest, consider **inverting your boundary layer** to mask surrounding areas. This helps concentrate attention on the area under assessment.

6.4 What You Will Learn

By the end of this module, you will be able to:

1. Set up a GIS workspace with the required layers.
2. Use the Regolith Type Classification and Look-up Tables to understand the landscape setting.
3. Screen for potential hotspots using the DRN Watershed Susceptibility Layer.
4. Investigate hotspots using the Regolith Activity Index, Overland Flow Index, Terrain Ruggedness Index, and recent aerial imagery.
5. Identify actual erosion and mass wasting features — slips, slumps, gullies, bare ground, and soil creep.
6. Apply SPR thinking to trace sediment Pathways from Source to Receptor.
7. Prioritise areas for action based on connectivity to receptors.
8. Identify where to intervene along pathways to intercept the sediment.

6.5 A Note on Skills

Steps 1 and 2 require only basic GIS skills, loading layers, navigating the map, and zooming in on the area of interest. Steps 3 and 4 involve interpreting the S-PAL layers and comparing them to aerial imagery, which takes little practice but quickly becomes intuitive. Steps 5, 6, and 7 involve recording what you find and making decisions about priorities and skills that improve with experience.

If you are new to GIS, do not be put off. The workflow is designed to be straightforward, and the visual nature of the layers means that you can learn a lot simply by exploring the data and comparing what you see on the screen to what you know about the landscape.

6.6 Step-by-Step Guide

Now, let us work through each step in detail. Remember: These steps work at **any scale** — FMU, catchment, or property.

SET UP YOUR WORKSPACE

What to do:

1. Load your base layers
2. Load your boundary layer(s) (FMU, catchment, or property)
3. Load the S-PAL layers

6.7. STEP 1: Screen by Watershed Susceptibility Layers (WSL)

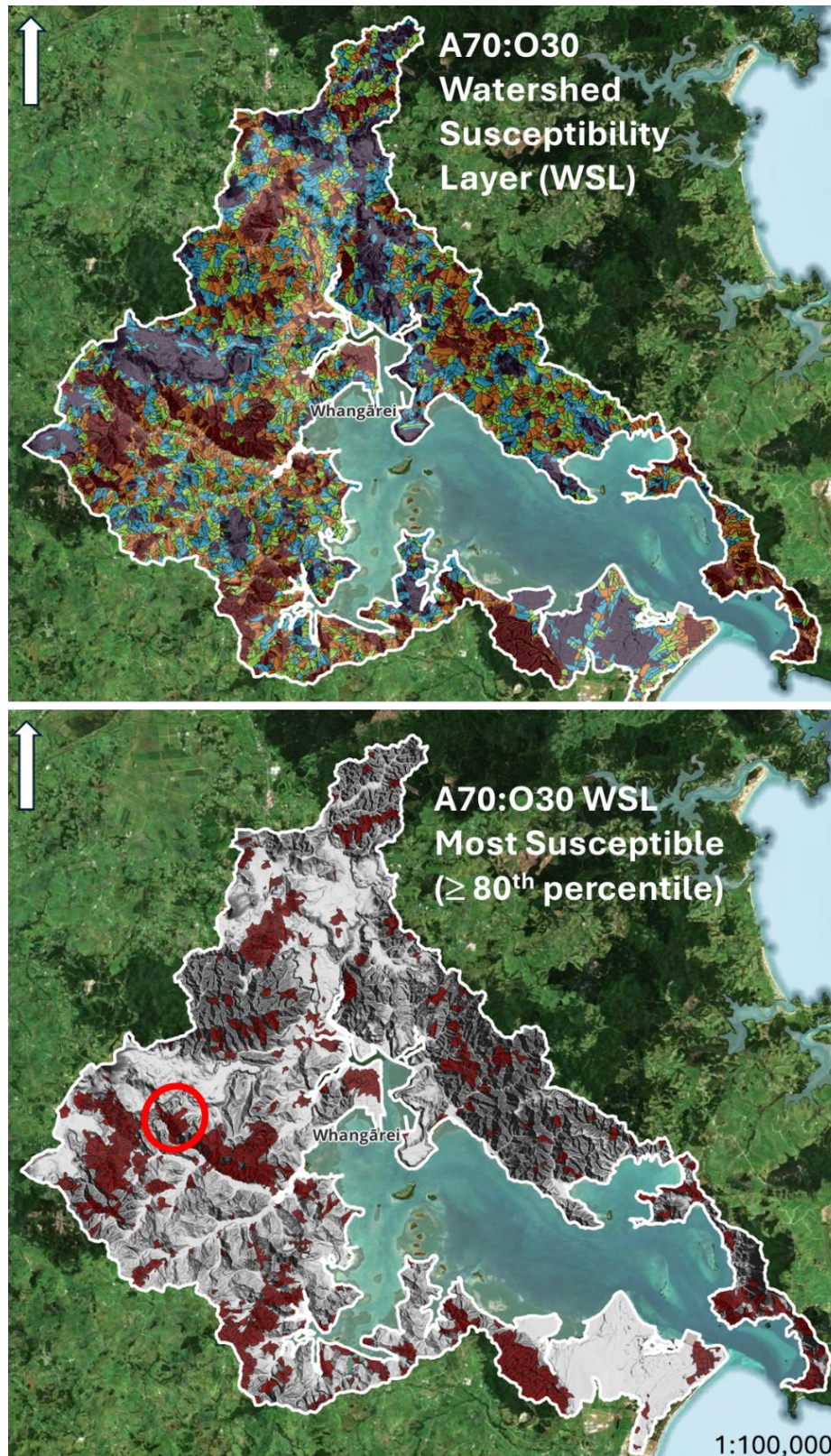


Figure 18. Watershed Composite Susceptibility Layer (WSL). Top: 70% Regolith Activity Index and 30% Overland Flow Index (A70:O30). Bottom: WSL filtered to show the most susceptible watersheds ($\geq 80^{\text{th}}$ percentile). The red ellipse represents an area of interest (AOI) for additional investigation.

6.7.1. Toggle on your BOUNDARY layer

Toggle on your boundary layer (FMU, Catchment, Property (e.g. farm, forest, etc.)). In GIS terms, this is described as your initial Area of Interest (AOI).

6.7.2 Use the DRN Watershed Layer as a 1st Pass Screening Tool

Use the Watershed Susceptibility Layer (WSL) as a 1st pass screening tool for identifying watersheds with elevated susceptibility – aka Source Watersheds (Figure 18). The WSL brings together several different signals that help identify priority areas for mitigation, including regolith type (Sibling), regolith activity (RAI), and runoff potential (OLF) (Table 1).

Table 1. Layers within the DRN Watershed Susceptibility Layer

Field	Type
fid	Integer64
OBJECTID	Integer64
Upstream_Slope_Mean	DRN
Upstream_Elevation_Mean	DRN
Upstream_Area	DRN
HydroCat	DRN
OLF_Classes_Majority	OLF
Regolith_Activity_Class_Majority	RAI
A70_O30_Quantile_Majority	Composite Susceptibility
A60_O40_Quantiles_Majority	Composite Susceptibility
A50_O50_Quantiles_Majority	Composite Susceptibility
A40_O60_Quantiles_Majority	Composite Susceptibility
A30_O70_Quantiles_Majority	Composite Susceptibility
Sibling_Class_Majority	Regolith Classification
Slope_Index_Mean	OLF
HYD_Index_Mean	HYD

HYD = Hydrological Index

If your AOI starts at stops at the FMU level, you may not need to delve any deeper, although our advice would be to undertake a careful evaluation of the changes in highly susceptible watersheds as part of cycling through the difference composite WSL, that is, from A70_O30 (RAI = 70% and OLF = 30%) to A30_O70 (RAI = 30% and OLF = 70%).

Table 2. Decision Guide: What Do the Combinations Mean?

Regolith Activity Index (RAI)	Overland Flow Index (OLF)	What This Suggests
HIGH	Low/Mod	Regolith is active due to mass wasting instability or erosion, but OLF assessment suggest low surface runoff potential. Check carefully for evidence of soil creep, slips, slumps, earthflows, or even erosion by water. Given the OLF layer is dependent on the 1:63,000 soil map to derive the soil structural vulnerability index, this layer has an effective resolution of c. 300 ha so may miss property scale runoff.

Regolith Activity Index (RAI)	Overland Flow Index (OLF)	What This Suggests
Low/Mod	HIGH	Surface runoff dominant — but may not be associated with high rates of erosion. Check carefully for visual signs of sheet erosion, rills, gullying. Note the airborne radiometric survey was conducted in 2012, large scale slips and slides or slumps that have occur since the survey may be missed.
HIGH	HIGH	The regolith is active as is surface runoff. Check carefully for visual signs of mass wasting and erosion. These areas have a high susceptibility.
Low	Low	Land use practices and intensity determine erosion risk (bare soil, pugging, intensive grazing).

6.7.3. Key Points:

- It is important to note that just because there is runoff, this does not mean that the regolith is actively eroding.
- Further work is required to validate the susceptibility occurring within watersheds that are identified by the WSL as having elevated susceptibility (see following text).

6.7.4. Filter the WSL by Susceptibility

Apply a filter to the selected WSL. You may be interested in identifying the least or most susceptible watersheds within an FMU. In the example above, we have filtered out all watersheds with a susceptibility <80th percentile (Figure 18). This enables us to focus on the most susceptible watersheds.

6.8. Step 2: Identify Regolith Types within AOIs

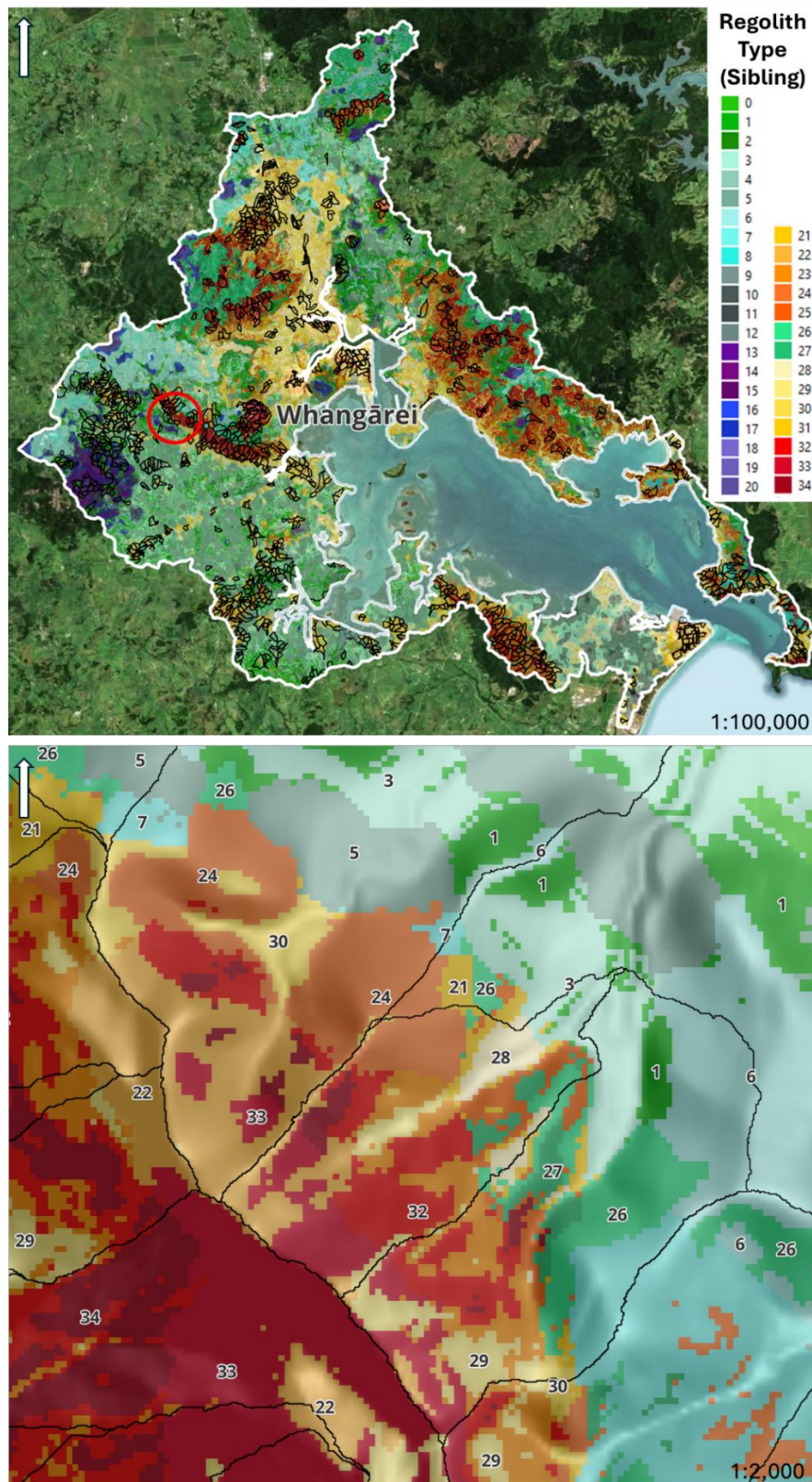


Figure 19. S-PAL Regolith Classification, Sibling Level (most detailed) within Primary AOI (Whangarei FMU). Top: Regolith Type Classification across Whangarei FMU, where red circle = secondary AOI. Bottom: Regolith types within the secondary AOI. Types 22 – 24 and 32 – 34 are associated with the deeply weathered Greywacke (Waipapa Group) (Ancient Basement Rocks, similar to that of the Brynderwyn Hills. Green and gray reflect a transition to regolith formed in much younger marine sedimentary rocks (Ruatangata Sandstone).

6.8.1. Use the Regolith Types Lookup Table in the Appendix

Use the Regolith Look-up Tables in the Appendix to this User Guide to determine the Regolith Types within your AOI(s). In this example, within the secondary AOI, the main regolith types within the areas of greatest susceptibility are associated with deeply weathered Greywacke that makes up the basement rock of Northland (Figure 19). This ancient greywacke basement rock (primarily belonging to the Waipapa Terrane) occurs at the surface along the eastern coastline and eastern hills and forms a regolith that is notoriously unstable, for example, Brynderwyn Hills. Within the secondary AOI, the green and grey classes reflect a transition to regolith formed in much younger, marine sedimentary rocks (Ruatangata Sandstone). These more recent sediments overlie the much older basement rock. Notably, where these younger materials occur, the severity of mass wasting and erosion decreases, as does the overland flow response (**see Steps 3 & 4**).

6.8.2 Why Regolith Type Matters

In the example above, the greywacke-derived regolith (Types 22–24, 32–34) and the Ruatangata Sandstone regolith behave very differently. The greywacke country slips. The sandstone country does not.

The S-PAL Regolith Type Classification identifies and encodes these differences. It captures:

- Rock type: ancient basement greywacke versus younger sandstone
- Regolith disturbance: how active or settled the surface materials are
- Steepness: gravitational potential for mass wasting
- Roughness: terrain ruggedness associated with past instability

Where the Ruatangata Sandstone mantles the basement rock, the classification picks up the shift: lower elevation, gentler slopes, lower TRI, and better soil drainage. These gradients are clearly associated with a reduction in mass wasting and erosion severity, as shown in **Steps 3 and 4**.

Key point: The Regolith Type Classification does not just label rock types. It encodes the landscape gradients that control erosion behaviour. Different classes reflect genuinely different conditions⁷.

Before moving to Steps 3 and 4, note which regolith types dominate the AOI. This will help interpret the activity and runoff signals that follow.

⁷ The Regolith Type Classification also opens the door to systematic analysis. A regional meta-analysis could identify which regolith types are consistently most susceptible and what erosion styles dominate each type. This work has yet to be undertaken but could support a knowledge framework with technical sheets for critical regolith types, drawing on expert input to recommend the most suitable mitigation approaches for each.

6.9. Step 3: Review RAI and OLF within your AOIs

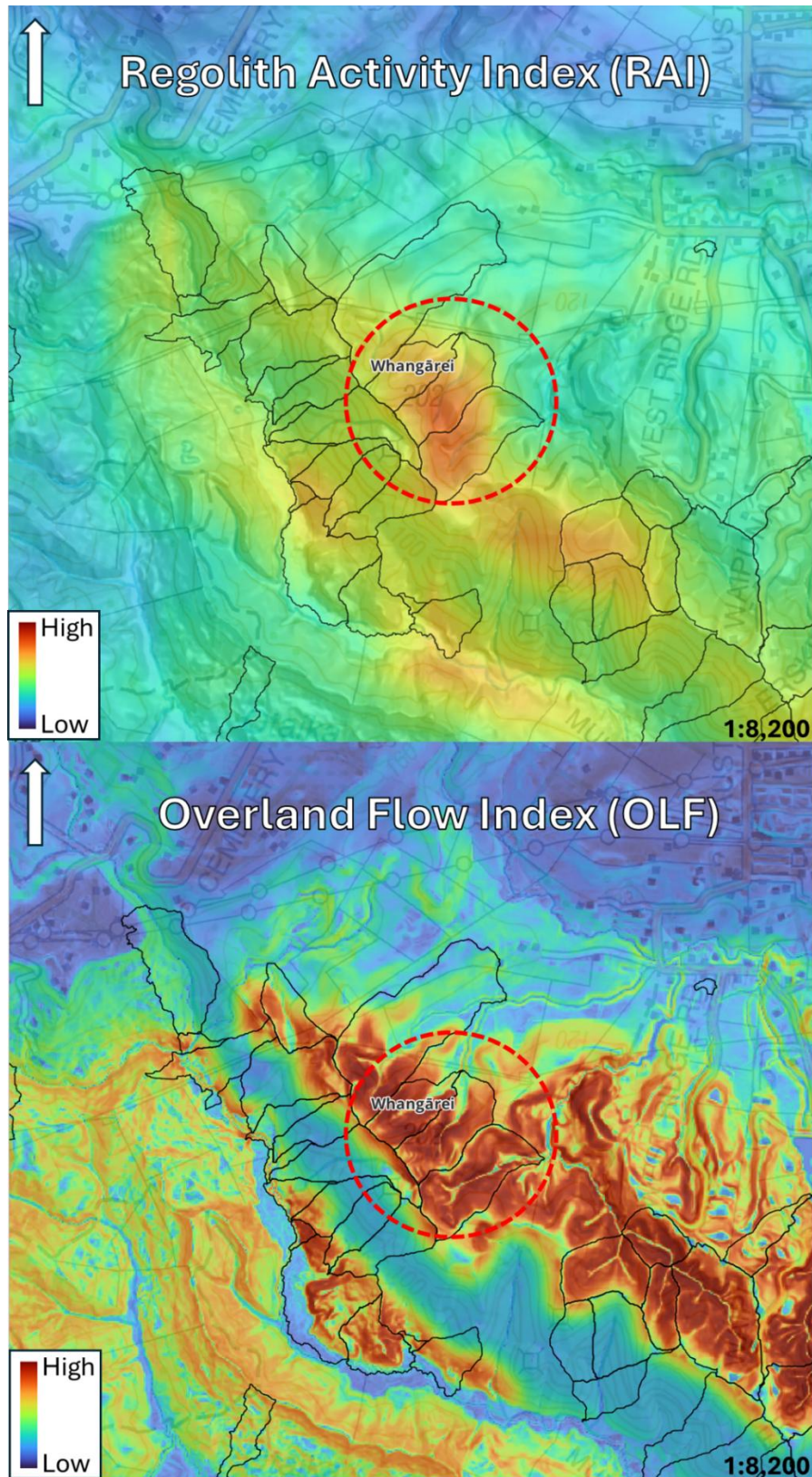


Figure 20. Top: Regolith Activity Index within the primary AOI (red ellipse in Figure 18). B. Overland Flow Index within the same AOI. The LiDAR-derived Hillshade Model and the Topo50 layers underlie each other. The red dashed circle is the secondary area of interest (AOI) as it has an elevated RAI score and elevated OLF score.

6.9.1. Toggle on the Regolith Activity Index (RAI)

The RAI shows where the regolith is most disturbed and areas where the radiometric data suggest recent exposure or active erosion (Figure 20). Toggle on the RAI layer and compare it to the regolith types identified in **Step 2**.

6.9.2. Toggle on the Overland Flow Index (OLF)

The OLF shows where the surface runoff potential is highest — a function of slope steepness and soil drainage properties (Figure 20). Toggle the OLF layer and compare it with the same area.

6.9.3. What the Figure Shows

Within the circled area,

- **RAI is elevated** - the regolith is active, indicating recent disturbance or exposure of underlying weathered subsoils or bedrock.
- **OLF is also elevated** - steep slopes and soil properties combine to produce high runoff potential

This is what high susceptibility looks like. The Composite Susceptibility Layer (**Step 1**) flagged these watersheds because it combines RAI and OLF. Here, we can see why both signals are elevated in the same location. The regolith is active, and runoff potential is high.

6.9.4. Linking Back to Regolith Type

Notice how both the RAI and OLF drop off markedly outside the circled area (Figure 20). This transition corresponds directly to the shift in regolith type identified in **Step 2** from the ancient greywacke (Types 22–24, 32–34) to the younger Ruatangata Sandstone.

The Regolith Classification captured this boundary. The RAI and OLF confirm this. Where the sandstone mantles the basement rock, regolith activity decreases, and the runoff potential drops. The layers tell a consistent story.

Key point: The Regolith Classification, RAI, and OLF are independent layers derived from different data sources, yet they align. This convergence builds confidence that the patterns are real and that the regolith-type boundaries mark genuine changes in landscape behaviour.

6.10. Step 4: Visual Validation Using Recent Aerial Imagery



Figure 21. Top: Aerial imagery of extreme soil creep (mass wasting), shallow landslides, and bare soil. Bottom: Zoomed in area within the red dashed rectangle. Visual imagery suggests a high sediment loss potential.

6.10.1. Toggle on Recent Aerial Imagery

The S-PAL layers indicate where susceptibility is elevated (Figure 21). Aerial imagery allows you to see what is actually happening on the ground. Toggle on recent (ideally < 12 months old) high-resolution aerial imagery and zoom in on the areas flagged in Steps 1–3.

6.10.2. What to Look For

Scan the imagery for visible signs of erosion and mass wasting.

- Soil creep, visible as terracettes (step-like ridges) across hillslopes
- Shallow landslides, often appearing as fresh slip scars lighter in colour
- Bare soil where vegetation cover has been lost
- Gullies incised into hillslopes
- Slumps where the ground has rotated or subsided

6.10.3. What the Figure Shows

The imagery confirms **Steps 2 and 3**. Within the greywacke regolith it's clear that:

- Terracettes are pervasive. Soil creep was active across all hillslopes.
- Shallow slips were visible as bare scars where the regolith failed.
- Bare soils are widespread. The vegetation cover has not recovered.

This is not subtle. The landscape was visibly unstable. The high RAI and OLF scores from **Step 3** were validated by what we can see in the imagery.

Key point: Visual validation closes the loop. The S-PAL layers flag potential, and the imagery confirms whether that potential is being expressed. Where you see features such as these, sediment loss occurs.

6.10.4. Susceptibility and Evidence of Failure

Areas classified as highly susceptible are more likely to show evidence of past and ongoing failures than are areas of low susceptibility. This may not be in the same location. Shallow landslides can occur anywhere within a susceptible zone. However, evidence will cluster within the same general regolith type⁸. The S-PAL framework identifies terrain that shares characteristics, making it prone to failure. Where the regolith type is susceptible, evidence of instability is widespread.

6.11. Step 5: Apply Source-Pathway-Receptor Framework to AOIs



Figure 22. Application of the Source-Pathway-Receptor Model to an AOI. Note that stabilisation at the source combined with interception (slowing the flow, trapping, or treating sediment) along the ephemeral pathway, prior to reaching a receptor, is required to mitigate sediment loss.

6.11.1. What is Source-Pathway-Receptor?

The Source-Pathway-Receptor (SPR) model provides a simple structure for thinking about sediment movement (Figure 22):

- **Source:** Where sediment is generated (the erosion and mass wasting features identified in Step 4)
- **Pathway:** The route sediment travels from source to waterway (ephemeral and intermittent channels, overland flow paths)

- **Receptor:** Where sediment ends up and causes harm (intermittent or perennial watercourses, wetlands, estuaries)

SPR is not a new layer. It is a way of organising what you have already found.

6.11.2. Toggle on the DRN Stream Network

Add the Digital River Network (DRN) to the map. If available, use a version that distinguishes ephemeral, intermittent, and perennial streams (Figure 22). This allows you to trace how sediment moves from hillslope sources to receiving watercourses. Otherwise, look carefully, using high-resolution imagery, and you can often see when channel formation starts, and a stream transitions from ephemeral to intermittent.

6.11.3. What the Figure Shows

The erosion features identified in **Step 4** is the **Sources**. Sediment mobilised from these areas enters ephemeral channels that flow only during and shortly after rainfall. These ephemeral streams feed into larger **Pathways** that carry sediment toward the **Receptor**, in this case an intermittent or perennial watercourse. Note there may only be a handful of runoff events each year that transport the majority of the annual sediment load to the **Receptor**.

The black polygon boundaries show the 2 ha DRN watersheds. Each watershed drains into its outlets. Tracing the blue lines downstream shows the connectivity from source to receptor.

6.11.4. Why SPR Matters for Mitigation

Effective sediment control requires action at more than one point:

- **At the source:** Stabilise the land to reduce sediment generation (e.g. retirement, planting, changed grazing).
- **Along the pathway:** Intercept and slow sediment before it reaches the receptor (e.g. sediment traps, vegetated buffers, constructed wetlands)
- **At the receptor:** Protect the watercourse margins to filter sediment and reduce direct delivery.

Intercepting along the **Pathway** (ephemeral runoff pathway, swale, etc.) may not be sufficient if the **Source** areas are highly degraded, as in the example used here. The SPR helps you to see the full picture and plan accordingly.

Key points: Not all sources are equally connected. A highly active source with a short, direct pathway to a receptor is of higher priority than a similar source with a longer, more attenuated pathway. SPR helps you prioritise based on connectivity, not just severity.

6.10.5. Repeat for Other AOIs

Once you have worked through **Steps 1–5** for your initial area of interest, repeat the process for other flagged watersheds or priority areas within your FMU, catchment, or property. The workflow is the same. Each iteration builds your understanding of where sediment sources are, how they connect to receptors, and where intervention will be most effective.

7. Appendix

7.1. S-PAL Regolith Type Lookup Guide

A simple guide to understanding the geology underlying each S-PAL Regolith Classification Type (class).

The S-PAL (Sediment-Process Attribute Layer) is a framework developed for Northland that combines multiple components to help understand erosion susceptibility across the region. This guide focuses on one component, the S-PAL Regolith Type Classification, and explains which landforms, rocks, and sediments are likely to underlie each class.

The regolith is all loose and weathered material that sits over the top of the unweathered bedrock and includes the soil zone and aquifer systems (Figure. A1). Soil erosion, which is the erosion of the uppermost part of the regolith, is not solely controlled by surface actions, such as rainfall, cultivation, and grazing. Often, the soil erodes when the regolith fails at depth, for example, slips, slides, and slumps, so it is wise to be aware of the sensitivity of the regolith to failure.

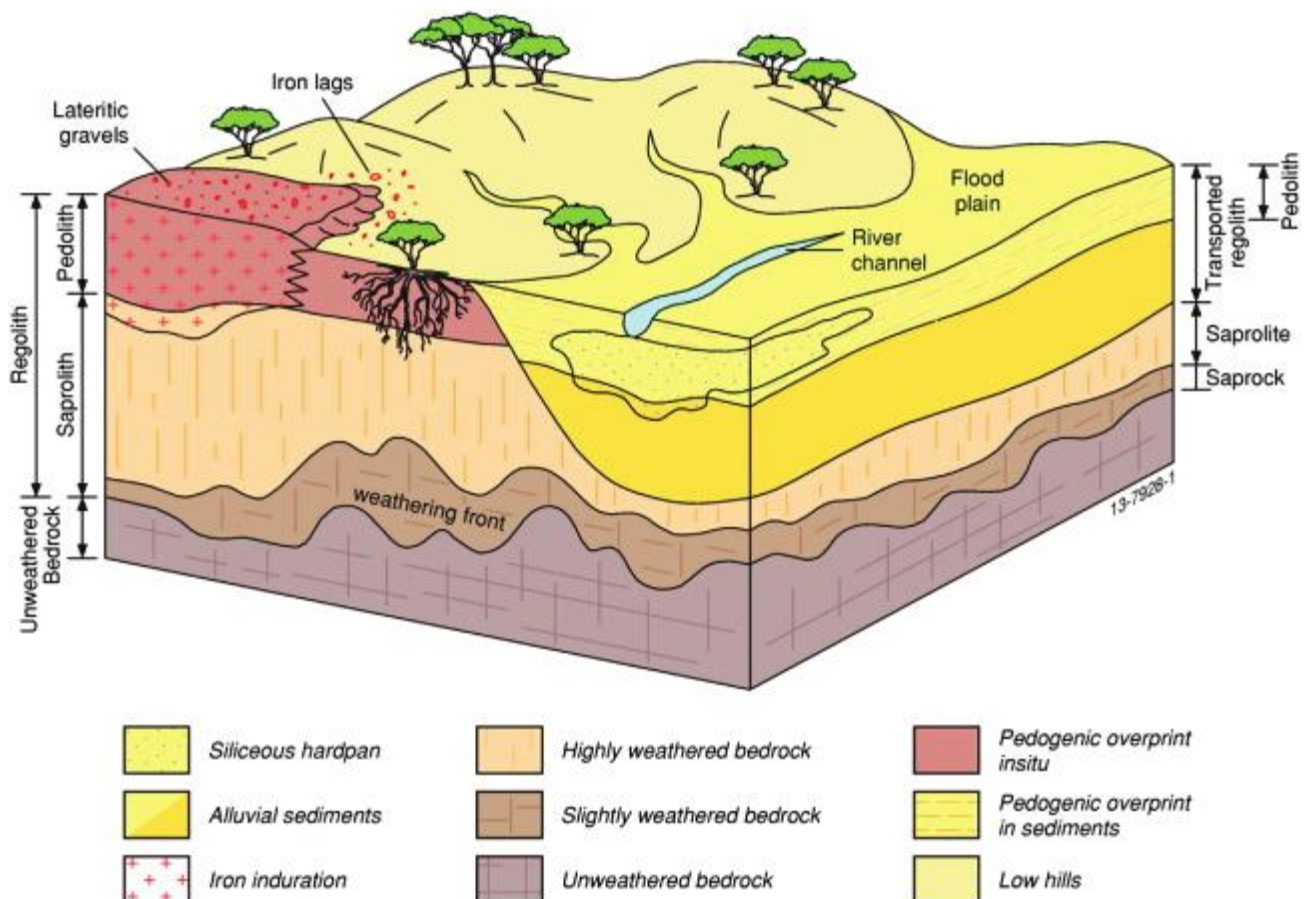


Figure A1. A diagram of the regolith, which includes the soil and weathered materials overlying the unweathered bedrock. The depth of the regolith varies from place to place, including the thickness of the soil component (diagram sourced from Wilford et al., 2016).

S-PAL FAMILY TREE

How Northland's Landscapes are Organised

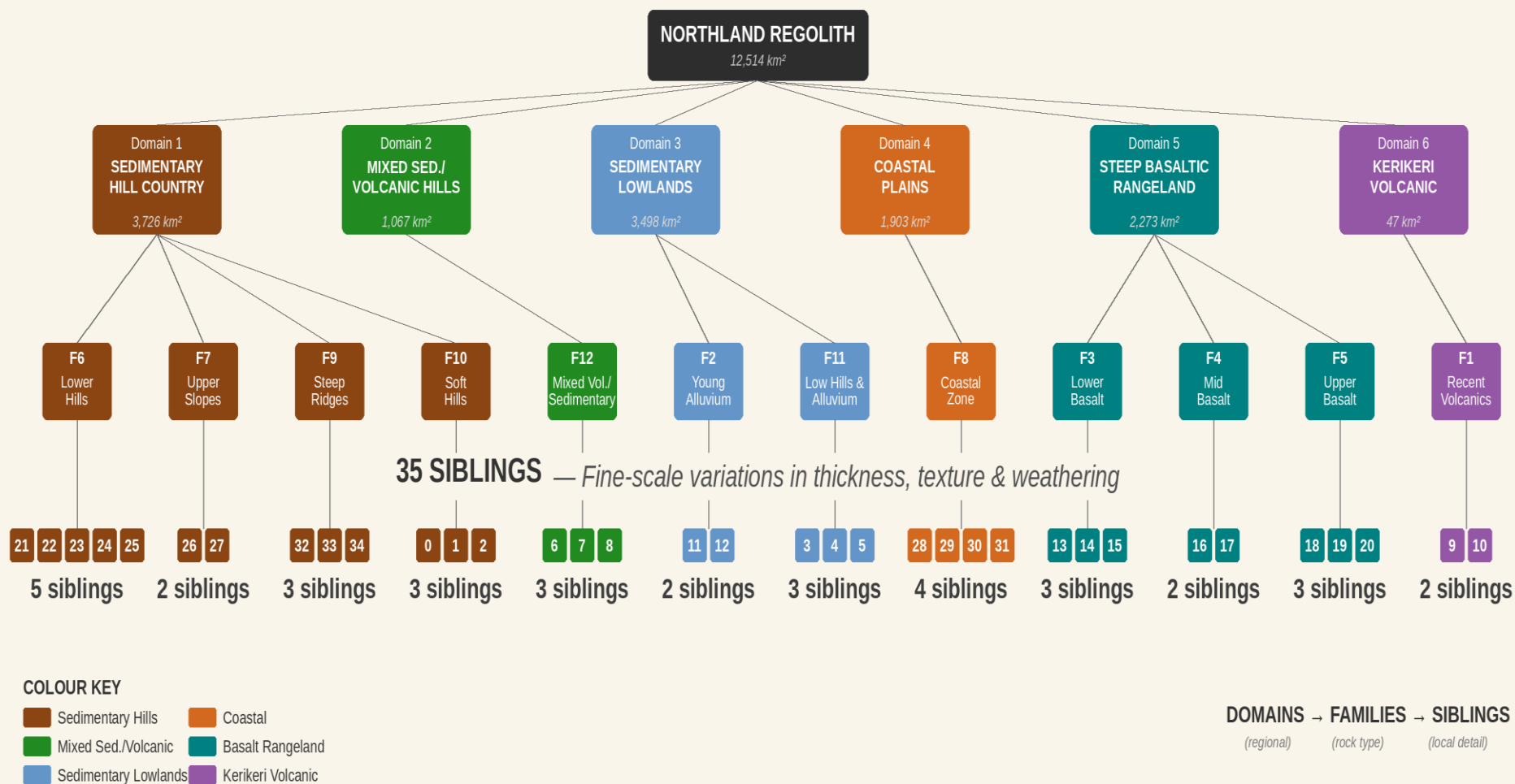


Figure A2. The S-PAL Family Tree shows different levels between Domains (100s – 1000s km²), Families (10s – 100s km²), and Siblings (1 ha to several km²).

The S-PAL Regolith Classification organises Northland's regolith into classes based on terrain shape (from LiDAR laser mapping) and surface chemistry (from a radiometric survey that measures natural radioactivity in rocks and soils). It tells you what type of regolith is present, the loose material (soil, weathered rock, and sediments) that sits above the solid, unweathered bedrock. Erosion and mass wasting occur within this loose material.

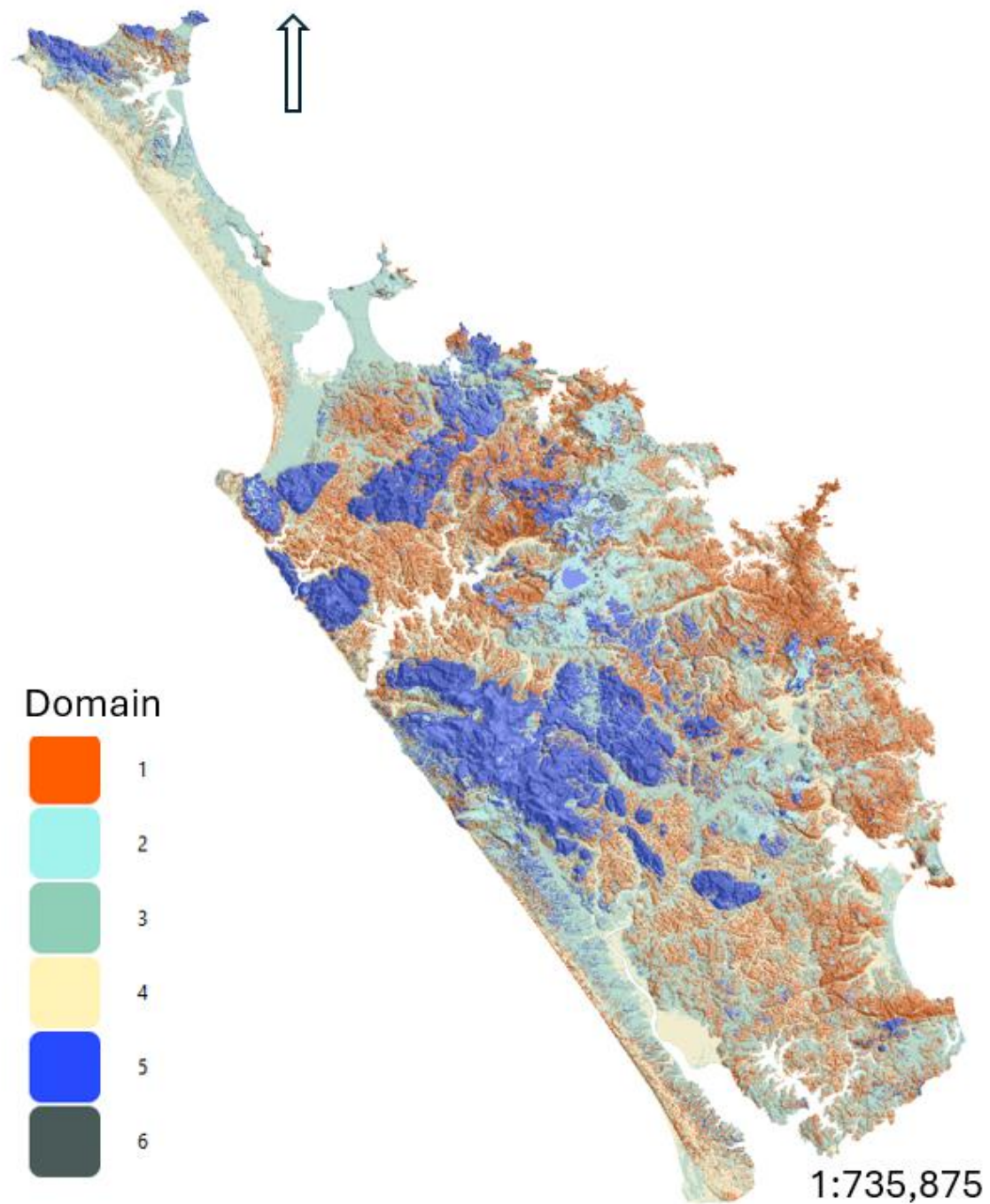
The classification uses a family tree structure with three levels: Domain (Level 1), Family (Level 2), and Sibling (Level 3) (Fig. 2). As you move down through the family tree from Domain to Sibling, the classes become smaller in area and more specific in character, and there are more of them.

There are three levels in the S-PAL Regolith Classification

- **Domains** (6 types) - The broadest level, representing major landscape regions (100s–1000s km²).
- **Families** (12 types): The middle level, reflecting dominant rock types and rock type groupings (10s–100s km²).
- **Siblings** (35 types): The finest level, showing local variations in regolith thickness, texture, and weathering (1 ha to several km²).

7.2. Regolith Type Lookup: Domain (Level 1)

Table 1 provides a general description of the landforms and rock types associated with the six S-PAL Domain classes (Figure. A3; Table A1).



Domain	Elevation (m RSL)	Ruggedness	K (%)	Elevation Rank	Ruggedness Rank	K Rank	Rank Code
1	102	5.1	1.6	4	1	2	4-1-2
2	180	2.2	1.3	3	4	5	3-4-5
3	49	1.3	1.3	6	6	3	6-6-3
4	53	1.7	1.8	5	5	1	5-5-1
5	250	5.0	1.2	1	2	6	1-2-6
6	194	2.3	1.3	2	3	4	2-3-4

Figure A3. Domain Level of the Regolith Type Classification hierarchy. Where K Rank = the abundance of radioactive potassium (^{40}K) in the regolith. The ranks were 1 = highest and 6 = lowest.

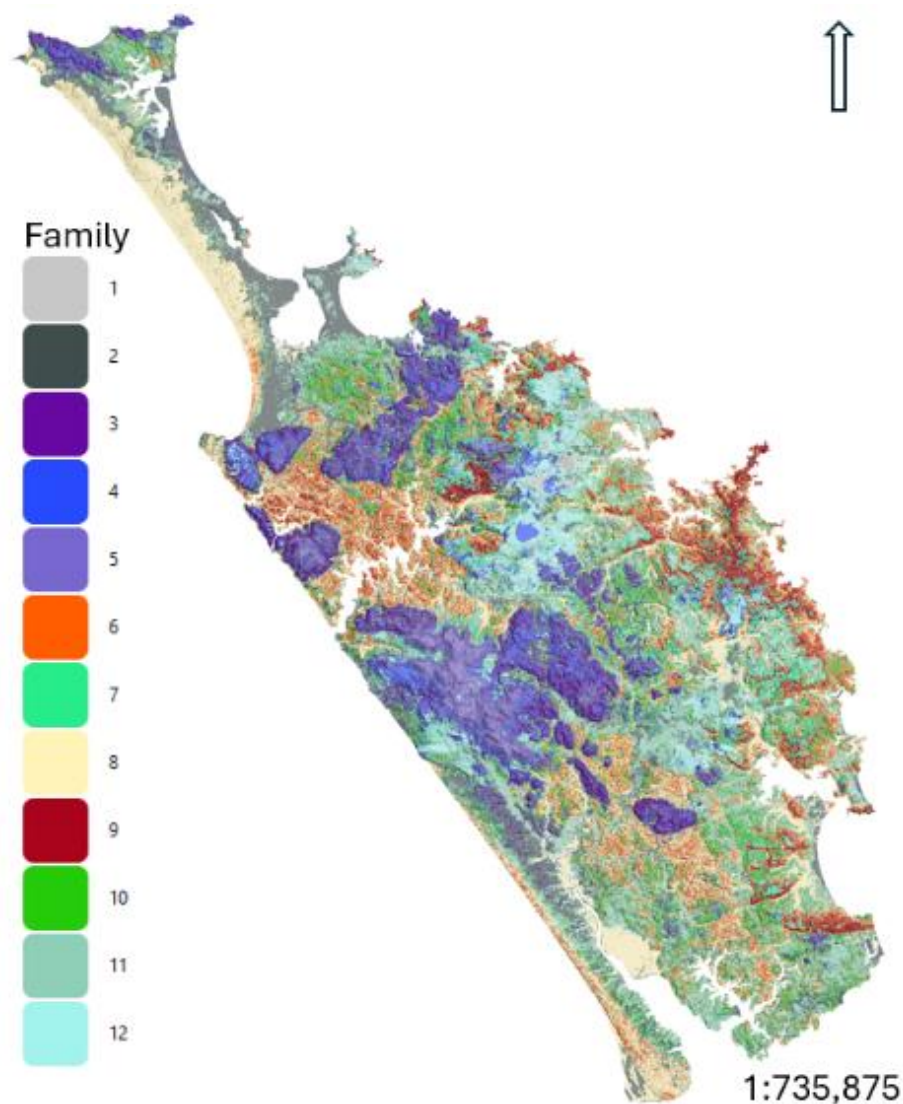
Table A1. S-PAL Regolith Type, Domain Level, Landform, and Geological Lookup.

ID	Domain Name	Main Rock Types	What This Means	Typical Geology
1	Sedimentary Hill Country	Greywacke (29%), Sandstone (28%), Mudstone (18%), Basalt (6%), Mélange (5%)	Steep hill country formed from deeply weathered or soft, easily eroded sedimentary rocks. Most actively eroding domain in Northland. Includes ancient seafloor sediments (Northland Allochthon) pushed onto land millions of years ago.	Waipapa Basement Greywacke (29%), Allochthon Sandstone (19%), Allochthon Mudstone (16%), Allochthon Mélange (5%), Tangihua Allochthon Basalt (3%), Kerikeri Basalt (1%), Miocene Basalt (1%)
2	Mixed Sedimentary/Volcanic Hill Country	Basalt (42%), Greywacke (15%), Sandstone (11%), Mudstone (8%)	Mixed terrain where patchy volcanic flows (42%) overlie or are interbedded with sedimentary basement. Rolling to hilly country with Kerikeri, Quaternary, and Miocene basalts partially covering older greywacke (15%) and Allochthon sediments (sandstone 11%, mudstone 8%). S-PAL reveals where underlying rock type affects soil character within Q-MAP volcanic polygons.	Kerikeri Basalt (20%), Waipapa Basement Greywacke (15%), Quaternary Basalt (11%), Miocene Basalt (7%), Allochthon Sandstone (7%), Allochthon Mudstone (5%), Tangihua Allochthon Basalt (2%)
3	Sedimentary Lowlands	Sand (24%), Mud (18%), Sandstone (13%), Mélange (12%), Mudstone (12%), Basalt (10%)	Low-relief terrain where Quaternary alluvium and colluvium (sand 24%, mud 18%) partially mantle underlying Allochthon and Waipapa bedrock. Bedrock (sandstone, mélange, mudstone) is exposed on low hills rising above alluvial flats, with scattered basalt (10%). S-PAL distinguishes sandy, muddy, and basement-influenced lowland types within generalised Q-MAP Quaternary units.	Holocene Alluvium (13%), Quaternary Sediments (13%), Allochthon Mélange (12%), Allochthon Mudstone (10%), Tangihua Allochthon Basalt (4%), Quaternary Basalt (3%), Kerikeri Basalt (2%)
4	Low-Relief Coastal Plains	Sand (34%), Mud (22%), Sandstone (21%), Mudstone (8%), Greywacke (5%)	Coastal terrain including sand dunes, beaches, and river flats. Recent sediments (sand 34%, mud 22%) partially cover underlying sandstone and mudstone bedrock (29%) exposed on low coastal hills. showing signs of active sediment movement.	Holocene Dune Sand (23%), Holocene Alluvium (20%), Allochthon Sandstone (19%), Quaternary Dune Sand (7%), Allochthon Mudstone (6%), Waipapa Basement Greywacke (5%)
5	Steep Basaltic Rangeland	Basalt (74%), Mudstone (11%), Sandstone (5%)	Highest and steepest terrain in Northland — rugged basaltic ranges formed from ancient Tangihua and Miocene basalt lava flows (74%) with underlying Allochthon mudstone (11%) and sandstone (5%). S-PAL distinguishes areas where these weak, underlying sediments influence regolith character and	Tangihua Allochthon Basalt (54%), Miocene Basalt (15%), Allochthon Mudstone (10%), Allochthon Sandstone (4%), Kerikeri Basalt (3%)

ID	Domain Name	Main Rock Types	What This Means	Typical Geology
			susceptibility to erosion, which Q-MAP basalt polygons do not differentiate.	
6	Kerikeri Volcanic	Basalt (58%), Rhyolite (24%), Mud (5%)	Gently rolling flood basalt terrain with deeply weathered, mature regolith. Low relief volcanic landscape with diverse rocks including basalt and rhyolite (a light-coloured volcanic rock). Most stable and least active domain due to thick weathering mantle.	Kerikeri Basalt (51%), Kerikeri Rhyolite (24%), Cretaceous Basalt (6%), Quaternary Sediments (4%), Quaternary Basalt (1%)

7.3. Regolith Type Lookup: Family (Level 2)

Table A2 provides a general description of the landforms and rock types associated with the six S-PAL Family classes (Figure. A4; Table A2). Families provide more detail about the regolith types occurring within each Domain.



Family	Elevation (m RSL)	Ruggedness	K (%)	Elevation Rank	Ruggedness Rank	K Rank	Rank Code
1	194	2.3	1.3	2	8	8	2-8-8
2	39	1.2	1.3	12	12	7	12-12-7
3	163	7.1	1.2	6	2	10	6-2-10
4	176	2.9	1.2	5	7	11	5-7-11
5	424	4.8	1.1	1	4	12	1-4-12
6	79	4.5	1.7	9	5	3	9-5-3
7	188	6.2	1.5	3	3	4	3-3-4
8	53	1.7	1.8	11	10	2	11-10-2
9	126	8.6	1.9	7	1	1	7-1-1
10	82	4.0	1.4	8	6	5	8-6-5
11	55	1.4	1.3	10	11	6	10-11-6
12	180	2.2	1.3	4	9	9	4-9-9

Figure A4. Domain Level of the Regolith Type Classification hierarchy. Where K Rank = the abundance of radioactive potassium (^{40}K) in the regolith. Ranks are 1 = highest and 6 = lowest

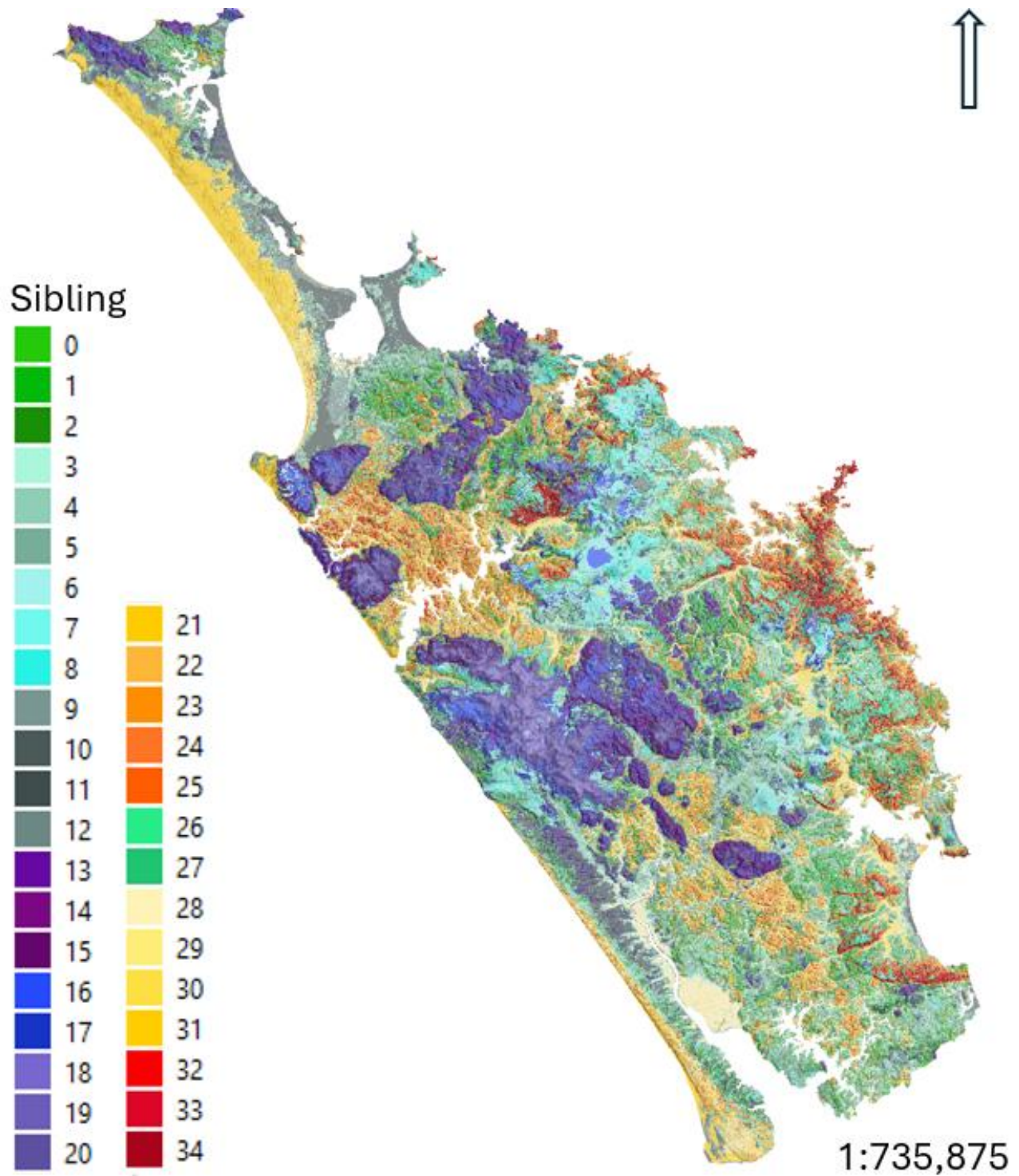
Table A2. S-PAL Regolith Type, Family Level, Landform, and Geological Lookup.

Fam.	Dom.	Family Name	Main Rock Types	What This Means	Typical Geology
F1	6	Recent Volcanics	Basalt (57%), Rhyolite (23%)	Gently rolling, recent, volcanic terrain. Low slopes, thick regolith, very stable. Long-term weathering has created very stable, deeply weathered soils.	Kerikeri Basalt (51%), Kerikeri Rhyolite (23%), Cretaceous Basalt (6%), Quaternary Sediments (4%)
F2	3	Young Alluvium/Colluvium	Sand (44%), Mud (14%), Sandstone (12%), Basalt (11%), Mudstone (7%), Mélange (6%)	Low-lying coastal and wetland areas with sandy soils and scattered volcanic rocks.	Quaternary Sediments (16%), Holocene Alluvium (12%), Pleistocene Sand (12%), Quaternary Dune Sand (11%), Tangihua Allochthon Basalt (8%)
F3	5	Lower Basalt	Basalt (75%), Mudstone (13%)	Lower elevation basalt terrain within the Tangihua ranges. Steep slopes with ancient ocean-floor basalts (75%) and underlying Allochthon mudstone (13%) exposed where volcanic cover is thinner.	Tangihua Allochthon Basalt (70%), Allochthon Mudstone (13%), Miocene Basalt (3%)
F4	5	Mid Basalt	Basalt (59%), Mudstone (16%), Sandstone (8%)	Mid-slopes of volcanic ranges with mix of basalt and underlying sediments.	Tangihua Allochthon Basalt (42%), Allochthon Mudstone (14%), Miocene Basalt (9%), Kerikeri Basalt (6%)
F5	5	Upper Basalt	Basalt (87%)	Highest elevation basalt terrain in Northland. Steep, rugged ridge country dominated by resistant Tangihua and Miocene basalt (87%).	Tangihua Allochthon Basalt (49%), Miocene Waipoua Basalt (34%)
F6	1	Lower Hills	Sandstone (37%), Greywacke (29%), Mudstone (15%), Sand (6%)	Soft sedimentary hill country prone to erosion. Mix of deeply weathered basement rock and soft allochthonous marine sedimentary rocks.	Allochthon Sandstone (31%), Waipapa Basement Greywacke (29%), Allochthon Mudstone (13%)
F7	1	Upper Slopes	Greywacke (39%), Sandstone (23%), Basalt (13%), Mudstone (12%)	Where ancient basement rocks meet younger pushed over (allochthonous) sediments. Complex geology, intensely faulted.	Waipapa Basement Greywacke (39%), Allochthon Sandstone (13%), Allochthon Mudstone (8%), Tangihua Allochthon Basalt (4%), Miocene Basalt (3%), Kerikeri Basalt (3%)
F8	4	Coastal Zone	Sand (34%), Mud (22%), Sandstone (21%), Mudstone (8%), Greywacke (6%)	Coastal sand country including active and stabilised dunes, beaches, and river deposits. Recent sediments mantle allochthonous sedimentary bedrock.	Holocene Dune Sand (22%), Holocene Alluvium (20%), Allochthon Sandstone (19%), Quaternary Dune Sand (7%)
F9	1	Steep Ridges	Greywacke (67%), Sandstone (23%)	Deeply weathered ancient basement rocks characterised by very steep	Waipapa Basement Greywacke (67%),

Fam.	Dom.	Family Name	Main Rock Types	What This Means	Typical Geology
				slopes. Includes Brynderwyn Hills. Highly active regolith, mainly associated with mass wasting (slips, slides, and slumps).	Allochthon Sandstone (13%)
F10	1	Soft Hills	Mudstone (31%), Sandstone (19%), Mélange (10%), Greywacke (9%), Basalt (9%)	Soft, clay-rich hill country with old, weathered soils. Moderate slopes but erodible materials.	Allochthon Mudstone (29%), Allochthon Mélange (10%), Waipapa Basement Greywacke (9%), Tangihua Allochthon Basalt (5%)
F11	3	Low Hills & Alluvium	Mud (21%), Mélange (16%), Mudstone (14%), Sandstone (14%), Sand (10%), Basalt (10%)	River valleys, estuaries, and low coastal hills. Mix of recent alluvium and older allochthonous sediments. Bedrock often mantled, with various outcrops.	Allochthon Mélange (16%), Holocene Alluvium (13%), Allochthon Mudstone (13%), Quaternary Sediments (11%), Quaternary Basalt (4%), Kerikeri Basalt (2%)
F12	2	Mixed Volcanic/Sedimentary	Basalt (41%), Greywacke (16%), Sandstone (11%), Mudstone (8%)	Rolling terrain where basalt flows (41%) discontinuously mantle greywacke (16%) and Allochthon sedimentary bedrock (19%). Mixed volcanic and sedimentary character.	Kerikeri Basalt (20%), Waipapa Basement Greywacke (16%), Quaternary Basalt (11%), Miocene Basalt (7%)

7.4. Regolith Type Lookup: Sibling (Level 3)

Lookup Table A4 provides a general description of the landforms and rock types associated with the six S-PAL Sibling classes (Figure. A5; Table A3). The Sibling level provides more detail about the regolith occurring within each Family.



Sibling	Elevation (m RSL)	Ruggedness	K (%)	Elevation Rank	Ruggedness Rank	K Rank	Rank Code
0	49	0.6	0.86	32	25	3	32-25-3
1	48	0.3	0.62	33	32	8	33-32-8
2	44	0.3	0.2	34	34	31	34-34-31
3	41	0.3	0.39	35	33	17	35-33-17
4	68	1.0	0.57	26	20	11	26-20-11
5	59	0.4	0.41	31	31	16	31-31-16
6	62	0.6	0.62	28	26	8	28-26-8
7	60	0.5	0.86	30	27	3	30-27-3
8	63	0.4	0.25	27	30	25	27-30-25
9	61	0.4	0.34	29	29	19	29-29-19
10	77	1.2	0.32	23	17	22	23-17-22
11	75	1.1	0.42	25	19	14	25-19-14
12	76	1.9	0.59	24	11	10	24-11-10
13	80	1.5	0.82	21	14	5	21-14-5
14	79	1.4	0.88	22	15	2	22-15-2
15	97	2.0	0.33	17	8	20	17-8-20
16	107	0.8	0.37	15	22	18	15-22-18
17	99	2.6	0.77	16	7	7	16-7-7
18	93	1.2	0.23	18	18	29	18-18-29
19	89	3.1	1.06	19	3	1	19-3-1
20	86	1.8	0.53	20	12	12	20-12-12
21	139	2.0	0.2	12	8	31	12-8-31
22	129	4.1	0.78	13	2	6	13-2-6
23	120	3.0	0.51	14	6	13	14-6-13
24	160	0.7	0.33	10	24	20	10-24-20
25	159	3.1	0.25	11	4	25	11-4-25
26	198	1.7	0.42	7	13	14	7-13-14
27	173	0.5	0.24	9	28	28	9-28-28
28	182	0.7	0.28	8	23	23	8-23-23
29	388	3.1	0.18	2	5	34	2-5-34
30	470	1.3	0.17	1	16	35	1-16-35
31	290	1.9	0.2	3	10	31	3-10-31
32	226	4.7	0.25	6	1	25	6-1-25
33	233	0.3	0.27	4	35	24	4-35-24
34	231	1.0	0.21	5	21	30	5-21-30

Figure A5. Sibling Level of the Regolith Type Classification hierarchy.

Table A3. S-PAL, Regolith Type Classification, Sibling Level, Landform, and Geological Lookup.

Sib.	Fam.	Dom.	Simple Name	Actual Rock Types	What to Expect
0	F10	1	Mudstone & mélange hills	Allochthon Mudstone (30%), Allochthon Sandstone (21%), Allochthon Mélange (13%)	Soft, clay-rich hill country with mixed sedimentary rocks. Variable stability depending on slope.
1	F10	1	Soft mudstone & sandstone	Allochthon Mudstone (29%), Allochthon Sandstone (19%), Allochthon Mélange (12%), Basement Greywacke (9%), Basalt (9%)	Soft, easily eroded hill country. Clay-rich soils prone to slipping.
2	F10	1	Mixed mudstone & basalt	Allochthon Mudstone (34%), Basalt (15%), Allochthon Sandstone (11%)	Soft sediments with some harder volcanic rock. Variable stability.
3	F11	3	River valley muds	Mud (28%), Allochthon Mélange (20%), Allochthon Mudstone (12%)	Low-lying valley floors. Recent river deposits over older rocks.
4	F11	3	Coastal & estuary sediments	Mud (17%), Allochthon Mudstone (16%), Sand (16%), Allochthon Sandstone (15%), Allochthon Mélange (14%), Basalt (13%)	Estuary margins and tidal flats. Mix of sand and mud.
5	F11	3	Mixed lowland sediments	Mud (17%), Allochthon Mudstone (15%), Allochthon Sandstone (15%)	Low hills and valleys. Mix of soft sediments and harder rocks.
6	F12	2	Rolling basalt & sediments	Basalt (38%), Allochthon Mudstone (14%), Allochthon Sandstone (13%), Basement Greywacke (12%), Allochthon Mélange (7%)	Gently rolling volcanic country with underlying soft sediments.
7	F12	2	Basalt over basement	Basalt (45%), Basement Greywacke (23%), Allochthon Sandstone (10%), Volcanic Breccia (5%)	Volcanic flows over ancient hard basement. Good stability.
8	F12	2	Lower basalt slopes	Basalt (39%), Basement Greywacke (11%), Sand (10%), Allochthon Sandstone (9%), Volcanic Breccia (7%)	Lower volcanic slopes. Weathered basalt soils.
9	F1	6	Light volcanic (rhyolite)	Kerikeri Rhyolite (59%), Kerikeri Basalt (38%)	Low-relief Kerikeri volcanic terrain with lighter-coloured rhyolite rock. Very deeply weathered — the most stable soils in Northland.
10	F1	6	Rolling basalt country	Kerikeri Basalt (66%), Kerikeri Rhyolite (8%), Mud (7%)	Gently rolling Kerikeri basalt country with thick, mature weathering mantle. Very low erosion activity due to deep weathering and low slopes.
11	F2	3	Sandy coastal plains	Sand (49%), Basalt (16%), Allochthon Sandstone (15%), Mud (11%)	Flat to gently rolling sandy country. Well-drained soils.
12	F2	3	Coastal lowlands mix	Sand (37%), Mud (17%), Allochthon Mudstone (12%), Allochthon Mélange (11%), Allochthon Sandstone (8%), Basalt (6%)	Coastal lowlands with mixed sand and clay deposits.
13	F3	5	Tangihua basalt (lower)	Tangihua Allochthon Basalt (71%), Allochthon Mudstone (15%)	Lower Tangihua ranges. Hard allochthonous volcanic rock (ancient ocean floor basalt).

Sib.	Fam.	Dom.	Simple Name	Actual Rock Types	What to Expect
14	F3	5	Tangihua basalt-mudstone	Tangihua Allochthon Basalt (68%), Allochthon Mudstone (21%)	Tangihua volcanic ranges with underlying soft allochthonous sediments.
15	F3	5	Pure Tangihua basalt	Tangihua Allochthon Basalt (91%)	Hard, resistant Tangihua Allochthon basalt. Steep terrain.
16	F4	5	Mid-slope basalt country	Tangihua Allochthon Basalt (73%), Allochthon Mudstone (7%)	Mid-elevation Tangihua slopes. Allochthon basalt over weak allochthonous sediments.
17	F4	5	Basalt over soft sediments	Tangihua Allochthon Basalt (43%), Allochthon Mudstone (26%), Sand (10%)	Tangihua basalt sitting on soft allochthonous mudstone. Watch for instability.
18	F5	5	Upper basalt ridges	Tangihua Allochthon Basalt (88%)	High, rugged Tangihua terrain. Hard allochthonous basalt, steep slopes.
19	F5	5	Elevated basalt ridges	Tangihua Allochthon Basalt (81%), Allochthon Mudstone (7%)	High Tangihua ridges with some underlying allochthonous sediments.
20	F5	5	Peak basalt terrain	Tangihua Allochthon Basalt (91%)	Highest Tangihua terrain. Very hard allochthonous basalt.
21	F6	1	Soft sandstone hills	Allochthon Sandstone (37%), Allochthon Mudstone (25%), Basement Greywacke (12%)	Rolling sandstone country. Moderate erosion risk.
22	F6	1	Sandstone-greywacke mix	Allochthon Sandstone (40%), Basement Greywacke (30%), Sand (14%)	Mixed allochthonous sedimentary and Waipapa basement rocks.
23	F6	1	Sandstone-dominated hills	Allochthon Sandstone (52%), Basement Greywacke (27%), Allochthon Mudstone (11%)	Sandstone hill country. Moderate stability.
24	F6	1	Greywacke-dominated	Basement Greywacke (58%), Allochthon Sandstone (21%), Allochthon Mudstone (7%)	Hard Waipapa basement rock dominant. Good stability.
25	F6	1	Mixed sedimentary hills	Allochthon Sandstone (37%), Allochthon Mudstone (23%), Basement Greywacke (22%)	Soft hill country with mix of rock types.
26	F7	1	Complex basement mix	Basement Greywacke (37%), Allochthon Sandstone (24%), Basalt (16%)	Mixed Waipapa basement and volcanic. Variable geology, intensely faulted.
27	F7	1	Greywacke hill country	Basement Greywacke (42%), Allochthon Sandstone (20%), Allochthon Mudstone (14%)	Hard Waipapa basement rock country. Generally stable.
28	F8	4	River flats & terraces	Mud (38%), Sand (15%), Allochthon Sandstone (15%)	River valley floors. Recent alluvial deposits.
29	F8	4	Sandstone ridges & sand	Allochthon Sandstone (44%), Sand (25%), Mud (14%)	Sandstone hills with coastal sand deposits.
30	F8	4	Mixed valley deposits	Mud (26%), Allochthon Sandstone (19%), Basement Greywacke (18%)	Valley floors with diverse rock types.
31	F8	4	Sand dunes & beaches	Sand (75%), Allochthon Sandstone (14%)	Active and stabilised sand dunes. Coastal margins.
32	F9	1	Lower greywacke ranges	Basement Greywacke (54%), Allochthon Sandstone (33%)	Lower slopes of steep basement ranges. High erosion activity despite hard rock due to steep slopes.
33	F9	1	Mid greywacke ranges	Basement Greywacke (62%), Allochthon Sandstone (28%)	Very steep basement rock terrain. Highest erosion activity in all of Northland. Most unstable sibling despite hard rock.
34	F9	1	High greywacke ranges	Basement Greywacke (76%), Allochthon Sandstone (14%)	High, rugged basement terrain. Steepest slopes (30°) and very high

Sib.	Fam.	Dom.	Simple Name	Actual Rock Types	What to Expect
					erosion activity. Brynderwyn-type country.

7.5. How do we know S-PAL reflects real geology?

The S-PAL Regolith Classification was developed without using geological maps. It relies solely on terrain shape (from LiDAR) and surface chemistry (from radiometric survey). Despite this independence, validation testing showed a strong alignment with the mapped geology, confirming that S-PAL detects real geological differences through surface expression in terrain and geochemistry.

Two validation approaches were used to confirm this alignment.

Predictive power testing compared S-PAL with other environmental variables (terrain (slope, ruggedness), climate, radiometrics, and land use) to determine which best explained the mapped soil, land use capability class (LUC), and geological patterns. S-PAL was the strongest single predictor, with a score of 2.2, which was more than double that of the next best variable. This means that S-PAL captured more of the variation in soils and geology than any other dataset tested.

Geological purity analysis measured the proportion of each S-PAL Domain that consisted of a single rock class when compared to Q-MAP. The result: 78%. For example, Domain 5 (Steep Basaltic Rangeland) was 74% basalt according to Q-MAP, although S-PAL was never told of this.

This independent alignment gives confidence that S-PAL classes represent meaningful landscape units. An S-PAL Domain, Family, or Sibling boundary reflects real differences in the underlying regolith, which controls how the land weathers, erodes, and responds to disturbances.

Key findings:

1. **S-PAL was the strongest predictor** of soil and rock patterns across Northland, with a predictive power score of 2.2, which was more than double that of the next best variable (radiometrics at 1.0). Other predictors ranked lower: Mean Annual Precipitation (0.8), elevation (0.8), Soil Moisture Deficit (0.8), slope (0.5), Land Use Intensity (0.3), and aspect (<0.05).
2. **Geological alignment without using geology as an input:** Despite being developed independently of geological maps, S-PAL Domains show 78% geological purity when compared to Q-MAP ROCK_CLASS. This means that 78% of each S-PAL Domain consists of a single broad rock class.
3. **Process-based correlations hold up:** steeper, more rugged terrain shows higher regolith activity ($p = 0.59$), and potassium enrichment strongly correlates with recent disturbances ($p = 0.65$), confirming that the classification captures real landscape processes.
4. **S-PAL captures variations that Q-MAP cannot resolve:** Each Q-MAP polygon contains a distinctive mix of S-PAL siblings, and larger Q-MAP units contain more S-PAL variation ($p = 0.81$). This confirms that S-PAL detects within-unit regolith variations at scales below the 1:250,000 resolution of Q-MAP.
5. **Land use is not a strong predictor of soil or rock type;** it does not control where the land is vulnerable but determines whether that vulnerability is exposed.

7.6. Quick Glossary of Rock Types

A simple explanation of the main rock types is provided in the above tables.

Rock Type	What It Is (Simple Explanation)
Basalt	Hard, dark volcanic rock formed from lava flows. Common in Northland's volcanic ranges. Generally stable but can be very steep.
Greywacke	Very old, hard sandstone that forms Northland's basement rock. Found in ranges like the Brynderwyns. Usually strong and stable when unweathered.
Mudstone	Soft rock made from compressed mud. Very common in Northland hill country. Often clay-rich and prone to slipping when wet.
Sandstone	Rock made from compressed sand. Varies from soft to quite hard. Found throughout Northland's hill country.
Mélange	A jumbled mix of different rock types created by ancient earth movements. Very common in the Northland Allochthon. Often unstable.
Rhyolite	Light-coloured volcanic rock, often associated with explosive eruptions. Found in some of Northland's volcanic areas.
Volcanic Breccia	Broken pieces of volcanic rock cemented together. Forms when volcanic explosions shatter existing rock, or when lava flows break apart. Found in some of Northland's volcanic areas.
Sand/Mud (unconsolidated)	Loose sediments not yet turned to rock. Found on beaches, dunes, river valleys, and estuaries. Easily eroded by water.
Alluvium	Sediment deposited by rivers. Found on floodplains and valley floors. Usually fertile soils.
Allochthonous	Rocks that formed elsewhere and were moved to their current location by tectonic forces. The Northland Allochthon is ancient seafloor (including Tangihua Allochthon Basalt) that was pushed onto land ~25 million years ago. Opposite of autochthonous (formed in place, like the Waipapa basement).
Colluvium	Material that has moved downhill by gravity — includes soil creep, small landslides, and slope wash. Found at the base of hills throughout Northland.
Regolith	The loose material sitting on top of solid bedrock — includes soil, broken rock fragments, and sediments. This is what S-PAL classifies.

7.7. Key Geological Groups in Northland

Group Name	What It Is
Northland Allochthon	Ancient seafloor rocks that were pushed onto land millions of years ago. Includes soft mudstones and sandstones. Covers large areas of Northland's hill country and is often prone to erosion.
Waipapa/Caples Terrane	Very old basement rocks (greywacke) that form the foundation of Northland. Hard and generally stable. Found in the Brynderwyns and eastern Northland.
Tangihua Allochthon Basalts	Very old ocean-floor basalts (over 100 million years old) now forming rugged ranges in Northland. Part of the Allochthon but made of hard volcanic rock rather than soft sediments.
Kerikeri Volcanic Group	Relatively young volcanic rocks from eruptions in the last few million years (Quaternary period). Forms rolling farmland around Kerikeri. Includes basalt lava flows that cover older rocks.
Holocene Sediments	Very recent deposits (last 10,000 years, since the ice age ended) including river sediments, coastal sands, swamp deposits, and dune sands. Found in low-lying areas.

7.8. Understanding Geological Time

These tables use geological-time terms. Here is what they mean in simple terms.

Time Term	What It Means
Holocene	Very recent — the last 10,000 years (since the ice age ended). Think: recorded human history.
Quaternary	Recent — the last 2.6 million years (the ice ages). Think: when early humans appeared.
Miocene	Old — 5 to 23 million years ago. Think: before humans, when apes were evolving.
Cretaceous	Very old — 66 to 145 million years ago. Think: the last age of the dinosaurs.

Note: This guide provides simplified information for general understanding. The actual geology at any location can be more complex. For detailed geological information, refer to QMAP geological maps or consultations with a geologist.

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