Evaluation of geospatial datasets and recognition of landscape gradients specific to water quality

Prepared by Clint Rissmann, Tapuwa Marapara, Simon Bloomberg, Jessie Lindsay, and Lisa Pearson

for Northland Regional Council, December 2017

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1 Introduction

This study evaluates the landscape relationships and suitability of existing geospatial datasets for the purposes of mapping physiographic water quality units for the Northland region. The physiographic method seeks to explain 'how' and 'why' water quality varies across a region by identifying the gradients driving key landscape processes that govern water quality outcomes and risk (Rissmann et al., 2016). The importance of understanding the role of the landscape reflects the observation that whilst land use is a prerequisite for poor water quality outcomes, it is the inherent physical, chemical and biological characteristics (attributes) of a landscape that are often responsible for a larger proportion (>2 times) of the variation in water quality outcomes (Johnson et al., 1997; Hale et al., 2004; Dow et al., 2006; Rissmann et al., 2016). This is particularly true for regions and/or countries, such as Northland and New Zealand (NZ), which are characterised by steep gradients in chemical, physical and biological landscape attributes (Close and Davis-Colley, 1990; Rissmann et al., 2016).

The fundamental basis of the physiographic approach is the recognition and mapping of gradients in those key landscape attributes that control variation in water quality outcomes, in addition to land use. For example, gradients in soil drainage class are known to strongly influence the degree to which nitrate is attenuated via denitrification (Webb et al 2010; Killick et al., 2015; Beyer et al., 2016b; Beyer and Rissmann, 2016); gradients in soil permeability and depth to slowly permeable (<4 mm/hr) layer determine the pathway water takes across the landscape and influence the potential for entrainment of contaminants via subsurface drainage and overland flow (Nash et al., 2002; Vidon and Hill, 2004; Soana et al., 2017) and; gradients in hydrological connectivity also determine the flushing potential of aquifers, streams, estuaries and lagoons (Volk et al., 2006; Larsen, 2012; Roselli et al., 2013; Outram et al., 2016). An understanding of the landscape level controls that govern variability in those key attributes that drive spatial variation in water quality, therefore, is fundamental to the physiographic approach (Figure 1; Rissmann et al., 2016).

In the following report, we provide a qualitative assessment of the relationships between nationally available soil, geological, elevation, and hydrological geospatial layers with radiometric survey imagery collected for the region in 2011 (NZP&M, 2011). Consultation with local experts of the Northland region was fundamental in understanding the relationship between the geospatial layers and radiometric imagery. Radiometric imagery is a useful ground truthing and integration tool providing a direct measure of the surficial (300 – 500 mm) composition and character of soil and geology at a far greater resolution than afforded by polygonal soil and geological maps. We consider radiometric imagery a useful ground truthing and integration tool and one important part in assessment of landscape level controls over the gradients governing hydrological and redox response.

The radiometric (gamma ray) survey of the Northland region (NZP&M, 2011) has a nominal resolution of 50 m that provides a direct measure of the spatial heterogeneity of the land surface relevant to deciphering the key landscape controls over water quality. The horizontal resolution of radiometric imagery (c. 50 m), means that it is more resolved than current polygonal maps of soil, geological, hydrological and ecological gradients. This contrasts with a generous estimate of 1 auger point per hectare that is typical of regional soil surveys (Lynn et al., 2009).

The key focus of this work is the development of an understanding of the landscape level controls over the gradients in soil (compositional and structural) and hydrological properties that drive gradients in hydrological pathways, redox and sediment response relevant to water quality outcomes. A quantitative assessment of the spatial relationships identified in this preliminary study will be produced during subsequent mapping of physiographic settings for Northland.

This section introduces the background climatic and hydrological setting, and geological evolution of the Northland region, including a high-level summary of soil characteristics. We also provide a summary of the nature of the radiometric survey data collected for Northland, which includes: (i) a review of the general controls over spatial variation in radiometric signals, and; (ii) a commentary on the use of the Northland radiometric survey as a regional extensive geospatial platform to better understand erosion and transport processes. The focus is on evaluating the relationship between gradients in landscape geomorphology, radiometric signals and key landscape attributes hosted by existing geospatial layers (e.g. QMAP[1], NZLRI[2], LINZ[3], RECv1[4]) in terms of their importance over water quality outcomes. As such, this evaluation departs from a traditional assessment of soil and geological domains.

[1] QMAP: Geological Map of New Zealand, includes geomorphology, stratigraphy, tectonic history, geological resources, geological hazards and engineering geology.

[2] NZLRI: New Zealand Land Resource Inventory, national database of physical land resource information including geology, soil, slope, vegetation type, and erosion type and severity.

[3] LINZ: Land Information New Zealand.

[4] RECv1: River Environment Classification, national database of catchment spatial attributes, summarised for every segment in New Zealand's network of rivers.

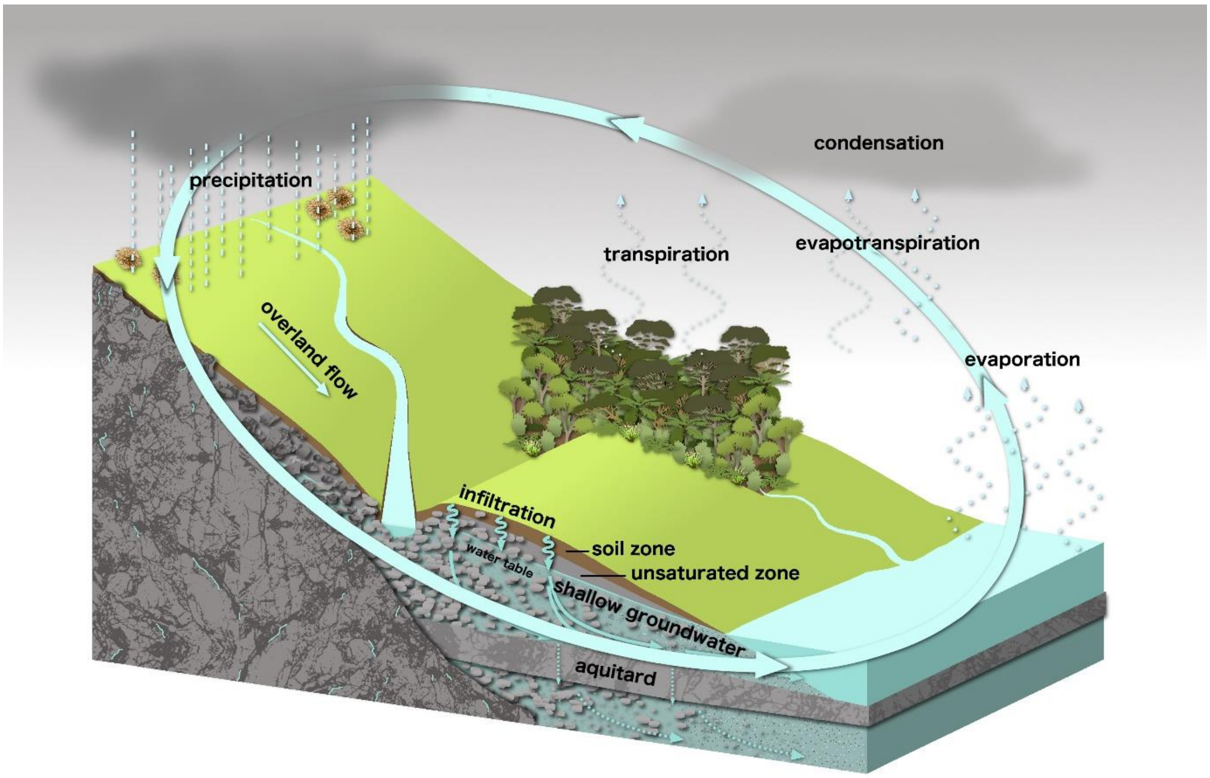

Figure 1. A hydrological cycle; the physiographic approach is holistic, considering the influence of each hydrological domain over water quality outcomes for both surface and shallow ground water.

1.1 Climatic and Hydrological Setting

Rainfall is abundant throughout the Northland region, ranging from mean annual averages of 1,000 mm in low lying coastal areas to 2,000 mm at high elevations (Figure 2; Chappell, 2013). High intensity rainfall events (max. 47 mm/hr) associated with the passage of tropical or subtropical storms can lead to flooding (Chappell, 2013).

There is an extensive network of rivers and streams in Northland, with over 1,400 individual source-to-sea catchments flowing through the narrow landmass. The narrow landmass (around 13,000 km^2) means that most rivers are short (<30 km), with small catchments. Most major rivers flow into harbours or estuarine environments, rather than discharging directly to the open ocean (Northland Regional Council, 2011; Ballinger et al., 2014). The largest river in Northland is the Northern Wairoa (near Dargaville), with a catchment area of 3,650 km^2.

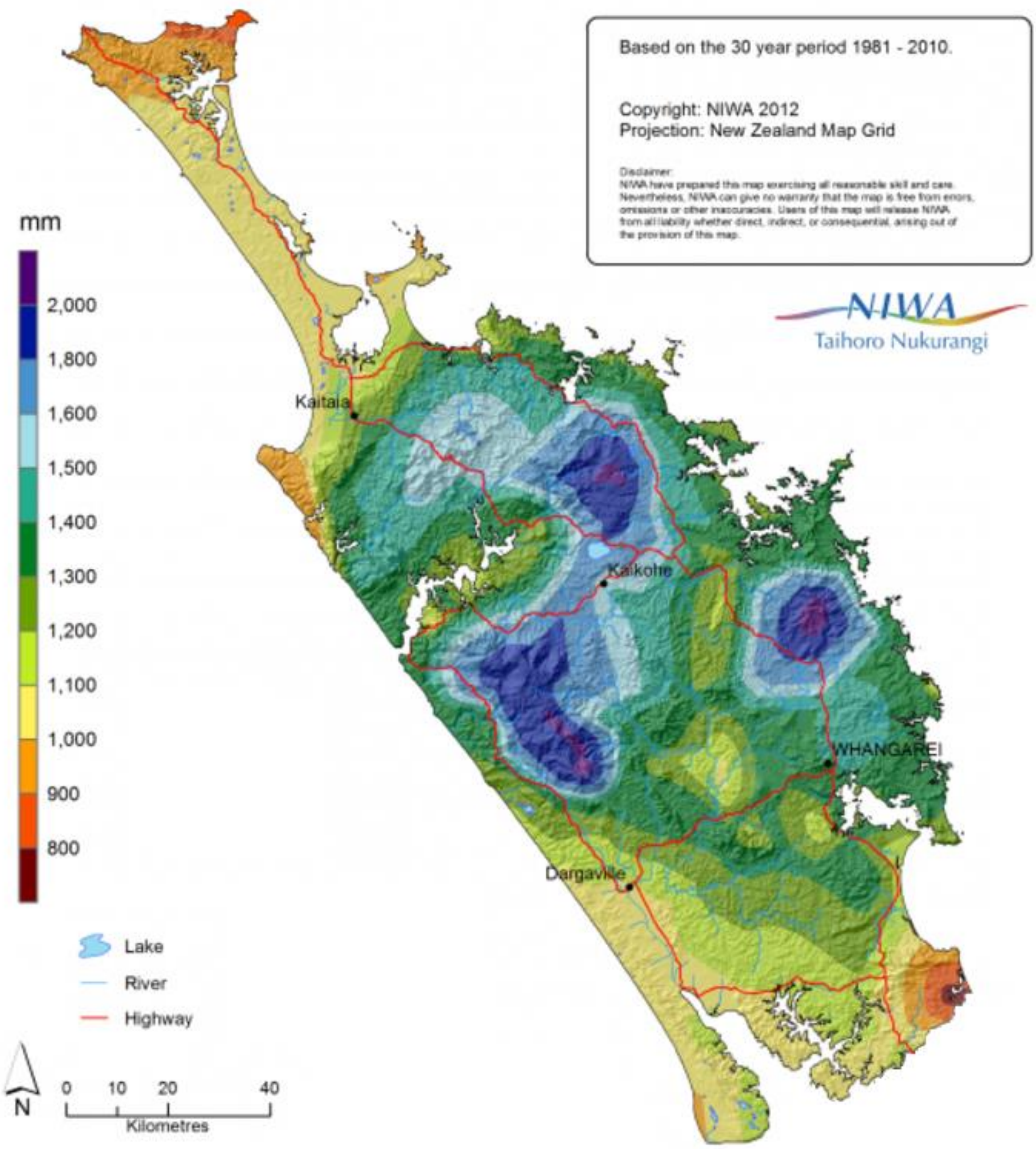

Figure 2. Northland median annual rainfall (1981-2010; adapted from Chappell, 2013).

1.2 Geology

Northland is geomorphically one of New Zealand's oldest regions, with no recent (Quaternary) glacial activity and few regionally significant volcanic ash deposits since the middle of the Miocene (c. 14 Ma ago). In part, this reflects the climatic history of the region but also the tectonic (faults & uplift) and eruptive (volcanic & intrusive) setting (Isaac, 1996; Edbrooke and Brook, 2009). The geological history of Northland is dominated by its location solely on the Australian plate, which means that it is not part of an active plate margin, nor an extensional back arc basin (such as the Taupo Volcanic Zone). Under this unique setting, the sedimentary succession ranges from the Permian-aged (299 – 252 million years ago) Waipapa-Composite and Caples terranes (greywacke-argillite/chert/melange) to Quaternary-aged beach sands, with infrequent pulses of local intraplate volcanism (Figure 3).

In Northland, sedimentary basement rock outcrops at the surface along the east coast, around Whangarei and to the north, and gently dips to the west to a depth of 3 km (Stagpoole et al., 2012). It is formed from several different terranes (including the Dun Mountain-Maitai Terrane which runs the length of New Zealand) that were amalgamated in the Mesozoic (252-66 Ma). These marine derived units show a history of seafloor activity found on the passive margins of a rift (where tectonic plates are pulling away from each other). Later, in the Oligocene (33.9-23 Ma) and Miocene (23-5.3 Ma), the western plate margin activated, and large-scale volcanism occurred (Hokianga Volcano/Waitakere Group; Stagpoole et al., 2012). A subduction zone likely existed to the northeast of Northland in the Early Miocene, causing the Northland Allochthon[5] to be thrust over much of the peninsula from the north east.

The Northland Allochthon is made up of the former passive margin wedge, therefore is mostly comprised of marine clastics, mudstones and sandstones (as well as volcanic piles of Tangihua complex pillow basalts) and tectonically derived melange. The thrusting of this wedge in layers upon the basement has thickened the allochthon in places to more than 3 km (in the west). During this time, volcanism occurred on the eastern edge of the allochthon as an extension of the Coromandel Group. As subduction slowed in the Early Miocene, block faulting occurred along the east coast, lifting and dipping the blocks to the west. From the middle of the Miocene through to modern day, only a few more units have been emplaced; namely, the Kerikeri group of intraplate basalts and felsic domes (9-2.6 Ma) and the recent beach dune sands along the west coast and Far North.

Rock strength and degree of induration, primary texture and provenance are key controls over sediment yields, soil hydrological properties and biogeochemical properties of both soil and aquifers, respectively. Accordingly, recognition of geological gradients provides critical constraint over the variation in water quality outcomes for surface, shallow ground water and near coastal environments.

[5] **A large block of rock which has been moved from its original site of formation, usually by low angle thrust faulting.**

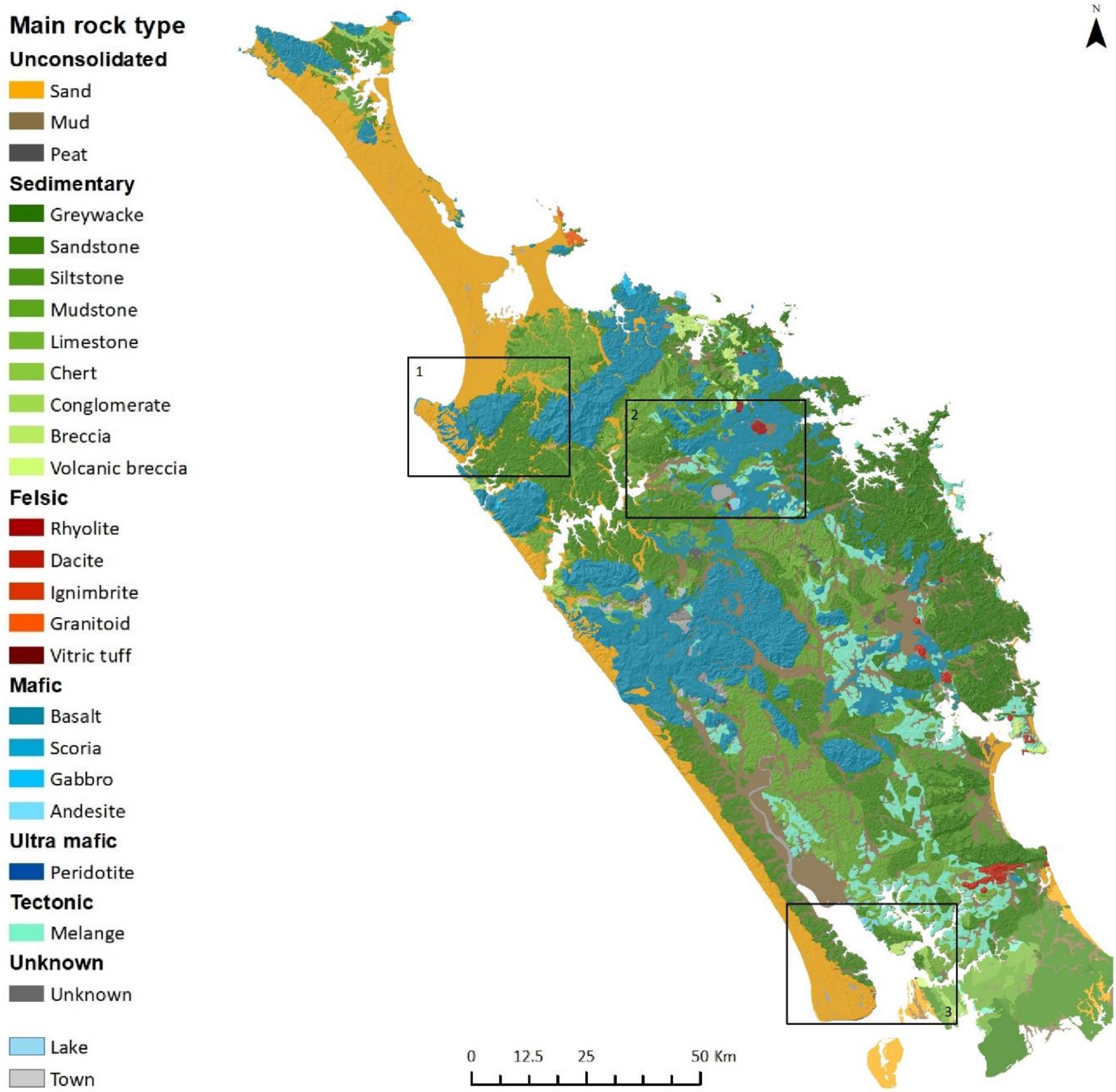

Figure 3. Northland geology from QMAP (attribute field: Main rock). Source: Isaac, 1996; Edbrooke and Brook, 2009; GNS Science.

1.3 Soil

The soils of Northland are predominantly Ultic according to the New Zealand Soil Classification (NZSC). Ultic soils are strongly weathered and contain well-structured clay-enriched horizons in the subsoil. Other NZSC orders present are; Brown soils (typically silt loams) on younger sedimentary land surfaces; Granular soils, a clay soil formed by the strong weathering of volcanic rocks; Podzol soils that are high in organic matter and are strongly acid beneath the top soil; Gley soils form in response to prolonged periods of soil saturation; Recent and Raw soils are weakly developed to minimally developed. In Northland, Recent and Raw soils are typically associated with recent beach sands and young alluvial floodplains.

Soil order can be limiting when attempting to understand the relationship between gradients in landscape attributes such as slope, geology and geomorphic setting and attendant gradients in a soil's physical and chemical properties (Rissmann et al., 2016, TC2, TC3 and TC6). Accordingly, this work seeks to refine the understanding of the landscape controls over soil properties that are relevant to water quality outcomes.

Soil texture (Figure 4), permeability and drainage class are the critical attributes determining the pathway water takes across the landscape and the strength of soil zone reduction, respectively (Rissmann et al. 2016a and b). Areas characterised by slow permeability (<4 mm/hr) are more prone to overland flow than soils with high permeability[6]. Areas of well drained soils with moderate to high infiltration rates favour deep drainage. The proportion of slowly permeable soils in Northland is 56%, the majority of which occur in lowland areas. The proportion of well drained soils is small (18.7 %), with most of the soils classified as poorly drained (35.7 %) or moderately well (45.6 %) drained. Poorly drained soils are often strongly reducing and therefore have higher denitrification rates than well drained soils, however, poorly drained soils have a greater tendency to leach phosphorus (P) and are also more prone to overland flow (McDowell et al. 2003).

Soil structure, texture and mineral composition are important attributes governing the evolution of macro-pore (bypass) networks, which are critical pathways for water and hence contaminant transport (Rissmann et al., 2016a and b; Beyer et al., 2016). Although there are a range of soil related features that may facilitate bypass, we consider the largest and most integrated structures (e.g. soil cracks due to the desiccation of clays and/or pedogenic features) the most important in terms of water quality outcomes (Rissmann et al., 2016b). Specifically, those soils with large and well-integrated macropore structures favour the bypass of the soil matrix and in our experience, are associated with poor water quality outcomes for nitrogen (N), microbes (i.e. *E. coli*, (M)), and at times phosphorus (P) (Rissmann et al., 2016a).

Across Northland, 68 % of soils are characterised as clay-rich (argillic, Figure 4) and may crack during the summer in response to soil moisture deficit. Consultation with local soil experts can be used to identify soils with large macropore structures that may be associated with contaminant bypass. Typically, soils that exhibit shrink-swell characteristics tend to be

[6] **It is anticipated that those areas with soils of slower infiltration rates have been modified by artificial drainage.**

clay-rich and/or are characterised by large and highly conductive pedogenic structures (e.g., massive columnar peds in some areas of 'gumland soils[7]') in contrast to the overall soil matrix. These large macropore networks provide a preferred pathway for water and contaminant transport and influence redox gradients by directly coupling shallow soil and groundwater to the atmosphere (Dif and Bluemel, 1991; Day, 1994; Guney et al. 2007; Beyer et al., 2016a).

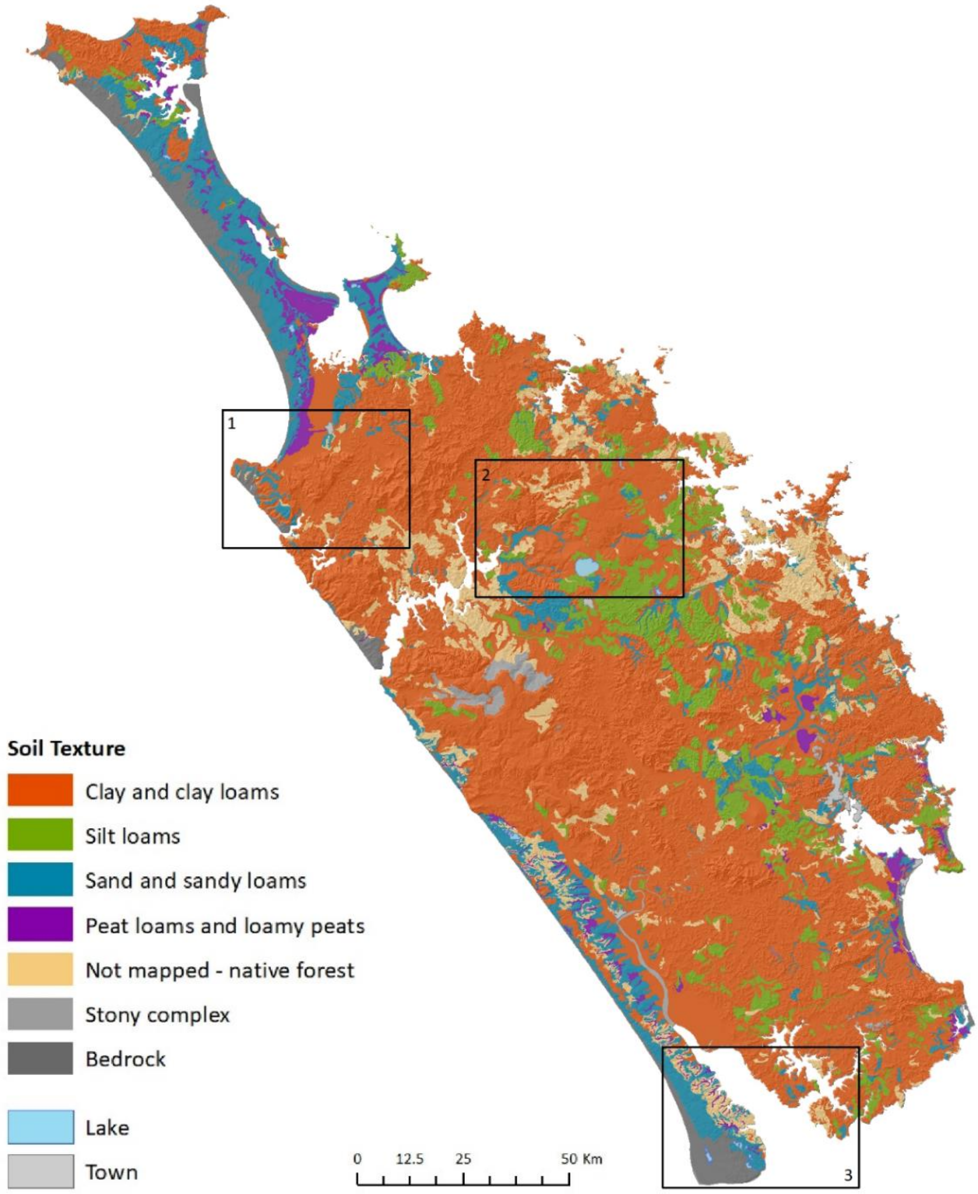

Figure 4. Soil texture from Fundamental Soil Layer (attribute field: Soil_Type). NB: The soil texture attribute layer of the NZLRI does not recognise soil depth, where areas of rock outcrop and steep slope may have a very thin to non-existent layer of soil cover (Lynn et al., 2009).

[7] Strongly leached soils that are derived from weathered sands, sandstones and claystones that contain Kauri gum (a fossil resin). The soils are typically low fertility soils with high moisture content.

The microbial load, free and sorbed N and P, organic carbon (C), and associated carbon to nitrogen (C:N) and carbon to phosphorus (C:P) ratios are important indicators of sediment quality. Developed soils have a higher potential microbial (M), N and P load along with organic carbon characterised by smaller C:N and C:P ratios relative to areas of indigenous land cover with undeveloped/natural state soils. The contaminant content associated with 1 kg of agriculturally derived sediment, therefore, can be large relative to 1 kg of sediment derived from a natural state setting (Cooper and Thomsen, 1988). Recognition of this difference in sediment quality is very important in terms of internal eutrophication of rivers, lakes, lagoons and estuaries.

Soil P-retention or anion exchange varies with soil age and parent material. According to the New Zealand Land Resource Inventory (NZLRI), 19% of Northland mapped soils are characterised by high P-retention (mostly associated with younger volcanic landforms) and 48% by low P-retention, with the rest having moderate P-retention. The ability of soils to sorb P has implications for P leaching, the P-content of sediment lost via farm drainage and/or the P content of stream banks that are eroded during peak flow events.

1.4 Water Quality

One of Northland's biggest water pollutants is sediment, particularly fine silt and clay sized particles including colloidal suspensions (Ballinger et al., 2014). Here we define sediment as a heterogenous assemblage of inorganic and organic constituents as well as microbiological organisms, such as bacteria and viruses. Sediment is mobilised during high intensity rainfall events, as soils with predominantly clay textures or slowly permeable horizons are slow to be infiltrated by water from rainfall, and consequently, rapid overland water flow results[8] (Collins et al., 2007; Ballinger et al., 2014). Overland flow is considered the transport pathway which mobilises the highest particulate contaminant load (McKegrow et al., 2007; McDowell, 2008; Monaghan et al., 2010). Almost all monitored rivers in Northland, including those that pass through land with mostly native forest cover, have turbidity and microbial (*E. coli*) levels worse than the national median (McDowell et al., 2013; Ballinger et al., 2014). Phosphorus, as dissolved reactive phosphorus (DRP) and total phosphorus (TP) are also elevated.

Nitrate (NO_3) concentrations in groundwater are elevated (3 - 6 mg/L, NO_3-N) in a few small areas, where well drained volcanic soils overlay fractured rock. In these areas, land surface recharge (winter rainfall) drives water movement and recharge of underlying aquifers. Elsewhere, due to poorly drained soils and/or reducing aquifers, nitrate concentrations are

[8] **The clearance of indigenous vegetation, development of agricultural land and soil compaction favour the drainage of water across the landscape at much faster rates than occurred in the past.**

thought to be low (Cameron et al. 2001). Phosphorus concentrations in groundwater is considered elevated in aquifers and stream baseflow in places, perhaps due to both a combination of anthropogenic and naturally elevated concentrations in aquifer materials (Unpublished data NRC, 2017; see also Rissmann and Lovett, 2016).

1.5 Radiometric Survey Data and Controls

Airborne gamma-ray spectrometry measures the strength of gamma-radiation emitted from naturally occurring radioisotopes. Of the naturally occurring radio isotopes ^{40}K, ^{232}Th and ^{238}U are the only radioactive species that emit enough gamma to be detected by scintillation counters at the altitudes typically flown by survey aircraft (60-140 m). Scintillation detectors measure the strength of gamma signal for each key radio nuclei and convert it to an equivalent gamma count.

The majority of the gamma radiation emitted to the atmosphere is derived from shallow depths with approximately 90% coming from the top 300 – 500 mm for dry material with a bulk density of 1.5 g cm^{-3} (Grasty, 1975; Wilford, 1997). Radiometric data is typically displayed using a red green blue (RGB) ternary, where red is the potassium gamma count, green is the thorium count and blue is the uranium count (Figure 5). Throughout this report we use the terms, 'radiometric signals', and 'gamma signals' interchangeably.

For the Northland survey, several thousand line kilometres were flown at intervals spaced 200 m apart and tied together every 2000 m. The plane flew with a sensor height of 60 m. The associated imagery derived from these surveys should have a nominal resolution of 50 m, making it much finer than existing soil and geological polygons. During this investigation, however, it was discovered that the New Zealand Petroleum & Minerals (NZPAM) information package did not contain the high-resolution ternary radiometric imagery. Accordingly, for this study the authors were restricted to a set of GeoTIFFs of lower resolution than is typical of radiometric imagery (c. ±150 m as opposed to ± 50 m). New Zealand Petroleum & Minerals may follow up with GNS Science to have the high-resolution ternary image processed and supplied for the Northland survey.

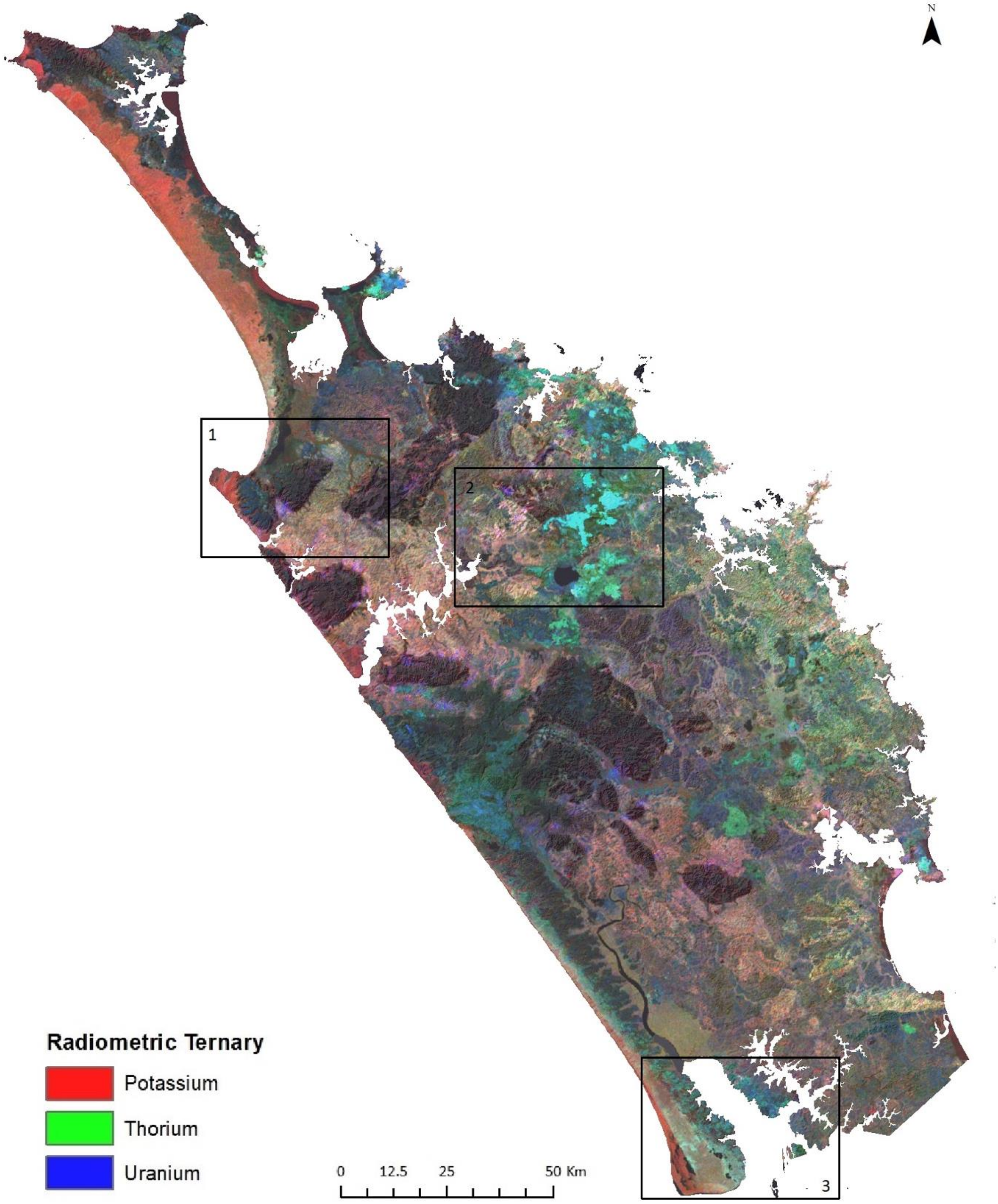

Figure 5. Northland radiometric ternary GeoTiff (NZP&M, 2011) showing test areas 1 = Ahipara; 2= Waipapa; 3 = Kaipara.

Despite the lower resolution of the imagery used for this study, meaningful relationships between radiometric signals and existing geospatial layers were still apparent during exploration within a GIS. The resulting figures produced by the export of imagery from GIS are of lower resolution than the geo-tiffs, which when combined with a smaller view (exported image to insert into this text), diminishes some of the clarity. This does not detract from the strength of the spatial relationships presented here but does limit, to some extent, the impact of the figures embedded within the text to showcase these relationships. For this reason, the authors provide a GIS package to accompany this report.

1.5.1 Controls over Radiometric Signals (gamma-ray emission)

Unweathered rock and sediments contain different abundances of radiogenic K, U and Th minerals that equate to distinct gamma ray spectra and gamma signal magnitude. Geologists and geochemists use the knowledge of different petrochemical assemblages to guide the interpretation of radiometric imagery and to better refine small scale heterogeneity in geological gradients. The weathering of rock and sediment can mask or modify the primary signal which generates heterogeneity at a scale finer than is typically captured by regional geological mapping.

In addition to better resolving surficial geological controls, radiometric imagery is useful for better defining fine scale variation in geomorphic controls that drive gradients in the physical, chemical and biological properties of the landscape (Wilford, 1995; Wilford et al., 1997; Pickup and Marks, 2000 and 2001; Wilford, 2012; Bierwirth 1996; Herrmann et al. 2010; Beamish 2015; Hedley et al. 2016). For example, gamma-ray emission is strongly mediated by soil bulk density and porosity, which vary according to soil age, climate, parent material texture and composition, topography and relief. Accordingly, many workers have used variation in gamma signal due to gradients in soil textural properties, permeability and drainage class to refine the spatial accuracy of catenary (topographical) gradients and associated hill slope hydrological models (Parfitt and Wilson 1985; Daniels and Hammer 1992; Beerten et al. 2012; Bockheim and Hartemink 2013; Dixon 2015).

Potassium, U and Th gamma signal also varies according to particle size. As a soil weathers, U and Th are liberated from primary minerals and move to sites of surface charge via a combination of co-precipitation and adsorption reactions onto iron and/or aluminium (oxy)hydroxides and/or structured clay minerals, whereas K is often leached (Misaelides et al., 1987; Sikalidis et al., 1989; Boekhout et al., 2015; and references therein). Residual sand-sized particles liberated during weathering of volcanic rock and or intrusive rock have little surface charge, equating to a lower concentration of U and Th, relative to secondary clay minerals. Whereas, sand-sized particles and Northland beach sands are by comparison, K-rich, reflecting the abundance of resistant feldspars including microcline, orthoclase and sanidine if derived from felsic volcanic rocks (Claridge, 1961). Winnowing of weathering products by wind or water separates out K-rich sand-sized grains from U and Th enriched silt and clays. This fractional sorting can produce sharp contrasts in gamma ray emission signals, especially in settings characterised by strong fluvial and/or aeolian gradients.

Water content is also a strong attenuator of gamma radiation, with areas characterised by standing water (e.g. lakes or lagoons) or shallow water tables, showing low gamma counts. Whilst gamma attenuation by water is a limiting factor for exploration geologists, attenuation by water has been used to identify areas with high water contents, such as wetlands and swamps, and low-lying stream channels and floodplains with naturally elevated water tables (Bierwirth 1996; Pickup and Marks, 2000; Beamish 2015). Organic carbon is naturally a low emitter of gamma radiation due to a lack of mineral material, with peat deposits showing naturally low gamma. Finally, masking or attenuation of gamma ray signals by vegetation is typically minimal, except where there are dense stands of forest for which reductions in gamma ray counts of 14 ± 22% have been reported (Aspin and Bierwirth, 1996; Pickup and Marks, 2000).

1.5.2 Weathering and transport limitation

A large body of authors note that regional radiometric imagery, when used in conjunction with digital elevation models (DEM) and other geospatial frameworks, provide a means to overcome the major obstacle of up-scaling smaller scale field based studies to whole regions (Wilford, 1995; Wilford et al., 1997; Pickup and Marks, 2000 and 2001; Wilford, 2012). These authors go on to note, that in areas without radiometric cover, the most critical obstacle to regional representation of the controls over erosion and sedimentation is the lack of ability to measure spatially distributed, regional-scale sedimentation processes, which makes it difficult to produce a high resolution regional scale representation of sediment sources and sinks.

All these studies demonstrate the value of radiometric imagery in discriminating between 'weathering' and 'transport' limited areas when used in conjunction with DEMs (see sections 2.1 and 2.2.) and existing soil and geological frameworks. Weathering limited settings (landforms and slopes) are characterised by greater rates of sediment export than accumulation; due mainly to greater relief, slope, altitude and an associated increase in rainfall intensity and volume. Weathering limited areas are also characterised by thin soils (<2 m) which are formed in moderately to slightly weathered bedrock regolith, or unweathered bedrock (Tonkin, 1984). Due to thinner soils, coarser textures and lower bulk density; gamma signals over weathering limited landforms typically reflect the mineralogy and geochemistry of the bedrock (Wilford, 1992; Wilford et al., 1997).

Where the steepness of a slope and/or stream confinement falls below some critical threshold, the rate of regolith production is greater than the capacity of transport processes to remove it (Tonkin, 1984). Typically, these settings are characterised by lower relative relief with a thick (>2 – 10m+) mantle of soil/debris overlying moderately to completely weathered bedrock regolith. Across transport limited settings, weathering and gradients in soil bulk density, porosity and local water tables may partially modify the primary signal of the parent material. Departures from this general rule occur where major slips or erosional surfaces expose relatively fresh, unweathered bedrock. By comparison, minor slips or surficial erosion of fine textured sediments from an area of deeply weathered soil and regolith is not expected to exhibit a significant contrast in gamma signals.

In the following sections, the relationships between landscape setting and key landscape attributes depicted by geospatial layers and radiometric signals are evaluated. The choice of geospatial layers reflects data availability and the desire for regional scale coverage. For each geospatial layer, we note the strength of correlation, evidence for misalignment between geospatial attributes, and sources of uncertainty in our evaluation before providing a summary of our interpretation. We also recognise that radiometric signals and geospatial layers are correlated at multiple scales: (i) broad scale correlation between radiometric signals and key landscape features (i.e., regional landform features such as hill country and lowland areas); (ii) drainage basins at level 3 and higher, and; (iii) finer scale variation occurring at 1 - 2 order drainage basin level.

Finally, we recognise that our knowledge of the local setting is limited relative to that of local experts within the Northland Regional Council and region. Thus, our emphasis is on better understanding the relationship between geomorphic setting, mapped landscape attributes and radiometric signals to better resolve key gradients for the purposes of physiographic mapping of the regional scale controls over shallow ground and surface water quality. As such, this work relies on expert judgement of landscape relationships considered most pertinent to water quality outcomes and is not an assessment of fine scale variation in soil or geological properties for the purposes of mapping of each.

1.6 Test Areas

The variation and relationship between radiometric imagery and geospatial layers for Northland were examined in detail in three test areas - Ahipara, Waipapa, and Kaipara. From an initial review of the geospatial and radiometric relationships across the wider Northland region, these three test areas were selected for detailed comparison in this report. The test areas have strong contrasts in geology and geomorphic setting.

1.6.1 Test site 1: Ahipara

The Ahipara test area is dominated by the raised relief of the Ahipara Massif (Herekino Forest), the western edge of the Maungataniwha Range and the rolling, dissected hill country between Tauroa Peninsula (Figure 5). The area also includes the western harbour of Herekino and the North Western facing Ahipara Bay. Kaitaia is the largest town. The main rivers in this area include Awaroa and Awanui and the southwest end of the Aupouri aquifer underlies the lowland areas northwest of Kaitaia. Ahipara was selected for its distinct boundaries between the basalt rocks of the Tangihua complex and the Punakitere sandstone rocks.

1.6.2 Test site 2: Waipapa

The Waipapa test area (Figure 5) is divisible into three geomorphic zones: 1. the north western Waipapa massif (which contains the Omahuta and Puketi Forests); 2. the easterly low altitude, gently sloping volcanic massif of the Kerikeri volcanics, which continues to the coastal town of Kerikeri, and; 3. the south and south west zone including Lake Omapere, Waihou Valley and the Pukewhararaki Forest. Geologically, the greywacke basement rock dips west underneath the overlying Kerikeri volcanics and the Waipapa massif is a horst of basement (Caples Terrane) and Northland Allochthon sandstone units. The main river valleys are Waipapa, Utakura, Kerikeri, and Waiaruhe. There are several aquifers in the area including the Ngawha geothermal reservoir in the south and the Kerikeri aquifer which follows the catchments of the Kerikeri River and Puketotara Stream. Waipapa was selected for further investigation as parts of the radiometric data set look to be decoupled from the QMAP geology (Figure 5).

1.6.3 Test site 3: Kaipara

The northern Kaipara barrier encloses the Kaipara Harbour in this test area (Figure 5). The barrier is made of windblown and longshore drift sand deposits on the seaward side, and estuarine and fluvial fill on the harbourside. Within the barrier spit there are dune lakes and swamps. The Puketotara and Hukatere peninsulas and Otamatea and Arapaoa river basins make up the eastern side of the test area. In the north is the Ruawai alluvial plain and aquifer. This area was selected because of the active erosion and deposition processes occurring in the barrier and for the dune lake and wetland/swamp features.

2 Radiometrics and DEM Slope

In this section, we evaluate the relationships between the regional 8 m DEM (LINZ) slope raster and radiometric ternary image. The radiometric image is provided as GeoTiff and is a composite image of the three key radiometric signals, K, U and Th.

2.1 Description of DEM data

The 8 m DEM was originally created by Geographx (geographx.co.nz) and was primarily derived from LINZ Topo50 20 m contours (data.linz.govt.nz/layer/768) in 2012. The DEM has been analysed in QGIS to produce a slope raster (units: degrees).

Table 1. DEM metadata.

Source	*Geographx (2012)*
Type	*Raster*
Limitations	
Links to text	*geographx.co.nz* *data.linz.govt.nz/layer/768*
Comments	*8m horizontal resolution. Primarily derived from LINZ Topo50 20m contours.* *DEM has been analysed in QGIS to produce a slope raster (units: degrees)*

2.2 DEM Slope, Geomorphic Understanding and Radiometric Signals

The first evaluation undertaken with the radiometric imagery was simply overlaying the radiometric ternary onto the 8 m DEM, with a transparency of 40%. Within the test areas it is easy to pick out high relief areas as the radiometric signal boundaries are often coincident. This is especially true of any ranges or massifs of the Tangihua complex.

The Ahipara massif in the centre of the Ahipara test area (Figure 6), and the Maungataniwha range in the east, are the dominant relief structures. These areas of highly resistant bedrock have been rafted on top of the underlying basement during Northland Allochthon emplacement. To the west, Gumfields plateau, the radiometric signal is dark blue, consistent with mantling of the low gamma signal of the underlying basalts by weathered Neogene sediments (cemented fine dune sands). These sediments are located on the plateaus and interfluves and as such are less prone to mass movement or erosion (in this study these locations are discussed as being transport limited). Within the steep sided valleys coming down off the Gumfields plateau, the radiometric signal changes to a more K-dominant red and mottled colour, reflecting the signal of the underlying basement rock. There is also evidence from radiometric signals of the ingress of windblown coastal dune sands (K-dominant) up low-lying and seaward facing valleys.

Between the two, high relief, steep sloped massifs lies a large area of dissected rolling hills. This area is comprised of a sandstone unit (Punakitere Sandstone) which shows a higher total gamma count (lighter shades) relative to the low gamma count of the Tangihua basalts (darker shades). Contrasting radiometric signals within the dissected rolling hills of the Punakitere Sandstone occur between river valley flats and the moderately sloping hills. The rivers that run through these valley floors derive sediment from the surrounding hill country and their radiometric signal appears to be related to their headwaters. For example, at the eastern base of the Ahipara massif, along the trace of the Uwhiroa Stream, tongues of dark, attenuated signal similar to that of the massif itself spread onto the flats before being joined by material from the dissected hill country at its lower reaches. The same gradient can be seen in the Manganuiowae Stream as it leaves the Maungataniwha Range and travels to the coast becoming the Rotokakahi River.

In the Waipapa test area (Figure 7), relief related radiometric signals are obvious in the Waipapa massif and volcanic plateaus west of Kerikeri. The Waipapa River valley is steep sided, and these valley slopes have either high gamma counts (in the western Waipapa massif, Omahuta Forest) or low gamma counts (in the eastern Waipapa massif, Puketi Forest). Where the Waipapa River emerges from the western Waipapa massif, it conveys high gamma sediments through the Waihou Valley. The western plateaus (Omahuta Forest) above the Waipapa River, contrast with dark blue, U-dominant signals. Down on the plateau and rolling hills west of Kerikeri, a bright teal, mixed Th-U signal, mantles the underlying Th-dominant valley slopes. These again are the transport limited interfluves and plateaus, while the steeper valley slopes and valley floors have contrasting signals that reflect the varying signal of the underlying basement rock.

In the Kaipara test area (Figure 8), the interfluves along the eastern side of the north Kaipara Barrier are mantled by teal coloured Neogene sediments, while steep, weathering limited valley slopes (lignite and mudstone) are contrasted with K-dominant (reddish/brown, mobile beach sands) signals and lower gamma counts associated attenuation by valley floor peat deposits. The long west coast of the barrier is split into the K-dominant signal of the flatter, active beach sands and mottled teal, Th-U mixed signal upslope on the dunes, associated with older surfaces and associated cementation of fine windblown sands and silts. These steep gradients in geomorphic setting are well correlated with radiometric signals.

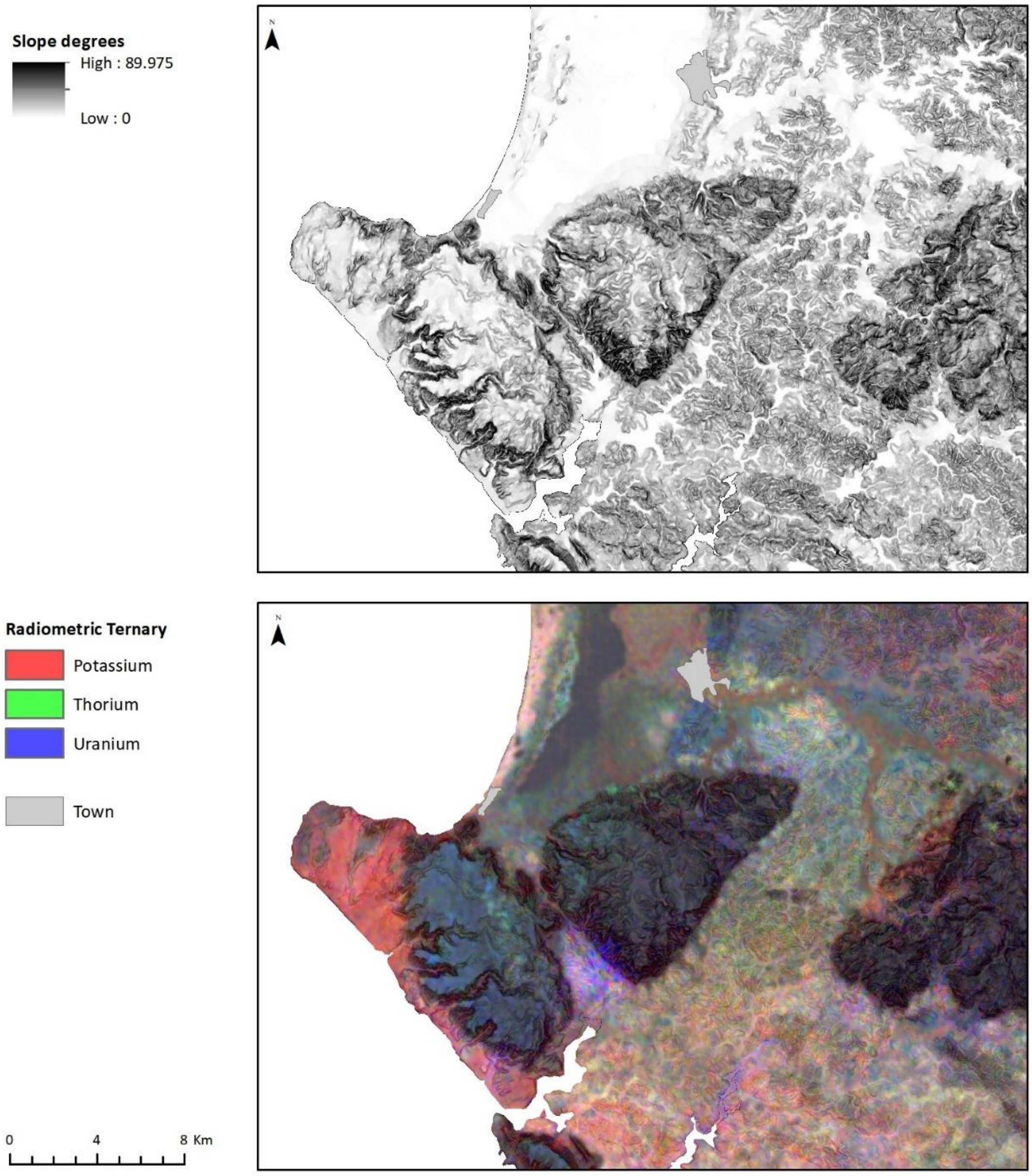

Figure 6. Ahipara test area comparison of radiometrics and DEM slope.

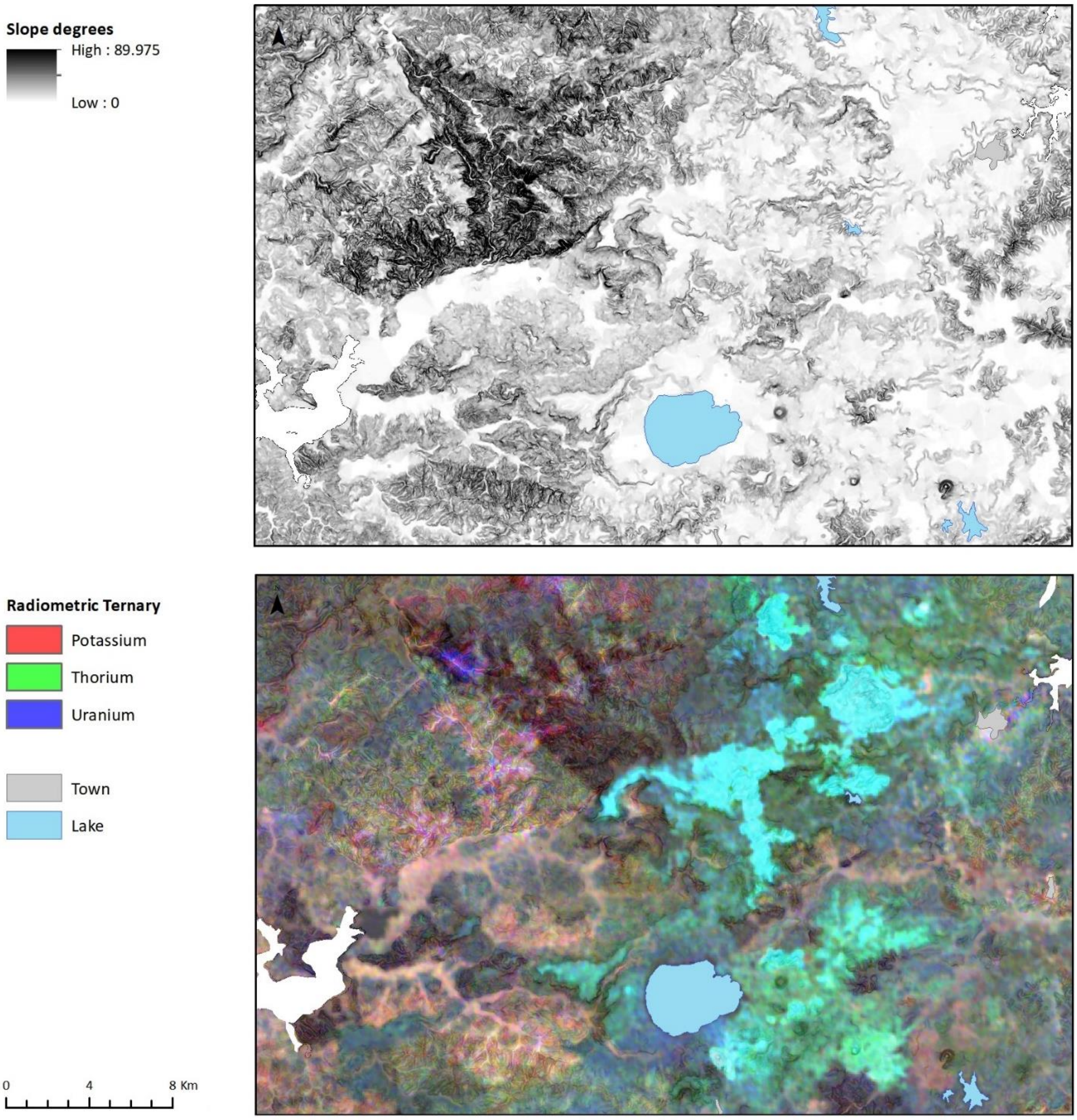

Figure 7. Waipapa test area comparison of radiometrics and DEM slope.

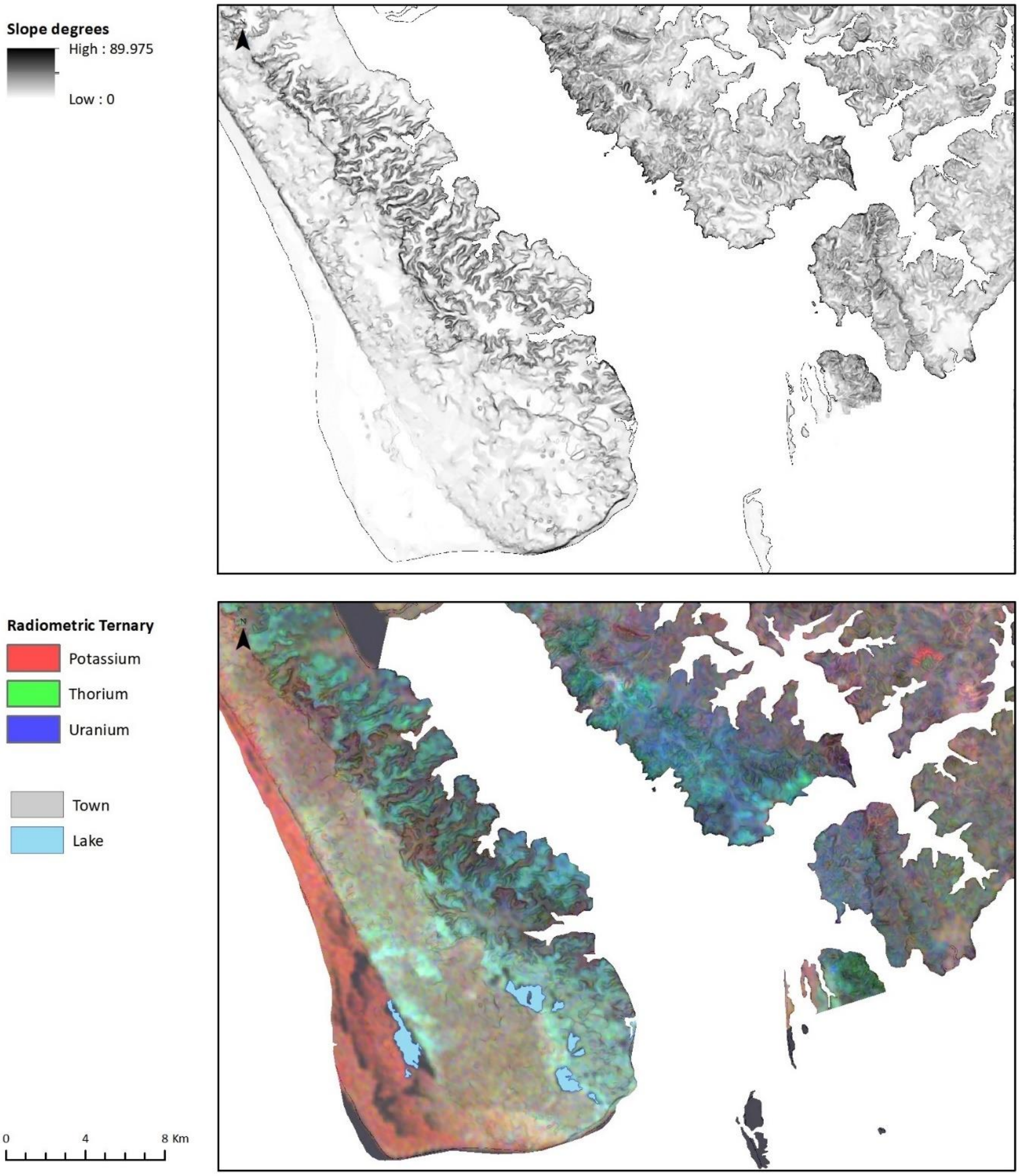

Figure 8. Kaipara test area comparison of radiometrics and DEM slope.

2.3 DEM Slope Summary

The strong spatial correlation between topographic relief and radiometric signal reflect spatial correlation between: (i) geological gradients that control primary parent material texture and provenance, and; (ii) associated geomorphic controls over the stability of surfaces, attendant weathering and geomorphic surface age.

The most obvious relationships identified from combining DEM slope and radiometric imagery include:

- A strong contrast between volcanic rocks and sedimentary sequences of the Northland Allochthon, including exposure of basement rock along the east coast.
- Flat lying volcanic plateaus and associated mantling by aeolian sands along coastal margins (especially the west coast) and localised tephras from rhyolitic and andesitic eruptive centres. These areas are characterised by relatively low relief with minor hydrological system interference. Generally dominated by Th and U signals (teals, greens, blues).
- Valley slopes and gulches[9], where fine material is removed during weathering events, have regolith development limited by high transport rates and regolith is generally thin with bedrock outcropping in places.
- Valley floors are areas of sediment transfer, from the source slowly to a sink (often coastal estuaries, river deltas or lakes). These areas are typified by a mottled radiometric signal that reflects the bedrock provenance of sediments from upper catchments. Differences between active river channels and inactive flood plains and terraces are clearly delineated by slope and radiometric signal.
- Coastal plains, beaches and dunes are areas have a K-dominant signal from sand deposition. Windblown fines bind Th and U in clays.

[9] A narrow v-shaped valley which has been made by a stream flowing through it.

3 Radiometrics and NZLRI Slope Class

In this section, we evaluate the relationships between the NZLRI slope class and radiometric ternary image. For ease of comparison, a slope model is displayed underneath the radiometric ternary image in all subsequent figures.

3.1 Description of data

Table 2: NZLRI slope class metadata.

Source	*New Zealand Land Resource Inventory, Landcare Research (updated 2012)*
Type	*Polygon*
Limitations	
Links to text	*https://lris.scinfo.org.nz/document/162-lris-data-dictionary-v3/*
Comments	*Slope class* *A 0-3° Flat to gently undulating Flats, terraces* *B 4-7° Undulating Terraces and fans* *C 8-15° Rolling Downlands, fans* *D 16-20° Strongly rolling Downlands, Hill country* *E 21-25° Moderately steep Hill Country* *F 26-35° Steep Hill Country and steeplands* *G >35° Very steep Steeplands, cliffs*

3.2 Slope Class and Radiometric Signals

Slope class provides further constraint over the likely sediment erosion risk and serves to better qualify gradients in weathering and transport limited settings. When combined with soil hydrological properties, slope allows for a more accurate assessment of overland flow risk and can better constrain landscape level controls over in-stream water quality (Pearson 2015a; Hughes et al. 2016).

Although sediment yields are broadly correlated with slope class (Snelder, 2015), sediment derived from natural state settings cannot cause the rapid increase in sediment flux and associated N, P and M export that has occurred since European colonisation of the region (see section 9.1.1). Therefore, although important, slope class alone is unlikely to explain the spatial variation in stream clarity and other particle reactive water quality indicators such as *E. coli*, ammoniacal N, organic N, TP or DRP.

In Northland, geomorphically controlled radiometric signals [Tanighua complex (steep), alluvial plains (flat)] can be picked out in the slope class comparison. In areas of mixed slope class, for example the dissected rolling hills between Ahipara Massif and the Maungataniwha range (Fig. 9), there is less correlation with radiometric signals.

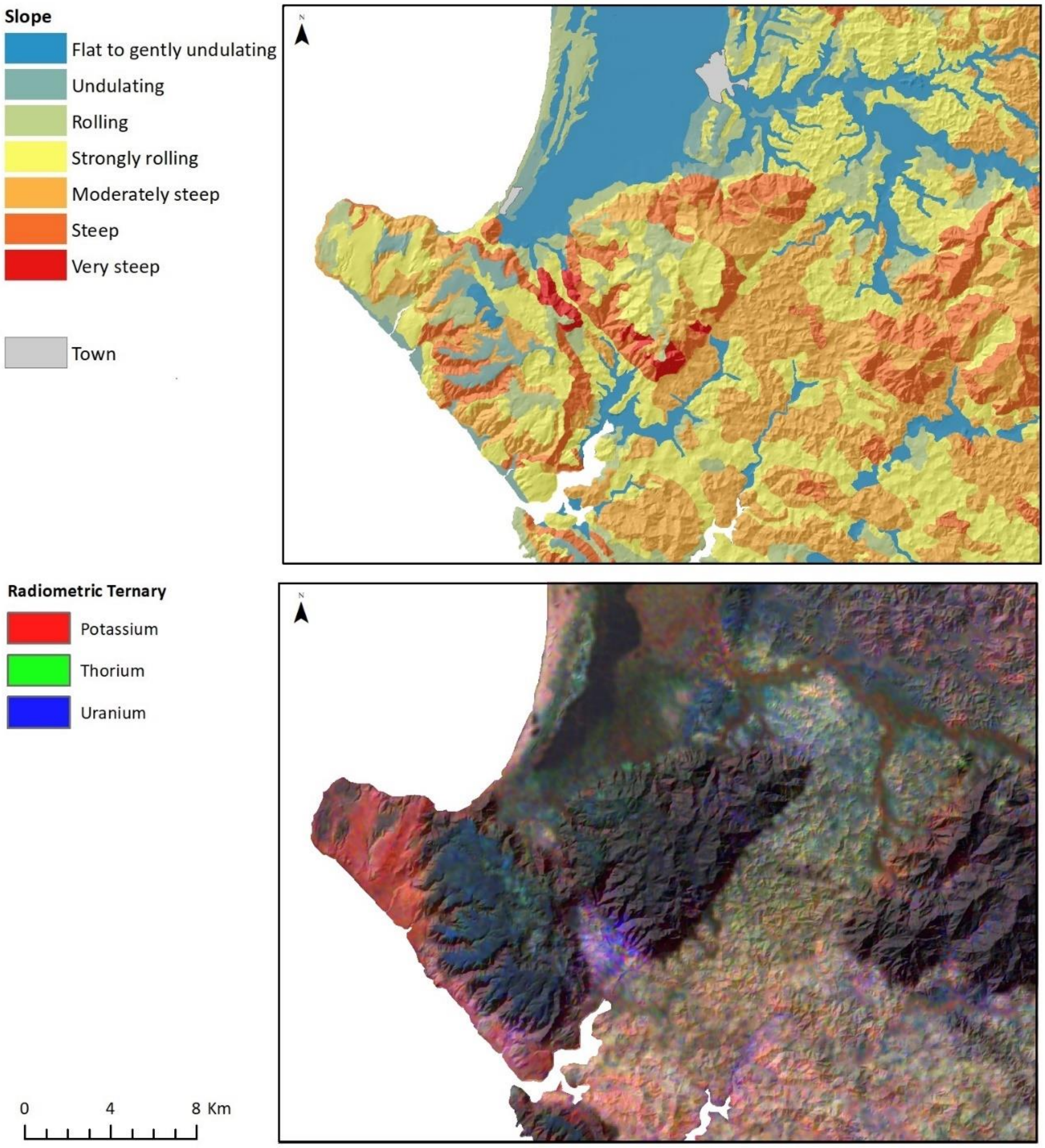

Figure 9. Slope class from NZLRI and radiometric ternary at Ahipara.

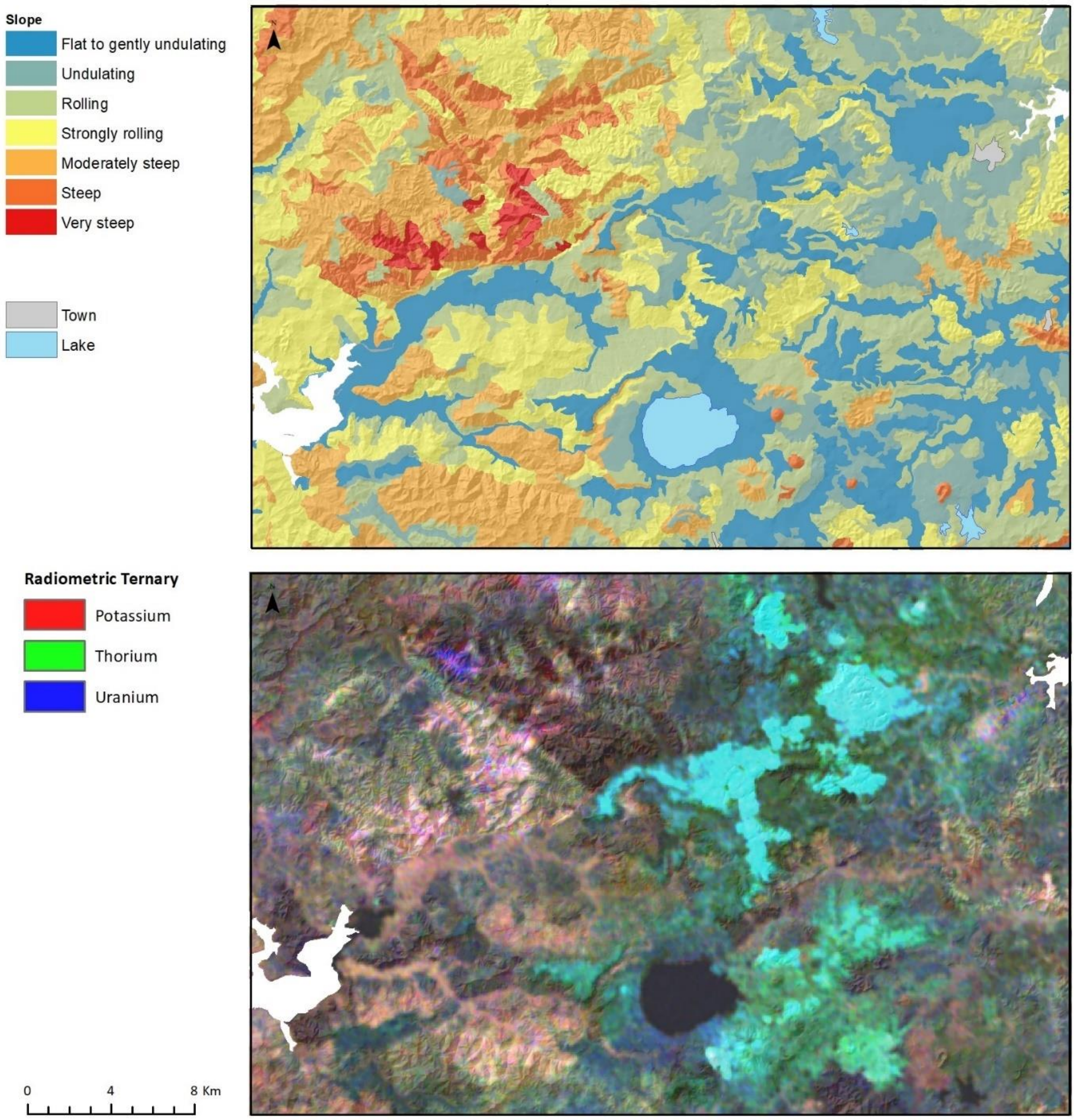

Figure 10. Slope class from NZLRI and radiometric ternary at Waipapa.

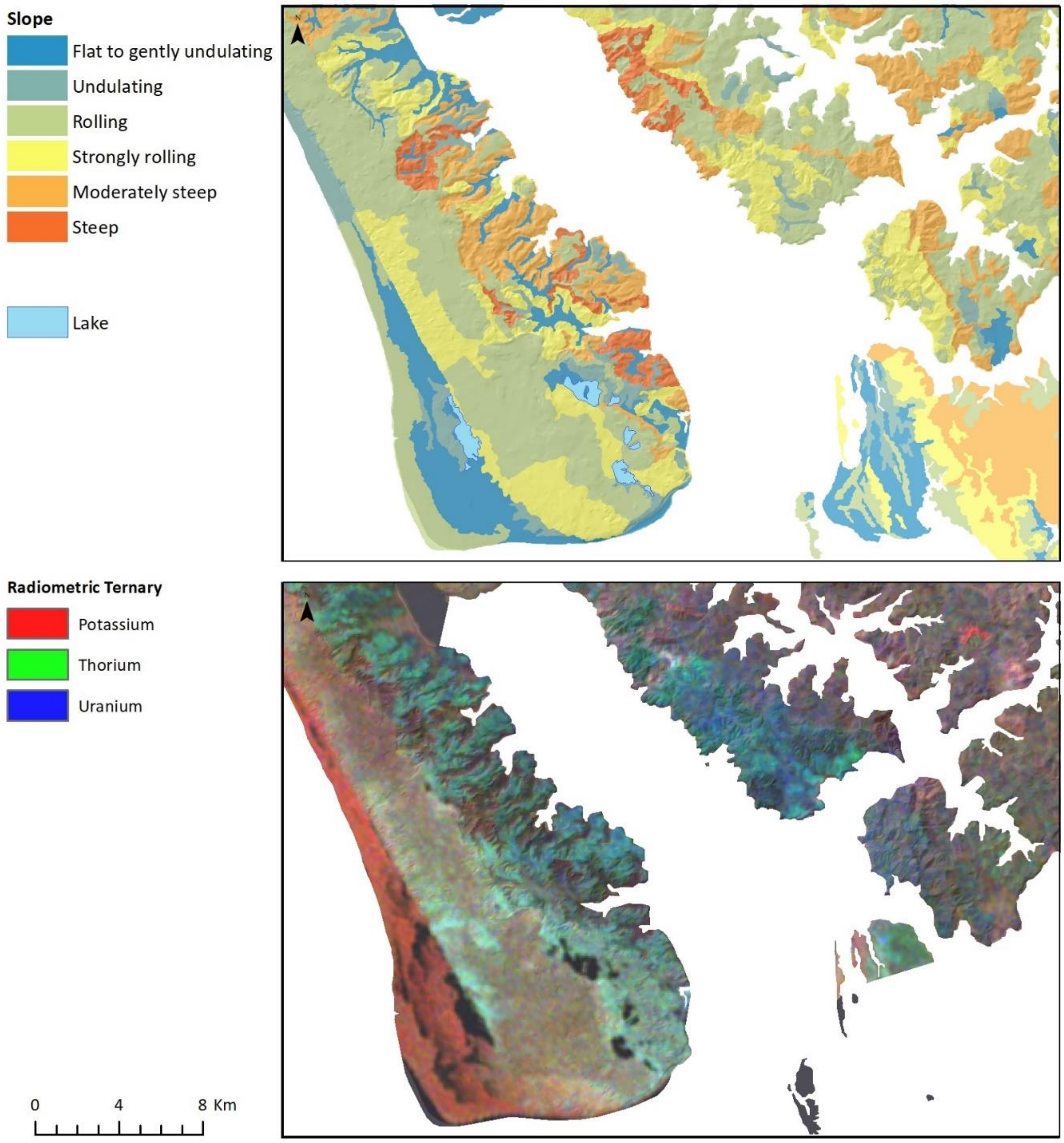

Figure 11. Slope class from NZLRI and radiometric ternary at Kaipara.

3.3 Slope Class Summary

The regional-scale resolution of the geomorphic gradients governing erosion and sedimentation stand to benefit the most from the radiometric survey. Specifically, Northland's radiometric imagery appears to be providing a strongly resolved regional-scale picture of the distribution and gradients of scale associated with weathering and transport limited settings. Recognition of these geomorphic controls in conjunction with slope class is critical when attempting to explain 'how' and 'why' clarity, turbidity and suspended sediment concentration vary between streams and stream reaches.

A number of authors (Wilford, 1995; Wilford et al., 1997; Pickup and Marks, 2000 and 2001; Wilford, 2012 and references therein) noted that regional radiometric cover provided a means to overcome the major obstacle of upscaling smaller field based studies to whole regions. In areas without radiometric cover, the most critical obstacle to any regional representation of the controls over erosion is the lack of ability to measure spatially distributed, regional-scale sedimentation processes; making it difficult to produce a high-resolution regional representation of sediment sources and sinks required for the verification of model predictions. Based on our current evaluation, we agree with these findings and suggest that the landscape controls over instream sediment concentration and load could be improved through combining the Northland radiometric survey data with other regional datasets such as DEM, LRI slope class, LRI erosion class and indigenous forest cover (see Section 9 for Physiographic method). The sediment model, SedNetNZ, is also a powerful tool to help better inform this work (Dymond et al., 2016).

4 Radiometrics and Geology

In this section, we evaluate the relationships between geology and radiometric signals by comparing the radiometric GeoTIFF with available geological data. The GeoTiff is a composite image of the three key radiometric signals, K, U and Th. The two data sources with spatial geological data are QMAP and the NZLRI.

Resolution of geological gradients across the landscape is critical for understanding hydrological response, erodibility and redox dynamics that contribute to variation in water quality outcomes across a region (Rissmann, 2011; Rissmann et al., 2016a).

4.1 Description of QMAP data

The QMAP Geology is a nationwide geological layer provided by GNS Science which holds tabulated physical attribute data, such as rock type and age. The data is linked to mapped unit boundaries (polygons), as such, each map unit contains data for numerous geological attributes.

Table 3. QMAP metadata.

Source	*QMAP (published 2012), GNS Science*
Type	*Polygon*
Limitations	*Scale at 1:250,000*
Links to text	*https://www.gns.cri.nz/research/QMAP/metadata/kaitaia/metadata/QMAPkaitaiageopolshp-v1-0.html , https://www.gns.cri.nz/research/QMAP/metadata/whangarei/metadata/QMAPwhangareigeopolshp-v1-2.html , https://www.gns.cri.nz/research/QMAP/metadata/auckland/metadata/QMAPaucklandgeopolshp-v1-2.html*
Comments	*Layer scale at 1:250,000 but data is derived from finer scale mapping.*

4.2 Comparison of radiometric signal with QMAP attributes

The QMAP attributes discussed in this section are stratigraphic age (STRAT_AGE), dominant rock type (MAIN_ROCK), and a combined rock type and stratigraphic age (SIM_NAME).

4.2.1 Stratigraphic Age (STRAT_AGE)

Stratigraphic age or STRAT_AGE is the attribute within QMAP which uses a geological time nomenclature for classification. Polygons are differentiated according to the geological epoch (e.g. Holocene) and period (e.g. Quaternary) during which the rock formed or the landform deposited. The Northland Allochthon, for example, was formed in stages over 100+ Ma and is comprised of multiple rock types of different ages. The landscape has thus been subjected to varying tectonic, geomorphic and climatic settings and attendant weathering durations and rates. In all instances, gradients in stratigraphic age are well correlated with radiometric signals, reflecting the contrasting rock geochemistry.

Within the Ahipara test area (Figure 12) STRAT_AGE is well correlated with radiometric signals, particularly, the boundaries are well matched suggesting geological control over radiometric signals. Variation in stratigraphy is well matched to compositional changes, notably the Taipa Mudstone (56 – 29 Ma) in the north east of the test area is younger than the more extensive Punakitere Sandstone (95 – 75 Ma); both contribute sediment to the Kaitaia plains via the Awanui River. The northern area of the Punakitere Sandstone which is within the Awanui catchment has slight U-dominant (blue) signal compared to the southern part which drains to the west. The Whangai Formation (100 – 61 Ma) mudstone and micrite/chert outcrops within the more voluminous Punakitere Sandstone unit as a narrow, arcuate band in the far southeast of the test area.

In Waipapa (Figure 13) the dominant stratigraphy is that of the basement Waipapa Group greywacke (270 – 154 Ma), upon which the Northland Allochthon (Punakitere sand- and mud-stone and Taipa and Whangai mudstones) has been rafted. These resistant layers form the steeper areas of the test area. The Waipapa Group is strongly incised and eroded, especially in the area where the Waipapa River flows. This valley is a highly active tectonic zone. Old sedimentary rocks are overlain by a large area of young (9.7 – 1.8 Ma) igneous extrusives of the Kerikeri Group basalts and basanites. On the basis of a strong Th dominated (teal blue) signature across the elevated, flat-lying sections of the basaltic plateau, we suggest overprinting of the basalts by fluvial erosion (and/or ash) of small-scale rhyolitic and/or andesitic eruptive centres northwest and west of Kerikeri, in the vicinity of the Remuera Settlement and Ngawha. Where the plateau has been dissected and eroded, Th-rich signals are absent and radiometric signals reflect that of the underlying basalts and/or sedimentary sequences. The soils associated with these rhyolitic or andesitic ash deposits exhibit allophanic properties including lower acidity and higher P-retention in subsoils (Mr Bob Cathcart, pers. comm., 2017).

In Kaipara (Figure 14), the stratigraphy increases in age from southwest to northeast. Across the Kaipara Barrier bar, age increases towards the east from the young and actively mobile dune sands of the western shoreline of the Kaipara Barrier bar (Q1; 0.014 Ma max) through a succession of Quaternary aged paleo shorelines and marine terraces (Q5 – Q7; 0.13 – 0.07 Ma). Across the Kaipara Harbour, towards Hukatere, Arapaoa and beyond the Arapaoa River towards Tanoa and Marohemo, stratigraphic age increases in response to outcropping of the Okaroro Formation (20 – 18 Ma) and Puketi Formation volcanic breccias and farther northwest to the melange of the Northland Allochthon (90.2 – 21.5 Ma). Further east, stratigraphic age increases in response to outcropping of Mangakahia mudstone (95 – 53 Ma) and Punakitere Sandstone (95 – 75 Ma), both associated with the Northland Allochthon. The Mahurangi Limestone (36 – 23 Ma) is locally important across the Okahukurua and Puketotara peninsulas.

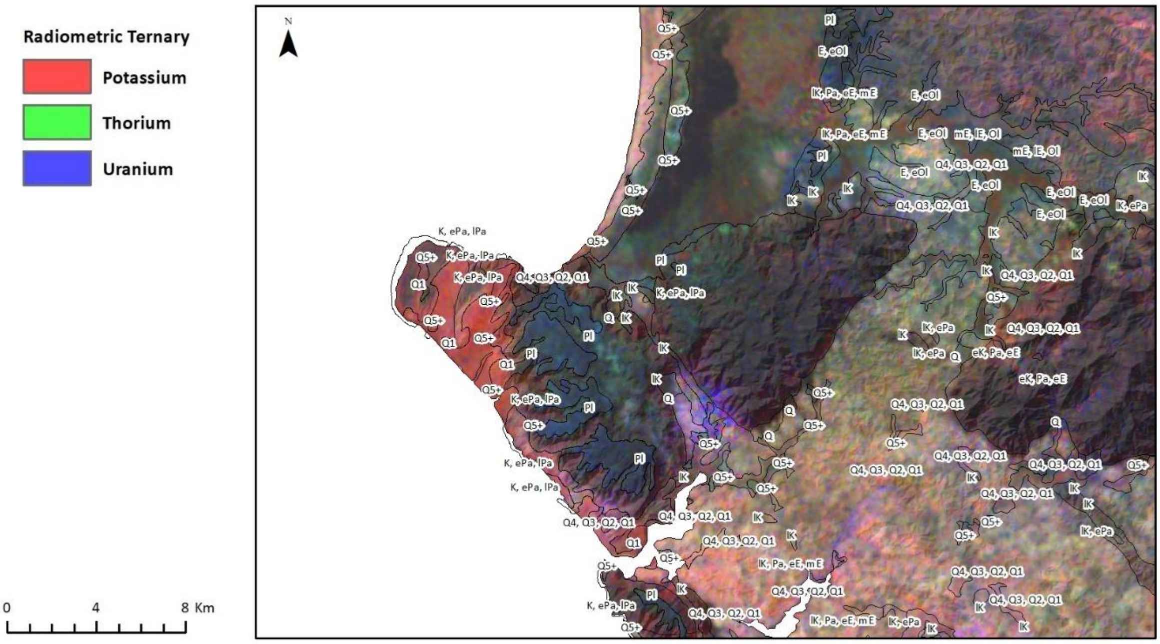

Figure 12. Radiometrics ternary with Strat_Age at Ahipara test area.

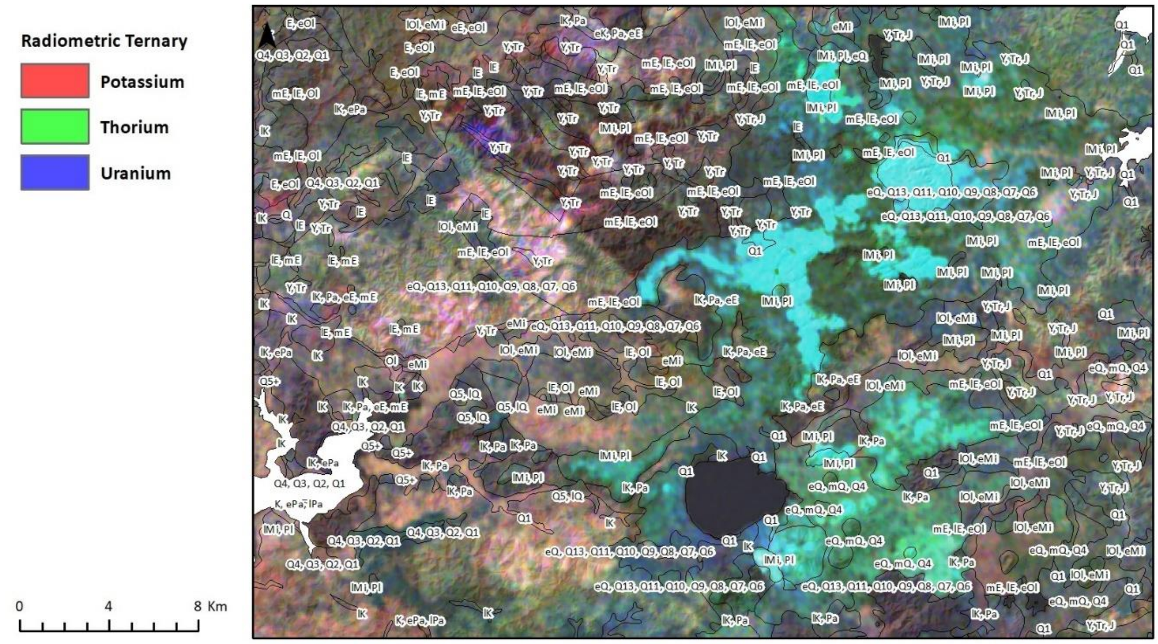

Figure 13. Radiometrics ternary with Strat_Age at Waipapa test area.

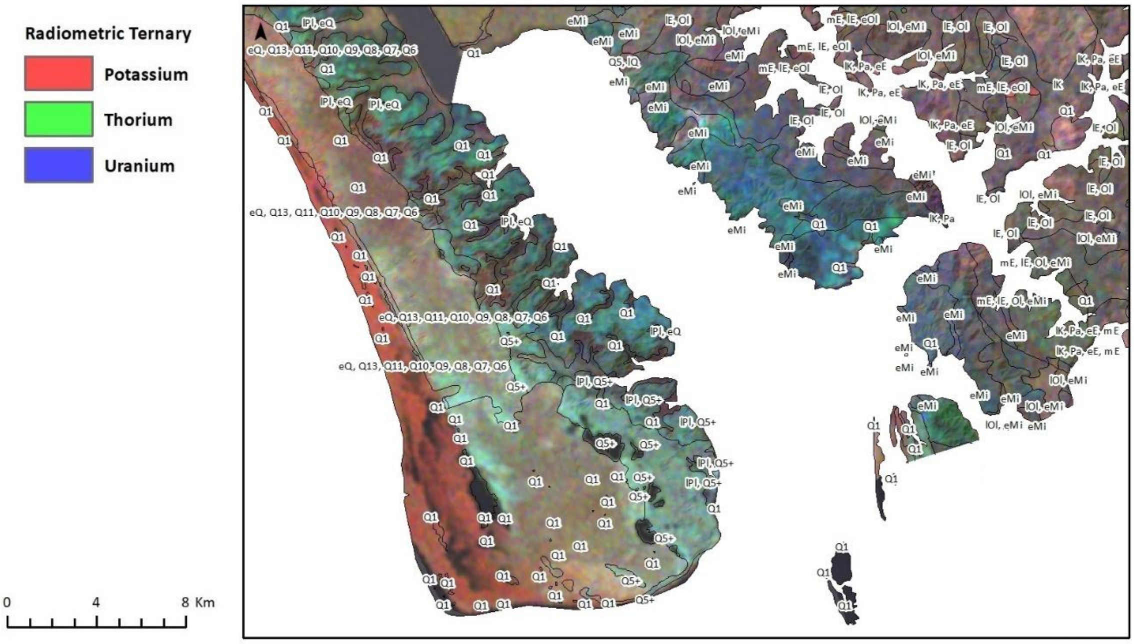

Figure 14. Radiometrics ternary with Strat_Age at Kaipara test area.

4.2.2 Dominant Rock Type (MAIN_ROCK)

The dominant rock type (attribute field: MAIN_ROCK) is defined on a volume basis (not stratigraphic), from the GNS rock names list. Correlations between QMAP polygons and radiometric signal are strong in areas of homogenous rock found in weathering limited settings (Northland Allochthon).

At the Ahipara test site we see a strong correlation between mapped QMAP units and gamma signals (Figure 15). The dark area in the middle of the radiometric ternary is the Ahipara massif, a Tangihua Complex basalt unit that has high relief (identified in Figure 15 with red arrows). Basalts have naturally low gamma signal and are surrounded at lower elevations by the Punakitere Sandstone, which show a higher gamma signal (lighter colour). The recent wind-blown dunes on Tauroa Peninsula (identified by the blue arrow in Figure 15) are notable for their high K gamma signal as is expected for sand-sized particles. The Tangonge wetland (the dark area identified by the green arrow in Fig. 15), is not identified in QMAP. Dark areas on the spit indicate attenuation of the signal by areas of elevated water content, including swamps, and areas of dune lakes (Figure 15).

Across the Waipapa test area, the geology is more complex and radiometric signals show finer granularity than afforded by the 1: 250,000 scale of QMAP (Figure 16). There is a general correlation between QMAP polygons and areas of sedimentary rock, basalt rock (areas of lower gamma signal – dark green/brown), rhyolite rock and andesite rock (strong aqua blue). The large area of strong aqua blue radiometric signals (U dominated) in Figure 16 likely reflects the mantling of the flat lying areas (plateaus) of the older Kerikeri basalt rocks by younger rhyolitic and/or andesitic ash from eruptive centres labelled W, X, Y, Z in Figure 15, and subsequent weathering to form U and Th enriched clay minerals. Where the plateau has been incised, a signal more consistent with the underlying Kerikeri basalt rocks is evident as dark green and brown gamma signals.

Elevated K gamma signal (red/pink) pick out the sedimentary rocks (greywacke sandstones, mudstones) and the brightest K signals are associated with intercalations of unconsolidated mud and alluvium across the Waipapa test area. There appears to be considerable misalignment between what is defined as Omahuta Sandstone and what is likely to be mafic metavolcanics (see yellow line in Figure 16).

Across the Kaipara test area (Figure 17), radiometric signals pick out finer scale variation than was intended to be provided by QMAP Main_Rock at 1:250,000. Here, the deep red of the western barrier bar corresponds to the active sand flats and dune complexes, with a striking linear contrast in gamma signal associated with a paleo-shoreline. Dune lakes and swamps are characterised by areas of very low gamma signal (black), many of which are not defined on QMAP. Eastwards, beyond the paleo-shoreline, K-rich beach sands are blown across the barrier bar, with blue colours corresponding to more stable areas that are mantled by finer textured and weathered aeolian sands, silts and clays. From an evaluation of Northland's western coastline, the role of windblown sand, silt and clay sized particles in mantling bedrock appears to be an important feature governing variation in radiometric signals.

Along the eastern side of the barrier bar, QMAP picks out some, but not all of the finer scale variability in gamma signal associated with unconsolidated mud and peat valley floor deposits. Beyond the Kaipara Barrier bar, the westward facing slopes of the Hukutere area show a blue U-rich signal which may relate to weathering of underlying andesitic rocks and Okaroro Formation sandstones (see section 4.2.1). Further inland, away from the aeolian influence of the western coast line, the radiometric signals are well correlated with the sedimentary rocks of the Northland Allochthon and Mangakahia Complex. Green Th signatures are associated with limestones and hyaloclastite breccias of the Hukatere Subgroup.

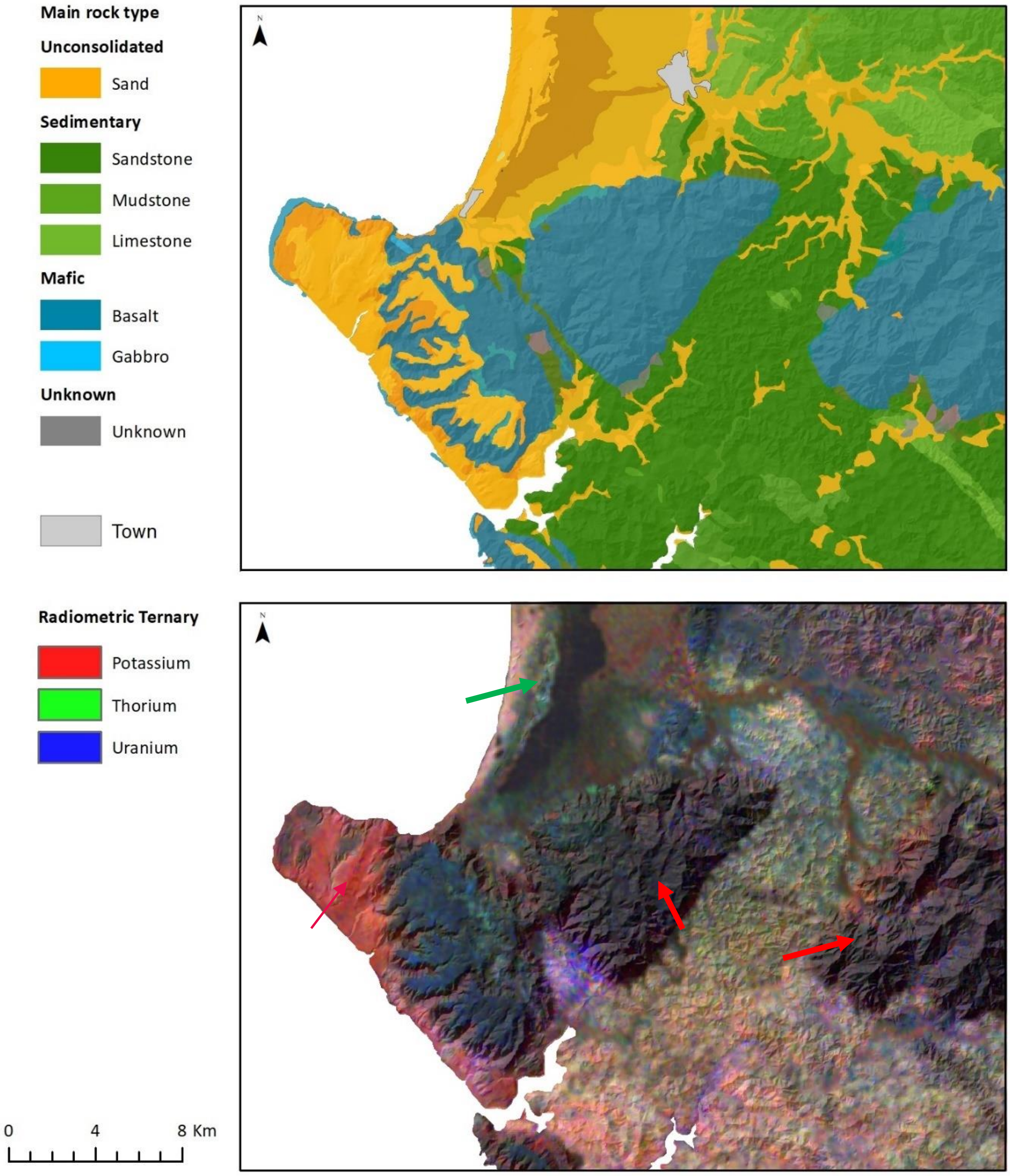

Figure 15. Dominant rock type from QMAP and radiometric ternary at Ahipara.

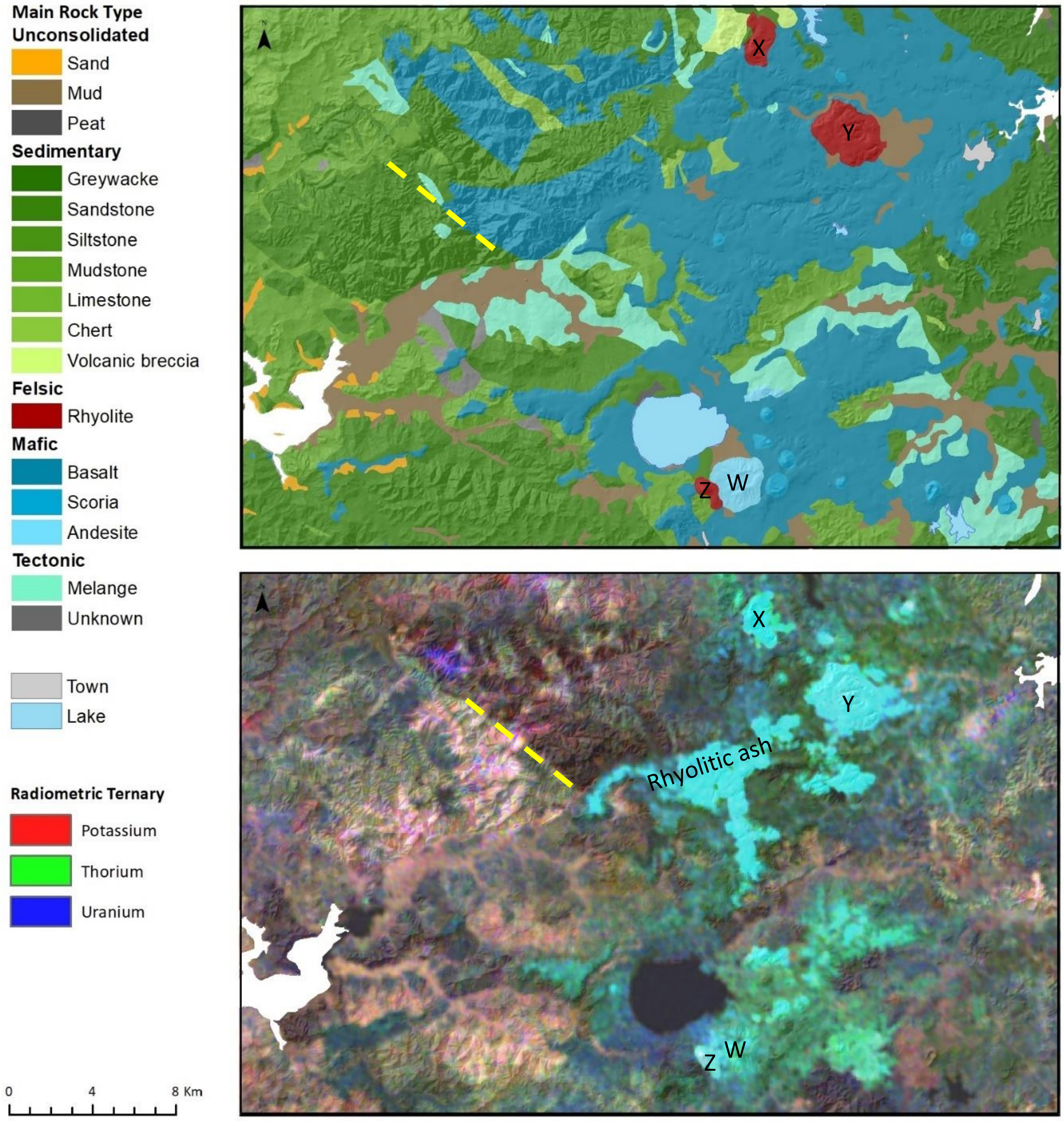

Figure 16. Dominant rock type from QMAP and radiometric ternary at Waipapa.

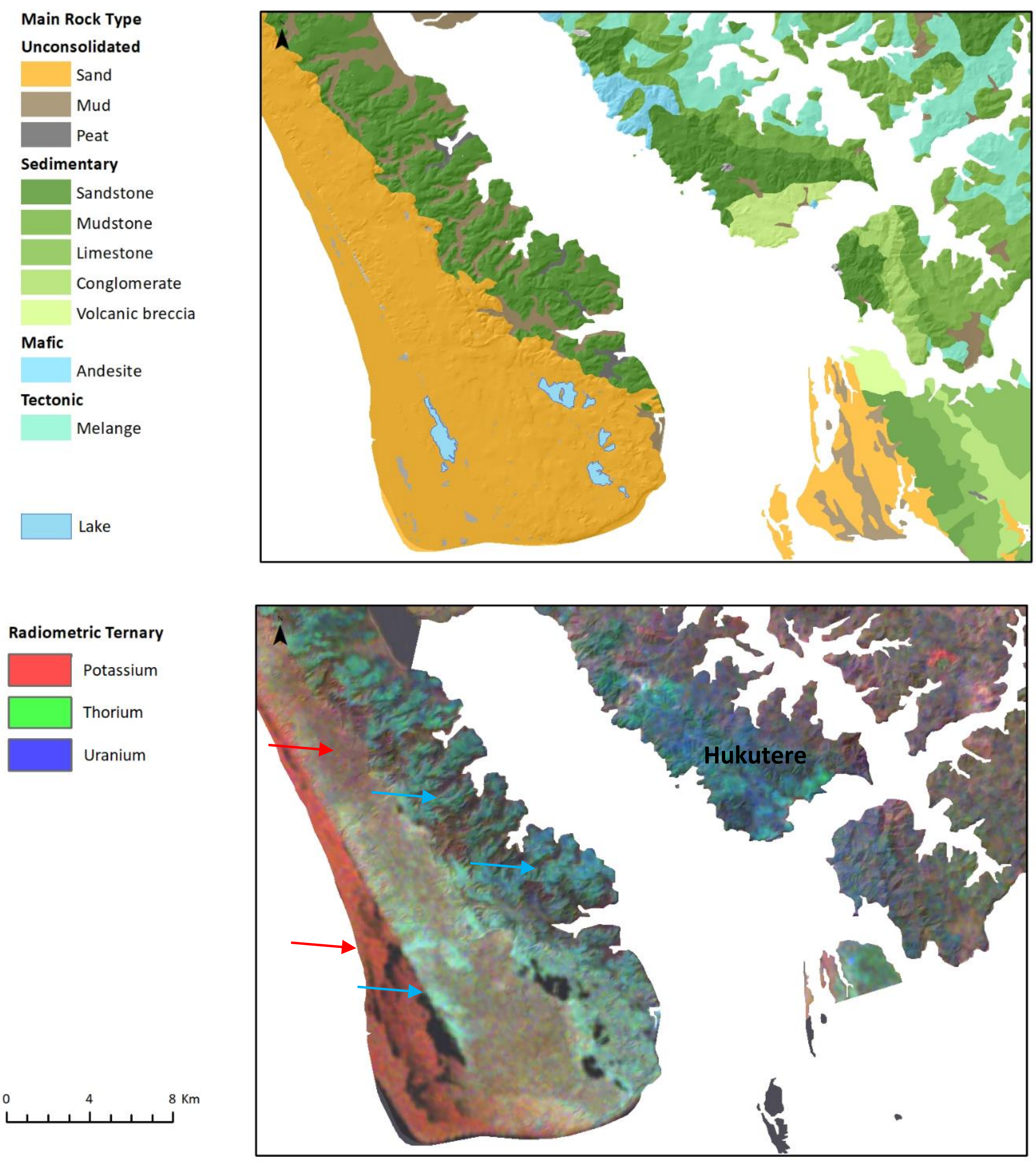

Figure 17. Dominant rock type from QMAP and radiometric ternary at Kaipara. Red arrows denote K-rich beach sands and beach sand derived sediments and blue arrows denote mantling by aeolian silt and clay.

4.2.3 Dominant Rock Type and Geological Age (SIM_NAME)

The attribute field SIM_NAME is a simplification of the dominant rock type (MAIN_ROCK) and stratigraphic age (STRAT_AGE), which divides the map units into basic geology according to age. Where stratigraphic age corresponds to the age of the rock or sediment, not the age of the landform. Areas where rock type and age coincide tend to be associated with depositional landforms (e.g. alluvial or colluvial valley infill). These areas of the landscape are predominantly 'transport limited', where the heterogeneity of radiometric signatures is best explained by weathering processes and associated soil pedogenic controls over hydrology (e.g. soil drainage class). For areas of erosive bedrock, the age of the rock is commonly very old whereas the geomorphic surfaces are young (Figure 18 and 19). Again, gamma signals from 'weathering limited' landforms tend to be more uniform and primarily reflective of the geochemistry of the rock type.

Across the Ahipapra test area (Figure 18), allocthonous rocks of Cretaceous to Paleocene age are well discriminated by the QMAP SIM_NAME. In particular, the low-lying Punakitere Sandstone of the Northland Allochthon is sharply contrasted against the darker signals of the Tangihua Complex basalts that make up the most prominent, high-relief features of the area. Early to late Pleistocene sediments are also reasonably well correlated with K-rich gamma signals across recent floodplains, including those of the Awanui River. In the northeast of the Ahipara test area, the Taipa Mudstone unit is well contrasted with the Punakitere Sandstone.

Across the Waipapa test area (Figure 19), the QMAP SIM_NAME classification is slightly better aligned with the gamma signal data, relative to the MAIN_ROCK classification. As with the Ahipapra test area, it is evident that the radiometric imagery could aid finer-scale resolution of the geological mapping in the area. For example, the igneous basement rocks (dark red in Fig. 19a) and the Pleistocene and Holocene river deposits (pink and red signals) are sharply resolved in the gamma signal image. The influence of rhyolitic rocks and associated weathering of rhyolite ash (bright aqua blue = U + Th rich in Figure 19) is not well defined as discussed above (preceding section).

For the Kaipara test area (Figure 20), the QMAP SIM_NAME category correlates reasonably well with radiometric signals, with finer resolution afforded by radiometric imagery.

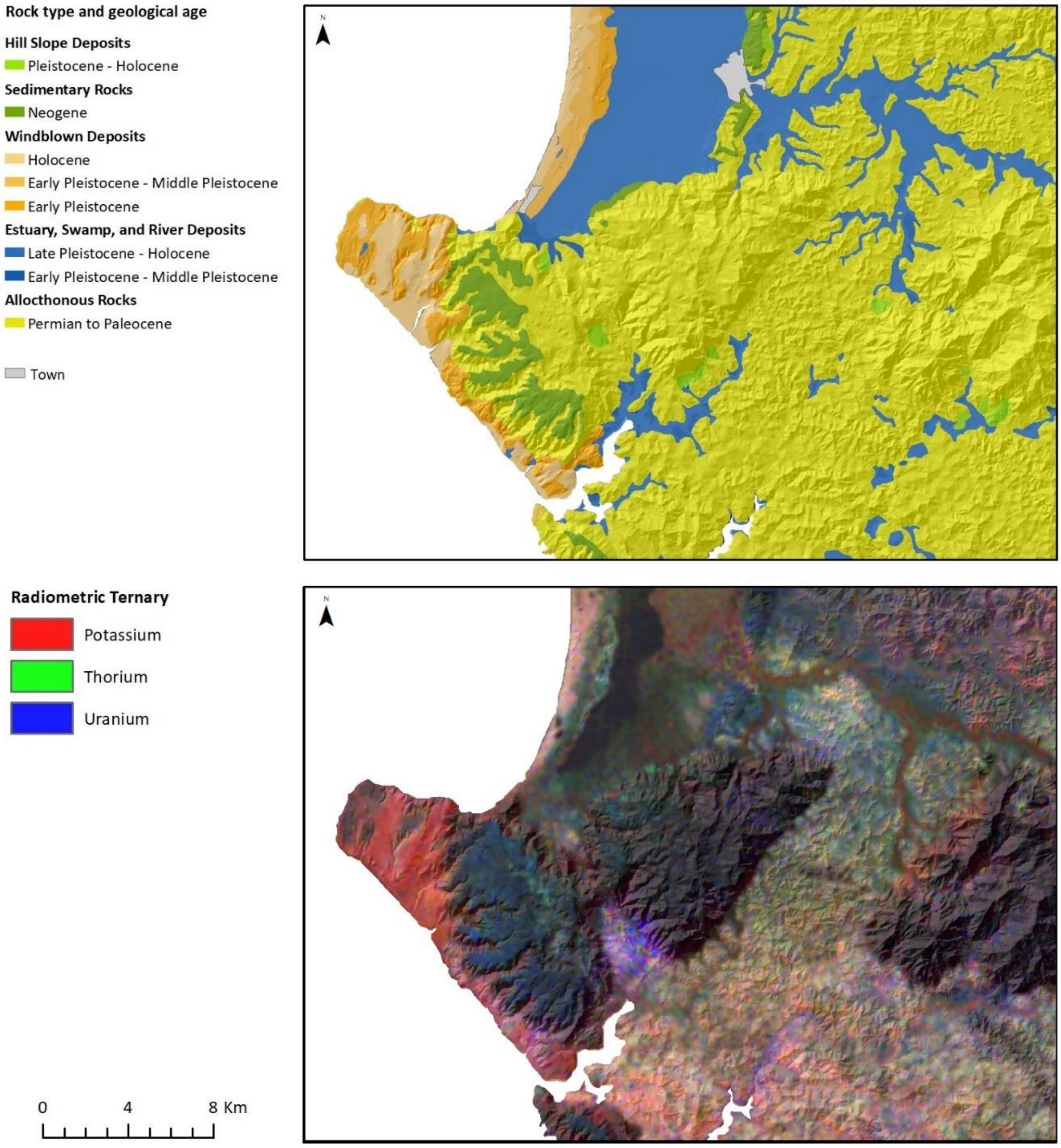

Figure 18. Rock type and age from QMAP and radiometric ternary at Ahipara.

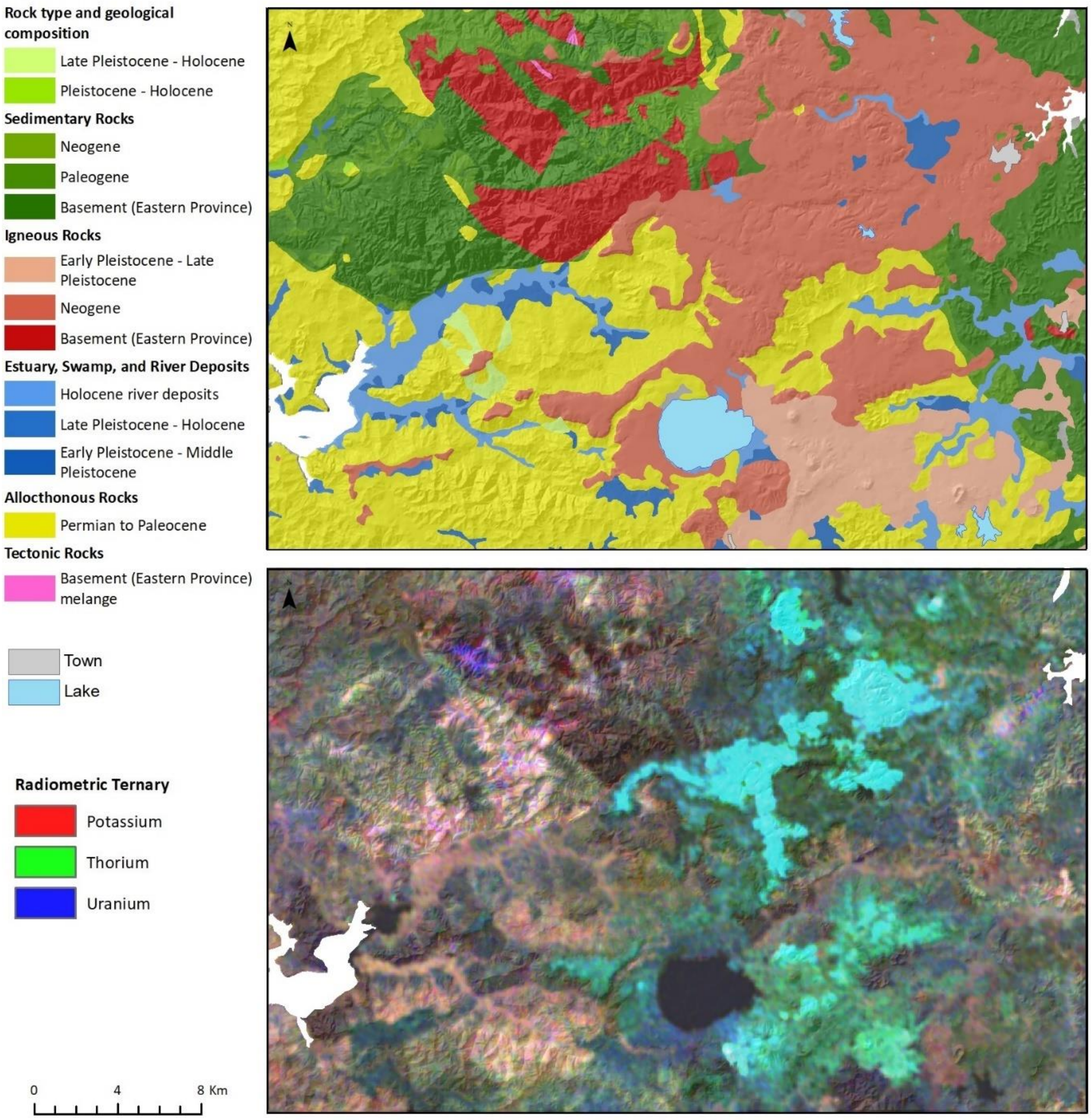

Figure 19. Rock type and age from QMAP and radiometric ternary at Waipapa.

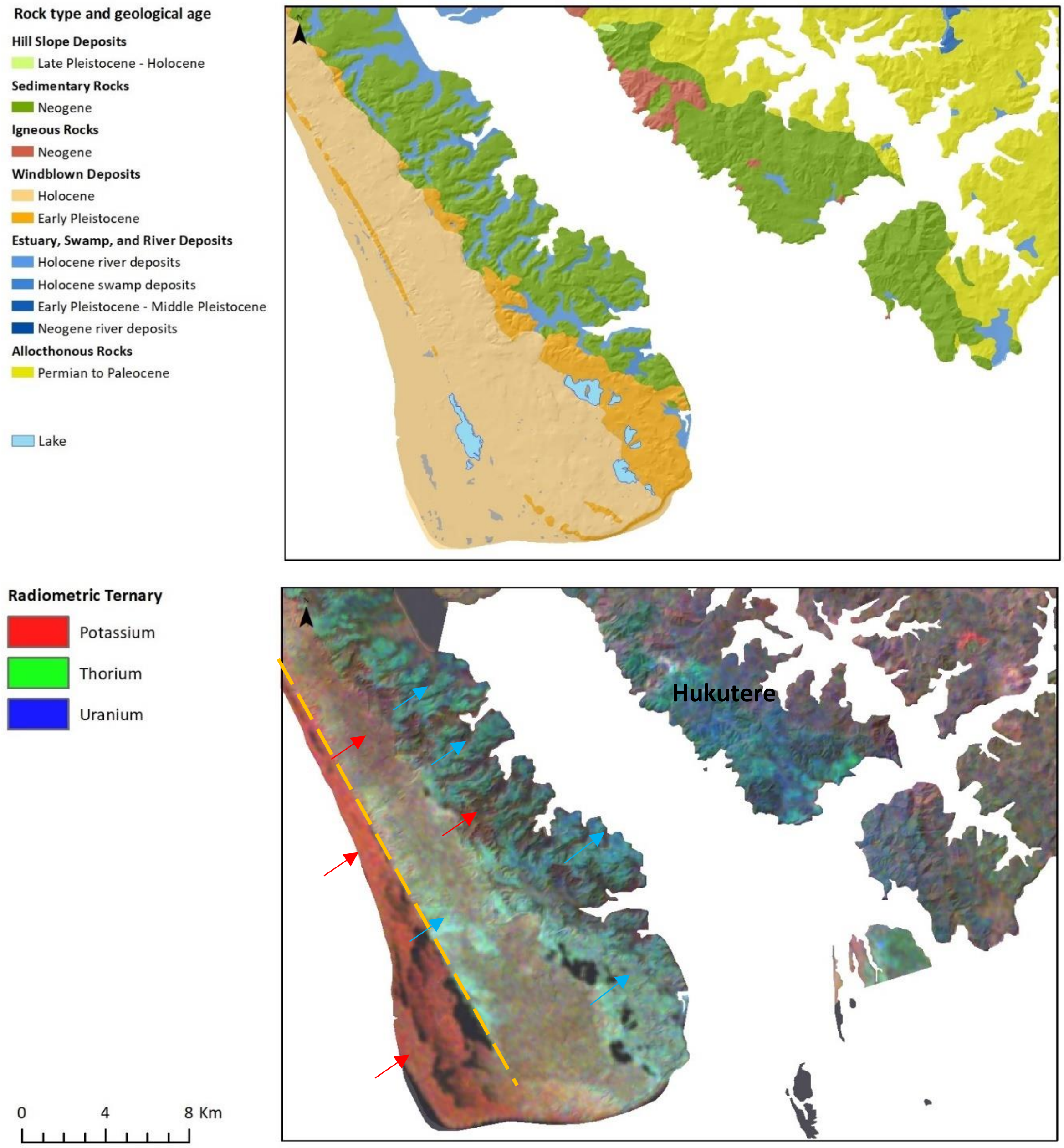

Figure 20. Rock type and age from QMAP and radiometric ternary at Kaipara. The blue arrows denote mantling by windblown silt and clay and red arrows show areas with K-rich sand.

4.3 Description of NZLRI data

The NZLRI is a national database of physical land resource information, held by Landcare Research, in which data concerning the physical properties of the land surface (rock type, soil type, slope, present type and severity of erosion and vegetation) are linked to polygonal map units. The NZLRI was compiled from decades of soil, geological, slope, vegetation and erosion surveys (1st ed. 1975-79, 2nd ed. 1985-1990; Harmsworth, 1996). The purpose for the NZLRI was to characterise the land features to produce a land use capability classification for primary production; this results in the data collected being weighted towards those areas that are more readily accessible and useful for land development. Importantly, this may limit the accuracy of the LRI across areas of steep rock outcrop and areas of extensive indigenous vegetative cover that have limited land use potential or activity. This layer uses a break-out trigger of a single point of difference to define unit boundaries, e.g. two boundaries might share similar rock type but have different erosion class.

Table 4. NZLRI metadata.

Source	*New Zealand Land Resource Inventory, Landcare Research (updated 2012)*
Type	*Polygon*
Limitations	*Limited geological information. Not all data has been field mapped, geared towards land use productivity, different classification systems were used during mapping in some regions*
Links to text	*https://lris.scinfo.org.nz/document/162-lris-data-dictionary-v3/*
Comments	*Original field work carried out in the late 70's, 80's and 90's. The NZLRI was updated in 2012. Methodology deriving for attribute classes involved qualitative and quantitative analysis of data.*

4.4 Comparison of Radiometric signal with NZLRI attributes

To assess the NZLRI geology data we dissolved polygons that shared attributes for Rock2 and Erosion class to improve visualisation of the relationship with radiometric signals and ease of use.

4.4.1 Near-surface lithology (LRI Rock2)

The NZLRI contains geological information for the polygons (attribute field: LRI Rock2) at the 1:50,000 scale, providing a more resolved representation of regional geology for Northland. The short code format of the data can be elaborated using the LRIS data dictionary (Newsome et al., 2008) and additional weathering qualifiers improve the utility of the data.

An advantage of LRI Rock 2 compared to QMAP is the addition of unconsolidated classes, which allows for the differentiation of unconsolidated silt, clay, sands, gravels and peats in addition to the degree of weathering and bedding of sediments (Figures 21, 22 and 23). This extra resolution is important when attempting to better understand landscape gradients that govern water quality variation including sediment concentration and flux.

Across the Ahipapra test area, the LRI Rock2 layer and radiometric signals are slightly more resolved, reflecting the finer scale (1: 50,000) of this mapping relative to QMAP (1:250,000). Similarly, across both the Waipapa and Kaipara test areas, the LRI Rock2 layer provides some additional resolution over finer-scale variation in radiometric signals. In particular, Rock2 appears to do a better job at resolving larger scale Quaternary floodplains and alluvial deposits and smaller scale extrusive rocks.

Although, as noted above, there is some inconsistency between QMAP and Rock2. Specifically, some significant variation in the provenance of geological units assigned by each layer. For example, within the Kaipara test area, the western slopes of the Hukutere and Tenopai areas are mapped as volcanic rock by Rock2 and as sedimentary rock by QMAP; across the Waipapa area, rhyolitic eruptive centres are designated as sedimentary rock by Rock2. The inconsistency between these layers can be resolved by field mapping.

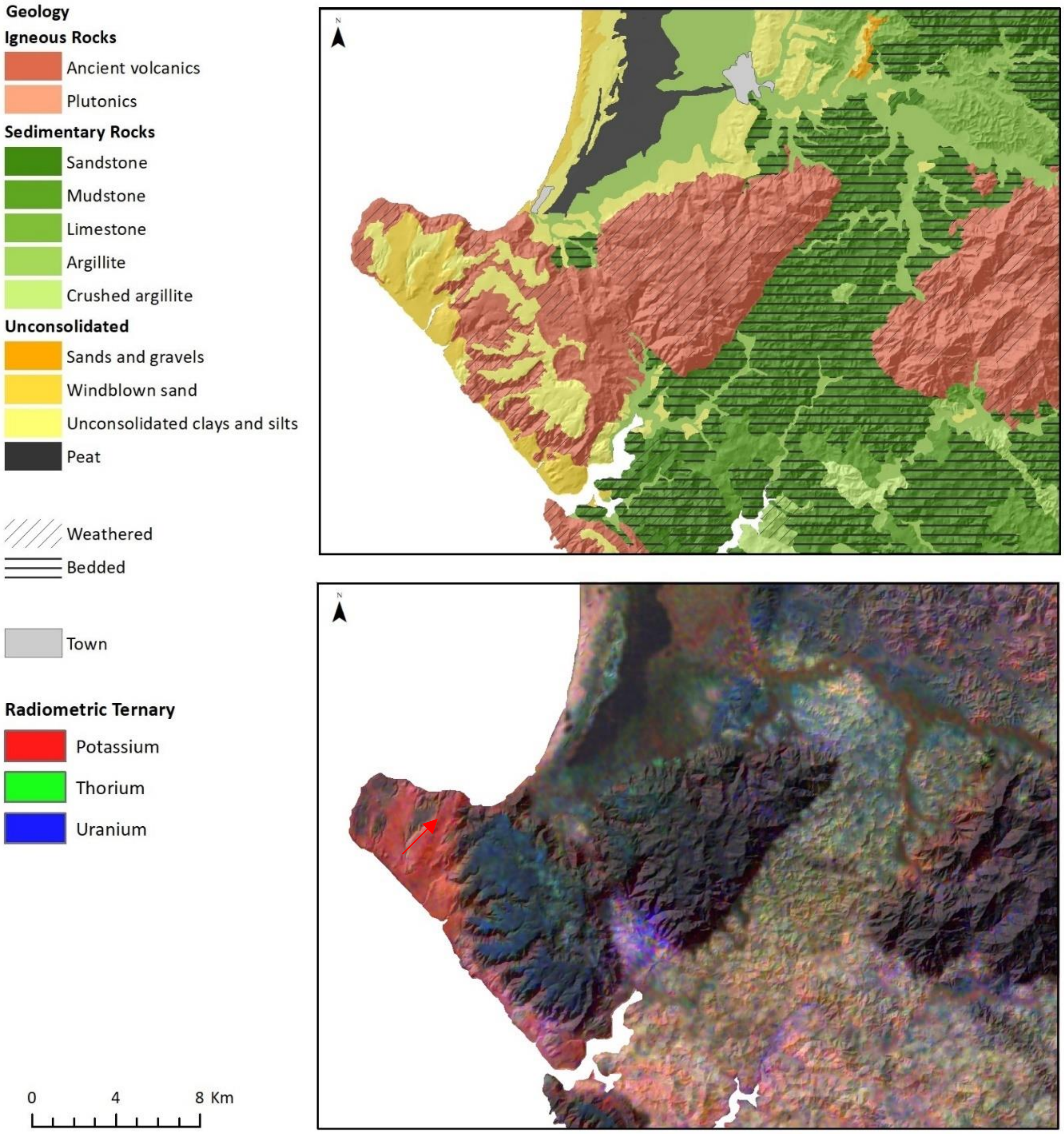

Figure 21. Rock type and transformation (LRI Rock2) and radiometric ternary at Ahipara.

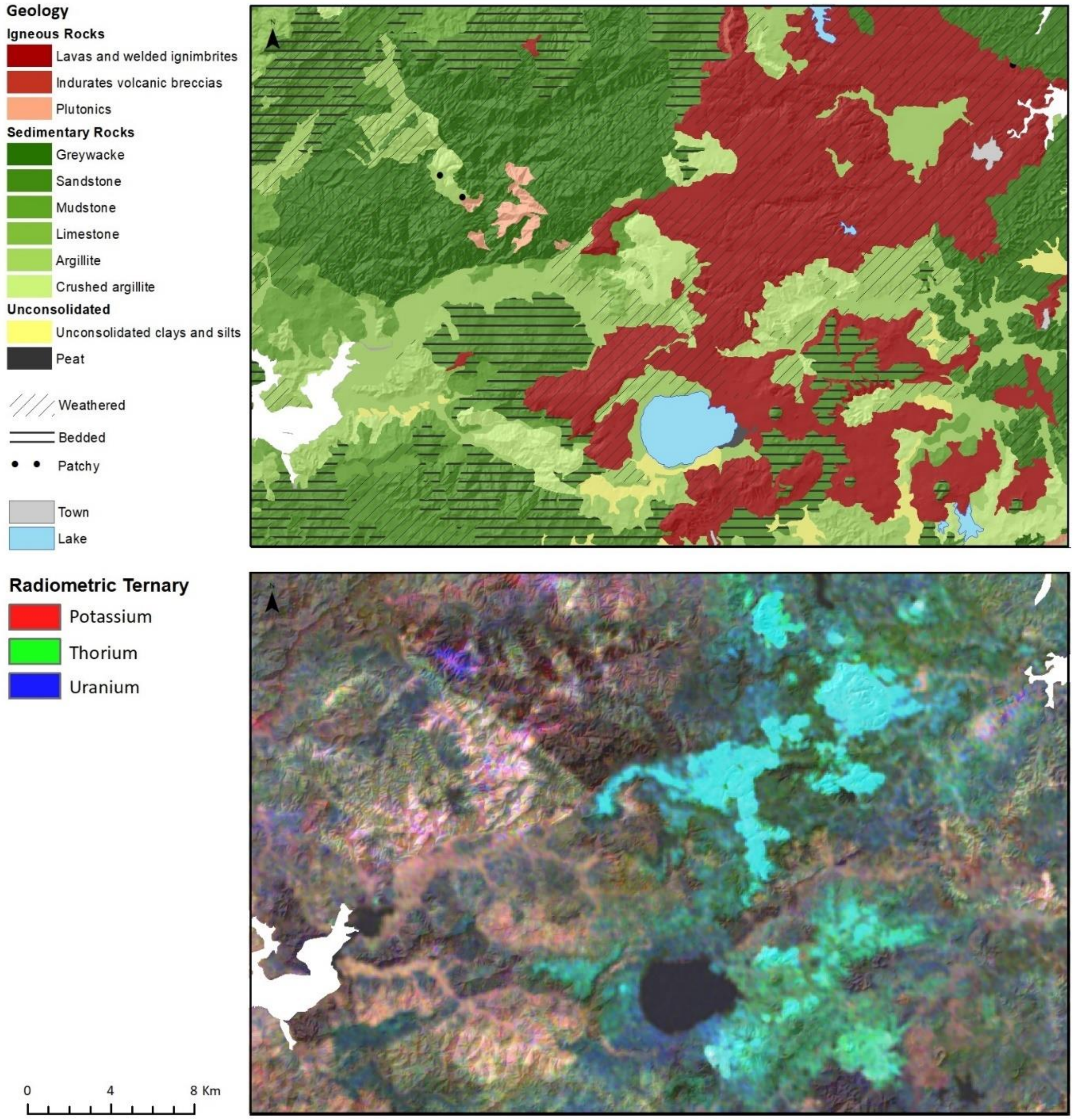

Figure 22. Rock type and transformation (LRI Rock2) and radiometric ternary at Waipapa.

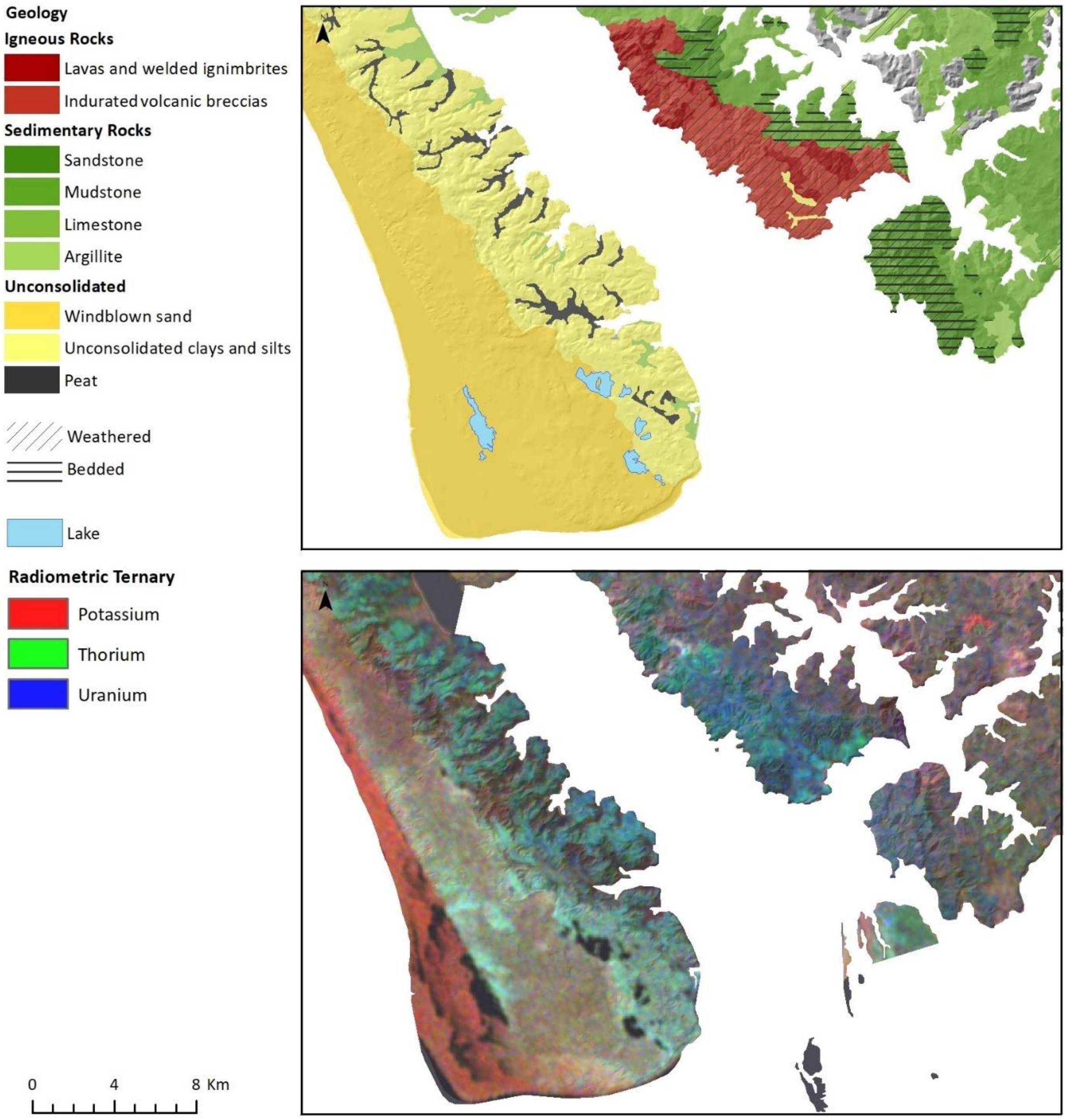

Figure 23. Rock type (Rock2) from NZLRI and radiometric Ternary Kaipara.

4.5 Geology Summary - NZLRI and QMAP

The challenges to geological mapping in the Northland region are thoroughly discussed in the QMAP map texts for Kaitaia, Whangarei and Auckland (Isaac 1996; Edbrooke 2001; Edbrooke and Brook 2009). The regions were mapped by multiple geologists, over several decades, and at varying scales. When GNS compiled the maps into a national dataset, they had to use the largest scale to achieve complete coverage. There are areas of Northland that were mapped at finer scales, and during the update of the NZLRI in 2012, this data was simplified and included as an attribute (Rock 2) of the near surface lithology.

When Rock2 is overlaid on QMAP, the rock types and boundaries do not always align. Often polygons map similar features, but as noted above, there is some variability. Discrepancies were partially resolved when the authors dissolved adjoining NZLRI polygons that share Rock2 attributes and further work could be done by using the radiometrics to aid in the refinement of geological mapping.

The overall broad-scale relationship between radiometric signals and mapped geology is very good at the 1: 250,000 scale, with the fine-scale Rock2 (1:50,000) providing refinement of smaller scale features. In addition to a finer scale, Rock2 layer adds additional resolution relevant to water quality through discriminating between consolidated and unconsolidated materials, weathered deposits and bedded deposits. In conjunction with QMAP, the Rock2 layer appears well suited for physiographic mapping of landscape level controls over water quality for moderate to larger scale drainage basins (i.e. c. >8 km^2).

5 Radiometrics and Soils

In this section, we evaluate the relationship between radiometric signals and soil attribute data relevant to physiographic mapping. Where soil data provides additional constraint over variation in radiometric signals within the broader scale geological polygons and associated weathering and transport limited settings.

There are two data sources with spatial soil data, New Zealand Land Resource Inventory (NZLRI) and the Fundamental Soil Layer (FSL). The FSL is a derived product from NZLRI but also contains an extended soil attribute table, a legacy of soil bureau surveys. This assessment used the FSL and its extended attribute table for comparison with radiometric imagery.

Again, for the sake of clarity, we note that in transport limited settings (predominantly low land), the variability in radiometric signals is larger than in areas of steep rock outcrop ('weathering limited'). This heterogeneity is governed by variation in soil forming factors, and in particular, topographic geomorphic gradients that influence the spatial distribution of soil forming factors such as degree of weathering (soil age), parent material, texture/structural compaction, drainage classes and soil permeability.

Confidence in the spatial distribution of soil hydrological gradients is critical for understanding the integrated landscape controls over water quality outcomes (Rissmann et al., 2016). Therefore, radiometric signals when evaluated in conjunction with mapped soil attributes provide an important platform for evaluating the resolution of soil hydrological attributes from the NZLRI and derived products such as the FSL for physiographic mapping.

5.1 Description of FSL data

The FSL is a national-scale soils layer provided by Landcare Research which holds tabulated physical attribute data, such as soil texture, permeability, drainage class, and a range of soil chemistry attributes such as pH and organic carbon. The data is linked to mapped unit boundaries (polygons), as such each map unit contains data for numerous soil attributes.

Table 5. Fundamental Soils Layer metadata.

Source	*Fundamental Soil Layer (FSL), Landcare Research*
Type	*Polygon*
Limitations	*Derived product of NZLRI – focus on agriculturally productive areas*
Links to text	*https://data.mfe.govt.nz/layer/2766-fundamental-soil-layers-new-zealand-soil-classification/*
Comments	*Soil texture* *Soil texture classes have been simplified to clay, silt, sand for the purposes of comparison with radiometric ternary.* *Drainage* *In NZLRI, Drainage class 1 and 2 are well drained, 3- moderately drained; 4- imperfect; 5- imperfect to poor; 6- poor; 7- very poor. N.B. in areas of cracking soils or those with significant macro-pore development drainage class may not be a good reflection of risk to water quality, due to high rates of matrix bypass.* *In FSL, the nomenclature for drainage class is in reverse order from the NZLRI, but based on the same factors (soil depth and duration of water tables). Drainage class 1- very poor; 2- poor; 3-imperfect; 4-moderately-well drained; 5-well drained.* *Permeability* *Permeability of each horizon is classified into permeability classes that are based on saturated hydraulic conductivity values of: Slow (S) <4mm/hr; Moderate (M) 4-72mm/hr; Rapid (R) >72mm/hr.* *Depth to slowly permeable horizon (DSLO)* *Depth to a slowly permeable horizon describes the minimum and maximum depths (in metres) to a horizon in which the permeability is less than 4mm/hr as measured by techniques outlined in Griffiths (1985). If no*

	slowly permeable horizon is observed, the taxon is allocated to Class 6 and a null value with numeric code -.99 is entered into the data fields. These classes, described more fully in Webb and Wilson (1995), are as follows: *In DSLO each class has a minimum and maximum depth (m below ground level):* *1. 0 -0.44 m, 2. 0.45 - 0.59 m, 3. 0.6 -0.89 m, 4. 0.9 -1.19 m, 5. 1.2 -1.49 m, 6. - 0.99 m*

5.2 Comparison of radiometric signal with FSL attributes

Soils are the primary interception surface for precipitation and the medium upon which all land use activities are undertaken. Soil hydrological properties are often the primary control over surface and ground water redox signatures (Killick et al., 2015; Rissmann et al., 2016). Soil hydrological properties also influence the net export of water from a recharge domain (e.g. hill country) and in conjunction with hydrological connectivity, of both the surface and shallow ground water network, influence recharge mechanism, and at a finer scale, the pathway water takes across the landscape (i.e. deep drainage to an aquifer, lateral soil flow (matrix and artificial) and overland flow).

Soil parent material and degree of weathering also strongly influence properties such as the abundance and type of clay minerals that drive soil hydrological gradients and the chemical and pedological characteristics of soils such as P-retention (anion exchange), pH, CEC, organic carbon content and the propensity for soils to crack in response to soil moisture deficit (Montagne et al., 2009; Bockheim and Hartemink, 2013; Rissmann et al., 2016 TC3; and references therein)[10.]

A strong understanding of the landscape level controls over the gradients in water quality specific soil attributes is key to application of the physiographic approach to Northland - where the degree of weathering (age), parent material and topographic position in the landscape are considered the key controls governing spatial variation in soil hydrological properties.

[10] Primary soil texture, primary parent material composition and subsequent weathering to form authigenic clay minerals (both poorly order and structured) are recognised as key controls over soil hydrological properties (Montagne et al., 2009; Bockheim and Hartemink, 2013 and references therein). Where soils formed in limestones, and mafic to ultra-mafic parent materials produce expansive clays that desiccate and crack in response to soil moisture deficit. Cracking soils exhibit temporally variable soil hydraulic properties that exert an important control over hydrological response and hence water quality outcomes (Rissmann et al., 2016a; Beyer et al., 2016a). Whereas soils formed in felsic parent materials tend to produce non-expansive clays such as illite and kaolinite that do not crack. Over time, expansive clays may weather to non-expansive forms (kaolinite) and if the climate is favourable to oxisols.

In the following section, we evaluate the spatial relationship between NZLRI and FSL soil attribute information and radiometric imagery. This section includes an evaluation of the geomorphic controls over soil permeability, depth to a slowly permeable horizon (DSLO) and soil drainage class.

5.2.1 Soil texture (SOIL TYPE)

Across Northland, fine textured soils (clay and silt loam) account for 68% of the region with only 12% classified as coarse textured. Of the coarse textured soils, NZLRI mapping associates the majority with areas of rock outcrop and steep slopes, whereas fine textured soils are most common across areas of valley infill and across elevated parts of the landscape that are flat lying (Harmsworth, 1996). The attribute field 'SOIL TYPE' differentiates soil by textural class and is based on the regional soil series grouping approach (Figures 24, 25 and 26).

Across all three test areas, a lack of constraint associated with soil thickness, drainage class and permeability limit the usefulness of the Soil Type, on its own, as an attribute for assessing soil hydrological gradients. Specifically, although mapped as clay and clay loam, the radiometric signals across the inland Tangihua Complex volcanic rocks, appear to primarily reflect the geochemistry of the underlying basement rock which is consistent with relatively thin soil development and moderately well drained soils typical of weathering limited landforms. Windblown beach sands show up as deep red gamma signals and do not appear to be well defined by the LRI textural class across parts of the western coastline of the Ahipara test area (Figure 24). Peat and sandy peat loams are well picked out by both the LRI textural class and the low gamma values of the Tangonge swamp. However, on its own, soil texture as an attribute is too broad for the discrimination of finer scale geomorphic gradients in soil hydrological properties and/or soil mineralogy, except where there are areas with sand textural classes, which correlate with K-rich (pink) gamma signals.

Across the Kaipara test area, there are steeper gradients in geomorphic setting (weathering versus transport limited) that are correlated with steeper gradients in soil texture and attendant radiometric signals (Figure 26). Specifically, across the northern barrier bar of the Kaipara Harbour, aeolian deposition appears to control soil textural class. Here, areas of mobile beach sand correlate with K-rich gamma signals. Significantly, soil textural class fines with distance from the coast, as coarse sand is winnowed out from the fine sand-, silt- and clay-sized particles. Soil textural class does pick out peat deposits in low lying valleys, but there is a large area without textural class data, for which radiometric signals could be used to improve resolution.

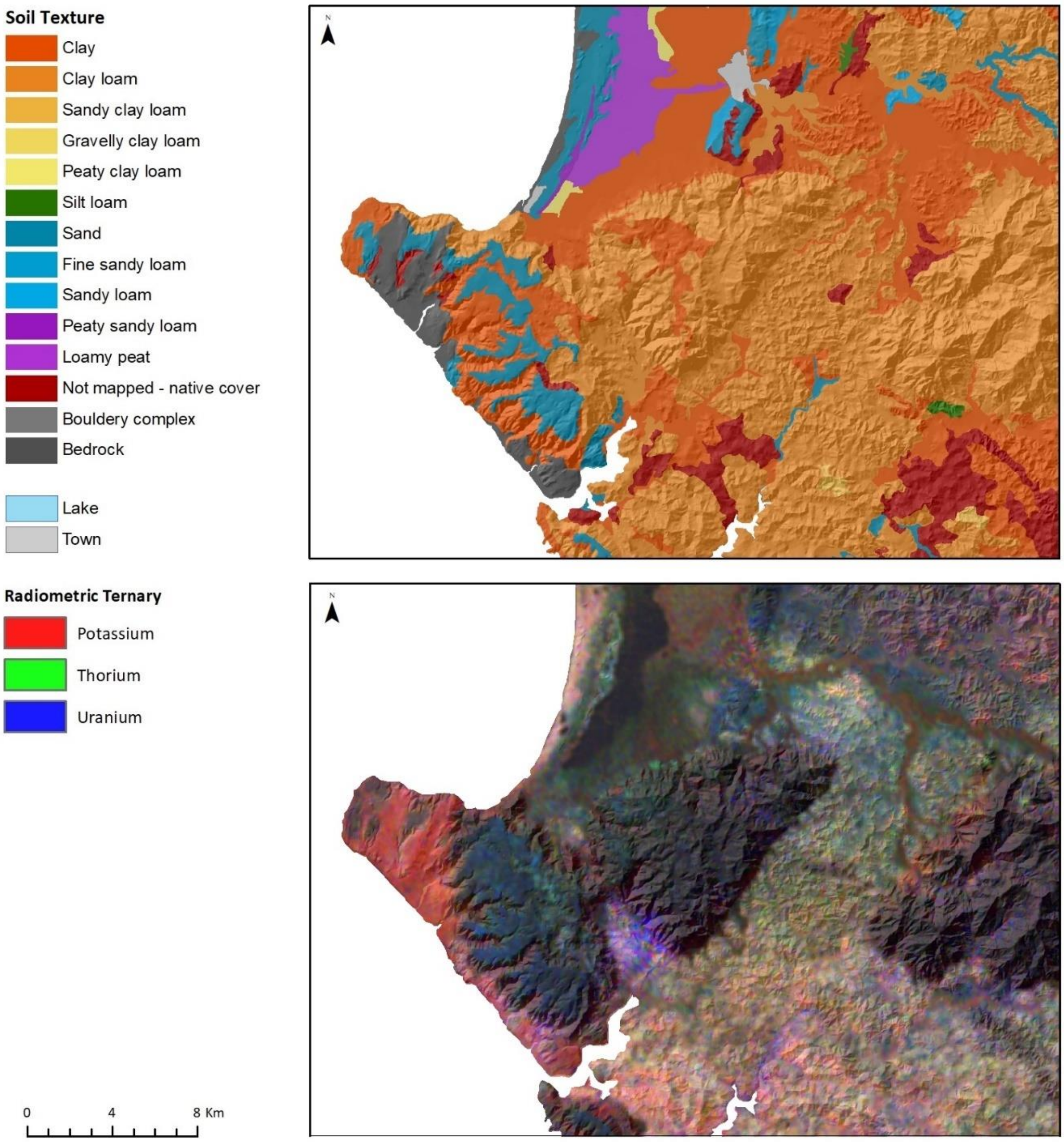

Figure 24. Soil texture from FSL and radiometric ternary at Ahipara.

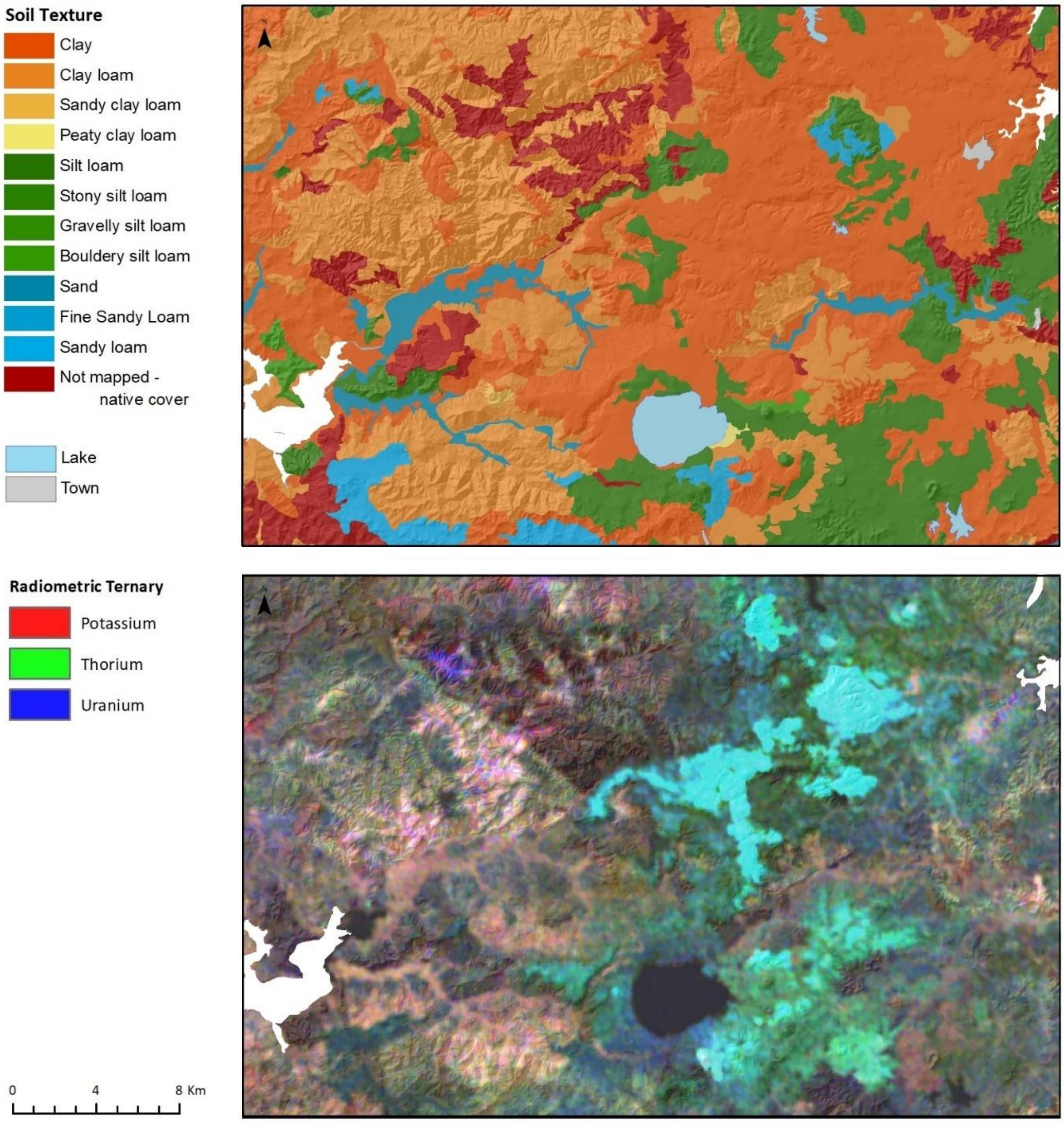

Figure 25. Soil texture from FSL and radiometric ternary at Waipapa.

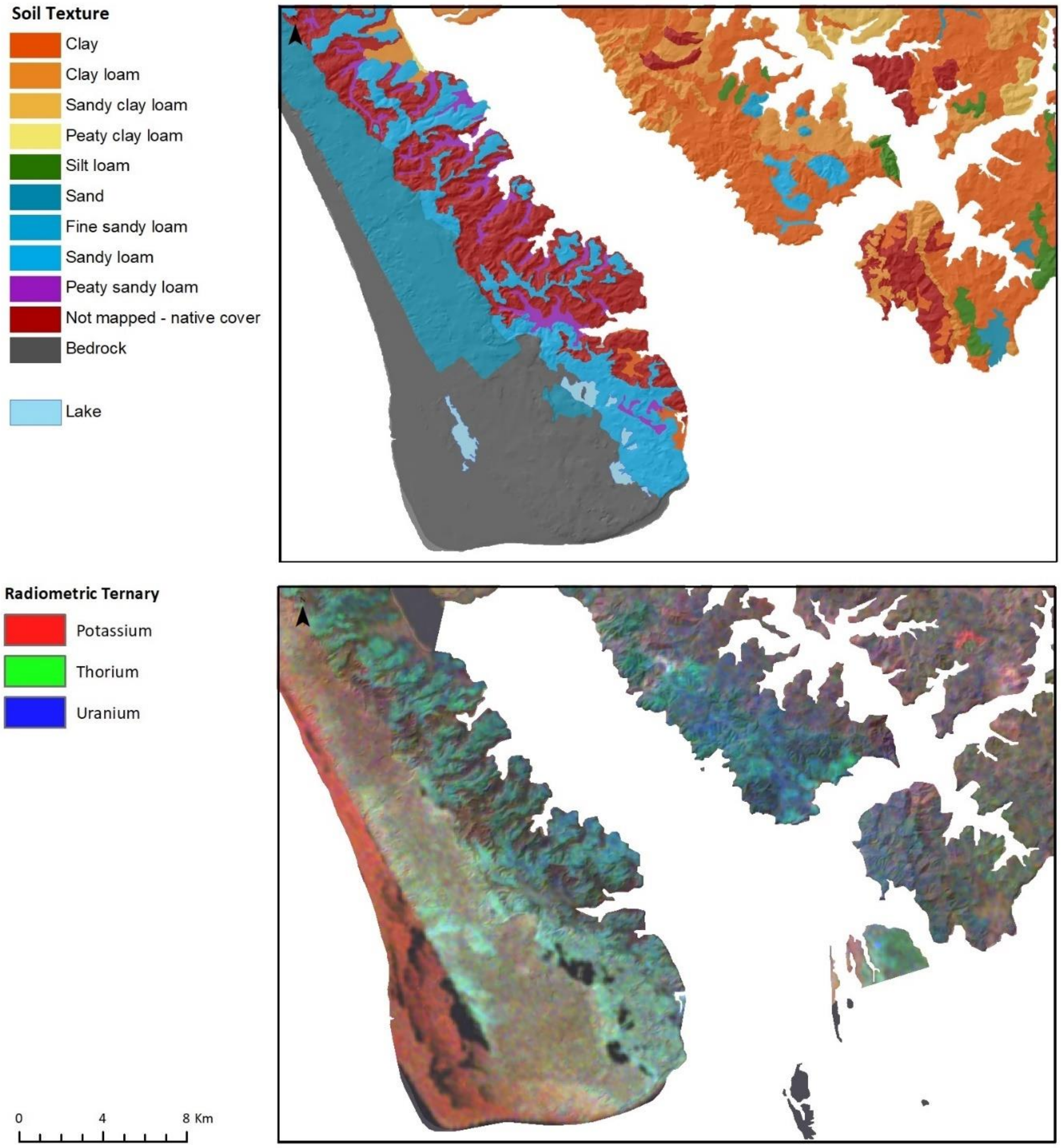

Figure 26. Soil texture from FSL and radiometric ternary at Kaipara.

5.2.2 Soil permeability (PERMEABILITY)

Overall, there is a clear broad scale correlation between soil permeability (as defined by saturated hydraulic conductivity) and gamma signal across all test areas (Figures 27, 28 and 29). More specifically, an evaluation of radiometric signals, landform relationships and LRI soil permeability class indicates a strong spatial correlation between primary parent material texture (i.e., clay, silt and sand grain size) and provenance and geomorphic setting. For example, permeability is typically higher across weathering limited landscapes, where coarser textured soils and steeper slopes enhance water infiltration and percolation.

Conversely, an abundance of finer textured and deeper soils, across flat lying transport limited settings, are associated with slower infiltration and permeability.

The LRI permeability class layer also appears well defined by finer scale geomorphic gradients. For example, finer scale gradients in radiometric signals at 1st and 2nd order drainage basin levels are associated with intercalations of more permeable beach sands within the lower lying and seaward facing valleys of the eastern Ahipara Gumfields Historic Reserve (Figure 27). At higher elevations, across flat lying areas, a mantle of cemented sand, silt and clay occur as deep blue radiometric signals and are associated with slowly permeable soils. Side slopes within these drainage basins are steep and the radiometric signals are most consistent with the geochemistry of the bedrock (Tangihua Complex basalt rocks).

Across the broader Waipapa test area (Figure 28), soil permeability shows a strong correlation with geomorphic setting and primary parent material provenance and texture. For example, permeability is lower for areas of mudstone (Moderate over Slow) and mixed sand and mudstone (Punakitere Sandstone; Moderate over Slow) relative to sandstones (stony phase of Omahuta Sandstone sandstone and siltstone rocks; Moderate). Soils formed from volcanic parent material are also more permeable (Moderate). For example, across the eastern portion of the test area aqua blue radiometric signals are correlated with moderately permeable soils formed in rhyolitic and/or andesitic ash that mantles the Kerikeri Volcanic Group basaltic rocks. Where these deposits have been eroded, the radiometric signal is more consistent with that of the underlying basalts, but soils still exhibit moderate permeability.

Conversely, soils formed in sedimentary rock, especially mudstones and some sandstones with a high mud content, are slowly permeable. For example, soils associated with the Punakitere Sandstone show a greater proportion of moderate over slowly permeable soils. Whereas soils associated with the Omahuta Sandstone, sand- and siltstone rocks (white gamma) in the northwest of the Waipapa test area are dominated by moderately permeable soils. The floodplain of the Waihou Valley is characterised by more rapidly permeable, sandy soils as is also reflected in the K-rich gamma signal, which shows an association with the Omahuta Sandstone. The evident relationship between rock texture and soil permeability is consistent with the role primary parent material texture and mineralogy plays over ensuing clay development (Parfitt and Wilson 1985; Daniels and Hammer 1992; Beerten et al. 2012; Bockheim and Hartemink 2013; Dixon, 2015).

Across the Kaipara test area (Figure 29) there is a clear correlation between radiometric signals and LRI soil permeability class, again reflecting the role of both geomorphic gradients and primary soil parent material texture and provenance over soil bulk density, porosity and potentially soil moisture content, at the time of the survey. For example, across the Kaipara Barrier bar, aeolian deposition appears to control soil permeability, with rapidly permeable soils correlated with windblown sand (K-rich signal = red) and areas of moderate permeability correlated with cemented fine-, silty- and clay-sized aeolian deposits (aqua blue signal; Figure 29). Here, the western paleo-shoreline demarcates a transition from young, K-rich beach sands with an increasing proportion of finer aeolian sand, silt and clay (U- + Th-rich) of lower permeability towards the eastern side of the barrier bar (aqua blue colour).

At a finer scale, radiometric signals indicate a pattern of highly permeable beach sands (K-rich gamma) at valley heads with a transition through to low total counts at lower elevations in response to poor internal drainage and/or elevated water tables and the development of valley floor peat deposits. At this fine scale, the LRI soil permeability class is somewhat limited. However, the broader relationship between soil permeability and radiometric signals could be used to refine soil permeability gradients across the Kaipapra Barrier bar. Beyond the Kaipara Barrier bar, the westward facing slopes of the Hukutere area show a blue U-rich signal which may relate to soil formation in volcanic rocks. Here, soil permeability is moderate and transitions to moderate over slow, and slow towards the north and northeast, in response to a shift from volcanic rocks to mudstones of the Northland Allochthon. This gradient in soil permeability is well defined by radiometric signals.

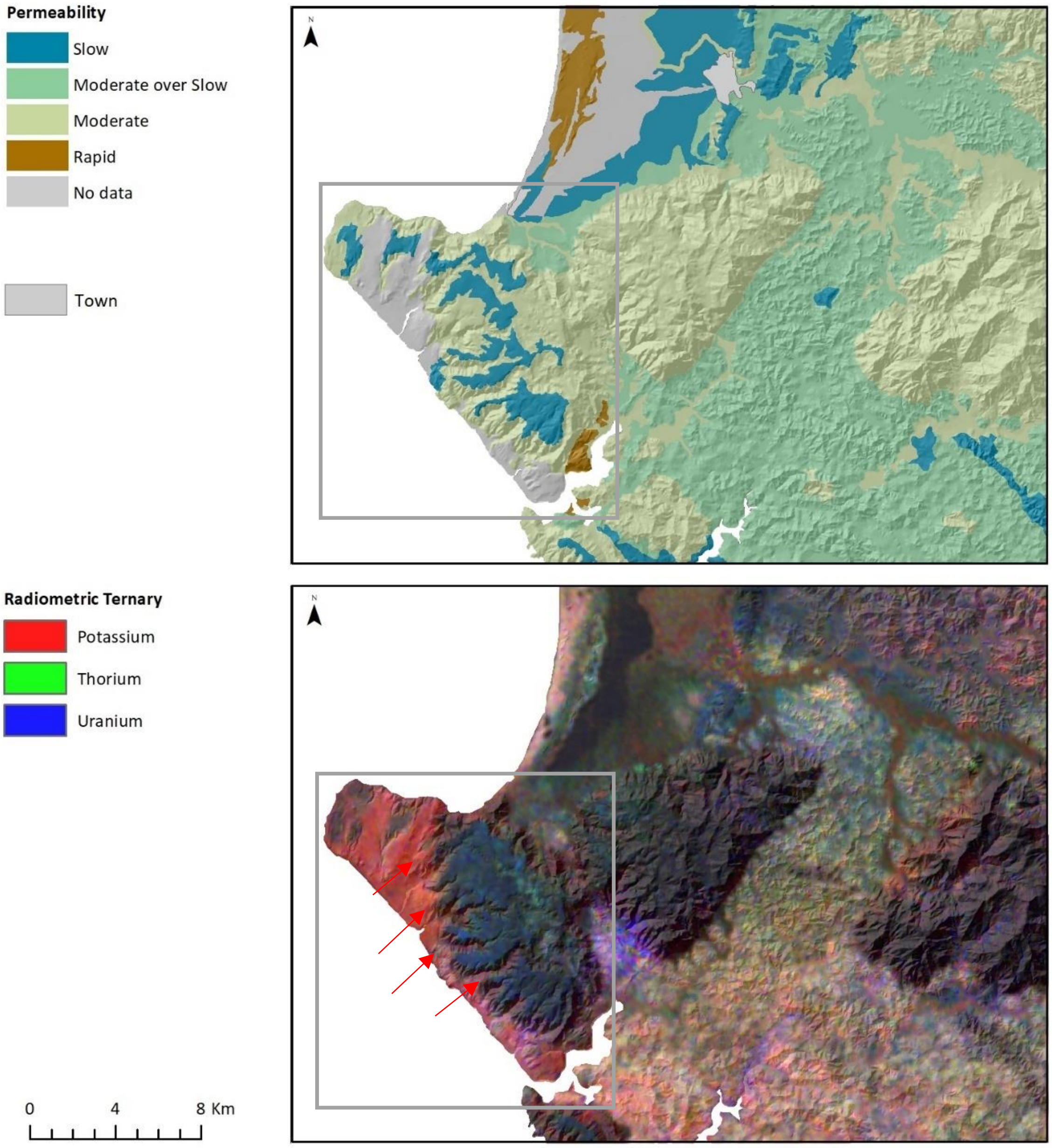

Figure 27. Permeability class from FSL and radiometric ternary at Ahipara. The grey rectangle outlining some of the areas with finer scale variation in landscape properties that do not appear to be well represented by the LRI. Red arrows in the radiometric ternary image denote intercalations of K-rich dune sand that has been blown along low lying valleys, which are not reflected in the LRI mapping.

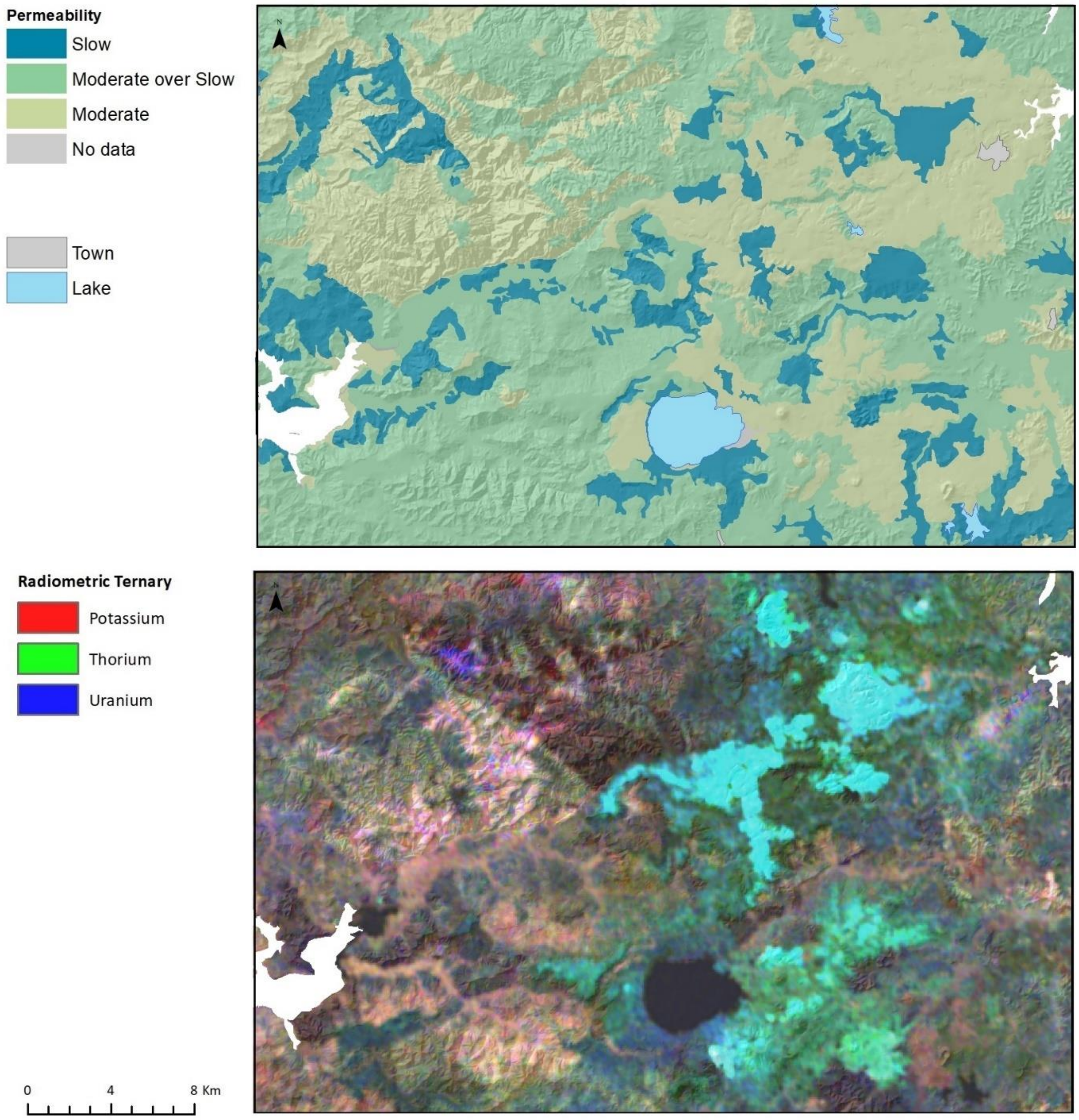

Figure 28. Permeability class from FSL and radiometric ternary at Waipapa.

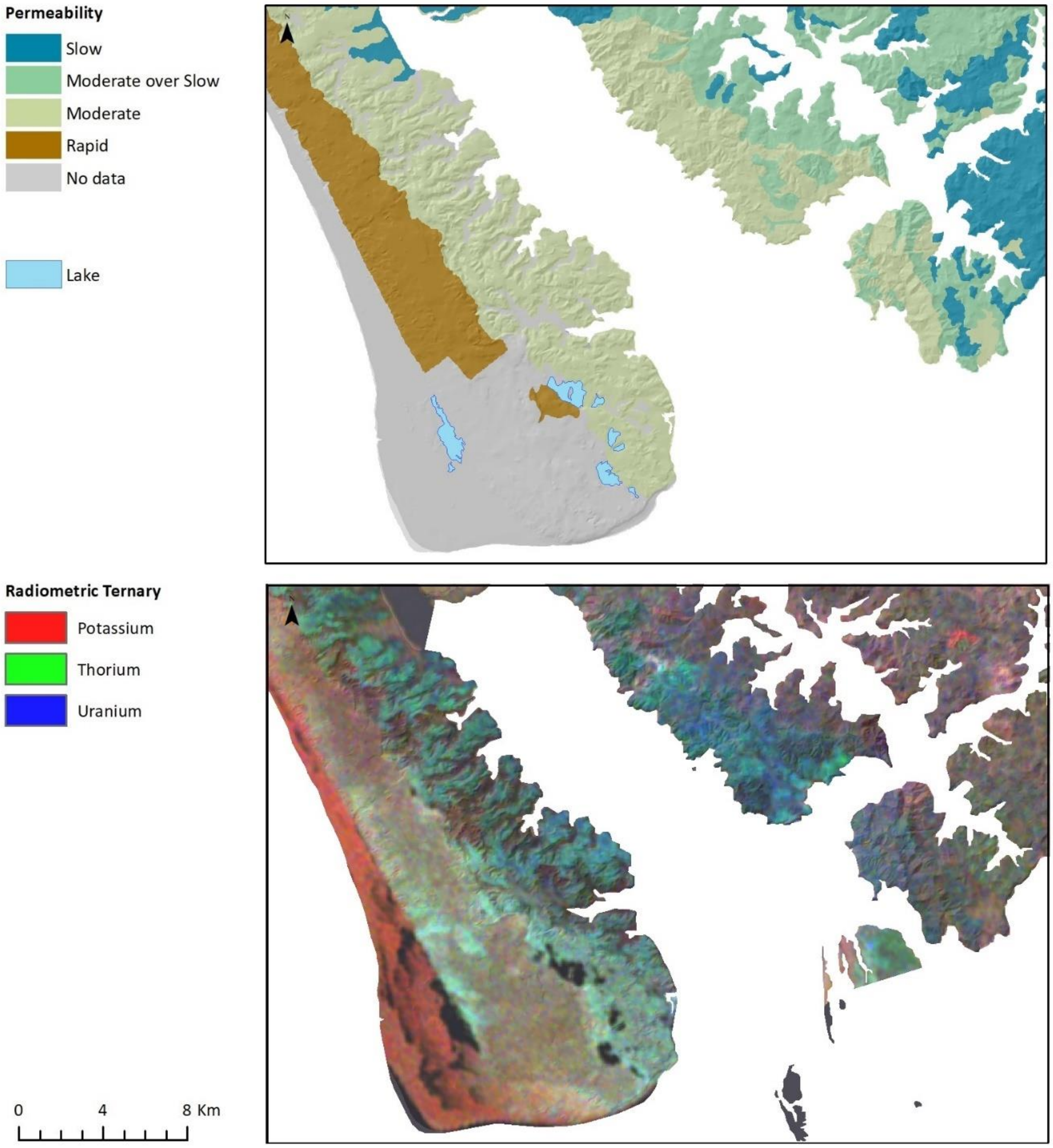

Figure 29. Permeability class from FSL and radiometric ternary at Kaipara. The grey rectangle outlining some of the areas with finer scale variation in landscape properties that appear to be better represented by the radiometric data.

5.2.3 Depth to Slowly Permeable Horizon (DSLO_CLASS)

An evaluation of the LRI DSLO class and radiometric imagery is suggestive of a similar set of controls to that governing soil permeability (**Error! Reference source not found.** 31, & 32). Namely, geomorphic gradients in the landscape and primary parent material textures appear to govern the spatial distribution of DSLO. Geomorphic surface age is likely important, but was not a focus, of QMAP.

DSLO tends to be shallower, <0.60 – 0.89 m, across areas characterised as transport limited, where the regolith is predominantly fine textured and deeply weathered [up to 30 m in places; here allochthonous and authigenic weathering drives the translocation of clay minerals to depth resulting in the formation of slowly permeable subsoils at relatively shallow levels (Bockheim and Hartemink, 2013 and references therein)]. Across weathering limited areas, the DSLO is typically deeper, e.g. across the inland Ahipara massif (Figure 30) and the Maungataniwha Range the DSLO is listed at 1.2 to 1.49 metres below ground level (m bgl). In these weathering limited settings, the DSLO is interpreted as delimiting the contact between the soil and underlying basement rock, with many soils across areas of uplift classified as being moderately to well drained. Here, the combination of thin and better drained soils results in radiometric signals that are generally consistent with the underlying geochemistry of the parent rock. As with soil permeability class, there is also a general association between primary parent material texture and DSLO. Specifically, DSLO is shallower for areas of mudstone and mixed sand and mudstone (Punakitere Sandstone) relative to sandstones.

Despite the broadly consistent correlation between soil DSLO and weathering vs. transport limited settings, it is apparent that there is considerable finer scale variation in radiometric signals across all the test areas. Here, the LRI permeability class layer is well defined by finer scale geomorphic gradients and attendant radiometric signal variation. For example, finer scale gradients in radiometric signals at 1st and 2nd order drainage basin levels are associated with intercalations of more permeable beach sands within the lower lying and seaward facing valleys of the eastern Ahipara Gumfields Historic Reserve (Figure 30). DSLO is deep across areas of mobile dune sands (K-rich) and areas of windblown sand within the lower lying and seaward facing valleys. At higher elevations, across flat-lying areas, cementation of a mantle of windblown fine sand, silt and clay is reflected in the deep blue radiometric signals and are associated with the shallowest DSLO class (e.g. 0.00 – 0.44 m bgl). Side slopes within these drainage basins are steep with radiometric signals most consistent with the geochemistry of the bedrock and (Tangihua Complex basalt rocks) and a DSLO of 0.9 – 1.19 m. Deeper DSLO (1.2 -1.49 m) occur in association with modern-day floodplains and K-rich signals associated with alluvial sands.

Across the broader Waipapa test area (Figure 31), DSLO class again shows a strong correlation between geomorphic setting and primary parent material provenance and texture, where primary parent material provenance and texture appear to be the most important control. For example, DSLO is shallower for areas of mudstone (class 2) and mixed sand and mudstone (Punakitere Sandstone; class 3) relative to sandstones (class 4 and 5: Omahuta Sandstone sandstone and siltstone rocks). Soils formed from volcanic parent materials are also better drained and associated with a deeper DSLO class (e.g., class 4 and 5). For example, across the eastern portion of the test area aqua blue radiometric signals are correlated with well drained soils formed in rhyolitic and/or andesitic ash that mantles the Kerikeri Volcanic Group basaltic rocks and deeper DSLO (i.e., class 5 or 1.2 -1.49 m). Where these deposits have been eroded, the radiometric signal is more consistent with that of the underlying basalts and are also moderately well drained with a DSLO class of 5 or 1.2 -1.49 m.

Across the Kaipara Barrier bar (Figure 32), areas of deeper DSLO (class 5) are correlated with windblown sand and areas of shallower DSLO are correlated with silt- and clay-sized aeolian deposits that mantle higher altitude areas (Class 2). Radiometric signals suggest some of the western margin of the Kaipara Barrier bar may be partially cemented (blue colour) and may have a shallower DSLO than assigned by the LRI. To the northeast, across the Hukutere and Tenopai areas, Whatoro and Rangiuru soils formed in volcanically derived materials (blue radiometric signature) are better drained and characterised by deeper DSLO class (i.e., classes 4 and 5). Further northeast, the transition from volcanic to allochthonous mud- and mixed mud- and sand-stones is correlated with a reduction in soil permeability, DSLO class (i.e., 3 – 1) and radiometric signatures. Areas of melange and limestone are also correlated with less permeable soils and shallower DSLO class (i.e., class 1 – 3).

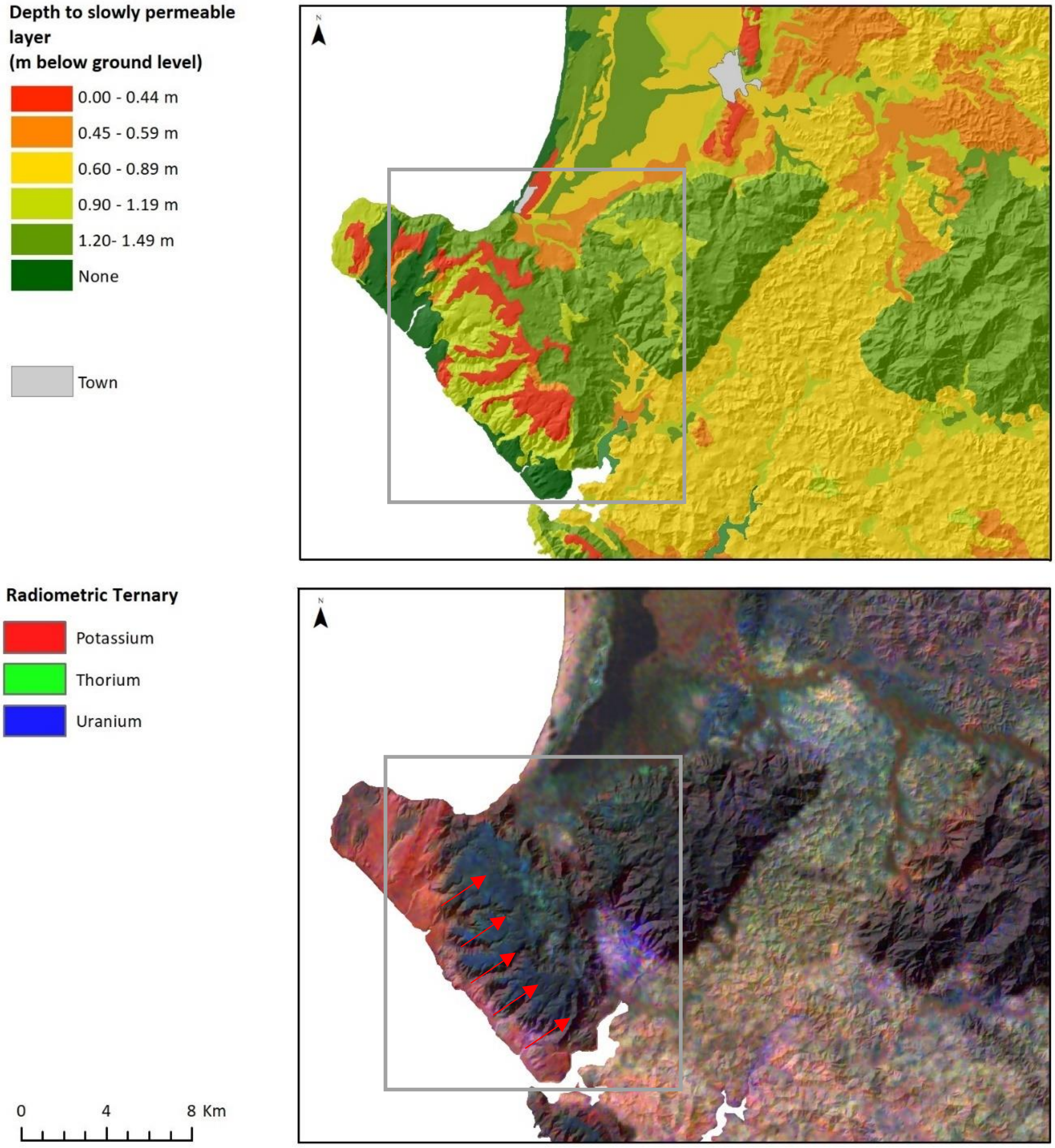

Figure 30. Depth to a slowly permeable horizon at Ahipara. The grey rectangle outlining some of the areas with finer-scale variation in landscape properties that do not appear to be well represented by the LRI. Red arrows in the radiometric ternary image denote intercalations of K-rich dune sand that has been blown along low lying valleys, which are not reflected in the LRI mapping.

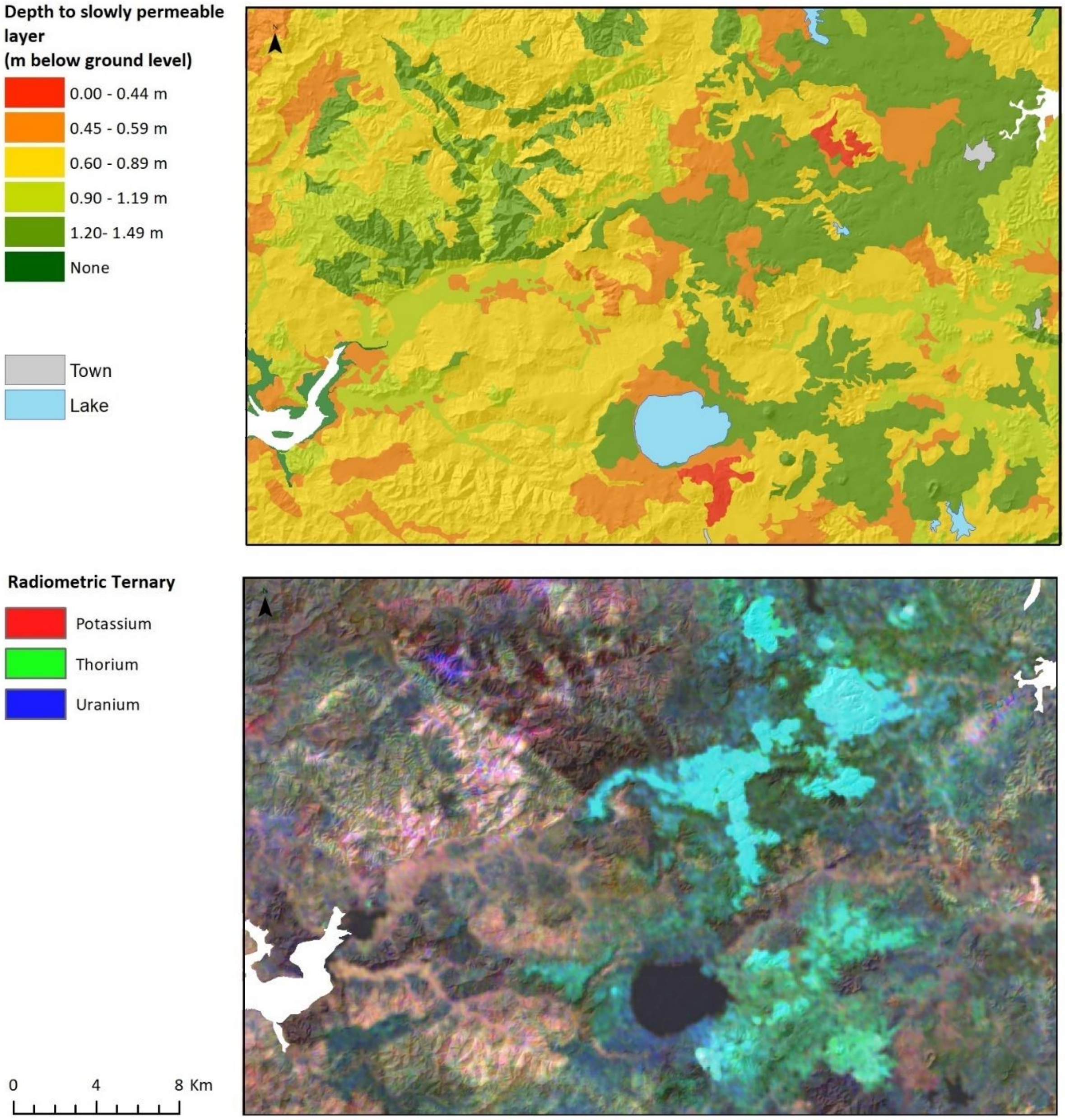

Figure 31. Depth to a slowly permeable horizon at Waipapa.

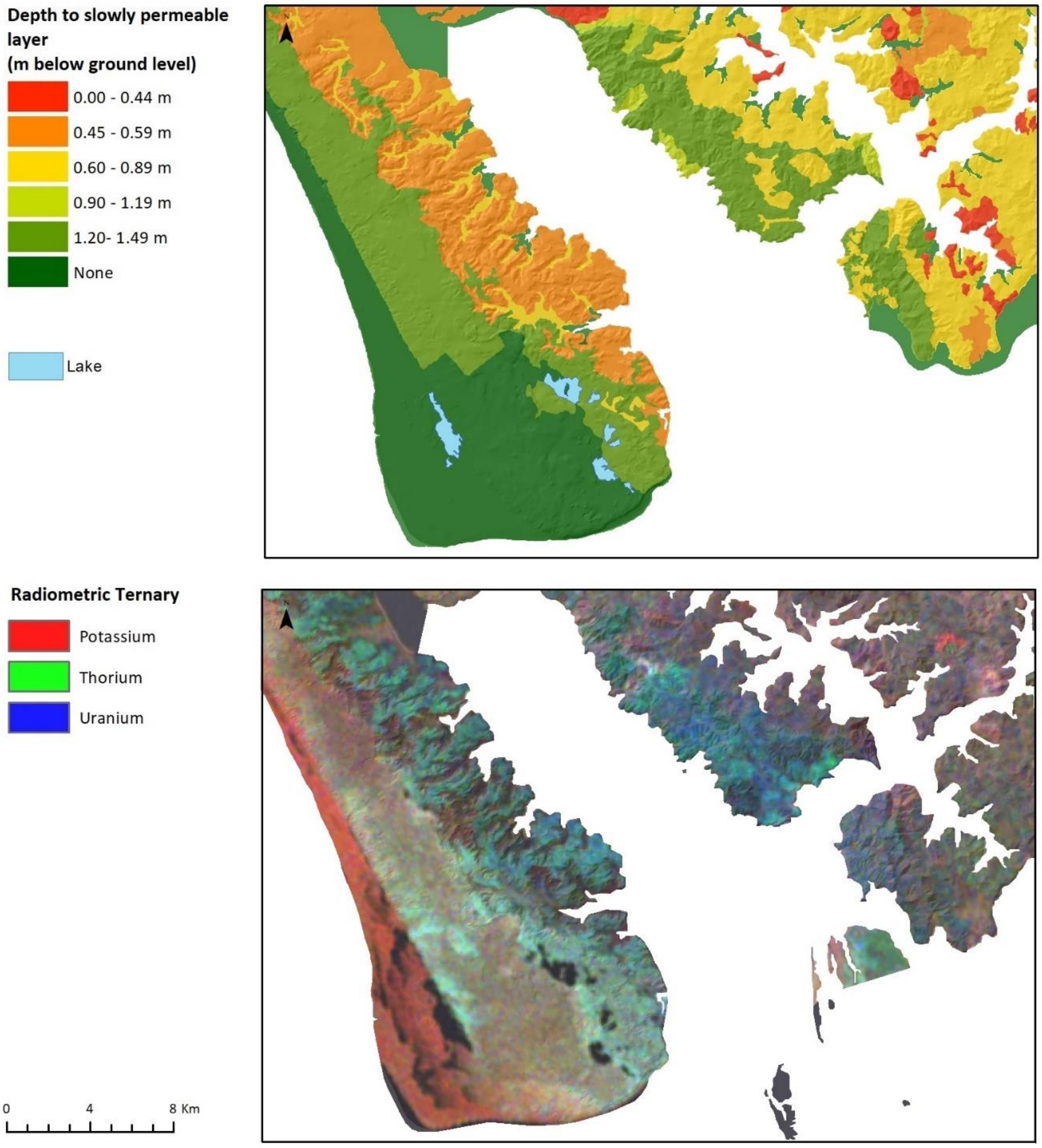

Figure 32. Depth to a slowly permeable horizon at Kaipara.

5.2.4 Soil drainage (DRAIN_CLAS)

Soil drainage class is based on the occurrence of redox segregations (mottling) and low chroma colours indicative of waterlogging and reduction within specific soil horizons. Drainage classes used here are the same as those used in the New Zealand Soil Classification (Hewitt 1993) and outlined by Milne et al. (1995). Across Northland, the proportion of well drained soils is small, 18.7%, with most of the soils classified as poorly (35.7 %) or moderately well (45.6 %) drained.

Across the Ahipara test area (Figure 33) soil drainage class and radiometric signals are well correlated with altitude, relative relief and soil parent materials. Specifically, soils are moderately and well drained (LRI class 4 and 5) across the steeper slopes of the Tangihua Complex basalt rocks. Across the volcanic plateau of the Ahipara Gumfields Scenic Reserve, cementation of a mantle of aeolian sand, silt and clay (deep blue radiometric signal) is correlated with poorly drained soils (class 1). At lower altitudes, across the broader area of Punakitere Sandstone (with sandstone rocks and subordinate mudstone rocks), the soils are dominantly poorly to imperfectly drained (classes 2 and 3). Small areas of moderately well drained (class 4) soils are associated with areas of greater relative relief. Modern day river channels and proximal floodplains are characterised by a range of drainage classes characterised by poorly to moderately drained soils.

Across the coastal plains west of Kaitaia, Karioitahi Group sandstone, peat and mudstone of Quaternary Q4 – Q1 age, exhibit a strong geomorphic control over soil drainage class gradients. Specifically, well drained soils (class 5) are associated with the mobile dune sands of the western coastline. Behind the western dune field, the Tangonge Wetland is associated with poorly drained peat soils (class 1). Further west, towards Kaitaia, soil drainage class increases with altitude and in response to outcrops of Punakitere Sandstone and Taipa Mudstone rocks. This west-north gradient in soil drainage class is also correlated with soil permeability and DSLO and is well expressed by radiometric signals.

Across the broader Waipapa test area (Figure 34), soil drainage class again shows a strong correlation between geomorphic setting and primary parent material provenance and texture. Specifically, primary parent material provenance and texture appear to be the most important control over spatial gradients in soil drainage class. For example, soils formed in rhyolitic and/or andesitic ash that overly Kerikeri Volcanic Group basaltic rocks are dominantly well drained (class 5). Whereas soils formed in mudstones and some sandstones with a high mud content (Punakitere Sandstone) are imperfectly to poorly drained (class 3 – 2). In the northwest of the Waipapa test area, stony soils associated with the Omahuta Sandstone sandstone and siltstone rocks (white gamma) are dominantly well drained. The evident relationship between rock texture and soil permeability is consistent with the role primary parent material texture and mineralogy play over ensuing clay development (Parfitt & Wilson 1985; Daniels and Hammer 1992; Beerten et al. 2012; Bockheim and Hartemink 2013; Dixon, 2015) and is spatially well correlated with radiometric signals. The floodplain of the Waihou Valley is characterised by moderately well drained, sandy soils with radiometric signals that correlate with the Omahuta Sandstone.

Across the Kaipara Barrier bar (Figure 35), areas of well drained soils (class 5) are correlated with windblown sand and areas of imperfect to poorly drained soils are correlated with silt- and clay- sized aeolian deposits that mantle higher altitude areas (Classes 2 and 3). Radiometric signals suggest some of the western margin of the Kaipara Barrier bar may be partially cemented (blue colour) and may have less well drained soils than assigned by the LRI.

Due to the small size (<8 km^2) of the drainage basins of the Kaipara Barrier bar poorly drained valley-floor peat deposits are not well defined at the scale of the LRI. Specifically, across valley heads and incised valleys there is no drainage class data listed by the LRI, yet the Rock2 layer identifies these areas as valley fill, including peat. These areas are characterised by a pattern of K-rich beach sands at the valley head which transitions through to low total counts at lower elevations in response to poor internal drainage and/or elevated water tables and associated valley-floor peat deposits (Figure 35).

To the northeast, across the Hukutere and Tenopai areas, Whatoro and Rangiuru soils formed in volcanically derived materials (blue radiometric signature) are imperfectly to moderately well drained (i.e., classes 4 and 5). Further northeast, the transition from volcanic to allochthonous mud- and mixed mud- and sand-stone is correlated with a reduction in soil drainage class (poorly drained, class 2) and radiometric signatures. Areas of melange and limestone are associated with imperfect drainage (class 3).

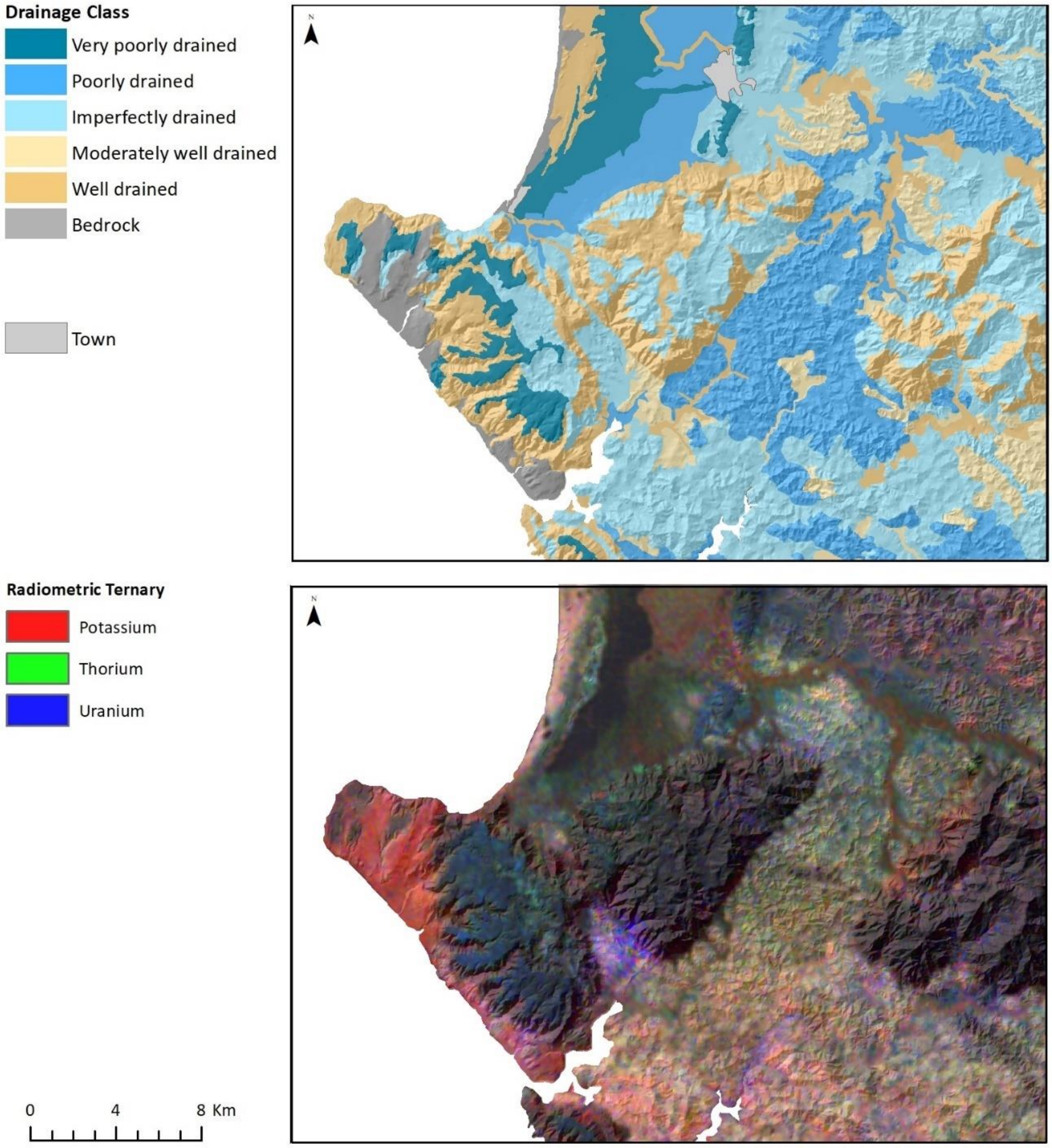

Figure 33. Drainage class from FSL and radiometric ternary at Ahipara.

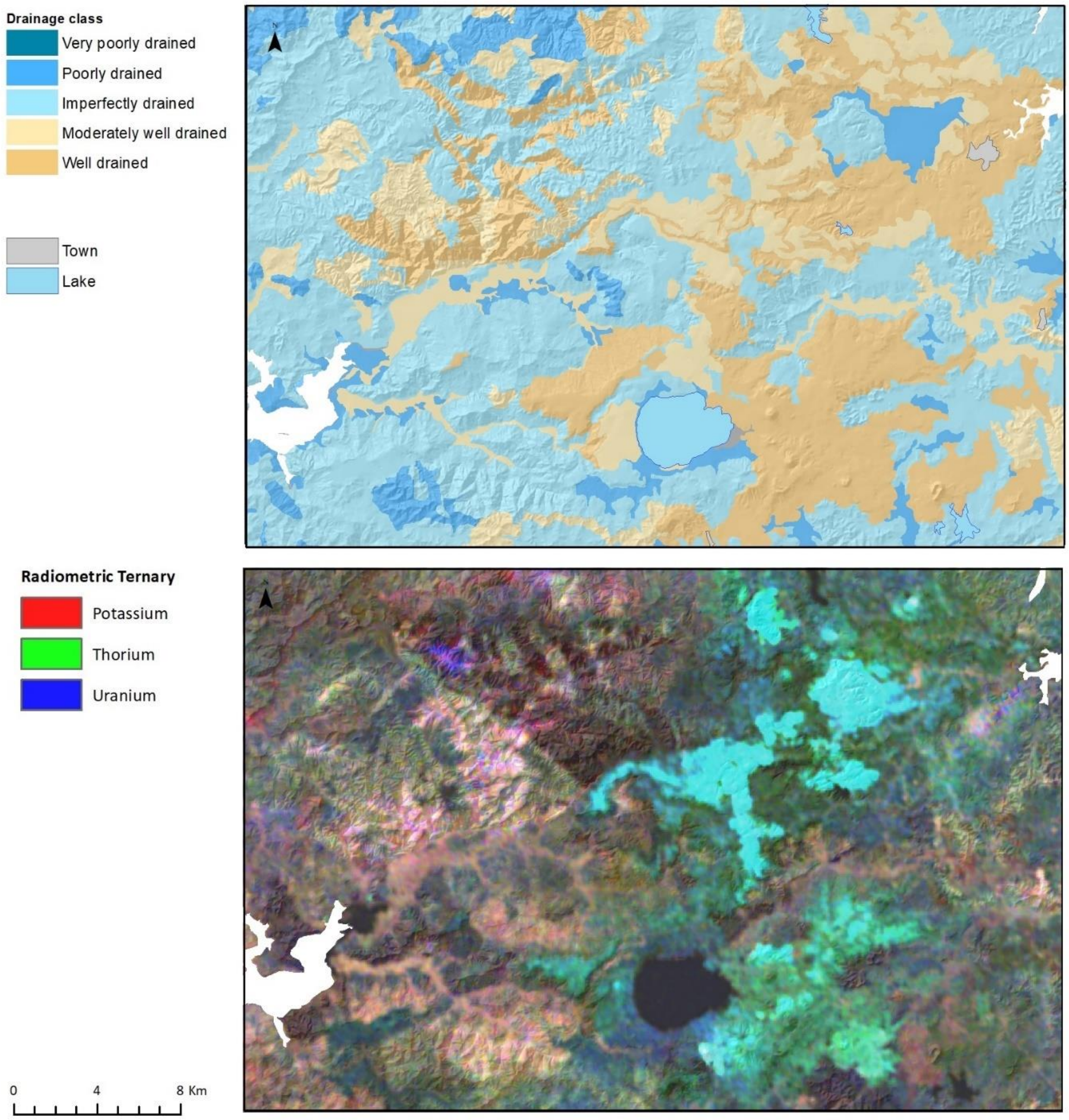

Figure 34. Drainage class from FSL and radiometric ternary at Waipapa.

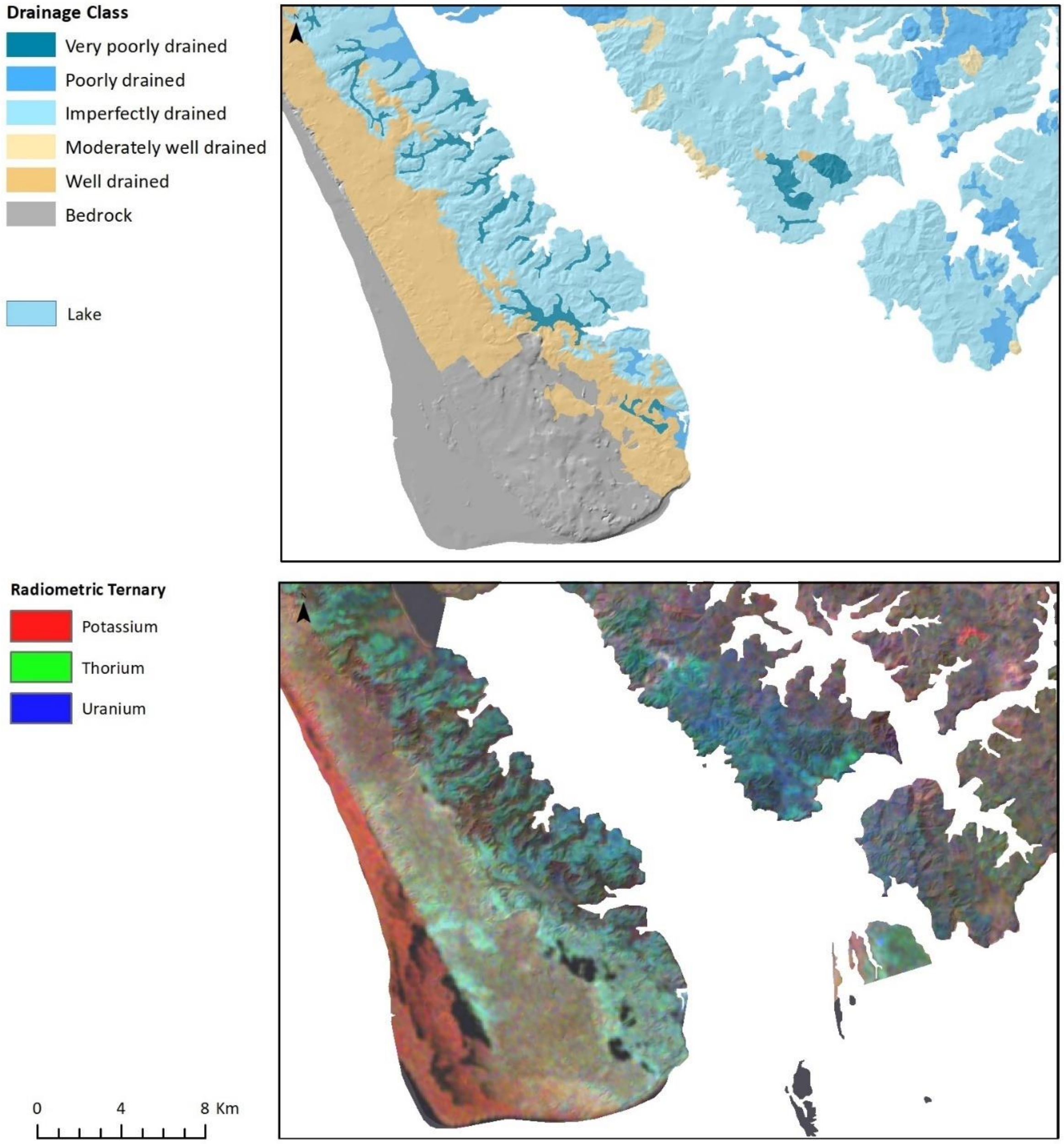

Figure 35. Drainage class from FSL and radiometric ternary at Kaipara.

5.3 FSL Summary

Assessment of the geomorphic and geological relationships governing gradients in soil hydrology across the three test areas were supported by radiometric data. From these three areas, it is apparent that primary parent material texture and provenance exerts a major control over gradients in soil drainage class. Geomorphic setting and weathering versus transport limited areas also influences the soil hydrological gradients in a predictable fashion.

With regards to primary parent materials, soil permeability, DSLO and drainage class deteriorate across the volcanic > sandstone > mixed sand/mudstone > mud- and lime-stone continuum. This observation is consistent with the understanding of soil parent material controls over primary soil texture, mineralogy and subsequent soil structural evolution (Parfitt and Wilson 1985; Daniels and Hammer 1992; Beerten et al. 2012; Bockheim and Hartemink 2013; Dixon, 2015). It is also important to note that the steepest and most elevated slopes across each test area are also associated with volcanic rocks, mainly basalts, which also favour the development of 'good soil structure' and associated soil drainage properties.

Overall, the landscape controls over gradients in soil permeability, DSLO and drainage class are very similar, outlining the dominant role of primary parent material texture and provenance, but also geomorphic setting over soil hydrological properties. This evaluation suggests that the soil hydrological attributes of the LRI are well suited to moderate- and large-scale drainage basins, c. >8 km^2, but for smaller scale drainage basins, radiometric signals provide finer scale resolution. If finer-scale resolution of small scale drainage basins is considered important, radiometric imagery could be used to improve the continuity and resolution of soil hydrological gradients across these areas.

6 LINZ Swamps Attribute Layer

LINZ swamp data is derived from the Topo50 map series. The Topo50 map series provides topographic mapping for the New Zealand mainland and Chatham Islands at 1:50,000 scale.

6.1 Description of data

Table 6: LINZ Swamp Layer metadata.

Source	*LINZ*
Type	*Vector Polygon*
Limitations	*None*
Links to text	*https://data.linz.govt.nz/layer/193-nz-swamp-polygons-topo-1250k/metadata/*
Comments	-

Swamps (also known as wetlands) with low inorganic sediment content emit little gamma radiation. Low gamma signal when combined with higher rates of attenuation by water equate to very low gamma counts and show up as black areas in radiometric imagery. There is also a strong correlation between swamps and wetland lakes [dark colours bound by yellow and blue polygon outlines (Figures 36, 37 and 38)] and attenuated radiometric signal. For these reasons, radiometric surveys are used to map or ground-truth wetland areas (Dent et al., 2013; Beamish, 2015). Swamps are important sites for denitrification but may also exhibit elevated P and *E. coli* levels associated with intensive land use (Rissmann et al., 2012 and references therein). As such, they are important landscape features for the mapping of landscape controls over water quality.

In Southland, radiometric signals and previously mapped swamps are strongly correlated, however, it is apparent that since mapping of the swamps, the extent of the wetlands has been significantly reduced due to drainage and encroachment (Ewans, 2015). That is, the extent of current day wetlands as displayed by radiometric signals is almost invariably smaller than the original polygons mapped in the 1980's and 1990's for areas of intensive land use. The same encroachment pattern is not evident in areas of natural state cover.

Within the Ahipara test area, the dominant wetland area is the historic Lake Tangonge west of Kaitaia (Figure 36). This area has been drained via three large central drainage channels to make way for agricultural land use. An attenuated radiometric signal indicates a larger area of organic soils associated with the historic Lake Tangonge that are not mapped by the LRI. Within the western coastal dunes of the north Kaipara Barrier there are several smaller scale dune lakes and swamps not mapped by LINZ. These areas are thought to be hosted by less permeable layers within the windblown sand dunes.

Across the Waipapa test area, LINZ swamp layer identifies a few small areas of swamp land, the bulk of which occur around Lake Omapere, adjacent to the floodplains of the Waihou and Punakitere rivers (Figure 37). For these larger swamps, there is a good correlation with radiometric signals. Smaller swamps show less correlation perhaps reflecting drainage of these areas. Estuarine areas are also well correlated with lower gamma signals especially in the most inland reaches.

The Kaipara test area is associated with a greater number and area of swamps (Figure 38). The majority of which occur in association with dune lake systems and valley-floor peat deposits associated with the Kaipara Barrier bar. It is apparent from radiometric signals that the LINZ swamp polygons that are associated with dune lake ecosystems could be refined using the gamma data. An evaluation of the LNZ swamp polygons, those associated with dune lake ecosystems from Hokianga Harbour north along Ninety Mile Beach, exhibit a similar opportunity for refinement using radiometric imagery. Within the small-scale, dissected valleys of the eastern Kaipara Barrier bar, LINZ swamp polygons are correlated with valley-floor peat deposits but could also be refined using radiometric imagery.

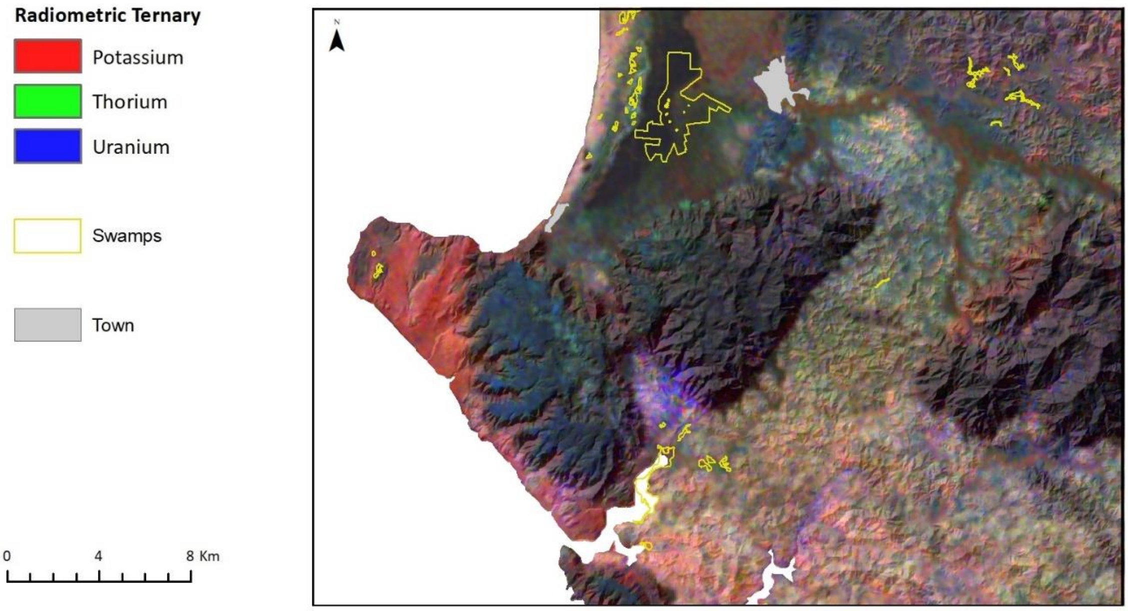

Figure 36. Swamps outline from LINZ and radiometric ternary at Ahipara.

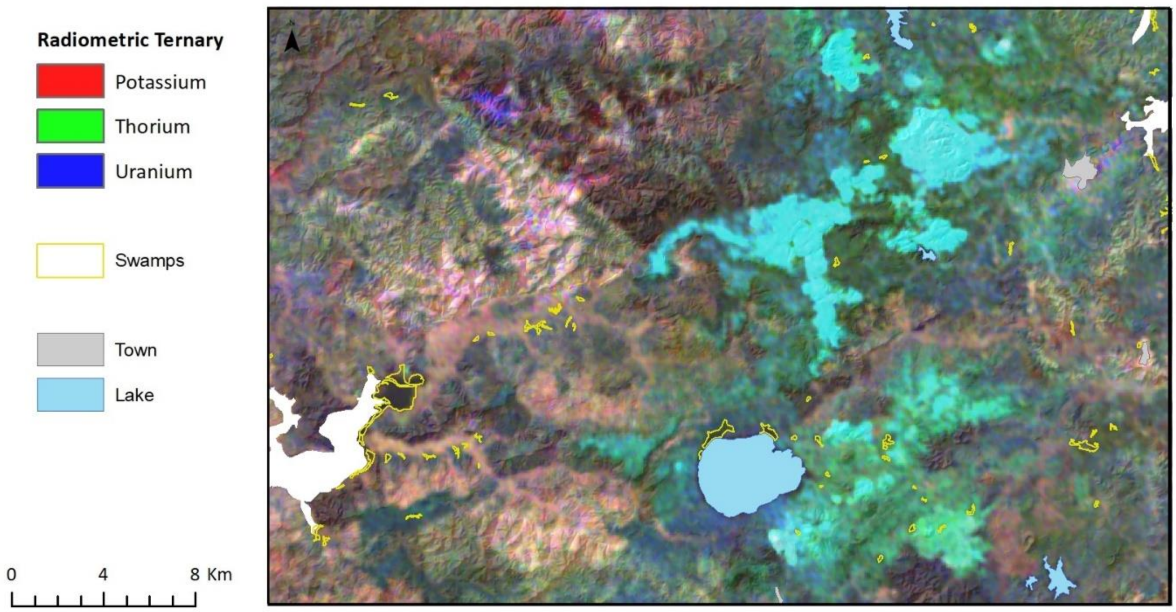

Figure 37. Swamps outline from LINZ and radiometric ternary at Waipapa. Gamma attenuation rates are high in areas of elevated water table (swamps). Drainage of swamps and subsequent soil evolution results in higher gamma values.

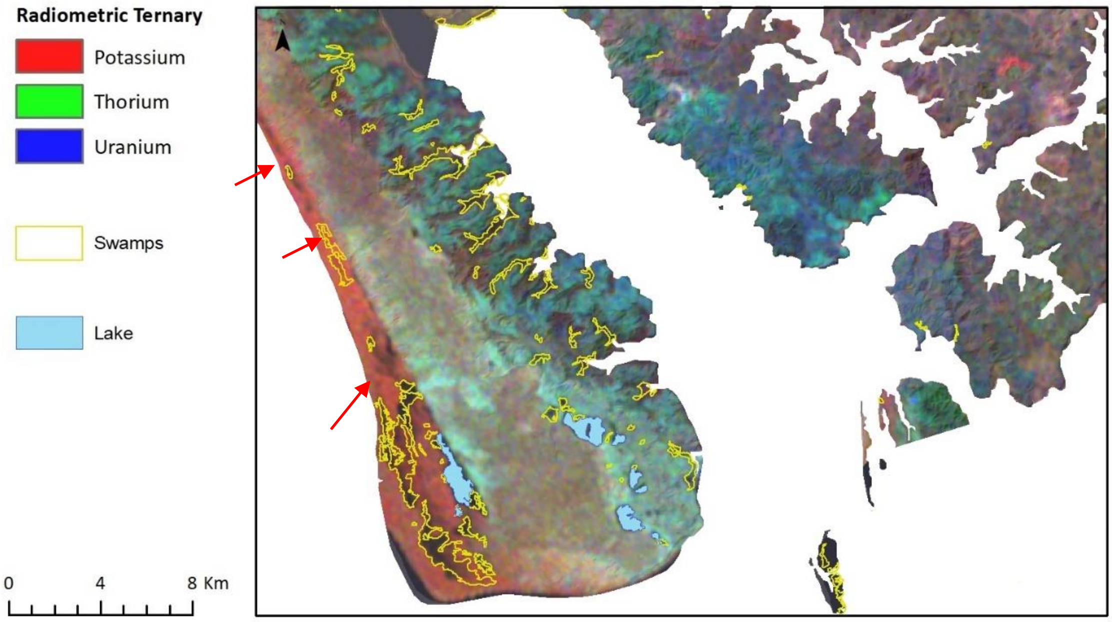

Figure 38. Swamps outline from LINZ and radiometric ternary at Kaipara. Gamma attenuation rates are high in areas of elevated water table (swamps). Red arrows denote areas of swamps and/or ephemeral dune lakes(?) that are not picked up by LINZ. The absence of these features in the LINZ data layer may be due to the highly dynamic setting, where highly mobile dune sands may infill or expose new features.

7 River Environmental Classification (REC1)

The River Environment Classification (REC; Snelder and Biggs, 2002) is a database of catchment physical characteristics, summarised for every segment in New Zealand's network of rivers. The physical attributes on which the individual rivers sections are based include topography, geology, climate, catchment land cover and source of flow for the river water.

7.1. Description of data

Table 7. REC1 metadata.

Source	*Ministry for Environment data service*
Type	*Vector line string*
Limitations	*Does not extend to the shoreline fringes of the Whangarei harbour. Does not have attributes that predict clay content or texture.*
Links to text	*https://data.mfe.govt.nz/layer/1805-river-environment-classification-northland-2010/*
Comments	*Useful to check if radiometrics matches with high stream orders*

7.2. Comparison to radiometric signal

Radiometric signals pick up the extent of modern day floodplains particularly for stream orders greater than or equal to 3 in the REC1 layer (Figures 39, 40, & 41). Within the test areas, the dendritic nature of stream valleys is noted. Channel avulsion and reworking of valley infill associated with the modern-day floodplain is strongly expressed. Importantly, higher order streams are characterised by higher flow volumes and stream power, with sediment yields in areas of fine textured soils often highly correlated (Deakin et al., 2016). Further, natural stream channel migration will result in remobilisation of deposited sediment. The risk being, that modern-day sediments in areas with a long history of land use are often highly enriched in P and N.

Overall, there is strong correlation between REC1 and the radiometric ternary image; flood plain corridors around REC1 polylines have a consistent radiometric signal and are traceable through the landscape. This has also been key for the Southland physiographic project, where REC1 was used to identify stream source, which is an important hydrological control over water composition and quality (including sediment source). However, it was shown in Southland that the Topo50 map was often a better tool for mapping water source than the digitised river network component of the REC1. Observations similar to this have been made by Northland Regional Council Staff (pers. comm. Duncan Kervell, Northland Regional Council). Accurate representation of stream headwaters is a critical consideration when developing a hydrological process layer for physiographic application and is likely to be important for sediment concentrations. Radiometric signals are also a useful tool for delineating additional resolution of stream channel width.

In Ahipara test area, the Awanui River and its tributaries form a complex dendritic network that has incised into the geological surface. The corridor of the dendritic network has a distinct radiometric signal which is generally a mottled mix of colours dependent on the provenance of sediments. Mottled corridors are associated with river valley floors that expand into larger flood plain areas (Figures 39 & 40). Of note in Figure 40 is the distinct high gamma signal associated with the head waters of the Waipapa River and the deposition zones around the Waihou River.

Longitudinal gradients in radiometric signals along floodplain corridors occur in response to inflow from tributaries of different sedimentary provenances. The latter, in conjunction with an appreciation of the primary sedimentary provenance source, provides a powerful tool for explaining variation in sediment size, source and attendant hydrological properties of floodplain soils. In conjunction with REC1, the radiometric imagery provides a link between sediment source (head water), transfer zone and depositional areas (deltaic systems and estuaries). The ability of the radiometrics, in conjunction with REC1 and floodplain mapping, to trace sediment source longitudinally downstream is an important observation.

Sediment removal and deposition by river networks forms a predictable and distinct gamma signal across all test areas. However, the Waipapa and Kaipara test areas are not typified by flood plains or large dendritic networks and yet sites of active weathering are identifiable from mottled radiometric signals (Figures 40 & 41). Here, as with other test areas, mottling is associated with strong pink to violet hues in the gamma spectrum, which is associated with low K counts relative to Th and U, suggesting the erosion of relatively old, weathered landforms.

Along the eastern shoreline of the north Kaipara Barrier, there are many short-run catchments which show a strongly mottled signal suggestive of active erosion. Similar, hotspots of mottling are associated with the Owhata, Whangape and Manukau valley areas with the Ahipara test area. Strong mottling is also associated with the Awaroa River Valley. South, towards Hokianga, pink mottling is associated with many of the harbour-facing slopes.

The association of higher gamma counts and bright pink and violet hues with areas of active floodplains, valleys, hill slopes is suggestive of active erosion. Although this is a preliminary interpretation, albeit supported by discussions with Bob Cathcart (a local soil and geomorphic expert), it is possible that radiometric imagery is an effective means of refining areas of elevated sediment generation and loss across Northland.

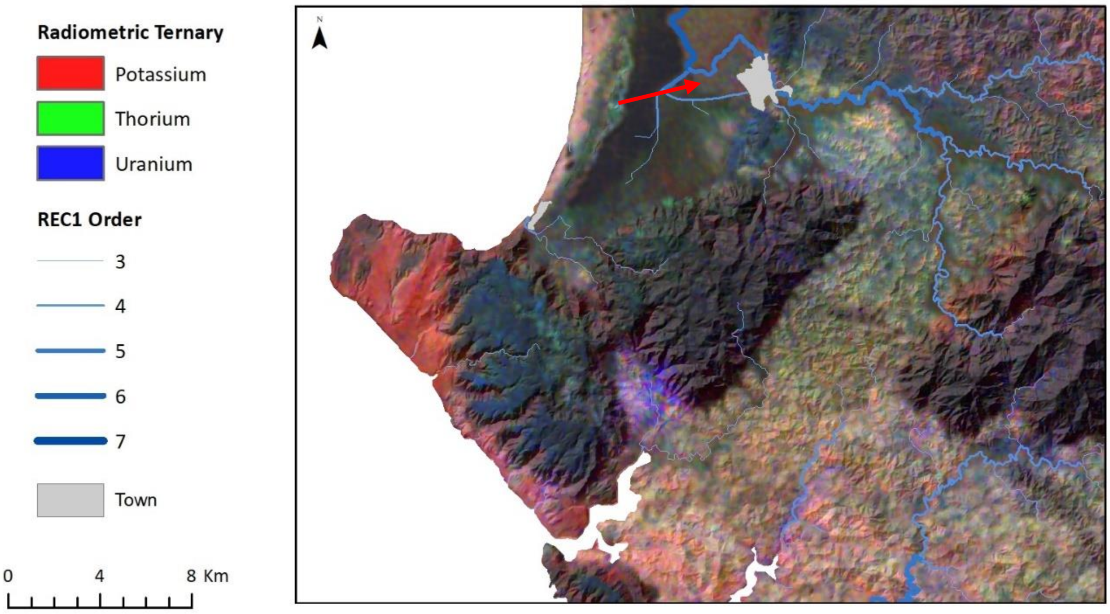

Figure 39. River order 3 and greater from REC1 and radiometric ternary at Ahipara. The red arrow indicates the Kaitaia flood plain.

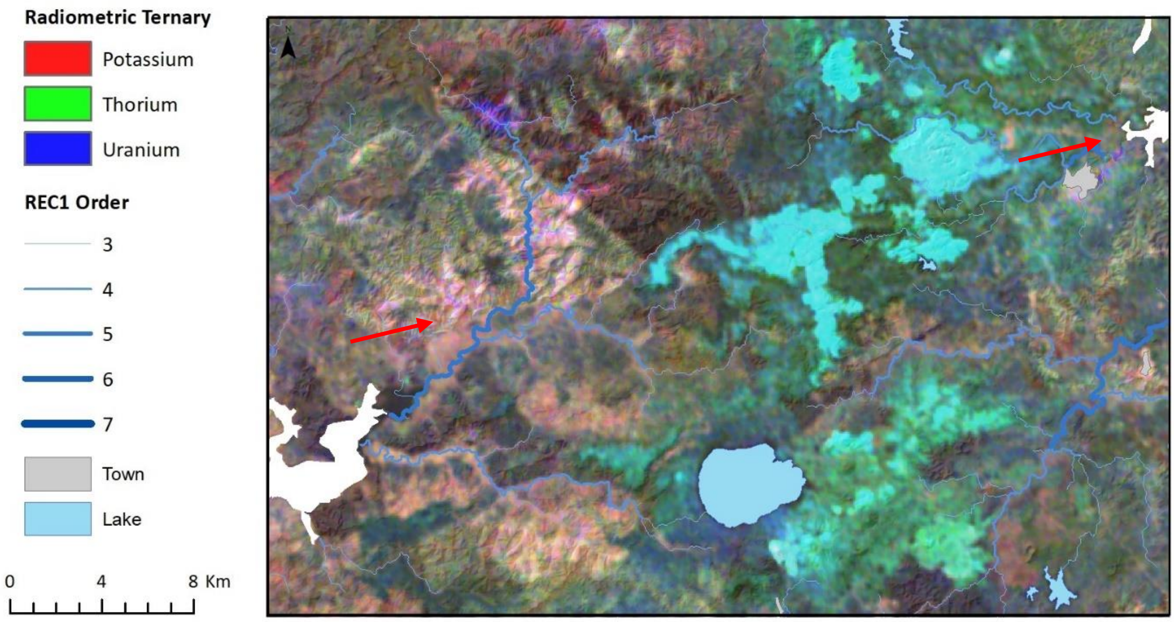

Figure 40. River order 3 and greater from REC1 and radiometric ternary at Waipapa. The red arrows indicate flood plains: Left; Waihou River Valley (and flood plains from the Waipapa and Whakanekeneke rivers), Right; Kerekeri River/Puketotara Stream flood plains.

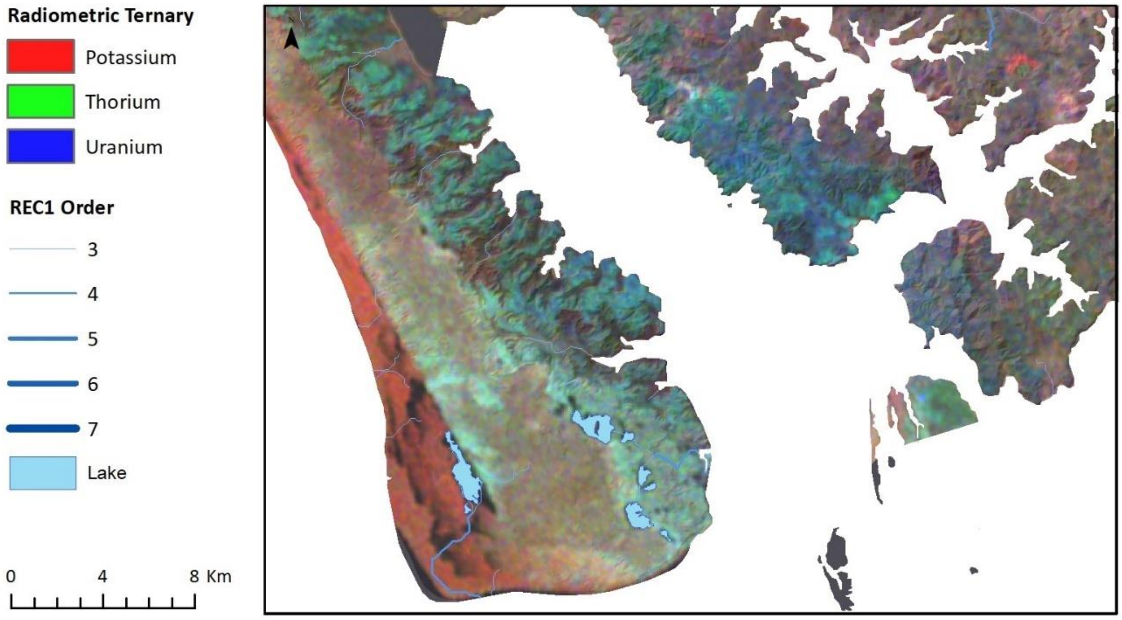

Figure 41. River order 3 and greater from REC1 and radiometric ternary at Kaipara.

8 Radiometric Evaluation Summary

Radiometric imagery, provided by the 2011 New Zealand Petroleum and Minerals survey of the Northland region, provides a platform for better understanding the key landscape relationships that govern hydrological, redox and sedimentary processes as they pertain to physiographic mapping for water quality. The value of radiometric imagery reflects the fact that radiometric signals are obtained from direct measurement, therefore are not inferred or derived products, and are generally of higher spatial resolution than map unit polygons in soil, geological, and other geospatial layers.

Although this work is purely qualitative, it is apparent that there is a good fit between existing geospatial layers and radiometric signals across the three test areas. QMAP captured geological information at 1:250 000 scale, and using mainly stereo aerial photograph interpretation, the LRI Rock 2 attribute layer has tried to refine the QMAP 1:250 000 scale mapping down to 1:50 000. Combination with the LRI Rock2, DEM and radiometric imagery helps to refine some of the finer scale variation associated with small scale drainage basins (<8 km^2) and areas characterised by steep geomorphic gradients. The key findings of this work are summarised in Table 8 below.

Table 8. Summary table of the relationship between geospatial data and radiometric signal.

Layer and attribute	Correlation with Radiometric signal	Importance within Physiographic context	Pros and Cons
DEM 8 m	Strong spatial correlation between altitude, relative relief, slope and radiometric signals. All subsequent evaluations of the relationship between radiometric signals and landscape gradients are made using the combined DEM-radiometric layer.	Correlation between radiometric signals and DEM is important to understanding the geological and geomorphic controls (weathering and transport limited settings and gradients therein) over surficial hydrological properties, the volume of stored sediment and the attendant risk of erosion.	Combination of DEM and radiometric imagery is used as a primary base layer for subsequent evaluation of landscape gradients (e.g. geological, geomorphic and biogeochemical gradients) that influence spatial variation in water quality.
QMAP Stratigraphic Age	Reasonable correlation between radiometrics and Strat_Age	In Northland, gradients in stratigraphic age are highly spatially correlated with radiometric signals. When combined with rock/sediment provenance (QMAP, Main Rock) and radiometric signals, stratigraphic age provides key constraints over: (i) gradients in soil hydrology, (ii) biogeochemical properties such as soil pH, P-retention and mineralogical composition; (iii) soil and regolith erodibility and dispersivity, and; (iv) for groundwater where the abundance of electron donors and redox buffers that determined the fate of leached nitrate and the solubility and mobility of P species.	Most powerful when used in conjunction with Main Rock (QMAP) as this provides information over primary rock/sediment texture and provenance.

QMAP **Main rock**	Overall, strong correlation in all test areas. However, a few areas of disconnect in Waipapa, associated with faulting and facies change.	Primary parent material texture and provenance are a critical control over: (i) soil hydrological properties that govern flow path and soil zone reduction potential; (ii) abundance of electron donor and redox buffers in aquifer systems; (iii) provenance of sediments and their attendant hydrological properties that are associated with the stream network/floodplain.	Despite being mapped at 1:250,000, QMAP is still highly relevant and contains a significant number of attribute fields that make it the most authorative source of geological information for physiographic mapping.
NZLRI Rock 2	Overall, strong correlation in all test areas. While LRI Rock2 does well to constrain general geological relationships, the dark (attenuated signal) dune lake and swamp areas on the north Kaipara Barrier are not mapped. The extent of these areas is not well correlated, and could indicate the dynamic setting and changes to the feature since mapping.		Rock2 (1:50,000) provides finer resolution, in places, relative to QMAP. Combined, Rock2 and QMAP with regional DEM and radiometric imagery provides powerful constraint over gradients in regional geology.
FSL Soil Type	On its own, soil type (as defined by texture) is not strongly correlated with radiometric imagery.	Textural class on its own appears too coarse when contrasted with soil hydrological measures such as permeability, DSLO and drainage class. However, there is obvious value when the LRI soil type layer is used in conjunction with soil hydrological, geological and radiometric imagery.	Provides useful textural information when used in conjunction with soil hydrological, geological and radiometric imagery. Limited if used on its own.
LRI Drainage Class	There is a strong spatial correlation between radiometric signals and LRI drainage class. Correlation is primarily due to gradients in parent material texture and provenance (geology), followed by geomorphic setting (weathering versus transport limited). Due to strong geological	Important for determining the reduction potential of the soil. Therefore, is used to produce the soil zone redox process layer. In conjunction with soil hydrological response, drainage class indicates areas where soil zone recharge is oxidising or reducing, which is critical for better understanding	Strongly correlated with: (i) primary parent material texture and provenance and radiometric signals, and; (ii) geomorphic setting (weathering vs transport limited). Enables a highly resolved representation of landscape gradients governing soil zone reduction potential.

	control, Drainage Class is well correlated with radio signals. Soil Drainage Class and DSLO appear strongly correlated. However, soil Permeability Class is not always correlated with Drainage Class or DSLO. As expected, there was some attenuation of signal in poorly drained areas.	variation in ground and surface water N and P concentrations. Correlation of soil drainage class with geological texture may also be correlated with aquifer reduction potential.	
LRI soil permeability	There is a good spatial correlation between radiometric signals and LRI soil permeability. Correlation is primarily due to gradients in parent material texture and provenance (geology), followed by geomorphic setting (weathering versus transport limited). Due to strong geological control, Permeability Class is well correlated with radio signals. Soil permeability is not always correlated with soil drainage class and DSLO.	Critical to determining the pathway water takes across the landscape and as such the risk profile of drainage to surface and shallow ground water. Therefore, is used to produce the hydrology process layer which shows where recharge occurs and the degree of connectivity between soils, surface and ground water.	Strongly correlated with: (i) primary parent material texture and provenance and radiometric signals; (ii) stratigraphic age, and; (iii) geomorphic setting (weathering versus transport limited). In conjunction with slope and DSLO, provides a highly resolved representation of landscape gradients governing the pathway water takes across the landscape. This includes the export of water between hydrological domains (i.e. Hill Country to Lowland) as well as the degree of hydraulic connectivity between soils and aquifers, aquifers and streams.
LRI DSLO	Strong spatial relationship between radiometric signals and LRI DSLO class. As expected, there was some attenuation of signal in poorly drained areas (areas with a shallow DSLO). The strong correlation reflects gradients in primary parent material texture and provenance, geomorphic setting (weathering versus	Important because in conjunction with soil permeability it gives an indication of the storage capacity of the soil. In conjunction with permeability and slope it determines flow pathways (i.e. deep drainage versus lateral soil zone drainage versus overland flow).	Strongly correlated with: (i) primary parent material texture and provenance and radiometric signals; (ii) stratigraphic age, and; (iii) geomorphic setting (weathering versus transport limited). The DSLO appears to represent the thickness of the regolith in weathering limited settings. In conjunction with permeability, DSLO enables a highly

	transport limited) and is strongly spatially correlated with radio signals. Highly spatially correlated with soil drainage class and to a lesser degree soil permeability.		resolved representation of landscape gradients governing the pathway water takes across the landscape, the export of water between hydrological domains (i.e. Hill Country to Lowland) as well as the degree of hydraulic connectivity between soils and aquifers, aquifers and streams. Collectively, the soil hydrological gradients of drainage class, permeability and DSLO are critical for better understanding hydrological pathways, including the degree of modification of the hydrological setting by artificial drainage and attendant stream power increases. The same measures in conjunction with slope are also critical for assessing Over Land Flow (OLF) and attendant sediment entrainment and transport.
LINZ Topo50 Swamps	There is a strong correlation between radiometric signal and swamps. Areas of elevated organic carbon emit little gamma radiation and in conjunction with higher water contents occur as dark areas in radiometric imagery. Swamp areas attenuate the signal as do water bodies such as lakes. It is well recognised that radiometric surveys are an effective means to map or ground-truth swamps/wetland areas and associated ecosystems (dune lakes).	Swamps are important sites of denitrification but may also exhibit elevated P and E. *coli* levels if associated with intensive land use or receive inputs from intensive land use. As such they are important landscape features when applying the physiographic method for mapping redox and P loss controls over water quality.	Important for identification of processes in transported limited areas.

REC1	Strong correlation in all test areas. Radiometric signals appear to pick up the extent of modern day floodplains particularly for stream orders greater than or equal to 3rd order. The composition and hydrological properties of floodplain sediments are also strongly correlated with head water and tributary inputs.	REC1 is useful to identify stream source, which is an important hydrological control over water composition and quality. Accurate representation of stream headwaters is perhaps the most important factor when developing a hydrological process layer. Modern day stream channels and floodplains are also highly correlated with physiographic application and is likely to be important for sediment concentrations.	Medium for transport of contaminants in transport limited areas. When coupled with measures or estimates of total P and N content it provides an upper maximum over the possible sediment yield from a catchment
Erosion Class	LRI erosion provides a different but complementary perspective to erosion. There are some strong correlations between erosion and high-K signal, particularly in Kaipara. However, there are a few areas of disconnect in Waipapa that have weathering/transport limited boundaries which do not trigger erosion class changes. Further, there is some evidence that radiometric imagery can potentially be used to positively identify areas of active erosion.	At this preliminary stage the authors are unsure that the current erosion class layer is directly relevant to water quality outcomes. However, erosion class mapping may add additional context to sediment generation across transport limited areas.	Currently, uncertain as to the directly value of Erosion Class in physiographic mapping. However, the relevance of Erosion Class will be further investigated in subsequent mapping.

9 Physiographic Method for Northland

Water quality can vary spatially across the landscape, even when there is similar land uses or pressures in a catchment. These differences in water quality occur because of the natural spatial variation in the physical landscape, which alters the composition of the water through coupled physical, chemical and biological processes. The water composition (of dissolved and particulate constituents) provides information about its origin, the pathway it has travelled and the processes to which it has been subjected. Of most significance to surface water quality are the processes occurring in the soil zone and shallow unconfined aquifers, as they are highly connected hydrologically to surface water. Identifying, mapping, and classifying these landscape features across an area forms the basis of the physiographic approach, making it possible to accurately predict the water chemistry of shallow groundwater and surface water.

At the heart of the physiographic approach is the depiction of the coupled relationship between specific landscape attributes and those key processes that drive water quality outcomes. For example, it is widely recognised that soil drainage class (attribute) is the primary landscape control over the magnitude of denitrification (process) (Webb et al., 2010; Killick et al., 2015; Beyer et al., 2016). Soil permeability (attribute) is also a critical control over water pathway (hydrological process), with the risk or potential for overland flow increasing as soil permeability decreases (Figure 42).

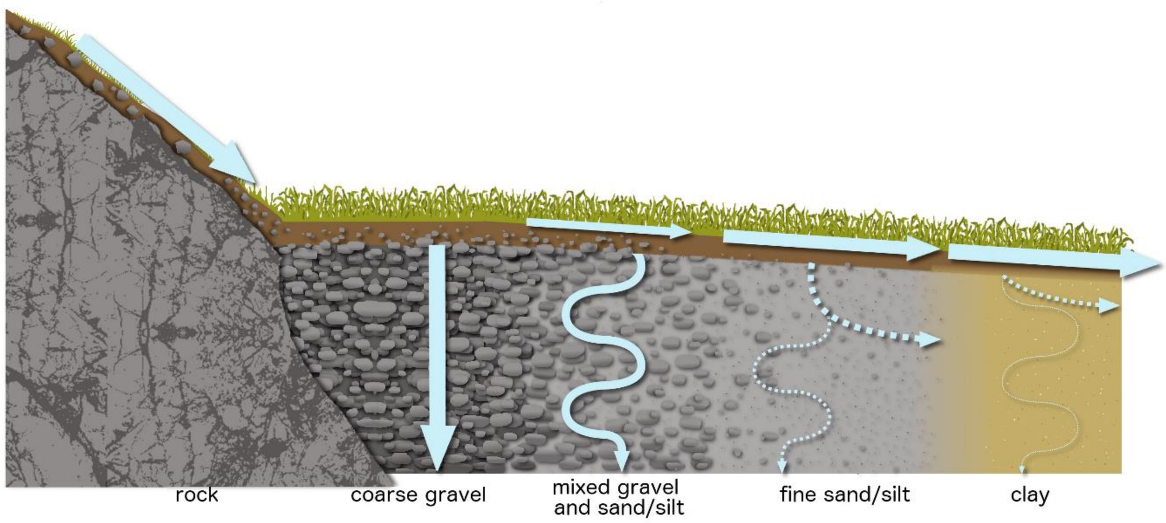

Figure 42. Diagram showing an idealised process-attribute gradient, governing the pathway water takes across the landscape.

9.1 Process-Attribute Layer Methodology

The ultimate aim is to produce a number of classed process-attribute layers (PAL) that depict the spatial coupling of key water quality attributes and attendant process signals within water. Across Northland, this includes consideration of the process-attribute gradients governing the physical (clarity, turbidity, sediment concentration), chemical (nitrogen, phosphorus, pH, sodium) and microbial (E. *coli*) composition of shallow ground and surface water. Each PAL is subsequently classified into categories according to the water quality data – letting the water determine the classes. Each classed PAL can operate as a stand-alone platform for estimating spatial variation in the key processes of interest (i.e. hydrological, redox and sediment processes). By overlaying each individual classed PAL, areas with similar class assemblages can be identified. Areas with similar class assemblages share common attributes and influence water quality outcomes in a similar way. The accuracy of each delineated PAL is verified by assessing the relationship between data from water quality monitoring sites and individual PAL using statistical methods including random forest modelling (see Section 9.2).

9.1.1 Northland Sediment Process Attribute Layer (S-PAL) Method

The ability to improve the spatial depiction of erosional and depositional processes by combining radiometric imagery with other geospatial layers is well supported in the international literature (Wilford, 1995; Wilford et al., 1997; Pickup and Marks, 2000 and 2001; Wilford, 2012 and references therein). A key factor is the recognition of two controls over sediment supply and quality:

1. Natural variation in rock/sediment induration, soil cohesion, soil erodibility, soil dispersivity and slope, and;

2. Anthropogenic perturbation of the landscape in response to vegetation clearance, artificial drainage and a corresponding increasing in N and P inputs.

Both of the above display natural gradients across the Northland region and interact to determine gradients in sediment supply and sediment quality.

Accordingly, we propose that areas characterised by steep slopes and old growth indigenous vegetation cover have not changed much since colonisation of the region by Europeans. Whereas, local studies of sediment accumulation in the harbours of Northland support a rapid increase in sediment deposition (10 to 20 times higher) following European colonisation, in response to widespread deforestation and drainage of lower relief parts of the landscape (Gibbs et al., 2015; Swales et al. 2012; Swales et al., 2015). Thus, it is important to acknowledge that although natural landscape attributes influence sediment supply, the increase in sediment flux to regional waterways is strongly correlated with the clearance of lower relief landforms.

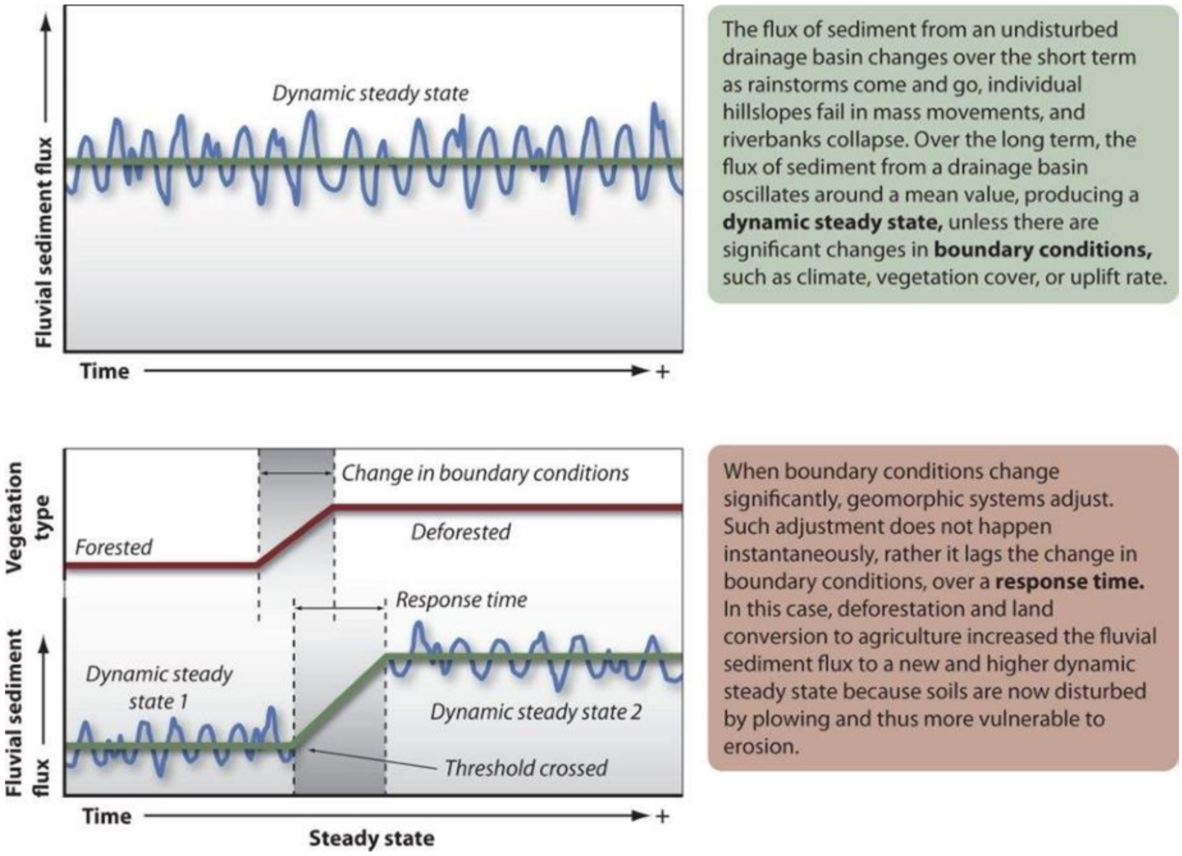

Figure 43. Proposed conceptual control over enhanced sediment loss from transport limited settings across Northland. Diagram from Bierman & Montgomery, "Key Concepts in Geomorphology, (2013)". Where the bottom text box refers to ploughing we redefine this as any activity that has significantly modified the hydrological response of the land surface.

Land clearance, drainage works, and soil compaction drive a shift in the boundary conditions governing the rate at which water leaves the landscape (Figure 43). An increase in the rate at which water leaves the landscape increases leaching, scouring and the capacity of water to entrain and transport contaminants to waterways under peak runoff conditions. A decrease in the residence time of water in the landscape drives an increase in the volume of water moving through a stream over a storm event, thereby increasing stream power and stream bank erosion. Sediment source tracking work by Gibbs et al. (2015) for the Northland region indicates a strong anthropogenic land use signal for riverine and estuarine sediments, with sediment from stream banks thought to contribute c. 40 – 50% of the sediment load.

A key factor is the change in boundary conditions across predominantly transport limited settings, where the greatest land use intensity occurs, has driven (and continues to drive) a readjustment towards a new dynamic steady state associated with much higher sediment yields and rates of stream bank erosion across modified, primarily transport limited parts of the landscape. The increase in the rate at which water leaves the landscape is responsible for the mining out of stored sediment at an unprecedented rate. Across the same period of land clearance and drainage, N, P and microbial content of soil materials has increased markedly in response to deposition by livestock and the widespread use of fertilisers.

Under this highly modified system, we propose that the natural susceptibility of the landscape to erosion is greatly amplified. This simple acknowledgement is critical to the following evaluation and subsequent proposal of a method to better discriminate between natural and anthropogenic sediment supply across Northland.

Against this dynamic backdrop, constraint over spatial variation in mean, total and log mean suspended sediment concentration, clarity and the turbidity of regional streams can be better estimated by extracting, combining and producing a single process-attribute layer of in-stream sediment controls. Specifically, we will map:

1. Gradients in sediment and rock induration (strength) as a feature of different rock types and their degree of weathering. Where weakly indurated rock is more susceptible to erosion than strongly indurated rock. Mapping the gradients in relative induration and degree of weathering will be aided by QMAP, LRI Rock 2 and regional radiometric imagery.

2. Gradients in slope and relative relief are important controls over the transport of sediment and are correlated with geomorphic setting. Depiction of weathering and transport limitation gradients provide an important constraint over the volume of stored fine sediment and landscape level thresholds in slope (regional DEM). Weathering versus transport limited gradients will be mapped via combination of radiometric imagery with the regional DEM.

3. Gradients in the susceptibility of an area to overland flow (OLF) as informed by LRI soil hydrological properties (i.e. soil texture, permeability and DSLO), radiometric imagery, geology and slope (DEM) are important determinants of sediment transport and contaminant entrainment. The OLF mapping includes a measure of the slaking and dispersion (based on soil texture) of soils (Pearson, 2015a). Where

soil hydrological gradients and slope combine to control the susceptibility of an area to OLF and entrainment of sediment and contaminants to waterways.

4. Gradients in the type and proportion of vegetation across the region enable land use gradients to be represented (e.g. pasture cover, agroforestry and indigenous cover). Where land cover/use is a sound proxy for the degree of disturbance/modification of the landscape by human activities including the likely density of artificial drainage (Pearson, 2015b), attendant hydrological response and sediment quality. Of particular relevance is the discrimination and depiction of areas of old growth indigenous vegetation that has not changed significantly since European colonisation, areas of indigenous regeneration, areas of plantation forestry, high producing exotic pasture and horticultural areas. This would be accomplished through combination of the LCDB v 4.1 with attribute fields from 1996 and 2012 to help better resolve areas of land cover change (e.g., regeneration of indigenous forest cover).

5. From our assessment, radiometric imagery appears to identify areas of active erosion. These areas or 'hotspots' of erosion exhibit high gamma counts and enriched Th and U signals that are suggestive of the active erosion of older parts of the landscape. If validated as localised areas of elevated sediment production, these 'hotspot' areas will form a key component of the S-PAL mapping of Northland.

The above attribute layers will be combined to produce a single unclassified PAL that can be used as a standalone layer for estimating instream sediment flux and to improve estimation of instream concentrations of particle reactive species such as *E. coli*, organic N, ammoniacal N, dissolved reactive phosphorus (DRP) and total phosphate (TP). The combination of these 'sub-attributes' into a single PAL reflects the fact that a singular water quality outcome (e.g. sediment) is seldom governed by just one landscape attribute.

In addition to estimating sediment flux, this classification will enable areas of natural state sediment generation and quality to be discriminated from modified areas characterised by enhanced sediment yields and poor sediment quality. This is important when attempting to discriminate the contributions from natural state versus disturbed landscapes to sediment loads.

Initially we will look to see if the above attribute gradients are sufficient to explain the spatial variability in the mean, log transformed mean, coefficient of variation and total sediment concentrations (clarity), *E. coli*, organic N, ammoniacal N, DRP and TP for Northland streams by comparing them against surface water Sate of the Environment (SoE) monitoring data sets. At this point, we may consider including the LRI or NRC erosion class mapping to further refine, if necessary, the sediment process-attribute gradient layer to estimate in stream concentrations.

The S-PAL will then be classified into sediment generation and quality categories using regional surface water quality data, again following the methods of Rissmann et al. (2016) developed for the Physiographics of Southland programme.

9.1.2 Northland Hydrological Process Attribute Layer (H-PAL) Method

To produce a hydrological process attribute layer (H-PAL) for Northland, a simplified version of the Southland method is provided below. A detailed outline of the method is available online (see Beyer et al. 2016[11]) for the interested reader.

The H-PAL represents the landscape level controls over surface and shallow ground water:

- Water source – where the water in a stream or aquifer originates from.
- Recharge mechanism – the broad scale mechanism/process by which water reaches an aquifer or stream.
- Water pathway – fine scale mechanism/process controlling the pathway water takes – bypass flow, overland flow, lateral drainage and deep drainage.

These three mechanisms are controlled by a wide range of physical processes (e.g. dilution, infiltration, exfiltration and percolation). The attributes of the landscape governing these processes are extracted from geological, soil and hydrological/hydrogeological (hereafter hydrological) information and presented as a single layer. The layer is then classified according to water signatures (Figure. 44).

For the purposes of mapping the H-PAL for Northland, water signals and an understanding of the process level controls, from relevant peer-reviewed literature, are used to identify the key attributes of the landscape governing hydrological response (e.g. water source, recharge mechanism and finer scale water pathway). High spatial resolution of surface runoff pathways can be incorporated into the H-PAL if LiDAR is available (Rissmann et al., 2017). With LiDAR, it is possible to map the surficial flow paths at farm and in some settings paddock scale resolution. Spatial information over aquifer properties, including confinement depth

[11]https://contentapi.datacomsphere.com.au/v1/h%3Aes/repository/libraries/id:1tkqd22dp17q9stkk8gh/hierarchy/Scientific%20reports/Physiographics%20of%20Southland%20-%20Part%201/TC%206%20

and degree of coupling to main stem rivers, is also important. Figure 45 provides an example of a catchment within the lowland recharge setting, with finer scale hydrological pathways mapped using LiDAR.

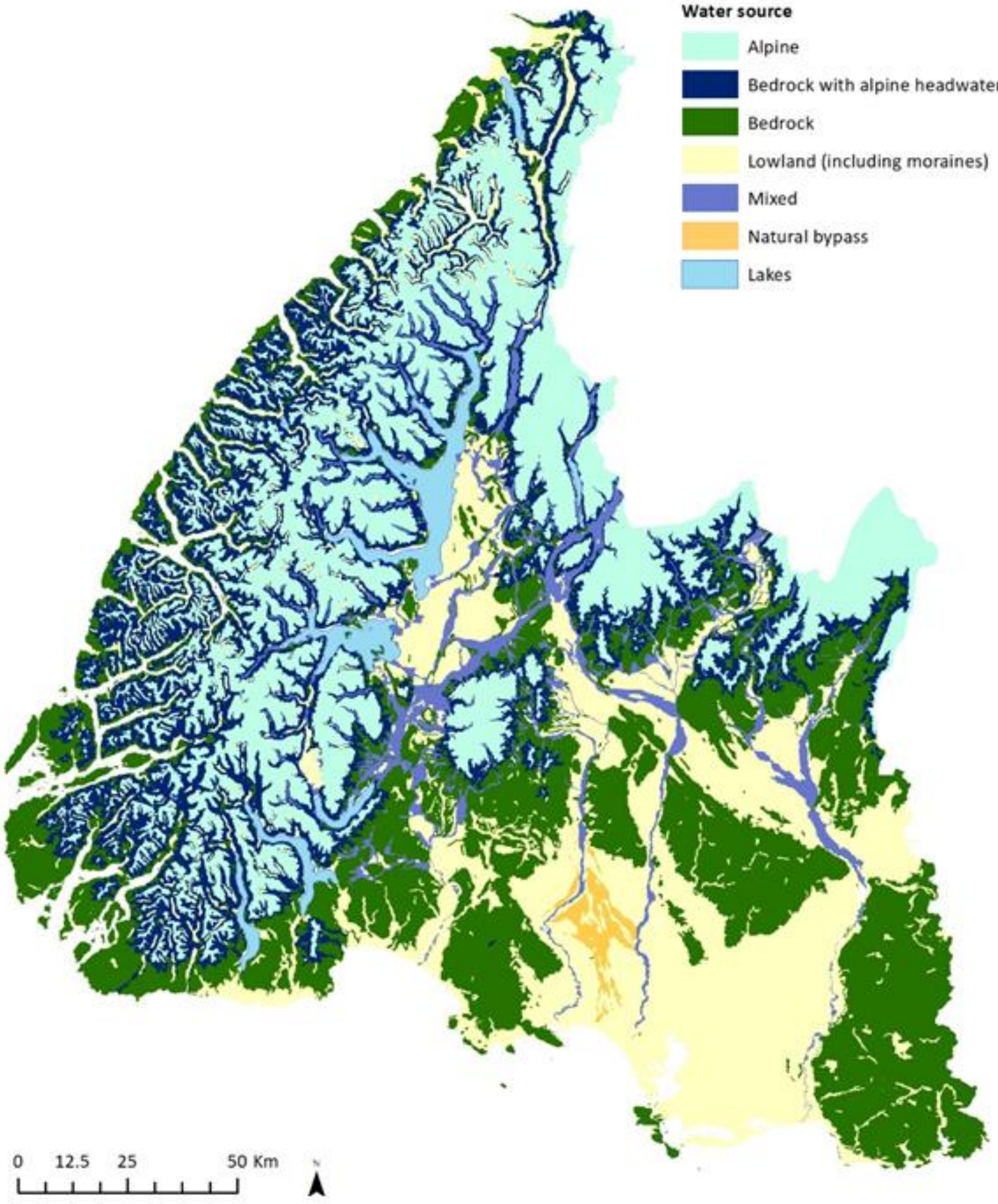

Figure 44. Classed process attribute layer for Southland hydrology (H-PAL). For clarity, overland flow layer and stream sources are not shown here. Where the map represents a classed process attribute layer which is classified according to hydrological tracers.

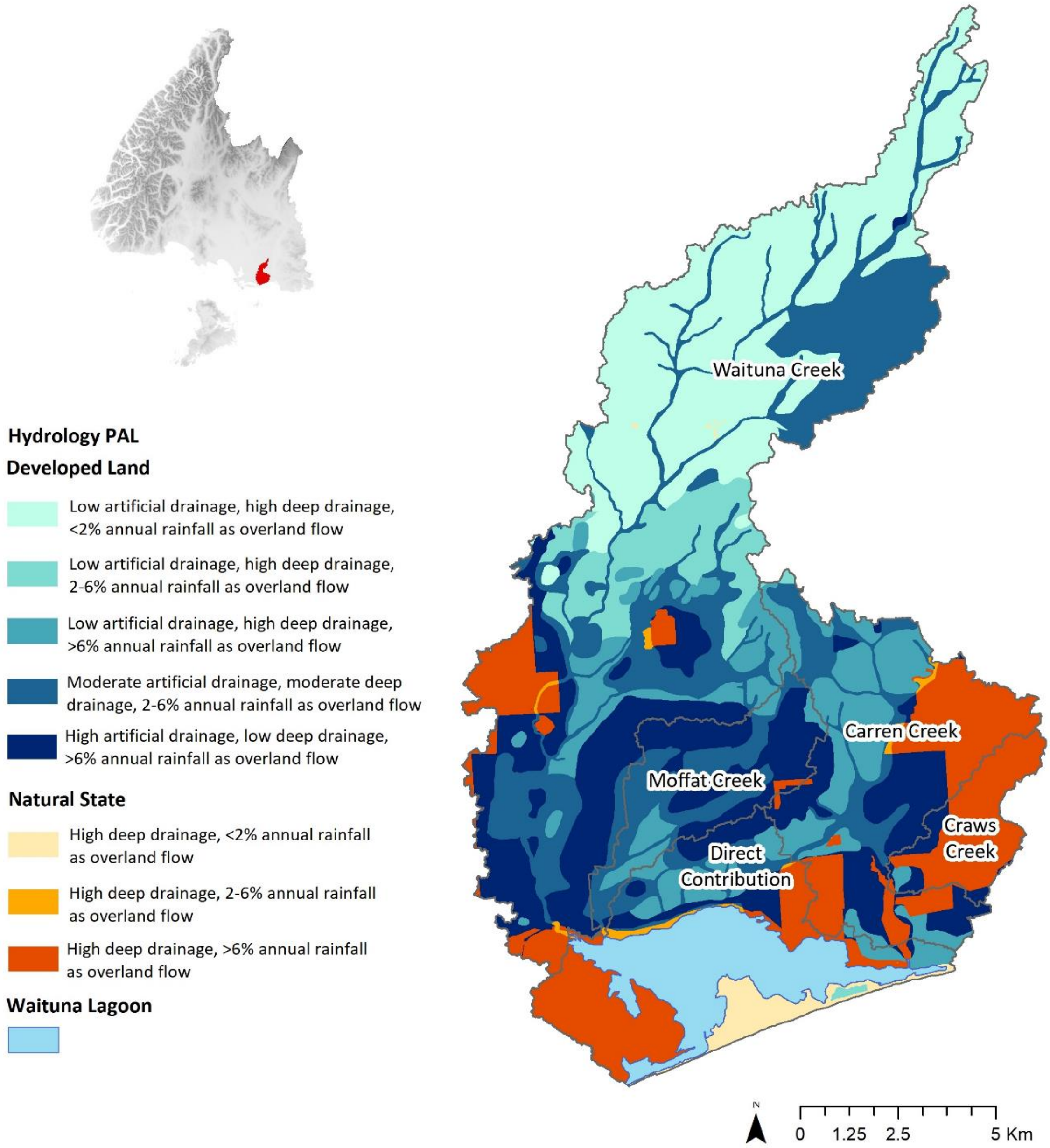

Figure 45. Classed hydrological process attribute layer for Waituna Catchment intersected with fine scale flow paths of overland flow, deep drainage, and artificial drainage density.

For Northland, the H-PAL will be generated from: LRI soil hydrological attributes; LINZ topo50 swamp layer; geological attributes from both QMAP and Rock2 (LRI); regional DEM, and; a digitised representation of the stream network (Topo50 and REC1). The radiometric layer will be used to refine areas that are incorrectly mapped or poorly constrained by existing geospatial layers.

After classification of the H-PAL, each class is shown by a different colour, the classes being determined by threshold values in water composition (both surface and ground water). Where water originating from different sources exhibits different signatures associated with distinct recharge environments, recharge mechanism and/or pathways taken across the landscape.

9.1.3 Northland Redox Process Attribute Layer (R-PAL) Method

A simplified version of the Southland method to produce a combined redox potential (both soil and geology) process attribute layer (R-PAL) for Northland is provided below. A detailed outline of the method is available in Beyer et al. (2016).

The R-PAL produced for Southland represents the combined influence of soil (unsaturated zone) and geological attributes over redox signatures in water (Figure 46). Soil reduction potential is controlled predominantly by soil drainage class and geological reduction potential, which is governed by the electron donor abundance and redox mineral buffering of rock and sediment (Rissmann, 2011; Tratnyek et al., 2012; Beyer et al. 2016). Depending on the distribution of these attributes, the general redox category (e.g. oxic, sub-oxic, anoxic, mixed(oxic-anoxic)) and the Terminal Electron Accepting Process (TEAP; O_2-reducing, NO_3-reducing, etc.) of shallow ground and surface waters varies significantly in space, and as such affects N and P loss and attenuation.

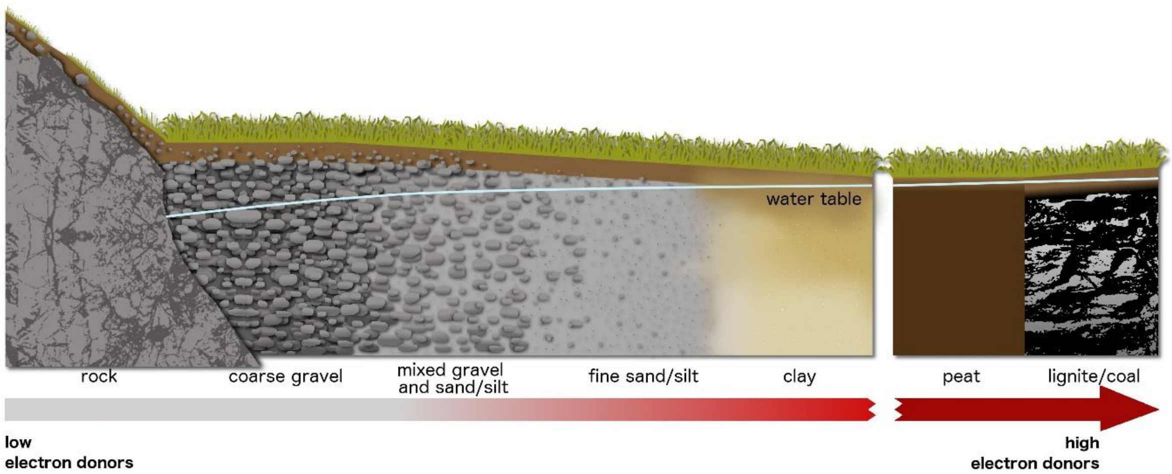

Figure 46. Process-attribute gradient for soil types and redox.

For the purposes of mapping the R-PAL for Northland, water signals and an understanding of the process level controls over water composition, from relevant peer-reviewed literature, are used to identify the key attributes of the landscape governing redox signals (e.g. general redox category, TEAP and the concentration of redox sensitive species and if sufficient data exists the saturation of redox sensitive species) within water. Identification of the attributes is governed by evaluating the signals in sampled waters against the character of the landscape from whence is has drained.

For Northland, we propose that the LRI attributes: lithology (Rock2 attribute), soil drainage class, redoximorphic features (FSL; low chroma colours, mottling and gleying) and organic carbon content, in conjunction with the radiometric survey data, are the best for evaluating the relationship between landscape attributes and shallow ground and surface water redox signatures across the region. The recognition of geologically driven gradients in soil hydrology are also of value when mapping the electron donor content of shallow aquifers. Specifically, the electron donor content and mineral buffering capacity of geological units is widely recognised as a key control over reduction processes such as denitrification and the solubility and mobility of P species within aquifers (Figure 47; McMahon and Chapelle, 2008; Rissmann, 2011; Rissmann et al., 2016).

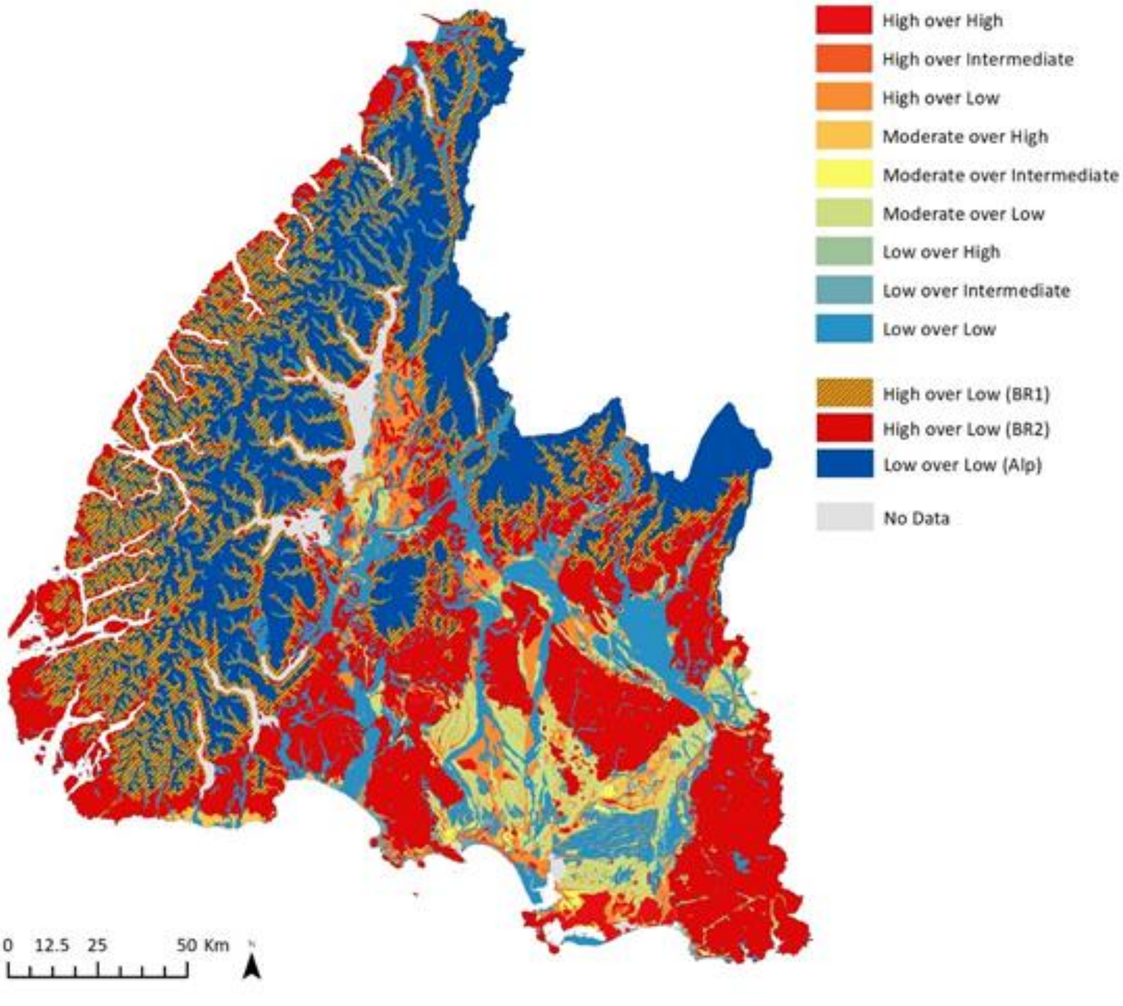

Figure 47. The combined (soil and geological) reduction potential layer for Southland (Rissmann et al., 2016a/b/c; Beyer et al., 2016a/b).

In the regional R-PAL, the reduction potential class for the soil is superimposed upon the geological reduction potential of the underlying rock or sediment. In areas of rock outcrop devoid of soil, the geological reduction potential dominates. In areas of low soil zone reduction over low geological reduction, recharge to an underlying aquifer will be oxidising (O_2-reducing), and the underlying aquifer materials also oxidising. In these settings, if not flushed by river waters, aquifers are prone to nitrate build-up. In areas of high soil zone reduction potential overlying high geological reduction potential, soil drainage is expected to be weakly reducing (i.e., generally mixed (oxic-anoxic) redox category) and any underlying aquifers will also be reducing (anoxic). In this setting, nitrate is rapidly denitrified, but P leaching and mobility may be significant.

9.2 Northland Specific Physiographic Environments for Water Quality

Following the mapping and classification of Northland specific attribute process layers, each will be intersected to produce so called 'physiographic environments' or units. Intersection of each classed attribute-process layer identifies areas with common class assemblages and reveals their distribution across the landscape. Specifically, where the same hydrological, redox and sediment classes occur, we expect to see similar water quality controls and associated outcomes (Rissmann et al., 2016; Figure 48).

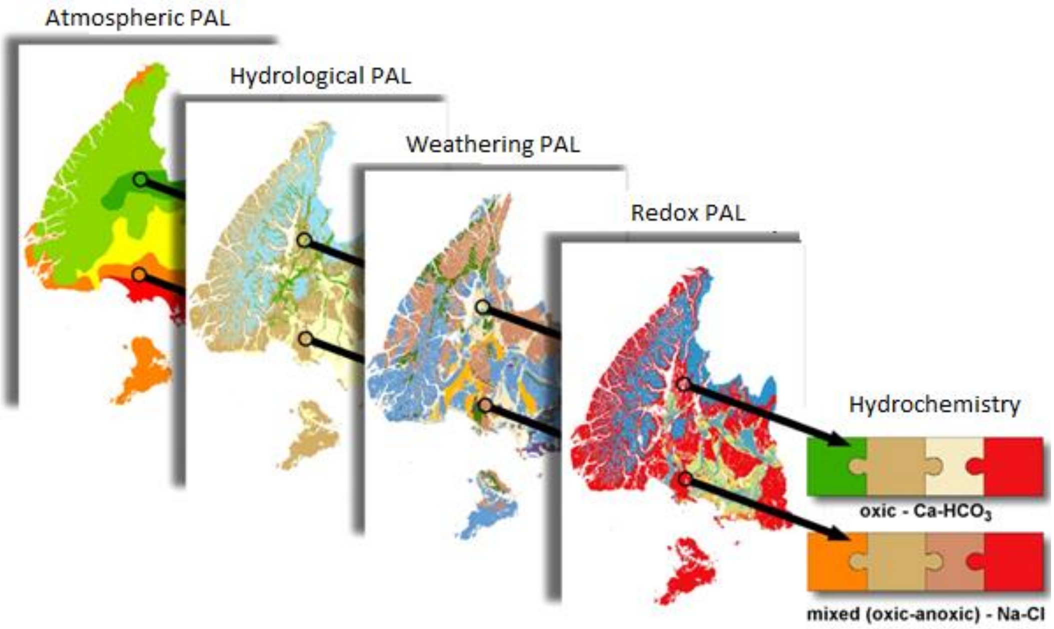

Figure 48. Conceptual diagram of how individual Physiographic Units that govern water quality were identified for the Southland Region. Areas with a similar PAL class assemblage for each PAL host similar process level controls and as such generate similar water composition.

Once physiographic environments have been identified it is relatively simple to evaluate the performance of the units to estimate in stream concentrations of N, P, S and M. This is done by intersecting the capture zone (drainage area) of a water quality monitoring site with the physiographic units to provide an assessment of the proportion of each unit within a capture zone. For the Southland work, the accuracy with which the physiographic map was assessed in three ways:

1. Hierarchal sorting of intersected stream and groundwater capture zones according to individual process-attribute classes (Rissmann et al., 2016);
2. Random forest model assessment (Snelder et al., 2016) of the ability of the combined attribute process layers to estimate water composition and quality outcomes, and;
3. A statistical assessment of the between physiographic unit variation in water quality (Snelder et al., 2016).

Each of these different assessments showed that physiographic mapping provided an accurate estimate of the water quality at SoE sites across Southland. The performance was considered successful enough that the mapping could be used to estimate water composition and likely quality at surface water sites without data (Snelder et al., 2016).

For Northland, the ability of individual attribute process layers to estimate surface and shallow ground water quality will be assessed using a variety of methods following expert input from spatial statisticians associated with the Physiographic Environments of New Zealand (PENZ) research programme. These researchers are part of a larger technical advisory team comprised of technical experts in soil, geology, hydrology, biogeochemistry, aqueous and isotope geochemistry, microbiology and statistics (please see Pearson and Rissmann, 2017 for a list of Senior Technical Advisors and more information on the national project).

9.3 Data requirements from NRC to classify PALs

9.3.1 Water quality data

The soil zone and shallow unconfined aquifers exert the most influence on surface water quality, as they are most often highly coupled. Therefore, it is critical that the same analytes are measured in both surface and groundwater samples to allow the controls over water composition to be understood.

For classification and validation of the PALs and Physiographic Environments, water samples should be collected and analysed for the analytes identified in **Error! Reference source not found.**. These analytes are those that are hydrologically conservative or redox sensitive.

The groundwater test set is the same as the National Groundwater Monitoring Programme (NGMP), operated by GNS Science in collaboration with regional authorities. The only additional analyte is a field measurement of dissolved oxygen.

Table 9. Surface and groundwater chemical analytes needed for classification and validation of PALs.

	Hydrological PAL	Redox PAL
Surface water (field or lab filtered sample)	• Alkalinity (Total) • Sodium (dissolved) • Potassium (dissolved) • Calcium (dissolved) • Magnesium (dissolved) • Silica (dissolved reactive) • Boron (dissolved) • Bromide • Fluoride* • Iodine (dissolved)*	• Dissolved Oxygen • Iron (dissolved) • Manganese (dissolved) • Sulphate
Surface water (sample not filtered in field)	• Nitrogen (Total Kjeldahl) • Electrical Conductivity • Chloride • Dissolved non-purgeable Organic Carbon	• Nitrogen (Nitrate+Nitrite)
Groundwater	• Alkalinity (Total) • Sodium (dissolved) • Potassium (dissolved) • Calcium (dissolved) • Magnesium (dissolved) • Silica (dissolved reactive) • Boron (dissolved) • Bromide • Nitrogen (Total Kjeldahl) • Electrical Conductivity • Chloride • Dissolved non-purgeable Organic Carbon	• Dissolved Oxygen • Iron (dissolved) • Manganese (dissolved) • Sulphate • Nitrogen (Nitrate+Nitrite)

* Non-essential analytes

We recommend that the Northland Regional Council complete 3 surface water sampling runs and 2 for groundwater to aid with classification of the hydrological and redox gradients, with each sample analysed for their usual water quality suite plus the set of parameters outlined in **Error! Reference source not found.**.

Surface water sampling events should be completed for each of the following flow conditions:

- Low (baseflow)
- Median
- High

Groundwater sampling of unconfined aquifers and/or artesian aquifers connected to surface water bodies should be during the following water level conditions:

- High (winter/early spring)
- Low (summer/early autumn)

Note that the groundwater levels should be recorded prior to sampling. Bore construction information (screen depth, final depth, bore logs), aquifer type and confinement status should be provided for each sampled bore if possible.

9.3.2 GIS Spatial requirements

All GIS spatial data should be provided in New Zealand Transverse Mercator 2000 projection. GIS spatial requirements include surface water catchment boundaries (water sheds) for main catchments, Freshwater Management Units and metadata of data sources used to create them (i.e. 8m DEM, RECv1). For ground water catchments, aquifer boundaries/zones should be provided. For each surface water sample site, point data of the sample location and capture zone for the site is required (if available) and metadata. If no surface water capture zones are available, e3 Scientific will produce them for the sampling locations provided to enable validation and performance testing.

9.4 Schedule of outputs for Northland Regional Council

The hydrology and redox PAL will be provided as part of the Physiographic Environments of New Zealand (PENZ), Our Land and Water (OLW) National Science Challenge, contestable bid. The due date for the science component of the PENZ programme is 31st May, 2019. A Northland specific sediment process-attribute layer (S-PAL) is subject to approval by NRC and can be delivered within an 8-month period if approval is given.

Assuming approval, the Physiographic mapping of Northland will provide:

- Three standalone process-attribute layers (PALs) that accurately represent the underlying landscape level controls over water quality risk: Hydrological PAL (H-PAL), Redox PAL (R-PAL) and Sediment PAL (S-PAL).

- Each PAL will be provided as a GIS package compatible with ESRI ArcGIS and/or Google Earth.
- A single layer depicting the distribution of physiographic units across the region. The combination of the 3 regional PALs provides an integrated package for understanding variation in the three key processes governing water quality outcomes in one layer. The hydrological, redox and sediment characteristics of each physiographic unit will be provided along with the associated risk profile. Where each physiographic unit identifies areas with a similar class assemblage and hence similar process level controls over water quality risk and state. Also provided as a GIS package and/or Google Earth Platform.
- Evaluation of the performance of each classed PAL and physiographic unit to estimate shallow ground and surface water across the Northland region.
- A detailed user guide for both technical and lay persons working in science, extension, consenting, compliance, and policy and planning is proposed through a National Envirolink Tools Project to accompany the Physiographic Environment science.

10 References

Aspin, S.J., Bierworth, P.N., 1997. GIS analysis of the effects of forest biomass on gamma-radiometric images. Third National Forum on GIS in the Geosciences. Australian Geological Survey Organisation Record 1997/36: 77–83.

Ballinger, J., Nicholson, C., Perquin, J-C., Simpson, E., 2014. River water quality and ecology in Northland- State and trends 2007-2011.

Beamish, D., 2015. Relationships between gamma-ray attenuation and soils in SW England. Geoderma, 259-260, 174-186.

Beerten, K., Deforce, K., Mallants, D., 2012. Landscape evolution and changes in soil hydraulic properties at the decadal, centennial and millennial scale: A case study from the Campine area, northern Belgium. CATENA 95:73-84

Beyer, M., and Rissmann, C., 2016. Tile drain and soil water sample assessment – relationships between Soil Denitrification Potential and redox processes. GNS Science Report 2016/60.

Beyer, M., Rissmann, C., Rodway, E., Marapara, T. R., Hodgetts, J., 2016a. Environment Southland report Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. Technical Chapter2: Discrimination of Recharge Mechanisms and Vulnerability to Bypass Flow. Environment Southland Report June 2016.

Beyer, M., Rissmann, C., Rodway, E., Killick, M., Pearson, L., Marapara, T. R., Hodgetts, J., 2016b. Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. Technical Chapter 6: Influence of Soil and Geological Composition over Redox conditions for Southland groundwater and surface waters. Environment Southland Report June 2016.

Bierman, P.R., and Montgomery, D.R., 2013. Key concepts in Geomorphology. W.H. Freeman 2013-12-27.

Bierwirth, P.N., 1996. Investigation of airborne gamma-ray images as a rapid mapping tool for soil and land degradation - Wagga Wagga, NSW. Record 1996/22. Australian Geological Survey Organisation.

Bockheim, J. G., and Hartemink, A. E. 2013. Distribution and classification of soils with clay-enriched horizons in the USA. Geoderma, 209–210, 153–160. https://doi.org/10.1016/j.geoderma.2013.06.009

Boekhout, F., Gérard, M., Kanzari, A., Michel, A., Déjeant, A., Galoisy, L., Descostes, M., 2015. Uranium migration and retention during weathering of a granitic waste rock pile. Applied Geochemistry, 58(Supplement C), 123-135. doi:https://doi.org/10.1016/j.apgeochem.2015.02.012

Cameron, S., Osbaldiston, S., Skuse, G., Revfem, C., 2001. Chapter 12 Northland, Part II - Regional Groundwater Summaries, In: Groundwaters of New Zealand, Michael R. Rosen and Paul A. White, editors, New Zealand Hydrological Society Inc; Wellington North, New Zealand; ISBN0-473-07816-3; 498 pp; 2001.

Chappell, P.R., 2013. The climate and weather of Northland. 3rd edition NIWA SCIENCE AND TECHNOLOGY SERIES, 59.

Claridge, G.G.C., 1961. An investigation of the fine fraction of some rock and soil materials from Antarctica. New Zealand Journal of Science 4:3.

Close, M.E., Davies-Colley, R.J., 1990. Baseflow water chemistry in New Zealand rivers. 1. Characterisation. New Zealand Journal of Marine and Freshwater Research 24: 319–341.

Collins, R., McLeod, M., Hedley, M., Donnison, A., Close, M., Hanly, J., Horne, D., Ross, C., Davies-Colley, R., Bagshaw, C., Matthews, L., 2007. Best management practices to mitigate faecal contamination by livestock of New Zealand waters. New Zealand Journal of Agricultural Research 50: 267-278.

Cooper, A.B., Thomsen, C.E., 1988. Nitrogen and phosphorus in stream waters from adjacent pasture, pine and native forest catchments. N.Z. J. Mar. Freshwater Res. 22, 279–291.

Daniels, R., and Hammer, R., 1992. Soil geomorphology. Wiley, NY, pp 236. ISBN 04710511536

Day, R.W. 1994. Swell–shrink behaviour of expansive compacted clay. Journal of Geotechnical Engineering, ASCE, 120(3): 618-623.

Deakin, J., Flynn, R., Archbold, M., Daly, D., O'Brien, R., Orr, A., Misstear, B., 2016. Biology and Environment: Proceedings of the Royal Irish Academy.116B, 3. 1-11.

Dent, D.L., MacMillan, R.A., Mayr, T.L., Chapman, W.K., Berch, S.M., 2013. Use of airborne gamma radiometrics to infer soil properties for a forested area in British Columbia, Canada. Journal of Ecosystems and Management 14(1):1–12.

Dif, A.F., and Blumel, W.F. 1991. Expansive soils with cyclic drying and wetting. ASTM, Geotechnical Testing Journal, 14(1): 96-102.

Dixon, J., 2015. Soil Morphology in the Critical Zone: The Role of Climate, Geology, and Vegetation in Soil Formation in the Critical Zone. Principles and Dynamics of the Critical Zone. Developments in Earth Surface Processes, Vol. 19.

Dow, C. L., Arscott, D. B., Newbold, J. D., 2006. Relating major ions and nutrients to watershed conditions across a mixed-use, water-supply watershed. Journal of the North American Benthological Society, 25(4), 887-911. doi:10.1899/0887-3593(2006)025[0887:rmiant]2.0.co;2.

Dymond, J. R., Herzig, A., Basher, L., Betts, H. D., Marden, M., Phillips, C. J., Roygard, J., 2016. Development of a New Zealand SedNet model for assessment of catchment-wide soil-conservation works. Geomorphology, 257(Supplement C), 85-93. doi:https://doi.org/10.1016/j.geomorph.2015.12.022

Edbrooke, S.W. (compiler) 2001: Geology of the Auckland area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 3. 74 p. + 1 folded map

Edbrooke, S.W., and Brook, F.J. (compilers) 2009. Geology of the Whangarei area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 2. 1 sheet + 68 p. Lower Hutt, New Zealand. GNS Science. QMAP Whangarei

Ewans, R., 2015. Environment Southland Wetland Inventory Project: monitoring wetland extent on nonpublic conservation land in the Southland region. Report for 2015. Eco-South contract report for Environment Southland. 63 pp.

Gibbs, N. M., Swales, A., Olsen, G., Ovenden, R., 2015. From Land to River to the Bay of Islands Waitangi River catchment Study Objective: (April).

Grasty, R.L., 1975. Atmospheric absorption of 2.62 MeV gamma ray photons emitted from the ground. Geophysics 40: 1058–1065.

Guney, Y., Sarı, D., Cetin, M., Tuncan, M., 2007. Impact of cyclic wetting-drying on swelling behavior of lime-stabilized soil. Building and Environment, 42(2): 681-68.

Hale, S. S., Paul, J. F., & Heltshe, J. F., 2004. Watershed landscape indicators of estuarine benthic condition. Estuaries, 27(2), 283-295. doi:10.1007/BF02803385

Harmsworth, G.R., 1996. Land Use Capability classification of the Northland region. A report to accompany the second edition (1:50 000) New Zealand Land Resource Inventory worksheets. Landcare Research science series 9. Lincoln, Manaaki Whenua Press. 269 p.

Hedley, C. B., Roudier, P, Peterson P., 2016. Gamma soil surveys – investigating soil patterns for nutrient and water management. In: Integrated nutrient and water management for sustainable farming. (Eds. L.D. Currie and R. Singh). Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 8 pages.

Herrmann, L., Schuler, U., Rangubpit, W., Erbe, P., Surinkum, A., Zarei, M., Stahr K., 2010. The potential of gamma-ray spectrometry for soil mapping. Proceedings of 19th World Congress of Soil Science, 1-6 August 2010, Brisbane, Australia, published on DVD.

Hewitt, A. E., 1993. Methods and rationale of the New Zealand Soil Classification. Landcare Research Science Series 2, Lincoln, New Zealand, Manaaki Whenua Press. 71p.

Hughes,B.,Wilson, K.,Rissmann,C., Rodway,E., 2016. Physiographics of Southland: Development and application of a classification system for managing landuse effects on water quality in Southland.

Isaac, M.J. (compiler) 1996. Geology of the Kaitaia area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 1. 1 sheet + 43 p. Lower Hutt, New Zealand. GNS Science. QMAP Kaitaia.

Johnson, L., Richards, C., Host, G., Arthur, J.,1997. Landscape influences on water chemistry in Midwestern stream ecosystems. Freshwater Biology, 37(1), 193-208. doi:10.1046/j.1365-2427.1997.d01-539.

Killick, M., Stenger, R., Rissmann, C., 2015. Estimating soil zone denitrification for Southland. Environment Southland Technical Report.

Larsen, G. R., 2012. Determination of coastal ground and surface water processes and character by use of hydrochemistry and stable isotopes, Fraser Coast, Queensland. Queensland University of Technology.

Lynn, I.H., Manderson, A.K., Page, M.J., Harmsworth, G.R., Eyles, G.O., Douglas, G.B., Mackay, A.D., Newsome, P.J.F. 2009. Land Use Capability Survey Handbook – a New Zealand handbook for the classification of land 3rd editon. Hamilton, AgResearch; Lincoln, Landcare Research; Lower Hutt, GNS Science. 163p.

McDowell, R. W., Monaghan, R.M., Morton, J., 2003. Soil phosphorus concentrations to minimise potential P loss to surface waters in Southland. New Zealand Journal of Agricultural Research, 46:3.

McDowell, R. W. 2008. A Commentary on Agricultural Sources, Transport and Impact of Phosphorus in Surface Waters: Knowledge Gaps and Frequently Asked Questions. Report prepared for Unitary Authorities via Envirolink, December 2008.

McDowell, R., Snelder, T., Cox, N., Booker, D., Wilkock, R., 2013. Establishment of reference or baseline conditions of chemical indicators in New Zealand stream and rivers relative to present conditions. Marine and Freshwater Research, 2013,64, 387-400.

McMahon, P. & Chapelle, F. 2008. Redox Processes and Water Quality of Selected Principal Aquifer Systems. Groundwater, 46: 259–271.

McKergow, L.A, Tanner C.C., Monaghan, R.M., Anderson, G., 2007. Stocktake of diffuse pollution attenuation tools for New Zealand pastoral farming systems. Prepared for Pastoral 21 Research Consortium under contract to AgResearch. NIWA Client Report: HAM2007--161, December 2007.

Milne, J.D.G., Clayden, B., Singleton, P.L., Wilson, A.D., 1995. Soil description handbook. Lincoln, New Zealand, Manaaki Whenua Press. 157p.

Misaelides, P., Sikalidis, C., Tsitouridou, R., & Alexiades, C., 1987. Distribution of fission products in dust samples from the region of Thessaloniki, Greece, after the Chernobyl nuclear accident. Environmental Pollution, 47(1), 1-8. doi:https://doi.org/10.1016/0269-7491(87)90117-5.

Monaghan, R. M., Semadeni--Davies, A., Muirhead, R. W., Elliott, S., Shankar, U.

2010. Land use and land management risks to water quality in Southland. Report prepared for Environment Southland by AgResearch, April 2010.

Montagne, D., Cornu, S., Le Forestier, L., & Cousin, I., 2009. Soil Drainage as an Active Agent of Recent Soil Evolution: A Review*1 *1Project supported by the Région Centre, France. Pedosphere, 19(1), 1-13. doi:https://doi.org/10.1016/S1002-0160(08)60078-8.

Nash, D., Halliwell, D., Cox, J., 2002. Hydrological Mobilization of Pollutants at the Field/Slope Scale. Agriculture, hydrology and water quality, 225.

Newsome, P. F. J.; Wilde, R. H.; Willoughby, E. J., 2008. Land Resource Information System spatial data layers: data dictionary. NLRI.

Northland Regional Council, 2011. Northland River Water Quality Monitoring Network Report - 2008-2009.

Outram, F. N., Cooper, R. J., Sünnenberg, G., Hiscock, K. M., & Lovett, A. A., 2016. Antecedent conditions, hydrological connectivity and anthropogenic inputs: Factors affecting nitrate and phosphorus transfers to agricultural headwater streams. Science of The Total Environment, 545, 184-199.

Parfitt, R., and Wilson, A., 1985. Estimation of allophane and halloysite in three sequences of volcanic soils, New Zealand. Catena Supplement 7.

Pearson, L., 2015a. Overland flow in Southland. Report prepared for Environment Southland, September 2015.

Pearson, L., 2015b. Artificial subsurface drainage in Southland. Report prepared for Environment Southland, September 2015.

Pearson, L., and Rissman, C., 2017. Physiographic Environments of New Zealand: Information Document for Regional Councils. e3Scientific Report 17060.

Pickup, G., and Marks, A. 2000. Identifying large-scale erosion and deposition processes from airborne gamma radiometrics and digital elevation models in a weathered landscape. Earth Surf. Process. Landforms, 25: 535–557.

Pickup, G., and Marks, A., 2001. Regional-scale sedimentation process models from airborne gamma ray remote sensing and digital elevation data. Earth Surf. Process. Landforms, 26:273-293.

Rissmann, C.F., Panno, S.V., Wilson, K.L., Elliotte, D.M., 2011. Estimating Background and Threshold Nitrate Concentrations in Southland groundwaters – A Graphical Statistical Approach. Accepted abstract submitted to the New Zealand Hydrological Society Conference, Wellington, 2011.

Rissmann, C., Wilson, K L., Hughes, B. N., 2012. Waituna Catchment Groundwater Resource Technical Report. Environment Southland publication number 2012-04, Invercargill. 92p.

Rissmann, C., Pearson, L., Killick, M., Rodway, E., Beyer, M., Marapara, T. R., Hodgetts, J., 2016a. Environment Southland report Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. Technical Chapter3: Soil Chemistry. Environment Southland Report June 2016.

Rissmann, C., Rodway, E., Beyer, M., Pearson, L., Killick, M., Dare, J., 2016b. Environment Southland report Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. Technical Chapter 4: Relationship between Soil Chemistry and Soil Water Chemistry. Environment Southland Report June 2016.

Rissmann, C., Rodway, E., Beyer, M., Marapara, T. R., Hodgetts, J., Pearson, L., Killick, M. 2016c. Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. Technical Chapter 5: Comparison of Soil Water with Surface water and Groundwater Chemistry. Environment Southland Report June 2016.

Rissmann, C., and Lovett, A., 2016. Hydrochemical analysis for the Otane waste water treatment plant, GNS science consultancy report 2016/83:32p.

Rissmann, C., Badenhop, A., Marapara, T.R., Lindsay, J., Beyer, M., Bloomberg, S.H., Pearson, L., (2017, in prep). An integrated spatial and temporal platform for the Waituna sub-catchments. e3Scientific ltd. client report for DOC/Fonterra Living Water Programme.

Roselli, L., Cañedo-Argüelles, M., Goela, P. C., Cristina, S., Rieradevall, M., D'Adamo, R., Newton, A. 2013. Do physiography and hydrology determine the physico-chemical properties and trophic status of coastal lagoons? A comparative approach. Estuarine, Coastal and Shelf Science, 117, 29-36.

Sikalidis, C. A., Alexiades, C., Misaelides, P., 1989. Adsorption of uranium and thorium from aqueous solutions by the clay minerals montmorillonite and vermiculite. Toxicological & Environmental Chemistry, 20-21(1), 175-180. doi:10.1080/02772248909357374

Snelder, T.H.; Biggs, B.J.F., 2002. Multi-scale river environment classification for water resources management. Journal of the American Water Resources Association 38: 1225-1240.

Snelder, T., 2015. Defining Freshwater Management Units for Northland: A Recommended Approach. LWP Client Report 2015-004.

Snelder, T, Hughes, B, Wilson K, and Day, K., 2016. Physiographic Zones for the Southland Region: Classification system validation and testing report. Prepared for Environment Southland by LWP Ltd, Christchurch. 73p.

Soana, E., Balestrini, R., Vincenzi, F., Bartoli, M., Castaldelli, G., 2017. Mitigation of nitrogen pollution in vegetated ditches fed by nitrate-rich spring waters. Agriculture, Ecosystems & Environment, 243, 74-82.

Stagpoole, V.M., Edbrooke, S.W., Christie, A.B., Davy, B.W., Caratori Tontini, F., Soengkono, S., Cox, S.C., Isaac, M.J., 2012. Northland airborne magnetic and radiometric survey: a geological interpretation, GNS Science Report 2011/54. 113 p. NZPAM Report MR480

Swales, A., Gibbs, M., Hewitt, J., Hailes, S., Griffiths, R., Olsen, G., Ovenden, R., Wadhwa, S., 2012. Sediment sources and accumulation rates in the Bay of Islands and implications for macro-benthic fauna, mangrove and saltmarsh habitats. NIWA Client Report HAM2012-048.

Swales, A., Gibbs, M., Olsen, G., Ovenden, R., 2015. Historical changes in sources of catchment sediment accumulating in Whangarei Harbour, (April), 39. NIWA Client Report No: HAM2015-037

Tonkin, P.J., 1984. Studies of soil development and distribution in the Eastern Hill Country, Central South Island, New Zealand.PhD thesis, University of Canterbury.

Tratnyek, P.G., Grundl, T.J., Haderlein, S.B. (editors). 2012. Aquatic Redox Chemistry. American Chemical Society symposium series 1071; Oxford University Press, 20.

Vidon, P. G. F., and Hill, A. R. 2004. Landscape controls on nitrate removal in stream riparian zones. Water Resources Research, 40(3).

Volk, J., Savidge, K., Scudlark, J., Andres, A., Ullman, W., 2006. Nitrogen loads through baseflow, stormflow, and underflow to Rehoboth Bay, Delaware. Journal of environmental quality, *35*(5), 1742-1755.

Webb, T.H., and Wilson, A.D., 1995. A manual of land characteristics for evaluation of rural land. Landcare Research Science Series 10. Lincoln, New Zealand, Manaaki Whenua Press. 32p.

Webb, T., Hewitt, A., Lilburne, L., Close, M., 2010. Mapping of vulnerability of nitrate and phosphorus leaching, microbial bypass flow, and soil runoff potential for two areas of Canterbury Prepared for Environment Canterbury by: Environment Canterbury.

Wilford, J.R., 1995. Airborne gamma-ray spectrometry as a tool for assessing relative landscape activity and weathering development of regolith, including soils. AGSO Research Newsletter 22, 12–14.

Wilford, J.R., Bierwith, P.N., Craig, M.A., 1997. Application of airborne gamma-ray spectrometry in soil/regolith mapping and applied geomorphology. AGSO Journal of Australian Geology and Geophysics 17(2):201-216.

Wilford, J.R., 2012. A weathering intensity index for the Australian continent using airborne gamma-ray spectrometry and digital terrain analysis, Geoderma 183:124-142, ISSN 0016-7061, http://dx.doi.org/10.1016/j.geoderma.2010.12.022.