# Soil Recovery after Cyclone Gabrielle: Building Back Better

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Environmental Management

At Massey University, New Zealand.

Alexandra Dickson

2025

This thesis is dedicated to those impacted by the devastating effects of Cyclone Gabrielle in 2023.

And to those recovering from the next ‘big one’.

There are brighter days to come.

# Abstract

Cyclone Gabrielle, which struck New Zealand's North Island in February 2023, caused unprecedented damage to the North Island of New Zealand; the East Coast including Hawke's Bay, Wairoa and Gisborne were some of the worst affected areas. As a result of the destructive flood waters, a vast amount of sediment was deposited on high-value horticultural and cropping land. In the aftermath, there was limited information available to guide landowners in restoring the productive capacity of this highly productive land (HPL). This research aimed to address knowledge gaps through a combined literature review and field-based study.

The initial objective was to understand the geographical and geological setting of Hawke's Bay and consolidate prior understanding of flood sediment impacts. Baseline soil and sediment data was collected from a range of affected sites shortly after the cyclone, assessing physical, chemical, and biological characteristics. A subset of these sites was revisited twelve months later to evaluate short-term changes and management outcomes. Results showed that sediment characteristics varied widely by texture and catchment, with sandy sediments presenting significant physical and fertility challenges. From 2023 to 2024 there was positive outcomes nutrient levels, linked to fertiliser application, and incorporation of sediment into antecedent soil. Soil organic matter levels were consistently low and continued to decline, and earthworm populations remained suppressed.

Despite variability in management responses, some growers observed improvements in soil physical properties, particularly where early interventions such as regrassing were employed. This research highlights the importance of rapid dissemination of management advice immediately after a flood, the need for longer-term monitoring to understand medium to long-term impact and recovery, and the value of coordinated knowledge storage for future events. The findings provide practical insights for growers and policymakers and lay the groundwork for further research into the economic and ecological dimensions of flood sediment recovery in high-value vegetable and horticultural systems, on highly productive land.

# Acknowledgements

Natural disasters, by nature, are unpredictable and difficult to plan for. In early 2023, as Semester 1 was about to kick off, I was thinking about what I might work on for my thesis. The plan was to focus on something in the realm of soil carbon and Regenerative Agriculture. And then on the 13th – 14th February, the world around me felt like it fell apart, as Cyclone Gabrielle battered the North Island, leaving behind a trail of destruction. This was the second major storm event I had been witness to; in 2004 when the Southern North Island Storm occurred, my family was living in Kimbolton, a small town in the Manawatū. As a kid, watching the land and waters change so quickly had a real impact on me. Years later, studies from this event were foundation in my own research. It seemed significant that these events occurred only 20 years apart, both causing significant long term damage to the landscape of places I know and love.

When Gabrielle hit, I was working for LandWISE, alongside Dan Bloomer. We decided early on that in the regional recovery effort, it would be best to spend time focusing on research, I can say I wouldn't have been much help on a digger. Dan reached out to his network of scientists and other experts to try to work out how our organisation could support farmers and growers in their recovery. From there our involvement steadily increased, as we shared information, started talking to impacted folks, and designing monitoring projects. I'm not sure now who suggested that I focus on Cyclone Gabrielle for my thesis, it's a bit of a blurred timeline in my head now, so much happened so quickly. I know I am grateful to have been suggested this as a topic, and to have spent the last two years focused on soil recovery.

There is a long list of people I need to thank, for helping to make this research happen.

Firstly, none of this work would have happened without the engagement of impacted farmers and growers from across the country. These people took time out of their absolute worst days, to speak with me and share their stories. I have been so moved by the generosity of those who have shared their stories of survival, recovery and resilience. I will be forever inspired and forever grateful for this experience. I will never forget visiting a farm that had been totally inundated with sediment a few weeks after grass seed had been flown on. After weeks of utter terribleness, I remember seeing the first new shoot of grass, and it seemed like a real symbol of hope and of new beginnings.

To Dan and Phillipa, thank you for supporting my growth at LandWISE and giving me the space to work on my studies. I am particularly grateful to Dan for his commitment not only to my research, but also to the wider horticultural sector. Thank you to my colleagues who joined the conversation, helped plan this project, collect data, and discuss their own findings; Stephen Trolove, Eduardo Dias de Oliveria, David Sluter, Bryce McLoughlin, Bryan Devantier, Mike Dodd, Luke Posthuma, Mark Redshaw, Garth Eyles, Olivia Webster & Dirk Wallace. To Sally Anderson, thank you for championing the funding efforts, and ensuring that this and other projects could happen. The LandWISE Cyclone Recovery Project was largely funded by the Ministry for Primary Industries (MPI), with additional support from Vegetable Research and Innovation (VR&I) and the Foundation for Arable Research (FAR).

I am so appreciative of my supervisors Callum Rees, Lucy Burkitt and Alan Palmer for imparting their wisdom and providing support through this process, and to Alan for his commitment to digging holes in the mud. A special thanks to Alec Mackay not only for his involvement in sampling and ongoing contribution to the land, but also his support of my career from as far back as my days with Palmy Surf Club, some 15 years ago.

And then there are the people behind the scenes. Working and studying simultaneously is something very intense, and I am very grateful to my support crew. Mum, thank you for showing me strength and resilience in your own academic journey, you have taught me so much. Dad, thank you for watching my presentations and always giving me the encouragement I need. Thank you both for always believing in me. Hugh and Sarah, thanks for keeping me humble. Kate, thank you for always listening to my nonsense, and for cheering me on. To my dear friends who have also been here before, Holly, Raul and Sotiri, thank you for sharing your experiences of writing a thesis with me. And last but not least, thank you to my Mitchell, thanks for riding the rollercoaster with me. You have been my anchor in the storm; I could not have done any of this without you.

# Table of Contents

# Table of Figures

# Table of Tables

# Chapter 1

## 1. Introduction

### 1.1. Background

In February 2023, ex-tropical Cyclone Gabrielle moved over the North Island of New Zealand, leaving a trail of destruction in its wake (Stone et al., 2024). The severe weather event has been described as the worst to hit New Zealand in the last century (Boston Consulting Group, 2023), killing eleven people and causing an estimated total economic cost $14.5 billion (Wilson et al., 2023).

**Figure 1-1 Map of North Island of New Zealand showing the key impacted areas of Cyclone Gabrielle. Map retrieved from GNS Science (Heron, 2020).**

An estimated 300,000 landslides were triggered along the North Island's east coast resulting in large-scale sediment deposition on lowland floodplains (McMillan et al., 2023). River management networks were quickly overwhelmed with large volumes of water, sediment and debris. Hawke's Bay and Gisborne/Tairāwhiti were impacted by sediment deposition, with an estimated 12 million/m$^3$ of sediment deposited across Hawke's Bay alone (Morris, 2024). An estimated 5.7 million tonnes of soil and sediment was eroded in the Esk River catchment, with approximately 1.5 million tonnes deposited across the lower floodplain (McMillan et al., 2023).

The East Coast, Hawke's Bay and Gisborne (Poverty Bay) plains have extensive Highly Productive Land (HPL), defined as Land Use Capability (LUC) Classes 1 – 3 (Ministry for the Environment, 2024). This land is used to grow a range of crops, from high value annual crops, pipfruit, stone fruit and vineyards (Eyles, 2019). Ninety percent of rural land on the Heretaunga Plains is identified as HPL with a further seven percent of LUC Class 7 land also considered high value for viticulture (Bloomer, 2011). The Poverty Bay Flats are New Zealand's single largest area of high quality fertile soils (Gisborne District Council, 2020).

The impact of Cyclone Gabrielle on this HPL was considerable. Many growers were just weeks away from harvest, and lost annual crops, orchards and vineyards, as well as stock and infrastructure. It is estimated that the cost to Hawke's Bay horticultural sector alone was $1.4 billion, related to the loss of crops and ability to produce, impacting around 35% of local crop production value (Boston Consulting Group, 2023). In the days, weeks, and months after Cyclone Gabrielle, farmers and growers needed information to support decision making for recovery and to identify pathways for restoring their livelihoods and productive capacity.

This prompted a collaborative industry project, led by LandWISE Inc., and this master's research working with a large group of organisations to compile all previous knowledge on flood recovery and help disseminate the information to growers. Initial funding was provided by the Ministry of Primary Industries, with additional funding from the Vegetable Research and Innovation Board. Despite the east coast of the North Island being impacted by several flooding events over the last 50 years, studies into the recovery of sediment laden land have mostly focused on pastoral production (Litherland et al., 2007). Only limited work has been completed on the recovery of high value horticultural or vegetable cropping land and so advice to landowners impacted by Cyclone Gabrielle was largely based on pastoral recovery. The main message was to plant annual ryegrass as soon as possible to drive evapotranspiration, dry the sediment out, begin building topsoil and allow time to establish a plan for moving forward.

This Master's research was initiated understand the impact of Cyclone Gabrielle on the whenua and on high value horticultural systems, and their initial recovery phase, through data collection and analysis related to the application different management practices. This work aims to compile and increase the visibility of prior knowledge and add information specific to the recovery of high value horticultural and vegetable cropping land. The importance of this work is further highlighted by the impacts of climate change, which are expected to increase the occurrence and intensity of natural hazard events around New Zealand (Renwick et al., 2016).

Data has been captured to better understand sediment physical, chemical and biological characteristics and recognise what these characteristics might mean for ongoing soil management. The methods used to analyse sediment are widely used across the primary sector, and can be repeated by researchers, or those farming the land. A 2023 baseline study was conducted across Hawke's Bay, Gisborne and Northland with sediment sampling undertaken to represent different catchments, positions in the landscape, and a range of land use types. The study was extended in 2024 to capture changes to sediment and soil over time on a small number of sites previously used for cropping in Hawke's Bay.

## 1.2. Objectives and thesis outline

The aim of this research was to add to the body of literature published related to flood sediment and soil recovery on highly productive land in New Zealand, through data collection and analysis. The overarching research question of this study is 'how do extreme flood events and subsequent sediment deposition affect highly productive land (HPL) used for high value horticultural and vegetable cropping systems, in New Zealand'. Data collected initially had the purpose of improving collective understanding of the immediate impact of sediment deposition to high value soils and eventually extended to understanding short term changes to sediment and soil.

There are four main thesis objectives:

1. Compile and review existing data and knowledge on flood impacts and recovery on highly productive land and identifying gaps in our knowledge.
2. Conduct regional baseline sediment and soil sampling and analysis of areas impacted by the flooding and sedimentation associated with Cyclone Gabrielle on highly productive land under a range of land uses.
3. Track a small subset of impacted properties on highly productive land under a range of land uses over the 12 months following the cyclone to quantify the influence of sediment characteristics and management on key soil functions.
4. Discuss lessons from this research and outline recommendations for future research.

This thesis will be structured as a series of five chapters. Following this introductory chapter:

- Chapter 2: Setting the Scene and Literature Review
  Outlines the geological setting of the Heretaunga Plains and analyses existing studies on flood sediment deposition on lowlands in New Zealand through a literature review. This review includes historical records that date back to the 1930's as accounts of floods became more reliable. Through this review knowledge gaps are identified and discussed.
- Chapter 3: Baseline Sampling
  Presents a baseline sediment sampling study, including background, methodology, results and discussion. This chapter is a revised version of a published professional report, presenting findings of the initial project to MPI. This report involved the contribution of other researchers from a range of organisations. As this is a full report, Chapter 3 contains an appendix. My involvement in this project included the coordination of data collection across Northland, Gisborne, Wairoa and Hawke's Bay and physical data collection in Hawke's Bay. I was the lead author of the final report; the contribution of other researchers is highlighted within the Chapter.
- Chapter 4: Repeat Sampling
  Building on Chapter 3, Chapter 4 presents the analysis of further soil and sediment data collected on a subset of paired sites in Hawke's Bay. This data includes soil management information provided by growers, as to what actions were completed after the cyclone. Methods and results are presented and discussed. This data was collected for a LandWISE project, where I was permitted to use the dataset for my own research purposes. I collected the majority of the data, with the support of other LandWISE staff. Supporting data can be found in the Chapter 4 Appendix.
- Chapter 5: Discussion
  Discusses the implications of this research, and what lessons can be drawn in relation to future recovery efforts. Provides a summary of research findings, recommendations and future research opportunities.

# Chapter 2

## 2. Literature Review

"The rivers flowing over the Plains are the bearers of Nature's richest gifts and it is folly to send into the ocean the millions of tons of valuable soil brought down. Settlers on the areas subject to floods should build their houses on stilts above the flood level, plant trees to intercept the flood and let the floods raise the level of their land".

- Mr. H. Tregelles, to the Philosophical Institute 15 September, 1898 (Mooney, 1973)

### 2.1. Introduction

Following Cyclone Gabrielle in February 2023, growers in Hawke's Bay, Gisborne and Northland needed information to support decision-making for recovery and to identify pathways for restoring their livelihoods and productive capacity. This prompted a LandWISE project and this master's research. We worked with a range of industry organisations to compile all previous knowledge on flood recovery and help disseminate the information to growers. Advice was largely based on pastoral recovery experiences because little work has been completed on the recovery of high value horticultural or vegetable cropping land. This thesis reports research conducted to address this knowledge gap by tracking a range of land management practices across different catchments, land use and soil types. It ensures the knowledge gained from the Cyclone Gabrielle recovery is not lost but can help with future decision making and building resiliency in the face of climate change.

This chapter provides context for the data chapters of this thesis. Part 1 outlines the geological setting of Hawke's Bay, regional Land Use Capability (LUC), and early flood management and describes the affected catchments. Part 2 reviews four past flood events used to help inform farmers and growers impacted by Cyclone Gabrielle. The review also documents efforts made to uncover lesser-known resources related to sediment deposition on flood plains in New Zealand. This work was conducted over more than a year and included searches through the Massey University Library, National Library of New Zealand, online journal article databases and archives, personal collections, industry reports and regional council databases, to fill the gaps in our sediment remediation knowledge. Useful resources relating to flood impact were found, however they did not add significantly to the information available immediately after Cyclone Gabrielle. These resources were not easily accessible, and therefore not readily available when needed. Other studies relevant to this thesis may have been completed, but either were not published or were not catalogued or digitised and could not be located.

In section 2.9 previous significant flood events are discussed. The 1938 Esk Valley flood was a catalyst for change in land and water management in New Zealand due to its unmitigated impact to the Esk Valley and Tutira districts. A review of studies from the 1948 – 1950 Gisborne floods, Cyclone Bola in 1988 and the 2004 southern North Island Storm shows how each flood has informed subsequent studies and post-flood management. The impact of Cyclone Gabrielle in 2023, and relevant subsequent studies are discussed 2.11. Included in 2.12 are two important reviews of historic flood damage, which are important to understanding the repetitive nature of storm impact. These storms had large social and physical impacts and required significant response from local and central government.

## 2.2. Geological setting

The 300 km2 Heretaunga Plains in the eastern North Island of New Zealand (Figure 2-1) are part of an alluvial plain built up by sediment deposition filling the Heretaunga marine basin over the last 250,000 years (Dravid & Brown, 1997; Griffiths, 2001; Lee et al. 2014). The deposits include material transported by air (loess and volcanic ash) and water (sand through to pebbles and boulders of greywacke and sandstone). The area is subject to active geological processes, including landscape altering earthquakes, such as the 1931 Napier earthquake (Lee et al., 2014). Additionally, some of the highest national rainfall intensities have been recorded in the ranges of Hawke's Bay (Dravid & Brown, 1997). Major flooding has been recorded in the region for well over a century, with accounts of severe flooding recorded as early as the late 1860's (Dravid & Brown, 1997).

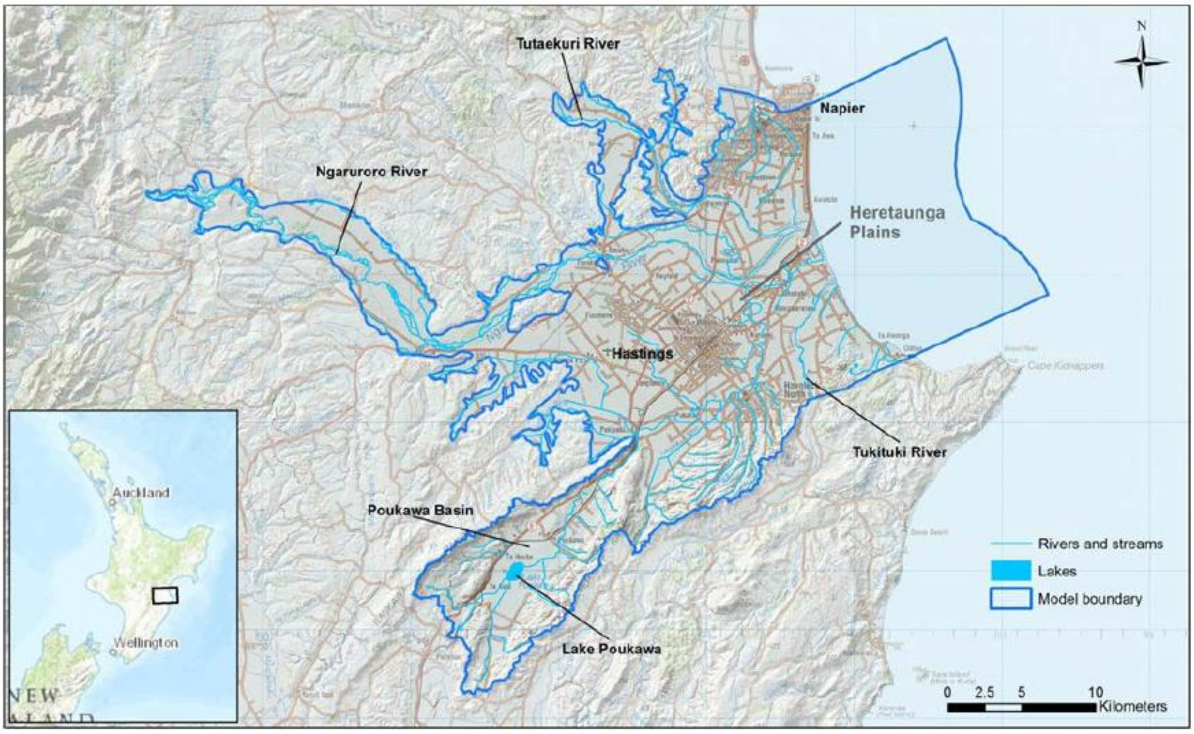


Figure 2-1 Location of the Heretaunga Plains, map from Lee et al. (2014).

The sediment deposits of the Heretaunga Plains, including that deposited in Cyclone Gabrielle, came from the western and northern ranges, carried by three major rivers: the Tukituki River which flows from the Ruahine Ranges, the Ngaruroro River which flows through the Kaweka and Ruahine ranges, and the Tūtaekurī River which flows from the Kaweka Ranges (Figure 2-1). The smaller Esk River, with headwaters in the Maungaharuru Range, has also contributed to the infill of the Heretaunga Basin (Griffiths, 2001). The Ngaruroro River carried the most sediment and largely filled the central and southern parts of the basin, with the Tūtaekurī and Esk Rivers depositing sediment in the northern area. The Tukituki River, to the south, filled the south-east of the basin. The rivers have changed their course many times, as a result of flooding, tectonic movement and, more recently, human intervention (Dravid & Brown, 1997). The Ngaruroro and Tūtaekurī Rivers converge near Clive. The rivers share a river mouth as a result of the 1931 earthquake.

During flooding events the rivers overflowed their banks and the eroded alluvial materials carried by the floodwater (greywacke and sandstone) were deposited. When a river floods, coarser sandy textured particles are typically deposited first, in the upper end of a catchment (Lower North Island Combined Provincial Federated Farmers Storm Group, 2007) or nearest the river, forming a levee

(Griffiths, 2001). Silt and clay particles are deposited downstream or further from the river as the velocity of the water slows (Griffiths, 2001). Figure 2-2 (Griffiths, 2001) provides an example of the distribution of sediment textures from a cross section of the Ngaruroro River.

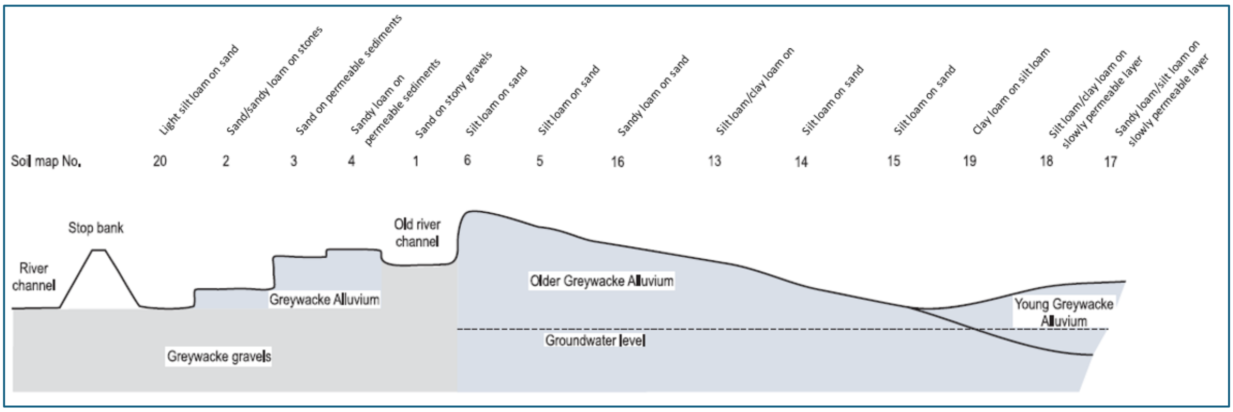


**Figure 2-2 Ngaruroro cross section showing soil types through river (Griffiths, 2001). Corresponding soil types added to figure for clarity.**

The Tūtaekurī, Ngaruroro and Tukituki Rivers all have their lower reaches confined by stopbanks to contain floodwater and protect the adjacent land from flooding. The stopbanks are part of the Heretaunga Plains Flood Control Scheme and are managed by the Hawke's Bay Regional Council (Hansen & Adye, 1999).

Griffiths (2001) notes that flooding on the Heretaunga Plains can bury topsoil with raw river sediment. The pre-existing topsoil pores can become filled with fine textured sediment, making the buried topsoil less permeable. This can create management issues related to drainage, soil compaction and potential rooting depth.

## 2.3. Tectonic activity

The two islands of New Zealand are located over the Pacific and Australasian tectonic plates. The plates collide east of the North Island, causing the subduction of the Pacific Plate, and the formation of the Hikurangi Trough. The Hikurangi trough is centred approximately 160km offshore of Napier (Dravid & Brown, 1997; Komar, 2010). The Hawke's Bay region has been subject to tectonic and geological activity as a result of the intersection (Figure 2-3). There is both collision and horizontal movement between the plates, which has given rise to the complex topography of the Hawke's Bay Region (Komar, 2010).

The tectonic movements in the region have had significant influence on river sediment sources and river courses in the last 2 million years (Dravid & Brown, 1997). The Ruahine Range has risen rapidly, estimated to have lifted 2000 m over 1 million years. This has been offset by erosion due to the high levels of rainfall experienced on the East Coast, so the highest point is approximately 1700 m today. The erosion of the mountain ranges provides large volumes of material derived from Mesozoic greywacke rocks, transported by rivers to the coastal environment (Komar, 2010).

Tectonic movements within the region have resulted in changes in elevation of the Heretaunga Plains. For at least the last 4000 years, the trend has been for earthquakes resulting in land subsidence. This was reversed in 1931 when the Napier earthquake caused a rapid uplift of the Ahuriri Lagoon (Komar, 2010). More recent research by Delano et al. (2023) has modelled that in the last 7000 years there have been eight rapid subsidence events, and two rapid uplift events at Ahuriri Lagoon. This is relevant to the landscape of Hawke's Bay, as subsidence earthquakes along the coastline makes land more susceptible to flooding, as well as other issues like sea level rise (Delano et al., 2023).

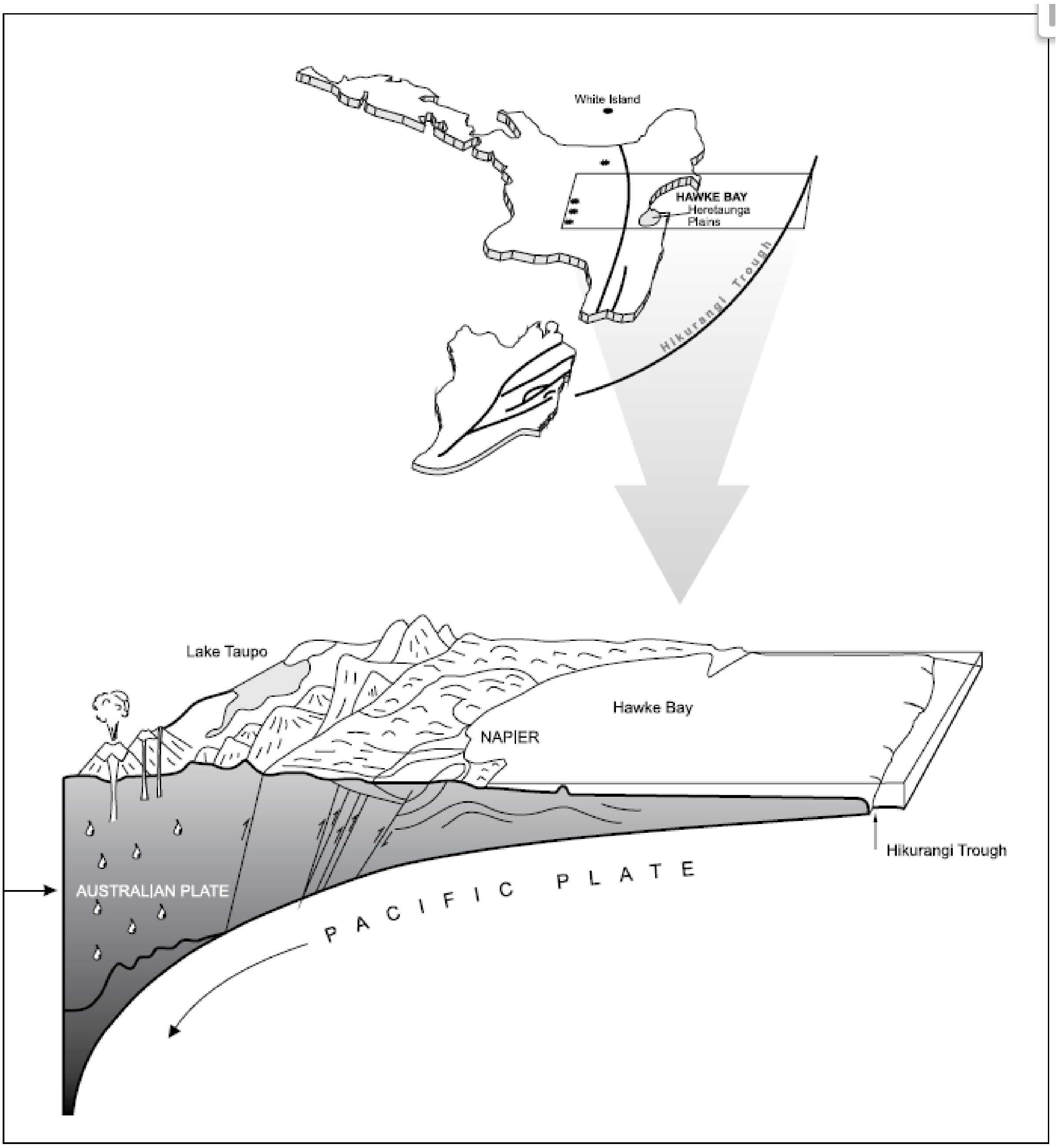


**Figure 2-3 Plate tectonics interpretation. Image from Heretaunga Plains Groundwater Study (Dravid and Brown, 1997)**

### 2.3.1. 1931 Napier earthquake

The Napier earthquake was geologically significant event to the Hawke's Bay region. The 7.8 magnitude earthquake which occurred in February 1931, impacted the cities of Napier and Hastings. The size of the earthquake indicated that this part of the east coast is one of the more seismically active areas in

New Zealand. The earthquake caused significant land surface deformation, in particular, land uplift near Napier. An area approximately 90 km long and 15 km wide domed upward. Land uplift was as much as 2.7 m at the mouth of the Aropaoanui River north of Napier (Hull, 1990; Balks & Zabowski, 2016). Prior to the earthquake, the Ahuriri Lagoon near Napier had the Esk River flow through it from the north and the Tūtaekurī River flow in from the south.

The lagoon, formerly a tidal mudflat, was uplifted approximately 1 m at the western margin, and 1.5 m at the eastern end of the lagoon, now forming part of the peninsular (see Figure 2-4) (Department of Survey and Land Information, 1989). The lagoon was observed to rapidly drain soon after the quake, and approximately 1,300 ha of new land was created (Dravid & Brown, 1997). The Tūtaekurī River which had flowed into the southern end of the lagoon, changed course to bypass the lagoon, and now flows into the see near Awatoto. Rather than discharging into the lagoon, the Esk River changed course and now flows directly into the sea near Whirinaki (Dravid & Brown, 1997).

**Figure 2-4 Maps of Napier before and after the 1931 earthquake (1865 vs 1965). Maps retrieved from NZ Department of Survey and Land Information (1989)**

## 2.4. Climatic influences

The weather in Hawke's Bay is to a large extent influenced by the mountain ranges to the west (Chappell, 2013). Hawke's Bay experiences a large regional variation in rainfall, with annual rainfall often over 2000 mm in the ranges but typically less than 800 mm per year on the Heretaunga and Takapau Plains (Chappell, 2013). Despite Hawke's Bay's typically warm summer temperatures, mild winters and low average annual rainfall, the region is prone to extreme weather events and has some of New Zealand's highest recorded rainfall intensities (Dravid & Brown, 1997).

Hawke’s Bay is impacted by topical and ex-tropical cyclones, which originate off the East Coast of New Zealand in the Pacific Ocean, bringing strong winds and heavy rain. Recent extreme weather events with intense rainfall include Cyclone Bola in 1988 (Chappell, 2013) and Cyclone Gabrielle in 2023. The intensity of cyclonic events with high rainfalls experienced in the inland mountain ranges, combined with the region’s topography and geology, culminates in erosion of unstable, steep mountainous regions and hill country and results in high flood discharges (Dravid & Brown, 1997).

Cowie (1957) provided descriptions of the Hawke’s Bay landscape and main rivers, as well as 91 flood events that occurred in the region in the 30 year period between 24th January 1923 and 6th July 1953. Given the region’s geographic position, it has often been an area impacted by flooding. Of particular note is the 23-25th April 1938 Esk Valley Floods.

## 2.5. Land Use Capability (LUC)

In New Zealand, land is classified into eight land-use capability (LUC) classes, based on the properties of the land and its capacity for ‘long-term sustainable production’ (Lynn et al., 2009). Productive capacity is influenced by physical qualities of the land, soil type and the environment. Land classed as LUC 1 – 4 is suitable for arable cropping and horticulture, pastoral grazing and forestry. LUC 5 – 7 are not suitable for cropping, however, can be used for pastoral production, tree crops and forestry. LUC 8 is unsuitable for grazing and forestry and is best used as conservation land (Lynn et al., 2009).

Highly Productive Land (HPL) is the most versatile land used for primary production, located in a favourable climate and has soils suitable for food and fibre production, with few limitations to production (Ministry for the Environment, 2024). HPL includes LUC 1 – 3, which makes up 14.4% of New Zealand’s total land area (0.7% LUC 1; 4.5% LUC 2; 9.2% LUC 3) (Lynn et al., 2009). New Zealand has approximately 3,830,000 ha of highly productive land (HPL).

Approximately 90 % of the Heretaunga Plains is classed as LUC 1 – 3, with a further 7% classed as LUC 7 which is high value for viticultural production (Bloomer, 2011). Of the whole Hawke’s Bay region, HPL accounts for only 12.8% of the total land area, with fruit and vegetable production occupying approximately 14,550 ha of this land area (Horticulture New Zealand, 2024). Given the position of this highly productive land in the landscape, within the lower reaches of the region’s major rivers, this highly productive land is at risk of flooding.

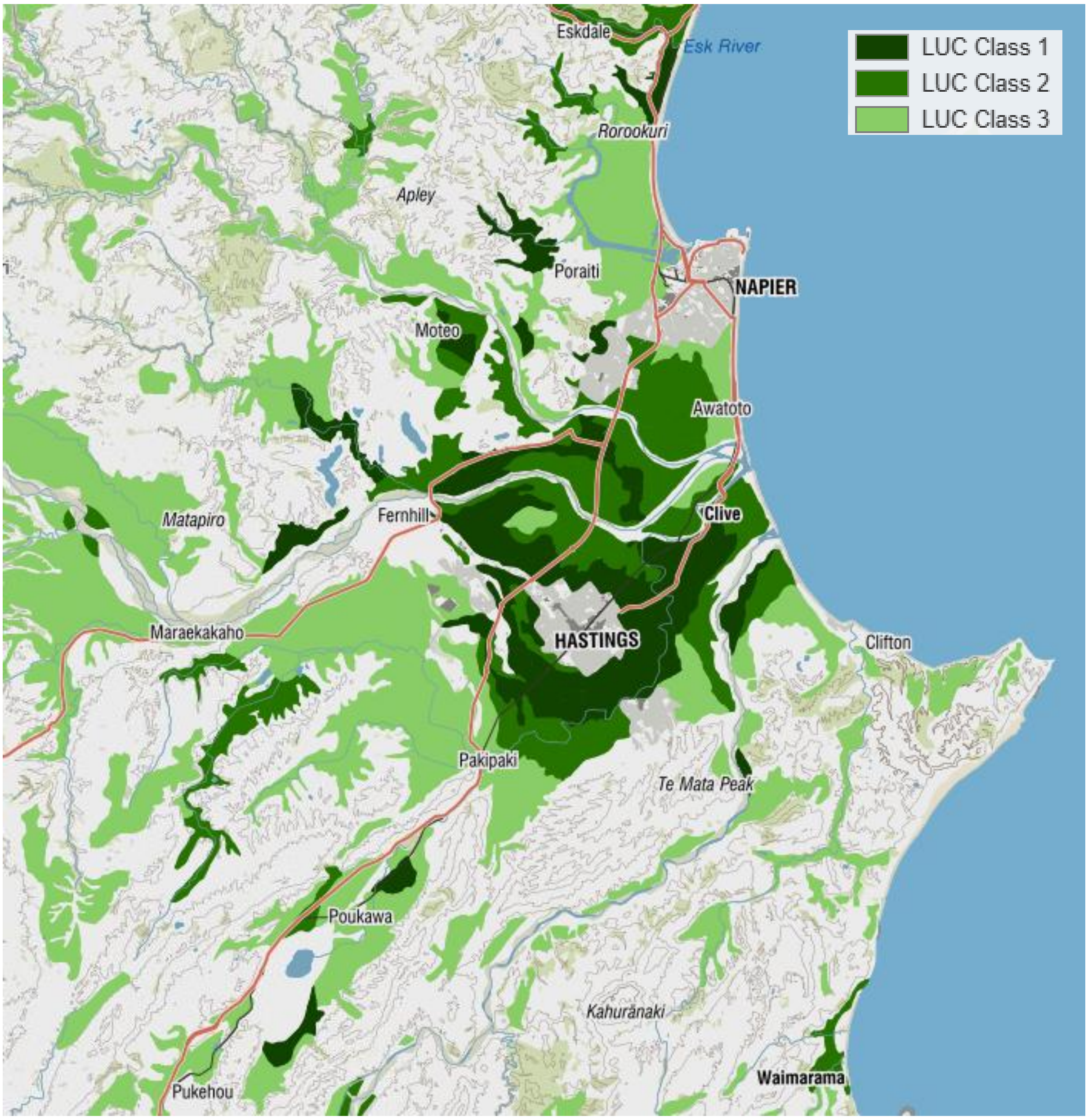


**Figure 2-5 Map of Highly Productive Land (LUC 1 - 3) for wider Heretaunga Plains area 1:250,000. Base map from LINZ Data Services, used by Landcare Research (2023). Licensed for reuse under the CC BY 4.0 licence.**

## 2.6. Human impacts

### *2.6.1.1. Land clearance*

Early settlers began clearing land in the 1800s to establish pastoral agriculture (Basher, 2013; Marden et al., 2018). This was done by slashing the thick undergrowth of the New Zealand rainforest and leaving it to dry for a season or two before setting it on fire. In this manner, vast tracts of land were cleared, altering slope stability, effecting both hydrological and mechanical mechanisms related to mass soil movement and increasing the risk of soil erosion as a result.

Hydrology is influenced by processes like evapotranspiration, drying the soil out and drawing the water table down, as well as rainfall interception, which reduces the amount of water available for infiltration. This reduces the amount and velocity of runoff down slopes during high intensity rainfall events. Mechanically, trees under native forest are able to root down several metres and physically bind soil layers, acting as a reinforcing membrane or bracing in the soil (Marin & Osorio, 2017). Pasture, on the other hand, typically roots to a much shallower depth, offering less physical protection to soil (Basher, 2013).

Through these mechanisms, tall, closed canopy woody vegetation typically reduces erosion by 70-90% during storms (Basher, 2013). Where woody vegetation has been replaced with pastoral land, higher amounts of surface runoff occur, increasing water velocity, giving it more erosive power and as a result, increases flood risk for downstream areas. Higher rates of erosion cause increased sedimentation, building up the bed of the river and further exacerbating flood risk.

#### *2.6.1.2. Early flood protection*

In the late 1860s it was generally accepted that there was no hope of stopping floodwaters. In the upper reaches of river catchments, bush was cleared for the development of farmland, increasing soil erosion and sedimentation of Hawke's Bay's rivers. Storms and heavy rain came regularly, and floodwaters brought with them increasing volumes of sediment from the river catchments, depositing sediment downstream (Mooney, 1973). Early flood protection measures included the parliamentary Hawke's Bay and Marlborough Rivers Act in 1868, which allowed property owners to construct their own stopbanks. The Act was introduced as a result of the Ngaruroro River flooding in 1867, which deposited 30 – 50 cm of silt across the Heretaunga Plains. The passing of the Act was problematic as it caused property owners to divert water into neighbouring properties (Mooney, 1973; Dravid & Brown, 1997). For land owners, the priority of flood control was "a matter of keeping the waters off MY land, off MY district" (Mooney, 1973).

These issues led to development of more coordinated flood control schemes, and the updating of the Hawke's Bay Rivers Act in 1876 (Mooney, 1973). When the Hawke's Bay Country Council was established in 1876, local river control works were implemented, including willow plantings near Clive. Early willow plantings were used to prevent the encroachment of the Ngaruroro to its bank at Clive, by mooring willows by wire and stakes in the bank. It was hoped that the trees would root, and their leaves would induce sediment deposition to form a stable bank. In the following decade, the willows caused problems as they blocked river water passages in the Ngaruroro, becoming the 'willow nuisance' (Mooney, 1973).

In 1898, river boards were created for each of the main rivers, which were subsequently amalgamated in 1910 to form the Hawke's Bay Rivers Board. The Hawke's Bay Rivers Bill passed in 1929, which approved the Rivers Board to proceed with flood protection works, and some stopbanks were constructed. The 1931 Napier earthquake was another event triggering action for river control. In 1933, the Hawke's Bay Rivers board approved the river control schemes that would embank the Ngaruroro and Tūtaekurī Rivers along their entire course over the Plains. Work began in 1934 and was partly completed by 1940 (Dravid & Brown, 1997). The Tūtaekurī and Ngaruroro stopbanks were completed around 1975. After 1950, when the Hawke's Bay Catchment Board was instated, the first major job was stopbanking the lower Tukituki River, this scheme was completed in 1975 (Williams, 1985; Dravid & Brown, 1997).

Today, Hawke's Bay Regional Council provides 27 flood control and drainage schemes within the region, aimed at reducing the risk of flood and erosion damage. The Heretaunga Plains Flood Control Scheme (HPFCS) is a major scheme which includes the historic river plains of the Tūtaekurī, Ngaruroro and

Lower Tukituki Rivers, directly protecting approximately 39,000 ha of land. This scheme has evolved over 130 years, from the early river control efforts in the late 1800s to the current river management system. There are approximately 155 km of managed stopbanks and deflection banks. The Upper Tukituki River (which protects approximately 24,750 ha of productive land) and the Esk River are managed under their own flood control schemes (Hawke's Bay Regional Council, 2021a).

## 2.7. Catchments

### 2.7.1. Ngaruroro River

#### *2.7.1.1. River course*

The 160km Ngaruroro River is the largest river flowing over the Heretaunga Plains. The river has a catchment area of 2,500 km2, rising in the Kaimanawa Range and flowing through the Kaweka and Ruahine ranges (Dravid & Brown, 1997). In the upper reaches, the Ngaruroro river travels through Department of Conservation forested land before passing through farmed hill country to flow out over the plains at Whanawhana. Between Whanawhana and Maraekakaho (see Figure 2-6) the Ngaruroro River spreads to form a braid plain. Downstream of Maraekakaho, the river becomes increasingly constrained by flood bank infrastructure, transitioning into a single engineered channel system as it makes its way across the full width of the Heretaunga Plains, towards the coast and the river mouth near Clive (Newton, 2024).

The upper Ngaruroro River catchment is a highly faulted, tectonically active and geologically complex area of steepland. Greywacke material found in the catchment is of the Jurassic and Triassic period and consists of dark blue/grey greywacke, sandstone, argillite or a combination of these rock types. The river initially flows through valleys recently infilled with volcanic ignimbrite deposits and pumice alluvium from the Taupō eruption approximately 2000 years ago (Williams, 1987). The river flows through greywacke mountains and the rugged greywacke steepland of the Ngaruroro Gorge (Hawke's Bay Regional Council, 2018d). The gravel bed material of the river originates from large erosion scars within the steepland (Wallis, 1966).

The Ngaruroro River contributed to the development of the Heretaunga Plains as material was deposited within the river channel. The Ngaruroro River naturally aggrades as it carries its gravel bed load across the Heretaunga Plains (Williams, 1987). The plains have been formed by the river breaking its banks and depositing its bed load as large scale fans. Over time, the Ngaruroro has often changed course to find more advantageous routes to the sea (Lee et al., 2014).

#### *2.7.1.2. Cultural significance*

Both the upper and lower Ngaruroro River hold cultural and spiritual significance to Māori, particularly for people of Heretaunga Tamatea. Present in the area are taonga including nohoanga (settlements) and urupā (burial places) as well as being home to a wide range of fish species valued by Māori as māhinga kai. In addition, the headwaters are recognised as a wilderness trout fishery, valued for its recreational fishing (Hawke's Bay Regional Council, 2018d).

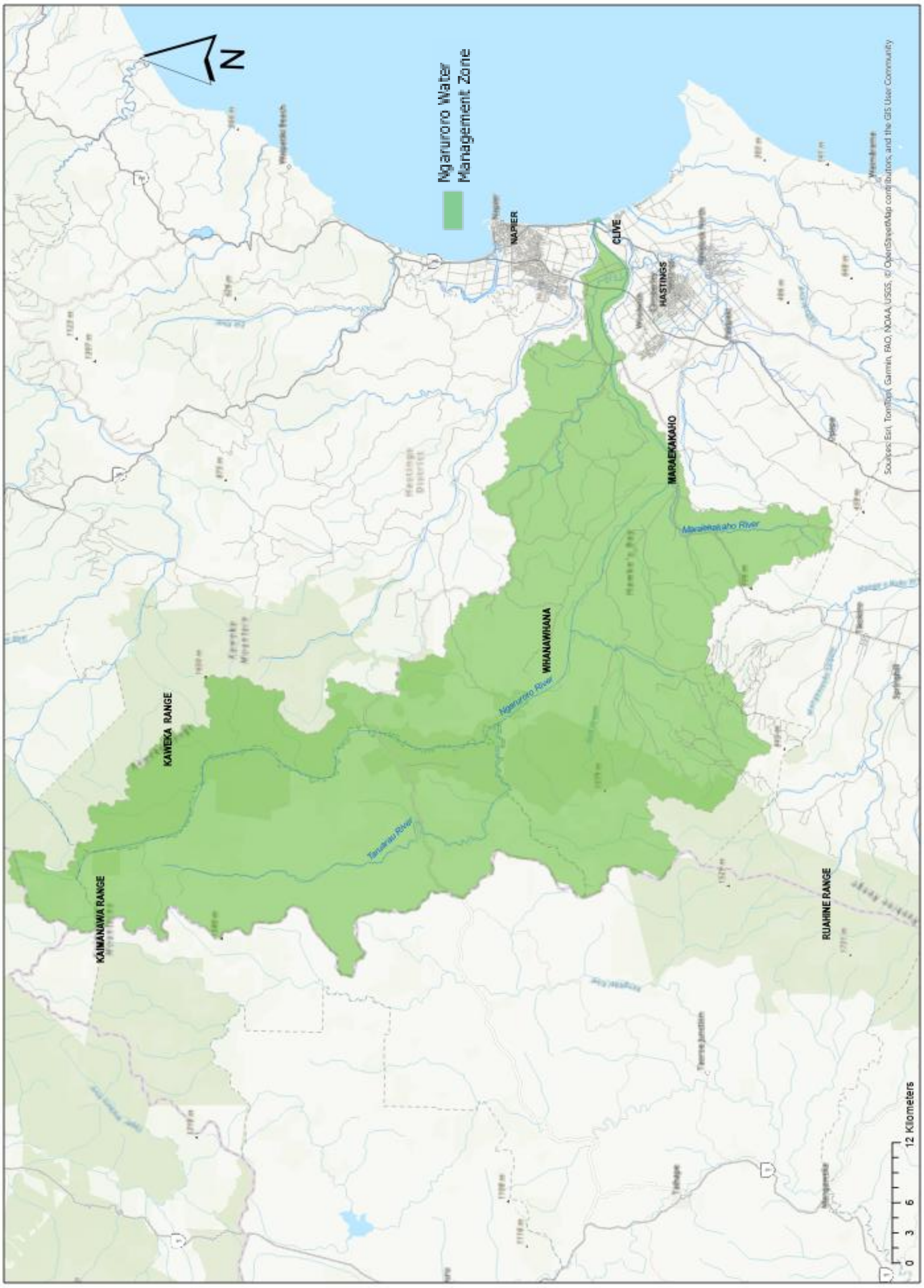


Figure 2-6 Ngaruroro Water Management Zone, featuring key landmarks (Simpson, 2018).

### 2.7.1.3. Land use

Pre-European arrival, the native vegetation of the Ngaruroro catchment was forest, scrubland and tussock plains in the mountain areas, and largely bracken and scrub on the lower hill country. Merino sheep farming began in the 1870s, developing into the current land pattern seen today by 1900.

Land use in the hill country today is predominantly pastoral grazing under private ownership. Farming becomes more intensive towards the coast where high value horticulture, arable and vegetable cropping takes advantage of the wide open floodplain with productive soils (Hawke's Bay Regional Council, 2018a).

Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 2-7 Map of Hastings showing location of the Awanui and Karamu streams (Ngaruroro river channel prior to 1867) (Simpson, 2018).

#### 2.7.1.4. *History of flooding*

The most significant flood on record was in 1867 when the Ngaruroro River broke its banks near Fernhill, depositing sediment across much of the plains (0.3 – 0.5 m deep) (Dravid & Brown, 1997). This was a significant event as the river changed its course to the north of Hastings, where it still flows today (Figure 2-6). The Awanui and Karamu Streams now flow in the old stream bed of the Ngaruroro River (Figure 2-7) (Dravid & Brown, 1997).

### 2.7.2. Tūtaekurī River

#### 2.7.2.1. *River course*

The main headwaters of the Tūtaekurī River are found in the south-eastern Kaweka Ranges, with a catchment area of 840 km2 (Figure 2-8) (Kolt, 2012). The Tūtaekurī River is approximately 100 km long and travels from the headwaters, through steep or rolling hills formed from marine sedimentary rocks from the early Pleistocene, before it flows over the Heretaunga Plains to the coast (Cunningham, 1969; Hawke's Bay Regional Council, 2018c).

The upper reaches of the catchment in the Kaweka Range have large areas of bare soil and rock. Establishment of native flora is impeded by climatic conditions including frost, rain and wind (Cunningham, 1969). One of the main tributaries is the Mangone Stream, with its headwaters in the sedimentary rock of the Te Waka Range. The predominant rock types in the south and east of the catchment headwaters are Mesozoic greywackes (Urewera and Kaweka greywacke) and tertiary sedimentary rocks, made up of sands, silts and limestones. The area also has deposits of material from volcanic ash showers (Cunningham, 1968).

#### 2.7.2.2. *Cultural significance*

The Tūtaekurī River is a culturally and spiritually significant waterway for many Ngāti Kahungunu marae and hapu. The river and its associated floodplain and swamps have high cultural value and have historically provided important resources for the different iwi and hapu connected to the river. In addition, the river has a large number of registered archaeological sites along its banks (Hawke's Bay Regional Council, 2018c).

#### 2.7.2.3. *Land use*

Pre-European vegetation included beech and podocarp forests, with large areas of scrubland and fern land. Bracken was an important component to the ground cover of the area. European ownership of the upper catchment began when land was purchased by the Crown in 1859. The land was subsequently leased for pastoral farming. Deliberate burning for grazing is recorded from 1878. Making room for sheep, bracken was destroyed by crushing and burning and was replaced by pasture.

By the 1960s, the headwaters of the river were being described as having suffered severe accelerated erosion, which had been occurring for the previous 60 years (Cunningham, 1968, 1969). Eroded material transported downstream during flood events is deposited when stream flow slows. This is noted as being significant in the lower reaches of the river as it approaches the sea. The river has a tendency for aggradation and the development of an alluvial fan. Destruction of native vegetation for grazing is considered a main contributor to the increased rate of erosion in the Tūtaekurī River catchment. While the natural process of aggradation cannot be stopped, the rapid aggradation of the lower portion of the river can be slowed through adequate vegetative cover in the upper catchment of the river (Cunningham, 1969).

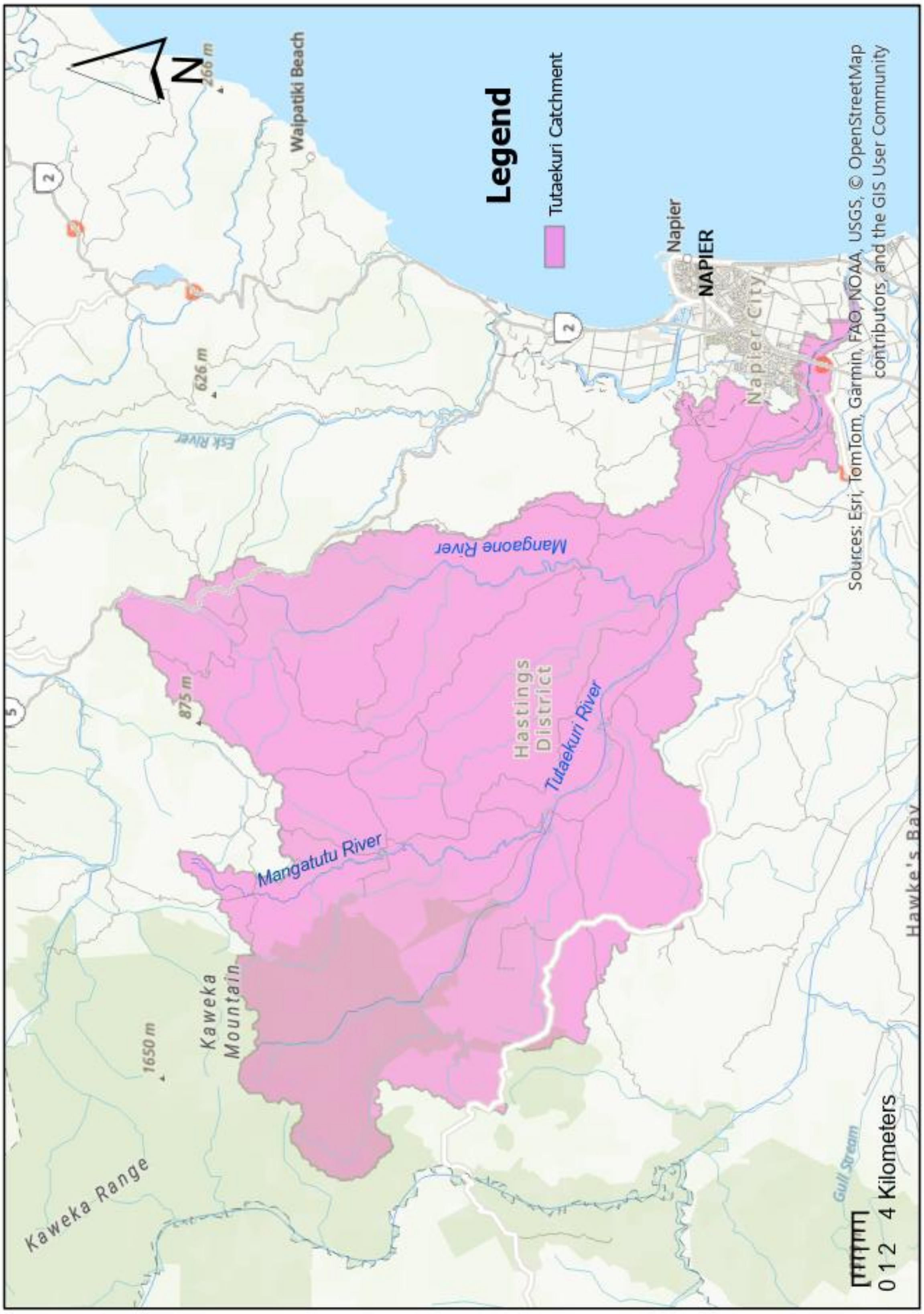


**Figure 2-8 Tūtaekurī River water quantity management zone (HBRC 2018)**

#### *2.7.2.4. History of flooding*

The Tukituki River is prone to flooding, to protect the developed lowlands, the river is now confined by stopbanks for most of its passage across the plains. The biggest flooding events are attributed to rainfall from cyclonic events in summer and autumn (Cunningham, 1969). Similar to the Ngaruroro, rainfall in the Tūtaekurī catchment in 1867 caused flooding on much of the plains (Dravid & Brown, 1997). After the 1931 earthquake, and the uplift of what was the Ahuriri Lagoon, the Tūtaekurī River was diverted to meet the sea just north of Clive. The Hawke's Bay Catchment Board carried out a programme in the 1960s to improve flood protection for the Tūtaekurī River. This included redesign of the levee banks to cope with greater water flow and the diversion of the river mouth to an outlet shared with the Ngaruroro River near Clive (Cunningham, 1969).

### 2.7.3. Tukituki River

#### *2.7.3.1. River course*

The Tukituki River is a large, braided river system which flows over the Ruataniwha Plains from the headwaters in the Ruahine Ranges and across the Heretaunga Plains, before it enters Hawke Bay (Figure 2-9). The main tributaries are the Waipawa, Makaretu and Tukipo Rivers (Hawke's Bay Regional Council, 2018b). The Tukituki catchment area is 2,473 km2 and is both geographically and topographically diverse (Figure 2-9). The region is tectonically active, influenced by six major fault lines (Ludecke, 1988). The Tukituki River takes a relatively short course across one side of the Heretaunga Plains. It is a major supplier of gravels to the coastal beach systems, ensuring the gravel barrier between the coastline and the Heretaunga Plains (Williams, 1987).

The Ruahine Range is formed predominantly from greywacke and argillite rock. These rock types originate from thick deposits of mud and sand in deep ocean trenches. The emergence of the Ruahine Range above sea level happened in the Pleistocene era (500,000 years ago) (Ludecke, 1988). The Ruahine Ranges are prone to erosion, due to constant freeze and thaw cycles during the winter, which breaks up already shattered greywacke base rock. Intense rainfall through the year carries away this material. High rainfall patterns typically occur in the winter and spring, with more extreme floods occurring in early autumn as a result of ex-tropical cyclones reaching New Zealand (Williams, 1985).

The Ruataniwha Plains formed over 200,000 years from the infill of a basin. Parent material of the plains is alluvial greywacke from the Ruahine Ranges, ash and loess from Central North Island volcanic eruptions, and minor deposits of sandstone and mudstone (Griffiths, 2004). The Ruataniwha Plains have developed by a process of river channel aggradation and river courses changing over time.

### *2.7.3.2. Cultural significance*

The Tukituki River has cultural and spiritual significance for the people of Heretaunga Tamatea, and the river itself is integral to the web of whakapapa connections shared by local hapū. The river is home to many fish species and is a significant area for the practice of mahinga kai. The Tukituki river is

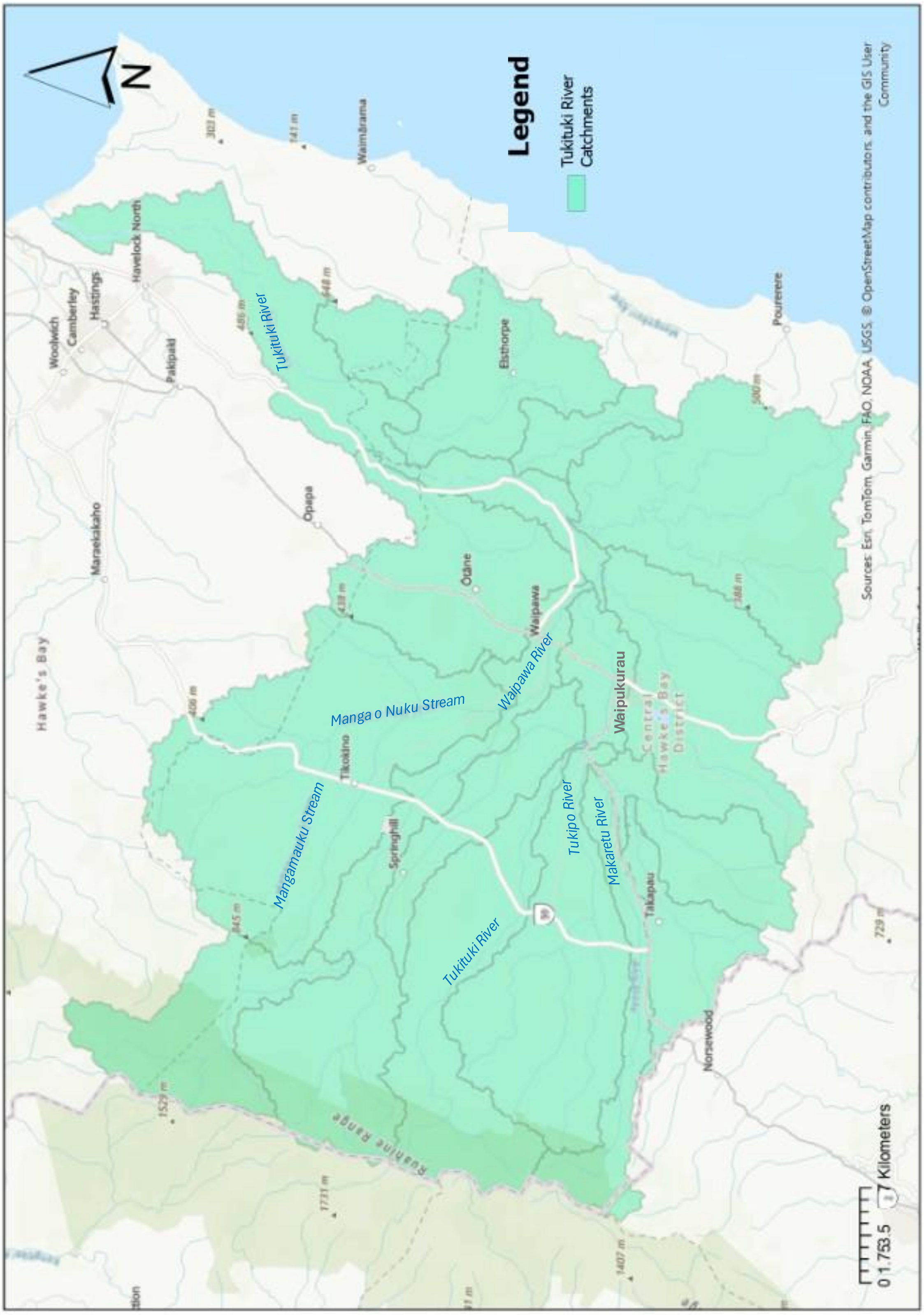


Figure 2-9 Tukituki Catchment Map, featuring key rivers (Hawke's Bay Regional Council, 2022).

identified as a Significant Conservation Area (SCA) due to the presence of wildlife and native fish (Hawke's Bay Regional Council, 2018b).

#### *2.7.3.3. Land use*

Prior to 1870, the forests of the Ruahine Range were almost uninfluenced by human or introduced animal activity. After Europeans settled, indigenous native forest with dense undergrowth was cleared on both sides of the range through burning, as land use changed from forest to pasture where sheep and cattle were grazed (Cunningham, 1979; Fuller et al., 2016). From the 1920s, the introduction of mammalian species including possums, deer, pigs and goats caused significant damage to the shrub tier of the forest. Ferns, mosses and humus were lost from the forest floor and defoliation, death and collapse of trees occurred in the forest canopy. In the 50 years from 1920 to 1970, there was reduction or elimination of forest understory, widespread collapse of the former rata-kamahi forest and increased frequency of slips (Cunningham, 1979).

When settlers first arrived, the river was deep enough to charter barges up river to the settlement of Waipawa. Over time, erosion and resulting sediment deposition have rendered the river too shallow (Dravid & Brown, 1997) due to the high volumes of gravel that enter the river in the Ruahine Ranges (Wilding & Waldron, 2012). This aggradation was ascribed to deforestation of the foot slopes of the Ruahine Range (Fuller et al., 2016).

#### *2.7.3.4. History of flooding*

A relatively recent landmark event related to the Tukituki River flooding was tropical Cyclone Alison (1975), which impacted the North Island of New Zealand, causing widespread flooding in Central Hawke's Bay (Fuller et al., 2016). Slipping occurred in the Ruahine Ranges, even in areas that were well forested, and a large amount of soil and parent material was deposited in the upper channels and basins (Grant, 1982). In the 1970s, intensive research of catchments in the southern Ruahine Range was conducted in response to significant stream aggradation occurring, particularly in response to the aftermath of Cyclone Alison (Williams, 1985; Fuller et al., 2016). The Tukituki catchment was also impacted by the 2004 Southern North Island Storm, however to a lesser extent than the Manawatū Region (Goodier, 2004).

To maintain flood water capacity and minimise the impact of erosion on flood protection infrastructure, Hawke's Bay Regional Council uses gravel extraction and dry river beach and bar raking. Gravel extraction has been an effective way of maintaining or increasing the river capacity, reducing the risk of flood waters damaging properties near the river. From 2019, gravel extraction in the Tukituki River became more challenging due to the presence of Chilean needle grass, which poses a significant biosecurity risk to productive land in Hawke's Bay (McLean, 2024). In 2020, a hold was placed on gravel extraction from the Tukituki river, at its junction with the Waipawa River, creating challenges for flood control management (Marlborough Chilean Needle Grass Action Group, 2021). This disruption to gravel extraction reduced river channel capacity in the years just prior to Cyclone Gabrielle in 2023.

### 2.7.4. Esk River

#### *2.7.4.1. River course*

The Esk River is one of Hawke's Bay's smaller rivers, with a catchment area of just 252 km2 (Hawke's Bay Regional Council, 2021b). The river headwaters are located in the Maungaharuru Range, and the river mouth is located in Whirinaki, just north of Napier (Figure 2-10). The predominant rock type forming the Maungaharuru Ranges is greywacke, consisting of banded Tertiary sandstones and mudstone, most of which are Miocene in age. Limestone beds are also found in this sequence (Hastings District Council, 2003; Page, 1988). The predominant soil types are pumice and brown soils, as well as some allophanic soils (Hawke's Bay Regional Council, 2021b).

Before the 1931 earthquake, the Esk River discharged into the Ahuriri Lagoon, near Napier. The earthquake resulted in 1 m of uplift, resulting in the Esk River flowing directly into Hawke Bay opposite the Esk Valley, north of Bayview (Dravid & Brown, 1997). The Esk and Whirinaki Flood Control Scheme begins at the river mouth and extends to the confluence of the Mangakopikopiko River. While the lower reaches of the river are not confined by stopbanks, the river is actively managed. The Hawke's Bay Regional Council is responsible for this scheme which includes clearing the channel of woody debris from willows and other vegetation, and maintaining the willow buffers on the riverbanks (Hawke's Bay Independent Flood Review Pae Matawai Parawhenua, 2024).

#### *2.7.4.2. Cultural significance*

The Esk River is known to local Maungaharuru-Tangitū Hapū as Te Wai-o-Hingānga. The river holds significance to Hapū as a marker for the traditional boundary of the Hapū, and as a mahinga kai location (food gathering). Prior to the earthquake, before the uplift of the Ahuriri Lagoon, the river was an abundant food basket, which was drastically changed in 1931 (The Maungaharuru-Tangitū Hapū and The Trustees of the Maungaharuru-Tangitū Trust The Crown: Deed of Settlement Documents, 2015). The Esk River is a good quality habitat for much of its course, and is home to many species of native and exotic fish including whitebait, flounder and tuna (Ausseil et al., 2016).

#### *2.7.4.3. Land use*

The Esk River catchment is dominated by indigenous forest in the upper reaches, and pasture on steep to rolling hill country in the lower reaches. The catchment land cover is predominantly high producing exotic farmland (48%), plantation forestry (33%) and native forest (14%) (Ausseil et al., 2016). Since the arrival of Europeans and the clearance of native forest, the rate of erosion and hillslope sediment load in the waterway is estimated to have increased threefold.

#### *2.7.4.4. History of flooding*

The Esk catchment is prone to erosion, with an average sediment yield of 682 tonnes/km2 per year (Hawke's Bay Regional Council, 2021b). The Esk Valley is susceptible to flooding, and risk of high sediment loading in floodwaters due to the soft marine sediments found in the upper reaches of the catchment (Leith, 2003). As there are no stopbanks within the Esk River Flood Control Scheme (established 1996), any flood over a 2-year return period will cause flooding.

Prior to Cyclone Gabrielle (2023), the notable and recorded flood events of the Esk River were the 1924 flood event, the devastating ANZAC weekend flood of 1938, Cyclone Bola in 1988, and more recently, a flood which damaged 80 homes in 2018 (Pocock, 2023).

**Figure 2-10 Esk River Catchment Map, featuring key rivers (Hawke's Bay Regional Council, 2022).**

## 2.8. Summary of geological setting

Hawke's Bay's unique combination of geological features and tectonic activities makes the mountainous and steep hill country areas of the main river catchments; the Ruahine, Kaweka, Kaimanawa and Maungaharuru Ranges, naturally susceptible to erosion. The arrival of European settlers and subsequent clearing of land for farming, and the introduction of animals like deer, has destroyed large areas of native ground cover, further destabilising the upper reaches of the river catchments.

The ranges are subject to high annual rainfall events, as high as 2000 mm in places, which causes this erodible material to enter Hawke's Bays major rivers and tributaries. The region is exposed to cyclonic events which originate off the east coast of New Zealand in the Pacific, these extreme events bring high winds and intense rainfall, which exacerbates the rate of erosion in the upper reaches of the river catchments.

Flood events have occurred throughout history, and the fertile Heretaunga Plains are the result of 250,000 years of sediment deposition into the Heretaunga Basin. The plains have a high proportion of Highly Productive Land (HPL), LUC 1 – 3, which is used for the production of high value fruit and vegetable crops. Flood protection schemes have been implemented to protect the cities of Hastings and Napier, and the regions productive land from destructive floodwaters. With the exception of the Esk River, all other rivers highlighted have stopbank infrastructure guiding their course across the Heretaunga Plains. This makes the Esk Valley perhaps one of the most vulnerable areas in the region.

Understanding the geological setting of the region, as well as weather patterns and the influence of human intervention aids in predicting flood risk and helps to contextualise the impact of flood events.

## 2.9. Significant North Island flood events

This section describes four major North Island storm events and reviews the reports that were produced in their aftermath.

### 2.9.1. 1938 Esk Valley Flood

McCaskill (1973) described the ANZAC Day 1938 Esk Valley flood as a landmark event which led to subsequent decades of soil conservation efforts in New Zealand. It was the second extreme rainfall event to impact the East Coast that autumn, just two months after a period of intense rainfall hit the Poverty Bay area causing significant slipping, washouts and damage on farms (McCaskill, 1973).

Over the three day period, 23 – 25th April 1938, prolonged heavy rain impacted much of the East Coast. Puketitiri, a small settlement 50 km north-west of Napier, received the most rainfall in living memory, with over 1000 mm of rain recorded. The Esk River catchment had the greatest concentration of rainfall, the highest discharge volume estimated to be 1347 $m^{3}$ $^{s-1}$ below the rail bridge. This triggered multiple landslides that filled the water with silt and debris, burying approximately 700 ha of farms in sediment between 1-3 m deep (Grant, 1939; Cowie, 1957; McCaskill, 1973). An image of the aftermath is seen in Figure 2-11 (Hall, 1938). Settlers living in the region had no warning of the flood, and many were rescued from atop houses or hay-lofts (Hill, 1938). In addition, large parts of the Heretaunga Plains were also inundated with floodwaters, including Clive, Meeanee, Pakowhai and Taradale (NIWA, 2018a).

Grant (1939) writes that the silt content of the flood water was ‘an outstanding phenomenon’ evidenced by the area covered by sediment and the depth of the deposits. Shallow soil slip and sheet erosion on hillsides was the major contribution of sediment to waterways. Across the county, 12 bridges were washed away and 42 were severely damaged (Cowie, 1957). Prior to the flood, the farming land in the lower Esk Valley was held as small blocks, used for market gardening, dairy, lamb fattening and grass seed production (Hill, 1938).

**Figure 2-11 Aftermath of flooding in the Esk Valley, April 1938 (Hill, 1938).**

#### *2.9.1.1. Sediment revegetation*

Hill (1938) describes the actions taken by the Flood Relief Committee, which was set up soon after the extent of the damage was known. The committee decided that the first work to be completed was to resow areas where silt had been deposited before the silt became too dry. The New Zealand Department of Agriculture purchased and distributed 24 tonnes of certified rye-grass seed and 3.6 tonnes of white clover seed and used this to resow pastures in the Esk Valley, Tangoio, Puketapu and Wairoa. Sowing started as soon as possible with 135 kg of ryegrass and 2.2 kg of clover sown per hectare. The surface of the silted area was found to be uneven, and in the longer term, unsuitable for farming. The Public Works Department provided tractors and graders which were used to level the surface, and pull logs into heaps (Hill, 1938).

Some questioned why grass was sown immediately after the event, as it was late in autumn and the potential for fast growth was low. Previous events (unspecified) had shown that sowing grass once the silt could be walked on was of value, however sowing too late meant that the silt would dry out too much, risking it blowing away. It was recognised that the silt deposited in the Esk Valley was a sandy silt, and spring sowing would be risky should there be a dry summer. If the silt was left too long the land would become overgrown with weeds. At this time weed, control was done using a plough, which would now be impractical due to the hidden debris in the silt. Analysis of the silt showed a high ‘lime percentage’ [which we now assume to be high pH], average phosphorus and potash quantities, and very little humus, so it was assumed to have little nitrogen. It was assumed that those living in the area might have some income the following year if just some of the grass established (Hill, 1938).

The need for top-dressing with fertiliser had been identified, and at the time of publication Hill (1938) highlighted that provisions were being made for loans to be able to facilitate the application of superphosphate to support clover growth. Nitrogen was likely a limiting factor, particularly for the ryegrass. It was anticipated that the mix of ryegrass and clover would, over time, would facilitate the silted areas to return to into fertile land. Grant (1939) described the sediment texture of the upper end of the valley as 3% coarse sand, 83% fine sand and 17% fine silt clay loam. In the lower stretches of the valley the proportion of fine silt increased to 30%.

As early as August 1938, there were fears of summer winds turning the valley into a dust bowl due to the silt (New Zealand Herald, 1938). Unfortunately, in January 1939, this concern came to be true as the Esk Valley was again impacted by extreme weather. This time, strong winds swept through the valley, blowing loose silt deposited from the flood 10 months earlier. The valley was described by newspapers as a ‘miniature desert’, the sparse grasses which had been growing through the spring and summer were torn from the ground, destroying much of the newly established pastures (Northern Advocate, 1939).

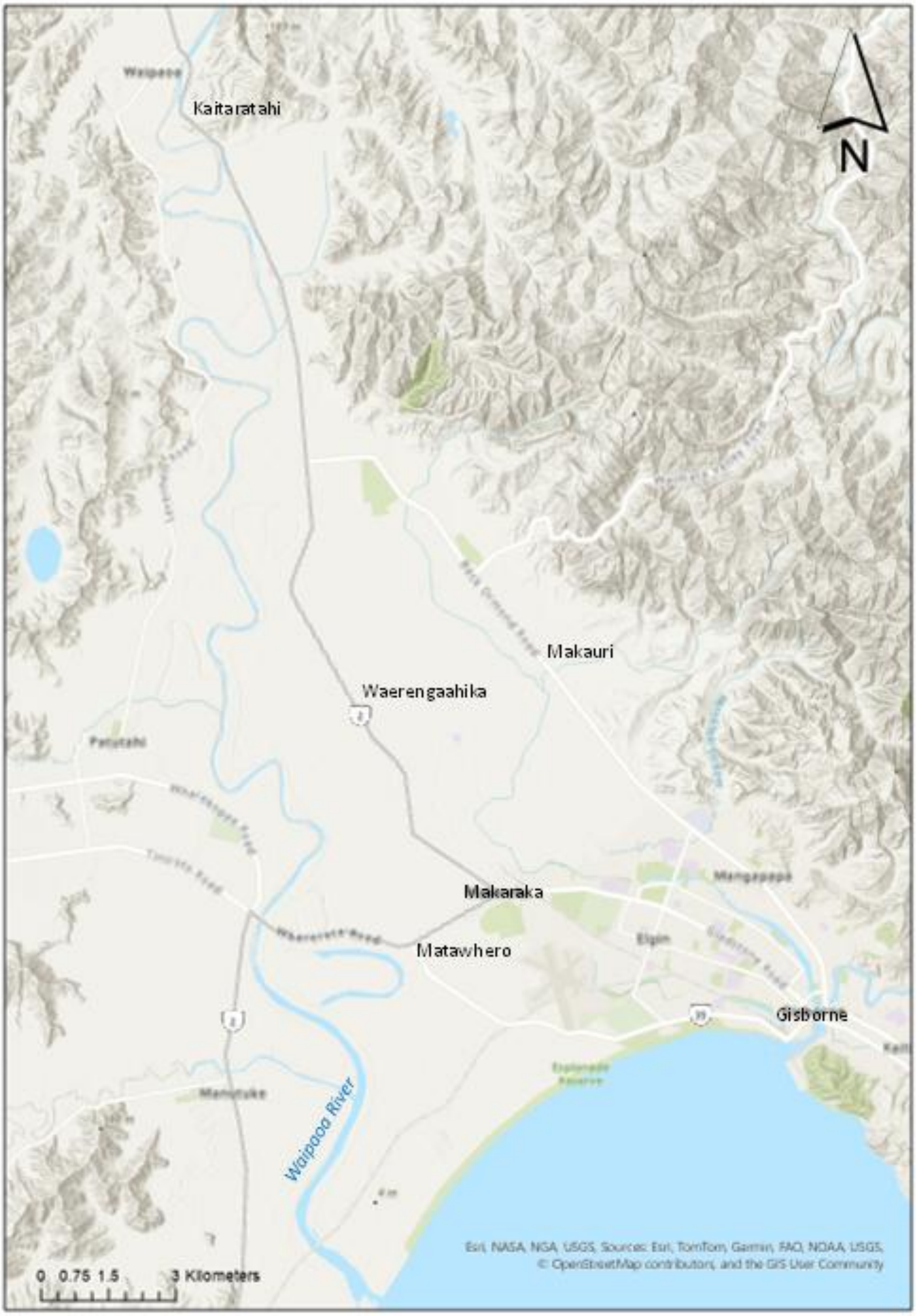
#### *2.9.1.2. Changes to policy*

After what McCaskill (1973) describes as the ‘1938 crisis’ after the Esk Valley flood, public support for soil conservation had been generated. The extreme erosion and flooding from this event, as well as several others in the 1930s triggered the passing of the Soil Conservation and Rivers Control Act 1941, and the establishment of Catchment Boards, whose main purpose was to minimise or prevent flood damage and erosion (Dravid & Brown, 1997). Soil conservationists at the time saw soil conservation taking many forms, from halting malpractice like burning, over grazing and cultivation of marginal areas, to improved grazing management, the construction of schemes aimed to reduce the effects of flooding on the land, the regeneration of native forests, and afforestation.

### 2.9.2. 1948 Gisborne Flood

The Gisborne/Tairāwhiti region was subject to extreme weather events that brought flooding and high winds (Chappell, 2016). The region is also prone to sediment deposition on the low-lying Poverty Bay flats. In 1948, a storm hit the east of the North Island, causing significant damage to the Gisborne Region.

Maize crops were flattened by wind or damaged by flood waters. Fields used to grow pumpkins were stripped of the crop, and many paddocks were heavily silted. As well as crop damage, there were significant losses of livestock across the Poverty Bay flats. The Waipaoa catchment was particularly affected, where the banks overflowed from Kaitaratahi to the coast. It is reported that the worst of the



Esri, NASA, NGA, USGS, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

**Figure 2-12 Map showing Gisborne area and key landmarks affected by the 1948 floods**

damage was around the Makauri, Waerengaahika and Matawhero areas. The value of agricultural losses was estimated at £165,000 or approximately $15 million in 2018 (NIWA, 2018c).

### *2.9.2.1. Sediment revegetation*

#### McKee & Graham (1952)

Farmers often attempted to regrass raw sediment, with apparently little data to support decisions of what to grow in these circumstances. After the 1948 and subsequent 1950 floods in Gisborne, McKee & Graham (1952) experimented with sowing different pasture species on flood sediments, at different intervals after the flooding, as well as experimenting with fertiliser applications and observing the effects of sediment texture. This is one of the earliest studies that focuses on the revegetation of downstream sediment deposits, rather than the upstream control of soil erosion.

The broad term 'silt' is often used to describe any material deposited by floodwaters. The paper discusses the correct use of the term 'silt' as a fine particle between the size of a clay and sand particle and suggests the use of the 'sediment' to broadly describe floodwater deposits.

One of the most important factors related to the establishment of pasture species on flood sediment is sediment texture. The three main sediment types are outlined in Table 2-1.

**Table 2-1 Flood sediment descriptions (McKee & Graham, 1952).**

| | Heavy sediment | Medium sediment | Light sediment |
|---|---|---|---|
| **Texture** | Clay loam to silty clay loam | Silt to silty sand | Sand |
| **Surface relief** | Flat or smooth | Ruffled | Rolling |
| **Feel** | Smooth or greasy | Slightly gritty | Gritty |
| **Speed of drying** | Retains water for some time. Surface glistens | Subsurface remains moist. Surface dries of rapidly | Water drains out very rapidly |
| **Where usually found** | Ponding areas | Fairly close to river | Adjacent to river. |

McKee & Graham (1952) suggested that in areas where light sediment (sand) has been deposited, the sediment should be cultivated immediately after the flood waters have receded. Where sediment is medium to heavy, cultivation will be impossible until after some drying has occurred, however, it is possible to sow seed in these areas with no cultivation, as long as the seed is applied to the sediment surface before the surface dries completely and loses its 'stickiness'. In both cases, timing is critical, and the window is short, so it is essential that farmers can quickly identify the sediment depth and texture on their farms in order to react quickly.

Trial plots were established in three locations two weeks after the May 1948 flood event in Matawhero, Te Karaka and Puha. It was from these trial sites that the importance of sowing soon after the flooding event was understood. Subsequently, after a flood in July 1950, six trial sites were established within just one week of the event. Trials were set up at Kaiteratahi, Waipaoa and Puha, chosen to represent the three key sediment types.

Table 2-2 Trial design and species selection (converted to modern units) (McKee & Graham, 1952).

| Plot No. | Species | Seed Rate (kg/ha) |
|---|---|---|
| **Plot 1** | Short rotation ryegrass<br>Perennial ryegrass | 42.6kg/ha |
| **Plot 2** | Short rotation ryegrass<br>Perennial ryegrass<br>White clover<br>Timothy<br>Subterranean clover | 42.6kg/ha |
| **Plot 3, 4 and 5** | Same as plot 2 but intervals of approx. 2 weeks according to surface conditions | 42.6kg/ha |
| **Plot 6** | Algerian oats | 200kg/ha |
| **Plot 7** | Black barley | 200kg/ha |
| **Plot 8** | Wheat | 200kg/ha |
| **Plot 9** | Same as Plot 2 but with treated clover seed. | 42.6kg/ha |

For each plot, half was treated with fertiliser (94 kg/ha superphosphate), and the other half remained untreated. The treated half was split again, with half being treated with 84 kg/ha superphosphate (SSP) and the other half treated with 168 kg/ha of sulphate of ammonia (SOA). The plots were sown by hand, but the authors acknowledge that in the 1950s, landowners were succeeding with aerial sowing.

Table 2-3 Description of the trial design including fertiliser applications rates for each plot (Mckee & Graham, 1952)

| Sub Plot | Initial Treatment | Second treatment |
|---|---|---|
| A | 0 kg/ha | 0 kg/ha |
| B | 94 kg/ha superphosphate | 84 kg/ha superphosphate |
| | | 168 kg/ha sulphate of ammonia |

The trial found that, in both 1948 and 1950, Italian and short rotation ryegrass struck the best, exceeding the strike of perennial ryegrasses, on medium to heavy sediments. Perennial ryegrass and red clover struck well but did not grow well over the winter. Cocksfoot, timothy and white clover struck poorly, and subterranean clover failed completely. All of the cereals planted failed, due to the predation by birds. The strike of all grasses improved with the addition of fertiliser, with greater responses on light and medium sediments, and a smaller response on heavy sediment.

Additionally, the trial found that oversowing light sediment does not work as the sediment dries too quickly. It was suggested that farmers grade the area to smooth the surface, ideally this will bring up some of the old topsoil and then plant in the ‘normal way.’ On medium and heavy silts, a good pasture can be established by oversowing, provided the seed is sown before the surface has dried fully. If the surface does dry, then farmers should wait until the surface can be cultivated and sown as the seasons allow.

### 2.9.3. 1988 Cyclone Bola

Cyclone Bola hit the East Coast of the North Island between the 6th and 9th of March 1988. The weather system slowed as it met an anticyclone north of New Zealand, resulting in three days of torrential rain as the storm remained almost stationary over the East Coast. The highest recorded rainfall was inland of Tolaga Bay, where 916 mm of rain fell over this period (APNZ, 2015). The highest maximum intensity was 85mm/hour. An unusual feature of Cyclone Bola was that the severity of the weather system extended over a wide section of the East Coast, from Gisborne - East Cape to Hawke's Bay (Harmsworth & Page, 1991).

The floodwaters broke through and overtopped stopbanks, damaged property and infrastructure across the region. It is estimated that 8000 ha of land on the East Coast had river sediment deposited up to 1.5 m deep (Gray & Korte, 1990). Losses from the primary sector (farmland and horticulture) were estimated to be $90 million ($225 million equivalent in 2025) (APNZ, 2015). The cost to the New Zealand Government was estimated to be over $111 million (equivalent of $277 million in 2025) (Manatū Taonga — Ministry for Culture and Heritage, 2023).

#### *2.9.3.1. Sediment revegetation*

#### Gray and Korte (1990)

Gray and Korte (1990) conducted an experiment after Cyclone Bola to provide recommendations on revegetating high pH alluvium deposits by oversowing. This experiment built on the work completed by McKee and Graham (1952) on sediment revegetation after the Gisborne Floods of 1948 and 1950.

The authors stated that if the alluvium deposits were sandy, or ~10cm deep, then resowing could be done with minimal issue after cultivating. Where sediments were deeper and silty, it was more difficult to resow pasture due to both physical and chemical traits of the sediment. Finer textured alluvial deposits from mudstone (soft calcareous sedimentary rock), containing montmorillonite clays had poor structure and were difficult to drain.

As part of the trial, soil nutrient tests were completed on sediment generated from several rivers on the East Coast. Average results are displayed in Table 2-4.

**Table 2-4 Average fertility level of sediment deposited in Gisborne area after Cyclone Bola, 1988 (Gray & Korte 1990).**

| Analysis | Average level across region |
|---|---|
| **pH** | 7.9 |
| **Olsen P units (mg/L)** | 7 |
| **Calcium (MAF)** | >20 |
| **Potassium (MAF)** | 7 |
| **Magnesium (MAF)** | 49 |
| **Sodium (MAF)** | 21 |
| **Sulphate Sulphur** | 32 |

The trial was established one month after the cyclone and was situated across the river from Ormond, which was flooded by the Waipaoa River, where approximately 1 m of alluvium had been deposited. Four replicates of 19 treatments (control + 18 seed combinations) with three fertiliser rates were established on the 7th of April 1988 after surface water had drained and, the sediment had cracked but the surface was still sticky. Two additional replicates were established on the 25th of May 1988 to make up for part of the original area that accidentally had seed flown on. By this time the sediment surface had dried, which made establishment by oversowing more difficult.

The results of the experiment showed that grasses established 'satisfactorily' when over-sowed, while legumes germinated sparsely. Results for the first sowing date were similar to McKee and Graham (1952), which showed that establishment was improved where the surface was drained but not fully dried, as the seed had adequate moisture for germination and was too wet for birds to feed. Once the sediment had dried, oversowing was ineffective due to predation by birds and low germination rates (seen in the replicates planted in May). The trial found that Moata ryegrass was the most vigorous species to grow, even more vigorous than perennial ryegrass. The trial did find that perennial ryegrass and white clover were also suitable for oversowing.

Overall, based on findings from the 1988 experiment and the previous McKee and Graham experiment in 1950, the most important factor for revegetating was timing oversowing to when surface water had drained, but the surface of the sediment was still moist, promoting germination. Additionally, applications of DAP (diammonium phosphate) improved establishment.

**Table 2-5 Summary of trial design following Cyclone Bola in 1988, species trialled and results (Gray & Korte 1990).**

| Species | Cultivar | Rate of seed (kg/ha) | Notes | Suitability |
|---|---|---|---|---|
| **Lolium multiflorum** | Italian ryegrass (Grasslands Moata) | 30 | Most vigorous of the grasses. Had highest yield with no fertiliser. Moata with no fertiliser yielded more than other grasses with 300kg DAP/ha. | Considered most suitable for over-sowing |
| **Lolium perenne** | Perennial ryegrass ('droughtmaster') | 30 | Intermediate grass (worked with white clover) | Considered suitable for over-sowing |
| **Bromus willdenowii** | Prairie grass (Grasslands Matua) | 50 | Slowest to grow, failed to persist and non-existent by 1989. | Considered not suitable (least suitable) |
| **Trifolium repens** | White clover (Grasslands Huia) | 5 | Lacked vigour but had effective nodulation. By summer became more vigorous and developed full ground cover. | Considered suitable (ideally with ryegrass) |

| | | | | |
|---|---|---|---|---|
| **Trifolium fragiferum** | Strawberry clover (Palestine) | 5 | Lacked vigour- noticeable chlorosis. By summer became more vigorous and developed full ground cover. | Considered not suitable for over-sowing. |
| **Medicago sativa** | Lucerne (AS13R+1) | 20 | Poor strike but what did strike grew vigorously over the summer. | Considered not suitable for over-sowing |

### 2.9.4. 2004 Southern North Island Storm

The Southern North Island Storm impacted many regions of the lower North Island including Manawatū, Rangitīkei, Horowhenua, Wairarapa and Whanganui on February 14th 2004 (M. D. Wilson & Valentine, 2005). The storm was a result of a depression of cool air from Antarctica slowing to the east of Hawke's Bay, as it met warm air from the tropics (NIWA, 2018b). The storm was rated to be on par with Cyclone Bola in 1988. It was estimated that around 20,000 ha of land was underwater for long enough to kill both pasture and crops (M. D. Wilson & Valentine, 2005). The cost of the storm was estimated to be $300 million (Fuller, 2005).

There were three key documents produced as a result of the flood. 'Regrassing silt: Technical document for rural professionals' (Litherland, 2004), 'Regrassing flood-damaged pastures' (M. D. Wilson & Valentine, 2005) and 'Silt recovery Southern North Island Storm Event 2004' (Litherland et al., 2007).

#### *2.9.4.1. Sediment revegetation*

#### Litherland (2004)

Litherland (2004) compiled "Regrassing silt: Technical document for rural professionals" in March 2004, one month after the storm. The document provided direction to farmers as to next steps in the weeks after the flood. The document provided details on sediment types and characteristics, including preliminary chemical characteristics from the data collected. Soil tests showed high pH, low Olsen phosphorus (P) and potassium levels and moderate sulphate levels. It is assumed that the sediment had little organic matter and low nitrogen content. The sediment was likely to have been structureless.

Pasture damage is discussed in the report, as well as damage to cereal and maize crops, typical of the regions impacted. Pastures generally recovered if the area was under water for less than 2 – 3 days, however, pastures underwater for a prolonged period, i.e., more than one week, tended to die in summer conditions. Pastures had worse outcomes where pasture had been grazed hard, or where sediment of more than 5 cm had been deposited. Flooding effects on cereal crops were similar to grasses, and long periods of water inundation led to poor root growth, delays in maturity and reduced grain size and yield. If maize had reached silking and had stayed upright, there was unlikely to be immediate damage to the crop, unless the maize remained underwater for more than one week. Prolonged submersion of maize crops caused significant root damage, particularly if the soil had been 'sealed off by silt'. Options discussed for disposing of a severely damaged crop included harvesting onto the ground and cultivated, using giant discs to mix chopped plants with the silt, or harvesting for silage.

Litherland (2004) discusses the effect of waterlogged soils and anaerobic microbial respiration, and the impact of ethylene gas and other toxins produced under anaerobic conditions, which impact plant growth and seed germination. Flooded sediments which are 'smelly' indicate the presence of these gases and toxins, which will impact the success of plant establishment. It is recommended that such sediments should not be oversown or direct drilled, and instead sediment should be cultivated before sowing, quickly reversing anaerobic effects. However, it may take time for the sediment to dry out enough to cultivate. It is unclear whether there would be some benefit to oversowing even if establishment was suboptimal, rather than leave the sediment bare until cultivation is possible.

Depth of silt (sediment) as a key factor in response options is discussed by Litherland (2004). Where silt is shallow (<5 cm) it can largely be ignored as the grass will likely grow through the crust, particularly older pastures. Where sediment is 5 – 10 cm deep and covers pastures entirely, the plants are unlikely to survive. Standard cultivation practices can be carried out to combine sediment with existing soil. Cultivating may be beneficial as it will disturb the interface between the buried pasture and the silt, which will help to improve drainage. Silt depths of 10 – 25 cm are likely to be varied across a paddock, when levelled the depth may be shallow enough to cultivate. Deep cultivation equipment can be used to incorporate the silt. Silt depths greater than 25cm are considered to be deep. The options for resowing deep sediment are either oversowing by helicopter or cultivating with light equipment when the sediment has dried, then drilling seed. There is little mention of optimum conditions for cultivation, however it is recommended that ‘normal cultivation methods’ apply, suggesting that silt and soil conditions should be considered and cultivated in a way that avoids adverse impact i.e., compaction.

Oversowing of silt is discussed further by Litherland (2004). Oversowing of sandy silt is not viable, as it drains and dries quickly, and not enough soil moisture is retained for adequate seed germination, plus birds are able to land and predate seed on the surface. Oversowing is however an option for clay/silt loams, when water has drained and the sediment is still damp and sticky, before the silt cakes and cracks. There will likely be a narrow window of opportunity for oversowing to be successful, and rewetting sediment should not be relied upon. Similar to the logic for sandy silt, it is not advisable to oversow dried sediments as there is not enough moisture retained for seed to germinate, plus birds are more likely to predate.  It is a riskier method of regrassing, so it is recommended that farmers use higher seed rates.

### Wilson and Valentine (2005)

Wilson & Valentine's (2005) study titled “Regrassing flood-damaged pastures” looked at the impact of flooding and sediment deposition to farmers in the Manawatū, as well as the outcomes of farmer regrassing strategies. The main focus of the study was on the success of different regrassing strategies, noting that not much can be done to lessen the impact of a flood like this, however there are many options to speed up recovery. The authors also noted that there was limited published work on recommended courses of action for flood recovery.

Fifty-two farmers were interviewed using a semi-structured interview format. Questions related to how they prepared the seed bed, seed sowing, fertiliser use and weed management. Interviews were conducted between November 2004 and January 2005 (nine to eleven months after the event). One hundred and ten cases were described through the interview process, and each case (site) was visited. Pasture cover was estimated using an eight-point scale, and pasture was assessed as green to not green using photo recognition. The site was then inspected for rooting depth, visible sediment depth and presence of anaerobic layers (M. D. Wilson & Valentine, 2005).

Of the sites/cases visited, 75% had less than 5 cm of sediment deposition. Only 1% of sites had more than 25 cm of sediment deposited. Where sediment had been deposited, it was found that full seedbed preparation improved establishment, and findings from the McKee & Graham (1952) study are highlighted in relation to the short window for success in broadcasting/oversowing seed, based on sediment moisture content and texture. Pasture establishment did not seem to improve with N fertiliser applications, bearing in mind the vast majority of sites had shallow sediment depths. Weed management was an ongoing issue for areas where little to no sediment was deposited, however there were comparatively less issues in areas where sediment was deeper.

The McKee & Graham (1952) study found that the most suitable species for sediment regrassing was short rotation and Italian ryegrass. However, the sites in Wilson & Valentine (2005) were predominantly sown in perennial ryegrass (65%), with only a quarter of sites having Italian ryegrass planted. This was largely driven by the strategic use of pasture species in a farmers annual regrassing rotation and not based on the plants ability to survive or thrive in suboptimal growing conditions. The survey found that the method used for regrassing impacted the success of establishment. Based on the findings of the study, a decision support tool was developed, with the aim of supporting farmers and industry after future flood events.

### Litherland et al. (2007).

The report "Silt Recovery" was compiled by Litherland et al. (2007), analysing two datasets collected after the 2004 flood event. One dataset was collected by Massey University, the other by AgResearch. The Massey dataset was collected approximately 9 – 11 months after the flood, the AgResearch dataset was collected approximately two years after the flood.

**Table 2-6 Details and descriptions of target scenarios for both datasets collected (Litherland et. al 2007).**

| Dataset and dates collected | Data collected | Testing | No. of farmers | No. of blocks | Farmers selected by | Sediment depth assessed |
|---|---|---|---|---|---|---|
| **Massey University Nov 2004 – Jan 2005** | Nature of sediment, regrassing & fertiliser strategies | Semi-structured interviews. Ground cover, pasture cuts, green cover, soil profile (sediment depth, anaerobic layer presence. | 52 | 110 | Random (referral) | Shallow sediment or no sediment |
| **AgResearch Jan – May 2006** | Regrassing strategies | Survey of dry matter production, soil profile, vegetation composition, green cover | 52 | 91 | Random selection | Shallow to deep sediment |

Both studies focused on determining sediment characteristics, and the success of regrassing strategies. Farms selected were predominantly pastoral farms (dairy and dry stock) with some arable production. On average, sediment had high pH, low organic matter and Olsen P and high sulphate sulphur levels. In the majority of cases, sediment wasn't regrassed until more than 30 days after the flood event due to wet conditions. Weed management was a consideration at almost all sites. Drainage was an ongoing issue across most sites. Deep sediment produced 50% less than unflooded paddocks 6 months after the flood, and 35% less 18 months after the flood. It is unclear what factors contribute to this gap in production closing, however, may be related to improved soil fertility or improvements to sediment structure. Data showed that full cultivation improved ground cover, however the first grazing was delayed by 2 months, compared to sites that were direct drilled.

The study found soil nutrient fertility differences in river sediment depositions; however, differences were not large enough to support different fertiliser regimes. Of the deeper sediments assessed by AgResearch, the average depth was 20 cm, and predominantly sandy or loamy textured. Sediment smell was assessed, with 'smelly' sediment indicating anaerobic conditions and the indication that ethylene gas may be present, which is noted to negatively impact seed germination. In contrast to initial comments and recommendations from Litherland (2004), the data collected by AgResearch found no correlation between sediment smell and pasture production.

The analysis of regrassing method success considered sediment incorporation and cultivation extent, and method of resowing. The analysis recommended the incorporation of silt and underlying topsoil where possible, as sediment deposited has low fertility and low organic matter. Drainage can be impeded at the interface between sediment and topsoil, so the incorporation can improve drainage outcomes. This study doesn't specifically discuss the negative impacts of cultivating soil or sediment when it is too wet, however it is worth noting there are potential issues for cultivating at above optimum moisture. These issues include compaction, which can impede root growth and drainage. The study suggests that the removal of sandy sediment may be appropriate, however can be costly. Pastures resown via direct drilling into sediment performed better than fully cultivating sediment in the short term (6 months), however was outperformed by the cultivated areas after 18 months. Pastures sown via oversowing performed well initially, however was less productive than the other two methods after 18 months.

The report reflects on the work of Gray & Korte (1990) after Cyclone Bola, where sandy sediments should not be oversown, however, oversowing is an option for clay/silt sediments, provided the sediment surface is still sticky. Perennial ryegrass was the most common species sown, followed by Italian ryegrass. In contrast to farmer actions after the 2004 flood, the Gray & Korte (1990) study showed that in the short term annual ryegrass (Moata) outperformed perennial ryegrass in sediment deposits. Litherland et al., (2007) suggested that the performance of both perennial and annual ryegrass would converge over time.

## 2.10. Summary of sediment revegetation recommendations from North Island storm events

In response to the impact of Cyclone Gabrielle, soil recovery on agricultural and horticultural land was informed by the five key studies/reports from the last 70 years, which have been summarised in this review. A key recommendation from all of the resources was to establish plants as soon as possible.

- From McKee & Graham's (1952) early work, each subsequent study supported the idea that sediment texture and depth were the two major factors to consider when assessing the management of river sediments deposited on farmland. This ultimately culminated in the development of a decision support tool (3.11.2 Appendix 2) after the 2004 Southern North

Island storm, of which many iterations were reproduced to support recovery after Cyclone Gabrielle.

- The results from McKee & Graham (1952) showed that oversowing of seed on heavy flood sediments was effective provided the sediment had not dried too much. They also concluded that short rotation and Italian ryegrasses were the best species to oversow. This was supported by Gray & Korte (1990). Interestingly, Litherland et al. (2007) found that although the most common species sown was perennial ryegrass, which was outperformed by Moata (short rotation grass) in the first year of production.
- After Bola, Gray & Korte (1990) discussed that sediment deposits that were sandy, or approximately 10cm deep could be sown with minimal issue after cultivating. In contradiction to this, Litherland et al. (2007) suggested that removal of sandy sediment may be necessary as these sediments are challenging to manage due to low fertility and organic matter, however this may not be feasible due to the cost.

While the previous flood events studied supported recovery post-Cyclone Gabrielle, the focus of previous studies was on recovery for pastoral production, with consideration for some arable crops. After Cyclone Gabrielle it became evident that there were considerable gaps in knowledge, particularly in relation to the impact on Highly Productive Land (LUC 1 – 3), the soils ability to produce high value fruit and vegetable crops, and medium to long term impact to soil of sediment deposition.

## 2.11. 2023 Cyclone Gabrielle

Cyclone Gabrielle in early 2023 was the third significant weather event to occur in New Zealand over a six-week period, following Cyclone Hale in early January and the Auckland Anniversary Weekend Floods in late January (Hawke’s Bay Independent Flood Review Pae Matawai Parawhenua, 2024).

Tropical Cyclone Gabrielle formed over open waters near the Solomon Islands in the Coral Sea and was named by Australia’s Bureau of Meteorology on the 8th of February (Murray, 2023). The sea surface temperature in the Coral Sea was warmer than usual at around 30℃, which contributed to the weather system maintaining its intensity and moisture for longer than expected. Cyclone Gabrielle stalled and re-energised north of New Zealand, causing some of the highest rainfall intensities recorded in the country’s history. In Hawke’s Bay, the highest rainfall recorded was 546 mm, with intensities of 56 mm/hour, exceeding the intensity of Cyclone Bola (1988) (McLean, 2024). The cyclone caused severe flooding across many regions of New Zealand. A National State of Emergency, applying to Northland, Auckland, Bay of Plenty, Waikato, Hawke’s Bay and Tararua district, was declared on the 14th of February, only the third time in history. Parts of the Central Plateau, Manawatū and Wairarapa also had significant damage (Wilson et al., 2023).

The intense rainfall caused floodwaters that exceeded the design flow of the Hawke’s Bay’s stopbank network, breaching and overtopping stopbanks in many places (Heslop, 2023). In all, there were 5.4 km of stopbank breaches and 28 km of weakened stopbanks (Lane, 2023).

With the flood waters came significant amounts of sediment which were deposited across the lowlands of the East Coast, including Hawke’s Bay, Wairoa and Gisborne. The sediment varied in depth and texture, depending on position in the landscape and proximity to the river. In an early review of flood damage, McMillan et al. (2023) estimated that 5.7 million tonnes of soil was eroded in the Esk River Catchment, of which 1.5 million tonnes was deposited in the valley.

The impact to farming communities was immediate. Almost every land use type was impacted, including permanent tree and vine crops, arable, fresh and process vegetable crops, and pasture, both dairy and drystock farms were impacted. Growers were weeks away from harvest and experienced significant crop damage, and in many cases, 100% crop loss.

**Figure 2-13 Aftermath of Esk Valley flooding, 1938 and 2023, as published in the Hawke's Bay Today (Pocock, 2023).**

While there is strong evidence to support oversowing of Italian or short rotation ryegrass soon after the flood waters drained, for most impacted farmers and growers in the wake of Cyclone Gabrielle, this was not adopted. In some cases, by the time oversowing was completed, the sediment had already dried too much. Large areas of deep, silty sediment which could have been oversown were left bare over the winter until the paddocks dried out and could be cultivated the following spring. In other cases, the recommendation to oversow was given too late, and the grower had missed the window. Blocks that were over sown with grass, were able to be grazed over the winter and early spring.

In the deep, sandy sediment deposits in the Esk and Dartmoor Valleys, the default response was to remove the sediment. This was particularly true for areas planted in permanent tree and vine crops, with the intent of saving buried orchards and vineyards. Areas that were left with 1 – 2 m of sand that was unable to be removed, struggled to establish seeds in the first 18 months as the sediment drained and dried quickly.

Funding was made available to complete projects related to the many aspects of recovery. The Ministry for Primary Industries allocated $30 million in funding through the NIWE Time-Critical Primary Industries Recovery Fund. This fund aimed to provide urgent maintenance, transport of essential supplies, and expert advice to inform decision making and management decisions (Ministry for Primary Industries, 2023). The Ministry of Business Innovation & Employment (MBIE) made $8.6 million available from the Strategic Science Investment fund by 31 June 2023 to fund time-bound science, where research and data collection was perishable (Ministry of Business Innovation & Employment, 2024). Funding was also made available through various Crown Research Institutes including AgResearch ($270,000) (AgResearch, 2024) and Plant and Food Research ($600,000) (Plant and Food Research, 2024).

Details of key land-based projects are listed below in Table 2-7. For a number of these projects, reporting and publishing is still underway, and final reports are not yet available.

**Table 2-7 Key land based projects completed in response to Cyclone Gabrielle**

| Organisation | Project Name | Contributors | Project term | LUC focus | Aims | Budget/Funding |
|---|---|---|---|---|---|---|
| **LandWISE & others** | Cyclone Gabrielle baseline sampling 2023* | Dickson, A., Bloomer, D., Mackay, A., Palmer, A., Anderson, S., Cavanagh, J., Schon N., Devane, M. | Short term (completed September 2023) | 1 – 3 | Assessment of sediment characteristics across East Coast and Northland before remediation undertaken, address gaps in data sets from 2004 Manawatū Floods, data collection from a large number of sites. (Thesis Chapter 3) | MPI |
| **LandWISE & others** | Cyclone Gabrielle repeat sampling 2024 & 2025 | Dickson, A., Bloomer, D., Mackay, A., Palmer, A., Anderson, S., | Short – medium term (to be completed June 2025) | 1 – 3 | Repeat sampling of subset of baseline sampling sites (*Cyclone Gabrielle Baseline Sampling 2023), analysis of changes in sediment and soil over two years. (Thesis Chapter 4). | MPI + Vegetables Research and Innovation (VR&I) |
| **Plant and Food Research** | Promoting crop resilience in silt-affected landscapes | Dias de Oliveria, E. | Short term – single cropping season | 1 – 3 | Investigating the viability of direct planting different crop types in silt affected soils – key crops incl. maize, carrot peas and transplanted broccoli. Crops were planted into different sediment depths. | Combined $600,000. Internal Strategic Science Investment Funding) |
| **Plant and Food Research** | The effects of Cyclone Gabrielle on pomefruit tree health in Hawke's Bay | Trolove, S., Husband, E., Sorensen, I., White, M., van der Weyden, J., Arnold, N., Walker, J., Horner, M., Brookes, J. | Short term (to be published early 2025) | 1 – 3 | Collect data from orchards impacted by Cyclone Gabrielle where there was uncertainty on recovery and long term effects. Assessments included waterlogging & ill thrift from orchards. | |
| **Plant and Food Research/ New Zealand** | Findings of a grower survey on the impacts of Cyclone Gabrielle | Trolove, S., Bews, A., Becker, M., Adsett, D | Short term (to be published March 2025) | 1 – 3 | Grower survey, aims to understand orchard waterlogging, collect management data in response to waterlogging, record grower observations and lessons. | NZ Apples and Pears (internal funding) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Apples and Pears** | on pipfruit orchards | | | | | |
| **ESR** | Microbiological food safety risks associated with flood-affected soils | King, N., Cressey, P. | Short term (completed May 2024) | 1 – 3 | Compile evidence on how flooding affects faecal indicators and microorganisms (Horticulture), identify sampling and testing methodology for assessing microbial safety, find out of faecal indicators and genetic markers are useful indicator for food safety, communicate findings to industry | New Zealand Food Safety Science and Research Centre, MBIE funding provisions. |
| **FAR** | Community support hubs – Supporting recovery and resilience on arable soils | Wallace, D., Mathers, D., Kale, A., Briant, A., Calendar, E. | Short term (completed beginning) | 1 – 4 | Community support through recovery, documentation of on-farm decision making and outcomes, develop enduring resources for growers impacted by extreme weather events in the future | $200,000.<br>MPI NIWE Fund |
| **GNS & others** | Cyclone Gabrielle landslide response and recovery | Massey, C., Leth K. (with contribution from NEMA, Manaaki Whenua, University of Canterbury, and the University of Auckland). | Short term (data available end 2023) | 6 – 7 | Identify and map landslides triggered by Cyclone Gabrielle, develop case studies of specific landslide damage and slow moving landslides, update and improve landslide susceptibility and rainfall-induced landslide forecasting. | $1.45 million, MBIE Strategic Science Investment Fund + $200,000 GeoNet |
| **Landcare Manaaki Whenua** | Rapid assessment of land damage – Cyclone Gabrielle | McMillan, A., Dymond, J., Jolly, B., Shepherd, J., Sutherland, A. | Short term (completed July 2023) | 6 – 7 | Deliver maps showing landslide density from 2023 severe weather events + maps of bare ground, summarise land damage by zone, catchment and land cover, estimate reduction that could be achieved through effective soil conservation, estimate highly erodible land impacted. | Prepared for MfE |

## 2.12. Additional reviews

### 2.12.1. A review of selected storm damage assessments in New Zealand

In 1991, Harmsworth and Page produced the report, 'A review of selected storm damage assessments in New Zealand', published by the New Zealand Department of Scientific and Industrial Research (DSIR) (Harmsworth and Page, 1991). The report evaluated the use of techniques used to measure storm damage, from 24 storm damage assessments published between 1971 and 1989. A key point made in the review was that land use intensification increases the value of properties and assets. When an intensively managed property is damaged by a significant weather event, the cost of damage and time needed for recovery increases. Climate change is expected to increase the intensity and frequency of storm events. As cost and time needed to recover increases (with land use intensification) a robust and quantifiable approach to measure the impact of storm events is required.

Most of the reviews assessed by Harmsworth and Page (1991) related to storm events in the East Coast of the North Island, as there is a greater susceptibility to cyclonic weather patterns and the area is characterised by erosion-prone argillites and mudstones (Harmsworth & Page, 1991). Half of the assessments reviewed were completed on Tertiary and Quaternary mudstone and sandstones. Almost all of the assessments were completed on the easter side of the North Island. The authors note that few assessments have looked at both the hill country and downstream effects of sedimentation and deposition. Most assessments reviewed were from hill country, where land use was mostly in pasture, with some scrub and forestry assessed.

The authors concluded that erosion producing storms occur year-round and in general, there is not enough data to say that one time of the year is a higher risk than another. Most of the storms that induced erosion followed extended wet periods, where soil moisture content will have been close to field capacity prior to the rainfall and subsequent erosion event. They recommended that further work was required to document the relationships between the climate and land use change to inform planning for sustainable land use. Additionally, they recommended that storm damage assessments be completed more regularly, and that a national archive for storm damage be established.

### 2.12.2. Soil erosion in New Zealand

Cumberland (1947) suggested that Hawke's Bay and the surrounding hill country experience higher rainfall intensity than many other parts of the country. In Hawke's Bay and Gisborne, the combination of soil type and rainfall irregularity and intensity puts both regions at high risk of severe erosion. At the time of publishing, automatic gauges were not available, however data is provided illustrating the rainfall intensity of the April 1938 rainfall event across Hawke's Bay and Northern Hawke's Bay, assuming that the 'accumulated weight, saturation and lubrication' of three days of high intensity rainfall will have been the leading cause of erosion from the storm.

Table 2-8 Rainfall recorded in the 1938 Esk Valley Flood - excerpt from Cumberland (1947). Units converted from inches to millimetres.

| | **Rainfall (mm)** | | | |
|---|---|---|---|---|
| **Rainfall station** | 23 April | 24 April | 25 April | 3-day total |
| **Puketitiri** | 232 | 391 | 378 | 1001 |
| **Putorino** | 102 | 421 | 293 | 816 |
| **Maraetotara** | 47 | 277 | 273 | 597 |
| **Rissington** | 85 | (254) * | 150 | (489*) |

*Gauge overflowed

Cumberland (1947) included a series of images of previous storm damage effects, including of Hawke's Bay hill country, commenting that the slips looked like 'snow from roofs' (Figure 2-14) after the April 1938 event. Cumberland noted that it seemed that the degradation of vegetation and soils in New Zealand after over 100 years of occupancy by settlers was at that time beginning to show up as a significant issue.

Figure 2-14 Cumberland (1947) image of soil erosion in Hawke's Bay hill country after 1938 Esk Valley flood.

Cumberland (1947) noted that the Esk, Te Ngaru and Mohaka Rivers left silt loam sediment on 'formerly valuable land' after the 1938 floods. Ten years after the flood, when the book was written, the lower part of the Te Ngaru River flats (Tangoio) was still covered by silt and debris, houses were abandoned and the landscape described as 'decrepitude'. Māori had started to grow maize and potatoes in the newly deposited sediments. Along the edge of the road in the Esk Valley, silt was still piled high with logs and other debris still present. The lower Esk Valley had an estimated 710 ha silted, with an average depth of 1 m, and up to 1.8 – 3 m in places.

## 2.13. Summary

The highly productive nature of the lowlands of Hawke's Bay are the result of a unique combination of topographic, geographic, climatic factors, overlayed with human intervention over the last 150 years. The rivers of the Heretaunga Plains naturally aggrade and deposit alluvial material on the plains, these rivers are dynamic and have changed their courses a number of times over millennia. In the last 100 years, flood control schemes have been established to protect towns, cities and productive land, the major rivers now confined to stopbanks, creating defined channels at the lower end of the river passages to the coast. While the force of Cyclone Gabrielle was devastating for Hawke's Bay, and indeed a large portion of the North Island, the phenomenon of sediment deposition should be unsurprising, given the nature of the landscape, and proven risk of high rainfall intensity.

There have been several key flood events which have triggered analysis of soil erosion and flood impact including Cyclone Alison and Cyclone Bola. Cyclone Gabrielle has been added to the list of landmark events which left a lasting scar on the landscape. From previous studies, it can be concluded that human clearance of vegetation in the upper portion of river catchments has indeed increased the rate of erosion, and the volume of the resulting erodible material entering our waterways.

Additionally, there have been several storm events which have deposited significant amounts of sediment on flood plains, which has led to the small number of studies which have been summarised in this review, which focused on understanding sediment characteristics and pastoral recovery. In reflecting on the results of previous studies, there are clear actions that can be taken by farmers in the days and weeks after a flood event. Rapid revegetation of sediment is a key recommendation from the studies completed to date. Studies completed focus largely on pastoral recovery, and there is limited understanding of recovery for high value fruit and vegetable crops on Highly Productive Land. These studies have focused on short term impacts, up to 1 years post-flood, however, have not considered the medium to long term impacts of flood sediment deposition and soil recovery.

In 2023, the scenes in the Esk Valley after Cyclone Gabrielle were strikingly similar to the situation after the 1938 flood. The decision to remove thousands of tonnes of sandy sediment from these areas seemed to disregard historical knowledge of the Esk Valley's susceptibility to flooding and deep sediment deposition. This raises the question, can we change the way we farm on these flood plains, to work with nature, rather than against it, to avoid or minimise the impact of these inevitable catastrophic events?

Resources for this literature review, were compiled over nearly two years, in an effort to collate existing knowledge related to flood sediment recovery, some resources date back nearly a century. Broadly relevant information related to erosion, flooding and sediment deposition has come from a range of sources. There are several old references which could not be located as the original documents had not been stored in a way that they were retained for future use. The challenges experienced in accessing old resources in the current study highlights the need to ensure that the information and knowledge gained over last century, including from Cyclone Gabrielle is stored in such a way that it will be accessible to future generations.

One of the aims of this thesis was to identify the knowledge gaps in relation to flood sediment recovery. This literature review outlined the geological setting of the main research area, the Heretaunga Plains. Historical records dating back to the 1930's have been reviewed and analyses of previous studies focused on flood sediment deposition have been completed. By doing so, knowledge gaps have been identified and discussed. This review is the basis for the subsequent field research in Chapter 3 and 4.

# Chapter 3

## 3. Baseline Sampling Report

This report was initially written for the Ministry of Primary Industries (MPI) as a final report for the LandWISE post-cyclone project, funded shortly after the event. Some minor emendations have been made to the report for the purpose of the inclusion in this thesis. I helped to lead this project and was the lead author of this report. My role included the planning and coordinating data collection in several regions, site visits and sampling in Hawke's Bay, data consolidation and analysis interpretation and reporting.

Where others have directly shared their knowledge, there is acknowledgement of their contribution. This report was prepared with support from Dan Bloomer (LandWISE Inc.), Alec Mackay (AgResearch), Alan Palmer (Massey University), Sally Anderson (Market Access Solutionz). With additional contribution from Jo Cavanagh (Manaaki Whenua- Landcare Research), Nicole Schon (AgResearch) and Megan Devane (ESR).

### i. What this report contains

- This report summarises a comprehensive survey of sites impacted by Cyclone Gabrielle in Hawke's Bay and Gisborne/Tairāwhiti, documenting flooding, wetness, sediment deposits, sediment and soil physical and nutrient status, potential contamination, and grower responses.
- The focus was on Highly Productive Land (HPL), which is used for growing high value fruit and vegetable crops, the land use types most significantly impacted.
- Overall field and laboratory analyses was completed for 155 sediment and soil samples from 116 sites located on the highly productive soils of Hawke's Bay, Tairāwhiti and Northland. Samples collected from Northland were from soils that were inundated with water for an extended period, not impacted by sediment deposition, the Northland data has been excluded from this Chapter (12 sites).
- Approximately 100 growers were involved in the study, suggesting and making sites available, providing information the cyclone's impacts, how it affected them, their families and businesses, and what information they were able to access and that they wished they had available.

### ii. Background

- On 13 February 2023, Cyclone Gabrielle tore across the North Island, causing devastation in Hawke's Bay, Tairāwhiti, Northland and Auckland, with significant impact felt in parts of the Manawatū, Central Plateau and Wairarapa. The cyclone decimated homes, productive land, crops, and livelihoods, with an estimated cost of rebuilding in the billions of dollars.

- While the biggest impact of the cyclone on Hawke’s Bay and Tairāwhiti has been sediment deposition, extended waterlogging preventing sowing and harvesting has been the main challenge in Northland. Extended wetness in all regions over the last 18-24 months was already an issue for growers, prior to Cyclone Gabrielle.
- Following the Cyclone, a group of organisations came together to provide immediate advice to affected growers. Activities broadened to capture data on the initial impact of the cyclone on farmers, growers, and their productive land, to fill a major gap in knowledge of the behaviour of soils and sediments in the weeks and months immediately following a storm event.

## iii. Essential findings

- Sediment deposition on the Hawke’s Bay and Tairāwhiti varied in depth (< 5 cm to > 100 cm), texture (sand to silty clay loam), volumetric moisture content (10 – 80%), bulk density (0.75 – 1.65 g cm-3), nutrient fertility including pH (5.5 – 8.5), Olsen P (2 – 30 µg ml-1), exchangeable potassium (2 – 16 MAF units), sulphate sulphur (2 – > 200 mg/kg) and in its biology (12 – 70 earthworms m-2). The physical condition of the sediment as assessed using the Visual Soil Assessment methodology varied from poor to moderate.
- Initial concern regarding chemical or biological contaminants in the sediments was not supported by any of 14 samples taken from sites in Hawke’s Bay.
- The study recorded actions growers took, or were intending to take, where significant amounts of sediment (5 – 20+ cm) were deposited on their highly productive land. Orchardists have removed up to 50 cm of sediment from within the tree-rows. Cropping farmers’ management included leaving sediment bare until the spring, sowing a cover crop, and mixing 5 – 20 cm of sediment into the soil. Vegetable growers have removed 20+ cm of sediment from some fields.

## iv. Why this study is important

- There is little or no documented information on best management of sediment impacted sites with high value crops on elite soils. Previous studies have been almost exclusively of re-grassing pastureland.
- The work done through this project has provided the first documented records of site impacts, sediments and grower actions immediately following a major storm event on high value crops on elite soils.
- Selected sites were revisited approximately six months after the cyclone to collect information about the soil and sediment following growers’ site management. The ongoing monitoring is part of an initiative to develop information and decision support tools that cover all land uses for the next time a community is impacted an extreme weather event.

- This report discusses some possible effects of sediment deposition and its properties on future crop performance, particularly where the sediment is more than 5 – 20 cm in depth and a major component of the growing medium for plants and new soil surface.
- This comprehensive study establishes sound baseline data upon which an ongoing longitudinal study can be built.

## v. What needs to happen next

- Ultimate value comes from understanding how different applied management affects the rate and degree of recovery at sites with different sediment conditions and the economic consequences
- Monitoring management, soil and crop performance at these sites for a five year period will help determine which practices enabled growers to most effectively build their soils back better.
- It will enable development of best management guidelines for growers to respond effectively and efficiently following future events.
- Funding should be made available to enable a multidisciplinary soil, agronomy and social science to follow the growers, their actions and results at these sites.

This project was funded by the Ministry for Primary Industries, with administrative support from Vegetables NZ.

## 3.1. Background

On the 13th of February Cyclone Gabrielle tore a path across Hawke's Bay, Tairāwhiti and Auckland/Northland, causing devastation across much of the regions (Figure 3-1). The cyclone decimated homes, productive land and crops, and livelihoods, with the estimated cost of rebuilding in the billions of dollars. This cyclone was the third in a series of serious storms to hit New Zealand in the previous two months. Across Hawke's Bay, Wairoa, Gisborne and Northland highly productive cropping land, orchards, vineyards, and pastoral land were inundated with water and buried under sediment and debris after rivers burst through stopbanks and shifted their courses. Cyclone Gabrielle also impacted coastal Wairarapa, parts of the Central Plateau and the Pohangina Valley in the Manawatū.

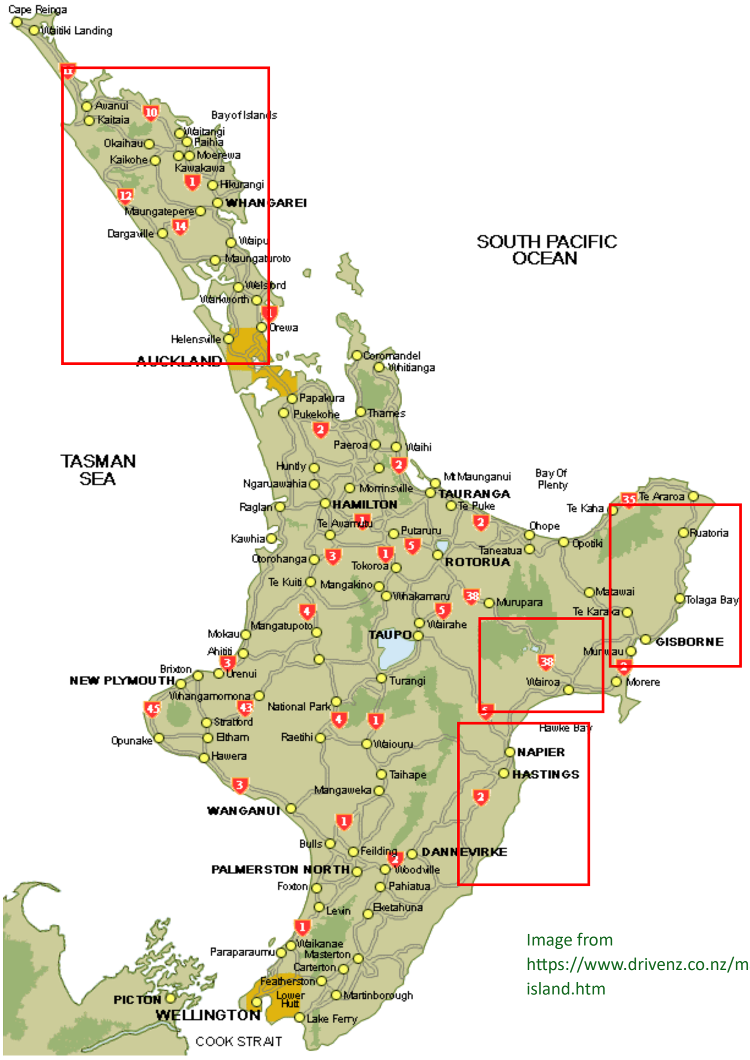


Image from https://www.drivenz.co.nz/map-north-island.htm

**Figure 3-1 NZ map of areas impacted by Cyclone Gabrielle**

Following Cyclone Gabrielle, our organisations came together to provide immediate advice to affected growers. Activities broadened to capture data on the initial impact of the cyclone on farmers, growers, and their productive land, and document the lessons that could be learnt in how to recover from a natural disaster such as this one. The group included LandWISE Inc., AgResearch, Massey University, Hawke's Bay Regional Council, Gisborne District Council, Plant and Food Research, Vegetable Research & Innovation Board, and Vegetables NZ, alongside the Ministry for Primary Industries and several of the national producer groups including NZ Apples and Pears, Summerfruit NZ, Citrus NZ, Onions NZ, New Zealand Buttercup Squash Council and the Foundation for Arable Research.

After the 2004 Southern North Island Storm Event[1] impacted Manawatū, Rangitikei, Horowhenua, Wairarapa and Wanganui Regions, information from farmers on successes and failures of re-grassing sediment deposits (silt) was collated. Approximately 50 farmers were involved in that study. The data were collected a year after the event, predominantly from pastoral farmers, and does not provide information specific to cropping farmers, vegetable growers, orchardists or viticulturalists. The aim of collecting baseline information in the months after Cyclone Gabrielle is to build on that previous work, update information, and inform the creation of decision support tools that cover all land uses for the next time a community is impacted an extreme weather event.

The collection of baseline data was collected as soon as possible (before any significant remediation was carried out). The sampling was a priority, as the information will address gaps in the data sets collected in 2004 and inform and provide a baseline for a five year longitudinal study. The initial information was collected from the four most impacted areas; Hawke's Bay, Tairāwhiti, Wairoa and Northland, in the first 1 – 3 months after the cyclone. Ministry for Primary Industries funding enabled commercial laboratory analyses for nutrients and contaminants, and labour and advisory costs. Funding was managed through Vegetables NZ. LandWISE, AgResearch, Massey University, Gisborne District Council and Plant and Food Research provided additional staffing supported by internal funds. The focus of the sampling was on cropping land, orchards and vineyards, which were the land use types most significantly impacted. A few sites sampled were impacted pastoral land.

The project budgeted on 200 samples across the four impacted regions. At the end of August 2023, 155 samples laboratory from 116 sites were completed as part of the initial baseline testing. A breakdown is given in Table 3-1. The remaining budget was used to revisit a selection of sites and capture information six months after the cyclone. This report focuses on the initial testing; a separate proposal document has been prepared to outline a proposed longitudinal study.

**Table 3-1 Breakdown of number of samples and sites per region**

| Region | Number of samples | Number of sites |
|---|---|---|
| Hawke's Bay | 82 | 60 |
| Gisborne | 55 | 39 |
| Wairoa | 6 | 5 |
| **Northland | 12 | 12 |
| Total | 155 | 116 |

**Data not included in this reporting

## 3.2. Sampling method

Initial plans only considered sampling for nutrient analysis. However, with sampling activity happening so soon after the event, there was a unique opportunity to capture more characteristics of the sediment deposited and impacts of the cyclone. The aim of collecting a wider range of data was to better understand where sediment has come from, the variation in sediment types deposited across the landscape, to provide information to growers on what sediment characteristics they were working with, to understand implications for future land use and management, and add to the knowledge base on the impacts of flooding.

The extent of damage to a particular area varied enormously due to many factors. The sampling protocol was developed at a workshop held 9th March 2023, by representatives from a range of

---

[1] https://hwe.niwa.co.nz/event/February_2004_North_Island_Storm

organisations to create consistency in sampling across the three regions. Some flexibility was built into the protocol as some sites required a 'bespoke' approach to sampling.

The impact of the cyclone on highly productive land was divided into three main categories:

(i) soil eroded and stripped leaving subsoils exposed
(ii) soil impacted by sediment and
(iii) areas inundated with water for an extended period.

A 50m long transect was established at the time of initial sampling, and data was collected from three points along the transect (0m, 25m & 50m). Transects were measured based on sediment depth, with the aim to have all sampled points within the same sediment depth class (Litherland et al., 2007). Eight key characteristics were captured across all sites, including sediment depth and texture, nutrient status, visual soil assessment, bulk density, earthworm abundance and diversity, eDNA, and contaminant levels (on selected sites). Details of how each characteristic has been measured are presented in 3.11.1 Appendix 1.

## 3.3. Site selection

Sites were selected to capture information in impacted catchments, with samples collected at different points along the river flow pathways. Different land uses were captured including orchards, vineyards, pasture, and cropland. Different sediment depth classes and textural types were included.

## 3.4. Site history and proposed recovery actions

Information on the land use and practices prior to the flood (soil fertility, crop type, etc.), along with any action the growers had taken or proposed to take was documented as part of the process at each site. It was critical to capture this information at this early stage as it builds a picture of management that will feed into the proposed longitudinal study.

## 3.5. Project challenges

Key challenges faced for baseline sampling were similar across all regions.

- Defining a sampling protocol to fit all land use types and scenarios to capture as much information as possible was an initial challenge.
- Given the magnitude of the cyclone and the land use types impacted there was significant variation across sites, which made gaining consistency across sites challenging. Where sampling needed to vary slightly from the sampling protocol, justification notes have been recorded.
- Access to blocks was impacted by extended wetness and sediment consistency i.e., very wet, deep sediment into which those collecting data sank.
- Prolonged wetness was a particular issue in Northland were consistent rain meant that sampling could not take place until June.
- Regional access was also a challenge as Gisborne and Wairoa were cut off from the south for many weeks, and it was not possible for sampling to be done from Hawke's Bay. Gisborne District council volunteered to complete the sampling in Wairoa.
- Time taken to complete the more comprehensive sampling deemed valuable was greater than originally budgeted.

## 3.6. Results and next steps

For each region details on site selection and an overview of the sampling are provided. Some of the results from the extended sampling programme are also presented. These include:

- Physical properties
    - Sediment Texture
    - Bulk Density
    - Visual Soil Assessment
- Chemical properties
    - Nutrients (pH, Olsen P, Potassium, Sulphur profile)
    - Contaminants- Heavy Metals and Residues (Hawke's Bay only)
- Biological properties
    - Earthworms (Hawke's Bay only)
    - Contaminants (E. Coli Hawke's Bay only)

Where relevant, optimum ranges for each characteristic are displayed on charts presented within this report.

Further analyses would be extremely valuable and should be completed as part of the proposed longitudinal study.

## 3.7. Hawke’s Bay

### 3.7.1. Overview

Sampling in Hawke’s Bay was led by LandWISE, supported by AgResearch, Massey University and Plant and Food Research. Over a three month period, 82 samples were collected across 60 sites, engaging with over 30 growers from across the region. The cyclone hit just before most fruit and vegetable crops were harvested. Some crops could be salvaged, but in many cases flood water either damaged the crop, buried it in sediment, or the edible part of the plant was inundated with flood water making it unsuitable for harvest.

**Figure 3-2 Examples of Hawke's Bay impacted areas: a sweetcorn paddock and an apple orchard.**

### 3.7.2. Sites

There were nine key impacted areas in Hawke’s Bay:

- Dartmoor Valley
- Esk Valley
- Fernhill
- Meeanee
- Otane
- Pakowhai
- Puketapu
- Tangoio
- Twyford

Sites for sampling were identified through existing grower networks and product group referrals and including some Hawke’s Bay Regional Council State of Environment monitoring sites.

The river catchments that were impacted and sampled in Hawke's Bay were:

- Tutaekuri River, leading from the Kaweka Ranges to the Pacific Ocean. Shares a river mouth with the Ngaruroro River and the Clive/Karamu River (LAWA, 2022).
- Ngaruroro River, headwaters in Kaweka and Ruahine Ranges (LAWA, 2022).
- Tutaekuri/Ngaruroro Rivers, where the two rivers became one in the flood through Pakowhai and Meeanee and sediment origin is difficult to determine.
- Waipawa River, largest tributary of the Tukituki River, draining from the Ruahine Ranges (LAWA, 2022).
- Mangaone River, which feeds into the Tutaekuri, upstream of Puketapu.
- Wharerangi Stream, historically flowed into the Tutaekuri, but was diverted into the Ahuriri Estuary for flood protection in the 1940's (LAWA, 2022).
- Te Ngarue Stream flows through the Tangoio Valley, tributaries are Rauwhirikokomuka and Kareaara Streams (Maungaharuru-Tangitu Trust, 2013).
- Esk River, headwaters in the Maungaharuru Ranges (LAWA, 2022).

Samples were collected from many different land use types and have been grouped into three categories for displaying results (Table 3-2). The land use type 'Field Cropping' includes fresh vegetables, process vegetables and arable cropping land. The land use type 'Permanent Tree Crops' includes mostly apples, but also grapes, avocados, and cherries. 'Pasture' includes dairy and drystock sites.

Table 3-2 Land use types sampled in Hawke's Bay

| Land Use Type | Number of sites | Number of samples |
|---|---|---|
| Field Crops | 33 | 45 |
| Apple Orchard | 18 | 25 |
| Dairy | 1 | 2 |
| Drystock | 2 | 2 |
| Vineyard | 4 | 4 |
| Avocado | 1 | 2 |
| Cherry | 1 | 2 |
| Total | 60 | 82 |

Samples were collected in four management or depth zones. The number of samples collected from each zone is provided below in Table 3-3.

Table 3-3 Number of sites in each sediment management zone (Hawke's Bay)

| Sediment Depth Zone | Number of sites in depth zone |
|---|---|
| 0 cm (no sediment deposited, or topsoil removed) | 5 |
| < 5cm | 13 |
| 5 – 20cm | 16 |
| >20cm | 26 |

The study documented actions growers had or were intending to take. Where there was a significant amount of sediment (5 – 20 cm or more), actions taken by cropping farmers include from leaving sediment bare until the spring, sowing a cover crop, through to mixing 5 – 20 cm of sediment into the soil. Some vegetable growers have mixed and or have removed 20+ cm of sediment from fields. Orchardists have removed up to 50 cm of sediment from within the tree-rows.

The spatial distribution of sampled sites and their land use type are presented in Figure 3-3. Several sites were not sampled in the 1 – 3 months following the cyclone, because the conditions remained too wet and muddy (people sank into the sediment), access to the site was not safe, or were still awaiting grower approval to access. Collection of information from these sites was underway at the time of compiling this report.

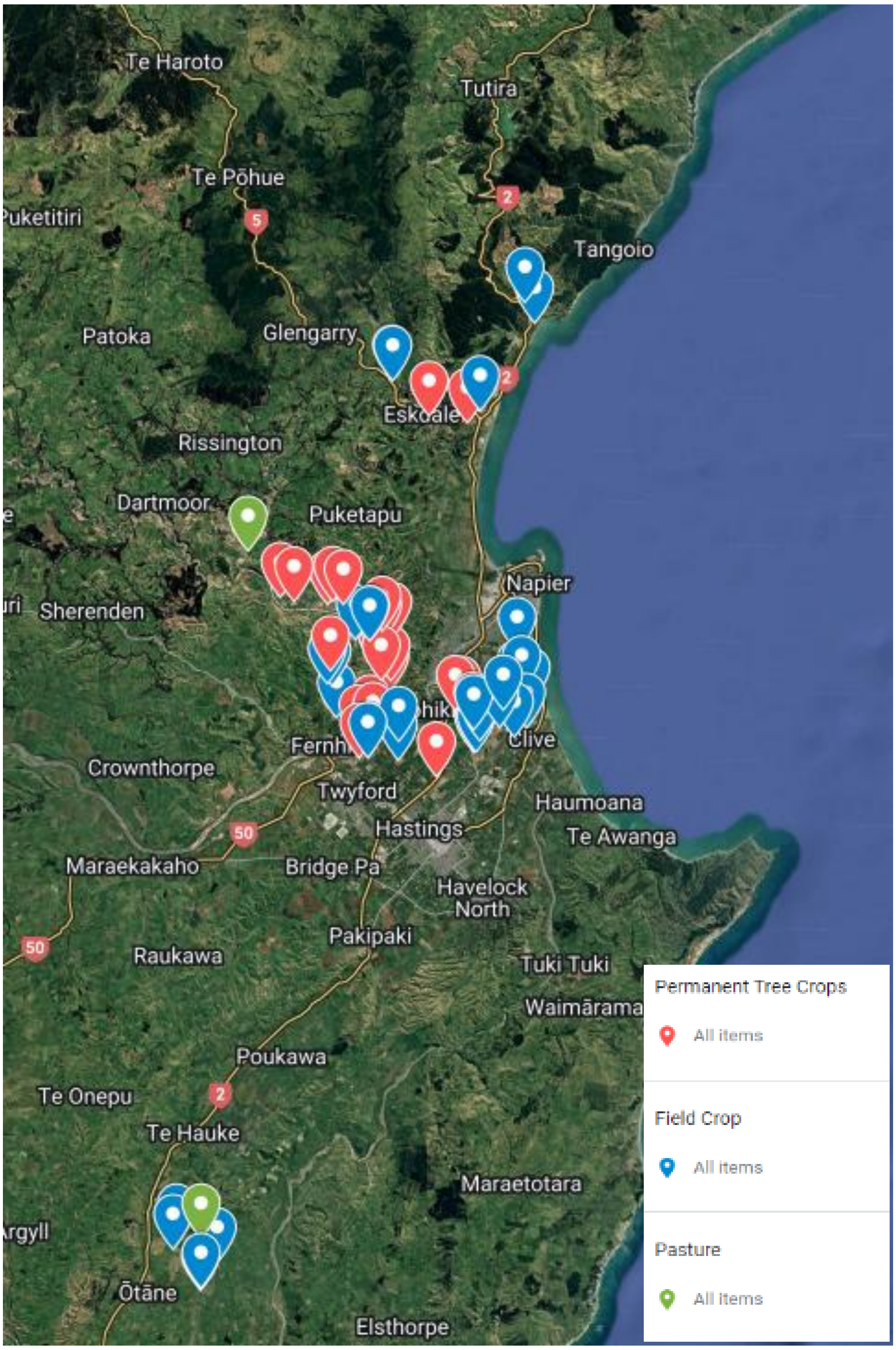


**Figure 3-3 Map showing distribution of sites sampled (Hawke's Bay)**

### 3.7.3. Physical properties

#### *3.7.3.1. Sediment texture*

The texture of the sediment varied across the catchments in the Hawke’s Bay. Textural classes were grouped for ease of interpretation (Figure 3-4). The map below shows locations of samples, and the main texture class found. Description of textural classes can be found in3.11.3 Appendix 3.

In the higher reaches of the Tutaekuri, in the Dartmoor valley coarser textures (fine to medium sands) were found. As the water flowed towards the coast the texture typically became finer (silty clay). The sediment textures from the flow path of the Ngaruroro are finer. Around Otane and Drumpeel Road, where a temporary lake formed from the Waipawa River moving into its historic flow path, water

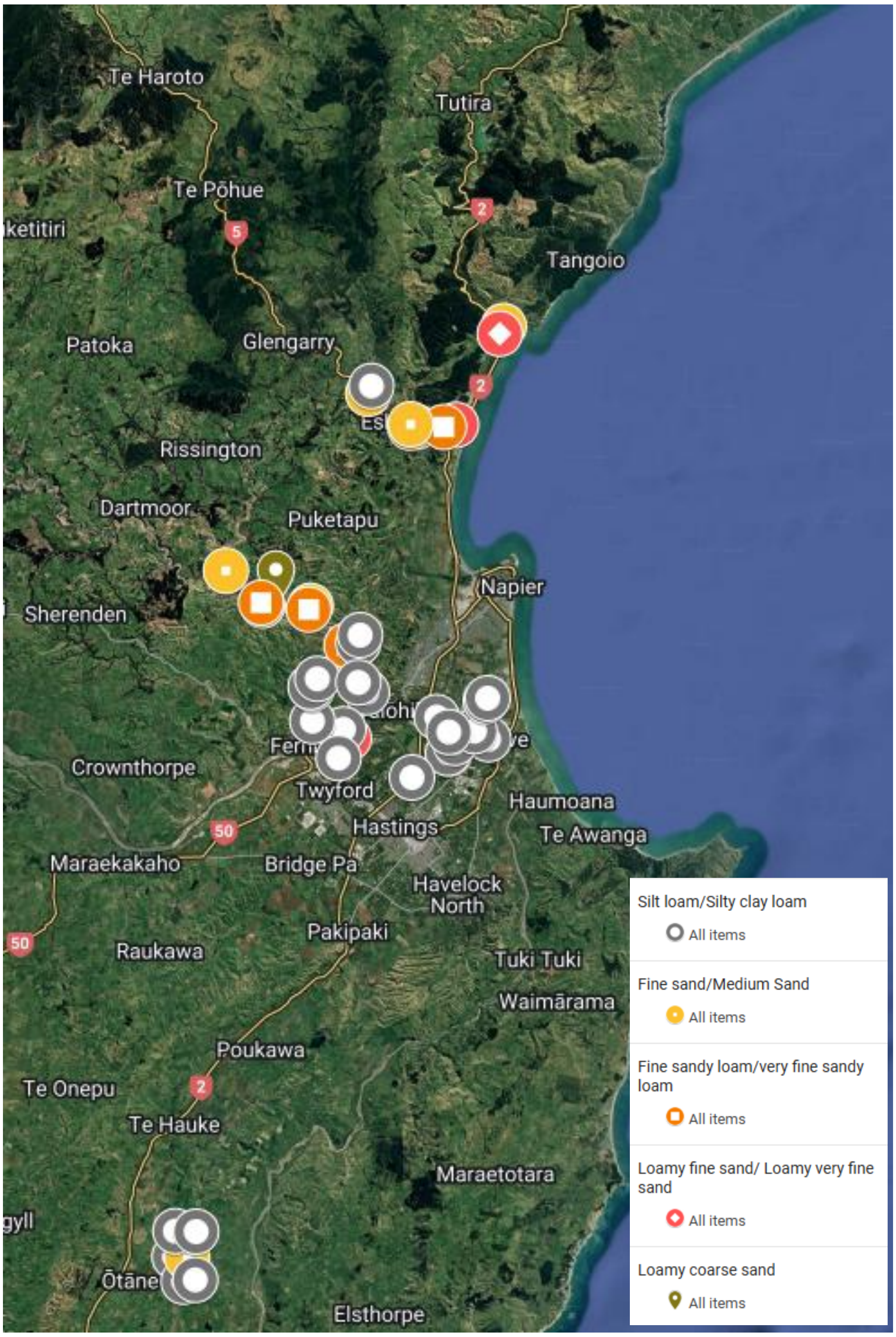


**Figure 3-4 Map showing distribution of sediment texture- Hawke's Bay**

remained for several weeks, and a finer (silty clay) sediment was deposited. North of Napier, coarse textures (fine to medium sands) were found along the entire length of the Esk Valley, except for a small area where water sat for several weeks. The Tangoio area also had coarse sediment (sand) deposited along the Te Ngarue flow path.

### *3.7.3.2. Bulk density*

The bulk density of the sediment sampled in the Hawke's Bay ranged from 0.70 to 1.49 g cm-3 Sediments sampled in the Mangaone, Te Ngarue stream and Esk catchments all had a bulk density value > 1.2 g cm-3 (Figure 3-5). This was associated with textures ranging from a fine sand, loamy fine sand, sandy loam, to fine sandy loam. This was also the case in the upper reaches of the Tutaekuri catchment. In the middle and lower reaches of the Tutaekuri and other four catchments, bulk density values ranged from 0.81 to 1.03 g cm-3 and textures of the sediment varied from a silt loam to a silty clay loam. As a guide, soil bulk density higher than 1.6 g cm-3 tends to restrict root growth. Sandy soils are more prone to high bulk density see 3.11.5 Appendix 5.

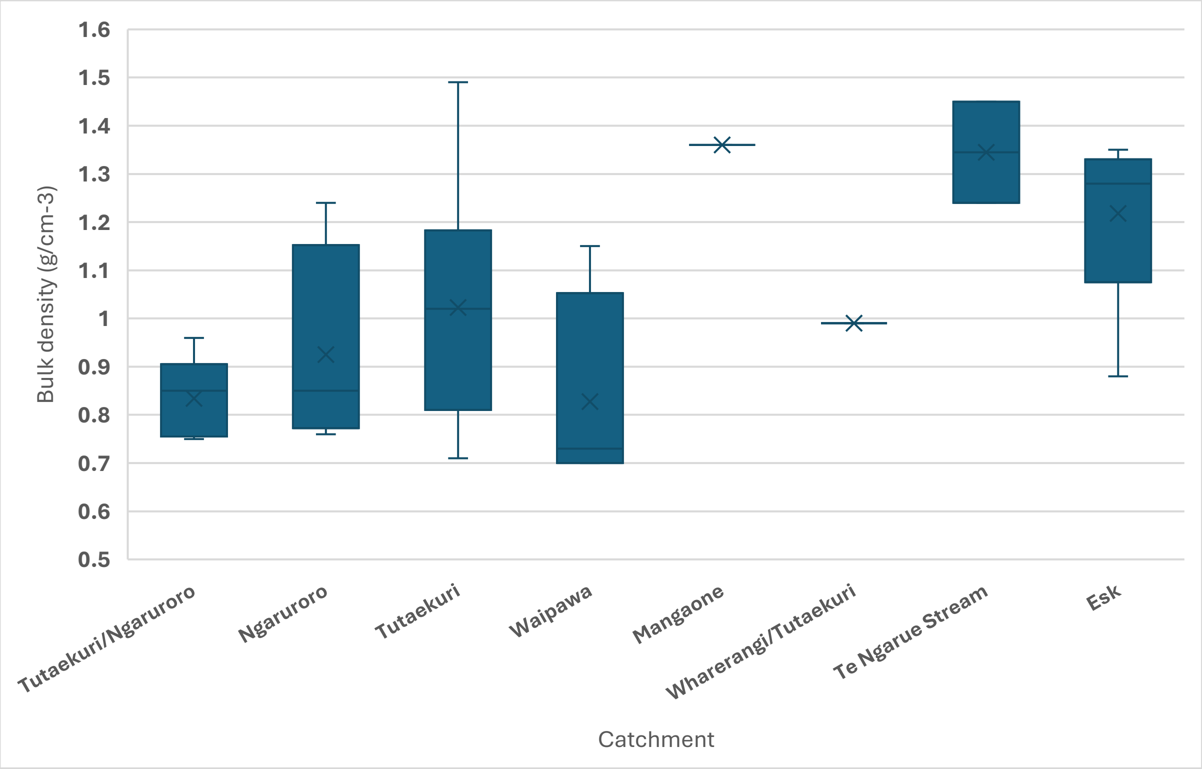


**Figure 3-5 Bulk density of sediment samples (Hawke's Bay)**

At the time of collection (33 – 80 days after the cyclone) the volumetric moisture content of the sediments sampled across the seven catchments within Hawke's Bay varied from 11 – 80%. The volumetric moisture content of the sediment at the time of sampling was highly correlated with the texture of the sediment (Figure 3-6). For example, the volumetric moisture content of the sediment collected from the Mangaone, Te Ngarue stream, Esk and upper reaches of the Tutaekuri catchments ranged from 12 – 33%, while the volumetric moisture content from samples from the middle and lower reaches of the Tutaekuri and other four catchments ranged from 43 – 61%. As sediment drains, particles slowly collapse, filling voids, and increasing the mass of material collected within a given volume.

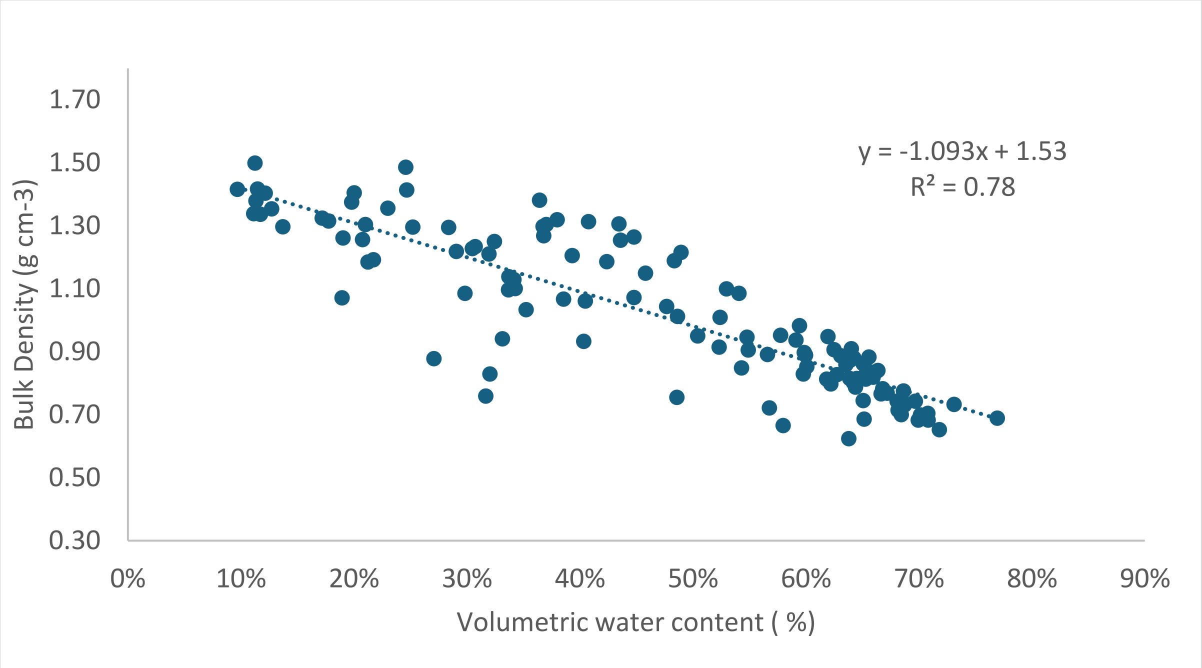


**Figure 3-6 Relationship between volumetric water content and bulk density sediment samples (Hawke's Bay)**

Scatter in the data may be due to the origin of the parent material containing different amounts of volcanic glass and organic matter, both of which will lower bulk density. In considering the effect of the physical properties of the sediment on plant growth, water infiltration, etc., bulk density, particle density and the porosity of the sediment have influence. The particle density of the coarse textured sediments (fine sand through to a loamy fine sand) which averaged 2.65 gm cm-3 was higher than the finer textured sediments (silt loam, silty clay loams) which averaged 2.48 gm cm-3 fine sandy loam. Most quartzo-feldspathic rocks such as greywacke, sandstone and mudstone are dominated by quartz and feldspar with specific gravities of 2.65 and 2.55-2.63 g cm-3, respectively. Sediments and soils with appreciable organic matter can have lower particle density because organic matter is generally in the range 0.8 – 1.1 g cm-3.

Soil porosity is the ratio of nonsolid volume to the total volume of soil. The porosities of the sediments across these two textural ranges were similar at 56 and 59%, respectively. In crop production, soil porosity is important in the conduct of water, air and nutrients. Further information and interpretation of bulk density and total porosity can be found in 3.11.5 Appendix 5.

#### *3.7.3.3. Visual Soil Assessment*

Of the 60 sites visited in Hawke's Bay, 55 had conditions that allowed for VSA to be completed (Table 3-4). The method of scoring Visual Soil Assessment is included in 3.11.1 Appendix 1. Sites generally achieved a moderate score where the sediment depth was less than about 15 cm and the pre-existing topsoil accounted for a significant proportion of the sample. Sites where soil structure was poor were generally deeper sediment deposits, where the topsoil below was not captured. The areas where the sites ranked as good had only a small amount of sediment deposited (< 5cm).

**Table 3-4 Average VSA total ranking scores per site**

| Soil Quality Assessment | Number of Sites | Average Ranking Score |
|---|---|---|
| Poor | 9 | 2.1 |
| Moderate | 44 | 12.1 |
| Good | 2 | 20.75 |

### 3.7.4. Chemical properties

#### *3.7.4.1. Contaminants (heavy metals and residues)*

Fourteen Hawke's Bay samples were submitted for contaminant testing. Results for heavy metals are presented in Table 3-15 (3.11.1 Appendix 1). The laboratory results were reviewed by Dr Jo Cavanagh at Landcare Research - Manaaki Whenua. Her full report is presented as 3.11.4 Appendix 4. The conclusion of this assessment was:

> *"There is no evidence for chemical contamination present in the deposited sediments. Trace element concentrations were largely within background concentrations across the region. Remarkably high copper concentrations were detected at one sampling site and warrants further investigation including assessment of current state of the biological health of the soil. Opportunities to minimise any ongoing copper should be considered. Pesticide residues were detected at two sampling site locations, although the source for these residues is unclear."*

#### *3.7.4.2. Nutrients*

Results for key nutrients are presented below. In the figures presented, indicative optimum bands for general crop performance are shown as green bands. Brief notes for each nutrient are provided.

#### pH

The pH of most sediment samples is elevated above the optimum range (Figure 3-7). This has been raised as an area of concern for nutrient availability in some crops. Outside of the optimum range, pH can lead to reduced availability of some macro and trace elements. The Waipawa samples had lower

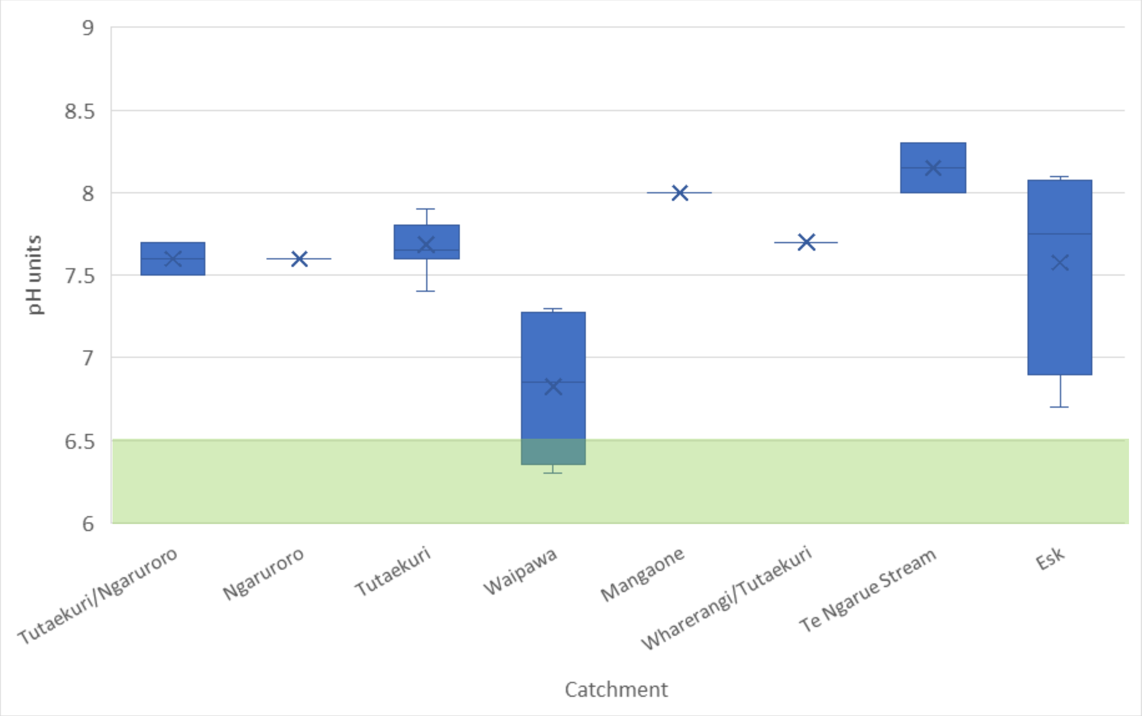


**Figure 3-7 Hawke's Bay sediment pH results by catchment. Optimum range for most crops shown from pH 6 – 6.5 (Reid & Morton, 2019).**

pH's, possibly due to a higher level of topsoil from upstream sites being included in the sediment samples. The source parent material (Whangai shale or Waipawa siltstone) also tends to be more acidic.

### Olsen P

With the exception of some samples collected in the Waipawa catchment, Olsen P was below optimum for most crop types (Figure 3-8). This can reduce crop yields and may need to be addressed through capital fertiliser programmes. Where sediment depth is within a cultivatable range (less than about 20 cm) the lower fertility sediment may be incorporated with existing topsoil, 'diluting' the sediment and raising phosphorous levels.

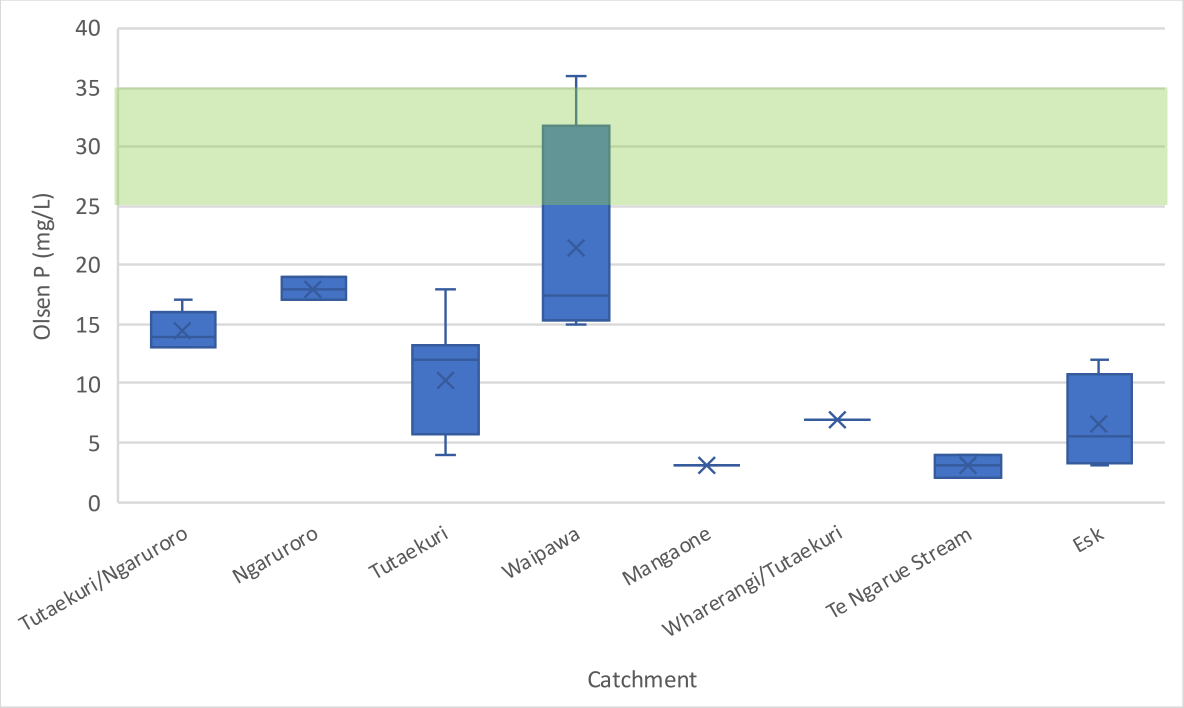


**Figure 3-8 Hawke's Bay sediment Olsen P results by catchment. Optimum range for most crops shown from 25 – 35 mg/L (Reid & Morton, 2019).**

### Quick Test (MAF K)

Quick Test Potassium (QTK) varied across catchments, and across the region Figure 3-9. Potassium is an important driver of yield for many crops (e.g. onions and tomatoes), so low potassium levels are likely to limit production. Higher K levels are not likely to cause concern. Low K levels are typically associated with sandier textured soils/sediments. These soil types can have high Total K levels (high proportions of orthoclase and mica) yet have low plant available K. Total K was not measured as part of the baseline sampling project.

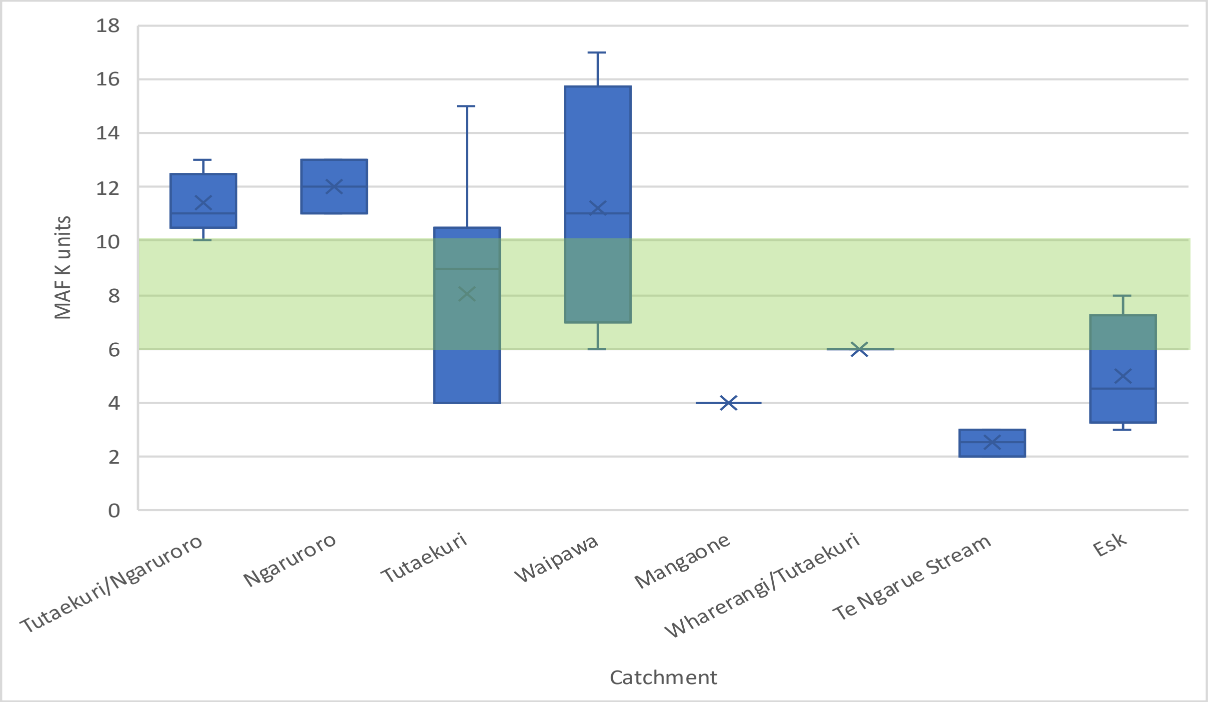


**Figure 3-9 Hawke's Bay Sediment Quick Test (MAF) Potassium Results by catchment. Optimum range for most crops shown from 6 – 10 MAF (Reid & Morton, 2019).**

### Sulphate Sulphur

Sulphate sulphur (plant available sulphur) levels across Hawke's Bay are typically low, generally less than 10 mg kg-1 pre-cyclone. Laboratory analysis of sediment samples following Cyclone Gabrielle showed that across most catchments sulphate sulphur is elevated and very high at some sites (Figure 3-10). Inconclusive discussion as to possible causes and impacts of the high sulphate sulphur levels indicates this should be further investigated.

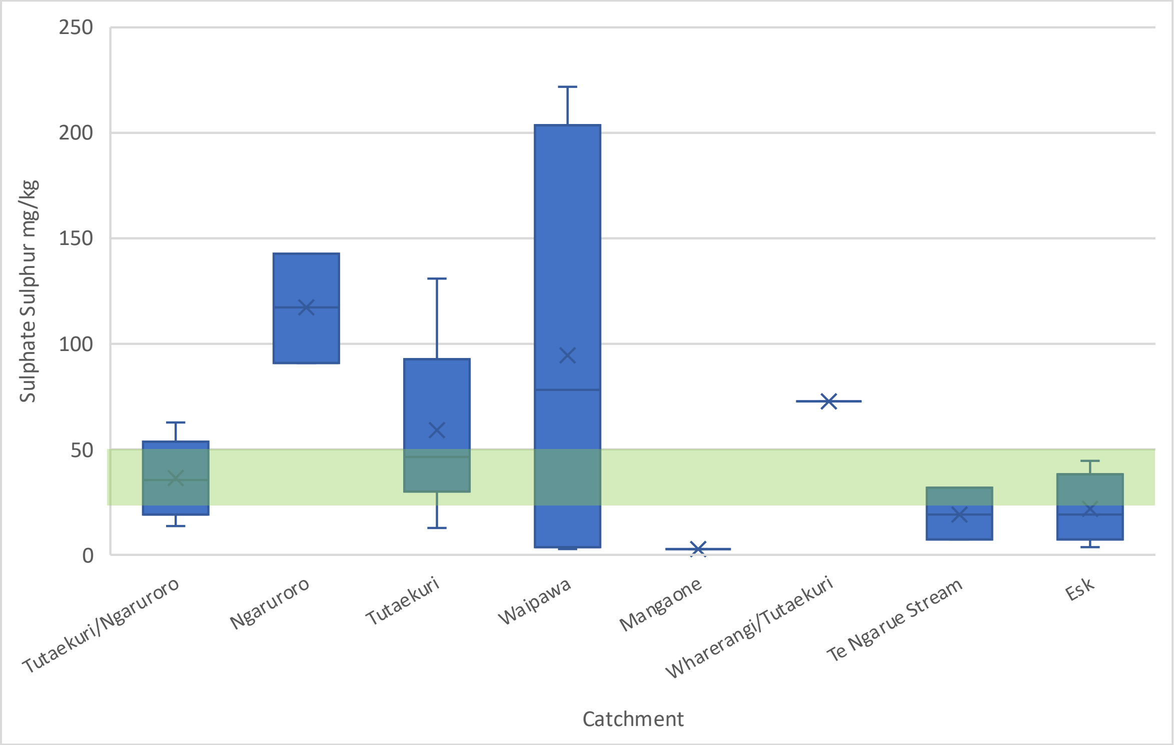


**Figure 3-10 Hawke's Bay sediment sulphate sulphur results by catchment. Optimum range for most crops shown from 25 – 50 mg/kg (Reid & Morton, 2019).**

### Organic Sulphur

While sulphate sulphur appears to be high, Extractable Organic Sulphur (slowly available) appears to be low (Figure 3-11). Where laboratory analyses found < 2 mg kg-1, the limit of detection, the data have been input with a value of 1.

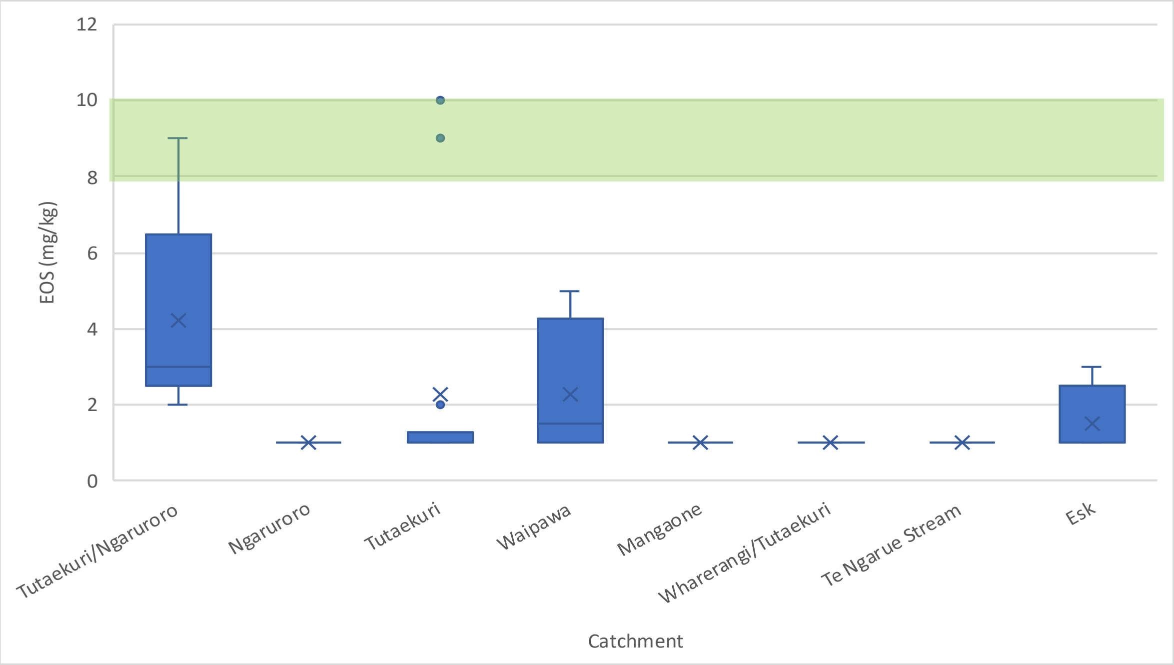


**Figure 3-11 Hawke's Bay sediment organic sulphur results by catchment. Optimum range for most crops shown from 8 – 10 mg/L (Reid & Morton, 2019).**

### Potentially Available Nitrogen (PAN)

PAN is a nitrogen test commonly used by vegetable and arable growers and provides an indication of how much nitrogen could be mineralised under ideal soil conditions. Results show a range of PAN values, most catchments had very low- low PAN, with the exception of Otane which had medium to very high PAN results (Hill Labs, 2023). 5 sites are excluded from this data as PAN was less than the minimum detection limit of 10kgN/ha.

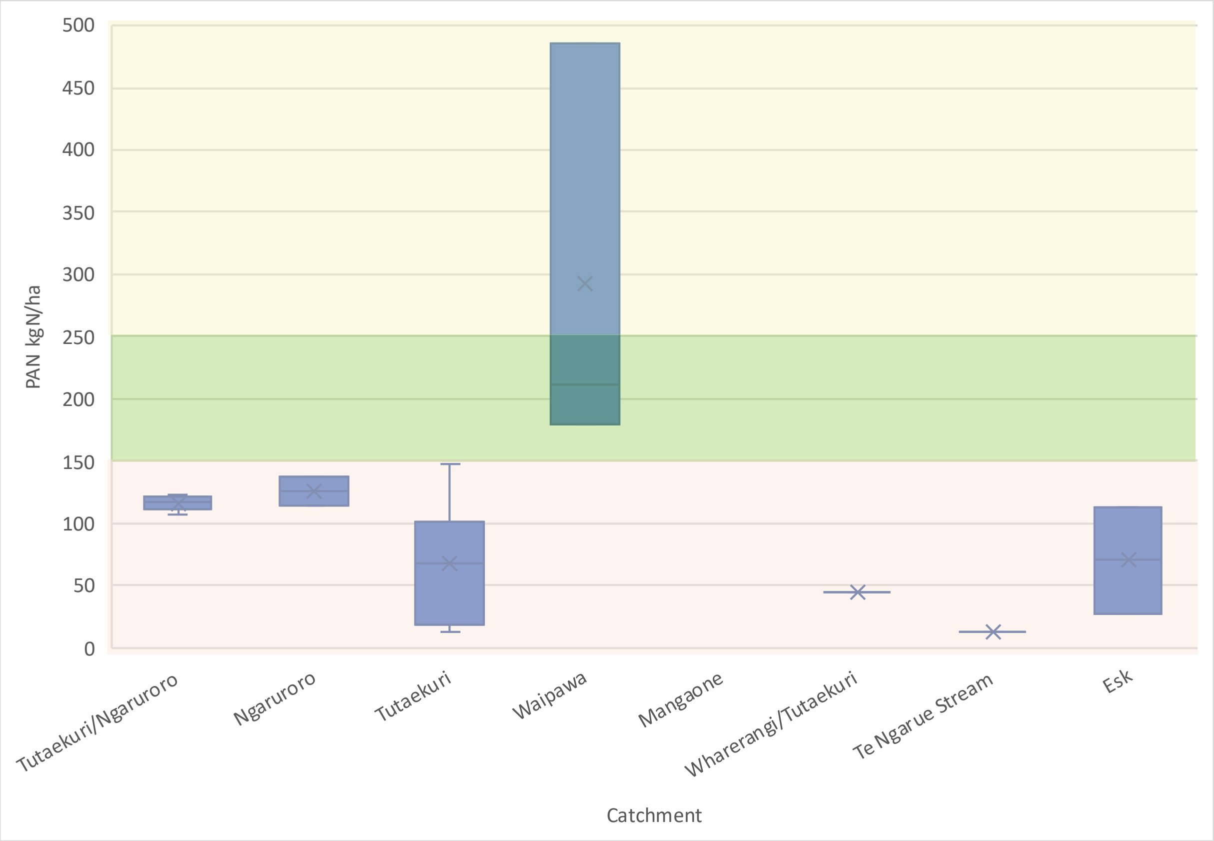


**Figure 3-12 Hawke's Bay sediment potentially available N by catchment. Optimum range for most crops shown in green from 150 – 250 kgN/ha (Reid & Morton, 2019).**

### Organic Matter Percentage

Organic matter plays a role in soil physical and chemical characteristics like nutrient availability, Cation Exchange Capacity (CEC), structure, moisture infiltration and retention. Hill Laboratories state that

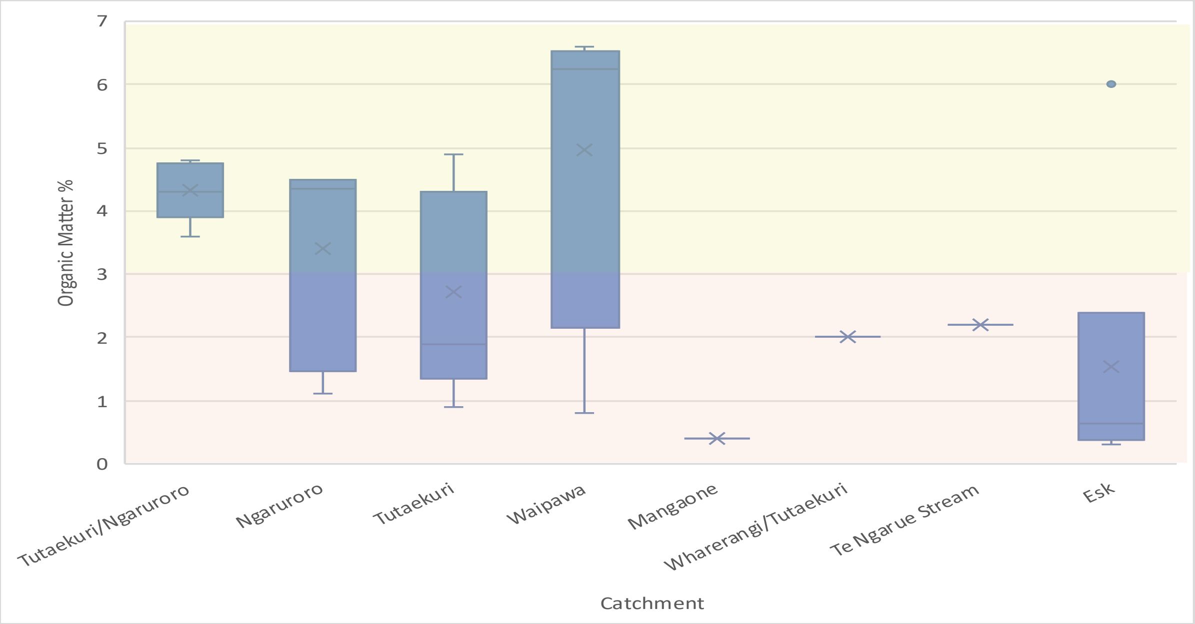


**Figure 3-13 Hawke's Bay sediment organic matter percentages by catchment. Very low shown in red (<3%), low in orange band 3 – 7% (Hill Labs, n. d).**

organic matter levels of 3 –7% are considered low, and < 3% is considered very low. On this basis, all sediment organic matter levels from Hawke's Bay are low or very low.

### Organic Matter vs Cation Exchange Capacity

As part of the interpretation of data, concerns have been raised over the low organic matter percentage and low CEC of some sediment deposits. Organic matter and CEC are two contributing soil characteristics that influence the soils ability to buffer herbicides. The below graph shows CEC vs organic matter percentage. All of the organic matter levels are low or very low. However, there is a range of CEC's from low to high.

Sites that are of concern are shaded blue in Figure 3-14 where organic matter levels are very low, and CEC is also low. We are concerned, but do not know, what this means for herbicide mobility, harm to crop, and loss to ground water.

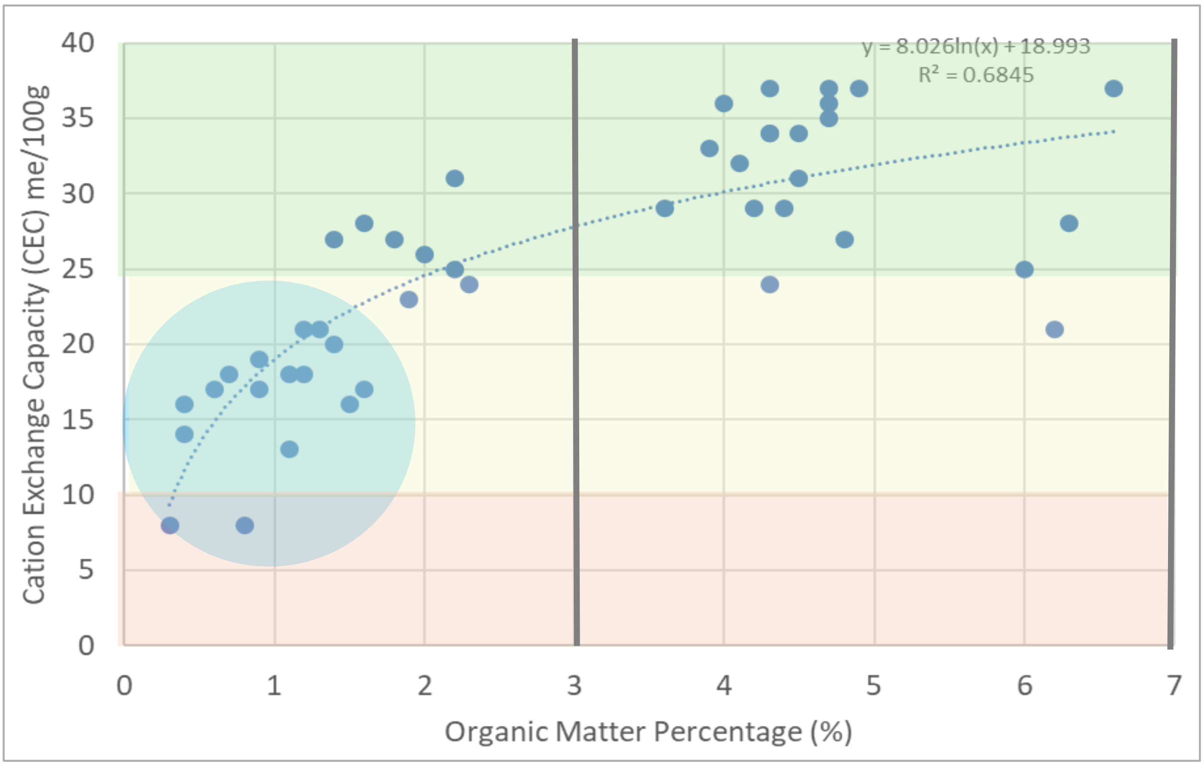


**Figure 3-14 Scatter plot of Hawke's Bay sediment cation exchange capacity versus organic matter percentage, showing many sites have very low levels which are of concern for herbicide use. Low CEC shown in red (<10 me/100g), moderate shown in orange (10 – 25 me/100g), high shown in green (>25me/100g) (Hill Labs, n. d.)**

### Total N Percentage

Total N content represents both chemically stable humus and partially decomposed organic matter fractions. This provides an indication of the amount of N the soil can provide. Most of the sites show low-medium Total N. One site in Otane had a very high Total N percentage. It is the same site that has higher PAN and OM% than other sites. Seven sites are excluded from this data as PAN was less than the minimum detection limit of 0.04%.

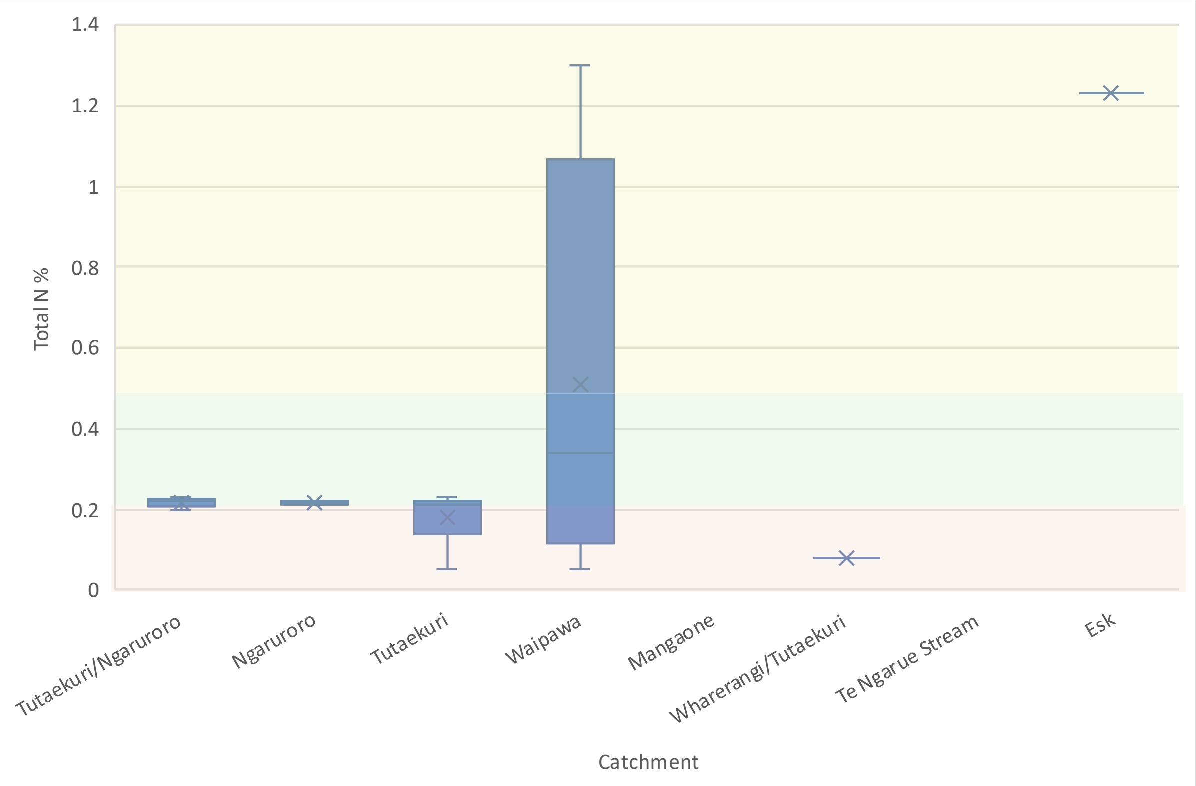


**Figure 3-15 Hawke's Bay Total N % by catchment. Low shown in red (<0.2%), medium in green (0.2 – 0.5%), high/very high (>0.5%) (Hill Labs, n. d.).**

## 3.7.5. Biological properties

### *3.7.5.1. Earthworm abundance and diversity*

Results from earthworm collection have been received for Hawke’s Bay samples. A short summary is provided from Dr Nicole Schon who completed the analysis, and data summarised in, Table 3-5, Table 3-6, Table 3-7.

Note: No statistical analysis has been completed, commentary is based on observations only and care should be taken when using this information.

*“The most common earthworm detected was endogenic Aporrectodea caliginosa, this species is the most common species found in agricultural soils in New Zealand. Endogenic species burrow extensively throughout the topsoil and form semi-permanent burrows. Other endogenic species found include Aporrectodea rosea and Aporrectodea trapezoides. Lumbricus rubellus was also found, this is an epigenic earthworm which decomposes organic matter on the soil surface, with another epigenic species, Eisenia andrei also found. Deeper burrowing anecic earthworms consisted of Aporrectodea longa. Native earthworms were also observed at two sites (#63 and 76).*

*Earthworm samples are normally collected in winter/spring to get the highest earthworm populations (aiming for 400 m$^{-2}$). Samples were collected in March to June (1-3 months) after flooding caused by Cyclone Gabrielle.*

*The effect of sediment depth, time since cyclone and the underlying land use had on earthworm abundance and diversity is summarized below. Given the samples are not balanced across sediment depth, time since the cyclone and underlying land use, treat any trends with caution.*

*Average earthworm abundance was low across all sites. Abundance tended to be lower at sites with > 20cm of sediment, these also had the smallest percent of samples with earthworms. The highest abundance of earthworms tended to be found on < 5cm of sediment, with the highest percent of samples with earthworms present in samples with no sediment.”*

**Table 3-5 Earthworm type and abundance ($m^{-2}$) by land use category**

| | Orchard | Cropping | Pastoral | Vineyard |
|---|---|---|---|---|
| Total earthworms | 55 | 27 | 0 | 13 |
| | | | | |
| Epigeic | 8 | 6 | 0 | 0 |
| Endogeic | 38 | 20 | 0 | 2 |
| Anecic | 8 | 1 | 0 | 10 |
| Native | 1 | 0 | 0 | 0 |

**Table 3-6 Earthworm type and abundance ($m^{-2}$) found in different depths of sediment.**

| | 0 | <5 | 5-20 | >20 |
|---|---|---|---|---|
| Total earthworms | 18 | 70 | 41 | 12 |
| Samples with earthworms (%) | 40 | 31 | 32 | 24 |
| | | | | |
| Epigeic | 3 | 13 | 9 | 1 |
| Endogeic | 13 | 54 | 26 | 9 |
| Anecic | 3 | 4 | 5 | 2 |
| Native | 0 | 0 | 2 | 0 |
| | | | | |
| Mature | 7 | 21 | 10 | 2 |
| Immature | 12 | 49 | 31 | 10 |
| Juvenile | 9 | 14 | 7 | 0 |

**Table 3-7 Earthworm type and abundance ($m^{-2}$) found in sediment sampled less than 40, between 40 and 80, and more than 80 days after flooding.**

| | <40 | 41-80 | >81 |
|---|---|---|---|
| Total earthworms | 28 | 14 | 77 |
| | | | |
| Epigeic | 2 | 4 | 14 |
| Endogeic | 23 | 10 | 49 |
| Anecic | 2 | 0 | 12 |
| Native | 0 | 0 | 2 |

**Figure 3-16 Earthworms found in Hawke's Bay samples**

### *3.7.5.2. Contaminants*

#### E. coli

Interpretation of E. coli concentration results was sought from industry experts. ESR Senior Scientist Dr Megan Devane provided an overview for the purpose of this report.

“There are some high concentrations of E. coli in sediment samples, which could be associated with faecal contamination. According to the current Biosolids Guidelines 2003 page 130 (and the draft revised guidelines, 2017) concentrations of E. coli > 100 MPN per gram of silt/sediment, indicate that there is a risk of exposure to disease-causing organisms from the sand/sediment.

Spatial variability of E. coli concentrations is expected as sediment/silt is a heterogenous environment, which is very different to the homogenous mixing that occurs in water samples.

E. coli will persist in sediment, especially the silty clay loams and less so for material with higher sand content. The concentrations are high for more than one month after the event. It is important to note that some pathogens associated with faecal contamination such as protozoa (Cryptosporidium and Giardia) and viruses will also persist long-term in environments such as sediments.

In future analyses, it would be appropriate to investigate those E. coli concentrations >100 E. coli /gram sediment by looking for faecal source tracking markers that identify human, ruminant (e.g. cows and sheep) and bird sources of faecal contamination. This could provide useful information and confirm the source of the E. coli particularly where you have indicated sites with proximity to sewage treatment plants etc.”

From the data presented, 12 out of the 14 samples submitted for E. coli testing exceeded 100 MPN/g, however the origin of this cannot be determined at this level of testing. Further evaluation by faecal source tracking could be warranted.

**Table 3-8 E. coli sampling results from fourteen Hawke's Bay sites**

| | **Site Number** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| E. coli MPN/g | 350 | 1,600 | 350 | >1,600 | 920 | 240 | 540 | 70 | 1,600 | 350 | <180 | 1,700 | 22 | 110 |
| Sediment texture | Silty clay loam | Silty clay loam | TBD | Silty clay loam | Silty clay loam | Silty clay loam | Silty clay loam | Silt | TBD | TBD | Mixed sample | Silty clay loam | Loamy very fine | Silt loam |

## 3.8. Gisborne

### 3.8.1. Overview

Sampling in Gisborne was undertaken by the Gisborne District Council Land Management team. Over three months, 55 samples were collected across 30 sites, engaging with over 22 growers from across the region. There was considerable impact to many crops including maize, squash, citrus, apples, and kiwifruit, as well as in the hill country. Cyclone Gabrielle came after two years of wet conditions, and the northern East Coast had already suffered several major weather events. There was already pressure on the region's people, crops and soils.

**Figure 3-17 Gisborne impacted areas: a maize paddock and a citrus orchard**

### 3.8.2. Sites

There were eight key impacted districts/catchments in the region:

- Hikuwai/Uawa
- Mangaheia
- Mata
- Pakarae
- Te Arai
- Waiapu
- Waihuka
- Waipaoa

The key impacted rivers are:

- Hikuwai River, the middle section of the Uawa River, north of Tolaga Bay (LAWA, 2022).
- Uawa River, headwaters near Tauwharepare, gullies prone to slipping and erosion (LAWA, 2022).
- Mata River, headwaters from the Raukumara Ranges, joins the Waiapu River (Gisborne District Council, 2022).
- Pakarae River, winds through hill country North of Gisborne. Highly erodible mudstones and sandstones (LAWA, 2022).

- Te Arai River, tributary of the Waipaoa River, lower reaches have tidal effects (Gisborne District Council, 2022).
- Waiapu River, formed by the joining of the Mata River from the Raukumara Ranges. Catchment prone to erosion (Gisborne District Council, 2022).
- Waipaoa River has a large catchment which formed the Poverty Bay Flats (highly productive soils). Typically, high sediment loading (Gisborne District Council, 2022).

**Table 3-9 Land use types sampled in Gisborne.**

| Land Use Type | Number of sites | Number of samples |
|---|---|---|
| Cropping | 11 | 16 |
| Apple Orchard | 9 | 14 |
| Citrus | 4 | 6 |
| Kiwifruit | 3 | 4 |
| Vineyard | 2 | 3 |
| Pasture | 10 | 12 |
| Total | 39 | 55 |

Samples were collected in four management or depth zone categories. The number of samples collected from each category is presented in Table 3-10.

**Table 3-10 Number of sites in each sediment management zone (Gisborne)**

| Sediment Depth Zone | Number of sites in depth zone |
|---|---|
| 0cm (no sediment deposited, or topsoil removed) | 0 |
| <5cm | 7 |
| 5-20cm | 23 |
| >20cm | 9 |

The spatial distribution of sites that have been sampled to date and their land use type are described in Figure 3-18 Map showing distribution of sites sampled (Gisborne)

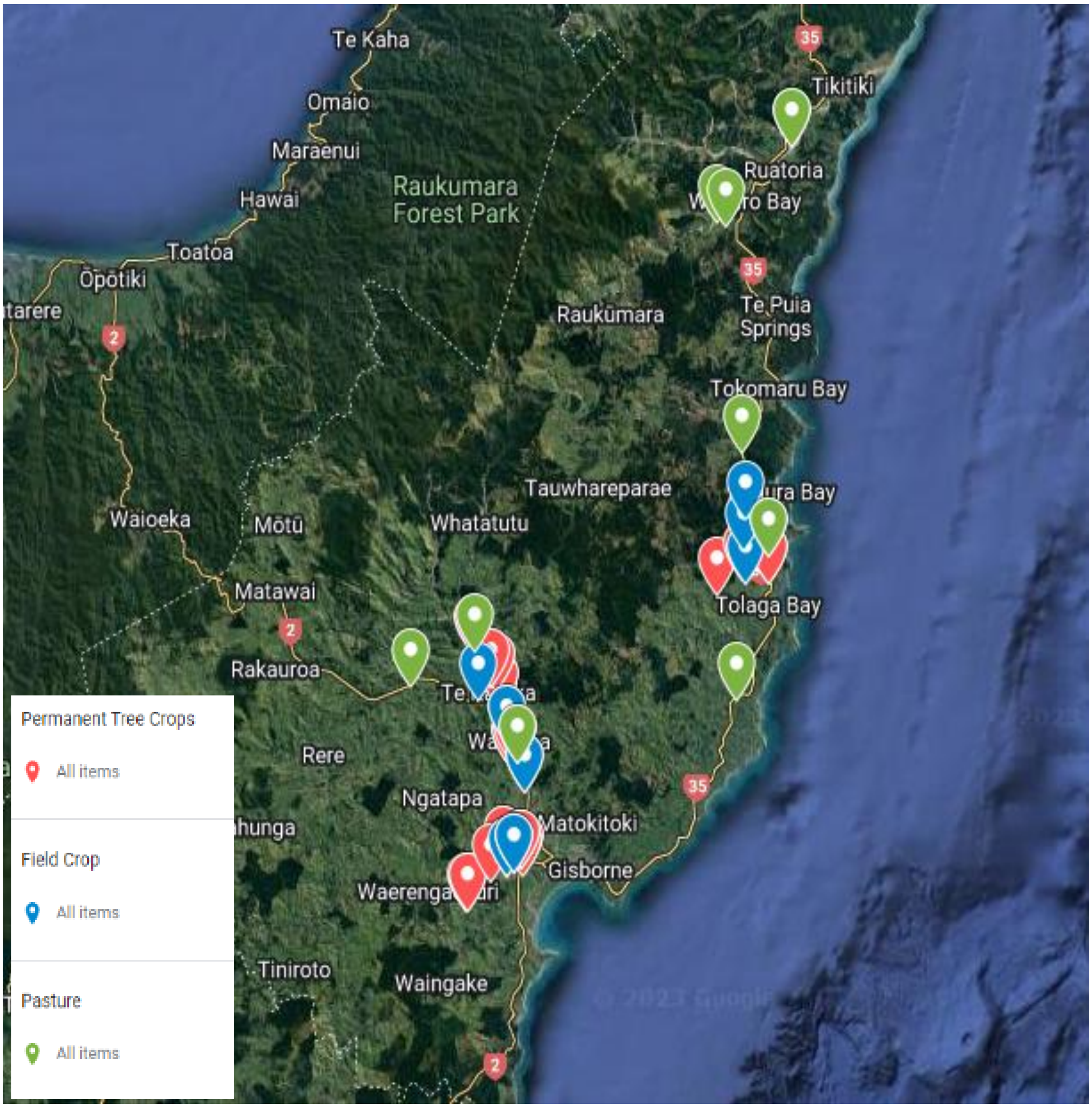


Figure 3-18 Map showing distribution of sites sampled (Gisborne)

.

## 3.8.3. Physical properties

### *3.8.3.1. Sediment texture*

There are a range of sediment textures deposited around the Gisborne and Northern- East Coast areas. In the northern end, deposits from the Mata River are medium sands-medium sandy loams. Where the Mata enters the Waiapu River which makes its way to the coast, deposits are coarse silts/coarse silt loams.

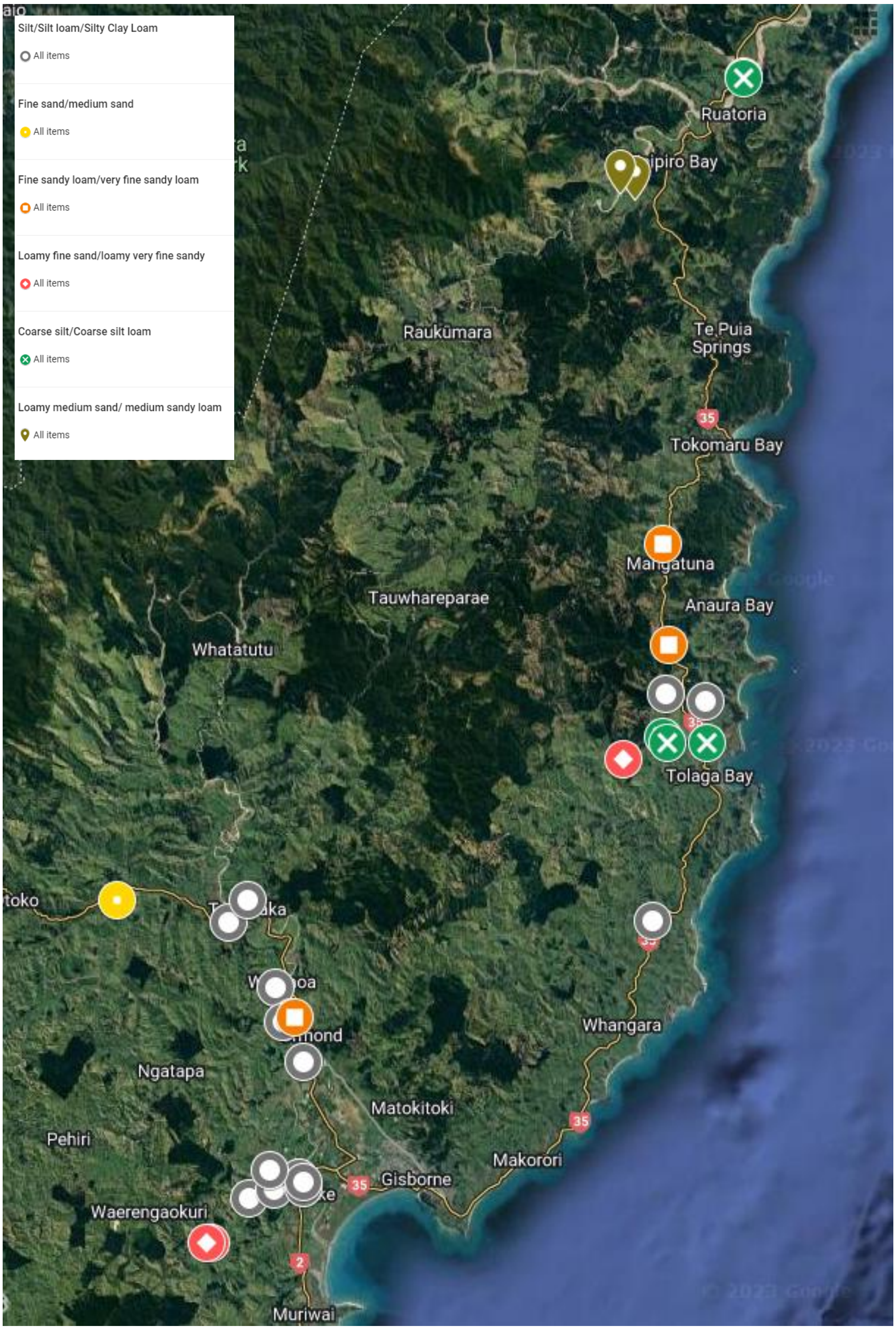


**Figure 3-19 Map showing distribution of sediment textures (Gisborne)**

In the northern reaches of the Hikuwai River, north of Tolaga Bay, sediment deposits are fine sandy loams/very fine sandy loams. As the Hikuwai becomes the Uawa river closer to Tolaga Bay, deposits are silt loams/silty clay loams and are coarse silts/coarse silt loams at the bottom of the catchment.

Closer to Gisborne, along the Waihuka river, deposits are fine sands. Along the Waipaoa River, where the majority of samples were collected, deposits are silt loam/silty clay loams. Samples collected along the Te Arai are loamy fine sands/loamy very fine sands.

Further details on textural classes can be found in 3.11.3 Appendix 3.

### *3.8.3.2. Bulk density*

The bulk densities of sediments sampled in the Gisborne District ranged from 0.91 to 1.55 g cm-3, higher than those in Hawke's Bay. Within each catchment there was a greater range in the textural classes of sediment than documented in the Hawke's Bay, which in part explains the wide range in the bulk density values reported. For example, in the Te Arai catchment the textures of the sediment varied from loamy fine sands through to silt and silt clay loams, and in the Waipaoa catchment the texture classes ranged from a very fine sandy loam through to silt loam to silty clay loam to a clay loam. The sediment in the Waihuka, Mata, and Waiapu catchments were less variable and tended to be at the coarse end of the textural range.

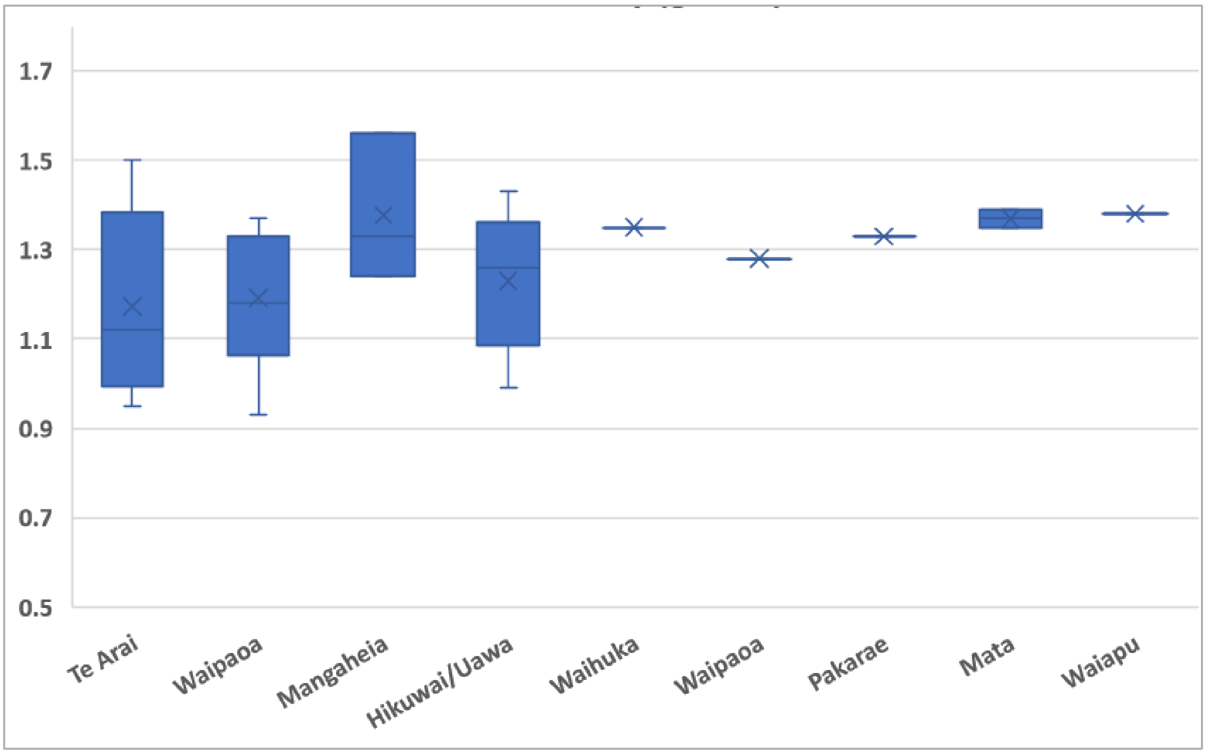


**Figure 3-20 Bulk density of sediment samples (Gisborne)**

### *3.8.3.3. Visual Soil Assessment*

Visual Soil Assessment for all 49 Gisborne sites was completed on sediment samples and on mixed samples (more than one VSA completed on some sites). If a site had a layer of sediment less than a spade depth, a VSA was completed on the whole top 20cm profile, and an additional VSA was completed for the sediment layer alone. Results below are split into two tables, one for sediment alone and one for mixed sites (Table 3-11).

**Table 3-11 Visual Soil Assessment Results Gisborne**

| Soil Quality Assessment | Number of Sites (mixed soil + sediment) | Average Ranking Score |
|---|---|---|
| Poor | 9 | 2.2 |
| Moderate | 14 | 11.6 |
| Good | 0 | N/A |
| | | |
| **Soil Quality Assessment** | **Number of Sites (sediment only)** | **Average Ranking Score** |
| Poor | 11 | 2.7 |
| Moderate | 17 | 11.1 |
| Good | 3 | 20 |

## 3.8.4. Chemical properties

### *3.8.4.1. Nutrients*

### Soil pH

The pH levels of all Gisborne sediment samples were significantly higher than the optimum range for most crop types (Figure 3-21). This is similar to Hawke's Bay's results and could impact macro nutrient and trace element availability of future crops and animal health.

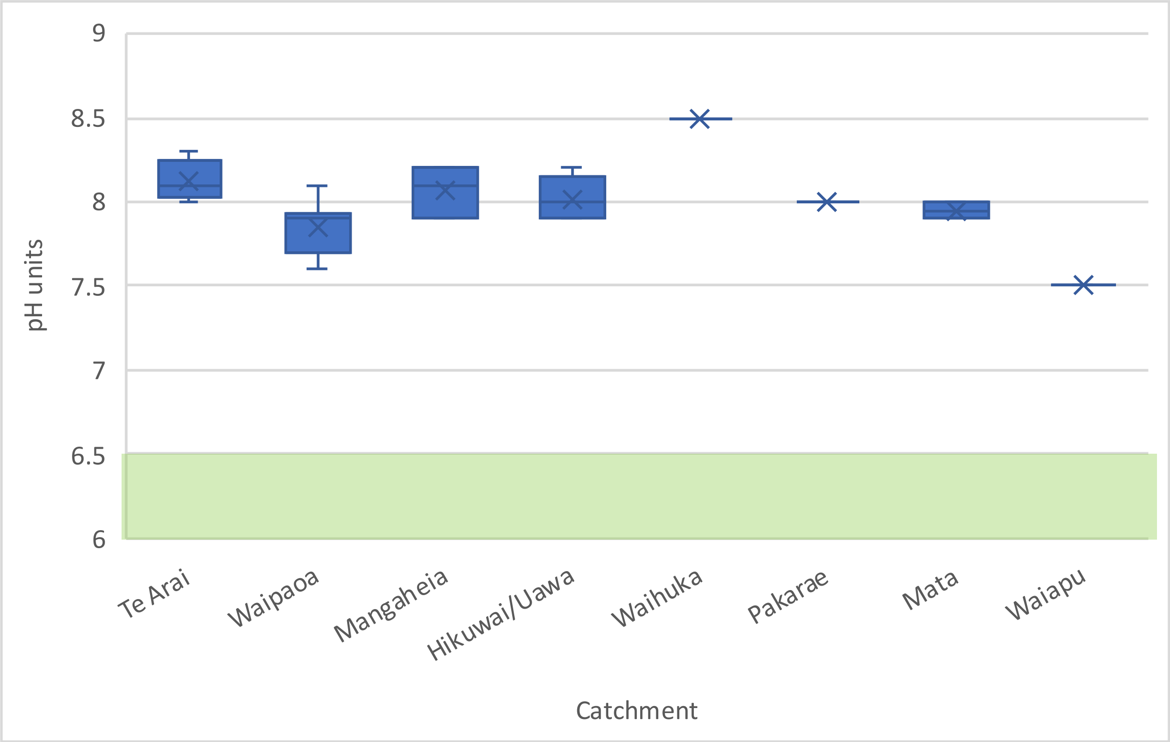


**Figure 3-21 Gisborne sediment pH levels by catchment. Optimum range for most crops shown from pH 6 – 6.5 (Reid & Morton, 2019).**

### Olsen P

For the majority of samples, Olsen P is below optimum for most crop types (Figure 3-22). This may reduce potential crop yield, although there may be opportunity to mix sediment with the pre-existing topsoil below. Questions have arisen as to whether maize planted directly into deeper sediment would be able to grow roots to access nutrients in the buried underlying soil.

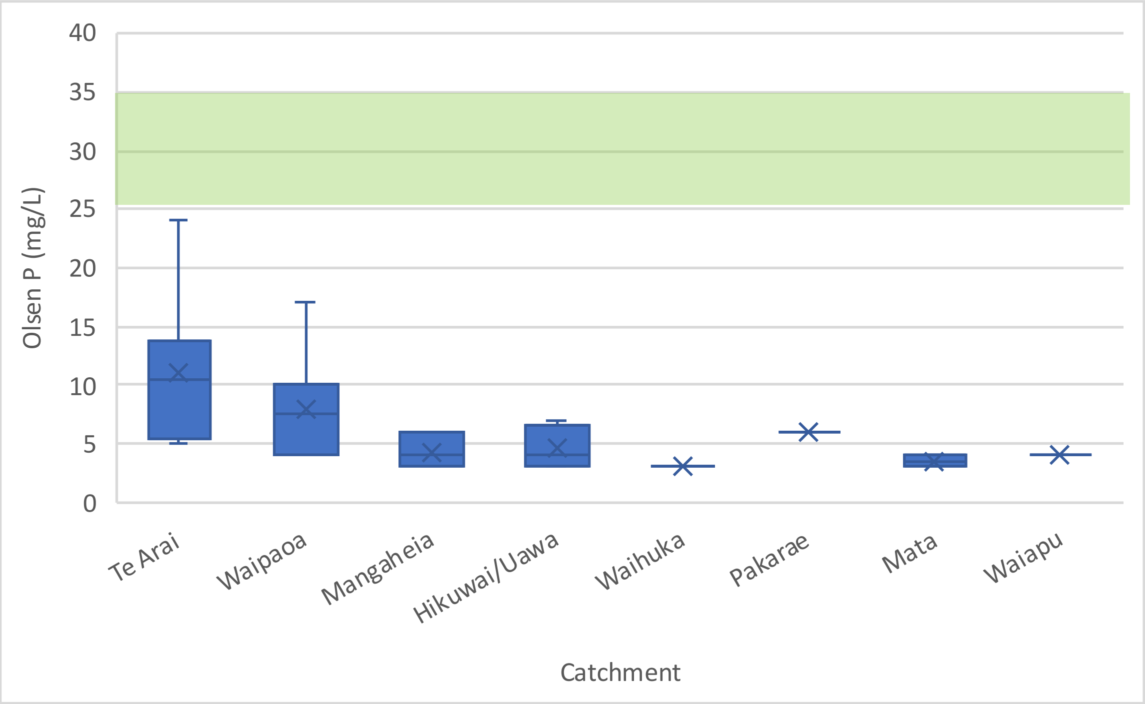


**Figure 3-22 Gisborne sediment Olsen P levels by catchment. Optimum range for most crops shown from 25 – 35 mg/L (Reid & Morton, 2019).**

## Quick Test K

Quick Test Potassium (QTK) varies across catchments, and across the region (Figure 3-23). Potassium is an important driver of yield for many crops, and low levels of K may limit yield. Growing depletive crops such as tomatoes that remove significant amounts of potassium from the soil may exacerbate already low soil K levels.

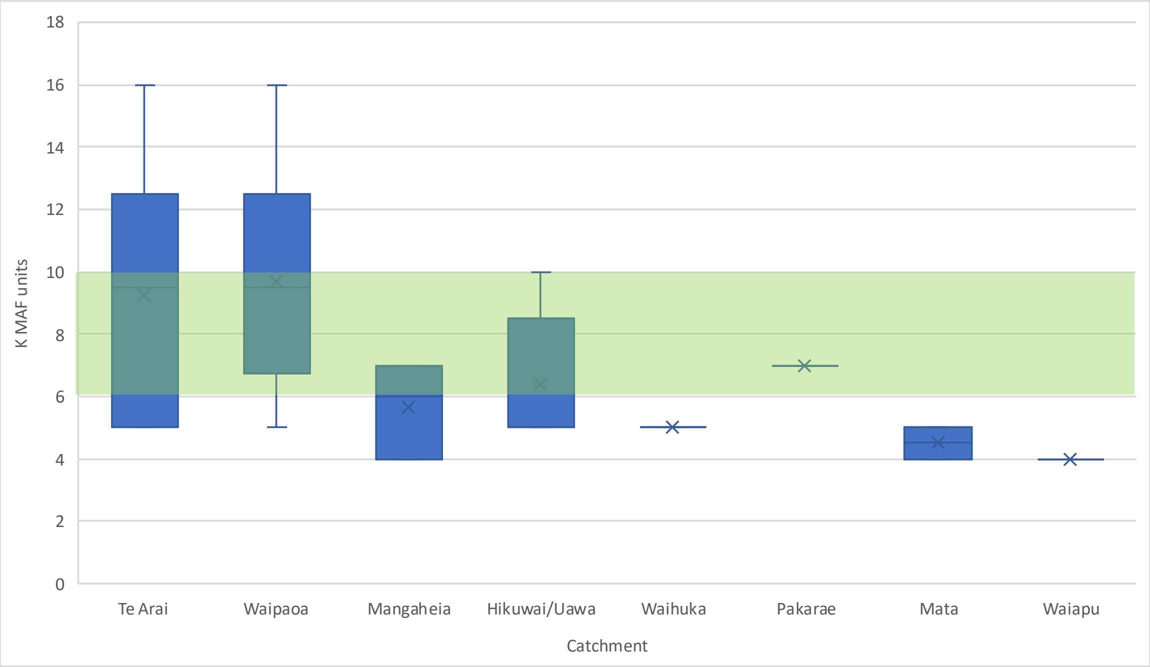


**Figure 3-23 Gisborne Sediment QTK Results by catchment. Optimum range for most crops shown from 6 – 8 MAF Units (Reid & Morton, 2019).**

### Sulphate sulphur

Laboratory analyses found sulphate sulphur levels were very high across most catchments (Figure 3-24). Inconclusive discussion of possible causes and impacts indicates this should be further investigated. Other questions raised include the interaction between sulphur, molybdenum (as influenced by pH) and copper availability to livestock, if these areas are sown to pasture as part of the restoration process.

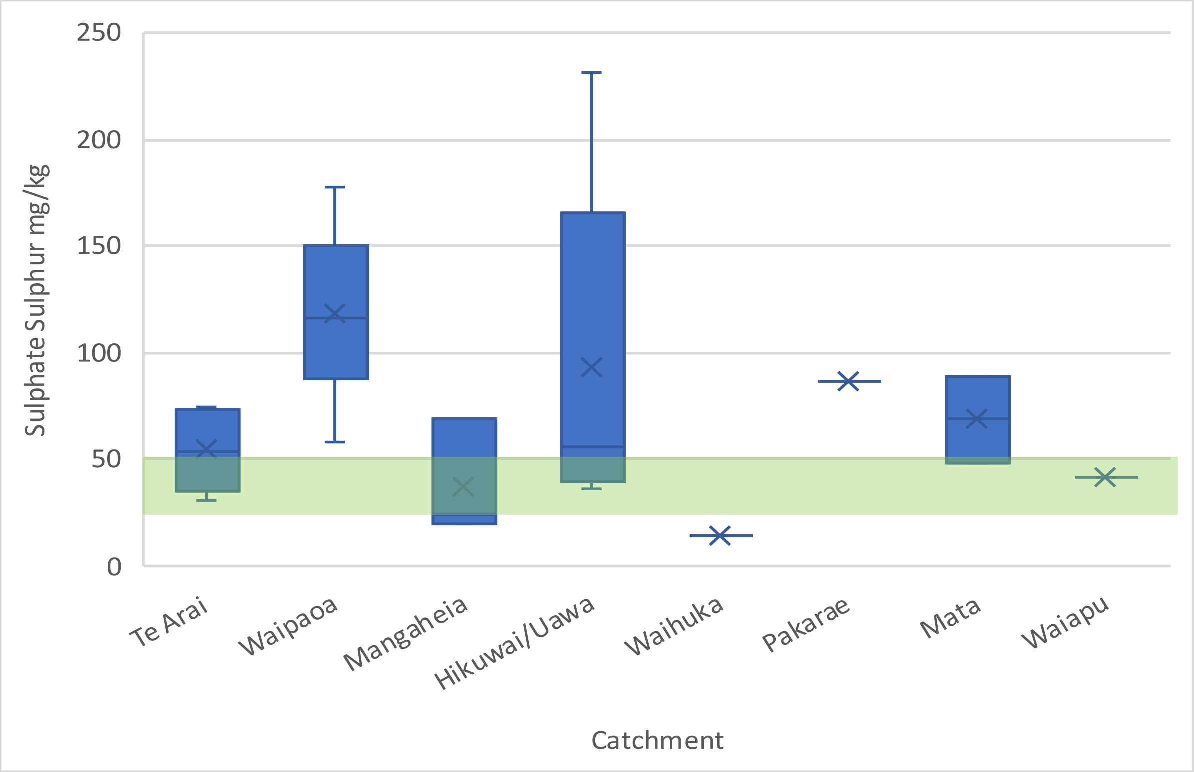


**Figure 3-24 Gisborne sediment sulphate sulphur by catchment. Optimum range for most crops shown from 25 – 50 mg/kg (Reid & Morton, 2019).**

### Organic Sulphur

While sulphate sulphur appears to be high, Extractable Organic Sulphur (slowly plant available) is low. In Figure 3-25, laboratory results below the minimum test level of 2mg/kg have been input as 1, showing very low levels of organic sulphur.

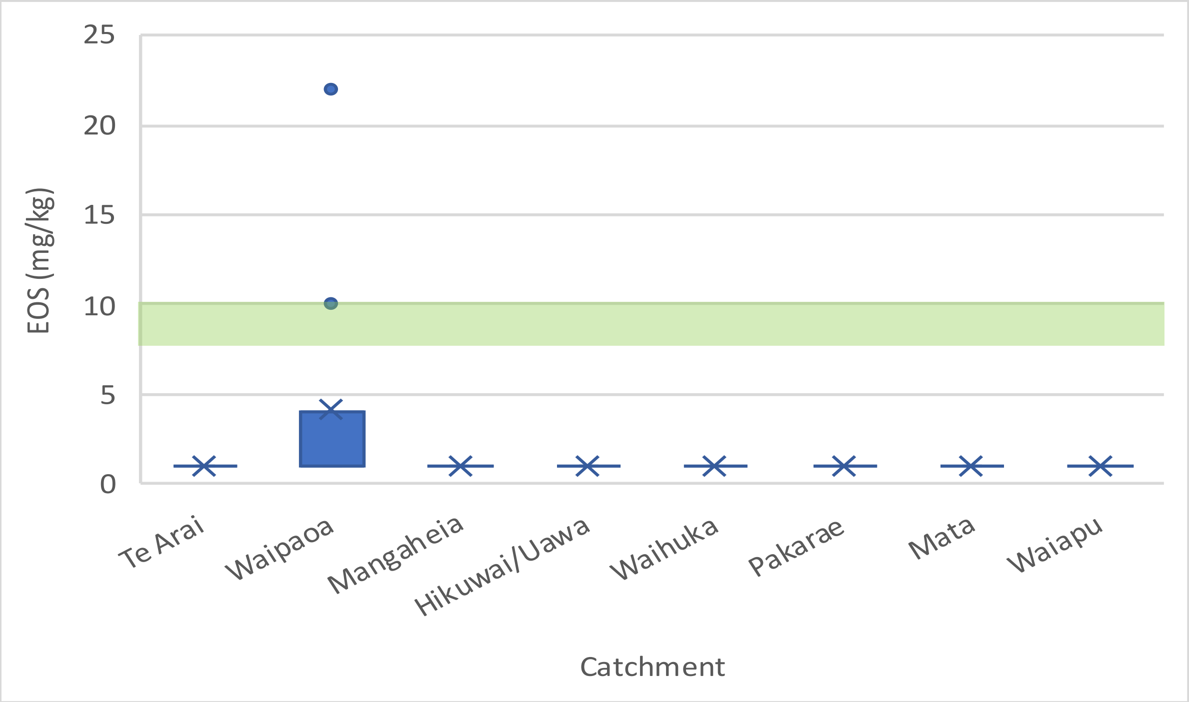


**Figure 3-25 Gisborne sediment Extractable Organic Sulphur (mg/kg) by catchment. Optimum range for most crops shown from 8 – 10 mg/L (Reid & Morton, 2019).**

### Potentially Available Nitrogen

In Gisborne PAN of sediment is very low (<50kg/ha) to low (50-150kg/ha). This shows that the ability for the sediment to provide N to growing plants is low (Hill Labs, 2023). Seven sites are excluded from this data as PAN was less than the minimum detection limit of 10kg/ha.

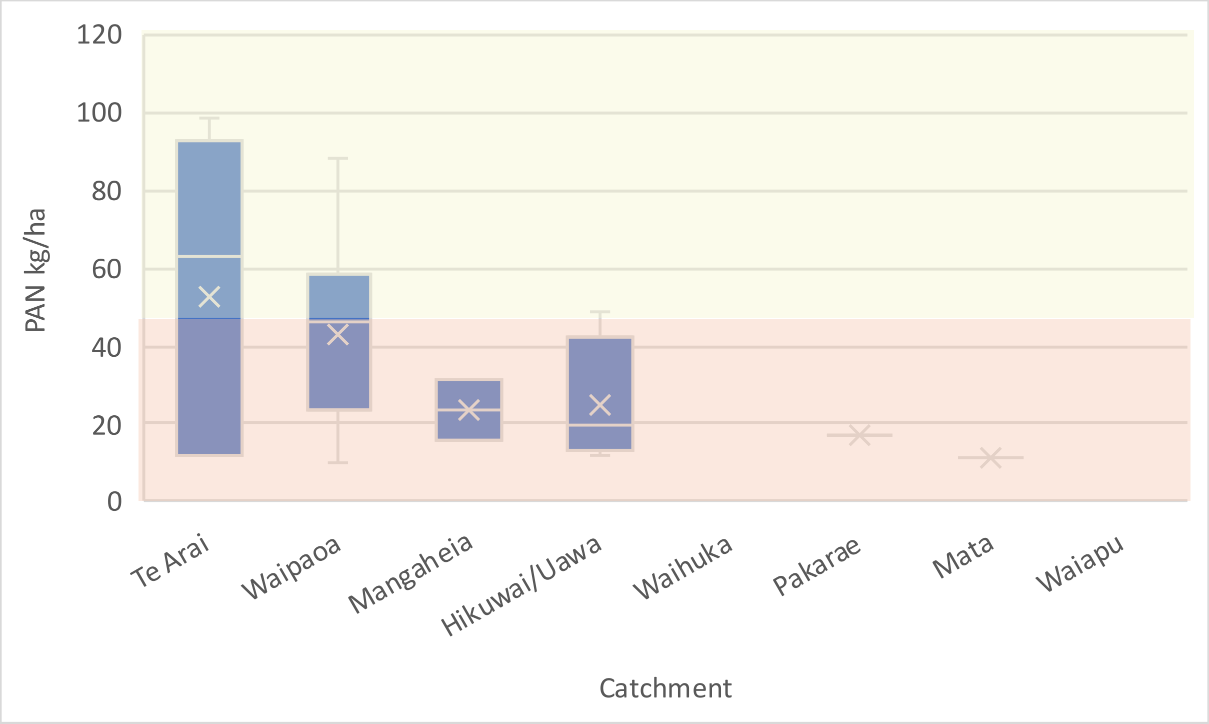


**Figure 3-26 Gisborne Sediment Potentially Available N (kg/ha) by catchment. Very low levels shown in red (<50kgN/ha), low levels 50 - 120 kgN/ha (Reid & Morton, 2019).**

### Organic Matter Percentage

In Gisborne the organic matter content of sediments is low (3-7%) to very low (<3%). These low organic matter levels may adversely affect soil structure, nutrient availability and water retention.

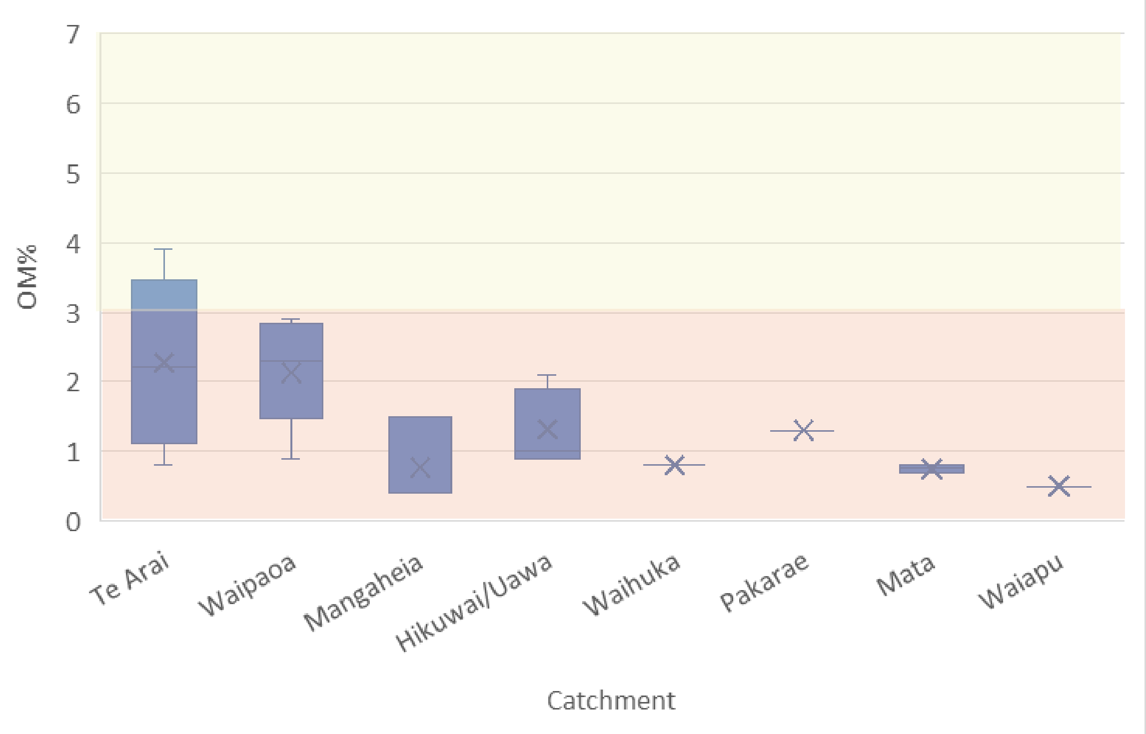


**Figure 3-27 Gisborne Sediment Organic Matter %. Very low shown in red (<3%), low in orange 3 – 7% (Hill Labs, n. d).**

### *3.8.4.2. Total N*

Due to submission error Total N was not tested for on the Gisborne samples.

## 3.9. Wairoa/Nuhaka (Northern Hawke's Bay)

### 3.9.1. Overview

Sampling in Wairoa was undertaken by the Gisborne District Council Land Management team. Wairoa was the last region on the East Coast to be sampled, due to access challenges. Six samples were collected across five sites, engaging with four impacted growers in the region. Nine farmers and growers were impacted by sediment deposition in the lower Wairoa catchment. Most of the impact was on lowland areas growing maize, squash and grass, as well as an apple orchard. Some of the impacted areas are part of dairy or drystock farms that have productive flats planted for maize over the summer.

Cyclone Gabrielle followed two previous very wet years, with Wairoa having been hit with several major weather events. The impacted flats are an important part of many farm systems in the area, providing feed for winter grazed stock.

**Figure 3-28 Wairoa impacted areas: maize paddocks.**

### 3.9.2. Sites

There were two key impacted areas in the region:

- Nuhaka
- Wairoa

The key impacted rivers are:

- Wairoa River, Hawke's Bay's largest river. River mouth can close due to sea currents. Upper boundaries in the Te Urewera National Park. Catchment dominated by soft sedimentary rock, prone to erosion (LAWA, 2022).
- Nuhaka River, origin in the Whareata Ranges.

Table 3-12 land Use Types Sampled in Wairoa

| Land Use Type | Number of sites | Number of samples |
|---|---|---|
| Cropping (sample no. 1-4) | 4 | 5 |
| Orchard (sample no. 5) | 1 | 1 |

Samples were collected in four management or depth categories. The number of samples collected from each category is shown in Table 3-13. With the depth of the sediment at four of the sites well in excess of 20 cm, the sediment and its properties represent the new soil surface.

Table 3-13 Number of sites in each sediment depth category (Wairoa)

| Sediment Depth Category | Number of sites in depth zone |
|---|---|
| 0cm (no sediment deposited, or topsoil removed) | 0 |
| < 5 cm | 0 |
| 5 – 20 cm | 1 |
| > 20 cm | 4 |

### 3.9.3. Physical properties

#### *3.9.3.1. Sediment texture*

Sediment textures along the Wairoa River are either silt loam, silty clay loam or loamy medium sand. The sediment texture from the sample taken from Nuhaka (Nuhaka River) was a fine sandy loam.

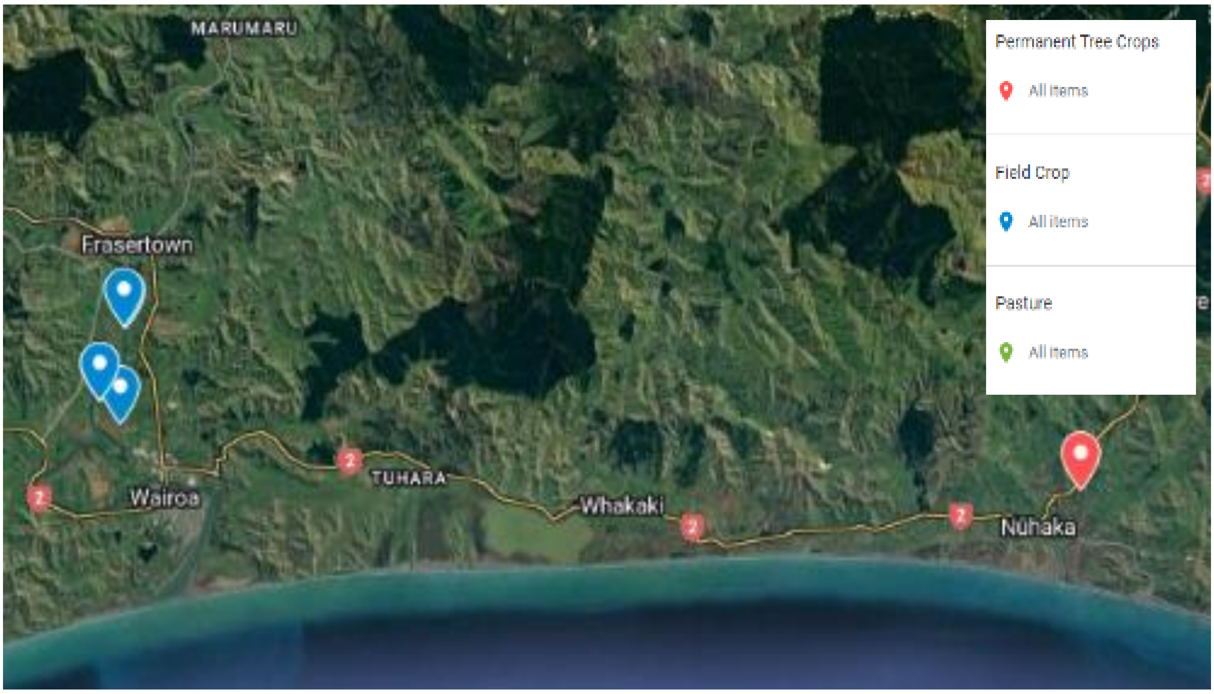


Figure 3-29 Map showing distribution of sites sampled (Wairoa)

### 3.9.3.2. *Bulk density*

The bulk density of sediment sampled in Wairoa averaged 1.09 g cm-3 with a volumetric moisture content of 53% (Figure 3-30). These values are similar to those reported in Hawke's Bay. The textures of Wairoa samples varied from a fine sandy loam (site 44 W), loamy medium sand (site 41 W) through to a silt loam (site 43 W) and silty clay loam (site 42 W). The low bulk density of the sediment samples at site 42 W was associated with a very high volumetric moisture content (70%) compared with the volumetric moisture content (40 – 43%) at the two sites where the sediment had a sandy texture.

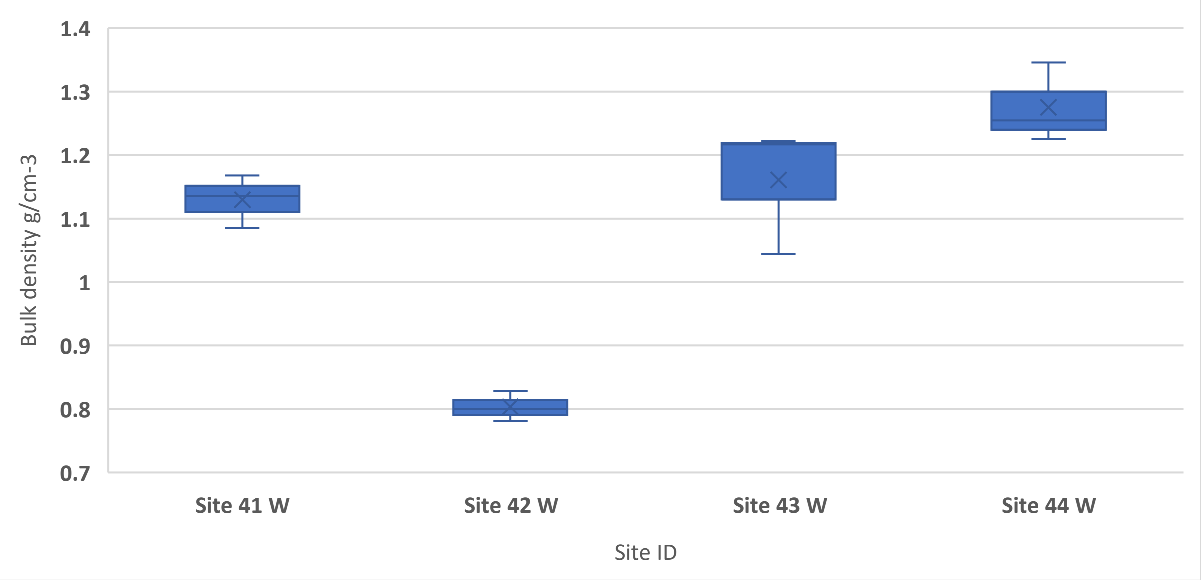


**Figure 3-30 Bulk density of sediment samples collected in Wairoa.**

### 3.9.3.3. *Visual Soil Assessment*

VSA was completed at all five sites visited in Wairoa and Nuhaka (Table 3-14). Four of the five sites had a 'poor' VSA score, and the moderate score was at the very low end of the moderate range. With the depth of sediments greater than 20 cm, these values represent the new growing surface.

**Table 3-14 Visual Soil Assessment Results Wairoa**

| Soil Quality Assessment | Number of Sites (sediment only) | Average Ranking Score |
|---|---|---|
| Poor | 4 | 2.75 |
| Moderate | 1 | 7 |
| Good | 0 | N/A |

### 3.9.4. Chemical properties

#### *3.9.4.1. Nutrients*

##### pH

All sediment samples analysed for Wairoa/Nuhaka have pH values in excess of the optimum range for most crop types (Figure 3-31). This is similar to Gisborne and Hawke's Bay and could impact macro and trace element availability for future crops and may impact animal health.

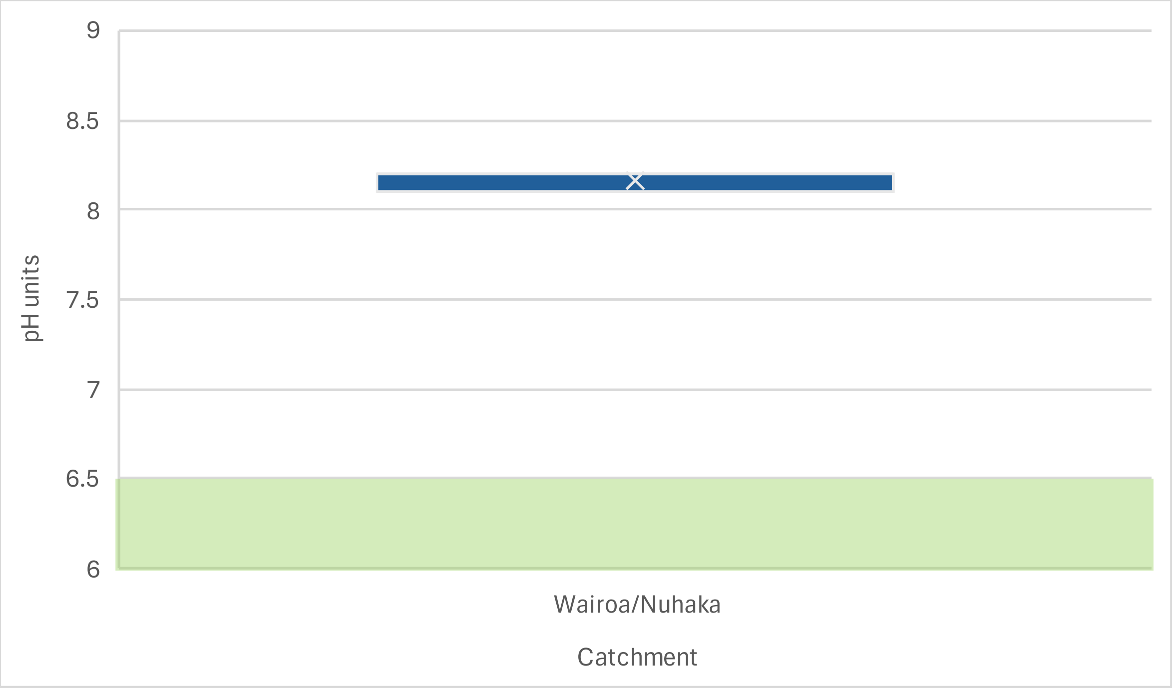


**Figure 3-31 Wairoa/Nuhaka sediment pH results by catchment. Optimum range for most crops shown from pH 6 – 6.5 (Reid & Morton, 2019).**

##### Olsen P

Sediment samples from Wairoa/Nuhaka have very low Olsen P values (Figure 3-32). Phosphorus availability is a key driver of yield in crops and pastures, and a low Olsen P level will likely impact future crop performance. With the sediment at four sites in excess of 20 cm, limiting the ability of plants to access nutrients in the underlying soil, these low P levels will have a major impact on the performance of crops like maize which are typically grown in these areas.

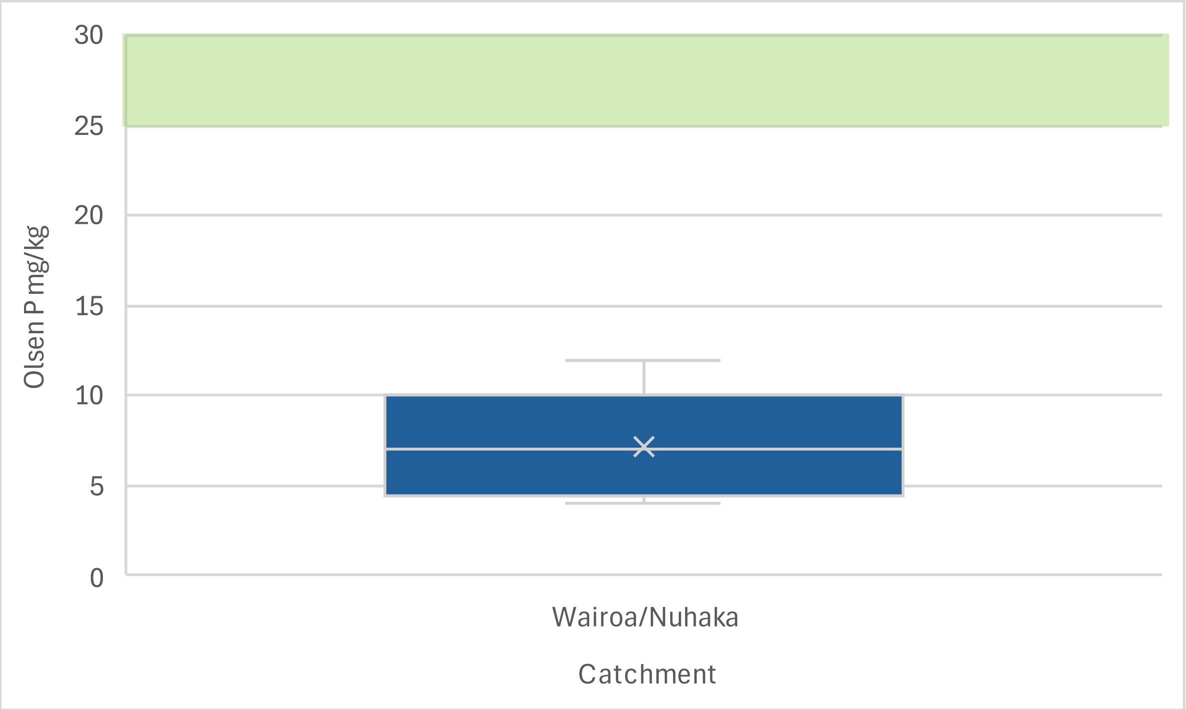


**Figure 3-32 Wairoa Sediment Olsen P Results by catchment. Optimum range for most crops shown as >25 mg/L (Reid & Morton, 2019).**

### Quick Test K

Quick Test Potassium (QTK) varies across catchments, and across the region (Figure 3-33). Potassium is an important driver of yield for many crops, so low levels of K may limit yield. This will be an important consideration where maize is grown, or if grass is planted and feed is cut and carried, removing large amounts of K from the soil. The further reduction of already low K levels may reduce yield potential and increase the cost of production if high rates of potassium fertilisers are required.

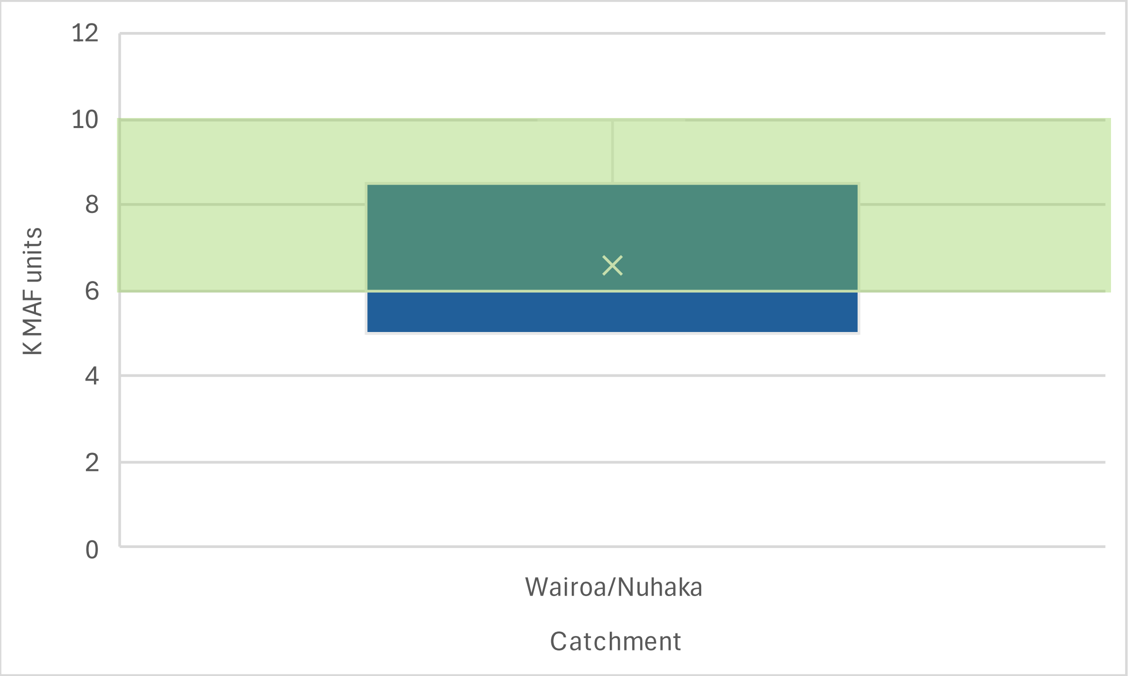


**Figure 3-33 Wairoa sediment Quick Test (MAF) Potassium levels. Optimum range for most crops shown from 6 – 8 MAF Units (Reid & Morton, 2019).**

### Sulphate Sulphur

Sulphate S is elevated at two sites in the Wairoa/Nuhaka catchment, within the expected range at two sites and slightly low at one site (Figure 3-34). This is different to results from Hawke's Bay and Gisborne.

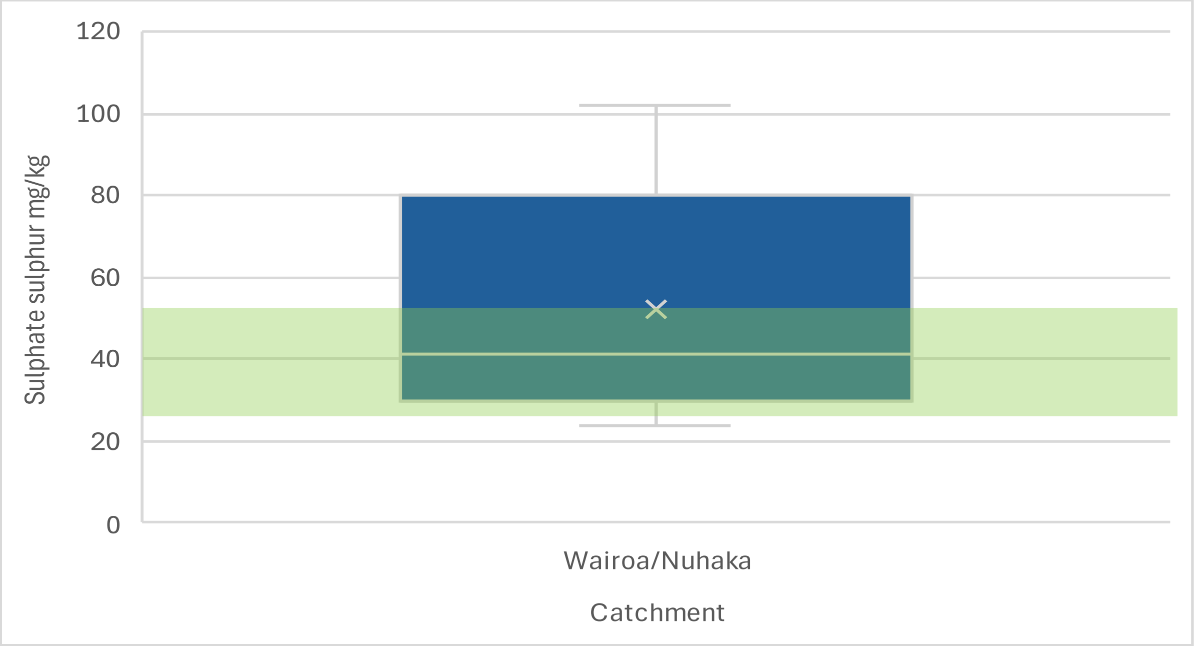


**Figure 3-34 Wairoa sediment Sulphate Sulphur results. Optimum range for most crops shown from 25 – 50 mg/kg (Reid & Morton, 2019).**

### Organic Sulphur

While sulphate sulphur appears to be high, Extractable Organic Sulphur (slowly plant available) appears to be low for most sites (Figure 3-35). This also aligns with results from Hawke's Bay and Gisborne.

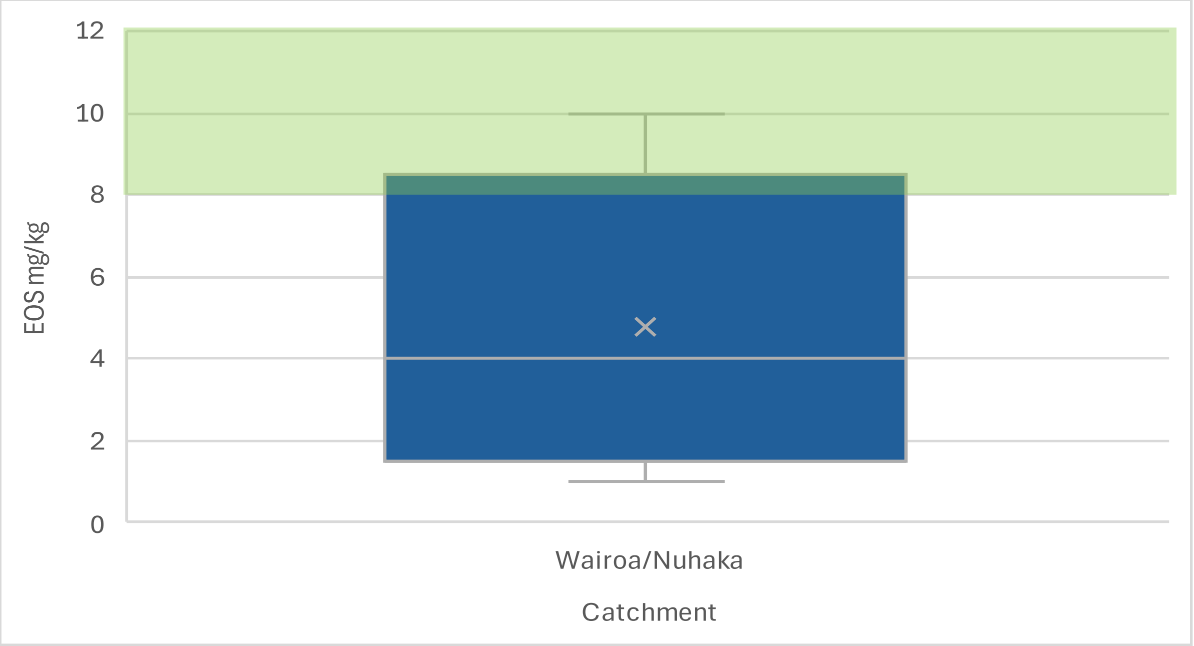


**Figure 3-35 Wairoa sediment Extractable Organic Sulphur levels. Optimum range for most crops shown >8 mg/L (Reid & Morton, 2019).**

### Potentially Available Nitrogen

Potentially Available Nitrogen from the Wairoa/Nuhaka catchment is either very low (<50kg/ha) or low (50-150kg/ha) (Figure 3-36). This is important to consider in the use of these areas for the production of maize which has a high N demand.

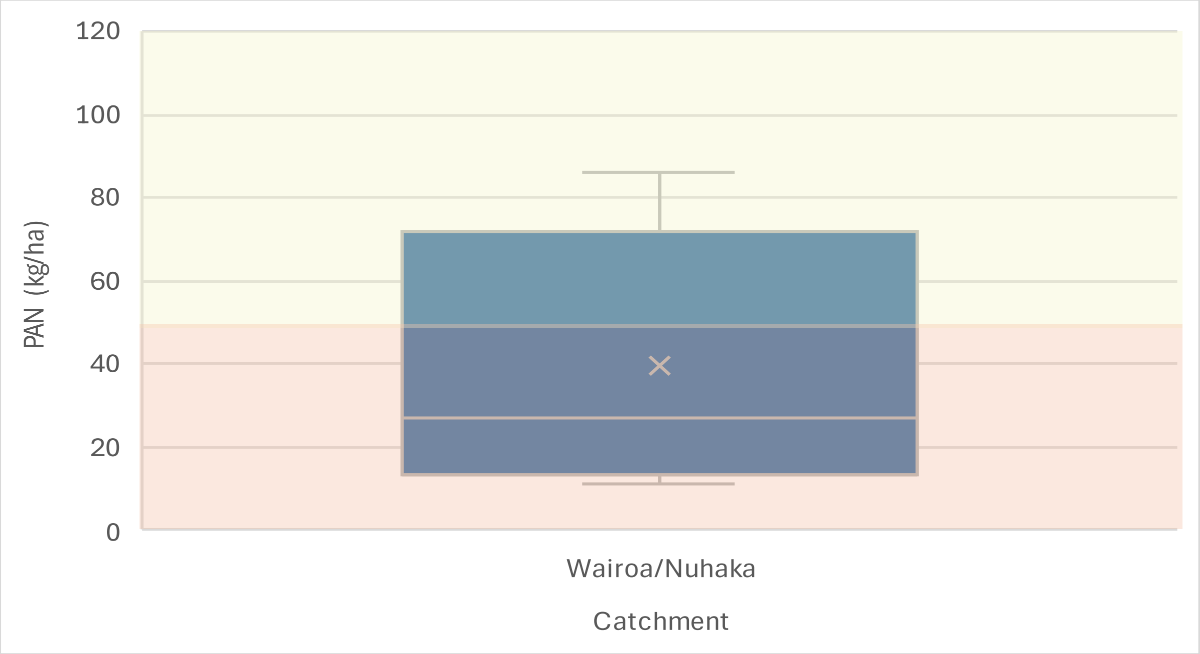


**Figure 3-36 Wairoa sediment Potentially Available Nitrogen. Very low levels shown in red (<50kgN/ha), low levels 50 - 120 kgN/ha (Reid & Morton, 2019).**

### Organic Matter

In Wairoa/Nuhaka the organic matter content of sediments is similar to Gisborne and is low (3-7%) to very low (<3%) (Figure 3-37). Low organic matter levels can relate to poor structure, nutrient availability and water retention.

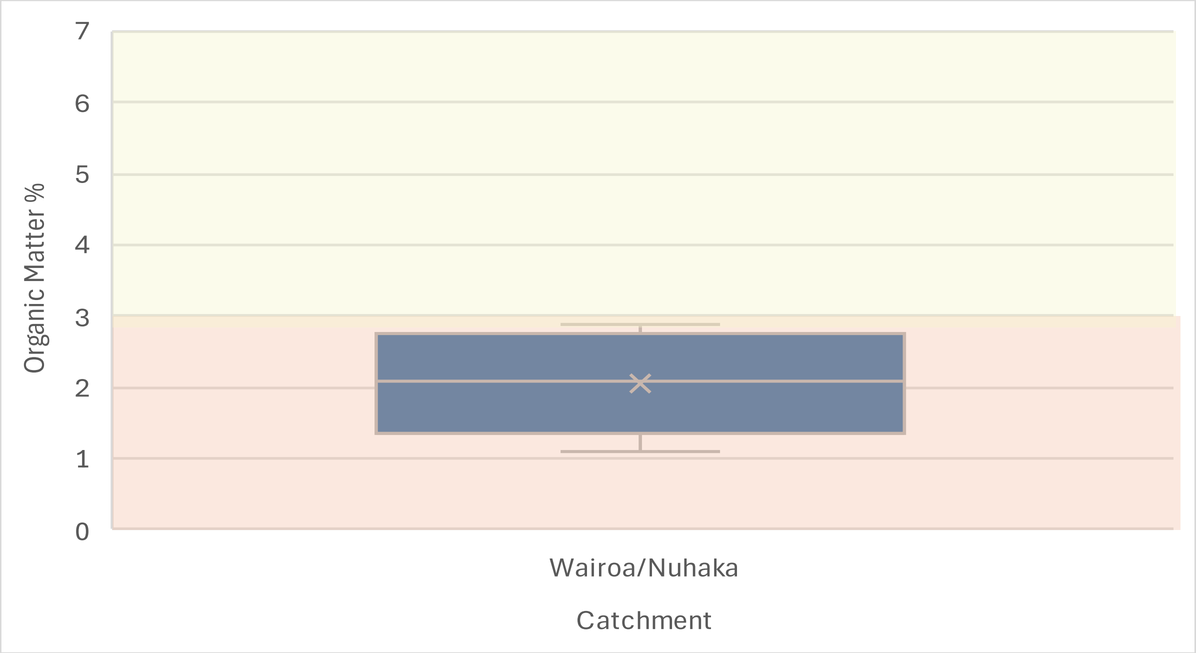


**Figure 3-37 Organic matter content as a percentage in Wairoa sediment samples by catchment. Very low shown in red (<3%), low in orange 3 – 7% (Hill Labs, n. d).**

## 3.10. Discussion

This report presents the findings from a comprehensive survey of sites impacted by Cyclone Gabrielle in Hawke’s Bay and Gisborne/Tairāwhiti, focusing on high value cropping land, orchards, and vineyards. The study documents flooding, waterlogging, sediment deposition, soil and sediment characteristics, potential contamination, and the management responses of approximately 100 growers. In total, 155 soil and sediment samples were collected from 116 sites across affected regions. Data from 12 Northland sites, which experienced waterlogging but not sedimentation, were excluded from this analysis.

Cyclone Gabrielle caused catastrophic damage across large areas of the North Island, with sediment deposition being the most severe impact in Hawke’s Bay and Tairāwhiti. In response, a collaboration of organisations quickly mobilised to support growers and capture critical data to fill major knowledge gaps on the immediate behaviour of soils and sediments after such extreme events.

The results show that sediment varied widely in depth (from <5 cm to >100 cm), texture (sand to silty clay loam), fertility, and biological activity. Despite early concerns, no chemical or biological contamination was detected in sediment samples.

This study is the first of its kind to focus on highly productive land (HPL) cropping soils in New Zealand and provides foundational data to support future recovery efforts. It also highlights the need for continued monitoring and research into long-term soil and crop responses under different management practices. To prepare for future events, the report recommends a multi-year, multidisciplinary approach to track outcomes, inform best practice guidelines, and support resilient land use planning.

# 3.11. Appendices

## 3.11.1. Appendix 1 Sampling method

### *3.11.1.1. Sampling transects and sediment depth*

Sampling was conducted along a 50m transect at each site, with samples collected at 0m, 25m and 50m (three points along the transect). The GPS co-ordinates for each point are recorded. The transect was measured out after the site was assessed, with the transect capturing one of the three categories. Sites impacted by sediment deposition were divided into four further categories. Previous studies of sediment deposits developed a decision support tool which discussed three different management pathways based on depth of sediment (Appendix 2).

Across the impacted regions where sediment was the issue, the depth of sediment varied widely. As sediment depth, alongside texture, were determined to be the two biggest factors when considering management options, transect location was determined based on four sediment depth classes:

- 0 cm
- < 5cm
- 5 – 20cm
- > 20cm

This is important to note as some areas had varying depths of sediment, so instead of capturing an average depth, i.e., from 5 cm to 50 cm, transects captured just one depth class, for example it would be 5 – 15cm or > 20 cm, as the management for each of these areas is quite distinct. Some sites had more than one transect and therefore more than one sample in order to capture these differences.

Depth was important to consider when taking a sample for nutrient analysis. The standard sampling depth for horticultural and cropping soils is 15 cm. In areas where sediment depth was less than 15 cm, two samples were collected for nutrient analysis.

- The first sample is of sediment only, the information from this sample can be used to classify sediment type etc.
- The second sample is a mixed sample, e.g., could be 10 cm sediment and 5 cm of original topsoil. This information is more useful to growers as this provides an indication of the nutrient levels in their new growing surface, should the sediment be incorporated.

See also “Bulk Density” which changes as sediments settle and are mixed with underlying soil layers.

### *3.11.1.2. Nutrient fertility*

Analysis of nutrient fertility was conducted by Hill Laboratories. Samples were sent chilled so that Mineral N tests could be completed. Hill’s technical team recommended the suite of tests to be completed and included:

- Basic Soil nutrient fertility
- Extractable Sulphur
- Mineral N
- Anion Storage Capacity
- Hot Water Extractable Organic N
- Potentially Mineralisable N
- Organic Matter
- Soluble Salts
- Total P

Some sites had more than one laboratory sample completed if the sediment depth was less than 15 cm. Three categories of samples were sent for nutrient analysis; 1) no sediment 2) sediment only 3) mixed (soil and sediment). For this report, only results from the sediment samples are presented.

Nutrient information can be grouped, interpreted, and presented in several ways. For this report, nutrient information on the sediment is presented by catchment.

#### *3.11.1.3. Contaminant analysis*

Following the cyclone there was considerable concern that the sediments may be contaminated. Contaminant tests were completed on a small number of strategically selected sites in Hawke's Bay as 'spot checks' to see if there was reason for concern. Contaminant samples were collected from sediment only, to avoid the previous soil surface influencing the results.

Collected with grower and industry approval, samples were sent to the laboratory anonymously. Testing was completed by Hill Laboratories and included:

- Multiresidues Pesticides
- Acid Herbicides
- Faecal Coliforms and E. coli Profile
- Heavy Metals

Results are shown in the below Table 3-15.

**Table 3-15 Contaminant sample results from randomised sites (heavy metals).**

| | Site Number | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Sediment texture | Silty clay loam | Silty clay loam | TBD | Silty clay loam | Silty clay loam | Silty clay loam | Silty clay loam | Silt | TBD | TBD | Mixed sample | Silty clay loam | Loamy very fine sand | Silt loam |
| Total Recoverable Arsenic (mg/kg dry wt) | 8 | 9 | 8 | 9 | 9 | 8 | 9 | 4 | 9 | - | 13 | 4 | 2 | 9 |
| Total Recoverable Cadmium (mg/kg dry wt) | <0.10 | <0.10 | 0.12 | 0.11 | 0.19 | 0.1 | 0.11 | <0.10 | 0.11 | - | 0.17 | < 0.10 | < 0.10 | 0.14 |
| Total Recoverable Chromium (mg/kg dry wt) | 23 | 25 | 23 | 27 | 29 | 24 | 29 | 14 | 25 | - | 18 | 14 | 12 | 19 |
| Total Recoverable Copper (mg/kg dry wt) | 15 | 11 | 10 | 17 | 12 | 12 | 12 | 5 | 12 | - | 151 | 5 | 3 | 21 |
| Total Recoverable Lead (mg/kg dry wt) | 17.1 | 17.6 | 16 | 23 | 18.7 | 16.5 | 18.7 | 7.6 | 18 | - | 19.6 | 7.7 | 4.6 | 26 |
| Total Recoverable Nickel (mg/kg dry wt) | 17 | 18 | 16 | 21 | 20 | 18 | 20 | 10 | 18 | - | 13 | 10 | 8 | 16 |
| Total Recoverable Zinc (mg/kg dry wt) | 71 | 71 | 62 | 88 | 78 | 69 | 75 | 40 | 74 | - | 84 | 39 | 31 | 84 |

### *3.11.1.4. Visual Soil Assessment (VSA)*

Visual soil assessment is a tool developed for farmers and growers (as well as wider industry) to assess the physical properties of soils, a key element of soil quality. This method of determining soil quality is relatively quick and can be completed in the field on a paddock scale across a farm. A 20cm cube of soil is dug, dropped several times on to a hard surface from 1m height, and then graded based on size of the resulting clods of soil. Reference images are then used to score structure, porosity, colour, and mottling, and earthworm numbers are counted.

Three VSAs were completed along each transect as an assessment of the sediments' "soil quality". Where sediment depth was less than 20cm, the test included some underlying soil. The soil conditions in which these VSAs were completed was not ideal, as the samples were very wet, however useful information was captured from the process and baseline photos taken. See Figure 3-38 for two examples of VSAs from different sites.

Figure 3-38 Examples of Visual Soil Assessment Results

An adapted VSA scorecard based on VSA Volume 1was used for baseline sampling (Table 3-16). Each indicator is given a weighting which contributes towards a total score.

Table 3-16 An example of an Adapted VSA scorecard completed for a site as part of sampling.

| Visual Indicator | VS Score<br>0= Poor<br>1= Moderate<br>2= Good Condition | Weighting | Maximum Score |
|---|---|---|---|
| Porosity | | X 3 | 6 |
| Colour | | X 2 | 4 |
| Mottles | | X 2 | 4 |
| Structure | | X 3 | 6 |
| Earthworm abundance | >35= 2<br>29-35= 1.5<br>22-28= 1<br>15-21=0.5<br><15= 0 | X 2 | 4 |
| | | Maximum score | 24 |

| Soil Quality Assessment | Ranking Score (Baseline Sampling |
|---|---|
| Poor | <7 (<30% of total score) |
| Moderate | 7-18 (30-74% of total score) |
| Good | >18 (>74% of total score) |

#### *3.11.1.5. Bulk density*

Soil bulk density is the weight of soil in a specified volume. Bulk density rings are used to take a sample core of soil of a known volume. The soil is dried and weighed to determine 'dry bulk density'. Bulk density is typically used as a measure of soil compaction and soil physical quality. For baseline sampling, bulk density is also used to understand more about the sediment type. Typically, the larger the soil particle size, the higher the bulk density, so sands will have a higher bulk density (e.g., 1.6g/cm$^3$) compared to clays (e.g., 1.1g/cm$^3$), with silts being somewhere in the middle (e.g., 1.3g/cm$^3$).

Three 10cm bulk density cores were taken per transect, and processing was completed by AgResearch in Palmerston North.

#### *3.11.1.6. Earthworm abundance and biology*

While soil biology is difficult to measure, how soil biology responds after an event like Cyclone Gabrielle is a key area of interest. Earthworm numbers can be used as a 'proxy' for soil biology i.e., if soil quality is good more earthworms will be present, acting to an extent as a surrogate for other microscopic soil biology.

Earthworms were counted as part of the VSA sampling, and the estimated total population over a given area was calculated. Earthworms collected along each transect were sent to Dr Nicole Schon at AgResearch for identification to species and functional group. The purpose was to determine what surviving populations might be present in different scenarios and follow changes over time.

**Figure 3-39 Examples of earthworms found in sediment deposits.**

### *3.11.1.7. Texture*

The texture of sediment deposited is related to water velocity. It varies across and along river flow paths and catchments and is influenced by factors such as sediment source, distance from a stopbank breach or water movement slowing through an orchard. Typically, sandy material is deposited at the higher reaches of a river where water velocity is fastest and as water movement slows, more of the silt, then clay, fractions will be deposited. Sediment texture is an important factor for growers to consider in recovery efforts, as it is likely to influence nutrient content, moisture content and revegetation options. Textural samples were taken from each site and sent to Dr Alan Palmer at Massey University for analysis. In some situations, there were two distinct layers of sediment deposited, in which case two samples were sent to be analysed.

**Figure 3-40 Example of two sediment deposits on one site**

Soil texture has been categorised as per the USDA texture nomenclature. Textural class information is included as 3.11.3 Appendix 3.

### *3.11.1.8. Environmental DNA (eDNA)*

Environmental DNA is a way to determine and classify microbial populations present in soil and water, providing information about soil biology and microbial communities. Samples were collected and frozen as part of baseline testing. Should future funding provide opportunity for analysis, these samples collected soon after the event can be used with additional sampling over time to describe changes to population.

## 3.11.2. Appendix 2 Regrassing Decision Tree 2004

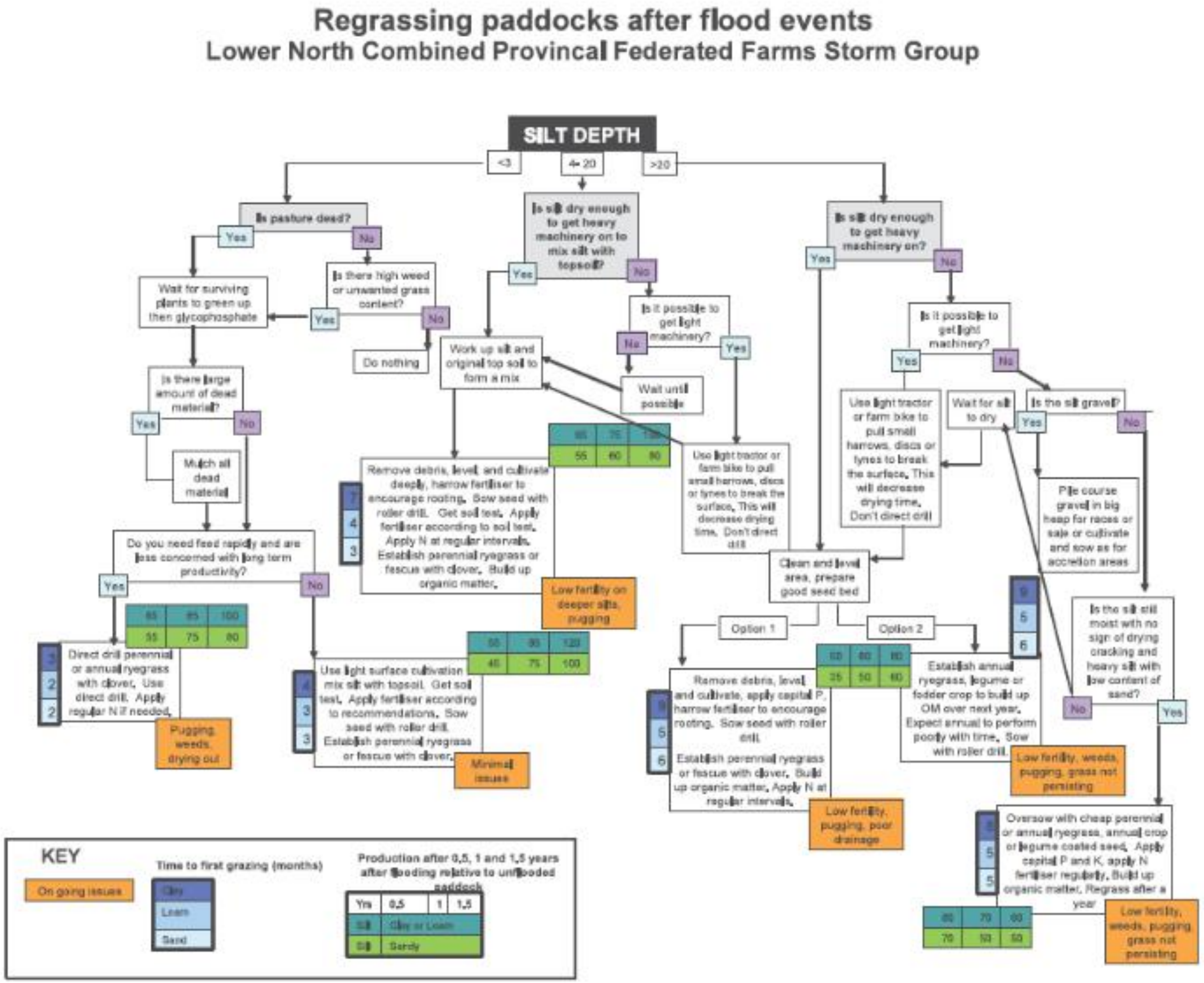


**Figure 3-41 Decision tree for regrassing paddocks after flood events (Lower North Island Combined Provincial Federated Farms Storm Group)**

### 3.11.3. Appendix 3 USDA Textural Triangle

Retrieved from https://www.researchgate.net/figure/USDA-Soil-Texture-Triangle_fig2_279631053

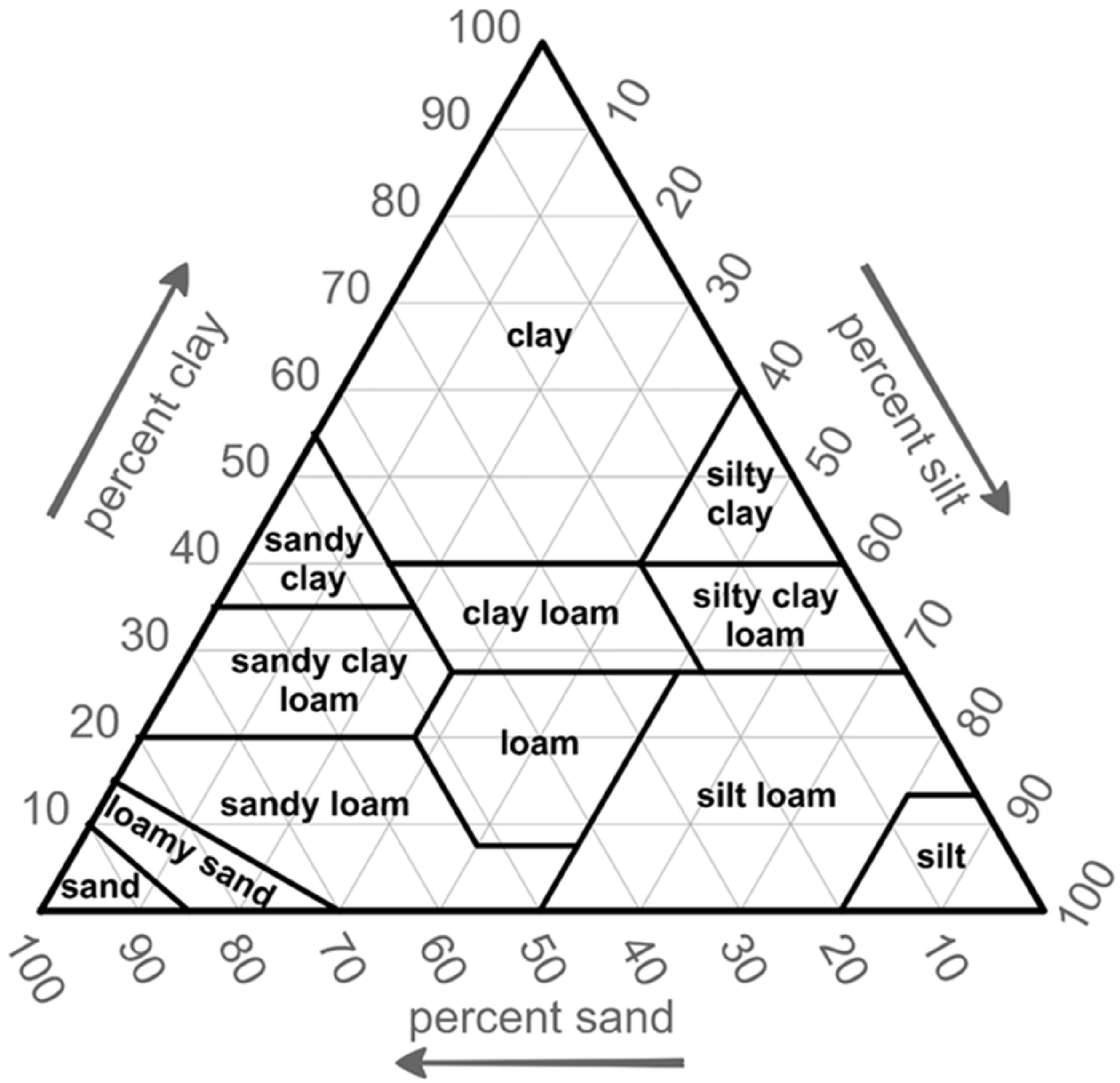


**Figure 3-42 Soil texture triangle (USDA)**

## 3.11.4. Appendix 4 Contaminant results summary report

### Assessment of potential contaminants present in sediment samples post-cyclone Gabrielle

Jo Cavanagh
Manaaki Whenua Landcare Research
Prepared for LandWISE, Hawke’s Bay
September 2023

### Introduction

LandWISE undertook sampling of sediment deposited at 14, predominantly vegetable cropping, sites in the Hawke’s Bay area post-cyclone Gabrielle to assess potential biological and chemical contamination. Samples were collected using a 15cm corer with approximately 15 to 18 cores collected along a 50m transect and composited as one sample. The results biological and contaminant analysis (pesticides, metals) along with other parameters including, pH, texture and CEC, and some site information, were provided to Manaaki Whenua for interpretation. This note provides assessment of the results of pesticide and trace element contaminant analyses.

### Summary of results

For all sites except one, samples of the deposited sediment were collected, and sediment depth noted. At site 11, deposited sediment had been cultivated into the underlying soil, hence a mixed soil and sediment sample was collected for analysis. A summary of the chemical analysis results is provided in Table 1.

The pH of the sediment samples (6.9-8.1) appears to be generally higher than is typically observed at state of the environment soil quality monitoring sites (typical range 6-7). A higher pH can reduce the bioavailability of metals – including essential elements such as copper and zinc.

With the exception of copper concentrations at site 11, trace element concentrations are largely within naturally occurring concentrations for the region (Cavanagh et al 2023). Copper concentrations at site 11 are remarkably high and fall between ecological soil guideline value protecting 80% and 95% of soil species (110 mg/kg - 95% protection; 245 mg/kg – 80% protection for a typical soil (pH> 5,4, CEC c.20 cmol/kg), Cavanagh and Harmsworth 2023). This site is the only location where a mixed soil and sediment sample was collected and suggests that the elevated copper is present in the soil. It would be useful to consider reducing any ongoing inputs of copper at this site, and to assess the biological health of soil at this site to ensure that functioning of the soil is not impaired (including crop productivity). Sediment from sites 8, 12 and 13 have very similar profiles in trace element concentrations, which are different to the other sites, suggesting a similar source of the deposited sediment.

Table 3-17 Summary of sampling sites and results of chemical analysis.

| Sample Name | Location | Land Use Type | Sediment depth | pH | CEC | Trace element concentrations (mg/kg) | | | | | | | # Pesticides detected[1] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | As | Cd | Cr | Cu | Pb | Ni | Zn | |
| Site 1 | Fernhill | Vegetable Cropping | <5cm | 7.3 | 26 | 8 | < 0.10 | 23 | 15 | 17.1 | 17 | 71 | - |
| Site 2 | Fernhill | Vegetable Cropping | 5-20cm | 7.8 | 35 | 9 | < 0.10 | 25 | 11 | 17.6 | 18 | 71 | - |
| Site 3 | Meeanee | Vegetable Cropping | >20cm | 7.9 | 33 | 8 | 0.12 | 23 | 10 | 16 | 16 | 62 | - |
| Site 4 | Pakowhai | Vegetable Cropping | >20cm | 7.6 | 29 | 9 | 0.11 | 27 | 17 | 23 | 21 | 88 | - |
| Site 5 | Meeanee | Vegetable Cropping | >20cm | 7.9 | 37 | 9 | 0.19 | 29 | 12 | 18.7 | 20 | 78 | 4[2] |
| Site 6 | Meeanee | Vegetable Cropping | 5-20cm | 7.6 | 34 | 8 | 0.1 | 24 | 12 | 16.5 | 18 | 69 | - |
| Site 7 | Meeanee | Vegetable Cropping | 5-20cm | 7.6 | 37 | 9 | 0.11 | 29 | 12 | 18.7 | 20 | 75 | - |
| Site 8 | Puketapu | Orchard | 5-20cm | 7.6 | 27 | 4 | < 0.10 | 14 | 5 | 7.6 | 10 | 40 | - |
| Site 9 | Pakowhai | Pasture | >20cm | 7.7 | 36 | 9 | 0.11 | 25 | 12 | 18 | 18 | 74 | - |
| Site 10 | Pakowhai | Cropping | 5-20cm | 7.5 | 34 | - | - | - | - | - | - | - | 1[3] |
| Site 11 | Twyford | Cropping | <5cm | 6.9 | 25 | 13 | 0.17 | 18 | 151 | 19.6 | 13 | 84 | - |
| Site 12 | Puketapu | Vineyard | >20cm | 7.7 | 26 | 4 | < 0.10 | 14 | 5 | 7.7 | 10 | 39 | - |
| Site 13 | Esk | Vegetable Cropping | >20cm | 8.1 | 16 | 2 | < 0.10 | 12 | 3 | 4.6 | 8 | 31 | - |
| Site 14 | Otane | Vegetable Cropping | >20cm | 7.2 | 21 | 9 | 0.14 | 19 | 21 | 26 | 16 | 84 | - |

[1] A total of 192 pesticides tested for as pesticide suite, organochlorine pesticide suite

[2] Alachlor – 0.082 mg/kg; Cyhalothrin – 0.027 mg/kg; Metribuzin – 0.049 mg/kg; Procymidone – 0.196 mg/kg

[3] Pendimethalin – 0.024 mg/kg

Pesticide residues were detected in only two samples, with four residues detected at site 5 (herbicides – alachlor and metribuzin, insecticide – cyhalothrin, fungicide - procymidone) and one at site 10 – the herbicide pendimethalin. Procymidone was present in the highest concentrations at 0.196 mg/kg. Information on the toxicity (and other information) of all detected residues to soil organisms is available from the University of Hertfordshire Pesticide properties database (http://sitem.herts.ac.uk/aeru/ppdb/en/), largely sourced from existing dossiers for pesticide registration. A summary of the available data is provided in Table 3-18, and suggests that no negative effects on soil organisms would be expected at the observed concentrations. No information was available on concentrations that might elicit non-target plant effects for the two herbicides (alachlor, metribuzin), although observed concentrations are generally low. It is unclear why site 5 has the highest number of residues – it is in close proximity to site 7 in particular, and over time these sites often appear to have been managed as a single pastoral land management unit (assessed via google earth imagery). The most recent imagery (04/2023) suggests site 5 may be slightly lower lying than the surrounding area, hence may be a preferential deposition zone for fine sediment containing pesticide residues.

**Table 3-18 Summary of terrestrial toxicity data and environmental half-life (days) for pesticide residues detected in sediment samples*.**

| **Pesticide** | **Terrestrial Toxicity data**[1] | **Environmental half-life (lab DT50, 20C) days** |
|---|---|---|
| Alachlor | Earthworms -acute 14 day LC50 – 368 mg/kg | 35 |
| Cyhalothrin | Earthworms -acute 14 day LC50 – >1000 mg/kg | 57 |
| Metribuzin | Earthworms -acute 14 day LC50 – >1000 mg/kg<br>Earthworms reproduction NOEC - >52 mg/kg<br>No significant effect on carbon or nitrogen mineralisation in 28 day study. | 7 |
| Procymidone | Earthworms -acute 14 day LC50 – >1000 mg/kg<br>No significant effect on carbon or nitrogen mineralisation at 20 mg product/kg. | 784 |
| Pendimethalin | Earthworms -acute 14 day LC50 – >1000 mg/kg<br>Earthworms reproduction NOEC – 33.45 mg/kg<br>No significant effect on carbon or nitrogen mineralisation at 20 kg/ha<br>Collembola (springtails) chronic NOEC – 193 mg/kg. | 182 |

*Source: University of Hertfordshire Pesticide Properties Database. http://sitem.herts.ac.uk/aeru/ppdb/en/index.htm

[1] LC50 - lethal concentration at which 50% of the test population died; NOEC – no observable effect concentration

## Conclusions

There is no evidence for chemical contamination present in the deposited sediments. Trace element concentrations were largely within background concentrations across the region. Remarkably high copper concentrations were detected at one sampling site and warrants further investigation including assessment of current state of the biological health of the soil. Opportunities to minimise any ongoing copper should be considered. Pesticide residues were detected at two sampling site locations, although the source for these residues is unclear.

## References

Cavanagh JE, McNeil S, Thompson-Morrison H, Roudier P, Martin A, Turnbull R 2023. Determining background soil concentrations of trace elements across New Zealand. Manaaki Whenua – Landcare Research Contract Report LC4324. Envirolink Grant: 2321-HBRC267.

Cavanagh JE, Harmsworth G 2023. An implementation framework for ecological soil guideline values. Manaaki Whenua – Landcare Research contract report LC4311. Envirolink Tools Grant C09X2206

## 3.11.5. Appendix 5 Notes on bulk density and total porosity

Alan Palmer, Massey University

Soils with a bulk density higher than 1.6 g/cm$^3$ tend to restrict root growth. Bulk density increases with compaction and tends to increase with depth. Sandy soil is more prone to high bulk density.

- Measures mass/unit volume, so includes pore spaces but not the mass of water within
- Most NZ soils in the range 0.6-1.8 Mg m$^{-3}$
- Organic, Pumice and Allophanic soils are lowest.
- Pallic and Podzol soils highest.
- Topsoils are generally lower bulk density than subsoils because of the influence of organic matter and aeration by earthworms on soil structure.
- Sandy soils are generally higher density than clay rich soils, particularly if the sand particles are even sized and well packed.
- Clay rich soils usually have greater total pore space leading to lower density.
- The same applies to rocks. Closely packed sandstones have higher density than mudstone.
- When sediment is gently settled through water, as in a flood, the particles are loosely packed with water filled voids between.
- If the samples taken for dry bulk density are carefully taken from wet sediment in the field and dried in the laboratory, this open framework remains, and bulk densities recorded can be very low.
- As flood sediment dries in the field, cracks develop. This shows that the sediment is becoming denser as the water drains, evaporates or is transpired through vegetation cover. High densities can result.
- Therefore, bulk density results must be interpreted with the state of the sediment (wet, cracking, or dry) in mind.
- This will depend on landscape position and underlying soil, sediment texture, days since flooding, vegetation cover and weather conditions.

### Notes on particle density

- Measures mass/unit volume of the solid portion of the soil or sediment, so excludes pore spaces.
- Most quartzo-feldspathic rocks such as greywacke, sandstone and mudstone are dominated by quartz and feldspar with specific gravities of 2.65 and 2.55-2.63 respectively.
- Sediments derived from quartzo-feldspathic rocks whether sand silt or clay, tend to have particle densities in the range 2.5-2.7 with sediment 0n the lower side of the range containing more clay, and sediments on the upper side of the range containing more sand with some heavier minerals such as titanomagnetite (4.5-5.5 Mg m$^{-3}$) or ferromagnesian minerals (3-4 Mg m$^{-3}$).
- Sediments and soils with appreciable organic matter can have lower particle density because organic matter is generally in the range 0.8-1.1 Mg m$^{-3}$.
- Sediments and soils with appreciable rhyolitic volcanic glass can have slightly lower particle densities because rhyolitic glass has a particle density of about 2.5 Mg m$^{-3}$.

### Notes on total porosity

- Total porosity is calculated as 1- (pb/ps) where pb is dry bulk density and ps is particle density.
- Porosity is influenced by texture and the way that sand, silt, and clay particles are packed.

- Sediments deposited by moving currents, such as on the bed of a river, are usually more tightly packed with fewer pore spaces.
- Sediments gently settled through still water are loosely packed until either dried or compacted by the weight of more sediment on top.
- Total porosity of soils is influenced by texture, mineralogy (quartzo-feldspathic vs volcanic parent materials), formation of structure and earthworm activity.
- Wetting and drying of soil tends to lower total porosity as particles pack more tightly together.
- Compaction by traffic or animals lowers total porosity.
- Total porosity is a crude measure and far less important than the distribution of pore sizes and their connectivity.
- Connected macropores (> 63 microns) provide drainage and aeration.
- Mesopores (2-63 microns) provide plant available moisture storage in the soil.
- Fine pores may store water but generally this water is not available to plants and nor does it drain readily from the soil.

# Chapter 4

## 4. Repeat Sampling

### 4.1. Introduction

After the Baseline Sampling Project was completed (Chapter 3), the project was extended to monitor a subset of samples in Hawke's Bay. The aim, as reported in this chapter, was to measure changes to sediment and soil in the short term and add to the collective understanding of soil recovery after sediment deposition. The focus is on areas previously used for vegetable production. Growers completed a range of soil management practices as part of their land remediation over the winter, depending on sediment depth, texture and soil moisture. A key outcome of this study was to understand the impact of different management practices on soil and sediment physical and chemical characteristics.

This chapter includes soil quality data and analysis from fourteen paired sites sampled in autumn 2024, 12 – 14 months after the cyclone. Selected pairs had similar location, sediment depth and sediment texture, but had been managed differently in the first six months after the cyclone. The sites represented seven management scenarios which allowed underlying changes in soil quality to be related to management during the first cropping season after the flood. The collection of this data was essential to increasing understanding of early-stage sediment and soil recovery. As part of the autumn measurements, crop performance data were collected from blocks that were planted in spring or summer crops, but these results are not discussed in detail here.

Sites were selected on land that had been previously used for vegetable, arable or forage crops in Esk Valley, Fernhill, Pakowhai/Meeanee and Ōtāne, based on the depth and texture of flood sediment. The fourteen sites were set up as seven pairs, matched by similar sediment texture and depth but with different post cyclone management response. A total of ten growers ranging from large-scale corporate operations through to small market gardens are included in this work.

### 4.2. Setting

Hawke's Bay was severely impacted by Cyclone Gabrielle, with high rainfall in the Ruahine and Kaweka ranges causing much of the destruction (Hawke's Bay Independent Flood Review Pae Matawai Parawhenua, 2024). At the Hawke's Bay Regional Council Glengarry weather station, north-west of Napier, 546 mm of rainfall was received during the storm, with nearly 400 mm falling within a 12-hour period (Hawke's Bay Regional Council, 2023). Extreme rainfall in the upper river catchments caused channel avulsion and stopbank failures downstream. Landslides delivered abundant sediment and woody debris to rivers, resulting in downstream inundation of farmland by sediment laden flood waters, burying crops and farm infrastructure. The Esk Valley, Fernhill, Pakowhai, Meeanee and Ōtāne areas were all impacted by significant flooding and sediment deposition.

Cyclone Gabrielle severely impacted the agricultural and horticultural sectors in Hawkes Bay, including vegetable and arable crops, permanent tree and vine crops and pastoral land. The estimated cost to the horticultural industry was $1.5 billion (Horticulture New Zealand, 2024). Land was inundated with sediment ranging from shallow crusts of <1 cm through to very deep over >1 m. Sediment texture ranged from fine silty clay loam through to coarse sands depending on the position of the site in the landscape and distance from the stopbank breach. Immediately after the flood the sediment was wet and very difficult to move with machines. Efforts focused on opening up drains and pumping water over stop banks in an effort to drain excess water away. Grass seed was successfully flown onto some blocks and once germinated, assisted in drying the sediment out by increased evapotranspiration. Deep sediment quickly turned anoxic and together with ponding water and high groundwater tables, provided an issue to orchards due to increased root disease.

A range of management practices were implemented by farmers and growers in the first 6 months of recovery. Decisions were largely based on the depth, texture and water content of the flood sediment. This included leaving sediment bare until spring, sowing a cover crop, through to mixing the sediment into the underlying soil. Decisions were supported by information from previous flood events including the 1938 Esk Valley, 1988 Cyclone Bola and 2004 Southern North Island Storm. However, most of the previous work focused on pastoral recovery and lacked details around recovery for high value crops.

## 4.3. Method

The methodology used for the paired site sampling (12 – 14 months post Gabrielle) was mostly consistent with the baseline sediment sampling completed 1 – 3 months after the cyclone (Chapter 3).

### 4.3.1. Sampling details

#### *4.3.1.1. Sampling transects and sediment depth*

Each site was resampled along the same previously established 50 m transect (see full details in Chapter 3, Appendix 1), which was recorded using an EOS Arrow 100 handheld GPS at the time of initial baseline sampling. Samples were collected from three points along the transect, at 0 m, 25 m and 50 m. In some cases, sediment had been incorporated into the underlying topsoil, and it was not relevant to record sediment depth.

#### *4.3.1.2. Nutrient fertility*

Nutrient fertility analysis was completed by Hill Laboratories. Six x 15 cm cores were collected from each of the three points along the established transect. One combined sample was submitted per site. Sites where the initial sediment depth was less than 15 cm had been cultivated, and a single mixed soil and sediment sample was submitted. Further details on nutrient testing can be found in Appendix 4.10.2.

Previous nutrient fertility levels were not a focus of this study. The transects measured for baseline sampling did not align with grower transects and it would not be best management practice to compare. In addition, soil testing frequency varies, and the accuracy of information across sites would vary. Therefore, prior soil nutrient levels were not captured for this study.

#### *4.3.1.3. Contaminant Analysis*

Contaminant analysis was not completed as part of this study as baseline sampling concluded that there was low risk of contaminant issues.

#### *4.3.1.4. Visual Soil Assessment (VSA)*

Visual Soil Assessment (VSA) was used to assess soil physical properties and soil quality. Three VSAs were completed along each transect as an assessment of the soil/sediment quality. As per VSA guidelines a 20 cm cube of soil was dug out, and dropped three times onto a firm surface from 1 m height (Shepherd, 2000). The soil was then graded based on size of the resulting clods. A modified VSA scorecard was developed for the baseline sampling to reflect measurement of traits relevant to sediment. This scorecard was used for subsequent analysis. The scorecard can be found in Appendix 4.10.3.

#### 4.3.1.5. *Earthworm abundance*

In the absence of more detailed biological analysis, the presence of earthworms was used as a proxy score for biological activity. Earthworms in VSA samples were counted to determine abundance. For the purpose of the analysis the VSA score of abundance is not used, as it does not provide sufficient detail. Instead, the average number of earthworms found across three VSA samples was multiplied to determine individuals per m$^2$, a unit of measure which is consistent with studies on earthworm abundance (Schon et al., 2023).

#### 4.3.1.6. *Bulk density*

Soil dry bulk density was measured at each point along the transect, in total three bulk density cores were sampled per site. Core dimensions used to collect samples for bulk density were 7.5 cm deep x 10 cm diameter, standard core dimensions used by AgResearch. Soil from the undisturbed cores was dried at 105°C for 72 hours to determine soil dry bulk density.

Changes to bulk density are only assessed for sites that had medium and deep sediment deposition. For the shallow sites (sediment depth <5cm) the initial 2023 sampling saw only the sediment portion of the core assessed for bulk density, not the full 7.5 cm depth. This was done by measuring the depth of the wet sediment, carefully removing the sediment from the core and drying the sample (as above). Bulk density was then calculated based on the volume of the core, to the depth of the sediment. Shallow sites Fernhill Scenario 2A and 2B and Ōtāne Scenario 7A and 7B have been excluded from repeat bulk density analysis as the sediment and soil has now been mixed mechanically and a comparison of the resulting texture to previous results was not considered worthwhile.

#### 4.3.1.7. *Management data*

Management information was captured through informal communication with the nine growers responsible for the fourteen sites sampled. This data was captured over a period of approximately 24-months, from the time of the flood event and the baseline sampling, through to mid-2025.

## 4.4. Site selection

Sites were selected to represent a range of different sediment depths, textures and catchments. The sites have been grouped into four main geographic zones, Esk Valley (1), Fernhill (2), Pakowhai/Meeanee (3) and Ōtāne (4) for ease of reference Figure 4-1. The flood sediment deposition map shown in is sourced from Hawke's Bay Regional Council (Eaves & Whitaker, 2024).

Each of the seven management scenarios comprises two sites that have been paired based on:

- **Geographic location** – Similar position in the landscape, close geographic proximity, and similar level of flooding damage.
- **Sediment texture** – Similar flood sediment textural class.
- **Sediment depth** – Same flood sediment depth class, as related to the 2004 Decision Support Tree of Litherland et al., (2007).
- **Winter management** – Each site in the scenario had different post flood winter management practices applied.

Table 4-1 provides an overview of selected sites, and scenarios. In total seven different scenarios or sets of paired sites were considered.

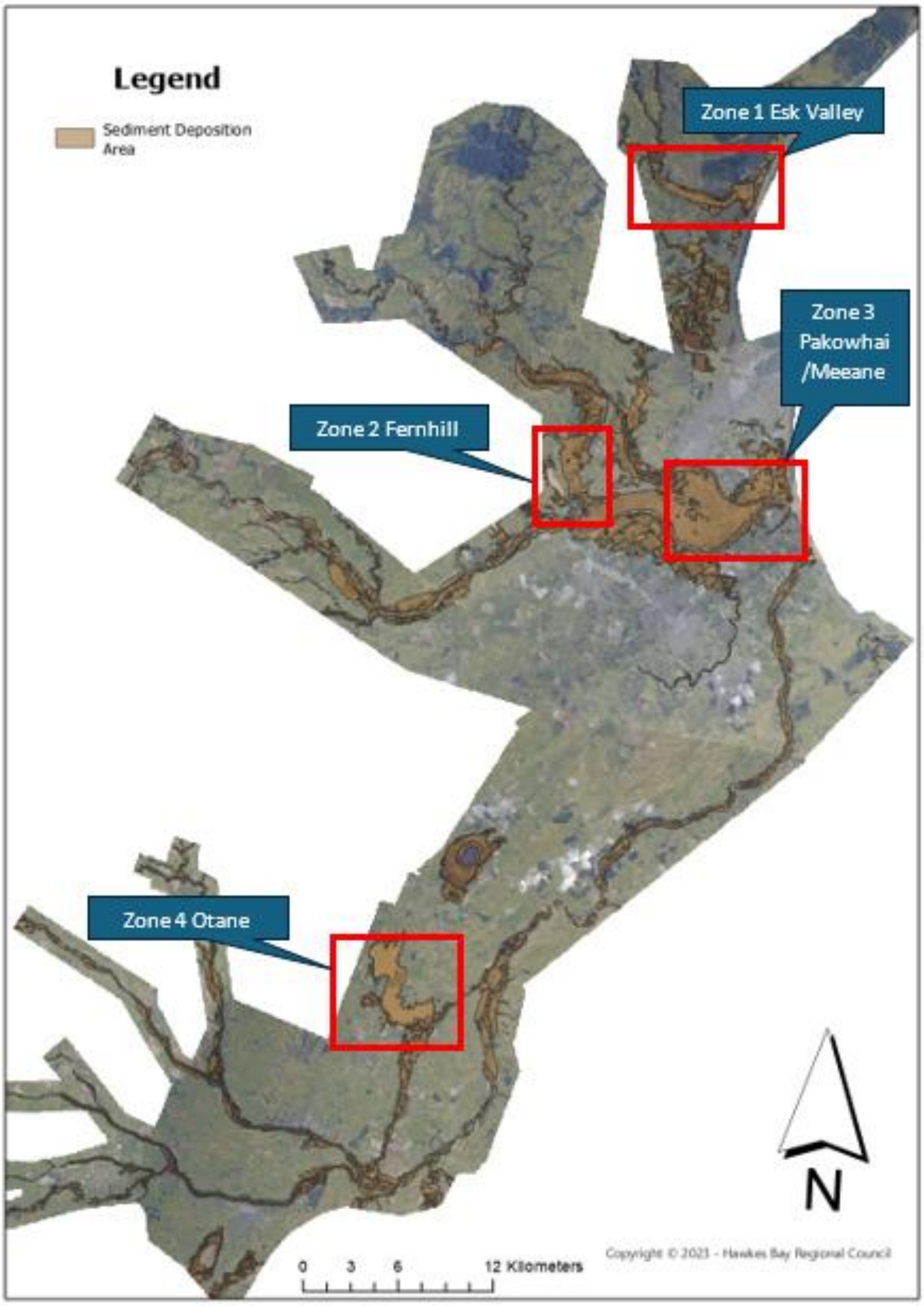


**Figure 4-1 showing Hawke's Bay sediment deposition map (HBRC, 2023) and geographic distribution of sampling zones 1 - 4**

## 4.5. Site details

Site details were collected from farmers and growers through informal communication over nearly a two-year period as plans were undertaken and modified as required. Summary reference tables are included at the end of Section 4.5, namely, Table 4-1 sediment details, Table 4-2 site descriptions and management, Table 4-3 antecedent soil descriptions, Table 4-4 nutrient applications, and Table 4-5 cultivation events.

### 4.5.1. Zone 1 – Esk Valley

The Esk River is one of the smallest rivers in the Hawkes Bay Region with a catchment area of 252 km$^2$. Its headwaters rise in the Maungaharuru Ranges, west of Lake Tutira, before flowing through the Esk Valley to the sea at Bay View (Hawke's Bay Regional Council, 2021b). The Esk River does not have stopbanks as part of flood protection measures, the active channel has capacity for a 2-year return period flood level. If rainfall exceeds this water overtops the channel and the flood plain starts to become inundated with water (Hawke's Bay Independent Flood Review Pae Matawai Parawhenua, 2024). During Cyclone Gabrielle there was wall to wall flooding across the lower parts of the valley (Hawke's Bay Independent Flood Review Pae Matawai Parawhenua, 2024). Vineyards, cropping areas and apple orchards were buried in deep, sandy sediment. Average sediment deposits ranged from 1 – 3 m, far exceeding the decision support tool upper threshold of 20 cm (Litherland et al., 2007). Figure 4-2 shows the location of the two sites, 1A and 1B, sampled in the Esk Valley Zone.

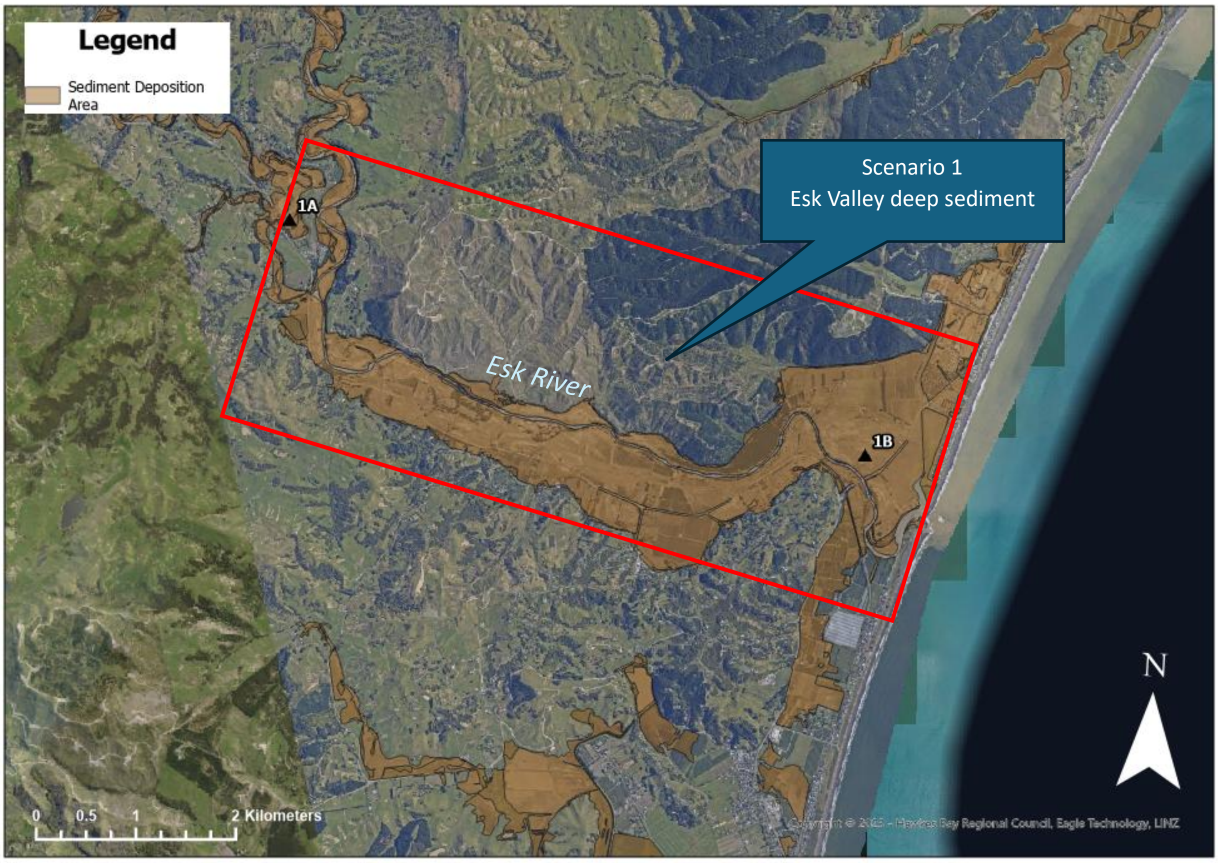


**Figure 4-2 Location of Scenario 1 (Sites 1A & 1B). Map overlayed with flood sediment deposition area mapped by Hawkes Bay Regional Council (Eaves & Whitaker, 2024). Basemap sourced from LINZ (2023).**

#### *4.5.1.1. Scenario 1 – Deep Sediment*

Scenario 1 represents the deep sandy deposits of the Esk Valley and had some of the deepest sediment deposits, similar to those in the Dartmoor Valley, near Puketapu.

Site 1A, located approximately 7km upstream from the coast, was impacted by approximately 1 – 2 m of fine sand sediment. Site 1B, located approximately 6km further downstream from Site 1A, was inundated with upwards of 50 cm of very fine sandy loam.

Site 1A was used for pastoral grazing and forage cropping prior to the Cyclone. The sediment was too deep to remove, so to start remediation, the site was drilled with oats soon after the cyclone, aiming to stabilise the sediment as soon as possible. Some oats established but cover was sparse. Sorghum was drilled late 2023 and grazed with cattle (set stocked) that summer. In late April 2024, annual ryegrass was drilled. Site 1A is located adjacent to a pig farm and has a consent to apply pig effluent. Regular applications of pig effluent were made in 2024, resulting in increased pasture growth where the irrigator could reach. Regular applications of fertiliser have also been applied to increase soil fertility.

Site 1B is a cropping block that had been leased to grow maize previously. It is located in the lower end of the Esk Valley and had a significant amount of debris deposited. Farm infrastructure was also damaged including a large pivot irrigator. Sediment removal was considered but as the farm had been severely flooded three times in the last forty years, this option was rejected. The leased block was returned to the owner after the cyclone. The owner removed debris and levelled the surface and planted a diverse species mix into the sediment. The mix included grasses, clovers, vetch, tic beans and plantain, and aimed to stabilise the sediment. Establishment was poor with dry conditions and windblown sand being key factors.

### 4.5.2. Zone 2 – Fernhill

The Fernhill area was impacted by floodwaters from the Tutaekuri and Ngaruroro Rivers. The Tutaekuri River rises in the south-eastern Kaweka ranges and has a river catchment of 840 km$^2$ (Kolt, 2012). The Ngaruroro River has headwaters are the Kaweka, Ruahine and Kaimanawa Ranges, and has a catchment area of 2,500 m$^2$ (Dravid & Brown, 1997).

Figure 4-3 shows floodwater movement from both rivers from Fernhill through to Meeanee. The Tutaekuri River breached the Moteo stopbank near Vicarage Road and flowed down Swamp Road,

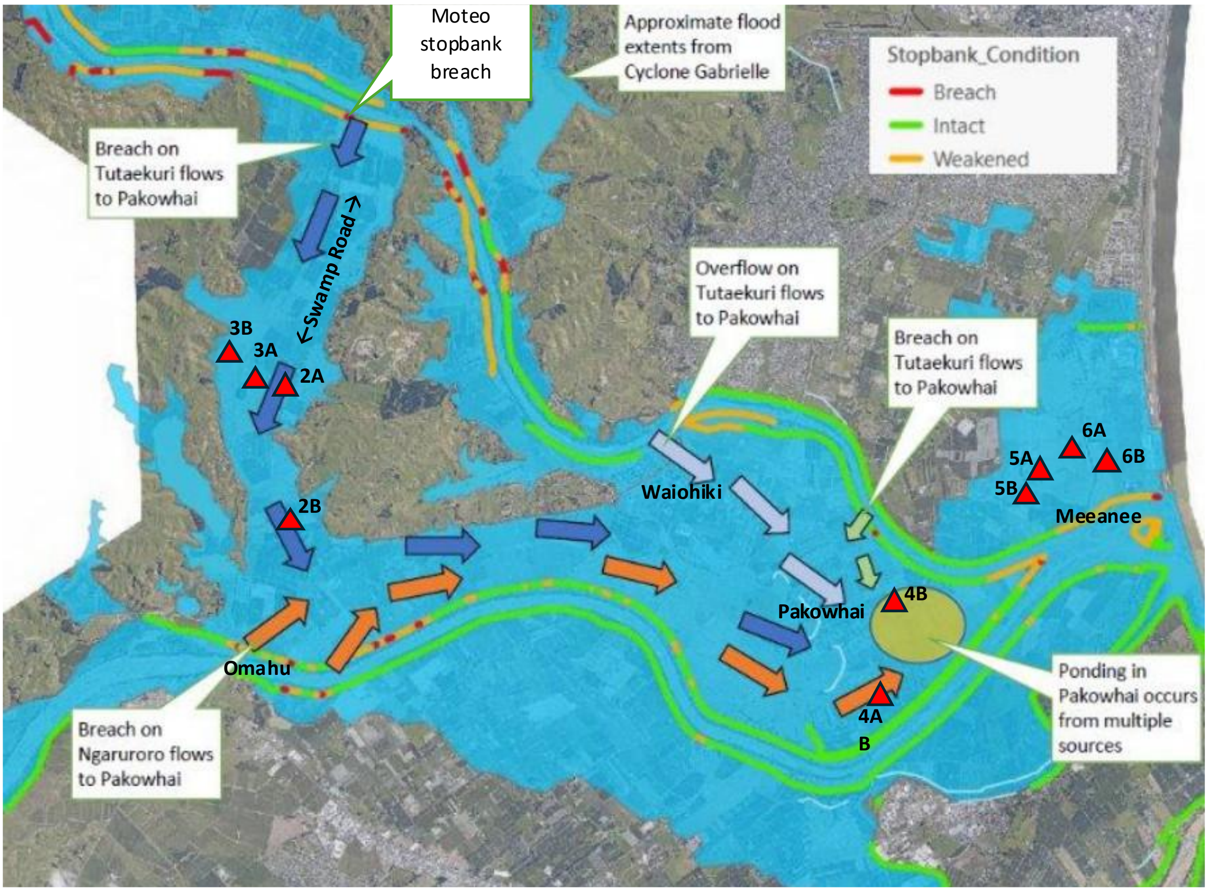


**Figure 4-3 Tutaekuri and Ngaruroro floodwater flow map over Heretaunga Plains. The location of Scenario's 2 - 6 are shown with red triangles. Image supplied by Hawke's Bay Regional Council (2024).**

impacting large areas of apple orchards and annual cropping land. The Ngaruroro River breached its stopbank near Omāhu caused flooding toward the southern end of Swamp Road and around the settlement of Omāhu.

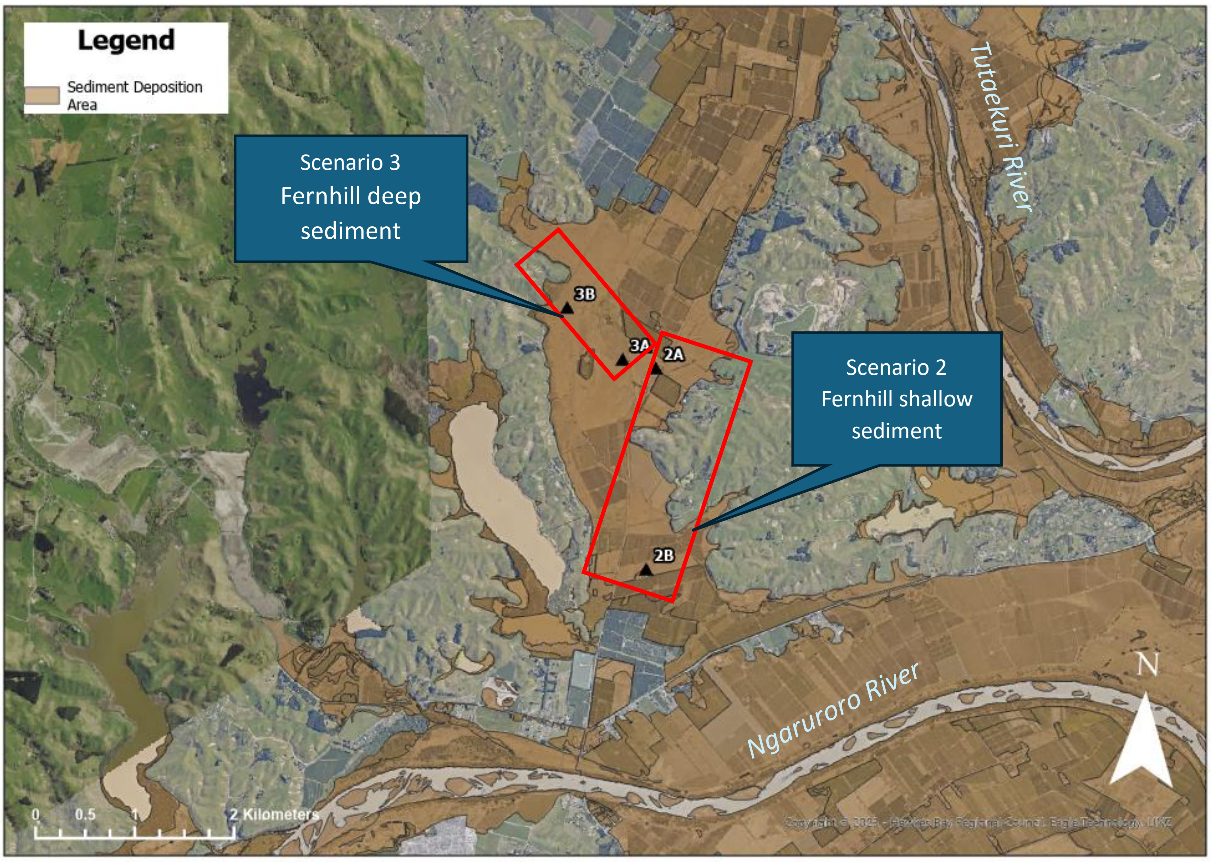


**Figure 4-4 Location of Scenario 2 (sites 2A & 2B), and Scenario 3 (sites 3A and 3B) in Fernhill. Map overlayed with flood sediment deposition area from the Hawkes Bay Regional Council (Eaves & Whitaker, 2024). Basemap sourced from LINZ (2023).**

#### *4.5.2.1. Scenario 2 – Shallow Sediment*

Scenario 2 represents shallow (<5 cm) silty clay loam sediment deposition. Site 2A and 2B are approximately 2 km apart and are both used for annual vegetable cropping. Prior to the cyclone, Site 2A had been harvested for squash, and Site 2B was planted in sweetcorn. Site 2A is located 4.2 km from the Moteo stopbank breach. Site 2B, located 2km south of Site 2A, is approximately 6.2 km from the Moteo breach, and 2.2 km from a breach of the Ngaruroro River stopbank near Omāhu marae. Site 2B may have been impacted by floodwaters from both rivers (Figure 4-4).

Site 2A had annual grass seed and superphosphate fertiliser aerially applied across the whole farm on the 16th of March 2023, thirty days after the flood. The block was grazed with light cattle from July 2023. The paddock was left in grass until early spring when it was aerated and then prepared for beetroot planting. The paddock was ploughed, and power harrowed to incorporate the sediment with underlying soil and create an adequate seed bed. Beetroot was planted in late November 2023 and harvested in late April 2024. The beetroot was planted with a compound fertiliser and had two side dressed applications of calcium ammonium nitrate (CAN). The beetroot was irrigated through the season with three 25 mm applications (75 mm total). The beetroot grew well, and a successful crop with yields similar to pre-flood expectations.

Site 2B had sediment incorporated into the underlying topsoil. Once the sediment had dried out, the paddock was disced and cultipressed (combined cultivator, leveller, consolidator) twice to break up large clods, then deep ripped and rolled twice, and rotary hoed. It was planted in mustard, which grew well over the winter. Mustard was selected as a cover crop for its biofumigant properties, particularly as early discussions indicated biological contaminants might have been present. The mustard cover crop was mulched and incorporated by rotary hoe (chip hoe) in late October. Gypsum was applied to condition the soil. In December, the field had two passes with a disc ripper and 3 passes with a rotary hoe and roller, before beetroot was sown mid-December, with a compound fertiliser. The crop was side dressed three times with CAN followed by urea. Emergence was even and a successful beetroot crop was produced (Wallace et al., 2024).

#### *4.5.2.2. Scenario 3 – Deep Sediment*

Scenario 3 represents deep silty clay loam deposits. Site 3A and 3B are approximately 4.5km from the Moteo stopbank breach and are 0.8km apart (Figure 4-4). At Site 3A 20 cm of silty clay loam was deposited. At Site 3B approximately 60 cm of silty clay loam was deposited. Site 3A was planted in sweetcorn, which was partially buried by sediment, Site 3B was planted in maize which was completely buried by sediment.

Site 3A (located on the same farm as Site 2 A) had annual grass seed aerially applied with superphosphate fertiliser on the 16th of March 2023. Light cattle grazed over the winter from July. Balage was cut from the block in early spring. No crop was planted in the 2023 – 2024 cropping season. Grass, clover, chicory and plantain were direct drilled into the sediment on mid-March 2024. The wrong seed was provided (long rotation ryegrass rather than short rotation Italian ryegrass) which impacted establishment, even with irrigation. The site was then lightly disced and conventionally drilled with annual ryegrass and diammonium phosphate (DAP) in early autumn 2024.

Site 3B had annual grass seed aerially applied in early April with serpentine super and DAP to apply nitrogen, phosphorus, sulphur and magnesium in one application. The site, located in an area prone to wetness and poor drainage, remained wet for an extended period. The first testing, significantly delayed due to wetness making it impractical to sample, was completed in August 2023. In anticipation of growing a crop in spring 2023, the site was sprayed out in October 2023. Access to the site was challenging for large tractors and harvesters. Peat springs started to emerge from the antecedent soil, making planting and harvesting a crop high risk. No crop was planted, and the grass was left to go rank over the summer. The sediment was worked using heavy discs, and then power harrowed in autumn 2024, and annual ryegrass was drilled.

### 4.5.3. Zone 3 – Pakowhai/Meeanee

The Pakowhai area was significantly affected by floodwaters from both the Tūtaekurī and Ngaruroro Rivers, which destroyed many hectares of agricultural and horticultural crops. Both rivers had stopbanks overflow or breach their banks upstream of Pakowhai (Figure 4-5). The most significant breach of the Ngaruroro River was at Omāhu (Figure 4-3). This floodwater joined with floodwater coming from stopbank breaches of the Tūtaekurī River at Moteo and Waiohiki, resulting in significant flooding in Pakowhai (Hawke’s Bay Independent Flood Review Pae Matawai Parawhenua, 2024). The floodwater pathways can be seen in (Figure 4-3).

The Meeanee sites were impacted by floodwater from the Tūtaekurī River overtopping its banks near Awatoto (Heslop, 2023). There was concern that floodwater was potentially contaminated with biological waste or heavy metals, given the proximity to the Awatoto industrial area (Cressey & Russell, 2024).

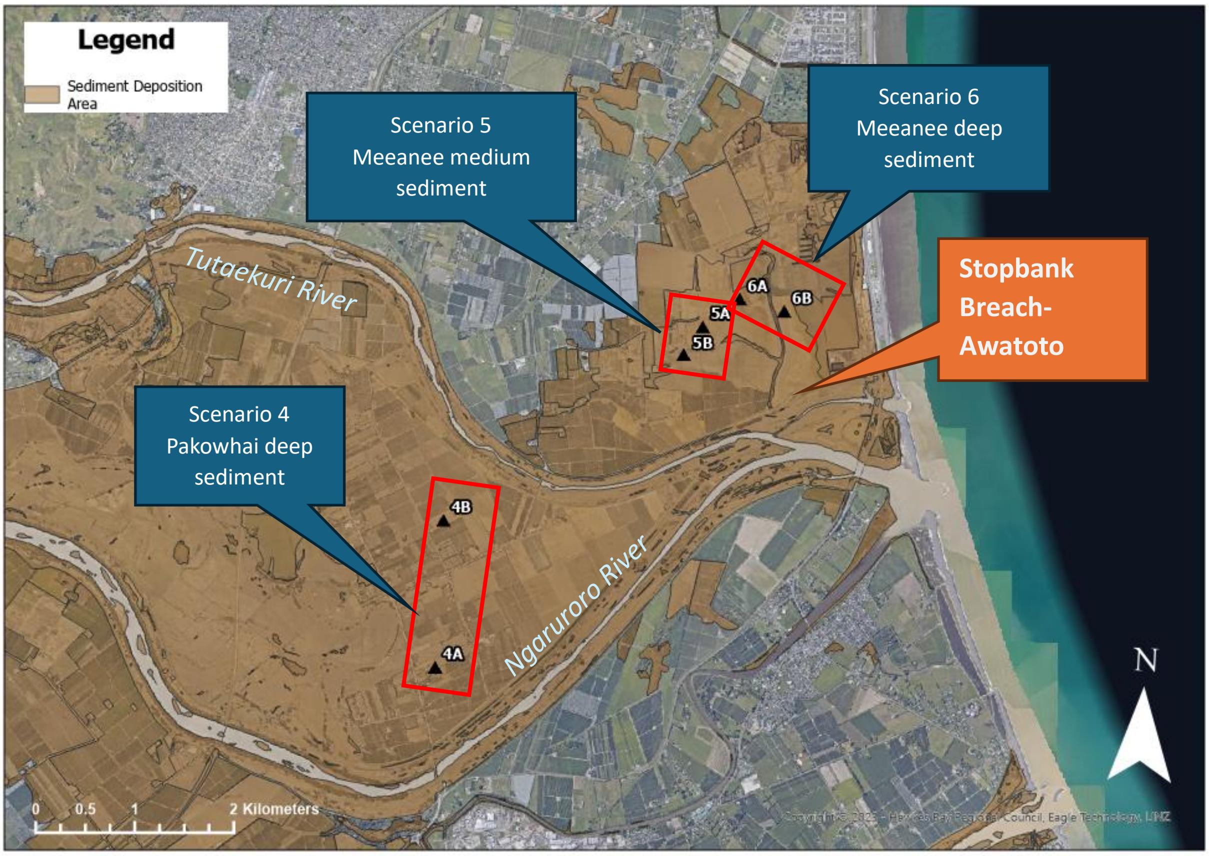


**Figure 4-5 showing Zone 3 Pakowhai/Meeanee, location of scenario 4 (sites 4A & 4B), scenario 5 (sites 5A and 5B), and scenario 6 (sites 6A & 6B). Map overlayed with flood sediment deposition area from the Hawkes Bay Regional Council (Eaves & Whitaker, 2024). Basemap sourced from LINZ (2023).**

#### *4.5.3.1. Scenario 4 – Deep Sediment*

Scenario 4 represents deep, silty clay loam sediment. Sites 4A and 4B are approximately 1.5 km apart. (Figure 4-5). Site 4A is closer to the Ngaruroro River, with deposits up to 25 cm deep, Site 4B is located closer to the Tūtaekurī River, and the measured transect is on deposits 18 cm deep. Site 4B is slightly shallower than the nominal 20 cm class range but is still deep enough to make incorporation with underlying soil difficult. There were several stopbank breaches upstream of these locations and the Tutaekuri and Ngaruroro merged causing significant flooding in their lower reaches. Because of this, the distance from the stop bank breaches to Site 4A and 4B is not cited here as it is considered irrelevant. Site 4A was planted in barley at the time of the flood and Site 4B was planted in fresh market brassicas.

Site 4A was left fallow over the winter. Sediment was removed, aiming to return quickly to full production. Sediment was windrowed (scraped into long piles) and trucked off the site in September 2023. The heavy vehicles compacted the underlying soil, which was then ripped twice, followed by a single pass with a spader, and two power harrow passes. Popcorn was planted with a starter fertiliser in mid-November and harvested in May 2024.

Site 4B was also left fallow over much of the winter. In August the sediment was ploughed, rotary hoed and planted in Nui perennial ryegrass. Ground work was delayed due to extended wetness of the site, making it challenging to work the sediment. The grass grew over the summer, was not grazed or cut, and eventually went to seed in the late summer/early autumn.

#### *4.5.3.2. Scenario 5 – Medium Sediment*

Scenario 5 (Figure 4-5) represents medium deposition (5 – 20 cm) of silty clay loam sediment. Both Site A and Site B are located approximately 0.3 km apart < 2km from the site of the stopbank failure at Awatoto and remained underwater for more than one week. Site 5A had 7 – 8 cm of silt clay loam deposited. Site 5B had 9 – 10 cm of the same textured sediment deposited. Beetroot at Site 5A was harvested just before the cyclone. Site 5B was planted in squash at the time of the flood.

Site 5A was left fallow over the winter. The sediment was initially cultivated by two passes with a tine grubber (spring tine), pulled by a light tractor working the top 10 – 15 cm. This was followed by two passes with a disc ripper (ripping to 25 cm), which aimed to cut sediment into smaller pieces. A deep subsoiler with large wings at the base of the ripper leg was used to raise the whole soil profile and open up the ground to 40 cm in the first pass, and 65 cm in the second pass. These passes were completed to incorporate sediment and break it into smaller clods, which were then ploughed to 30 cm. 'Normal' annual site preparation followed, with the soil power harrowed twice before being rolled. Tile drains were cleared twice (using a 'water rat'), open drains were cleaned four times to remove sediment and improve drainage. Ahead of the tomato planting a 1 m strip cultivation pass was completed. Tomatoes were planted in October; had above standard rates of fertiliser applied and were harvested in early March.

Site 5B was cultivated in May 2023 once dry enough, using two passes with a rototiller and two passes with a deep ripper. A winter cover crop of mustard was planted, having been selected for its biofumigant properties. Tile drains were cleared to improve drainage and speed up drying. The site was cultivated using one pass with a disc ripper and two passes with a rotary hoe and sown in sweetcorn in mid-October. A base application of gypsum and phosphate and potassium was applied; and the crop was planted with DAP and urea. The grower noted that the sweetcorn germinated and grew adequately, but that cultivation was completed too early and caused soil damage. This was highlighted as a reason for poor performance, and some for some unexpected fusarium disease in the crop. The crop was harvested in early February. After harvest the site was cultivated twice using discs, and a cultipress (combined cultivator, leveller, consolidator), once with a deep ripper plus roller, and once with a disc ripper and roller (Wallace et al., 2024).

#### *4.5.3.3. Scenario 6 – Deep Sediment*

Sites 6A and 6B were impacted similarly to Scenario 5 but with deeper sediment deposition (Figure 4-5). Sites 6A and 6B were impacted similarly to Scenario 5. Floodwater overtopped the nearby stopbank of the Tūtaekurī River at Awatoto and remained underwater for more than one week. Site 6A had >20cm of silty clay loam deposited (21 – 23 cm) and Site 6B approximately 20cm. The sites are approximately 1.3 – 1.5 km from the stopbank failure and are 0.5 km apart. Site 6A was planted in tomatoes before the cyclone and Site 6B was in sweetcorn.

Site 6A was left fallow over the winter before sediment was worked. Similar to Site 5A, the sediment was cultivated using a tine grubber to open the soil and improve drying. In this scenario the sediment was deep and took more time to dry compared to 5A. Once dry enough, the field was cultivated twice using a disc ripper, followed by a deep subsoiler which worked to 40 cm first pass, and to 65 cm in the second pass. The grower aimed to incorporate sediment into the underlying soil in each pass, the sediment was broken into large clods, which could be treated normally ahead of spring crop planting. The site was ploughed to break sediment into smaller clods and power harrowed twice. Sweetcorn (super-sweet variety) was planted in late October. Growth was slow in early stages but resulted in a yield comparable to pre-cyclone results. High rates of nitrogen were applied to support growth.

Site 6B was also left fallow over the winter and cultivated in September. The area was disced once and ripped twice before undergoing discing and rotary hoeing as part of standard cultivation. The block had a base dressing of gypsum, phosphate and potassium applied. In November, sugary (SU) sweetcorn was planted with DAP and urea, germination was even, but early growth was slow. Extra nitrogen was applied to enhance growth (sulphate of ammonia) (Wallace et al., 2024).

### 4.5.4. Zone 4 – Ōtāne

The Waipawa River's headwaters are located in the Ruahine Ranges. The river flows over the Ruataniwha Plains before joining the Tukituki River east of Waipawa (Figure 4-6). Sites near Ōtāne were impacted by a stopbank breach along the Waipawa River near Walker Road, about 5 km east of Waipawa. The river returned to its old channel connecting with the Papanui Stream, causing significant flooding of vast areas of agricultural land near Ōtāne. A large portion of the flooded area was previously Lake Roto-ā-Tara, which was drained in the late 1800's to be used for farming (Hawke's Bay Independent Flood Review Pae Matawai Parawhenua, 2024)

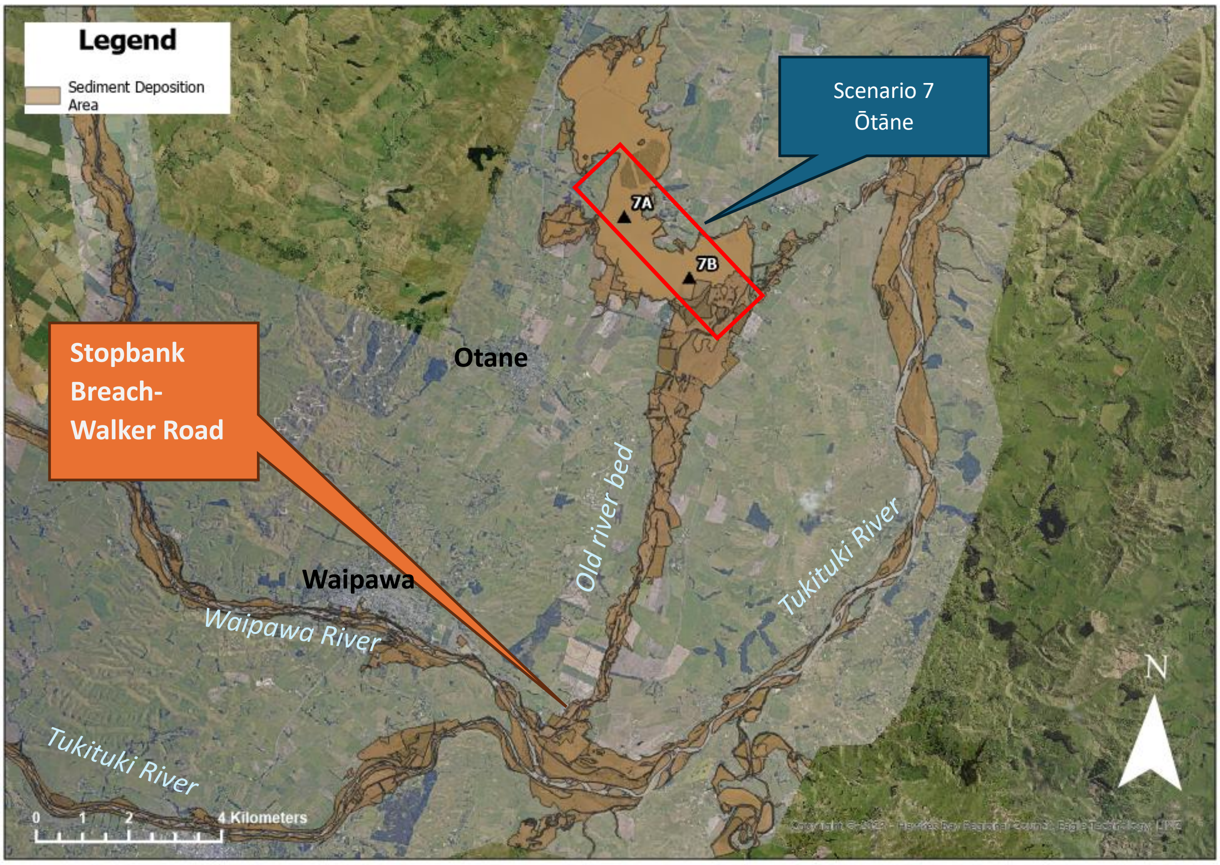


**Figure 4-6 Zone 4 Ōtāne, location of scenario 7 (sites 7A & 7B). Map overlayed with flood sediment deposition area from the Hawkes Bay Regional Council (Eaves & Whitaker, 2024). Basemap sourced from LINZ (2023).**

#### *4.5.4.1. Scenario 7 – Shallow Sediment*

Scenario 7 represents shallow, silty clay loam/clay loam/silt loam sediment deposits. Site 7A is approximately 12 km from the Waipawa River stopbank breach, and Site B is approximately 11 km from the breach (Figure 4-6). These sites remained underwater for more than three weeks while the water slowly drained away. Sediment deposition for both sites was shallow at <5cm. Site 7A had silty clay loam/clay loam deposits, Site 7B had silt loam deposited. Prior to the cyclone Site 7A had been planted in sweetcorn prior to the Cyclone and Site 7B had been planted in a cereal crop.

Site 7A was not cultivated after the cyclone. Once dry enough in April 2023, grass was direct drilled into the shallow layer of sediment. Lambs were grazed over winter, which worked to mix sediment into underlying soil. The grass was sprayed out and direct drilled with malting barley and mono ammonium phosphate (MAP) in September. Two additional nitrogen applications were completed (SOA and urea). The crop was harvested in late January and left fallow until grass was planted in late autumn 2024, after soil sampling was complete (Wallace et al., 2024).

Site 7B was tine cultivated to incorporate shallow sediment with underlying topsoil once the sediment was dry enough to work in May 2023. The ground was levelled and rolled. Winter wheat was direct drilled with a compound fertiliser into the levelled surface in mid-May. The crop was side dressed with urea in October. The crop grew well and achieved respectable yields at harvest in January 2024. The stubble was retained (not burnt off), and the paddock was left bare. In April, after soil sampling was completed, the site was disced and rolled to incorporate crop residue and annual ryegrass was planted.

**Table 4-1 Selected site sediment details**

| Zone | Scenario | Site | District | Initial sediment depth class | Initial depth | Texture | Days after event first sampled | River Catchment | Industry Type | Distance from stopbank KM | Duration of saturation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Zone 1 Esk | 1 | A | Esk | > 20cm | 1-2m | Fine sand | 72 | Esk | Forage Cropping | N/A | |
| | 1 | B | Esk | > 20cm | > 50cm | Loamy very fine sand | 66 | Esk | Cropping | N/A | |
| Zone 2 Fernhill | 2 | A | Fernhill | <5cm | 4-5cm | Silty clay loam | 34 | Tutaekuri | Cropping | 4.5 | |
| | 2 | B | Fernhill | <5cm | 4-5cm | Silty clay loam | 35 | Ngaruroro | Cropping | 2.1 | |
| | 3 | A | Fernhill | > 20cm | 20cm | Silty clay loam | 34 | Tutaekuri | Cropping | 4.5 | |
| | 3 | B | Fernhill | > 20cm | > 60cm | Silty clay loam | 196 | Tutaekuri | Cropping | 4.5 | |
| Zone 3 Pakowhai/Meeanee | 4 | A | Pakowhai | > 20cm | 25cm | Silty clay loam | 35 | Tutaekuri/Ngaruroro | Cropping | N/A | |
| | 4 | B | Pakowhai | 5-20cm | 15cm | Silty clay loam | 45 | Tutaekuri/Ngaruroro | Cropping | N/A | |
| | 5 | A | Meeanee | 5-20cm | 7-8cm | Silty clay loam | 38 | Tutaekuri | Cropping | 1.5 | 8 days |
| | 5 | B | Meeanee | 5-20cm | 9-10cm | Silty clay loam | 38 | Tutaekuri | Cropping | 1.5 | 8 days |
| | 6 | A | Meeanee | > 20cm | 21-23cm | Silty clay loam | 38 | Tutaekuri | Cropping | 1.3 | 10-12 days |
| | 6 | B | Meeanee | 5-20cm | 15-20cm | Silty clay loam | 41 | Tutaekuri | Cropping | 0.5 | |
| Zone 4 Ōtāne | 7 | A | Ōtāne | <5cm | 3-5cm | Silty clay loam | 34 | Waipawa | Cropping | 12 | > 21 days |
| | 7 | B | Ōtāne | <5cm | 4-5cm | Silt loam | 62 | Waipawa | Cropping | 10 | |

**Table 4-2 Summary of selected site descriptions and management, showing management annotations. Aerial grass seed application (A), winter fallow (F), cultivation (C), direct drilling (D), grazing (G), removal (R), crops planted (P).**

| Zone | Scenario No. | Scenario | Site A | Site B |
|---|---|---|---|---|
| Zone 1 Esk | 1 | Esk, deep sand | Oats direct drilled (D) > sorghum > annual ryegrass > grazed (G) > pig effluent applied | Winter fallow (F) > removed debris > levelled > attempts to establish diverse mix (D) |
| Zone 2 Fernhill | 2 | Fernhill, shallow silty clay loam | Aerial annual grass seed application (A)> cattle grazed (G) > cultivated (C)> beetroot (P) planted (harvested after sampling) | Sediment incorporated > cultivated (C) > mustard cover crop (D)> cultivated (C)> beetroot planted (P) (harvested after sampling) |
|  | 3 | Fernhill, shallow silty clay loam | Aerial annual grass seed application (A) > cattle grazed (G)> cut balage > drilled new grass (D) > cultivated (C)> replant grass (D) | Aerial annual grass seed application (A) > sprayed out > too wet to crop > disced (C) > grass drilled (D) |
| Zone 3 Pakowhai/Meeanee | 4 | Pakowhai, deep silty clay loam | Winter fallow (F)> Sediment removed (R) > cultivated (C) > popcorn (P) | Winter fallow (F)Sediment incorporated (C) > grass planted (D) > ground leased |
|  | 5 | Meeanee, medium silty clay loam | Winter fallow (F) > cultivated (C) > tomatoes planted (P) (harvested after sampling) | Cultivated (C) > winter cover crop (D)> grazed (G) > cultivated (C)> sweetcorn planted (P) |
|  | 6 | Meeanee, deep silty clay loam | Winter fallow (F) > cultivated (C)> sweetcorn planted(P) (harvested after sampling) | Winter fallow (F)> cultivated (C)> sweetcorn planted (P) (harvested after sampling) |
| Zone 4 Ōtāne | 7 | Ōtāne, shallow silty clay loam | Grass seed direct drilled into crop stubble and sediment (D) > grazed (G) > spring barley planted (P)> barley harvested | Sediment incorporated (C)> winter wheat planted (P)> wheat harvested (fallow until after sampling) |

**Table 4-3 Paired site antecedent soil details**

| Zone | Scenario No. | Site | Source | NZSC | Soil Type | Drainage Class | Comment |
|---|---|---|---|---|---|---|---|
| Zone 1 Esk | 1 | A | Griffiths 1997 | Typic Sandy Recent | Esk sand | Well drained | WT> 60cm depth |
| | 1 | B | Griffiths 1997 | Typic Sandy Recent | Esk sand | Well drained | WT> 60cm depth |
| Zone 2 Fernhill | 2 | A | Griffiths 1997 | Typic Recent Gley | Moteo silt loam on peat | Poorly drained | <60cm silt loam/clay loam on peat, WT<30cm |
| | 2 | B | Griffiths 1997 | Mottled Fluvial Recent | Pakowhai sandy loam on old topsoil | Imperfect | 30-45cm sandy loam/silt loam on old topsoil, WT 30-60cm |
| | 3 | A | Griffiths 1997 | Typic Recent Gley | Moteo silt loam on peat | Poorly drained | <60cm silt loam/clay loam on peat, WT<30cm |
| | 3 | B | Griffiths 1997 | Typic Recent Gley | Moteo silt loam on peat | Poorly drained | <60cm silt loam/clay loam on peat, WT<30cm |
| Zone 3 Pakowhai/Meeanee | 4 | A | Griffiths 1997 | Mottled Fluvial Recent | Karamu silt loam | Imperfect | 45-60cm silt loam/clay loam, WT 60-75cm |
| | 4 | B | Griffiths 1997 | Typic Recent Gley | Moteo silt loam on old topsoil | Poorly drained | 30-45cm silt loam/clay loam on old topsoil, WT <30cm |
| | 5 | A | Griffiths 1997 | Saline Recent Gley | Farndon clay loam on sand (saline) | Poorly drained | > 30cm clay loam on sand (saline), WT<30cm |
| | 5 | B | Griffiths 1997 | Saline Recent Gley | Farndon clay loam on sand (saline) | Poorly drained | > 30cm clay loam on sand (saline), WT<30cm |
| | 6 | A | Griffiths 1997 | Saline Recent Gley | Meeanee silt loam on lagoon sediment (saline) | Poorly drained | > 45cm silt loam on lagoon sediment (saline), WT<30cm |
| | 6 | B | Griffiths 1997 | Saline Recent Gley | Meeanee silt loam on lagoon sediment (saline) | Poorly drained | > 45cm silt loam on lagoon sediment (saline), WT<30cm |
| Zone 4 Ōtāne | 7 | A | HBRC | Mellow Humic Organic | Poukawa peaty loam | Moderately well drained | Organic soils on the flats, Poukawa peaty loam |
| | 7 | B | HBRC | Acid Humic Organic | Pongakawa Peaty silt loam | Poorly drained | Peat over rhyolitic alluvium |

**Table 4-4 Nutrients applied to each site first 12 months after flood**

| Zone | Scenario | Site | N kg/ha | P kg/ha | K kg/ha | S kg/ha | Mg kg/ha | Ca kg/ha |
|---|---|---|---|---|---|---|---|---|
| Zone 1 Esk | 1 | A | 66 | 56 | 0 | 57.9 | 0 | 42 |
| | 1 | B | 0 | 0 | 0 | 0 | 0 | 0 |
| Zone 2 Fernhill | 2 | A | 165 | 31 | 38 | 42 | 4 | 100 |
| | 2 | B | 293 | 25 | 46 | 551 | 4 | 716 |
| | 3 | A | 21 | 42 | 0 | 23 | 0 | 44 |
| | 3 | B | 35 | 53 | 0 | 19 | 10 | 33 |
| Zone 3 Pakowhai /Meeanee | 4 | A | 154 | 17.5 | 31.3 | 8 | 3 | 0 |
| | 4 | B | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | A | 136 | 42 | 239 | 69 | 13 | 21 |
| | 5 | B | 182 | 72 | 30 | 569 | 0 | 713 |
| | 6 | A | 249 | 30 | 54 | 13 | 5 | 0 |
| | 6 | B | 226 | 71 | 30 | 599 | 0 | 713 |
| Zone 4 Ōtāne | 7 | A | 100 | 29 | 30 | 30 | 3 | 5 |
| | 7 | B | 107 | 18 | 31 | 7 | 3 | 0 |

**Table 4-5 Total number of cultivation events at each site in first 12 months after the flood**

| Zone | Scenario | Site | No. Shallow Cultivation | No. Deep Cultivation | Total Passes |
|---|---|---|---|---|---|
| Zone 1 Esk | 1 | A | 0 | 0 | 0 |
| | 1 | B | 0 | 0 | 0 |
| Zone 2 Fernhill | 2 | A | 1 | 2 | 3 |
| | 2 | B | 5 | 6 | 11 |
| | 3 | A | 1 | 0 | 1 |
| | 3 | B | 1 | 2 | 3 |
| Zone 3 Pakowhai/ Meeanee | 4 | A | 2 | 3 | 5 |
| | 4 | B | 1 | 1 | 2 |
| | 5 | A | 5 | 4 | 9 |
| | 5 | B | 2 | 5 | 7 |
| | 6 | A | 4 | 4 | 8 |
| | 6 | B | 2 | 3 | 5 |
| Zone 4 Ōtāne | 7 | A | 0 | 0 | 0 |
| | 7 | B | 1 | 0 | 1 |

## 4.6. Results

Results for each measure are presented by zone, depth and scenario. Along the x-axis of the charts the sites relating to a scenario, A & B, are annotated with the site's predominant sediment texture; fine sand (fs), loamy fine sand (lfs), silty clay loam (scl).

At the time of testing in 2024 a range of management practices had been applied, including aerial grass seed application (A), winter fallow (F), cultivation (C), direct drilling (D), grazing (G), removal (R), crops planted (P), or a combination of these practices. Relevant practices are indicated by an annotation above the columns on each of the charts.

### 4.6.1. Nutrient fertility

Hill Laboratories completed all nutrient analysis. Samples were taken to 15 cm, which is the standard sampling depth for cropping soils.

#### *4.6.1.1. pH*

Optimal pH for most crops is between 5.8 – 6.3 (Clarke et al., 1986). Figure 4-7 shows changes to pH from 2023 to 2024. Sites where acidic fertilisers were applied are indicated with a green circle, sites where non acidic fertiliser was applied shown by yellow circles.

In autumn 2023 all sites with medium and deep sediments had pH's between 7.5 – 8.1 (average 7.8), above the optimum range for most crops. pH at these sites reduced between 0.2 – 0.8 units in the 12-months after the cyclone, except for site 4B (deep) which did not change. The range in autumn 2024 was between 6.7 – 7.6 (average 7.3).

The shallow sites had an initial pH range of 6.2 – 7.3 (average 6.7). Sites 2A, 2B and 7A showed reductions in pH between 0.2 – 0.5 units over 12-months. Site 7B showed a slight increase of 0.1. The pH range of the shallow sites in autumn 2024 was between 6.0 – 6.9 (average 6.4).

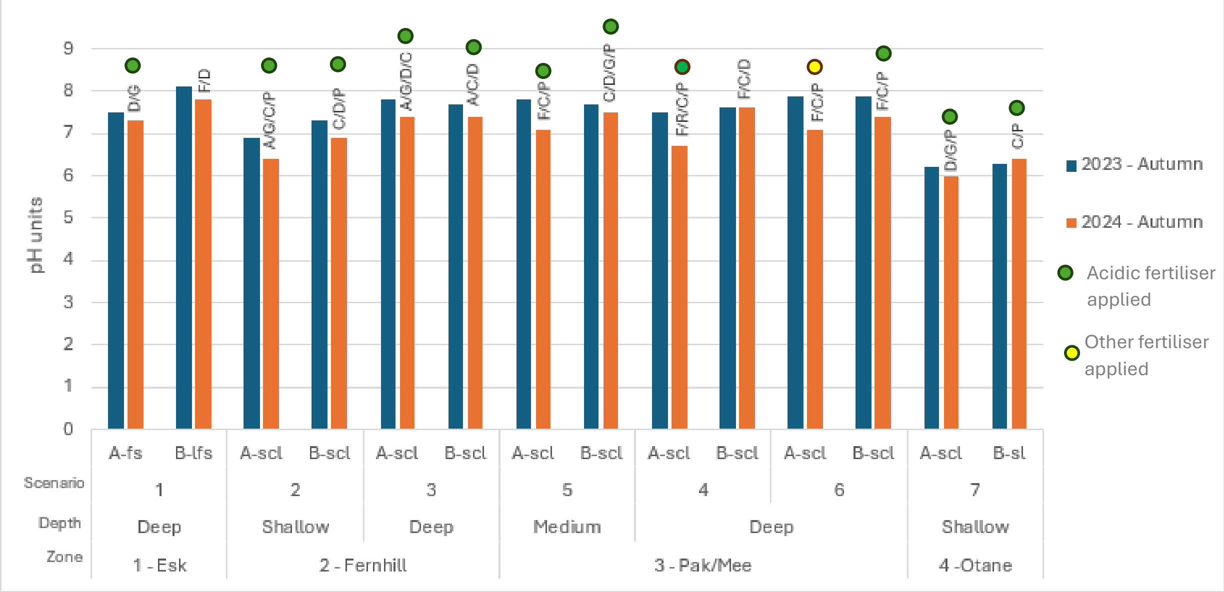


**Figure 4-7 pH results from 2023 and 2024 analysis, by zone, depth and scenario.**

#### *4.6.1.2. Olsen P*

Optimum Olsen P levels for cropping and pastural production are shown Table 4-6. At the time of baseline sampling twelve of the fourteen sites had Olsen P levels below the optimum range for vegetable crop production. In autumn 2024, nine of the fourteen sites had Olsen P levels within or above the optimum range for pasture production (based on soil type), six sites had levels within or above levels for general crop production (> 30 mg/L) (Figure 4-8).

**Table 4-6 Optimal Olsen P ranges for cropping and pastoral land use according to soil type.**

| Land Use Type | Target Olsen P |
|---|---|
| Cropping (crop dependent) (Reid & Morton, 2019) | 30 – 50 mg/L |
| Pasture – Sedimentary soils (Morton & Roberts, 2024) (Scenario 1 – 6) | 20 – 30 mg/L |
| Pasture – Peat (Morton & Roberts, 2024) (Scenario 7) | 35 – 45 mg/L |

At sites where sediment was deep, phosphorus levels ranged from 3 – 21 mg/L (average 12 mg/L), below optimum levels for vegetable or pastoral production. The lowest Olsen P levels were found at Sites 1A and 1B in the Esk Valley where sediment was sandy. After 12-months levels had increased across all sites, except for Site 3B where Olsen P was static. In autumn 2024 Olsen P had increased to a range of 5 – 64 mg/L (average 26.5 mg/L), the change in Olsen P over this time ranged from 0 – 43 mg/L (average increase of 14.5 mg/L). Five of the eight sites had Olsen P's within the optimum range for pasture, and three at or above optimum for cropping. The largest change in Olsen P was seen at Site 4B, where levels increased from 21 to 64 mg/L from autumn 2023 to autumn 2024.

The medium sediment depth sites showed initial Olsen P of 21 – 24 mg/L (average 22 mg/L), slightly below optimum levels for cropping but satisfactory for pasture production. Site 5B had a slight increase of 5 mg/L from autumn 2023 to autumn 2024, where site 5A saw an increase of 26 mg/L to 50 mg/L, which is a significant increase.

The shallow sites had initial Olsen P levels of 28 – 68 mg/L. All sites had optimum levels for pasture production, and two of four sites were optimal for cropping. The shallow sites show variable changes in Olsen P, for instance, Sites 2A and 7B show a decrease in Olsen P of 1 and 6 mg/L respectively while Sites 2B and 7A saw slight decreases in levels of 3 and 2 mg/L respectively.

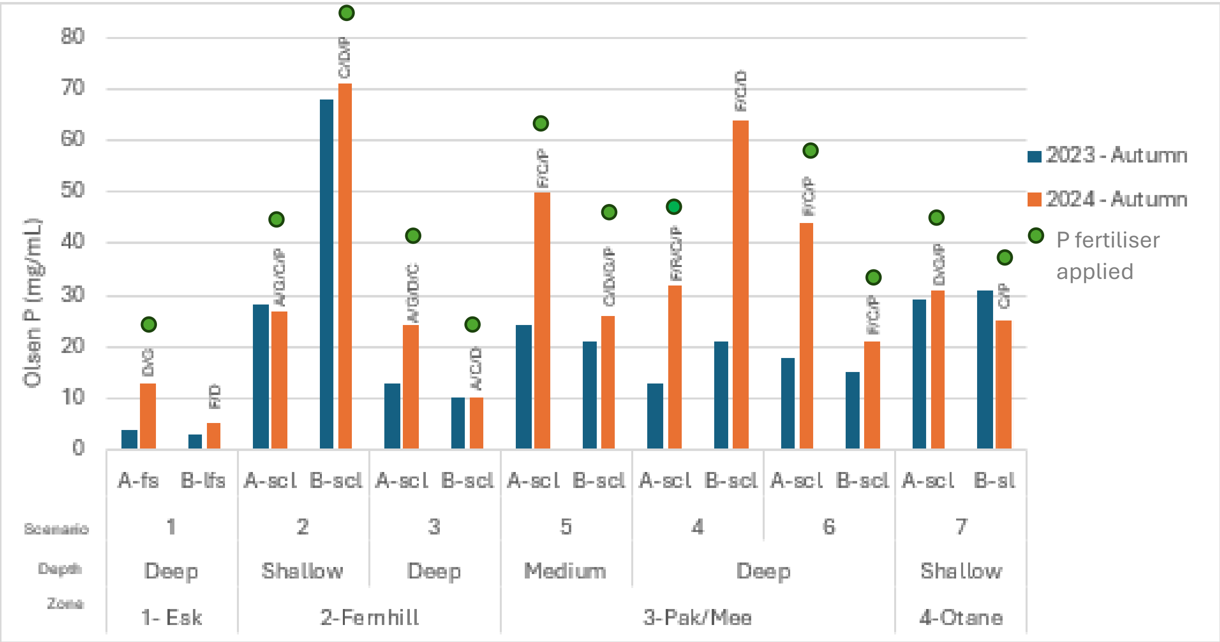


**Figure 4-8 Olsen P results from 2023 and 2024 analysis, by zone, depth and scenario.**

### *4.6.1.3. Quick Test Potassium (MAF QTK)*

Optimal potassium ranges for most vegetable crops are between 6 – 12 QTK units (Reid & Morton, 2019), and for pasture 5 – 8 (sedimentary soils) (Morton & Roberts, 2024) (Figure 4-9). Baseline testing in 2023 shows twelve out of fourteen sites had QTK levels within the optimal range for pastoral production and eleven out of fourteen achieved optimal ranges for general crop production.

**Table 4-7 Optimal potassium ranges for cropping and pastoral land use according to soil type.**

| Land Use Type | Target ranges QTK |
|---|---|
| Cropping (crop dependent) (Reid & Morton, 2019) | 6 – 12 |
| Pasture – Sedimentary soils (Morton & Roberts, 2024) (Scenario 1 – 6) | 5 – 8 |
| Pasture – Peat (Morton & Roberts, 2024) (Scenario 7) | 5 – 7 |

In the sites with deep sediment, QTK levels ranged from low to high, 3 – 12 units (average 8.5 units). The lowest levels occurred at Sites 1A and 1B in the Esk Valley. All other deep sites had levels between 9 – 12 units. Most deep sites saw an increase in QTK levels ranging between 1 – 13 units, with the exception of site 3B (no change) and 6B (-2 units). In autumn 2024, all sites except for 1B were within the optimum range for potassium ranging from 6 – 23 units. Site 4A saw the largest increase in potassium from 10 to 23 units.

The medium depth sites (5A and 5B) both had potassium levels at or above the optimum range, 12 and 16 respectively, in autumn 2023. These levels changed slightly over 12-months; however, both remained above the optimum range 16 and 15 respectively.

The shallow sites initially had potassium levels ranging from 5 – 18 QTK units (average 10.5) and largely saw small decreases (1 – 4 units) in potassium levels from autumn 2023 to autumn 2024. Site 7A initially had below optimum K levels (5 QTK units), however this lifted slightly, and in autumn 2024 all sites were within the optimum range for potassium, between 6 – 14 units (average 9).

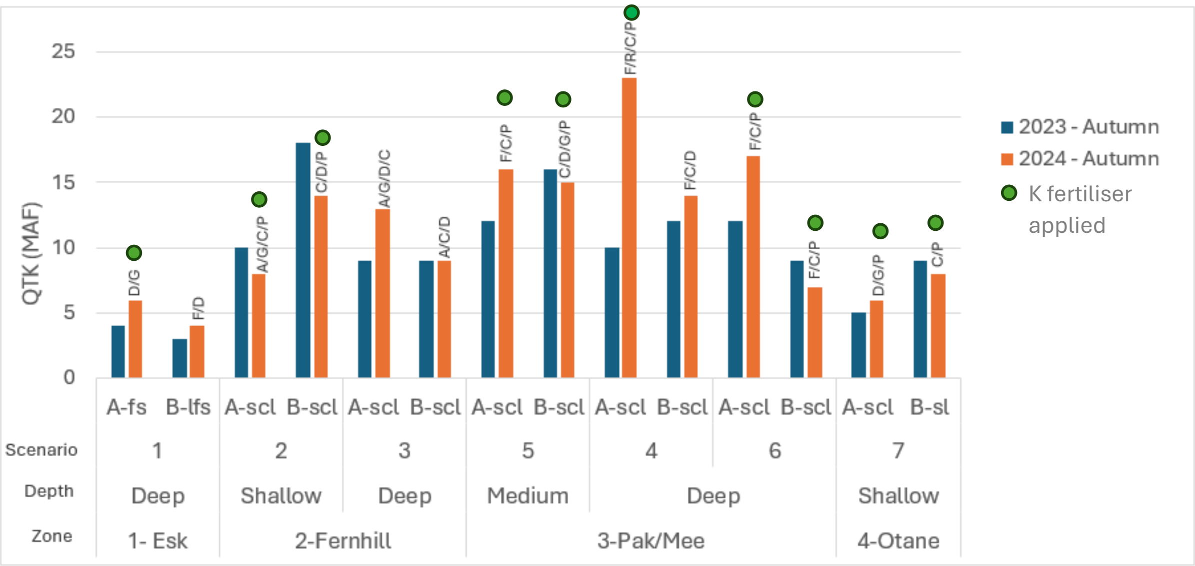


**Figure 4-9 Potassium results from 2023 and 2024 analysis, by zone, depth and scenario.**

#### *4.6.1.4. Sulphate Sulphur*

Sulphate sulphur levels were highly variable, influenced by soil moisture, temperature, and vulnerable to leaching losses. Levels <10 mg/kg are considered low, 10 – 20mg/kg medium and 20 – 50 mg/kg are considered high (Hill Labs, n.d.-a). The minimum detection limit (MDL) for sulphate sulphur at Hill Labs is 1 mg/kg, levels below the MDL are shown as 0 mg/kg.

Results showed a wide range of sulphate sulphur levels in both autumn 2023 and autumn 2024 (Figure 4-10). Baseline sampling in Autumn 2023 shows thirteen of the fourteen sites had at least moderate sulphate sulphur levels. In Autumn 2024, all sites apart from the two Esk sites had at least moderate levels of sulphate sulphur.

The deep sandy sediments of Zone 1 in the Esk Valley had detectable levels of sulphur in autumn 2023, 1A had low sulphate sulphur levels and 1B relatively high sulphate sulphur levels in comparison. In autumn 2024, both sites had sulphate sulphur levels below the MDL.

The deep, silty clay loam sediment sites of Zone 2 in Fernhill had high sulphate sulphur levels in autumn 2023 (3A >20 mg/kg, 3B >150 mg/kg). In 2024, these levels elevated, 3A > 150 mg/kg, 3B > 300mg/kg. In contrast, deep sediment sites in Zone 3 – Pakowhai, Sites 4A and 4B, displayed decreases in sulphate sulphur levels, average 37 mg/kg to average 19.5 mg/kg. Sites 6A and 6B in Meeanee showed increases in levels from moderate to high levels, to well above 'high' levels of 80 mg/kg and 193 mg/kg respectively.

Both medium sediment depth sites, Site 5A and 5B in Zone 3 Meeanee displayed increases in sulphate sulphur levels from high (28 – 29 mg/kg respectively) to above 50 mg/kg (66 – 156 mg/kg respectively).

Shallow sites 2A and 2B in Zone 2 Fernhill displayed increased sulphate sulphur levels to varying degrees. 2A lifted from a medium level of 20 mg/kg to a high level of 34 mg/kg. Site 2B increased from 28 mg/kg to 177 mg/kg, showing levels significantly higher than the top end of the expected range. Shallow sites 7A and 7B in Zone 4 Ōtāne displayed decreases in sulphate levels, from 74 and 35 mg/kg to 46 and 30 mg/kg respectively.

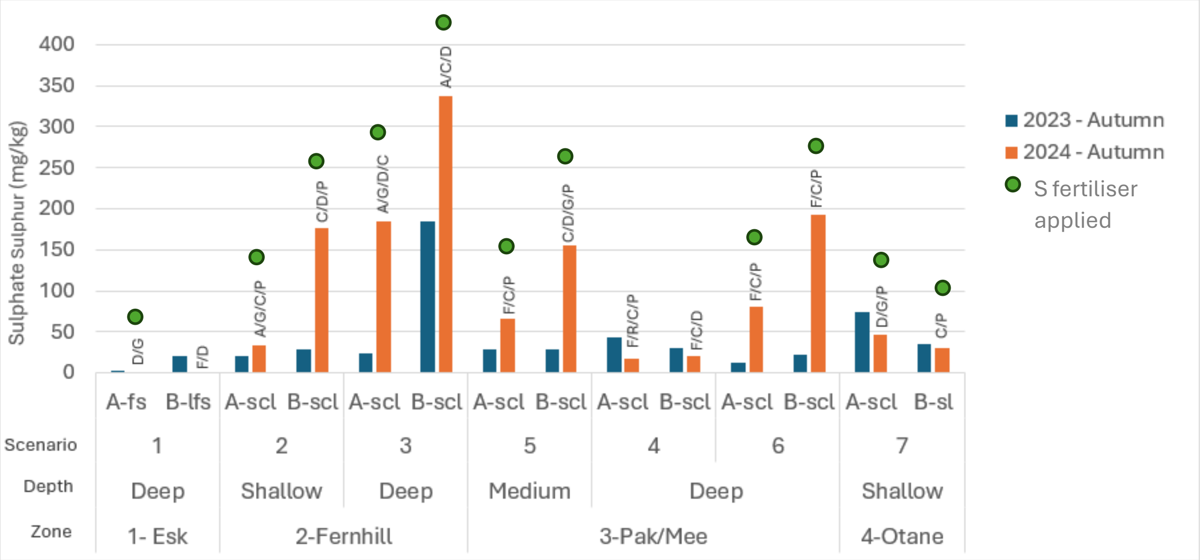


**Figure 4-10 Sulphate sulphur results from 2023 and 2024 analysis, by zone, depth and scenario.**

### *4.6.1.5. Organic Matter*

Organic matter is an important contributor to soil physical, chemical and biological characteristics. In soil very low OM% is <3%, low 3 – 7%, medium levels 7 – 17%. High levels range from 17 – 35% (Hill Labs, n.d.-c).

In 2023 and 2024, deep sediments in Zone 1 Esk Valley had very low organic matter levels, however Site 1A and 1B saw increases in the first 12 months of 1.4% and 0.2% respectively. Sites with deep sediment deposition in Zone 2 Fernhill and Zone 3 Pakowhai/Meeanee all displayed low organic matter in 2023 and 2024. Sites 3A and 3B in Fernhill had small changes to organic matter levels between 2023 and 2024, -0.1 & +0.1% respectively. Sites 4A, 4B, 6A and 6B in Pakowhai/Meeanee all saw decreases in organic matter, ranging from 0.7% – 1.2% with an average reduction of 1%. These sites all had low organic matter levels in the 2023 and 2024 sampling rounds (Figure 4-11).

Sites 5A and 5B with medium sediment deposition in Meeanee, showed low organic matter levels with a decrease in organic matter of 0.3% between 2023 to 2024.

Sites 2A and 2B with shallow sediment deposition in Fernhill displayed low organic matter levels in 2023-2024 with small to no change of -0.2 or 0% respectively. Sites 7A and 7B with shallow sediment deposition in Ōtāne displayed medium levels of organic matter in 2023-2024 and displayed a decrease in organic matter of -0.5% to -0.3% in the first 12 months after the cyclone, respectively (Figure 4-11).

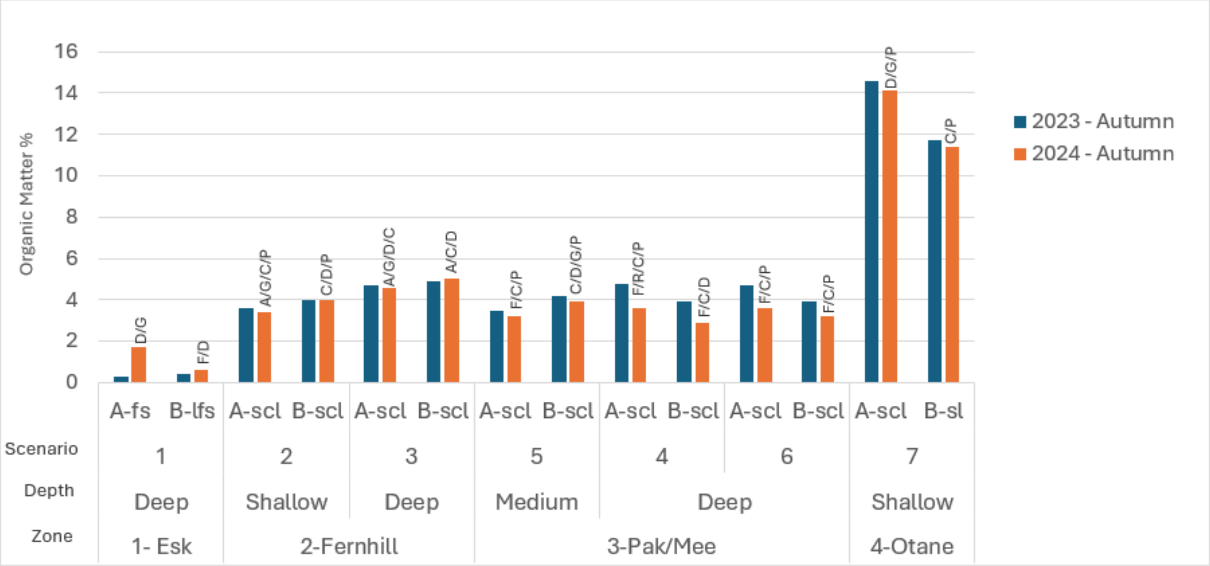


**Figure 4-11 Organic matter results from 2023 and 2024 analysis, by zone, depth and scenario.**

### *4.6.1.6. Extractable Organic Sulphur*

Extractable Organic Sulphur is a measure of the slowly available sulphur in soil. Levels <11 mg/kg are considered low, moderate levels 12 – 20 mg/kg and high >20 mg/kg. The minimum detectable level (MDL) is 2 mg/kg, results showing levels less than the MDL are given as 0 mg/kg in (Figure 4-12). Similar to the sulphate sulphur results, there is a wide range of results from both autumn 2023 and 2024, but all testing showed levels were low (<12 mg/kg) across all sites.

Sites 1A and 1B with deep sandy sediment deposition in the Esk Valley had levels below the MDL in both 2023 and 2024. Site 3A with medium sediment deposition in Fernhill had some detectable organic sulphur in 2023, however this dropped to below detectable levels in 2024. Site 3B results were both below the MDL. Site 4A with deep sediment deposition in Pakowhai showed stable levels of 2 mg/kg while 4B showed consistent levels below the MDL. Site 6A with deep sediment deposition in Meeanee had some detectable organic sulphur in 2023, but no detectable sulphur in 2024 and 6B showed levels of organic sulphur increasing from 2 to 11 mg/kg over 12 months.

Sites 5A and 5B with medium sediment deposition in Meeanee had no detectable organic sulphur is 2023, however levels increased to within the detectable range in 2024, 3 and 11 mg/kg respectively.

Of the shallow sites, Site 2A in Fernhill showed a slight increase in organic sulphur levels (from 3 – 4 mg/kg) over 12 months, while Site 2B showed no change and consistently had levels below the MDL. Shallow sites in Zone 4 Ōtāne showed different trends, with Site 7A increasing from 5 mg/kg to 11 mg/kg, and Site 7B showing a slight decrease from 4 mg/kg to 3 mg/kg between 2023-2024 respectively.

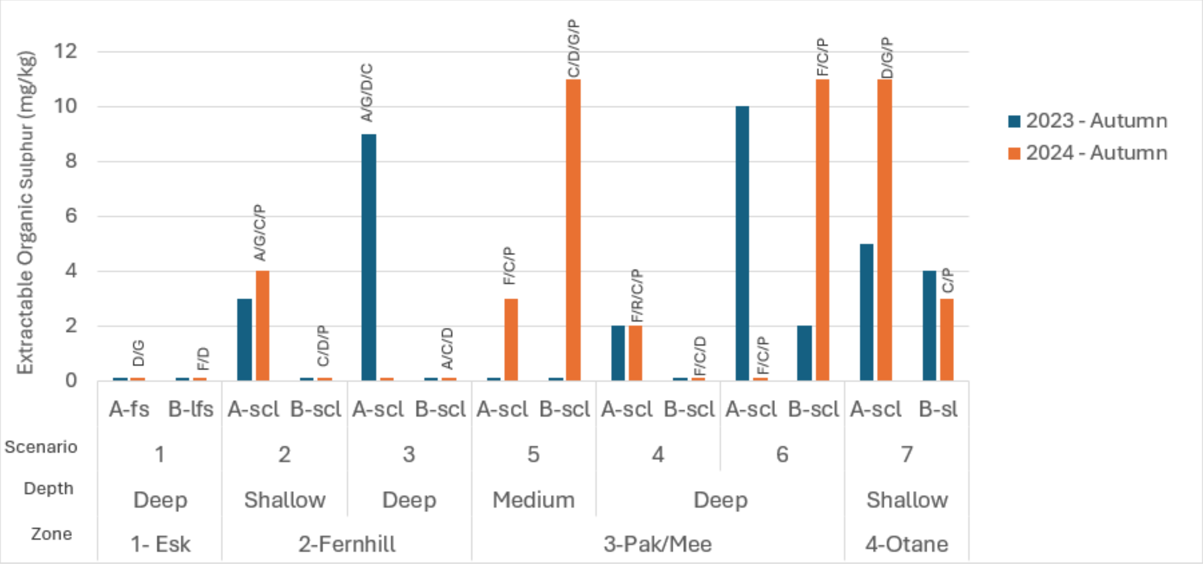


**Figure 4-12 Extractable Organic Sulphur results from 2023 and 2024 analysis, by zone, depth and scenario.**

### *4.6.1.7. Potentially Mineralisable Nitrogen (PMN)*

Potentially Mineralisable Nitrogen (PMN) is measure of the amount of nitrogen that can be mineralised and become plant available during a cropping season. Note that this test has been adopted by laboratories to replace the previous Potentially Available Nitrogen (PAN) as PMN is a more accurate test (Hill Labs, n.d.-b). To date, optimum ranges have not been defined for many crop types. The minimum detectable level (MDL) is 30 mg/kg, any results lower than this have been shown as 0 mg/kg.

Sites 1A and 1B with deep sandy sediment deposition in Esk Valley had PMN level below the detectable limit in 2023 and 2024. Other sites characterised by deep sediment deposition in Zone 2 Fernhill and Zone 3 Pakowhai/Meeanee saw a decrease in PMN from 2023 to 2024, with the exception of Site 4A which remained almost static (increase of 1 mg/kg). Overall, the average PMN for sites with deep sediment deposition decreased from 52 mg/kg to 43 mg/kg (Figure 4-13).

Sites 5A and 5B with medium sediment deposition in Meeanee showed no change and a slight increase of 13 mg/kg, respectively.

Sites with shallow sediment deposition in Fernhill and Ōtāne all show a decrease in PMN, apart from Site 2B in Fernhill which showed a slight increase between 2023-2024. On average the PMN for sites with shallow sediment deposition decreased by 14.5 mg/kg between 2023-2024.

All sites had PMN lower than 100 mg/kg in 2023-2024, with the exception of Sites 7A and 7B with shallow sediment deposition in Ōtāne which have elevated PMN levels.

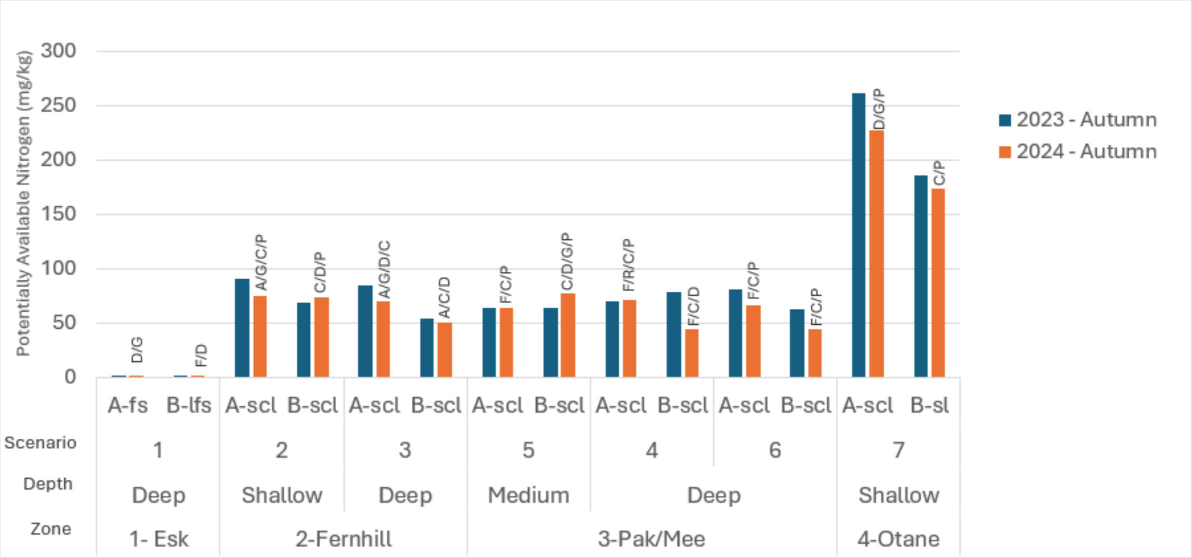


**Figure 4-13 Potentially Mineralisable Nitrogen results from 2023 and 2024 analysis, by zone, depth and scenario.**

### *4.6.1.8. Cation Exchange Capacity*

Cation Exchange Capacity (CEC) is related to organic matter (humus) levels, pH and soil clay content (McLaren & Cameron, 2002). Soils with higher CEC have a greater ability to exchange/buffer cations or soil nutrients into soil solution, making them available to crops through the growing cycle. CEC levels 5 – 12 me/100g are considered low (sandy/low organic matter), medium 12 – 25 me/100g (average, low to moderate organic matter), 25 – 40 me/100g high (high fertility, medium to high organic matter), very high >40 (clay soils with high organic matter or peats) (Hill Labs, n.d.-c).

Apart from Sites 2A and 2B with shallow sediment deposition in Fernhill, all other sites showed a decrease in CEC from 2023 to 2024.

Sites with deep sediment deposition all showed medium CEC values, apart from Site 1A with deep sandy sediment in Esk Valley that displayed low CEC and Site 3B with deep sediment deposition in Fernhill that displayed high CEC in 2023. Sites with deep sediment deposition displayed a decrease in CEC between 2023 to 2024 of between 1 – 12 me/100g, with Sites 4A, 4B, 6A and 6B in Pakowhai/Meeanee displaying the largest decrease (6 – 12 me/100g).

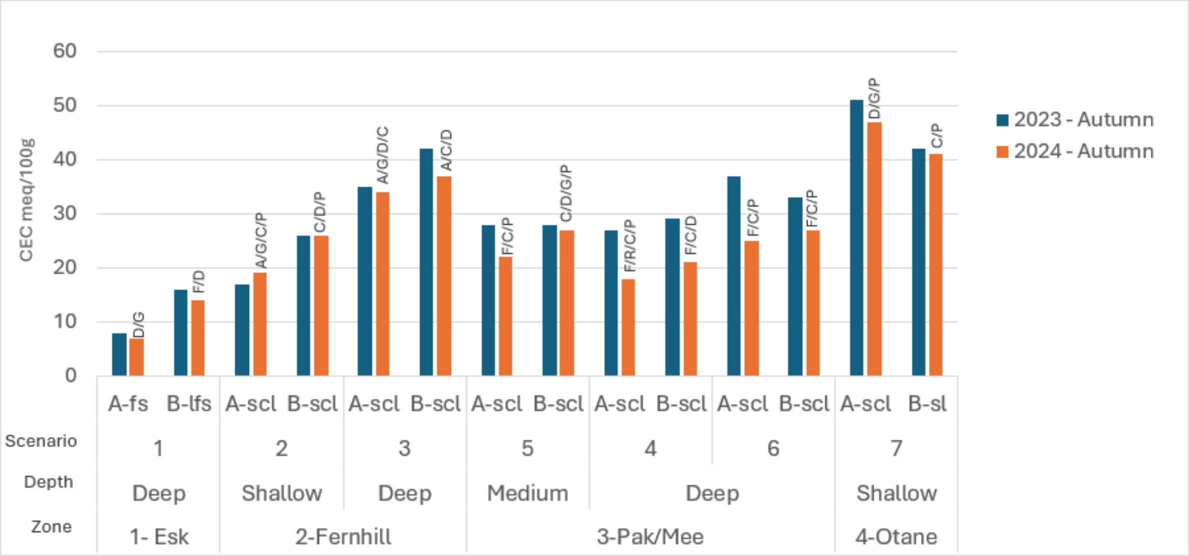


**Figure 4-14 Cation Exchange Capacity results from 2023 and 2024 analysis, by zone, depth and scenario.**

Sites 5A and 5B with medium sediment deposition in Meeanee show a decrease in CEC between 2023-2024, falling within the medium to high range.

The shallow sites 2A and 2B have medium CEC and show either a slight increase or no change in CEC between 2023 and 2024. The shallow sites 7A and 7B have high CEC in both 2023 and 2024.

#### *4.6.1.9. Anion Storage Capacity*

Anion Storage Capacity (ACS%) is a measure of a soils ability to store negatively charged ions like phosphate and sulphate which can be bound by soil mineral particles, affecting their availability to plants. It is strongly controlled by the presence and type of clay minerals, iron and aluminium oxides and soil pH. There are three classes of ASC, low (0 – 30%), medium (31 – 85%) and high (86 – 100%) (McLaren & Cameron, 2002). Out of the 14 sites assessed, 5 had low ASC% and 9 had medium ASC%. The ASC% ranged from 7-67% in 2023 with an average of 40%. In 2024, this average had dropped to 27%, with eight sites categorised as low, and six as medium.

Sites 1A and 1B with deep sandy sediment deposition in Esk Valley have very low ASC and show minimal change between 2023 to 2024. Site 1A had no change while 1B had a slight increase of 3 percentage points, from 10 to 13%. All other sites with deep sediment deposition showed a decrease in ASC from 2023 to 2024, ranging from 1 – 43 percentage points with an average decrease of 23 percentage points.

Sites 3A and 3B with deep sediment deposition in Fernhill display medium ASC in both years, with Site 3B showing a very minor decrease. Sites 4A and 4B with deep sediment deposition in Pakowhai both decreased from medium to low ASC 12 months after the cyclone. Sites 6A and 6B with deep sediment deposition in Meeanee display significantly decreased ASC from medium, to the very low end of medium between 2023-2024.

Site 5A and 5B with medium sediment deposition in Meeanee show significant decreases in ASC with levels falling from the lower end of medium ASC to low ASC. Site 5A saw a reduction by 12 percentage points while Site 5B reduced by 14 percentage points.

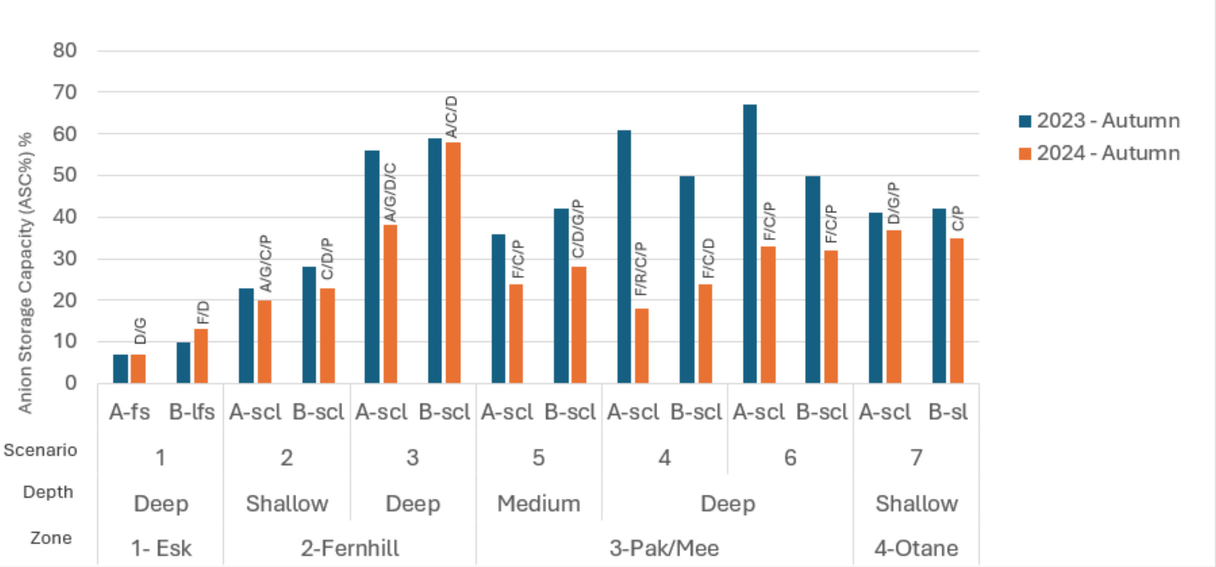


**Figure 4-15 Anion Storage Capacity results from 2023 and 2024 analysis, by zone, depth and scenario.**

Sites 2A and 2B with shallow deposition in Fernhill show low ASC and relatively small decreases in ASC of 3 and 5 percentage points between 2023-2024, respectively. Similarly, Sites 7A and 7B with shallow sediment deposition at Ōtāne display medium ASC and decrease between 2023-2024

### 4.6.2. Visual Soil Assessment (VSA)

Visual Soil Assessments (VSA) were completed in both autumn 2023 immediately after the cyclone, and again in autumn 2024 approximately 12 months after the initial sampling. The modified VSA score card used to assess sediment and soil after the cyclone included porosity, structure, colour, mottles, and earthworm abundance. Total VSA scores ranked as low <7, moderate 7 – 18 and good >18, respectively. An example of a change in VSA in 2023 and 2024 can be found in Figure 4-16. Additional discussion of VSA indicators can be found in Appendix 4.10.3.

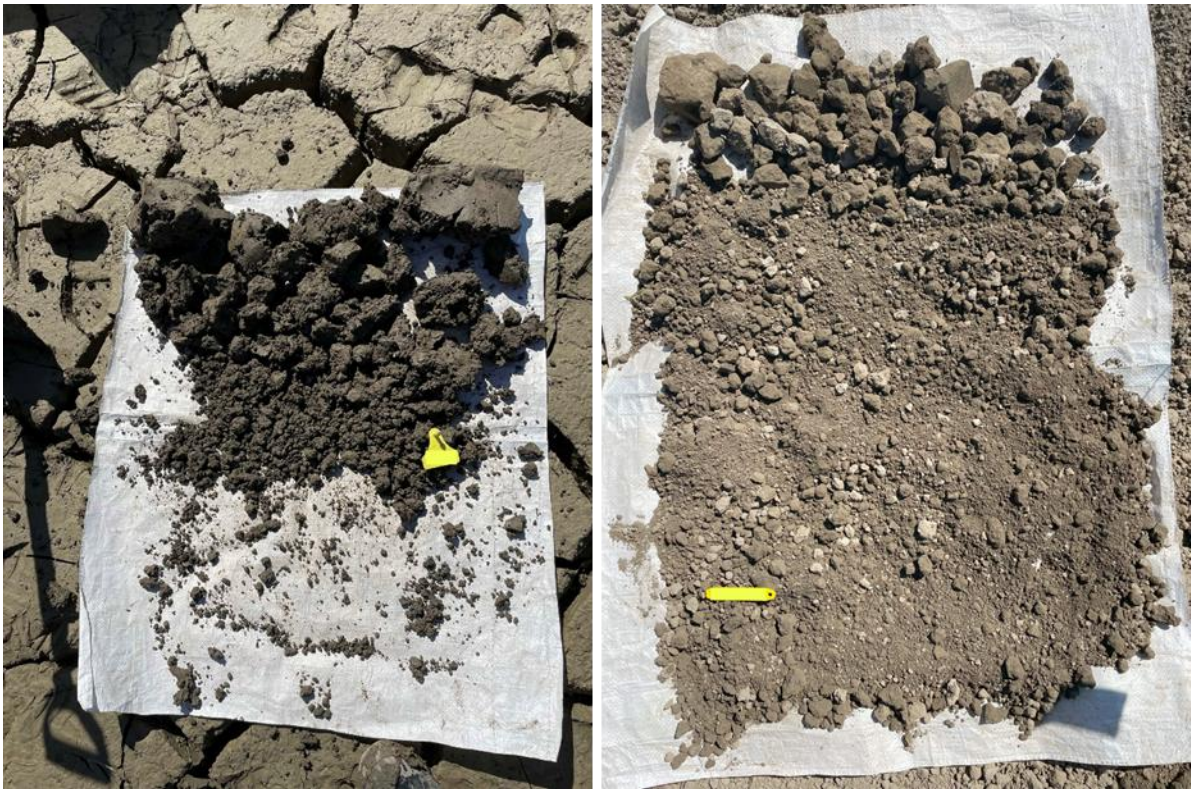


**Figure 4-16 Visual Soil Assessment (VSA) layout, 2023 (left) and 2024 (right).**

#### *4.6.2.1. Total VSA Ranking Score*

Sites 1A and 1B with deep sandy sediment deposition in the Esk Valley display moderate VSA scores with no change 12-months after the sediment deposition. Scenarios 3, 4 and 6 all had deep silty clay loam sediment deposited, and all saw an increase in VSA from low scores at the 2023 baseline testing to moderate scores in 2024 (Figure 4-17).

Sites 5A and 5B with medium sediment deposition in Meeanee, showed an improved VSA score of 5 and 2 points between 2023-2024, respectively.

Sites 2A, 2B, 7A and 7B with shallow sediment deposition in Fernhill and Ōtāne display moderate scores with relatively small decreases for Sites 2A and 7A and increases for Sites 2B and 7B between 2023-2024, respectively.

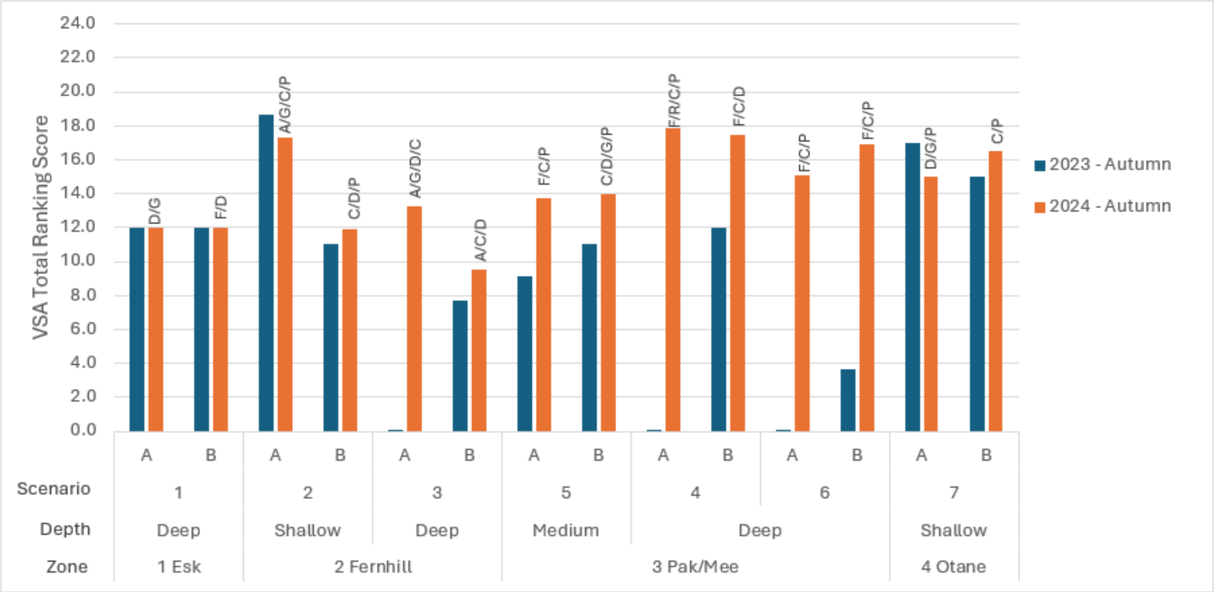


**Figure 4-17 Total VSA Ranking Score results from 2023 and 2024 analysis, by zone, depth and scenario.**

### 4.6.3. Earthworm abundance

The presence of earthworms was used as a proxy score for biological activity, in the absence of more detailed biological analysis. As part of the VSA, earthworms were counted to determine abundance. To provide greater clarity on earthworm abundance the actual numbers counted are compared in Figure 4-18 rather than the VSA ranking scores.

In the deep sandy deposits of Zone 1 in the Esk Valley, no earthworms were found in 2023 or 2024. Sites 3A, which had deep silty, clay loam sediment deposition, displayed the most substantial increase in earthworm abundance of any of the sites, numbers increased from <100 to 800 individuals/m$^2$. In contrast Site 3B saw a slight decrease in population. Sites 4A and 4B with deep sediment in Pakowhai

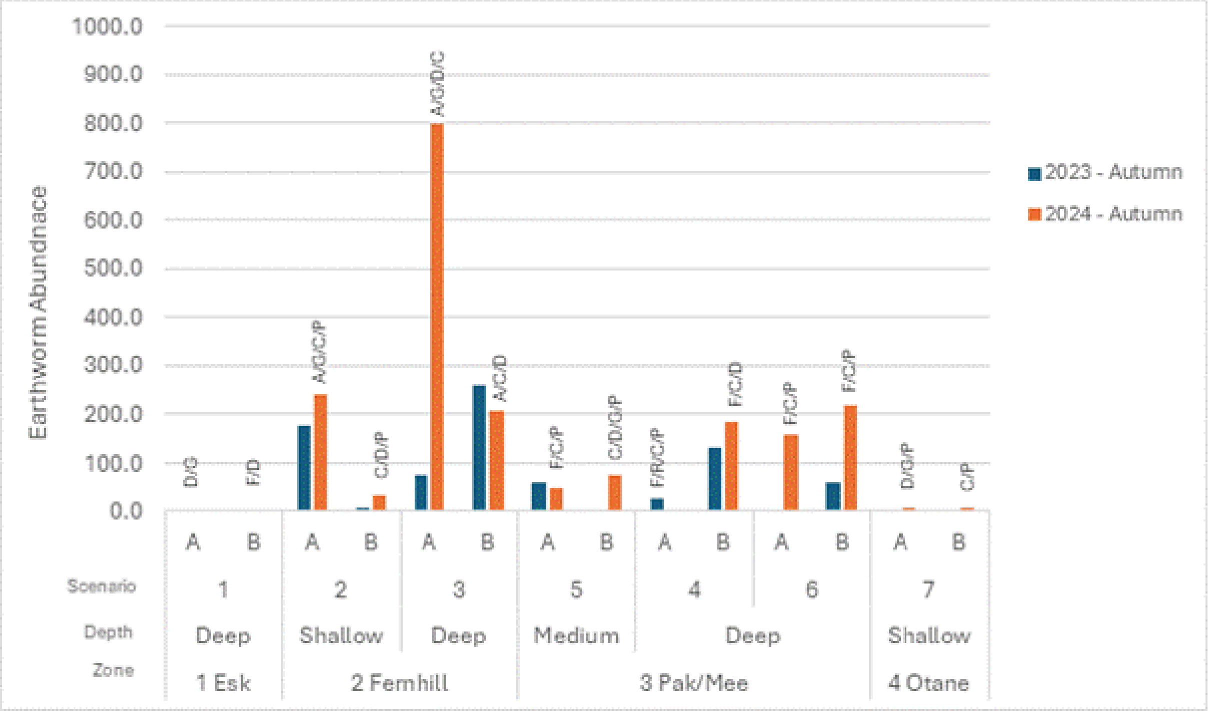


**Figure 4-18 Earthworm count results from 2023 and 2024 analysis, by zone, depth and scenario.**

displayed consistently low numbers, on average <200 earthworms per VSA. Sites 6A and 6B with deep sediment deposition in Meeanee showed low but improving scores between 2023-2024, with both sites showing substantial increases in populations. Site 5A and 5B with medium sediment deposition displayed variable but overall low earthworm populations <100 individual/m$^2$. In the shallow site of 2A, earthworm numbers increased from 2023 to 2024. The remaining shallow sites, 2B, 7A and 7B, all had on average <100 individuals/m$^2$.

### 4.6.4. Bulk density

Soil bulk density is the weight of soil in a specified volume expressed as g/cm$^3$ and is related to soil structure, texture and organic matter content. It can be used as an indicator of soil compaction and soil quality. Soil bulk density is linked to soil porosity, water holding capacity and effective rooting depth (McLaren & Cameron, 2002). Coarse sandy soils have naturally higher bulk density than fine grained soils due to lower total porosity. For optimal plant growth, sandy soils should have a bulk density of <1.6 g/cm$^3$, while silty clay soils should be <1.4 g/cm$^3$ (USDA, 2019). Results over these values indicate potential issues with root penetration due to compaction.

Changes to bulk density are only assessed for sites that had medium and deep sediment deposition. For the shallow sites (sediment depth <5cm) the initial 2023 sampling saw only the sediment portion of the core assessed for bulk density, not the full 7.5 cm depth. This was done to try to assess the bulk density of the sediment, even where sediment was not deep enough to fill a full density ring. This means that Fernhill Scenario 2A and 2B and Ōtāne Scenario 7A and 7B (both shallow) have been excluded from repeat sampling and analysis (Figure 4-19).

All sites had an increase in soil dry bulk density from 2023 to 2024; the only outlier was site 1B, which had a decrease in bulk density. Sites 1A and 1B with deep sandy sediment deposition in the Esk Valley had initially higher bulk densities than the other sites where finer grained sediment was deposited. In 2023, both Site 1A and 1B had densities >1.2 g/cm$^3$ (1.26 and 1.36 g/cm$^3$ respectively). In 2024, 1A had a 4.1% increase in bulk density to 1.31 g/cm$^3$ and 1B had a 14.6% decrease to 1.18 g/cm$^3$.

Sites 5A and 5B with medium sediment deposition in Meeanee displayed increases in bulk density from <1 g/cm$^3$ in 2023 (0.73 g/cm$^3$ and 0.92 g/cm$^3$ respectively), to >1 g/cm$^3$ in 2024 (1.26 and 1.1 g/cm$^3$ respectively).

The deep silty clay loam sites of Scenario 4 and 6 in Pakowhai/Meeanee showed an increase in bulk density from 2023 to 2024. All sites started with relatively low bulk density in 2023, <0.9 g/cm$^3$ (range from 0.72 – 0.89 g/cm$^3$), all of which increased to >0.9 g/cm$^3$ in 2024 (range from 0.91 – 1.26 g/cm$^3$) in 2024. The percentage increase in bulk density ranged from 9.4% - 67.7%.

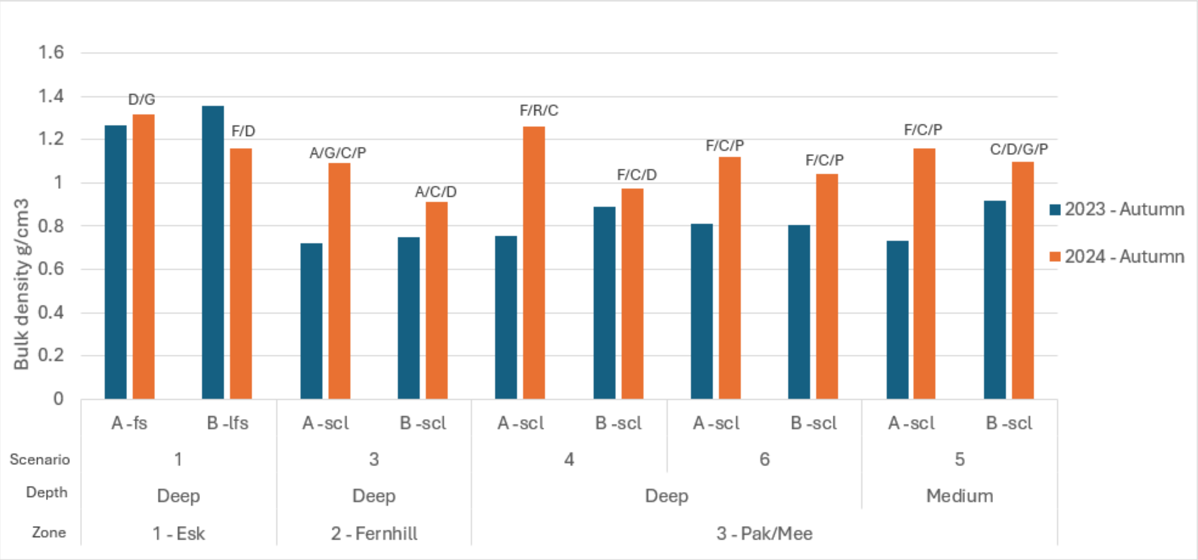


**Figure 4-19 Bulk density results from 2023 and 2024 analysis, by zone, depth and scenario.**

## 4.7. Discussion

### 4.7.1. Nutrient fertility

#### *4.7.1.1. pH*

The baseline pH at sites that received medium or deep sediment deposition was elevated, well above the top end of the optimal range for most crops (pH 6.3). Both sandy and silty clay loam textured sediments had elevated pH's indicating grain size doesn't appear to affect the pH of the flood sediment. At twelve of the fourteen sites, pH decreased or acidified in the first 12 months after the cyclone, one site had no change and one sites pH increased, becoming more alkaline. The overall decrease in pH from baseline to repeat sampling likely relates to the addition of fertilisers but may also partially reflect organic matter from newly sown pasture and crops breaking down to release acids into the soil (de Vries & Breeuwsma, 1984).

The shallow sites of Ōtāne had the lowest initial pH (at the top end of optimum), which is likely due to the influence of the underlying soil type and depth of sediment deposition. Sites 7A and 7B in Ōtāne are underlain by organic peaty soils that have been drained for agriculture. Organic soils can naturally have pH as low as 4.5 (Hewitt, 2010). In order to productivly farm organic soils, lime is incorporated to improve production and nutrient availaibility (Reid & Morton, 2019). This can also enhance microbial acitivty (Mitsuta et al., 2025), reduce toxicity from alumium and maganese and improve soil structure (McLaren & Cameron, 2002). As less than 5cm of river sediment was deposited at Sites 7A and 7B, the influence of high pH sediment was relatively minor compared to other sites where sediment was deeper.

The shallow Fernhill sites, 2A & 2B, had pH's above the top end of the optimum range, but below the average of the medium or deep sites. This is likely related to the relatively shallow sediment deposition (<5cm) and the influence of the underlying soil type (Gley and Recent soil). The underlying Gley and Recent soil types at Fernhill are likely less acidic than the Organic soils at Ōtāne, so overall the pH to 15 cm depth showed relatively elevated pH's at Fernhill compared to Ōtāne. Further insight into underlying soil fertility prior to the cyclone would be valuable for this analysis. It is also possible that the pH of the sediment deposited at Fernhill and Ōtāne had a different pH due to differences in headwater geology.

The data collected after Cyclone Gabrielle aligns with earlier flood sediment data collected after Cyclone Bola, where average sediment pH was 7.9 (Gray & Korte, 1990), and the Southern North Island Storm, sediment pH averaging 6.9 (Litherland et al., 2007). It is likely the geology in the catchment headwaters will play a role in the pH of the flood sediment, particularly the occurrence of sulphide minerals in geological units such as the Whangai Formation that are present along the east coast of the North Island. However, detailed provenance studies to better understand the source rocks that have contributed to the flood sediment and how they differ between catchments is beyond the scope of this study due to constraints on time and funding.

Elevated pH's can impact the availability of many plant nutrients including iron and manganese, which may lead to nutrient deficiencies in crops (O'Kennedy, 2022). A reduction in pH towards the optimum range (5.8 – 6.3) will be beneficial for nutrient availability, however, it may take a number of seasons to adjust the pH back into the optimum range. Ongoing soil sampling for pH and careful management of fertiliser applications is recommended during the recovery phase. A range of factors could have contributed to this predominant trend of pH decreasing, however the largest contributing factor is likely the application of acid fertilisers. Other factors like organic matter mineralisation and oxidation of reduced minerals may have also had a lesser effect on changes to pH (Kılıç & Sönmez, 2018; McCauley et al., 2017).

Most of the sites, particularly those that grew a crop in spring 2023 used a range of fertiliser products, some of which have acidic properties (to varying degrees) including diammonium phosphate (DAP), urea, calcium ammonium nitrate (CAN) and ammonium sulphate (SOA) (Edmeades, 2005). Sites where acidic fertilisers were applied are indicated in Figure 4-7 by a green circle. These fertilisers have an effect on soil acidity through the release of $H^+$ ions, with the change in pH dependent on application rate. Fertiliser applications are likely to be one of main reasons there is a reduction in pH seen across the majority of sites.

#### *4.7.1.2. Olsen P*

Generally low Olsen P levels were measured in sediment deposits at the time of baseline sampling. Sites impacted by deep sediment deposition where the underlying soil type is unlikely to have influenced the results, the sediment had an average Olsen P of 12 mg/L. The overall trend for Olsen P in the 12-month period following the Cyclone was positive, with eleven of the fourteen sites increasing and eight of the sites still having Olsen P levels below optimum in the 2024 repeat sampling.

Low Olsen P levels in the sediment are consistent with sediment samples collected after previous flood events, average Olsen P for the medium and deep sites was 13 mg/L, excluding the shallow sites where antecedent soil contributed more to overall result. After Cyclone Bola, Olsen P was 7 on average (no units given, likely mg/L), which was considered low for pasture production (Gray & Korte, 1990). Of the 30 sites assessed after the 2004 Southern North Island Storm average Olsen P was 8.3 (mg/L) (Litherland et al., 2007). Low Olsen P levels will likely lead to reduced crop yields depending on crop type (Reid & Morton, 2019), and capital fertiliser will be required to address deficiencies.

The changes to Olsen P observed in this study between the 2023 baseline and 2024 repeat analysis likely relate to sediment depth, underlying soil fertility, phosphorus budget, cultivation or a combination of these factors which are discussed in more depth below.

##### Sediment depth and underlying soil fertility

Of the four shallow sites, two had small decreases in Olsen P and two small increases. These sites had an initial sediment depth of <5cm at baseline testing. In a 15 cm soil core, >10 cm was made up of underlying soil, which will have significant influence on the overall concentration of available phosphorus. Pre-cyclone soil test results have not been included as the measured transect is not necessarily reflective of previous soil test results. For sites where sediment depth is medium or deep, the underlying soil type will have had a lesser effect, or possibly no influence on the changes seen between 2023 and 2024.

#### Phosphorus budget

Of the eleven sites that had an Olsen P increase over the first 12 months, nine of these sites had fertiliser containing phosphorus applied, as indicated by the green dots in Figure 4-8. Olsen P increase will be linked to the overall phosphorus budget or the amount of phosphorus applied, versus the amount of phosphorus removed in product either in exported vegetable material, or in livestock weight gain. Some crops grown in spring 2023 were high yielding, depletive crops, where significant amounts of nutrient are removed, e.g., beetroot and tomatoes. Several of the sites remained in pasture, where nutrient demands are lower. On sites where Olsen P increased, phosphorus applications likely exceeded maintenance levels (capital application). Conversely, on the two sites where Olsen P declined (2A and 7B), where beetroot and wheat crops were planted respectively, applied P may have been less than the maintenance requirements. Detailed analysis of site phosphorus budgets is beyond the scope of this research, however, is recommended for future work.

#### Cultivation

The degree to which cultivation was completed at each site will influence changes in Olsen P. Sites that were cultivated using deep ploughs or rippers will have had a significant influence on Olsen P by mixing of raw river sediment with underlying fertile topsoil. Such implements worked to a depth of between 30 – 60 cm, dragging up soil to be mixed and levelled. This underlying soil will have then had some influence on the soil nutrient concentration in the measured top 15 cm.

Sites where cultivation was completed using implements which worked the surface, for example shallow discs, power harrow or tine implements, likely had a lesser impact as there will have been less mixing of underlying soil with the existing topsoil.

The Olsen P level of the original topsoil prior to the cyclone will also influence post cyclone Olsen P levels. This study did not assess the Olsen P levels of soils prior to the cyclone due to inconsistency in previous records, and as tests were not reflective of grower soil test transects. In future studies, prior transects, and underlying nutrient fertility could be considered where information is available.

### *4.7.1.3. Quick Test Potassium (MAF K)*

The levels of potassium found in the baseline sediment samples were in most cases above average for both pasture and general crop production (QTK 5-18). The sites with low K levels (< QTK 5) were those in the Esk Valley (Site 1A and 1B), where sediment texture was sandy. Sandy soils typically have low organic matter and Cation Exchange Capacity (CEC), giving them poor ability to naturally supply or retain cations like $K^+$ (Osman, 2018). Excluding the Esk sites, in 2023 the average K level of the deep sediments was QTK 10.1, which is at the upper end of the optimum range crop production (Reid & Morton, 2019).

There are a range of outcomes related to potassium levels from 2023 to 2024 sampling. In 2024, eight sites showed increased K levels, and six sites displayed either no change or decreased (Figure 4-9). Overall, thirteen of the fourteen sites had levels within or above optimum for both pasture and general cropping production, indicating that sediment K supply was likely sufficient for some crop types. These results are in line with sediment samples collected after Cyclone Bola where average results from the montmorillonite clays were QTK 7, sufficient for pastoral production and some crop types (Gray & Korte, 1990).

The sediment was initially assumed to have low nutrient value, so the moderate potassium levels found in the fine textured sediment was positive news for growers. The changes to potassium levels are likely linked to sediment depth, the pre cyclone fertility of the underlying topsoil, 2023-2024 potassium budget and cultivation practices, or a combination of these factors.

#### Sediment depth and underlying soil fertility

At the shallow sites, the underlying soil type will have an influence on the overall fertility of the top 15 cm of soil. These sites had <5 cm of sediment deposited, therefore the 15 cm cores taken for nutrient testing were predominantly underlying soil. The reduction in the QTK levels from 2023 – 2024 at three of the four shallow sites could be linked to low potassium levels in the underlying soil. Peat soils, like those at Scenario 7 Ōtāne, can be characterised by low potassium levels (Hewitt et al. 2021).

The largest increase in potassium was at Site 4A with deep sediment at Pakowhai, where sediment was removed to 'speed recovery' by utilising the underlying soil fertility for future crop production. In 2024 the test taken was not of sediment, but the underlying soil type, and therefore the elevated potassium was reflective only of the original soil.

#### Potassium balance

Only half of the ten sites that had potassium fertiliser/effluent applied saw an increase in potassium levels. Some of the crops grown, for instance tomatoes at 5A, and the beetroot crops at 2A and 2B have high demand for potassium (Reid & Morton, 2019). If potassium supply does not meet demand, then soil levels will decline. Conversely if K supply exceeds demand, levels will increase.

Potassium levels at site 1A (sandy) increased to within optimum range, despite the texture of this sediment having characteristics of low Cation Exchange Capacity (Figure 4-14). This site is neighbouring a pig farm, and high potassium pig effluent (Wang et al., 2004) has been discharged on the site. Volumes of effluent and concentration have not been measured by the farmer; however, these applications are likely to have contributed to increasing potassium levels.

Potassium is susceptible to leaching so potential loses to leaching may also be a factor where potassium levels have declined. Complete potassium budgets are beyond the scope of this research; however, is recommended for future work.

#### Cultivation

The potassium levels of the original topsoil will have influenced the post cyclone soil test results. Cultivation and incorporation of original topsoil into the raw river sediment is likely to have increased potassium levels. Where deep sediment was worked to a shallow depth, limited mixing with the underlying soil will have occurred. If the paddock was worked using deeper reaching implements like deep ploughs or rippers, which lift soil from lower in the profile, then there will be a greater amounts of soil incorporated into sediment and a greater influence on fertility.

### *4.7.1.4. Sulphate Sulphur*

The soils of Hawke's Bay typically have low sulphate sulphur levels, so the moderate to high levels (30-180 mg/kg) seen in the baseline sampling after Cyclone Gabrielle are atypical. As part of this discussion, it is relevant to consider that sulphate sulphur is very mobile, and changes over time may be linked to external factors like soil temperature, rainfall and timing of sampling. Sulphate is at risk of leaching due to the soils poor ability to retain negatively charged anions.

Relatively elevated levels of sulphate sulphur at the time of baseline testing may have been due to the oxidation of sulphide minerals, similar to the formation of acidic sulphur soils (ASS). This process typically occurs in areas with warm climates with high rainfall (M. Hedley, pers. comm., 2024). As

Cyclone Gabrielle hit in late summer, conditions were still relatively warm through to late autumn. Waterlogged conditions in the flood sediments promote anaerobic decomposition of organic matter and can result in the reduction of sulphates to sulphides e.g. FeS and MnS (Roberts & McConchie, 2017). When the sediment dries, aerobic conditions are promoted, creating an environment where metal sulphide compounds are oxidised to sulphates ($FeSO_4$ and $MnSO_4$) and acid ($H^+$). This leads to an increase in available sulphate sulphur in solution, which is likely weakly bound to sediment particles, due to the low to moderate Anion Storage Capacity (ASC%) of the sediments sampled. The generation of hydrogen ion's during oxidation of sulphide minerals can acidify soil solution and may be partially responsible for the common decrease in pH observed at sites between 2023-2024.

The sulphate sulphur levels recorded after Cyclone Bola were also described as being elevated at 32 (no units given) (Gray & Korte, 1990). Levels reported after the SNI Storm were also elevated, ranging from 3-120 mg/kg with an average of 27.6 mg/kg. Following the initial moderate to high sulphate sulphur levels recorded during baseline sampling, some sites continued to increase, as shown by elevated 2024 results. There are two possible explanations for these increases: 1) continued wetting and drying cycles converting sulphide to sulphate, 2) addition of sulphur through fertiliser. It is possible that catchment headwater geology could have also influenced the sulphate sulphur results. In particular, the occurrence of geological units such as Whangai Formation that are known to contain sulphide minerals. However, this possibility requires detailed provenance studies to confirm and that is beyond the scope of this study.

### Wetting - drying cycles

The weakly structured sediments, particularly the finer textured sediments, are susceptible to continued water logging. This was exacerbated by artificial drainage at some sites being inundated and blocked by sediment, slowing drainage. Wetting and drying cycles may continue to mineralise sulphate sulphur from organic matter under anaerobic conditions and convert sulphide to sulphate in aerobic conditions. Aerobic conditions can be created through cultivation or gradual drying of the sediment with time, enhanced by the re-establishment of drains.

Site 1A and 1B with deep sandy flood sediment in the Esk Valley may have had some release of sulphur early on, however, the sandy particles have very low anion storage capacity and therefore sulphate would have been very susceptible to leaching. In addition, there is low organic matter at these sites, so low ability for these sediments to supply sulphur is also low. The sands are also free draining and after the initial saturation, may not have experienced the same level of wetting and drying or anaerobic conditions as other sites with finer grained flood sediment or a higher groundwater table.

### Fertiliser application

Sites 2B, 5B and 6B saw some of the largest increases in sulphate sulphur levels from 2023 to 2024. These sites all had the addition of 3 T/ha of gypsum. Gypsum is used as a soil conditioner and supplies sulphur (18%) and calcium (22%) to the soil. Applied at such a high rate, in conjunction with other fertilisers containing sulphur, these sites had > 550 kgS/ha applied, which will have increased the amount of available sulphate sulphur at these sites. At the other sites (e.g., Site 3A) where sulphur was applied at lower rates (13 – 69 kg/ha), there were smaller increases to soil levels, which may have been related to fertiliser applications.

Sites 7A and 7B with shallow flood sediment at Ōtāne had low rates of sulphur applied and both sites saw a decrease in sulphate sulphur. The decline may relate to sulphate sulphur leaching, demand exceeding supply or the timing of sampling.

#### *4.7.1.5. Organic Matter*

Organic Matter content of a soil influences both physical properties and chemical properties. The link between SOM % and organic sulphur (EOS) and Potentially Mineralisable N (PMN) are discussed in subsequent sections. The general trend across the majority of sites is that organic matter decreased from 2023 to 2024.

Twelve of fourteen sites had low or very low organic matter levels (<7%) (Hill Labs, n.d.-c) at the time of baseline sampling. Sites 1A and 1B, with sandy flood sediment in the Esk Valley had the lowest organic matter (Osman, 2018). At the Zone 2 – Fernhill and Zone 3 – Pakowhai/Meeanee sites, silt clay loam sediment was deposited, which had low levels of organic matter (3 – 7%), typical of undeveloped or raw sedimentary material (Litherland et al., 2007). The remaining two sites with medium levels of organic matter (7 – 17 %) were the two sites at Zone 4 – Ōtāne. While the sediment texture deposited was silt clay or silt clay loam, the underlying soils at both sites are organic, with high proportions of peat. These soils have characteristically high soil organic matter levels (Hewitt, 2010), which will have an influence on the 15 cm soil test results as the sediment was <5 cm at both sites.

Of the sites that had increases in soil organic matter, Zone – 1 Site 1A had the most substantial increase in OM%. This site has had pig effluent applied at regular intervals, which may have contributed to increased levels.

Low levels of organic matter at baseline testing align with results after the 2004 SNI Storm, where average OM% was 1.6 (range 0 – 3.7) (Litherland et al., 2007).

The decrease in organic matter from 2023 to 2024 may relate to extended, or repeated wetting and drying cycles of these sites due to weak structure and poor drainage in the 12-month period after the cyclone. Artificial drainage was blocked with sediment, and where fine textured sediment was deposited, sediment particles sealed off the original soil, creating a physical barrier to drainage. These water-logged soils promote anaerobic microbes which decompose or mineralise organic matter, potentially reducing overall organic matter levels. In addition, nine of these sites were cultivated, which aerates the soil, inducing organic matter mineralisation through mechanical soil disturbance and soil aeration (Liu et al., 2006). The action of incorporating crop residue can also increase soil organic matter, so cultivation might not be the full explanation for decreasing organic matter levels.

A key consideration for the sites where organic matter is low, is the impact to herbicide mobility and efficacy. Low organic matter soils have less adsorptive capacity, which may leave higher concentrations of some herbicides in solution that could cause crop injury or be leached through the soil profile (Takeshita et al., 2019). Where organic matter levels are low particularly in deeper sediments where there is little to no influence of underlying topsoil, growers may need to adjust herbicide strategies to protect crops and the receiving environment.

#### *4.7.1.6. Extractable Organic Sulphur*

Extractable Organic Sulphur levels are strongly correlated to soil organic matter (SOM). Where soil organic matter levels are higher, typically organic sulphur levels will be higher as well. The data for Extractable Organic Sulphur does not show clear trends based on depth, texture or management, except for Scenario 1 with sandy sediment in the Esk Valley, where results are below the laboratory minimum detection limit (MDL) for both sites in both years.

Sulphur fertiliser applied across the sites was in the available sulphate sulphur form, not in the slowly available organic form (elemental), so would likely not have had a significant influence on EOS concentration. Of those sites where high levels of gypsum (sulphur) were applied (2B, 5B and 6B), two sites (5B and 6B) saw an increase in EOS, however, this trend was not seen at site 2B, where results were consistently below the MDL.

In Figure 4-20, EOS is plotted against organic matter (OM%), the $R^2$ is <0.3 indicating weak correlation between the two results. The amount of organic matter appears to have little influence on the organic sulphur levels in the top 15 cm. This indicates that organic matter levels do not fully explain the measured organic sulphur levels.

Overall, despite relatively large variation in levels of organic sulphur, all results from 2023 and 2024 showed low levels, which means the sulphur supplying power of the soil is relatively low.

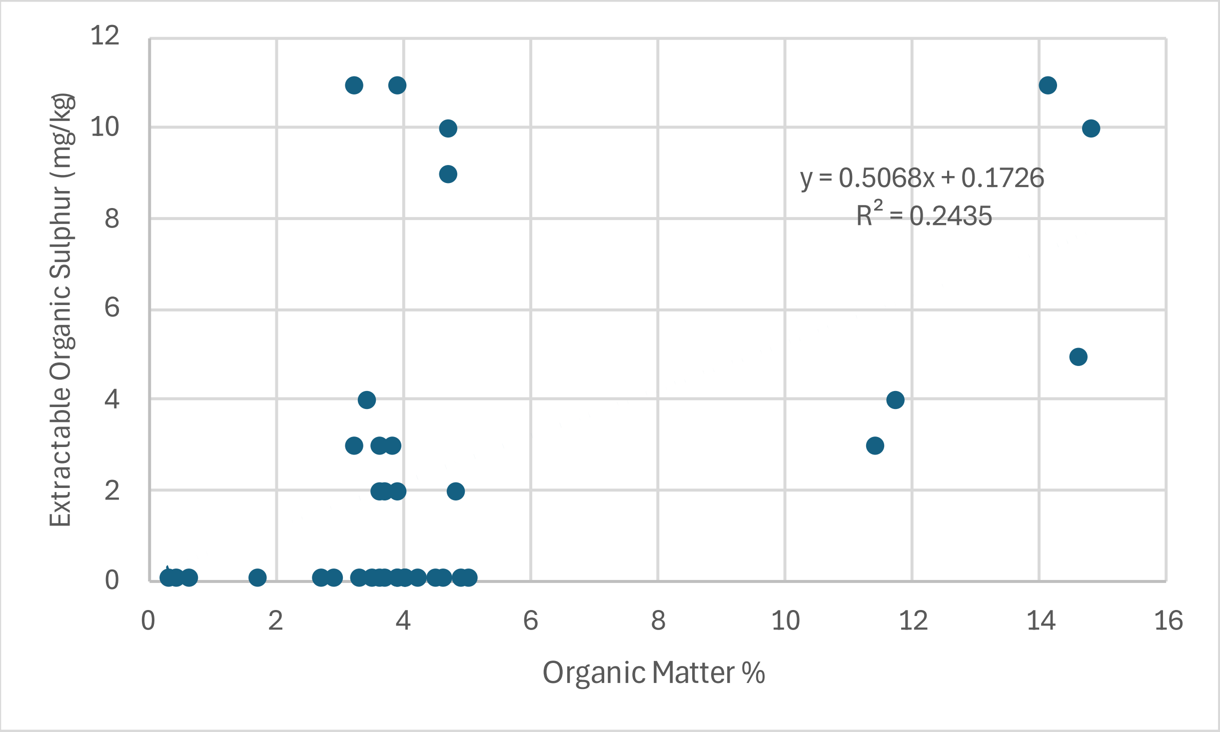


**Figure 4-20 Relationship between Extractable Organic Sulphur and Organic matter levels, all sites, from both 2023 and 2024**

### *4.7.1.7. Potentially Mineralisable Nitrogen*

Potentially Mineralisable Nitrogen (PMN) is linked to the amount of soil organic matter (SOM). Soils and sediments with high SOM typically have higher PMN. The general trend across the majority of the sites is that PMN decreased slightly from 2023 to 2024 (eight sites).

Sites with the highest PMN values, are those at Zone 4 – Ōtāne, where the underlying Organic Soils have 'moderate' organic matter levels (7-17%). The relatively high levels of PMN measured at Site 7A and 7B with shallow sediment deposition in Ōtāne will be strongly influenced by the nature of the underlying topsoil. Site 1A and 1B with deep sandy sediment in Esk Valley had the lowest PMN consistent with very low (<3%) organic matter. The silty clay loam sites in Zone 2 – Fernhill and Zone 3 – Pakowhai had relatively similar levels of PMN, regardless of depth.

The declining levels of PMN between 2023-2024 likely relate to declining levels of organic matter, possibly from cultivation or decomposition driven by wetting and drying cycles (Roberts & McConchie, 2017; Liu et al. 2006). Seven of the eight sites where PMN decreased were cultivated, which may have contributed to lower SOM, and therefore lower PMN.

Figure 4-21 shows the relationship between PMN OM% measured. In both 2023 and 2024 there is a strong, positive correlation, showing that sites with higher SOM levels have higher PMN ($R^2$=0.9457).

z PMN is an important factor for growers to consider. If levels are low, the soil may not be able to supply sufficient N throughout the growing season and therefore increased inputs of nitrogen fertiliser may be required to meet crop demands. It is also important to take PMN into consideration when calculating fertiliser inputs to match N to crop demand through the growing season. By taking PMN into consideration growers can potentially save money on fertiliser and reduce the risk of N loss from the root zone.

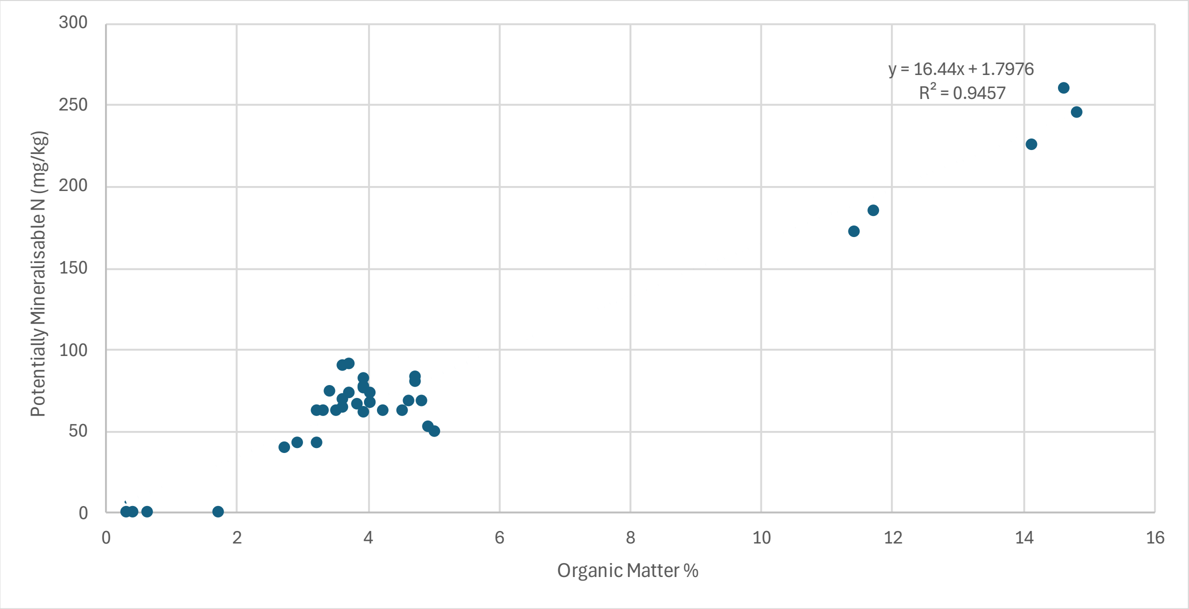


**Figure 4-21 Relationship between Potentially Mineralisable Nitrogen and Organic Matter, all sites, from 2023 and 2024.**

### *4.7.1.8. Cation Exchange Capacity*

The Cation Exchange Capacity (CEC) of a soil is linked to other soil characteristics like soil organic matter and clay mineral content, two variables that vary across the measured sites. Across the majority of sites CEC decreased in the period from 2023 to 2024, likely explained by decreased organic matter (OM%).

Th highest CEC levels were found at Sites 7A and 7B with shallow deposition over organic soils at Ōtāne. High levels of organic matter within the underlying organic soils likely influenced the high CEC results. The lowest CEC values were found at Site 1A and 1B with deep sandy sediment deposition in the Esk Valley. The sandy sediment has low organic matter and low clay content resulting in low CEC. The Zone 2 Fernhill and Zone 3 Pakowhai/Meeanee sites have medium CEC which can be explained by the presence of organic matter, albeit at low levels. These sites have a proportion of clay mineral particles which also contribute to a soils ability to exchange cations. The strong positive relationship between CEC and organic matter is seen Figure 4-22. The same relationship exists in the data from the Manawatu 2004 storm where average OM% was 1.9% (very low) correlating with low CEC (Litherland et al., 2007).

As organic matter content declines so too does CEC or the amount of exchange sites for positively charged ions. Reduced organic matter and CEC results in a reduced capacity to buffer herbicides, which might make these products more mobile in soil, increasing risk of crop injury or leaching losses. A higher risk of leaching nutrient cations (K+, Ca2+, Mg2+) means fertiliser should be applied at lower rates and more frequently to ensure optimum levels are maintained for crop growth.

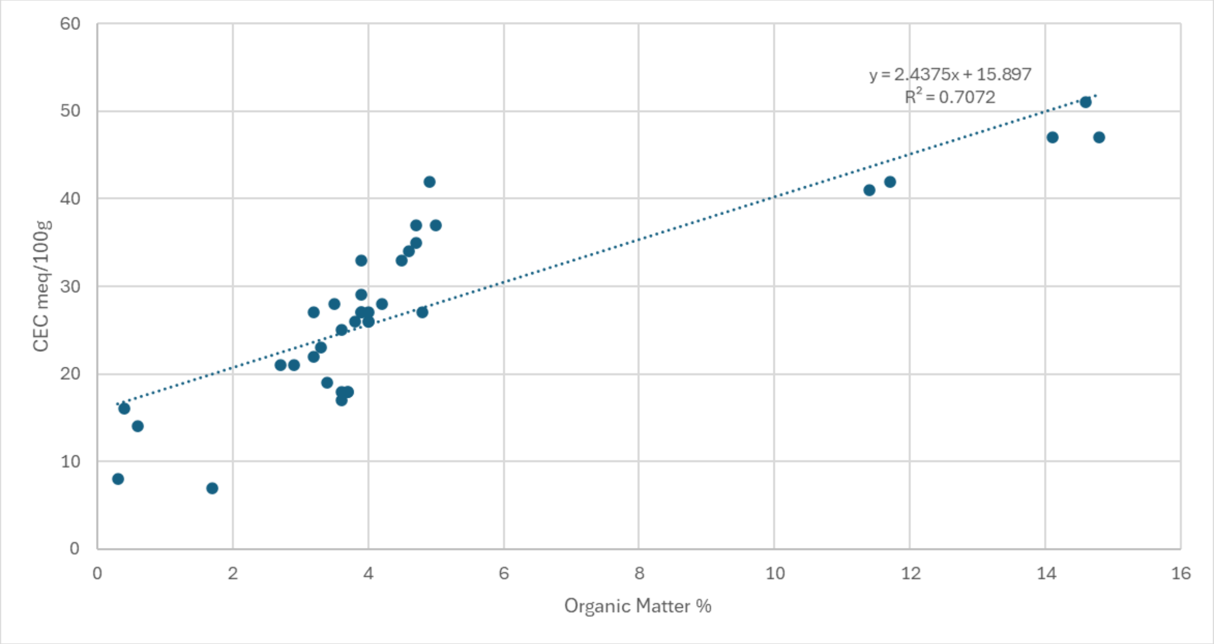


**Figure 4-22 Relationship between Cation Exchange Capacity and Organic Matter, all sites, from 2023 and 2024.**

### *4.7.1.9. Anion Storage Capacity*

Anion Storage Capacity is generally understood to be an inherent characteristic of soil; however, the sediments deposited in flood water are in a transient state as particles settle and consolidate to a new equilibrium, further disrupted by grower interventions. Across the majority of sites Anion Storage Capacity (ASC%) decreased in the period from 2023 to 2024. Those sites that had medium and shallow depth sediment deposits will have had varying degrees of the underlying soil influencing the test results. The low (0-30%) ASC% are indicative of unweathered sediment deposits (Litherland et al., 2007).

The decrease in ASC% across most of the sites may be explained by the changes to soil bulk density. As sediment compacts or condenses, there is a greater amount of soil per unit volume, which reduces the total surface area available for anion adsorption. Tighter packing of particles reduces the interaction between anions and particle bindings sites. Figure 4-23 below shows the relationship between bulk density and ASC for sites impacted by medium to deep sediment deposition. The $R^2$ value is 0.788 which indicates a strong relationship between the two variables. A reduction in organic matter between 2023-2024 from cultivation or decomposition from wetting and drying cycles may also cause a decrease in ASC.

The ASC% of the sediment deposits considered in this study (5-68% with an average of 45%) are similar to that of the 2004 Southern North Island Storm study (3-52% with an average of 25.5%) (Litherland et al., 2007). Note, the sites assessed by Litherland et al. (2007) were pastoral sites sampled to 7.5cm, while in this study we assessed a range of pastoral and arable sites to a depth of 15cm.

The overall reduction of ASC% indicates that the soil/sediments ability to retain negatively charged ions like phosphate and sulphate has reduced (Morton & Roberts, 2024). This means that these anions are at greater risk of leaching, this is predominantly a concern for the eight sites categorised as having low ASC% (<30%) in 2024. Lower rates of superphosphate application are recommended for sites with low ASC to minimise potential loss through leaching.

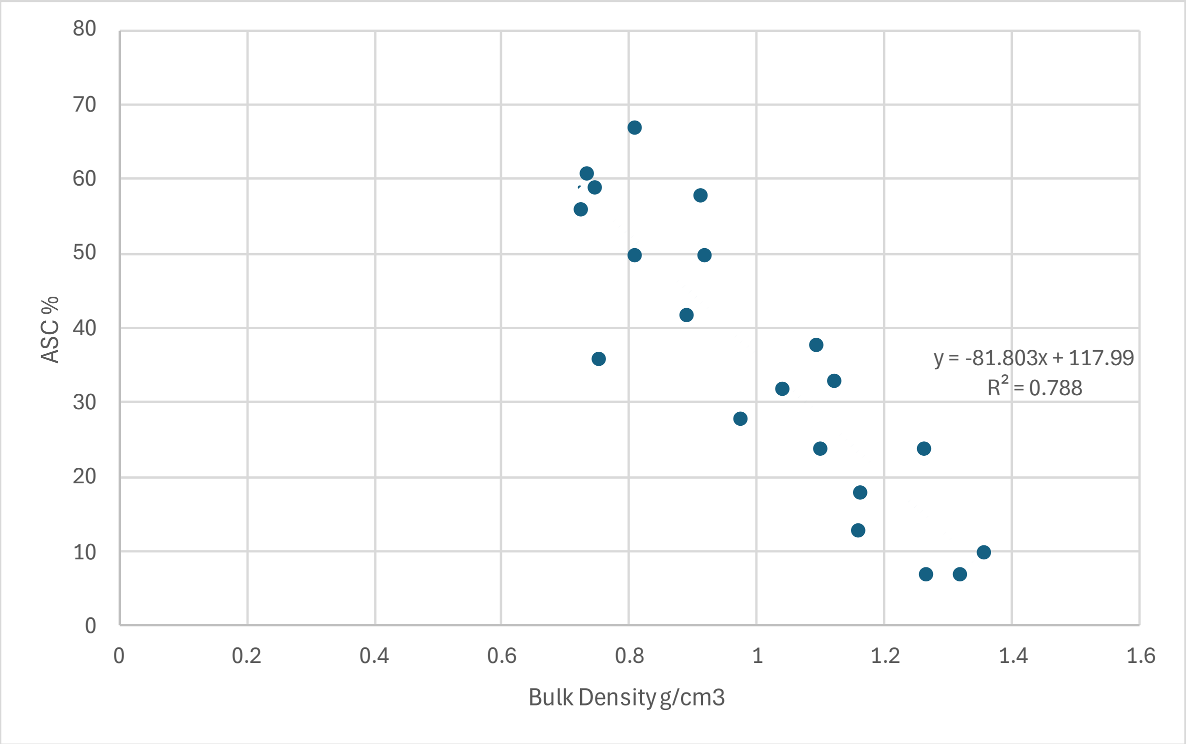


**Figure 4-23 Relationship between Anion Storage Capacity and soil bulk density.**

## 4.7.2. Visual Soil Assessment (VSA)

### *4.7.2.1. Total VSA Ranking Score*

Visual Soil Assessment (VSA) was selected as a cost effective tool to assess different soil attributes from a single sample. It is widely applied across New Zealand, on different soil types and land uses (Shepherd, 2000).

In general, VSA scores improved from 2023 to 2024. This change in some cases will largely be related to soil moisture at the time of assessment. Timing of VSA is important and should be completed at a soil moisture content which is cultivatable (Shepherd, 2000). For some sites, the sediment baseline assessment was completed when moisture content was too high, so the drop test did not cause sediment to crumble or crack apart, but rather 'splat'. This error in sampling may have resulted in initial VSA scores being lower than if completed at the correct moisture level, however this was unavoidable in some cases, given the circumstances and the scale of baseline sampling. The increase in VSA seen at ten sites, may be related to other factors, including cultivation, which will likely increase aeration and may reduce mottling. Sites 2A and 7A had a small decrease in scores (-1.4 and -2 points respectively), both are shallow sediment sites, where underlying soil had a greater influence on the overall result compared to the deep sediment sites. It was expected that these sites would also show an increase in total VSA score from 2023 to 2024 during the initial recovery phase, however results deviate from the majority of sites, maybe related to soil moisture, cultivation or sampling error.

VSA does have some limitations, particularly in that it does not capture the nuances of different sediment types. For instance, the sandy sites at Esk Valley scored 'Moderate', underpinned by characteristics like no mottling, good porosity, and overall colour. These sandy soils should be characterised as poor, particularly due to the absence of any soil structure or earthworms, and overall potential productive capacity for this sediment type, based on other characteristics like low fertility and low organic matter. The overall scores, based on the reference images, did not adequately reflect the actual state of the sediment characteristics.

While VSA score may not have been the most appropriate tool for assessing sediment characteristics, it did provide context for the baseline assessment, and a foundation for subsequent recovery assessments. The 2023 baseline VSA images of sediment/soil can now be compared to the 2024 results and show in most cases an improvement in overall visual score. These successive images provide a visual comparison of improvements over a short time, which is an important insight to capture into short term recovery outcomes. This is a powerful tool for growers, as it emphasises that positive changes to soil can happen relatively quickly.

### 4.7.3. Earthworm VSA Ranking Score

There are a range of outcomes in the Earthworm VSA ranking score. The data collected after Cyclone Gabrielle mostly related to physical and chemical properties of sediment. Earthworm abundance was the only measures of sediment biology. Assessment in both 2023 and 2024 was completed in autumn, which is not the optimum time to assess earthworm abundance. The best time to assess earthworm populations is in wetter months from late winter to early spring when populations are at their highest (Schon et al., 2023). Cyclone Gabrielle was a late summer storm, therefore initial assessment was completed during the autumn, and for consistency, so was subsequent sampling. On this basis, the scores may not reflect actual populations. However, because the assessments have been made at a consistent time of year, comparing the 2023-2024 results is still considered useful. Target levels for earthworms under pastoral grazing is >400 individual/m$^2$, however cropping soils tend to have lower numbers, often <200 individual/m$^2$ (Schon et al., 2023).

At the majority of sites, earthworm abundance was low in both 2023 and 2024. At eight sites, earthworm numbers were <100 individual/m$^2$ both years, which may relate to sediment depth and texture, extended wetness, or previous earthworm abundance. No earthworms were found at either Zone 1 – Esk Valley sites, these sediments are between 1 – 2 meters deep. This sediment type is not a preferred habitat for earthworms, due to low organic matter and abrasive sandy texture (Van De Logt et al., 2023). The shallow sites of 2B, 7A and 7B all had populations of <100 individual/m$^2$. Zone 4 – Ōtāne sites 7A and 7B were inundated with water for several weeks, which may have significant reduced populations of earthworms due to extended anaerobic conditions (Singh et al., 2019). In the case of site 2B, this site has been intensively cropped for many years, and had upwards of ten cultivation passes in the preparation for the beetroot crop. This disturbance may have impacted any surviving earthworms (Rothwell et al., 2011). At Site 4A where sediment was removed, earthworm score was low in both 2023 and 2024. The process of removal caused soil compaction, as seen in bulk density results, which was remediated by cultivation, likely supressing earthworm recovery.

Five sites had an increase in earthworm abundance, which might be reflective of recovering earthworm populations. These sites may have had existing populations, of which some individuals were able to survive the flood and increase population over time. Invertebrate populations can take several years to recover after flooding (Singh et al., 2019).

Areas with stressed earthworm numbers due to agricultural management practices in arable or cropping settings are more susceptible to flooding than earthworm populations inhabiting less disturbed soil (i.e., permanent pasture) (Kiss et al., 2021). There was no pre-Cyclone data available on earthworm populations on the assessed sites as it is not a commonly used metric by growers. All sites assessed were used for cropping production, with varying cultivation practices and rotations. Prior management may have influenced earthworm numbers, and therefore the ability for populations to recover. In areas where sediment is deep or sandy, populations may take longer to recover.

### 4.7.4. Bulk density

Bulk density measured at each site is linked to sediment texture, with the sandy deposits naturally having a higher bulk density than the silty clay loams (USDA, 2019). Nine of the ten assessed sites had an increase in bulk density in the first 12 months after the cyclone, which is an expected outcome for newly deposited sediments (Guo et al., 2015). While these changes are significant in places, none of the sites had bulk densities above the ideal level where root penetration may be restricted (USDA, 2019). Key contributing factors include settling, consolidation and compaction of particles and loss of moisture.

#### *4.7.4.1. Settling and consolidation*

The particles of newly deposited sediment are arranged loosely, resulting in large pore spaces, filled with water and air. After the deposition of medium to deep flood sediment, the moisture content will be high, contributing to a lower bulk density. Over time, sediment particles will settle, reducing total pore space within the sediment. Particles will slowly consolidate and pack closer together, expelling water, thereby increasing bulk density (Guo et al., 2015; van Rijn & Barth, 2018). The coarser textured sediment of Zone 1 – Esk, had smaller changes to bulk density than the majority of the other soils, with 1B being the only site that had a decrease in bulk density. This might be related to slight differences in sediment texture between the two sites and the proportion of fine particles deposited at 1B, or potentially due to differences during measurement (i.e., presence of plant roots) or sampling error.

Of the sites where bulk density increased, Site 1A had fine sand deposited, the other sites silty clay loam. The fine sandy sediment of Site 1A will have a smaller surface area, lower total porosity and lower water holding capacity compared to the silty clay and therefore less capacity for the sediment to consolidate over time.

#### *4.7.4.2. Compaction*

Compaction relates to the reduction of pore spaces of a soil, increasing soil bulk density. All fields have been exposed to factors that can lead to soil compaction, including mechanical intervention by way of cultivation (C), livestock grazing (G), a combination of the two practices (C/G), or sediment removal (R). Fresh flood sediments are weakly structured, have poor aggregation and can behave plastically, making them susceptible to compaction (Warren & Taylor, 2017). The silty clay loam sediment deposits have a greater susceptibility to compaction compared to the sandy deposits due to their fine particle size, water retention and higher cohesion and plasticity. Soil/sediment moisture content at the time of grazing or cultivation will play a role in susceptibility to compaction.

The site with the greatest percentage increase in bulk density was Site 4A with deep sediment in Pakowhai, where sediment was removed from the site in spring 2023. The process of removal required heavy machinery tracking over soil/sediment surface, causing significant compaction of the underlying soil. The magnitude of the increase to the remaining sediments likely relates to the timing of either cultivation or grazing, and the moisture content of the soil.

## 4.8. General discussion

Within the scope of this research, a range of data was collected, however further information related to the biological characteristics of the sediment may have been useful to monitor. Aggregate stability is another test that may have been valuable in monitoring changes in sediment over time, particularly in the context of cropping where soil structure is mechanically disrupted through the year.

Tools like VSA were used to assess physical characteristics, however the results need to be considered within the context of the site and the sediment texture and depth. In future, if sites are monitored in this way, it may be preferable to compare sites within sediment texture and depth classes. Sediment moisture will have had a significant influence on the baseline results. At the time of baseline sampling, the impact of soil moisture on the overall results and ability to compare to subsequent measurements was not considered, in future this should be considered when selecting when to sample sites. This is likely true for initial bulk density results if sediment moisture was high then the volume of sediment/soil per unit area will have been lower.

A key analysis that would be valuable in the future would be to include financial analysis of management practices. For instance, the cost of flying on grass seed early, as per recommendations from previous events, compared to the cost of cultivation or removal. These remediation costs could be compared to sediment/soil physical or chemical outcomes, or on crop yield in the first growing season after the Cyclone. In addition, analysis into why growers decided to complete different management practices may also support future decision making.

This study focuses only on selected sites in Hawke's Bay; however other areas of the country were impacted by Cyclone Gabrielle. If the project scope had allowed, monitoring of sites inundated with water and sediment in Gisborne or those impacted by extended wetness in Northland would have added to the richness of the data collected. The focus of the paired site analysis was only on areas used for growing annual crops, however there would also be value in extending this monitoring to other land use types, i.e., permanent tree and vine crops, or pastoral production. This study captured additional short-term monitoring information. Additional data collection to analyse medium to long term changes, not only to soil, but also to productive capacity and crop yields would be valuable to include in future studies.

## 4.9. Conclusion

The aim of this analysis was to understand the impact of different management practices on soil and sediment physical and chemical properties 12-months after flooding caused by Cyclone Gabrielle. The purpose of pairing sites based on location, sediment depth and texture was to explore early stage soil recovery in the context of areas involved in the production of annual crops (forage, arable, vegetable).

The analysis of physical and chemical properties of soil and sediment at fourteen selected sites in the first 12-months after the cyclone shows that many changes have occurred. These changes are linked to sediment texture, management practices like cultivation and fertiliser inputs, underlying soil type, as well as the influence of nutrient dynamics linked to anaerobic and aerobic conditions. In many cases, there are general trends, where the majority of sites had the same overall outcome i.e., increase or decrease in a specific metric. One exception to this is the extractable organic sulphur results, which do not show a clear trend over time.

In addition, this study aimed to build on the work completed after previous flood events, over the last century (1938, 1948, 1988 & 2004 floods), to add to the body of work that exists in flood sediment recovery. Previous studies did not monitor sites over time, all studies looked at only a single point in time. This study provides an insight into early stage changes in different sediment scenarios, which may inform future decisions after similar events. The medium to long term implications of sediment deposition on highly productive land (HPL) are still poorly understood, further analysis building on this study would also allow for improved response options.

# 4.10. Appendices

## 4.10.1. Appendix 1 - Paired site soil classification

### *4.10.1.1. Recent Soils*

Young, weakly developed, showing limited signs of soil-forming processes. Deposits are relatively fresh and have not been significantly altered. A developed topsoil is present; however, B horizons are absent or weakly developed (McLaren & Cameron, 2002). Occurrence predominantly on young land surfaces, for example alluvial floodplains. Typically, recent soils are deep rooting. Recent soils are prone to erosion and sedimentation (Hewitt, 2010). Recent soils generally fall into the low category for Anion Storage Capacity (McLaren & Cameron, 2002).

#### Typic Sandy Recent (RST)

Sandy recent soils have sands or loamy sands as dominant material, to depth. Occurrence is in sandy deposits originally from aeolian, or alluvial deposits. Subsurface horizons are sandy (McLaren & Cameron, 2002) (Hewitt, 2010).

- Esk sand – alluvial deposits from greywacke and sandstone, sand deposits since 1867, deep deposits after 1937 flood, overlaying permeable older deposits (Griffiths, 2001).
    - Sites 1 A and B

#### Mottled Fluvial Recent (RFM)

Occurrence of fluvial recent soils are from sediments deposited by flowing water, particularly on land which is prone to flooding (Hewitt, 2010).

- Pakowhai sandy loam – alluvial deposits from greywacke, sandstone or lime stone, active flood plain, sand or silt deposits over buried top soils (Griffiths, 2001).
    - Site 2 B
- Karamu silt loam – alluvial deposits from greywacke or sandstone, upper end of flood plain, deeper than 1m overlaying Taupo pumice, silt and clay loams overlaid on sand (Griffiths, 2001).
    - Site 4 A

### *4.10.1.2. Gley Soils*

Strongly impacted by waterlogging and have been chemically reduced by anaerobic soil conditions. Soils are grey coloured due to the reduction of iron caused by waterlogging related to high water table; often red or brown mottles are present. Grey colours can extend to more than 90 cm depth (McLaren & Cameron, 2002). Soils are poorly and very poorly drained soils, waterlogged in the winter and spring, or year round. Gley soils occur in low points in the landscape where water tables are high. Typically, these soils have shallow potential rooting depth, high bulk density and high organic matter. When used for agricultural land, drainage is necessary as the soils can have low trafficability. Soil organisms can be limited due to anaerobic conditions (Hewitt, 2010). Gley soils can have a range of Anion Storage Capacities (McLaren & Cameron, 2002).

#### Typic Recent Gley (GRT)

Recent gley soils typically occur on young land areas in alluvial or estuarine environments, often there is a risk of regular flooding (McLaren & Cameron, 2002).

- Moteo silt loam – alluvial deposits from greywacke, sandstone or lime stone, active flood plain, high water table, silt or clay deposits over old buried top soils (Griffiths, 2001).
    - Sites 2 A, 3 A, 3 B and 4 B,

#### Saline Recent Gley (GRQ)

Saline recent gley soils are recent gley soils which have electrical conductivity of 0.8mS/ca or more within 60 cm of the mineral soil surface (Hewitt, 2010).

- Farndon clay loam – Tūtaekurī alluvial deposits from greywacke, sandstone or lime stone, next to old lagoon, slightly saline, saline groundwater, textures vary depending on position (Griffiths, 2001).
    - Sites 5 A and B
- Meeanee silt loam – Tūtaekurī alluvial deposits from greywacke or sandstone on lagoon deposits, low lying area of old lagoon, silt & clay on lagoon sediments (Griffiths, 2001).
    - Sites 6 A and B

#### *4.10.1.3. Organic Soils*

Organic soils are soils dominated by organic material, formed by partly decomposed remains of wetland plants or forest litter. Peat materials are decomposed to the point where original wetland plants cannot be recognised through the profile. In some instances, mineral matter may be present but is not the dominant material. These soils have low bearing strength, high shrinkage potential and high water availability capacity. Chemically these soils have high cation exchange capacity, nutrient deficiencies are common (Hewitt, 2010). Organic soils generally have low to very low Anion Storage Capacity (McLaren & Cameron, 2002).

Humic organic soils are formed in peat that is strongly decomposed. These soils occur in very wet sites, and in wet sites that have been artificially drained (Hewitt, 2010).

#### Mellow Humic Organic (OHM)

- Poukawa peaty loam – alluvium from greywacke over peat, silt loam over peat (Griffiths, 2004).
    - Site 7 A

#### Acid Humic Organic (OHA)

Acid humic soils are soils where the top 60cm of the soil surface has a pH of 4.5 of less.

- Pongakawa peaty silt loam - Peat over rhyolitic alluvium
    - Site 7 B

### 4.10.2. Appendix 2 – Soil test descriptions

All samples were sent chilled as mineral-N tests were completed. The suite of tests complete were as follows (not all reported):

- Basic soil nutrient fertility (pH, Olsen P, Potassium, Calcium, Magnesium, Sodium, CEC)
- Extractable Sulphur
- Mineral Nitrogen
- Anion Storage Capacity %
- Hot Water Extractable Organic N
- Potentially Mineralisable N
- Organic Matter
- Soluble Salts
- Total P

#### *4.10.2.1. pH*

Soil pH measures whether a soil is acidic or alkaline. The pH of a soil will influence the solubility of and plant availability of some soil compounds (Clarke et al., 1986).

#### *4.10.2.2. Olsen P*

Phosphorus is an essential nutrient for plant functions. Olsen P is a measure of plant-available phosphorus in soil, measuring phosphate in soil solution and soil exchange surfaces. The Olsen P test is commonly used in New Zealand for determining phosphate fertiliser requirements (McLaren & Cameron, 2002).

#### *4.10.2.3. Quick Test Potassium (MAF K)*

The amount of potassium in soil is related to parent material, soil type, mineralogy and previous land-use (Heller et al., 2021). There are several ways potassium levels in soil can be expressed. MAF QT values is an index used to express the amount of exchangeable cations in soil. These values have been calibrated to determine optimum ranges of cations, and nutrient application requirements for crop production. QTK is a measure of plant available potassium in soil (ARL, 2020b). Potassium is an essential plant nutrient involved in many plant physiological and biochemical functions (McLaren & Cameron, 2002).

#### *4.10.2.4. Sulphate Sulphur*

The Hill Laboratories sulphate sulphur test ($SO_4^{2-}$ S) tests for readily available sulphur (dissolved and adsorbed forms). Sulphur is an essential element for plant growth, having a vital role in plant proteins and chlorophyl synthesis (Hill Labs, n.d.-c).

#### *4.10.2.5. Organic Matter*

Organic matter plays a large role in soil physical characteristics, including structure, soil moisture retention and water infiltration, and chemical characteristics like cation exchange capacity and nutrient supply. Organic matter percentage (OM%) is measured from organic carbon %, multiplied by a standard factor of 1.72 (Hill Labs, n.d.-c).

#### *4.10.2.6. Organic Sulphur*

The Extractable Organic Sulphur test tests for the readily soluble fraction of the organic sulphur pool and is a measure of medium term sulphur availability (Hill Labs, n.d.-a).

#### *4.10.2.7. Potentially Mineralisable Nitrogen*

PMN is a value determined using Hot Water Extractable Organic Nitrogen (HWEON) and a calibration factor, expressed as mg/kg.

#### *4.10.2.8. Cation Exchange Capacity*

Cation Exchange Capacity (CEC) is a quantitative measure of soils ability to hold exchangeable cations (e.g., $K^+$, $Ca^{2+}$, $Mg^{2+}$), indicating the amount of negative charge per unit mass of soil. CEC is expressed as milliequivalents per 100 grams (me/100g).

#### *4.10.2.9. Anion Storage Capacity*

Anion Storage Capacity (ASC), formally known as Phosphorus Retention, refers to soils capacity to immobilise or fix phosphate. ASC is an inherent property of the soil, which typically does not change. ASC is related to soil minerology, and particularly the amount of short-range order iron and aluminium compounds in soil (ferrihydrite and allophane) (McLaren & Cameron, 2002; ARL, 2020a). Soils with higher ASC require higher levels of phosphorus fertiliser to maintain or increase soil phosphate levels.

### 4.10.3. Appendix 3 - Modified Visual Soil Assessment Score Card

| **4. Visual Indicator** | **VS Score**<br>**0= Poor**<br>**1= Moderate**<br>**2= Good Condition** | **Weighting** | **Maximum Score** |
|---|---|---|---|
| Soil porosity | | X 3 | 6 |
| Soil Colour | | X 2 | 4 |
| Number and colour of mottles | | X 2 | 4 |
| Soil structure & consistence | | X 3 | 6 |
| Earthworm abundance | > 35= 2<br>29-35= 1.5<br>22-28= 1<br>15-21=0.5<br><15= 0 | X 2 | 4 |
| | | Maximum score | 24 |

| **Soil Quality Assessment** | **Ranking Score (Baseline Sampling** |
|---|---|
| Poor | <7 (<30% of total score) |
| Moderate | 7-18 (30-74% of total score) |
| Good | > 18 (> 74% of total score) |

# Chapter 5

## 5. Discussion

### 5.1. Introduction

When Cyclone Gabrielle impacted the North Island of New Zealand in February 2023, the storm devastated large areas of land used for high value fruit and vegetable production. When searching for information to support grower decision making and recovery, it was found that there was little available information on how to restore the productive capacity of high value horticultural and vegetable cropping on highly productive land (HPL).

Chapter 2 comprises a literature review that aims to compile and increase the visibility of prior knowledge of flood deposition and recovery. This review, in combination with data collected from sites impacted by Cyclone Gabrielle, aims to add to available information specifically related to the recovery of high value horticultural and vegetable cropping land.

The baseline data set was gathered one - three months after Cyclone Gabrielle, in the majority of cases sampling was completed before any remediation had taken place across Hawkes Bay and Gisborne. Sediment and soil samples were taken for physical, chemical and biological analysis and presented in Chapter 3. This data was collected to improving collective understanding of the impact of sediment deposition to horticultural production systems. Data collected was shared with farmers and growers to aid in immediate decision making.

This master's research also aims to identify and understand changes that occurred to the sediment and soil in the initial recovery period. Chapter 4 outlines repeat sampling and analysis undertaken twelve months following Cyclone Gabrielle from a small subset of impacted sites in the Hawkes Bay Region.

In this chapter, overall findings from each of the previous chapters are discussed, practical management implications presented, policy implications highlighted, and the limitations of the study discussed, finishing with conclusions and recommendations for further research.

### 5.2. Findings: Objectives 1–3

#### 5.2.1. Objective 1 (setting the scene)

The literature review presented in Chapter 2 has two key sections:

1) Setting the scene and providing context for the impact of Cyclone Gabrielle on Hawke's Bay.

2) Outlining previous knowledge related to flood impact and recovery in New Zealand.

Cyclone Gabrielle in February 2023 was described as the worst storm to impact New Zealand in living memory. Prior to this, Cyclone Bola in 1988 was the weather event for which storm intensity and damage on the East Coast was measured against, but Cyclone Gabrielle was considered to exceed Bola in terms of intensity and damage. It should come as no surprise that the rivers of Hawke's Bay are the source of such destruction. Geology, geomorphology, river patterns and land use, were all factors in the susceptibility of Hawke's Bay, and other parts of the East Coast, to both flood events and sediment deposition. The Heretaunga Plains were developed from sediment deposition over approximately

250,000 years, which has contributed to the high proportion of valuable and productive Land Use Capability (LUC) 1 – 3 land in the region.

Stopbanks are a key feature for three of the four major Hawke's Bay rivers, developed to protect houses and farmland from recurrent storm events. The stopbanks have their design limitations, and in the case of Cyclone Gabrielle, the stopbanks failed at several points. In the case of the Esk River where there are no stopbanks, there is no possibility of intervening with the river flow path in a flood, leaving the Esk Valley particularly vulnerable to flood events as shown in the 1938 flood.

There are four key flood events discussed in the literature review which shaped both New Zealand land use policy, and flood response. The flood recovery studies discussed were all integral in decision making for farmers and growers after Cyclone Gabrielle. Two gaps in the collective knowledge informed the basis of this research.

1) previous studies focused on recovery for pastoral production, not on recovery for high value vegetable and horticultural crops.

2) little to no work had been carried out to assess short or long term changes to soil and sediment after sediment had been deposited on the land.

This study did not explore international sources of information, which could have added to this literature review. In future, relevant overseas studies should be considered.

### 5.2.2. Objective 2 (baseline characterisation)

Baseline sampling collected data from a wide range of impacted sites across Hawke's Bay, Gisborne and Northland to address the knowledge gaps identified during the literature review. Regional scale sampling and analysis were completed by September 2023, resulting in a professional industry report presented in Chapter 3.

Key findings:

- Physically, the sediment was weakly structured, regardless of sediment texture. Sediment texture varied by catchment, and by proximity to stopbank breaches.
- Chemically, the results varied largely by sediment texture, sandy sediments of the Esk and Dartmoor Valleys had low nutrient levels. Finer textured sites, in most cases had adequate fertility for pastoral production, which was a positive insight for growers.
- Biological indicators showed low earthworm abundance.
- Early concerns that sediment was contaminated with pesticides, faecal material and heavy metals were not supported by this analysis. This was valuable information for growers and for industry groups working on recovery.

This baseline sampling built the foundation for the research completed in Chapter 4, where changes to sediment/soil characteristics could be monitored over the short term. The project allowed for industry engagement and grower support at an important time in the decision making process.

### 5.2.3. Objective 3 (short-term changes)

Objective 3 involved capturing the influence of post cyclone management on soil properties and production as growers worked towards recovery in the short term. This was important for documenting the management strategies used by impacted growers and also provided context for assessing the results from the paired sites. Anecdotally, farmers impacted by Cyclone Bola, who were subsequently impacted by Cyclone Gabrielle noted that they recall doing something after Bola, but they couldn't remember what. While only a small subset of sites had detailed information collected, a range of management practices were implemented, overall showing similar trends for many of the measured attributes. This represents an important resource for future flood recovery work.

Key findings:

- The baseline sediment pH was above the optimum range for most crops, over time these levels mostly reduced, however still remained elevated after 12 months. This has implications for nutrient availability.
- Overall, positive trends were seen for plant available phosphorus and potassium, two key nutrients for plant growth. This change is linked to both fertiliser application and incorporation of antecedent soil through cultivation.
- Both sulphate and organic sulphur showed a range of results. The trend in sulphate sulphur was an overall increase, linked to both fertiliser input and prolonged anaerobic conditions causing iron oxides and associated minerals to go into solution. Changes in organic sulphur showed no clear trend.
- Organic matter levels were low and overall declined over the one year sampling period. This is likely related to factors such as mechanical intervention and sediment/soil water logging.
- Visual Soil Assessment showed that physical properties improved over the one year period, however the magnitude of the improvement needs to be considered in the context of soil moisture content at the time of baseline sampling.
- As sediment consolidated, bulk density increased. Again, this needs to be considered in the context of soil moisture at the time of baseline sampling.
- Growers completed a range of management practices. Few aligned with the recommendations from prior studies, i.e., to aerially apply grass seed to still moist sediment.
- Growers impacted by fine textured sediment largely were able to operate 'as normal' in the following season.

## 5.3. Practical management implications

As mentioned in Chapter 4, growers implemented a range of management practices to begin the process of soil restoration. This varied based on sediment depth and texture and the type of cropping system. Overall, the deep, sandy sediment deposition experienced in the Esk Valley (as well as Dartmoor – Chapter 3), appeared to be the most difficult to manage, due to both physical and chemical limitations.

In Chapter 2, early studies on sediment revegetation are discussed. From as early as 1950, there has been published information on aerial application of seed to establish pasture cover. While this is not directly related to cropping, this approach allows for more rapid drying of soil through evapotranspiration, aeration of the sediment by plant roots, stabilisation of sediment minimising dust and potentially provides an income stream from grazing livestock. Three of the monitored sites proceeded with this early intervention, and grass was established early, giving the growers options for next steps i.e., grazing, cutting hay or leaving fallow. In a large portion of the remaining sites, sediment was left bare over the winter, as growers waited for adequate drying for cultivation. In some cases, by the time growers received recommendations to sow grass, the sediment had dried too much. Others did not want to take the financial risk of aerial spreading. In future, it is important for information related to options for next steps to be disseminated quickly, and resources made available so growers can act quickly. Growers who did regrass quickly appeared to have more options and flexibility the following season and appeared to have a positive influence on short-term soil outcomes.

In terms of short term recovery, fine textured sediment, regardless of depth can be managed with relative ease compared to the deep sandy sediments found in the Esk and Dartmoor Valleys. In all of the previous research, there does not seem to be a quick solution to this situation, other than endeavouring to maintain plant cover by whatever means possible. Overtime, natural weathering will occur, and sediment will develop into soil, however there is not a well-defined timeframe for how long this process will take.

As growers move into medium to long term recovery phases, ongoing monitoring will be essential to ensure that any potential issues can be addressed. Regular soil testing, VSA and crop health and yield assessments should be completed. Organic matter should be considered in more detail, particularly in the context of cropping soils where soil is disturbed, and organic matter mineralised, annually. Growers should consider how they might restore and protect organic matter on paddocks that have been impacted by flood sediment. Earthworm populations, and other biological indicators should also be integrated into monitoring programmes, as the biological systems have had significant disruption.

The most important factors for growers to assess is sediment depth and texture, as these two variables will inform what options are possible in terms of both incorporation and plant species selection etc. Following this, nutrient testing should be completed to assess fertility status of the sediment, this information will inform nutrient management decisions. Growers should pay close attention to pH, as well as macronutrients (nitrogen, phosphorus, potassium, and sulphur) in the first instance. If is not feasible to go through the whole VSA process, growers should regularly dig holes to assess sediment and antecedent soil conditions, monitoring the soil for signs of poor drainage (mottling, smelly soil), earthworm activity, as well as to assess the depth that plant roots are travelling.

A key visual measure is for growers to take photos in the same place month on month. Figure 5-1 shows a series of images taken at one of the paired sites one month before the Cyclone, immediately after, and then 12-months after the Cyclone. This is a simple way of visually measuring progress over time.

**Figure 5-1 Example of short term visual changes captured at an impacted site.**

## 5.4. Policy & planning implications

As part of the literature review the question was asked “can we change the way we farm on these flood plains, to work with nature, rather than against it, to avoid or minimise the impact of these inevitable catastrophic events in future?”

It is not clear how many of the baseline sampling sites had the sediment removed, as they have not all been revisted. It is understood that approximately 750 ha of orchard (Eldin, 2023) and 2,000 ha of cropping land was silt impacted by Cyclone Gabrielle in the Hawkes Bay Region (Flaws, 2023). Sediment was removed mostly in permanent tree and vine crops, in an attempt to save trees. Only one of the paired sites had sediment removed, as the cost of restoring sediment was considered to be greater than removing it. This is an area which requires further research and economic analysis.

While the impact of Cyclone Gabrielle was devastating to many, the situations in the Esk and Dartmoor Valley’s continue to be a stark reminder of the damage caused by this event. This is not the first time destructive flooding and sediment have occurred in these areas; both were impacted in a similar way by Cyclone Bola in 1988. A key issue in these situations is that the sediment is essentially raw sand, with little productive value. To remediate land after Cyclone Gabriele many growers responded by removing the sediment and debris to start fresh, an activity that has come at huge financial and energy expense.

Given what is known about the landscape of the East Coast, and the propensity for upstream soil erosion to cause downstream aggradation through flooding of the major rivers, it is important that a wider industry discussion on future land use and land use policy is had. While not directly linked to the objectives of this thesis, the literature review presented in Chapter 2 highlights that primary production on the East Coast is at risk of significant flood impact, which is likely to intensify through future climate change. The impact to food producers is highlighted in Chapter 3 – almost every land use type was impacted by Cyclone Gabrielle including dairy and dry stock, pipfruit, stone fruit, vines (grapes and kiwifruit), fresh and process vegetables, as well as arable crops. This has ongoing effects on both natural and built environments, and on the local and national economy.

While this research focused predominantly on LUC 1 – 3, there is a direct link to LUC 5 – 8 in the upper reaches of the river catchments, where farmers also faced significant losses. Decision makers from local and central government, in conjunction with primary producers need to consider how to manage both upstream and downstream land use to mitigate the effects of extreme storm events. This raises the question of whether land use be reshaped to be more resilient to the effects of high intensity weather events like Cyclone Gabrielle?

## 5.5. Limitations

### 5.5.1. Sampling design

The design of the baseline sampling project was determined in collaboration with soil researchers to monitor agricultural soils that had been inundated by sediment approximately three weeks after the Cyclone. The aim of the design was to capture as much detail as possible, while still allowing for a large number of sites to be visited. The method was designed to be repeatable, using resources that are commonly available to growers and technical staff. In an ideal world, all of these sites would have been revisited as part of Chapter 4. Unfortunately, funding was limited, so only a small subset of sites could be revisited.

For the study to have paired sites, the initial baseline data set was analysed to determine which sites had a suitable pair to be matched with. The selection of the sites aimed to have geographic spread across Hawke's Bay and encompass a range of cropping systems. While best efforts were made to evenly distribute the sampling, there was comparatively more sites sampled from around Zone 3 - Pakowhai/Meeanee than any other Zone. There were more deep sites sampled than medium and shallow sites, only one pair was on medium sediment depth. In future, site selection should be more evenly distributed.

Initially, one of the aims was to create a specific decision support tool for annual cropping systems using the data collected. It became evident early in the research that not enough 'replicated' data was collected, so the focus turned to capturing more detail from fewer sites.

Overall, the design of this study could be improved. In considering the time pressured conditions the research planning was completed in, useful data was collected, adding to the knowledge of short-term recovery. This study can be used as a foundation for future studies, and built upon, much like this research has built upon previous research.

### 5.5.2. Field variability

As discussed in Chapter 4, the sediment conditions at the time of baseline sampling were varied. This was related to the time elapsed between the flood and the time of assessment, sediment texture and depth, and moisture content. For the physical assessment of VSA and bulk density, soil moisture had a significant impact on the outcome of the baseline results. This variation in sediment conditions therefore had implications for the subsequent analysis. In future, a framework should be developed for assessing when a site should be sampled, so there is consistency and results from different sites can be more accurately compared. This framework would factor in texture and depth and could relate to the visual state of the soil, for instance, the extent to which fine textured sediment has cracked, to decide the best time to sample.

### 5.5.3. Single-year window vs. multi-year recovery.

This study looked only at changes to sediment and soil over a single year. While this monitoring adds to the knowledge of short-term changes to soil/sediment, which have not thoroughly been investigated before, it does not address the issue of medium to long term recovery. To date, there has been little done to understand ongoing changes or issues, particularly in an annual cropping situation.

An example of a potential long-term issue is the low or very low organic matter levels seen across different sediments. These levels declined further from 2023 to 2024, likely due to mineralisation induced by cultivation and waterlogged conditions. In this situation, fields cannot feasibly be left in permanent pasture or similar for several years to remediate and increase soil organic matter. Additional research is necessary to understand the temporal dynamics of organic matter levels. Furthermore, research into how low organic matter levels in sediment influence factors like herbicide buffering, water holding capacity and overall productivity is important for future long-term studies.

## 5.6. Recommendations – future considerations

Previous studies did not provide information relating to future research priorities. When Cyclone Gabrielle hit, researchers began investigating areas to study. Overall, there was a coordinated approach, however there was uncertainty as to what the most pressing research priorities were, and where funding would be best allocated. In reflecting on previous studies, as well as the body of work produced after Cyclone Gabrielle, including by LandWISE Inc., Plant and Food Research, and FAR, areas for future work should be established now, ahead of any weather event, to inform funding bodies (e.g., Ministry for Primary Industries) and researchers so funds can be allocated efficiently.

In addressing the impacts of climate change, including intensifying weather events, these questions will likely be asked more frequently. A range of projects have been completed by different organisations since Cyclone Gabrielle, and it would be valuable to collate all of the research, in an attempt to better understand the data collected and what it means, and enable the creation of more robust knowledge, to better support future impacted communities.

In addition, there are four key areas of future research that should be considered:

### Longer-term monitoring

This research looked at a small subset of impacted sites and 'short term' changes to soil/sediment. To better understand the true impact of flood sediment deposition and recovery, funding should be allocated to monitor a larger number of sites, representing more scenarios, over a 3 – 5 year period. More land use types should be considered, particularly permanent tree crops, where management is quite different to that of field crops or pastoral production. By collecting more data from more detailed, replicated sites, data can be analysed, and more specific insights gained, with the objective of developing more specific decision support tools for different industries over-time.

### Controlled trials on remediation techniques

This research assessed an in-field monitored transect, and compared two sites, where management of sediment varied. There were a large number of variables to consider during analysis which created a very complex data set. In future, more controlled trials focused on remediation techniques should be investigated to directly compare the outcomes of management options side-by-side. An example of this after Cyclone Gabrielle, was the study completed by Eduardo Dias de Oliveria where a replicated plot trial was designed to test the success of different crops planted directly into sediment.

In future, this would be a way to assess the success of other interventions, for instance of different cultivation practices, or applications of nutrients, biostimulants and different composts or mulches, (specifically mulch from woody debris left after a flood).

### Economic dimensions

In addition to the physical, chemical and biological tests completed as part of this research, completing financial analysis of grower management decisions would be another valuable metric to include in future studies. In the sites monitored in Chapter 4, the number of cultivation passes completed varied from 0 – 11 in the first twelve months after the cyclone, the total cost of which will vary significantly. There are also significant differences in applied nutrients as well. These total costs could be compared to subsequent crop yields, and gross margins determined over time. This analysis would be useful to complete over a 3 – 5 year period to understand the true cost of remediation for growers. This information would help growers and industry to make informed decisions on how to respond to future flood events.

### Knowledge storage

During the literature review presented in Chapter 2, difficulties were encountered locating and sourcing different resources. This raised the question of 'how do we store information, so it is accessible infinitum'. This is important in considering how information and knowledge gained in the last century, including from Cyclone Gabrielle will be available to future generations.

In several cases, it appears that additional studies to those identified existed at some point, however these were never digitised, or archived, and therefore not accessible. In addition, many of the resources available were hard to access, given their storage locations. To maximise the benefit from past studies, and of those completed after Cyclone Gabrielle, it is essential that material related to flood recovery be stored together in a repository, possibly managed by the government, so next time it is needed, it is more easily accessible.

## 5.7. Conclusions

Cyclone Gabrielle was a defining storm for the East Coast of New Zealand, which will likely be felt for years to come. From the beginning, the overall aim of this research was to build on previous knowledge of flood recovery, to learn from this event, in the hope that lessons from now could support those impacted by Cyclone Gabrielle, and for those impacted by future storm events.

The regional outlook 12-months after the storm was overwhelmingly positive, showing that a lot can change it a year. This kind of responsive research is hard to precisely replicate as it relies on something devastating to occur, at an unknown point of time. While we don’t know when ‘the next big storm’ will be, history shows that it will happen again. Much like this research built on studies in the last century, this study should be built upon in years to come, to better understand the impact of flood events, and support the development of more resilient landscapes across New Zealand.

# 6. References

AgResearch. (2024). *2024 annual report*. https://www.agresearch.co.nz/assets/Uploads/Report-PDFs/AgResearch-Annual-Report-2024.pdf

APNZ. (2015, March 15). Cyclone Bola cost more than $100m. *Hawke's Bay Today*. https://www.nzherald.co.nz/hawkes-bay-today/news/cyclone-bola-cost-more-than-100m/H25DKP7ADRNNYAVNYYR2VS4ITY/

ARL. (2020a). *Anion storage capacity (phosphate retention test)*. https://www.ravensdown.co.nz/media/5070/a4-tech-sheet-anion-storage-capacity-arl-nov20-1.pdf

ARL. (2020b). *Cation exchange capacity of soil* [Technical sheet]. https://www.ravensdown.co.nz/media/5071/a4-tech-sheet-cation-exchange-capacity-arl-oct20v3.pdf

Ausseil, O., Hicks, A., Wade, H., & Death, F. (2016). *Waikari, Aropaoanui and Esk Catchments; state and trends of river water quality and ecology.* [HBRC Report RM16-10-4789]. Hawke's Bay Regional Council.

Balks, M. R., & Zabowski, D. (2016). When the Earth moves: Earthquakes, landslides and erosion. In *Celebrating Soil*. Springer International Publishing. https://doi.org/10.1007/978-3-319-32684-9

Basher, L. R. (2013). Erosion processes and their control in New Zealand. In J. R. Dymond (Ed.), *Ecosystem services in New Zealand—Conditions and trends* (pp. 363–374). Manaaki Whenua Press.

Bloomer, D. (2011). *Versatile soils—Productive land* [Report for Hawke's Bay Regional Council]. Page Bloomer Associates Ltd.

Boston Consulting Group. (2023). *Hawke's Bay Horticultural Sector: Economic recovery following Cyclone Gabrielle*. https://web-assets.bcg.com/2d/ac/c7e654af43e995c10fabfdf4f4d1/hawke-bay-horticulture-recovery.pdf

Chappell, P. R. (2013). *The climate and weather of Hawke's Bay* (NIWA Science and Technology Series 58).

Chappell, P. R. (2016). *The climate and weather of Gisborne* (NIWA Science and Technology Series) [2nd edition]. NIWA.

Clarke, C. J., Smith, S. G., Prasad, M., & Comforth, I. S. (1986). *Fertiliser recommendations for horticultural crops* (First Edition). Ministry of Agriculture and Fisheries.

Cowie, C. A. (1957). Hawke's Bay. In *Floods in New Zealand 1920-53: With notes on some earlier floods.* (pp. 62–98). The Soil Conservation and Rivers Control Council.

Cressey, P., & Russell, K. (2024). *Supporting community recovery from Cyclone Gabrielle: Contamination resulting from flooding events* (FW24009). ESR.

Cumberland, K. B. (1947). Region IIIB Wellington-Hawke's Bay Tertiary 'Hill Country'. In *Soil Erosion in New Zealand* (2nd ed., pp. 44–58). Whitcombe & Tombs Ltd.

Cunningham, A. (1968). *Surface cover in the Tutaekuri catchment headwaters* (Protection Forestry Report No. 44). Forestry Research Institute.

Cunningham, A. (1969). *The Tutaekuri catchment headwaters, Kaweka Range* (Protection Forestry Branch Report No. 57). Forestry Research Institute.

Cunningham, A. (1979). A century of change in the forest of the Ruahine Range, North Island, New Zealand: 1870-1970. *New Zealand Journal of Ecology*, *2*, 11–21.

de Vries, W., & Breeuwsma, A. (1984). Causes of soil acidification. *Netherlands Journal of Agricultural Science*, *32*, 159–161.

Delano, J. E., Howell, A., Clark, K. J., & Stahl, T. A. (2023). Upper plate faults as a source for coastal subsidence along the central Hikurangi subduction zone, Aotearoa New Zealand [Preprint]. *Geochemistry, Geophysics, Geosystems*.

Department of Survey and Land Information. (1989). *100 years ago: Plan showing Ahuriri Lagoon, Scinde Id. & surroundings -up to & at 1865 ; 100 years of progress: The same area after reclamations & earthquake action, 1965.* [Map].

Dravid, P. N., & Brown, L. J. (1997). *Heretaunga Plains Groundwater Study Volume 1: Findings*. Hawke's Bay Regional Council.

Eaves, A., & Whitaker, J. (2024, April). *Cyclone Gabrielle sediment deposition*. Hawke's Bay Regional Council.

Edmeades, D. (2005). *The fertiliser review: Acidification due to fertilisers*. agKnowledge.

Eldin, B. (2023, October 12). Survey findings provide insights into Cyclone Gabrielle's impact on apple orchards. *The Orchardist*, *96*(No. 09), 46–48.

Eyles, G. O. (2019). Farming in Hawke's Bay. *Journal of New Zealand Grasslands*, 15–20. https://doi.org/10.33584/jnzg.2019.81.416

Flaws, B. (2023, March 8). Hawke's Bay horticulture takes a massive hit in Cyclone Gabrielle. *The Orcharist and NZ Grower*, *March 2023*, 28–31.

Fuller, I. C. (2005). February floods in the lower North Island, 2004: Catastrophe – causes and consequences. *New Zealand Geographer*, *61*(1), 40–50. https://doi.org/10.1111/j.1745-7939.2005.00014.x

Fuller, I. C., Riedler, R. A., Bell, R., Marden, M., & Glade, T. (2016). Landslide-driven erosion and slope–channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand, 1946–2011. *CATENA*, *142*, 252–268. https://doi.org/10.1016/j.catena.2016.03.019

Gisborne District Council. (2020). *State of our Environment 2020*.

Goodier, C. (2004). *Flood report Central Hawke's Bay February 15-16, 2004* [HBRC Plan Number 3389]. Hawke's Bay Regional Council.

Grant, A. P. (1939). Hawke's Bay Flood, April 1938. *New Zealand Institute of Engineers*, *25*, 55–64.

Grant, P. J. (1982). Coarse sediment yields from the upper Waipawa River basin, Ruahine Range. *Journal of Hydrology*, *21*(2), 81–97.

Gray, M. H., & Korte, C. J. (1990). *Revegetation of river silt deposits* (Fertiliser and Lime Research Centre Occasional Report No. 4; pp. 232–235). Massey University.

Griffiths, E. (2001). *Soils of the Heretaunga Plains: A guide to their management*. Grifftech & Hawke's Bay Regional Council.

Griffiths, E. (2004). *Soils of the Ruataniwha Plains: A guide to their management*. Grifftech & Hawke's Bay Regional Council.

Hall, I. (1938). *Photograph of the aftermath of flooding in the Esk Valley in April 1938 where up to three metres of silt covered the area.* [Black and white photograph].

Hansen, G., & Adye, M. (1999). *Heretaunga Plains flood control scheme Part 1: Rivers. Asset management plan.* (HBRC Plan 2770). Hawke's Bay Regional Council.

Harmsworth, G., & Page, M. J. (1991). *A review of selected storm damage assessments in New Zealand* (DSIR Land Resources Scientific Report No. 9). Department of Scientific and Industrial Research.

Hastings District Council. (2003). *Hastings District plan; Section 2.2 significant resources of the district*.

Hawke's Bay Independent Flood Review Pae Matawai Parawhenua. (2024). *Report of the Hawke's Bay Independent Flood Review*. https://www.hbrc.govt.nz/assets/Document-Library/Cyclone-Gabrielle/Report-of-the-Hawkes-Bay-Independent-Flood-Review-Digital-Version.pdf

Hawke's Bay Regional Council. (2018a). *Lower Ngaruroro River (below Whanawhana)—Outstanding Waterbody (OWB) Report*. Hawke's Bay Regional Council. https://www.hbrc.govt.nz/assets/Document-Library/Projects/Outstanding-Water-Body/Ngaruroro-River-Lower-candidate-OWB-report-201807111.pdf

Hawke's Bay Regional Council. (2018b). *Tukituki River- Outstanding Waterbody (OWB) Report*. Hawke's Bay Regional Council. https://www.hbrc.govt.nz/assets/Document-Library/Projects/Outstanding-Water-Body/Tukituki-River-candidate-OWB-report-201807111.pdf

Hawke's Bay Regional Council. (2018c). *Tutaekuri River report*. Hawke's Bay Regional Council. https://www.hbrc.govt.nz/assets/Document-Library/Projects/Outstanding-Water-Body/Tutaekuri-River-Report-pdf.pdf

Hawke's Bay Regional Council. (2018d). *Upper Ngaruroro River (above Whanawhana)—Outstanding Waterbody (OWB) Report*. Hawke's Bay Regional Council. https://www.hbrc.govt.nz/assets/Document-Library/Projects/Outstanding-Water-Body/Ngaruroro-River-Upper-candidate-OWB-report-201807111.pdf

Hawke's Bay Regional Council. (2021a). *Executive summaries for Heretaunga Plains Flood Control Scheme, Upper Tukituki Flood Control Scheme and Small Schemes Asset Management Plans*. /https://www.consultations.nz/assets/Consultations/HBRC-LTP-Time-to-Act/Executive-Summaries-for-HPFCS-UTTFCS-and-Small-Schemes-AMPs-.pdf

Hawke's Bay Regional Council. (2021b). *Hawke's Bay state of the environment 2018-2021* (pp. 137–147).

Hawke's Bay Regional Council. (2022). *Tukituki catchment map* [Map].

Hawke's Bay Regional Council. (2023, March 1). *Rainfall data shows intensity of Cyclone Gabrielle*. https://www.hbrc.govt.nz/home/article/1415/rainfall-data-shows-intensity-of-cyclone-gabriellehttp://

Hedley, M. (2024, December 23). *Sediment sulphate sulphur* [Personal communication].

Heller, S., Müller, J., Kayser, M., & Jensen, S. (2021). Status of plant-available potassium after 17 years of wet grassland restoration on a degraded minerotrophic peat soil. *Mires and Peat*, *27*(28), 1–14. https://doi.org/10.19189/MaP.2021.APG.StA.2158

Hewitt, A. E. (2010). *New Zealand soil classification* (3rd edition). Manaaki Whenua Press.

Hill Labs. (n.d.-a). *Laboratory tests for soil sulphur in pastoral soils.* [Technical Note]. https://www.hill-labs.co.nz/media/ohvbej2u/26493v3_technical-note-laboratory-tests-for-soil-sulphur-in-pastoral-soils.pdf

Hill Labs. (n.d.-b). *Soil Nitrogen Tests*. Hill Labs. https://www.hill-labs.co.nz/media/3zcji4lr/14666v9_services-offered-soil-nitrogen-tests.pdf

Hill Labs. (n.d.-c). *Technical Note: Soil Tests & Interpretation*. Hill Labs. https://www.hill-labs.co.nz/media/djdbzzhl/3196v6_technical-note-soil-tests-and-interpretation.pdf

Hill, R. P. (1938). Work of rehabilitation. The flood disaster of the Esk Valley. *The New Zealand Journal of Agriculture*, *57*(1), 1–5.

Horticulture New Zealand. (2024). *Submission on Hastings—Napier future development strategy*.

Hull, A. G. (1990). Tectonics of the 1931 Hawke's Bay earthquake. *New Zealand Journal of Geology and Geophysics*, *33*(2), 309–320. https://doi.org/10.1080/00288306.1990.10425689

Kiss, T. B. W., Chen, X., Ponting, J., Sizmur, T., & Hodson, M. E. (2021). Dual stresses of flooding and agricultural land use reduce earthworm populations more than the individual stressors. *Science of The Total Environment*, *754*, 142102. https://doi.org/10.1016/j.scitotenv.2020.142102

Kılıç, F. N., & Sönmez, O. (2018). The effect of different sulphur sources applied at various rates on soil pH. *Turkish Journal of Agriculture - Food Science and Technology*, *13*(1), 59–64. https://doi.org/10.24925/turjaf.v13i1.59-64.7256

Kolt, J. (2012). *Tutaekuri River instream flow assessment* [Environment Management Group Technical Report]. Hawke's Bay Regional Council.

Komar, P. (2010). Shoreline evolution and management of Hawke's Bay, New Zealand: Tectonics, coastal processes and human impacts. *Journal of Coastal Research*, *26*(1), 143–156.

Lee, J. M., Tschritter, C., & Begg, J. G. (2014). *A 3D geological model of the greater Heretaunga/Ahuriri Groundwater Management Zone, Hawke's Bay* (GNS Science Consultancy Report 2014/89; p. 31 p).

Leith, K. (2003). *The role of deep-seated landsliding in the geomorphic evolution of the Esk Valley, Hawke's Bay: An innovative approach to hazard evaluation* [Master of Science in Engineering Geology]. University of Canterbury.

Litherland, A. (2004). *Regrassing silt technical document for rural professionals*. AgResearch.

Litherland, A., Brown, M., Wilson, M., Benn, D., Stobie, L., McNabb, I., Hunt, C., Kemp, P., & Valentine, I. (2007). *Silt recovery Southern North Island storm event 2004* (Project 06/60 Sustainable Farming Fund). AgResearch & Massey University.

Liu, X., Herbert, S. J., Hashemi, A. M., Zhang, X., & Ding, G. (2006). Effects of agricultural management on soil organic matter and carbon transformation—A review. *Plant, Soil and Environment*, *52*(12), 531–543. https://doi.org/10.17221/3544-PSE

Lower North Island Combined Provincial Federated Farmers Storm Group. (2007). *Flood Sediment. Sustainable Farming Fund Project 05/060 Meat and Wool FITT project*.

Ludecke, J. E. (1988). *The Tukituki River catchment water and soil resource management plan* (No. 2285). Hawke’s Bay Catchment Board & Regional Water Board.

Manatū Taonga — Ministry for Culture and Heritage. (2023, February 17). *Cyclone Bola strikes*. https://nzhistory.govt.nz/page/cyclone-bola-strikes

Marden, M., Lambie, S., & Phillips, C. (2018). Biomass and root attributes of eight of New Zealand’s most common indigenous evergreen conifer and broadleaved forest species during the first 5 years of establishment. *New Zealand Journal of Forestry Science*, *48*(1), 9. https://doi.org/10.1186/s40490-018-0113-y

Marin, R. J., & Osorio, J. P. (2017). Effects of vegetation on slope stability: A review (Translated). *Revista Politécnica*, *13*(24), 113–126.

Marlborough Chilean Needle Grass Action Group. (2021). *Chilean needle grass newsletter 2021* [Newsletter]. https://landcare.org.nz/wp-content/uploads/2022/10/CNG-Newsletter-2021.pdf

McCaskill, L. W. (1973). *Hold this land*. A.H & A. W Reed Ltd.

McCauley, A., Jones, C., & Olson-Rutz, K. (2017). *Soil pH and organic matter*. Montana State University Extension.

McKee, J. G., & Graham, G. J. (1952). Pasture establishment on flooded areas of Gisborne flats. *New Zealand Journal of Agriculture*, *84*, 197–198.

McLaren, R. G., & Cameron, K. C. (2002). *Soil science: Sustainable production and environmental protection* (2nd edition). Oxford Univ. Press.

McLean, J.-A. (2024). *Restoring our environment- Our Cyclone Gabrielle recovery journey*. Hawke's Bay Regional Council. https://www.hbrc.govt.nz/assets/Document-Library/Cyclone-Gabrielle/Restoring-our-Environment-Recovery-Report-V1.0-12-March-2024.pdf

McMillan, A., Dymond, J., Jolly, B., Shepherd, J., & Sutherland, A. (2023). *Rapid assessment of land damage – Cyclone Gabrielle* (Contract Report LC4292). Manaaki Whenua- Landcare Research.

Ministry for Primary Industries. (2023). *2023 North Island weather event primary sector funding*. https://www.mpi.govt.nz/dmsdocument/56905-2023-North-Island-weather-event-Primary-sector-funding-fact-sheet-

Ministry for the Environment. (2024). *National Policy Statement for Highly Productive Land 2022*. https://environment.govt.nz/assets/publications/land/NPS-HPL-with-2024-Amendments.pdf

Ministry of Business Innovation & Employment. (2024). *Extreme weather science response: Urgent scientific research and data collection*. https://www.mbie.govt.nz/science-and-technology/science-and-innovation/funding-information-and-opportunities/investment-funds/extreme-weather-science-response/urgent-scientific-research-and-data-collection#manaakiwhenua

Mitsuta, A., Lourenço, K. S., De Oliveira, B. G., De Assis Costa, O. Y., Cantarella, H., & Kuramae, E. E. (2025). Soil pH determines the shift of key microbial energy metabolic pathways associated with soil nutrient cycle. *Applied Soil Ecology*, *208*, 105992. https://doi.org/10.1016/j.apsoil.2025.105992

Mooney, K. (1973). *History of The County of Hawke's Bay Part IV*. Hawke's Bay County Council.

Morris, R. (2024). *The year of silt*. New Zealand Geographic. https://www.nzgeo.com/stories/cyclone-gabrielle/

Morton, J. D., & Roberts, A. (Eds.). (2024). *Fertiliser use on New Zealand sheep and beef farms* (Revised 2024). Fertiliser Association of New Zealand Inc.

New Zealand Herald. (1938). *Devastated land. Restoring Esk Valley. 23119*, 15.

Newton, K. (2024, December 2). Room for the river. *RNZ*. https://www.rnz.co.nz/programmes/in-depth-special-projects/story/2018966353/room-for-the-river-the-future-of-hawke-s-bay-s-ngaruroro-river

NIWA. (2018a). *April 1938 Gisborne and Hawke's Bay Flooding*. NZ Historic Weather Events Catalogue. https://hwe.niwa.co.nz/event/April_1938_Gisborne_and_Hawkes_Bay_Flooding

NIWA. (2018b). *February 2004 North Island Storm*. NZ Historic Weather Events Catalogue. https://hwe.niwa.co.nz/event/February_2004_North_Island_Storm

NIWA. (2018c). *May 1948 North Island Storm*. NZ Historic Weather Events Catalogue. https://hwe.niwa.co.nz/event/May_1948_North_Island_Storm

Northern Advocate. (1939). Esk Valley becomes a miniature desert. *Northern Advocate*, 9.

O'Kennedy, S. (2022). Soil pH and its impact on nutrient availability and crop growth. *International Journal of Geography, Geology and Environment*, *4*(2), 236–238.

Osman, K. T. (2018). Sandy soils. In K. T. Osman, *Management of Soil Problems* (pp. 37–65). Springer International Publishing. https://doi.org/10.1007/978-3-319-75527-4_3

Page, M. J. (1988). *Land use capability classification of the Northern Hawke's Bay Region* (Water & Soil Miscellaneous Publication Number 109). Ministry of Works and Development.

Plant and Food Research. (2024). *Annual report 2024*. https://assets.ctfassets.net/y9no91j9bwnp/60x16XU7TjVhfkQdsaSF8F/c19a7fab26ca7f54187d5734e384c052/plant-and-food-research-annual-report-2024.pdf

Pocock, J. (2023, February 24). Losing sight of history: Esk Valley flooding reminder of disaster risks. *Hawke's Bay Today*. https://www.nzherald.co.nz/hawkes-bay-today/news/losing-sight-of-history-esk-valley-flooding-reminder-of-disaster-risks/PIQPTCIAH5EL5IGLZ6N5W3IHY4/

Reid, J. B., & Morton, J. D. (2019). *Nutrient management for vegetable crops in New Zealand* (1st edition January 2019). Horticulture New Zealand on behalf of Vegetable Research & Innovation Board and the Fertiliser Association of New Zealand.

Renwick, J., Anderson, B., Greenway, A., Ngaru King, D., Mikaloff-Fletcher, S., Reisinger, A., & Rouse, H. (2016). *Climate change implications for New Zealand*. The Royal Society of New Zealand.

Roberts, R. C., & McConchie, J. (2017). Preliminary assessment of the acid sulphate soils hazard in the Auckland region. In G. J. Alexander & C. Y. Chin (Eds.), *20th NZGS Geotechnical Symposium*. New Zealand Geotechnical Society.

Rothwell, A., Chaney, K., & Haydock, P. (2011). The impact of cultivation techniques on earthworm populations. In A. Karaca (Ed.), *Biology of Earthworms* (Vol. 24, pp. 159–172). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-14636-7_10

Schon, N. L., Fraser, P. M., & Mackay, A. D. (2023). Earthworms for inclusion as an indicator of soil biological health in New Zealand pastures. *New Zealand Journal of Agricultural Research*, *66*(3), 208–223. https://doi.org/10.1080/00288233.2022.2041676

Shepherd, T. G. (2000). *Visual Soil Assessment. Volume 1: Field guide for cropping and pastoral grazing on flat to rolling country* (Vol. 1). horizons.mw & Landcare Research.

Singh, J., Schädler, M., Demetrio, W., Brown, G. G., & Eisenhauer, N. (2019). Climate change effects on earthworms—A review. *Soil. Org*, *3*(91). https://doi.org/10.25674/SO91ISS3PP114

Stone, D. A., Noble, C. J., Bodeker, G. E., Dean, S. M., Harrington, L. J., Rosier, S. M., Rye, G. D., & Tradowsky, J. S. (2024). Cyclone Gabrielle as a Design Storm for Northeastern Aotearoa New Zealand Under Anthropogenic Warming. *Earth's Future*, *12*(9), e2024EF004772. https://doi.org/10.1029/2024EF004772

Takeshita, V., Mendes, K. F., Alonso, F. G., & Tornisielo, V. L. (2019). Effect of organic matter on the behaviour and control effectiveness of herbicides in soil. *Planta Daninha*, *37*, e019214401. https://doi.org/10.1590/s0100-83582019370100110

*The Maungaharuru-Tangitū Hapū and  The trustees of the Maungaharuru-Tangitū Trust The Crown: Deed of Settlement documents*. (2015).

USDA. (2019). *Soil bulk density/moisture/aeration*. Natural Resources Conservation Services. https://www.nrcs.usda.gov/sites/default/files/2022-10/Soil%20Bulk%20Density%20Moisture%20Aeration.pdf

Van De Logt, R., Van Der Sluijs, T., & Van Eekeren, N. (2023). Lumbricus terrestris abundance in grasslands on sandy soils in relation to soil texture, hydrology and earthworm community. *European Journal of Soil Biology*, *119*, 103545. https://doi.org/10.1016/j.ejsobi.2023.103545

Wallace, D., Mathers, D., Briant, M., Calendar, E., & Kale, A. (2024). *Cyclone Gabrielle cropping recovery: Examples of getting back to growing* (p. 260) [Draft Report].

Wallis, F. P. (1966). *Report on a survey of the condition of the forests, scrublands and grasslands of the upper Ngaruroro catchment* (Protection Forestry Report No. 24).

Wilding, T., & Waldron, R. (2012). *Hydrology of the Tukituki catchment. Flow metrics for 17 sub-catchments.* [HBRC Plan No. 4405]. Hawke's Bay Regional Council.

Williams, G. J. (1985). *Upper Tukituki catchment control scheme, investigations & proposed scheme*. Hawke's Bay Catchment Board & Regional Water Board.

Williams, G. J. (1987). *The Ngaruroro river scheme, investigations and review* (HBRC No. 4449). Hawke's Bay Catchment Board & Regional Water Board.

Wilson, M. D., & Valentine, I. (2005). Regrassing flood-damaged pastures. *Journal of New Zealand Grasslands*, *67*, 117–121. https://doi.org/10.33584/jnzg.2005.67.2584

Wilson, N., Broadbent, A., & Kerr, J. (2023, August 14). *Cyclone Gabrielle by the numbers- A review at six months*. Public Health Communication Centre Aotearoa. https://www.phcc.org.nz/briefing/cyclone-gabrielle-numbers-review-six-months