Manaaki Whenua
Landcare Research

Ecological impacts of Cyclone Gabrielle

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Ecological impacts of Cyclone Gabrielle

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In mid-February 2023 Cyclone Gabrielle struck the North Island of New Zealand causing widespread destruction. As part of the cyclone response, the Ministry of Business, Innovation and Employment (MBIE) contracted Manaaki Whenua – Landcare Research to deliver a high-level, integrated assessment of the immediate impacts of Cyclone Gabrielle on native ecosystems and species in affected areas. This work was completed in collaboration with the National Institute of Water and Atmospheric Research (NIWA) over the period April 2023 to October 2024.

Objectives

- Identify changes in the extent and condition of vegetation cover of native ecosystems immediately after the cyclone.
- Evaluate impacts on uncommon native ecosystems (lowland forest, wetlands, braided rivers, coastal active dunes), conservation infrastructure (ecosanctuaries), and threatened species.
- Quantify the resilience of resident fish and macroinvertebrate communities and recolonisation of migratory fish species, especially threatened taonga (e.g. īnanga, whitebait).

Methods

- *Spatial intersection analysis:* To assess the spatial extent of cyclone impacts on a range of native land-cover types, we intersected cyclone impact maps of flooding, erosion and deposition with several maps describing (primarily) native vegetation cover. Impacts on these ecosystems were compared across slope classes and by distance from rivers.
- *Wind damage:* We used Normalised Difference Vegetation Index (NDVI) data from the Sentinel-2 satellite to indicate potential areas where leaf stripping or wind throw of trees may have occurred. This was complemented by a field assessment of wind damage to native forest in Bay of Plenty.
- *Lowland forest:* Working with mana whenua,[1] QEII National Trust, and Gisborne District Council, we established 41 permanent monitoring plots in 19 floodplain native forest fragments that varied in their severity of cyclone impacts. In each plot we quantified the local severity of Cyclone Gabrielle (e.g. flood height and sediment depth), tree dieback, and forest regeneration potential.
- *Wetlands:* Working with Auckland Council and Hawke's Bay Regional Council, we re-surveyed 52 wetlands in Auckland and 27 wetlands in Hawke's Bay following Cyclones Hale and Gabrielle. At each wetland we collected data to quantify plant diversity,

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[1] Mana whenua: territorial rights, power from the land, authority/jurisdiction over land or territory, power associated with possession and occupation of tribal land. The term is sometimes used, as here, to describe those associated with such rights/authority, or (more loosely), with tribal links to a specific area.

composition, and structure; soil and plant nutrient status; and wetland condition and pressure indices.

- *Braided rivers:* With Hawke's Bay Regional Council, we re-surveyed braided rivers in three catchments, and quantified post-cyclone changes in the abundance and distribution of native riverbed-breeding shorebirds and their habitat (vegetation cover and substrate composition).
- *Freshwater fauna:* Cyclone Gabrielle's impacts on, and the recovery of, īnanga (and their spawning habitats), other fish, and macroinvertebrate communities were assessed in Hawke's Bay catchments. Four spawning habitats were surveyed for īnanga eggs and assessed for condition. Both environmental DNA (eDNA) and electric fishing[2] were used to assess changes in fish species richness and abundance. Physical and eDNA samples were collected before and after the cyclone were used to assess changes in macroinvertebrate community composition.
- *Coastal active dunes:* We used data from the Northland Regional Council coastal dune vegetation monitoring programme to characterise changes in active dune extent and vegetation cover at 14 sites following Cyclone Gabrielle.
- *Conservation infrastructure:* We interviewed representatives from 65 ecosanctuaries across the North Island to assess the types of cyclone damage (e.g. flooding, erosion, sedimentation) and impacts (e.g. disruption to pest management and damage to pest fences) experienced by conservation projects.
- *Threatened species:* We collated information from a variety of stakeholders on the impacts of Cyclone Gabrielle on some of New Zealand's most threatened species.

Results

- *Spatial intersection analysis:* Although some native ecosystem patches and fragments were severely affected by Cyclone Gabrielle, overall impacts to mapped areas did not exceed 2%. Impacts were generally higher on flat land, reflecting sediment deposition. Areas closer to rivers, and surrounding rivers with higher stream orders, received greater impacts from slips and sediment deposition.
- *Wind damage:* The NDVI analysis of satellite imagery showed promise as a method for measuring wind damage, successfully identifying areas of severe wind fall or canopy discoloration but proving less useful for identifying individual tree falls. Wind impacts on native forest were low overall, mostly restricted to canopy stripping and individual tree falls rather than widespread wind throw. Wind-damaged trees in permanent forest plots in Bay of Plenty accounted for just 0.07% of the total basal area.
- *Lowland forest:* Sediment depth ranged up to 66 cm and flood debris height up to 4.1 m. Tree dieback patterns were species-specific, but generally increased with greater sediment depth but not flood height. Forest fragments with stock access had

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[2] 'Electric fishing is a way to find out what fish species are in the water. An electric current is passed through the partially submerged rods at the front of the boat. The current temporarily stuns the fish, which float to the surface. They are scooped up in nets and identified.' (https://teara.govt.nz/en/photograph/15675/electric-fishing)

almost no regeneration, whereas regeneration was occurring in fenced sites, although these were more heavily invaded by non-native plant species.

- *Wetlands:* Both Auckland and Hawke's Bay wetlands experienced substantial inundation during Cyclone Gabrielle, highlighting their flood mitigation services. They were largely resilient to the extreme weather, with a 4% decline in wetland condition observed in Hawke's Bay. A few wetlands suffered severe impacts, caused by sediment deposition and damage to vegetation.
- *Braided rivers:* Nationally and internationally significant populations of banded dotterels (pohowera), black-fronted dotterels, pied stilts (poaka), and South Island pied oystercatchers (tōrea) on Hawke's Bay braided rivers declined by 15%, 30%, 16%, and 43%, respectively, after Cyclone Gabrielle. Braided riverbeds experienced increased cover of fine substrate after the severe flood event, while vegetation cover (mostly non-native species) decreased.
- *Freshwater fauna:* No īnanga eggs were found in post-cyclone surveys of spawning habitats in Hawke's Bay. Macroinvertebrate communities showed distinct shifts in composition immediately after Cyclone Gabrielle, but largely recovered to pre-cyclone composition in all but the highest impact sites by the following summer. Fish communities also recovered rapidly, with community structure the following summer comparable to that before the cyclone. The recovery of migratory taonga species indicated that sufficient connectivity of habitats and availability of refuge (cover) habitats were present post-cyclone.
- *Coastal active dunes:* An average of 2.1 m (4%) of coastal active dune width was lost after Cyclone Gabrielle, with the largest declines observed in Bream Bay, Northland. Overall cover and native plant dominance of active dune vegetation were unchanged by the cyclone, although some species-specific changes were observed.
- *Conservation infrastructure:* Most ecosanctuaries experienced multiple impacts from the cyclone. Damage to infrastructure (e.g. buildings, roads, trails) was widespread and often paired with loss of access to management areas, disruption to pest control and native species monitoring, damage to restoration plantings, and decreased capacity of the conservation workforce. Of particular concern, 40% of pest fences were damaged during the cyclone, with rapid pest incursions detected in most cases.
- *Threatened species:* There is a general lack of long-term monitoring data for many populations of threatened species. Several threatened species suffered negative impacts as a direct result of the cyclone, including fairy terns (tara iti), shore plovers (tuturuatu), whio (blue ducks), pepeketua (Hochstetter's frog), Northland button daisy (*Leptinella rotundata*), and ngutukākā (kākābeak).

Conclusions

- Native ecosystems, including forests, wetlands and active dunes, were largely resilient to the extreme weather of Cyclone Gabrielle. However, localised severe impacts were observed across all ecosystems and their recovery should be monitored and managed.
- Freshwater fish and macroinvertebrate communities were resilient to the impacts of Cyclone Gabrielle, with biodiversity recovering to pre-cyclone levels 1 year after the cyclone. However, habitat alteration may lead to long-term changes in fish

community composition and abundance. Īnanga spawning habitat is slow to recover following extreme weather events.

- Uncommon ecosystems and threatened species are especially at risk from extreme weather events due to their limited spatial distribution, low population sizes, and interactions with pre-existing threats such as habitat loss and fragmentation, invasive plants, and mammalian predators and browsers.
- Conservation infrastructure is vulnerable to extreme weather events. A rapid response is required to prevent the loss of hard-won conservation gains and to avoid ecosanctuaries and other conservation projects 'running to standstill'.
- Standardised, long-term monitoring across multiple independent sites is crucial for quantifying change in the ecosystem condition and populations of threatened species so that management responses in the aftermath of extreme weather events can be informed and effective.

Recommendations

To mitigate the impacts of future extreme weather events on natural ecosystems we recommend taking the following actions. A summary of cyclone impacts is presented in Figure 1, and the recommendations to mitigate them are presented in Figure 2.

General recommendations for native ecosystems

- Continue to protect and restore native forest, wetlands, and riparian vegetation, from high in catchments down to the floodplain, to increase the provision of flood and erosion mitigation services.
- Continue to manage the many global change pressures that interact with extreme weather events, such as invasive plants and mammalian browsing. Disturbed ecosystems should be fenced to limit stock and ungulate access, promoting regeneration. Monitor for non-native plant invasions and act swiftly to prevent the establishment and spread of new and existing invasive species.

Recommendations for freshwater ecosystems

- Maintain and improve connectivity for freshwater species to provide refuge habitat and facilitate recovery and resilience after flood events.
- Deploy artificial spawning substrates to promote īnanga spawning and prevent population sinks from developing before riparian habitat has been restored.
- Continue non-native plant management in braided rivers to improve shorebird habitat.
- Increase predator management efforts along braided rivers, especially in areas known to host breeding native shorebirds, to offset the impacts of extreme weather events.

Recommendations for ecosanctuaries, conservation projects, and threatened species and ecosystems

- All stakeholder organisations should create, review, and regularly update their climate adaptation and disaster response plans. These should anticipate individual and collective risks from extreme weather to a range of terrestrial and aquatic ecosystems and species, with a focus on mitigating impacts.

- Non-charismatic and lesser-known species should be explicitly integrated into the ecosanctuary network. This would help to protect greater taxonomic and functional diversity, and to restore functioning and resilient ecosystems – a stated goal of many ecosanctuaries.
- To distribute risk, new and additional conservation translocations should be considered, especially for range-restricted and intractable species (i.e. species that continue to decline despite conservation efforts), including assisted migration beyond a species' historical range.
- The conservation community should continue to improve capability, communication, and cooperation among diverse stakeholders to develop cross-project resilience across large spatial scales.
- A pest management buffer zone should be maintained around the boundary of pest fences to reduce pest densities and limit incursions if fences are damaged.
- A 'disaster response kit' should be assembled to facilitate rapid response and recovery after extreme weather events.
- Land managers should use cyclone warning periods to prepare several days in advance of storm arrival.

Recommendations for data and long-term monitoring

- Continue to establish and/or maintain standardised monitoring programmes for at-risk species and ecosystems. Standardised, long-term monitoring across multiple independent sites is crucial for quantifying change in ecosystem condition and populations of threatened species, so that management responses in the aftermath of extreme weather events can be informed and effective. Standardised monitoring is particularly important for distinguishing natural variability from significant ecological changes resulting from the cyclone.
- A centralised, accessible database should be established for the storage and sharing of monitoring data. This will enhance coordination among researchers, conservationists, and policy-makers. Such a database will facilitate long-term monitoring of species and ecosystems and improve our ability to detect and respond to ecological changes.

Recommendations for future research

- Continue to monitor the long-term impacts on, and recovery of, affected ecosystems. This will provide vital information on how the recovery of various ecosystems is influenced by modern pressures such as invasive plants, feral ungulates, and other disturbances, and under different management regimes.
- Reanalyse data from Sentinel-1 and -2 satellites, initially conducted by Dragonfly Data Science, to monitor the broad-scale temporal recovery of affected sites.
- Further develop the spatial analysis methods employed in this report and other Extreme Weather Research Platform projects for rapid deployment following extreme weather events and other natural disasters.

- Carry out research to better quantify and understand the co-benefits and trade-offs of flood mitigation and other ecosystem services provided by wetlands, native vegetation, and other land-use types in New Zealand.
- Aim for future research to inform planning on which types of ecosystems to revegetate, and where, to optimise land use, future resilience, and mitigation services.
- Ensure future work investigating wind damage to forests incorporates a larger network of recently measured permanent plots across a broad spatial scale.
- Further analyse lowland forest plot data to characterise forest regeneration potential, based on the soil seed bank and the composition of seedling, sapling, and mature plant communities.
- Further analyse wetland State of the Environment monitoring data to assess post-cyclone changes in soil characteristics, plant diversity, and composition. Future research should explicitly investigate the relationships between wetland condition and pressure index indicators, on the one hand, and measures of ecological integrity.
- Continue to monitor shorebird populations along Hawke's Bay braided rivers and coastlines, and establish similar monitoring programmes in other regions.
- Further analyse coastal active dune monitoring data to place cyclone impacts in the context of long-term trends (i.e. by investigating state change across a longer time).
- Conduct a spatial conservation risk assessment of threatened species and ecosystems under a range of natural disaster scenarios. This analysis would identify gaps in our understanding of which species and ecosystems are being managed and where, so that risk can be distributed spatially and swift action taken when a regional event is forecast.
- Carry out studies to understand how spatial connectivity influences recovery rates, including for terrestrial (i.e. lowland forests connected through seed dispersal) and freshwater (i.e. stream connectivity) ecosystems. Differentiating between recovery times for local disturbances and broader catchment-level disturbances will provide insights into the scale-dependent effects of cyclone events.
- Investigate the frequency of the monitoring required to disentangle natural variability from post-disturbance change across various ecosystems.
- Investigate in-stream structures susceptible to becoming fish migration barriers, resulting in long-term changes from extreme weather events.

CYCLONE GABRIELLE

Impacts on native ecosystems

Manaaki Whenua Landcare Research

NIWA

Native vegetation cover

Less than 2% of native vegetation was impacted, although some individual patches were severely affected by flooding, sediment deposition and slips. Areas closer to rivers received more slips and sediment deposition.

Wetlands

Hawke's Bay and Auckland wetlands were largely resilient to flooding, with a 4% overall decline in wetland condition in the Hawke's Bay and no change in Auckland. Some wetlands suffered severe impacts from sediment deposition and damage to vegetation.

Ecosanctuaries

88% of North Island ecosanctuaries experienced physical damage from the cyclone, 77% experienced disruptions to pest management activities, and 40% of predator exclusion fences were damaged.

Freshwater streams

Macroinvertebrate communities showed distinct shifts in composition immediately after Cyclone Gabrielle but had largely recovered to pre-cyclone composition in all but the highest impacted sites by summer 2023/24.

Lowland forests

Some forest fragments had up to 66 cm of sediment deposited and flooding up to 4.1 m above the ground. Tree dieback was species-specific but generally increased with greater sediment depth. Forests with stock access had almost no regeneration of native trees.

Braided rivers

Nationally and internationally significant populations of four shorebird species declined between 15–43% after the cyclone. Two of the three riverbeds surveyed experienced increased cover of fine substrates, including a 290% increase in sediment in the Ngaruroro catchment.

Spawning habitats of īnanga

No īnanga eggs were found in four known and potential spawning sites in Hawke's Bay one year after the cyclone due to ongoing smothering of intertidal vegetation by sediment.

Coastal sand dunes

An average of 4% of coastal dune width was lost in Northland after the cyclone, with the largest declines observed along the east coast. Overall cover of native and non-native dune vegetation was unchanged by the cyclone, although some species-specific changes were observed.

Native freshwater fish

Fish communities recovered to comparable pre-cyclone community composition by summer 2023/24, including migratory taonga species īnanga and smelt.

This work was funded by MBIE as part of the extreme weather science response.
For more information and to access the full report, please contact Rowan Sprague at spraguero@landcareresearch.co.nz

Figure 1. Infographic summarising the impacts of Cyclone Gabrielle on native ecosystems.

CYCLONE GABRIELLE

Recommendations

for native ecosystems

Manaaki Whenua
Landcare Research

NIWA

Native vegetation cover

Continue to restore and protect native vegetation and riparian areas to help stabilise existing landslides and reduce future erosion and downstream sedimentation. Species planted should be carefully selected for resilience to damage from wind, flooding, and sediment deposition.

Wetlands and freshwater streams

Establish significant buffers of native vegetation around waterways and wetlands to reduce erosion and sedimentation. Protect and restore wetlands, from high in catchments to the floodplains, to increase provision of flood and erosion mitigation services.

Ecosanctuaries and conservation projects

Create and regularly update climate adaptation and disaster response plans. These should anticipate individual and collective risks to ecosystems and species from extreme weather to mitigate potential impacts.

Lowland forests

Install fences around forest fragments to exclude stock and feral ungulates and promote forest regeneration. Monitor for non-native plant invasions and act swiftly to prevent establishment and spread of new and existing invasive species.

Braided rivers

Continue to monitor shorebird populations on braided rivers to better understand the vulnerability and recovery of these populations to extreme weather events. Implement landscape-scale predator control along braided rivers to improve shorebird breeding success.

Spawning habitats of īnanga

Deploy artificial spawning substrates to promote īnanga spawning until riparian habitat has been restored.

Coastal sand dunes

Restore coastal dunes by planting native sand-binding species, controlling non-native plants, and preventing vehicle and stock access to mitigate further erosion.

Native freshwater fish

Improve connectivity between waterways and ensure suitable refuge habitat is present to facilitate recovery after flood events.

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Figure 2. Infographic summarising the recommendations for managing native ecosystems to improve native ecosystem resilience to extreme weather events such as Cyclone Gabrielle.

1 Introduction

1.1 Background

1.1.1 Tropical cyclones in New Zealand

Tropical cyclones are large-scale, extreme weather events that can inflict catastrophic impacts on the environment, economies, and human well-being (Estrada et al. 2015). They typically form over large bodies of warm water and develop into a rapidly rotating storm system with a low-pressure centre, extremely strong winds, and a spiral arrangement of thunderstorms with high precipitation. New Zealand experiences an average of one tropical cyclone per year (between December and April) (Sinclair 2002), although most cyclones have considerably weakened by the time they reach New Zealand.

However, a few cyclones in recent history have had wide-ranging and major impacts on parts of New Zealand. An unnamed storm (February 1936), Cyclone Ida (March 1959), Cyclone Giselle (April 1968), Cyclone Alison (March 1975), and especially Cyclone Bernie (April 1982), all caused severe damage to native forest, especially in the North Island (Shaw 1983b). Cyclone Gisele produced wind gusts of up to 270 km/h in Wellington, and the storm caused the sinking of the Wahine interisland ferry, with the loss of 51 lives. Cyclone Bola (March 1988) produced record rainfall totals of over 900 mm in some locations, and the worst damage to land and infrastructure occurred in the Gisborne and Hawke's Bay regions. Cyclone Ita (April 2014) produced high rainfall and wind gusts that peaked at 130 km/h, causing damage to homes, infrastructure, and land, including large-scale blow-down of native forest in the West Coast Region (Platt et al. 2014).

Although still a contentious issue, current evidence indicates that the frequency of tropical cyclones may be slightly decreasing over the South Pacific basin, but the cyclones that do form are of greater strength (NIWA 2017; Roberts et al. 2020; Chand et al. 2022; Ministry for the Environment & Stats NZ 2023). Other studies have found that the landfall and peak wind intensity of tropical cyclone locations have shifted poleward in recent decades, which is predicted to continue (Kossin et al. 2016; Altman et al. 2018; Feng et al. 2021; Studholme et al. 2022). This could mean that cyclones reach New Zealand more regularly, counteracting the predicted decrease in frequency of development.

Similarly, the location of atmospheric rivers (i.e. long, narrow bands of water vapour in the atmosphere that bring heavy rain and storms) has shifted polewards over the last 40 years (Li & Ding 2024), and global temperature rise is projected to increase the frequency of extreme rainfall events in New Zealand by 7–20% (Wratt et al. 2006). Altogether, it appears likely that New Zealand will experience stronger and potentially more frequent extreme weather events in the future.

1.1.2 Effects on ecosystems

Tropical cyclones are among the most destructive natural processes for biological systems. Their strong winds, storm surges, and intense rainfall can have large-scale consequences for the extent, structure, composition, and functioning of ecosystems (Bellingham 2008; Lugo

2008; Xi 2015; Lin et al. 2020). These impacts occur through flooding and inundation, erosion of surfaces, deposition of material, and the direct effects of wind (Bellingham 2008).

Such destructive forces are not new to New Zealand ecosystems (Shaw 1983b). For example, there are many records of large areas of forest being blown down by strong winds (Thomson 1936; Shaw 1983a; Martin & Ogden 2006; Platt et al. 2014), while wetlands, rivers, and historical floodplains have long experienced severe flooding and sediment deposition (Martin 2006). These natural processes cause (often temporary) harm to some ecosystems and species, and yet benefit others that are well adapted to cope with disturbance, contributing to the maintenance of biodiversity. In sum, tropical cyclones both destroy and rejuvenate, and could thus be considered biologically neutral.

However, the most serious threats to biodiversity probably arise from interactions between extreme weather events and the many anthropogenic changes to New Zealand’s environment (Macinnis-Ng et al. 2021). For example, historical land-use change from forest and wetlands to pasture has created a landscape more prone to flooding and erosion (McGlone 1978; McMillan et al. 2023), altering the sedimentation of wetlands, waterways, and historical floodplains (Wilmshurst 1997; Trustrum et al. 1999). Similarly, newly disturbed substrate that once provided opportunities for a suite of native species may now facilitate invasion by non-native species (Murphy et al. 2008). Post-disturbance recovery of ecosystems and species could also be disrupted by other agents of global change (e.g. habitat loss and fragmentation, browsing mammals, and other disturbances such as fire), further exacerbating the ecological impacts of extreme weather events. Finally, the ongoing biodiversity crisis has left many native species in a highly vulnerable state (Department of Conservation 2020), such that extreme weather events have the potential to further affect their already much-reduced populations, along with the vital conservation infrastructure used to protect them.

The large number of potential interactions and the complex mechanisms by which they are likely to occur mean that we currently have little understanding of how our ecosystems and biota will respond to extreme weather events in the decades ahead (Lundquist et al. 2011; Keegan et al. 2022). Given these uncertainties, it is important to undertake research to identify the species, ecosystems, and conservation infrastructure most at risk, and how these risks might be managed (Keegan et al. 2022; Macinnis-Ng et al. 2024). This improved understanding will help to safeguard hard-fought conservation gains against future extreme weather events through improved monitoring and adaptive management of at-risk ecosystems and species.

1.1.3 Cyclone Gabrielle

Originating in the Coral Sea, Cyclone Gabrielle moved along the northeast coastline of the North Island of New Zealand between 12 and 14 February 2023, bringing widespread destruction to parts of Northland, Auckland, Coromandel, East Cape, and Hawke’s Bay (Figure 3). Eleven people tragically lost their lives. Properties, roads, and electricity and flood protection infrastructure were severely damaged; and large areas of farmland, rivers, and the coastline were affected by flooding and erosion. On the morning of 14 February a national state of emergency was declared for just the third time in New Zealand’s history (NIWA 2023a).

Over 500 mm of rain fell in some areas, with a maximum recorded intensity of 56 mm per hour (Hawke's Bay Independent Flood Review 2024). Severe flooding deposited vast quantities of eroded sediment on adjacent floodplains, while peak river flows were the highest ever recorded on many Hawke's Bay rivers (Harrington et al. 2023; NIWA 2023b).[3] Wind gusts of up to 140 km per hour were recorded, with the strongest winds experienced in Auckland, Northland, the central North Island, and Taranaki. Waves reached as high as 11 metres in the Bay of Islands,[4] contributing to storm surges of over 0.5 m, with erosion and flooding most severely felt along the eastern coastlines of Northland and the Coromandel Peninsula (Harrington et al. 2023).

The impact of Cyclone Gabrielle was exacerbated by the preceding Cyclone Hale (10/11 January 2023) and the Auckland Anniversary storm (27 January 2023), which left many regions vulnerable due to an already saturated landscape (Harrington et al. 2023; Macinnis-Ng et al. 2024). These extreme weather events caused a combined estimate of $9–14.5 billion dollars of physical asset damage, making this New Zealand's costliest non-earthquake natural disaster (Ministry for the Environment & Stats NZ 2023; New Zealand Treasury 2023).

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[3] https://www.hbrc.govt.nz/assets/Document-Library/Reports/External-Reports/NIWA-letterreport-230224.pdf (accessed 10 September 2024).

[4] https://blog.metservice.com/TropicalCycloneGabrielleSummary (accessed 2 October 2024).

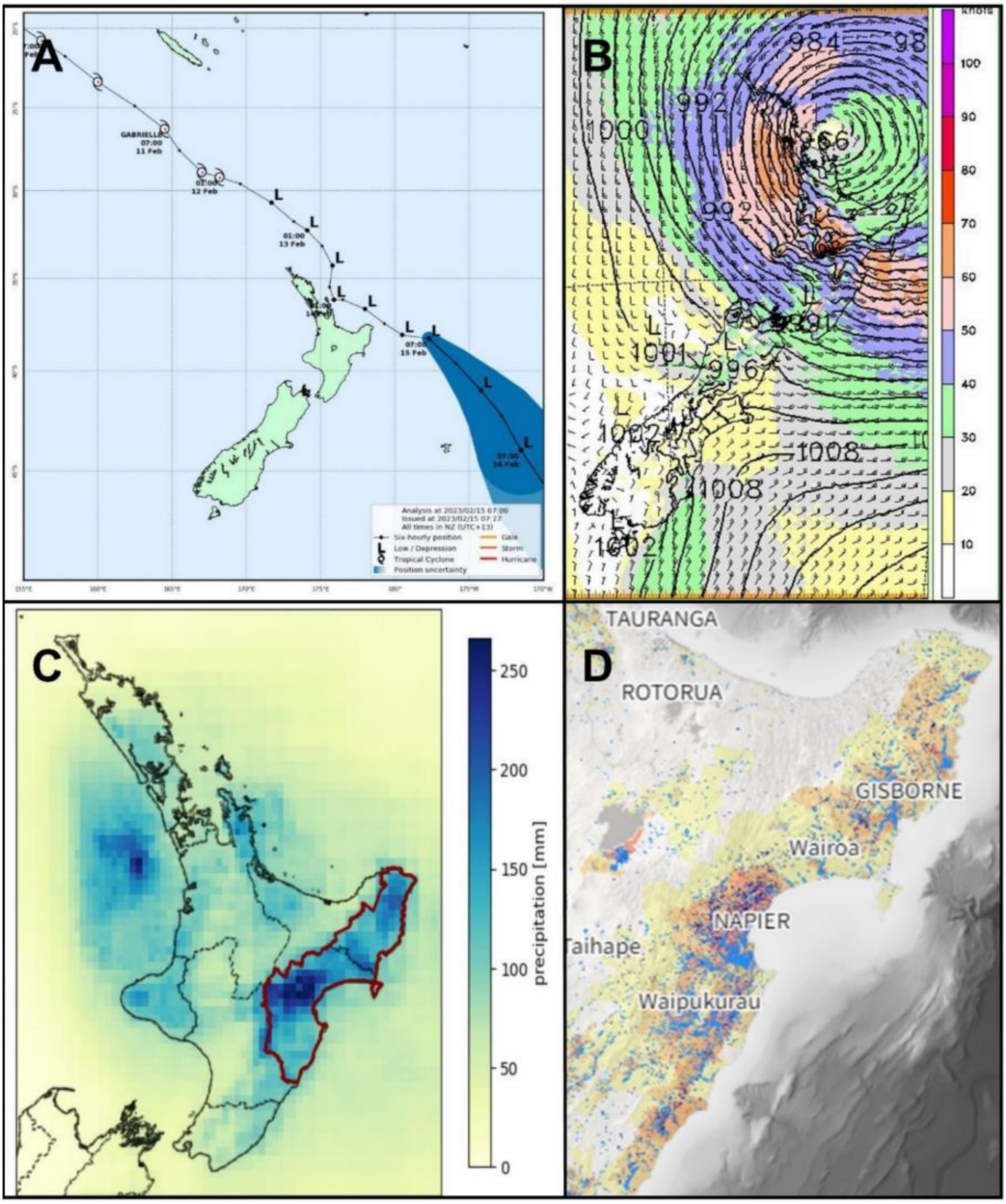

Figure 3. Composite figure showing: A, the storm track of Cyclone Gabrielle along the northeast of New Zealand; B, maps of wind gusts early in the morning of 14 February 2023 (measured in knots, 1 knot = 1.85 km/hr); C, 2-day accumulated precipitation during 13/14 February 2023; and D, impacts on suburbs in the eastern North Island, where darker-coloured suburbs represent those with a greater proportion of their area affected by the cyclone. (Sources: map A, MetService (https://blog.metservice.com/TropicalCycloneGabrielleSummary); map B, MetService; map C, figure modified from Harrington et al. 2023; map D, Dragonfly Data Science (https://www.dragonfly.co.nz/work/cyclone-impact-map.html).

1.2 Objectives

As part of the cyclone response, the Ministry of Business, Innovation and Employment contracted Manaaki Whenua – Landcare Research to deliver a high-level integrated assessment of the immediate impacts of Cyclone Gabrielle on native ecosystems and species in affected areas of New Zealand. Our assessment aimed to identify the ecosystems and species that were most adversely impacted, and to provide recommendations for management interventions.

In collaboration with NIWA, we examined native forest ecosystems, wetlands, naturally uncommon ecosystems (e.g. braided rivers and coastal active dunes), and freshwater macroinvertebrate and resident and migratory fish communities, including threatened taonga species. Our specific objectives were to:

- identify changes in the extent and condition of vegetation cover of native ecosystems immediately after the cyclone
- evaluate impacts on uncommon native ecosystems (lowland forest, wetlands, braided rivers, coastal active dunes), conservation infrastructure (ecosanctuaries), and threatened species
- quantify the resilience of resident fish and macroinvertebrate communities and recolonisation of migratory fish species, especially threatened taonga (e.g. īnanga, whitebait).

1.3 Overview of work programme

To deliver this research we partnered with mana whenua, regional councils, government departments, national trusts, community groups, local schools, ecological consultants, and private landowners. This broadly collaborative approach allowed us to connect with the communities affected by Cyclone Gabrielle and to direct our research towards questions considered most important by stakeholders.

In addition to fostering these new and established relationships, other emergent benefits included the establishment of permanent forest monitoring plots in previously under-surveyed areas, improved capability of our team and research partners, and the collection of evidence to inform post-disturbance management and preparation for future extreme weather events.

We used a range of approaches to assess the impacts of Cyclone Gabrielle on native ecosystems and species, including spatial data intersection, environmental DNA (eDNA), permanent forest plots, analysis of long-term monitoring data sets, and interviews with land managers. We collected data from throughout the North Island, with a focus on heavily affected regions, especially Hawke’s Bay, Gisborne, Northland, and Auckland (Figure 4). The ecosystems examined ranged from the mountains to the coast, and included forests, wetlands, rivers, estuaries, and coastal dunes (Figure 1 and Figure 2).

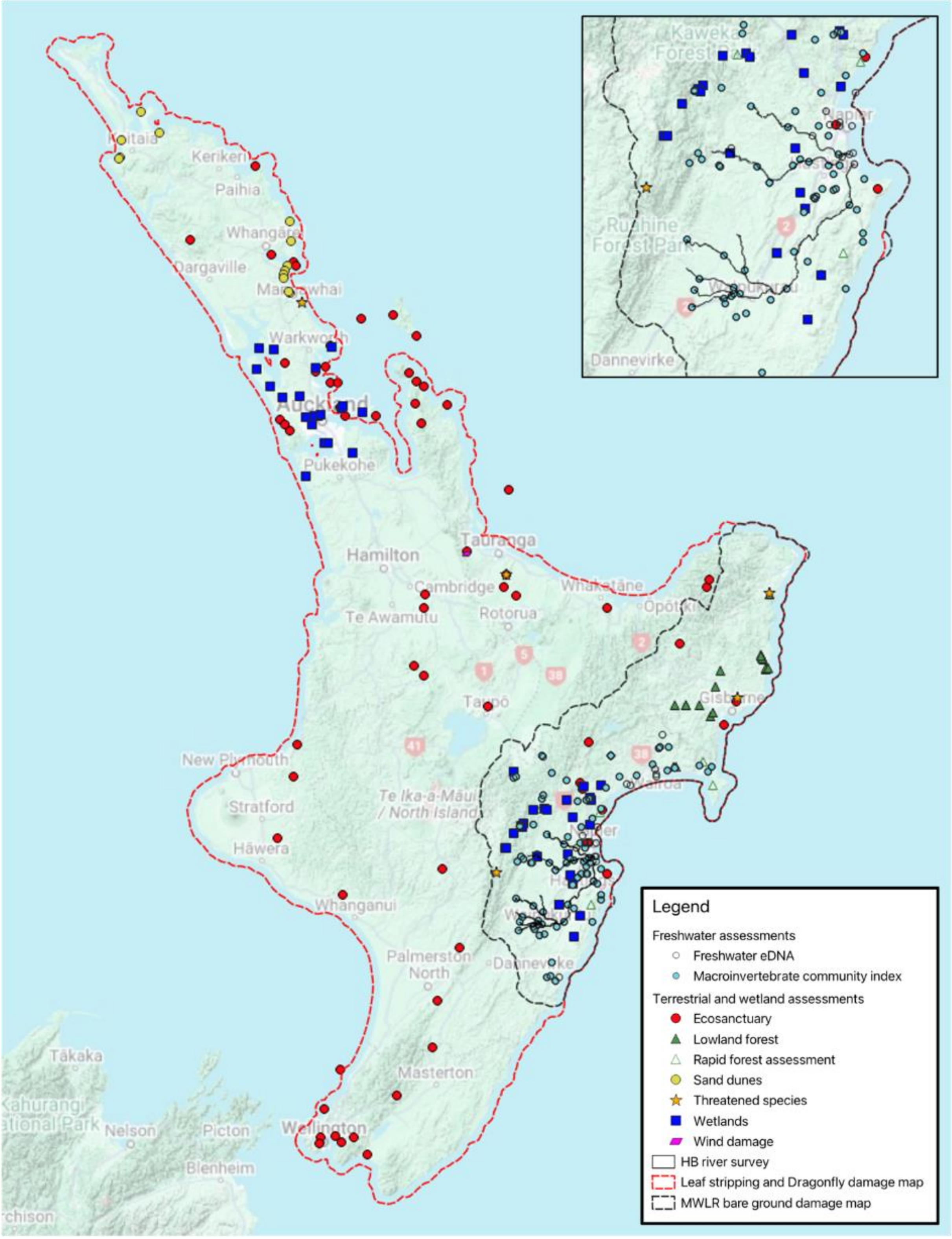

Figure 4. Map of the North Island, New Zealand, showing sampling sites or study areas for various components of the project. A more detailed map of part of the Hawke's Bay region is inset.

Note: Some sampling points are jittered or not shown to protect landowner privacy.

2 Changes in extent and condition of vegetation

2.1 Spatial intersection analysis

2.1.1 Introduction and methods

Tropical cyclones affect ecosystems through the combined effects of intense rainfall and strong winds. Three major ways in which terrestrial ecosystems are affected are:

- flooding and inundation
- wind
- erosion of surfaces (slips) and deposition of material (mostly silt/sediment).

To assess the spatial extent of these impacts across various ecosystems, we conducted a spatial analysis based on two mapped cyclone impact data sets using a combination of vegetation layers to assess impact by ecosystem.

The two cyclone impact data sets, Manaaki Whenua – Landcare Research (MWLR) Rapid Assessment of Land Damage (McMillan et al. 2023) and the Dragonfly Cyclone Gabrielle Impact Map (Dragonfly 2023), are satellite-based assessments of cyclone impacts that compare imagery from time periods immediately before and after the cyclone event. The MWLR map was compiled from Sentinel-2 satellite images selected from available cloud-free images nearest to the dates of the cyclone.

A change detection algorithm was designed to detect bare ground that appeared following the cyclone (McMillan et al. 2023). This analysis was unable to differentiate between disturbance (bare ground) caused by cyclone 'damage' (e.g. slips, deposition) and activities unrelated to the cyclone (e.g. cultivation). Therefore, in their report, McMillan et al. (2023) focused their analysis on steep land where there is little cultivation and where impacts can be more confidently attributed to the cyclone.

The Dragonfly maps show the extent of flooding, slips, and silt deposition separately and were generated using a combination of Sentinel-1 and cloud-free Sentinel-2 satellite imagery. However, few details outlining how these maps were developed are available.[5]

The MWLR map is focused on the Hawke's Bay and Gisborne regions (we restricted our analyses using this map to these regions). The Dragonfly map covers the whole North Island, but we restricted our analyses to the regions along the North Island's northeast coastline that were most affected by the cyclone (Northland, Auckland, Waikato, Bay of Plenty, Gisborne, and Hawke's Bay). Unfortunately, we were unable to incorporate the high-resolution map of landslides produced by GNS Science[6] because it was not available at the time of this analysis.

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[5] But see: https://www.dragonfly.co.nz/work/cyclone-impact-map.html

[6] https://resiliencechallenge.nz/project/rainfall-induced-landslide-forecasting-rapid-assessment-and-hindcasting/ (accessed 20 September 2024).

To assess the spatial extent of cyclone impact on a range of native land-cover types, we intersected the MWLR and Dragonfly maps with several maps describing (primarily) native vegetation cover:

- the Land Cover Database version 5.0 (LCDB5; Manaaki Whenua – Landcare Research 2020) – we quantified impact to areas mapped into the following native woody vegetation classes: Broadleaved Indigenous Hardwoods, Indigenous Forests, and Mānuka and/or Kānuka
- Land Environments of New Zealand (LENZ; Leathwick et al. 2002) – we quantified impact to LENZ Level 1 classes, restricted to areas of native woody vegetation as mapped by LCDB5 (see above)
- EcoSat Forests (North Island; Landcare Research 2014), which is a map of 11 native forest and scrubland classes
- the Protected Areas of New Zealand (Department of Conservation 2023)
- QEII National Trust Covenants (QEII National Trust 2023)
- Freshwater Ecosystems of New Zealand (FENZ) current wetlands layer (Department of Conservation 2010; Ausseil et al. 2011; Leathwick et al. 2012) (note that this layer is c. 16 years old and may not represent the full extent of current wetlands)
- Hawke's Bay Regional Council mapped wetlands (Hawke's Bay Regional Council 2023)
- River Environment Classification, version 2.0 (NIWA 2023c) – this layer was included to look at impacts to areas potentially containing riparian vegetation, which is largely unmapped.

We quantified the total proportion of all mapped areas impacted by the cyclone. To assess impacts depending on land steepness, we also quantified the total proportion impacted over three slope classes: flat (0–7°), moderate (7–20°), and steep (>20°), broadly following the New Zealand Land Use Capability Classification (Lynn et al. 2009) and classified using the LENZ slope spatial layer (Leathwick et al. 2002; McCarthy et al. 2021), resampled to 500 m resolution. The slope analysis was only completed for the MWLR map.

For rivers, impact was assessed at four buffer distances: 0–10 m, 10–50 m, 50–100 m, and 100–500 m. This was to quantify potential impact at a range of distances to waterways to give an indication for how riparian vegetation might have been affected by the cyclone. We also assessed impacts across Strahler stream orders, which specify the level of branching in a river system, with larger numbers indicating rivers further from the source with a greater number of tributaries. For the analysis of rivers, impact might have been overestimated due to activities unrelated to the cyclone being identified in the MWLR and Dragonfly maps, such as cultivation.

All analyses were completed in R 4.4.1 (R Core Team 2024), except for the definition of the river buffers, which was completed in ArcGIS Pro 3.3.0 ('Multi Ring Buffer' tool).

2.1.2 Results

Overall impact on native woody ecosystems was minor, not exceeding 2% of mapped areas for any native woody vegetation type (from LCDB5) in any of the affected regions (Figure 5). Impact was higher in Hawke's Bay than Gisborne, and more extensive in Broadleaved Indigenous Hardwoods and Mānuka and/or Kānuka than in Indigenous Forest (Figure 5A). Impact was primarily due to slips (Figure 5D), with silt deposition and flooding contributing to less than 1% (Figure 5B, C).

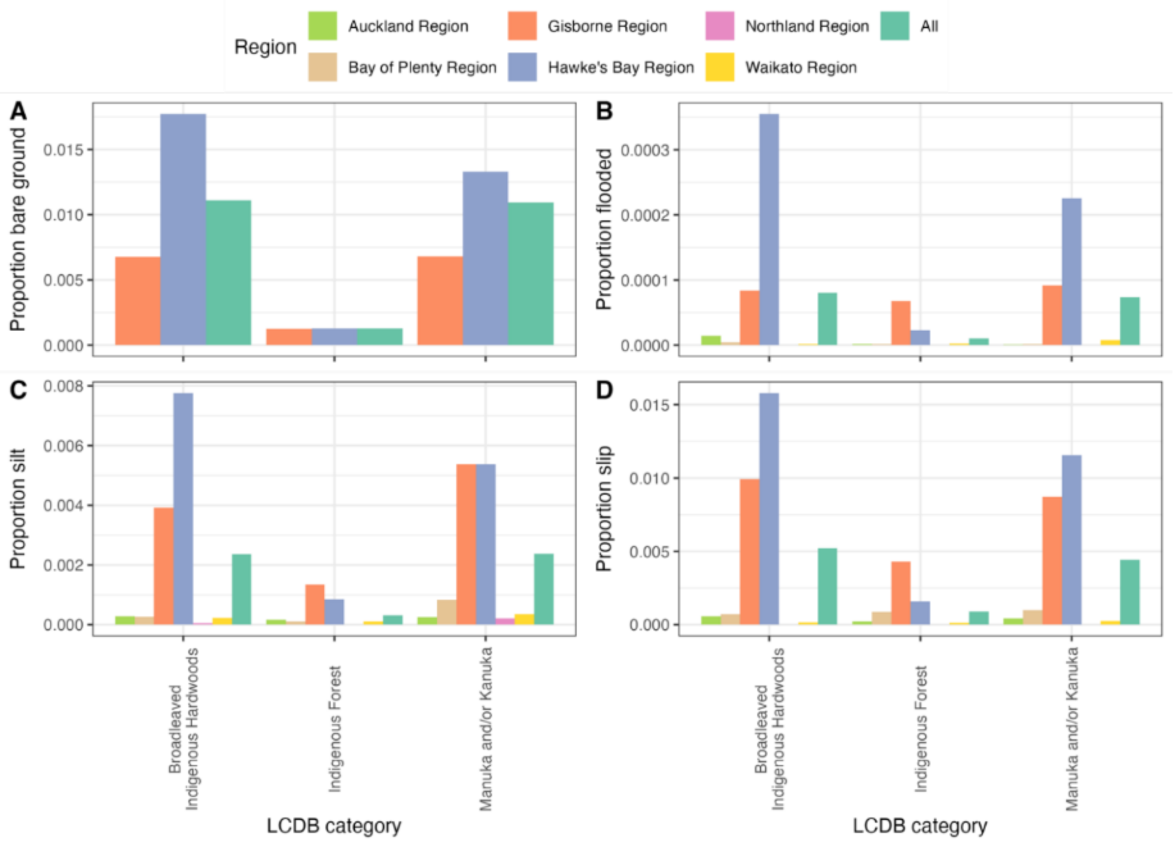


Figure 5. Proportion impact to areas mapped as native woody vegetation in the Land Cover Database (LCDB5; Manaaki Whenua – Landcare Research 2020) across the cyclone-affected regions of the North Island. Cyclone impact is based on two maps: A, the Manaaki Whenua – Landcare Research map (McMillan et al. 2023); and three types of impact (B, flood; C, silt; and D, slip) based on the Dragonfly maps (Dragonfly 2023).

Impact was greatest in the Hawke's Bay and Gisborne regions. Within Hawke's Bay and Gisborne, impact (identified using the MWLR map) in flat areas was close to 2.5% for Broadleaved Indigenous Hardwoods, dropping to just over 1.5% in Mānuka and/or Kānuka and less than 0.5% in Indigenous Forest (Figure 6).

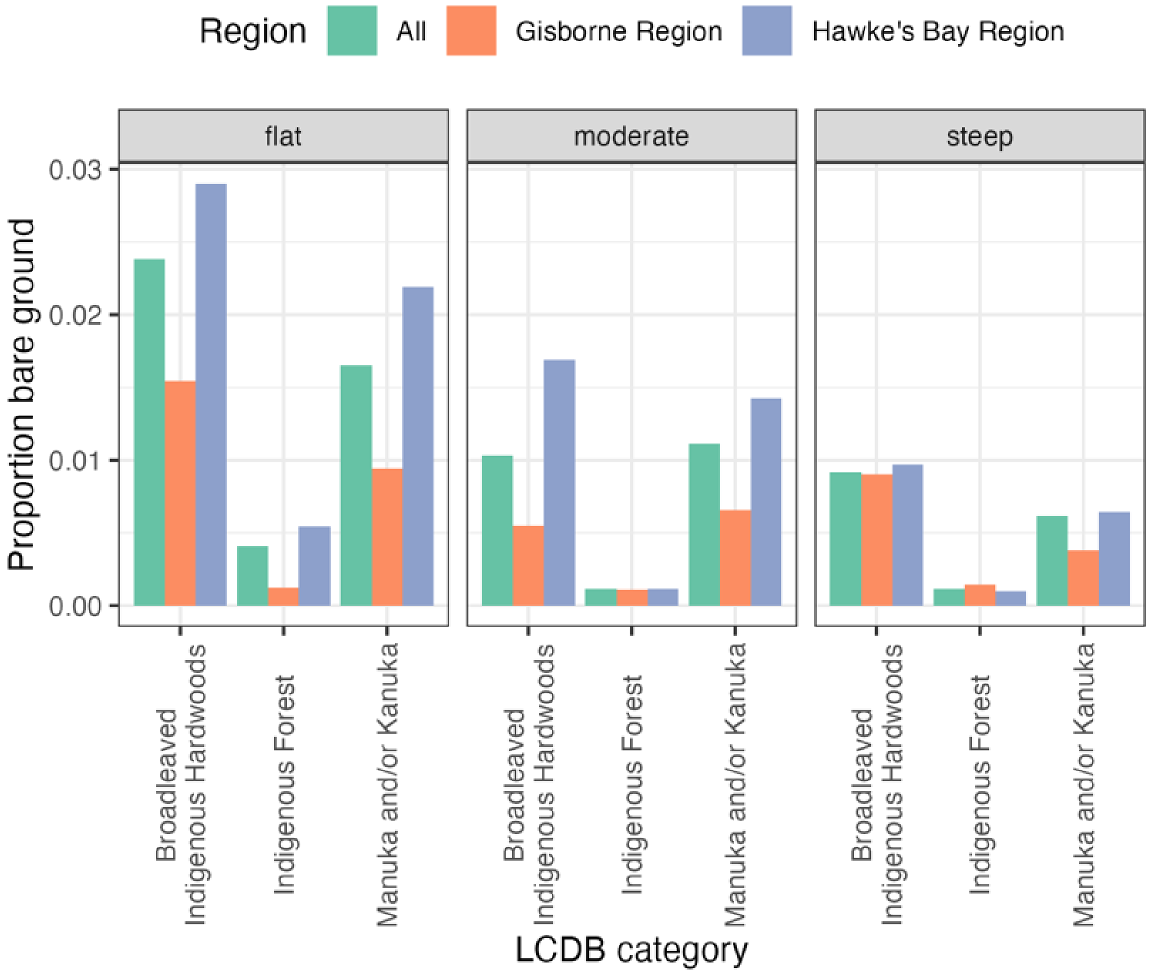


Figure 6. Proportion impact on areas mapped as native woody vegetation in the Land Cover Database (LCDB5; Manaaki Whenua – Landcare Research 2020) across different slope classes. (Cyclone impact is based on the Manaaki Whenua – Landcare Research map: McMillan et al. 2023)

Within areas of native woody vegetation mapped by LCDB5, those in LENZ environments G (Northern recent soils), I (Central poorly drained recent soils), and J (Central well-drained recent soils) had the greatest proportional impact (Appendix 1; Figure A1.1). Impact was greatest in environment I, with close to 20% in Gisborne (Hawke's Bay was close to 10%; Figure A1.1), and was much greater in flat areas (Figure A1.2). In Gisborne this environment is found in the floodplains of the Waipaoa River, and in Hawke's Bay it is found in coastal areas around Napier and Hastings (Leathwick et al. 2003). In steeper areas, impact was greatest in environment G, which is found in the rolling hills of Gisborne (Figure A1.2).

From the EcoSat Forest map, impact as recorded in the MWLR map was greatest in Unspecified Indigenous Forest (Figure A1.3), the primary forest type mapped in the lowlands of Hawke's Bay and Gisborne. Impact was primarily from slips and sediment deposition. Impact was less than 1% for this forest type across all land types (Figure A1.3), but when considering just flat land, impact was just over 1.5% in Hawke's Bay (and just under 1% in Gisborne; Figure A1.2).

Within the Protected Areas of New Zealand, impact was greatest in Marginal Strips, with just over 15% and 10% in Hawke's Bay and Gisborne, respectively (Figure A1.4). Marginal Strips are areas of land protected to maintain adjacent aquatic ecosystems (lakes, wetlands, rivers, or ocean), and public access to these areas. Impact was primarily from slips and sediment deposition, probably resulting from cyclone impacts originating from the adjacent aquatic ecosystems. Impact was highest on flat lands, but was also relatively high in moderate and steep (Hawke's Bay only) slope classes (Figure A1.2). Impact on QEII covenants was highest in Hawke's Bay, with up to 2%, mostly caused by slips (Figure A1.5). Impact was higher on flat land, reducing as steepness increased (Figure A1.2E).

Based on the FENZ wetlands spatial layer and the MWLR map, impact in Gisborne was greatest in bogs, at close to 4% (Figure A1.6A). In Hawke's Bay, marshes, pakihi, seepages, and swamps all received over 4% sediment deposition (Figure A1.6C). There was also around 2% sediment deposition to wetlands in Gisborne (bogs, seepages, swamps) and Waikato (gumlands, swamps). In contrast to other native ecosystem types, impacts were only slightly higher in flat areas than in moderately steep areas (Figure A1.2E), and there were no mapped FENZ wetlands in steep areas.

Impacts on wetlands mapped by Hawke's Bay Regional Council were relatively consistent across all wetland types at around 2–5%, except for bogs and fens, which each received <1% (Figure A1.7A). Impacts to wetlands in Hawke's Bay were primarily a result of silt deposition (i.e. just over 12% for shallow-water wetlands), and flooding (c. 5% for ephemeral wetlands) (Figure A1.7C, D). Impacts were relatively consistent across flat and moderately steep land, with shallow-water wetlands located in the vicinity of steeper land receiving greater impacts (c. 3%; Figure A1.2F). It should be noted, however, that impacts in the case of wetlands could represent, at least in part, the detection of a temporary increase in turbidity from silt deposition following rain events. This report presents a more detailed field analysis of wetland condition following Cyclone Gabrielle in section 3.2.

Impact on land adjacent to rivers was greatest at closest proximity to the river, with just over 5% in Hawke's Bay and Gisborne (Figure 7A), the two regions where cyclone impacts around rivers were greatest (Figure 7B–D). Impacts were primarily a result of silt deposition (Figure 7C), which we also observed in the braided rivers section of this report (section 3.3). Impacts increased with stream order, becoming greater in rivers that result from the confluence of multiple tributaries (Figure 8).

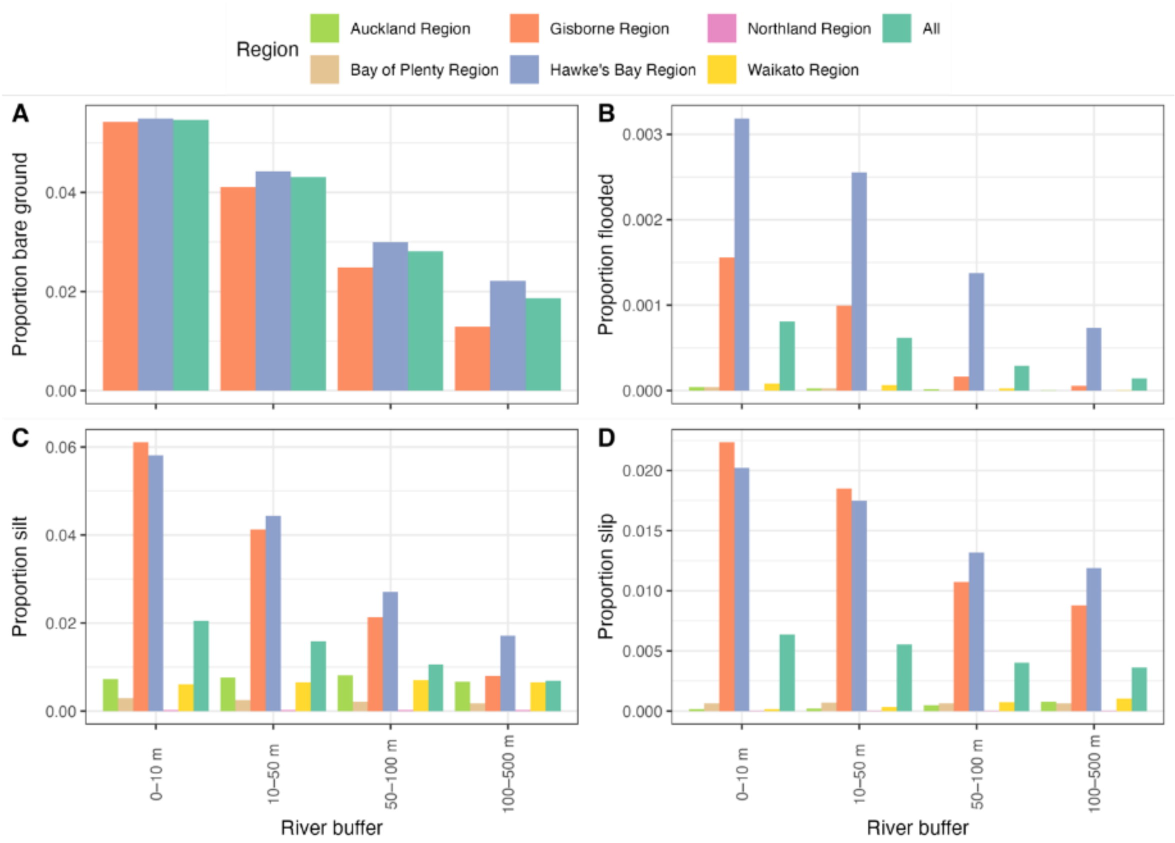


Figure 7. Proportion impact on areas surrounding rivers, as defined by the River Environment Classification (NIWA 2023c), at different distance buffers. Cyclone impact is based on two maps: A, the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact (B, flood; C, silt; and D, slip), based on the Dragonfly maps (Dragonfly 2023).

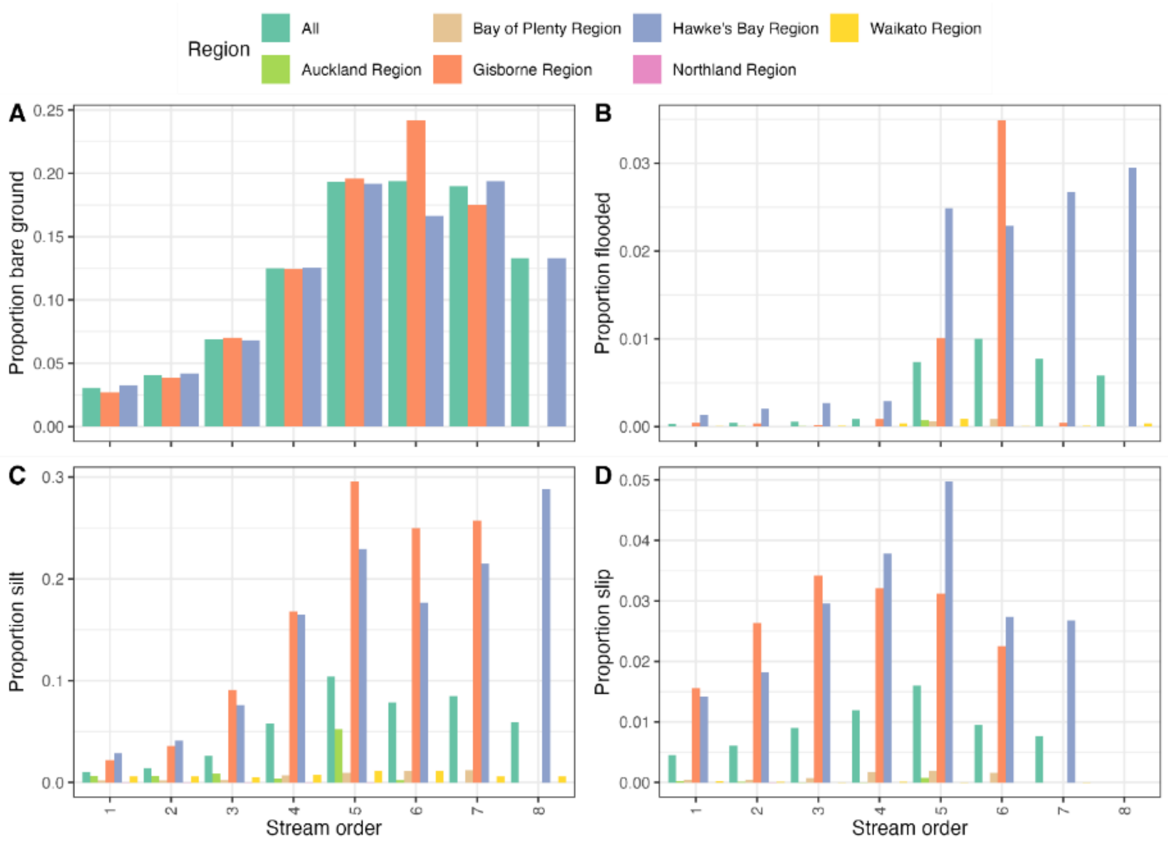


Figure 8. Proportion impact on areas surrounding rivers, as defined by the River Environment Classification (NIWA 2023c), depending on Strahler stream order. Higher stream orders indicate rivers with a greater number of tributaries. Cyclone impact is based on two maps: A, the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact (B, flood; C, silt; and D: slip), based on the Dragonfly maps (Dragonfly 2023).

2.1.3 Conclusions

We found that, while some native ecosystem patches and fragments were severely affected by Cyclone Gabrielle (see sections 3.1, 3.2, 3.3, and 3.4), impacts were relatively restricted overall. However, ecosystem impacts, as measured by satellite imagery, may be underestimated if these are restricted to the understorey and therefore not visible from above. Further, impacts from sustained inundation (i.e. flood-related dieback) may not manifest for several months (or years; see section 3.1) and would therefore not be detected in any of the impact maps used in this exercise.

Areas most affected were those on flatter topography, where deforestation and degradation of lowland forest has already reduced the quantity and quality of native forest cover (e.g. Wilmshurst 1997; Ewers et al. 2006; Burns et al. 2011). Limited impacts on native forests across the Gisborne and Hawke's Bay regions from Cyclone Gabrielle contrast with the extensive damage to native forests along the West Coast of the South Island from Cyclone Ita in 2014 (Platt et al. 2014). In this project, we found that <0.2% of native forest was impacted across the Gisborne and Hawke's Bay regions combined (Figure 5A). In contrast, c. 2.8% of native forest was damaged by Cyclone Ita across the West Coast region (based on values in Table 1 from Platt et al. 2014). This difference reflects how that cyclone manifested as weather on landfall in New Zealand (i.e. wind vs rain) and the large difference in native forest cover between the West Coast of the South Island (>1.4 million ha), and the Gisborne and Hawke's Bay regions (c. 0.5 million ha).

Wetlands received impacts of up to c. 12% in Hawke's Bay, but the long-term impacts of these systems, which commonly receive heightened sediment input following rainfall events, is currently unknown (but see section 3.2). Areas closer to rivers, and surrounding rivers with higher stream orders, received greater impacts from slips and silt deposition. Given the resilience of native forest ecosystems to impacts from Cyclone Gabrielle, retention and restoration of forest ecosystems alongside rivers may increase the resilience of the landscape to the impacts of future cyclones. Detailed records of restoration activities (location, dates, species composition, etc.) will assist in an assessment of the success of riparian revegetation following future extreme weather events.

2.2 Satellite imagery assessment of wind damage to North Island native forest

2.2.1 Introduction and methods

Strong winds are probably the most widespread and frequent disturbance to New Zealand forests (Martin & Ogden 2006; Moore et al. 2013; Moore & Watt 2015). To gain an overview of the extent of wind damage to forest canopies, we derived Normalised Difference Vegetation Index (NDVI) data from the Sentinel-2 satellite data to indicate potential areas where leaf stripping or wind throw occurred. The freely accessible Sentinel-2 data from the European Space Agency (ESA) offer a spatial resolution of 10 m. Although these medium-resolution data are ideal for mapping larger features, detecting changes smaller than 10 m in size can be challenging.

The Sentinel-2 wind damage modelling employed the methods developed for detecting flowering in beech trees (Jolly et al. 2022). The analysis modelled Sentinel-2 NDVI values from February 2017 to immediately before (5 February 2023) Cyclone Gabrielle. This provided inter- and intra-seasonal Sentinel-2 NDVI baselines. Observations immediately after the cyclone event (15 February to 30 April 2023) were compared to the long-term baseline and post-cyclone declines in the NDVI values, and their magnitudes were mapped.

Our expectation was that wind damage to forest would result in post-cyclone NDVI values that deviated from long-term modelling. The analysis was conducted across the whole of the North Island (Figure 4), but was restricted to native vegetation classifications in LCDB5 (Manaaki Whenua – Landcare Research 2020). Some ground-truthing was conducted at Bream Head Scenic Reserve, Northland, and at Aongatete forest, Bay of Plenty.

2.2.2 Results and conclusions

Wind damage at Bream Head resulted in large areas of vegetation 'browning', which was readily detected by the Sentinel-2 analysis (Figure 9). However, the method provided little value for predicting the location of wind damage in Aongatete forest and was unable to detect tree falls mapped by researchers on the ground. We suggest two main reasons for this difference in effectiveness between the two locations.

First, the wind damage observed in Aongatete forest mainly consisted of single wind-thrown trees, meaning it was at a smaller scale than the large extents of wind-damaged trees observed at Bream Head and therefore likely to constitute only part of a 10 m Sentinel-2 pixel. Accordingly, the Sentinel-2 analysis performed well where the extent of damage was large, as can be seen in Figure 10, which presents an example of the more extreme wind throw from the central North Island.

Second, tree falls at Aongatete forest exposed a similarly green understorey, whereas wind damage at Bream Head resulted in canopy discoloration, meaning that the latter damage was more likely to result in significant deviations in NDVI. Therefore, the spatial extent of the damaged area, and the type of damage incurred, are important factors to consider when applying this method in future studies.

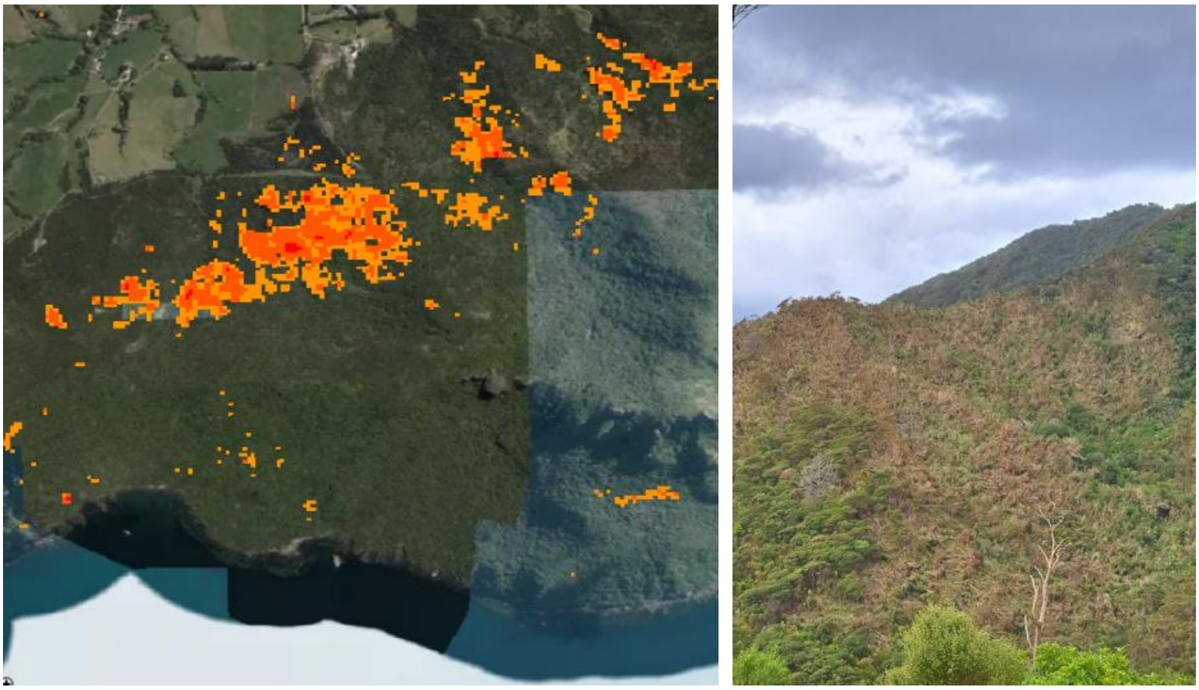


Figure 9. Left: post-cyclone NDVI change indications at Bream Head Scenic Reserve, Northland (Base map imagery CC-BY, Land Information New Zealand 2023). The redder the colour, the greater the deviation in post-cyclone NDVI values compared to the long-term baseline. Right: post-cyclone wind damage to vegetation at Bream Head Scenic Reserve that corresponds to the damage detected by the NDVI analysis. (Photo: Tom Flynn-Plummer)

The methods used in this work were trialled to indicate the potential of the approach. Further work is required to reduce the large amounts of noise and false positives generated by the initial model, including the indication of vegetation loss that was unrelated to wind damage, such as landslides, anthropogenic change, and fluvial erosion. Other sources of error included those induced by atmospheric effects found in the imagery, such as haze and thin cloud, which were not captured in the cloud-masking process. For this model to be effective for future extreme weather events, more research needs to be conducted to decrease its sensitivity to NDVI change that is not related to wind damage.

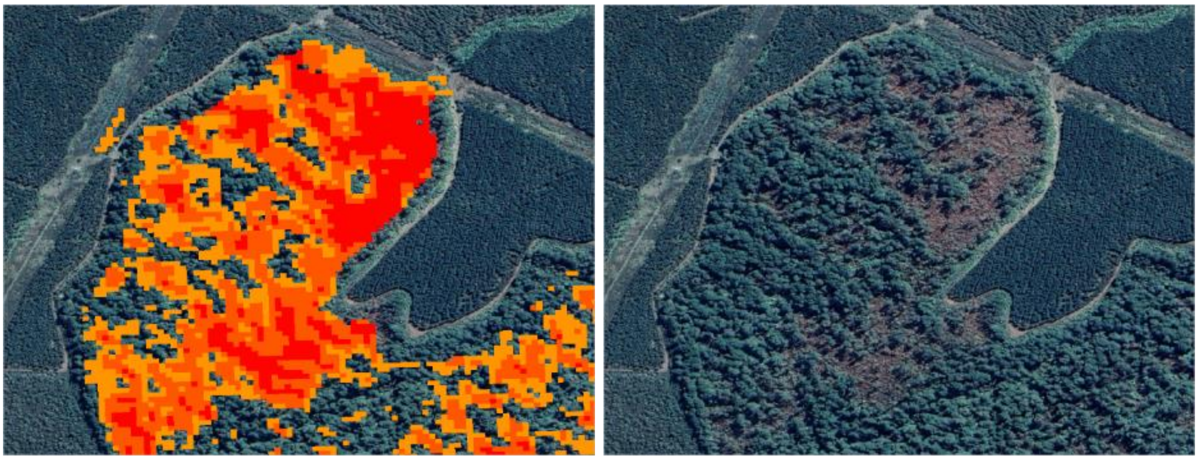


Figure 10. Left: post-cyclone NDVI change indications in native forest east of the Desert Road, central North Island (Base map imagery CC-BY, Land Information New Zealand 2023). The redder the colour, the greater the deviation in post-cyclone NDVI values compared to the long-term baseline. Right: post-cyclone satellite imagery showing the corresponding wind throw in the native forest.

2.3 Field assessment of wind damage to Aongatete forest, Bay of Plenty

2.3.1 Introduction and methods

Aongatete forest in the Kaimai Range, Bay of Plenty, was reported as suffering significant wind damage during Cyclone Gabrielle, with widespread tree fall resulting in the opening of canopy gaps (Helen Saville, Operations Manager for Aongatete Forest Project, pers. comm., October 2023). The installation of 13 permanent forest monitoring plots in 2022 (Mason & Brownstein 2022) represented an opportunity to quantify cyclone wind damage to trees. Trees in these plots with a diameter at breast height greater than 2.5 cm had been tagged, as per standard protocols (Hurst et al. 2022).

We visited Aongatete Forest Project between 31 October and 3 November 2023 and quantified wind damage to tagged trees in the 13 plots established in 2022 (Mason & Brownstein 2022). We categorised wind damage using a scale adapted from Thadani (2023), whereby each tree was assigned a score based on visual estimates of wind damage:

- 0 = no damage: trees that suffered no damage or minor branch breakage
- 1 = branch broken: one or more major branches (>20% of total foliage) broken off
- 2 = bole snapped: main bole snapped, resulting in loss of main leaf-bearing branches
- 3 = tree fallen: entire tree uprooted and prostrate on the ground.

While surveying the 13 plots we also recorded any significant wind damage observed within the forest (e.g. damage scores 2 and 3, resulting in a canopy gap of at least 10 m in any direction).

2.3.2 Results and conclusions

Wind damage was identified from just three of the 13 permanent plots. Six trees were damaged, with four uprooted entirely, one snapped at the bole, and one with a broken major branch (Table 1). These trees accounted for 0.07% (0.41 m^2/ha) of total basal area (563.90 m^2/ha) across the 13 plots.

Outside the plots we recorded 40 significant wind falls that resulted in canopy light gaps (Figure 11). Of the 36 damaged trees that could be identified, 30 (83%) were tawa (*Beilschmiedia tawa*), a dominant canopy tree of the region (Mason & Brownstein 2022). There was also one each of rewarewa (*Knightia excelsa*), rimu (*Dacrydium cupressinum*), kohekohe (*Didymocheton spectabilis*), tānekaha (celery pine, *Phyllocladus trichomanoides*), māmāngi (*Coprosma arborea*), and porokaiwhiri (pigeonwood, *Hedycarya arborea*). The predominant form of wind damage was a snapped bole (69% of damaged trees), then uprooting (23%) and major broken branches (8%).

Finally, we observed the growth of early successional species in canopy gaps associated with old wind falls that occurred several years before Cyclone Gabrielle. These were generally dominated by dense growth of tree ferns, especially ponga (silver fern, *Alsophila tricolor*) and some wheki (rough tree fern, *Dicksonia squarrosa*). We also observed some early successional palatable species such as makomako (wineberry, *Aristotelia serrata*) in these older canopy light gaps, and suggest that these could eventually progress to early canopy dominants with ongoing ungulate management.

Taken together, our findings indicate that wind damage to Aongatete forest was low overall. If remote-sensing approaches (e.g. section 2.2) indicate a large extent of wind damage following future extreme weather events, we suggest that field assessments incorporate a larger network of recently measured permanent plots across a broad spatial scale. This approach would help to improve future predictions of wind damage to different forest types and across a range of site and species characteristics (e.g. Ibanez et al. 2024).

Alternatively, distance sampling of tree falls along transects may be better suited to quantifying the local impacts of wind damage after future cyclone events. Such approaches can also assist with systematic ground-truthing of remote-sensing methods for estimating forest damage and carbon loss after extreme wind (Stas et al. 2022).

Table 1. Wind-damaged trees recorded in 13 surveyed permanent plots at Aongatete forest, Bay of Plenty

Plot	Species	Damage score	Diameter at breast height (cm)	Basal area of plot (%)
8	Kāmahi (*Pterophylla racemosa*)	3 (tree fallen)	41.2	0.538
8	Kāmahi (*Pterophylla racemosa*)	3 (tree fallen)	21.2	0.143
8	Tawa (*Beilschmiedia tawa*)	1 (major branch broken)	3.1	0.003
10	Kāmahi (*Pterophylla racemosa*)	2 (bole snapped)	11.9	0.050
13	Tawa (*Beilschmiedia tawa*)	3 (tree fallen)	14.3	0.047
13	Rewarewa (*Knightia excelsa*)	3 (tree fallen)	15.3	0.053

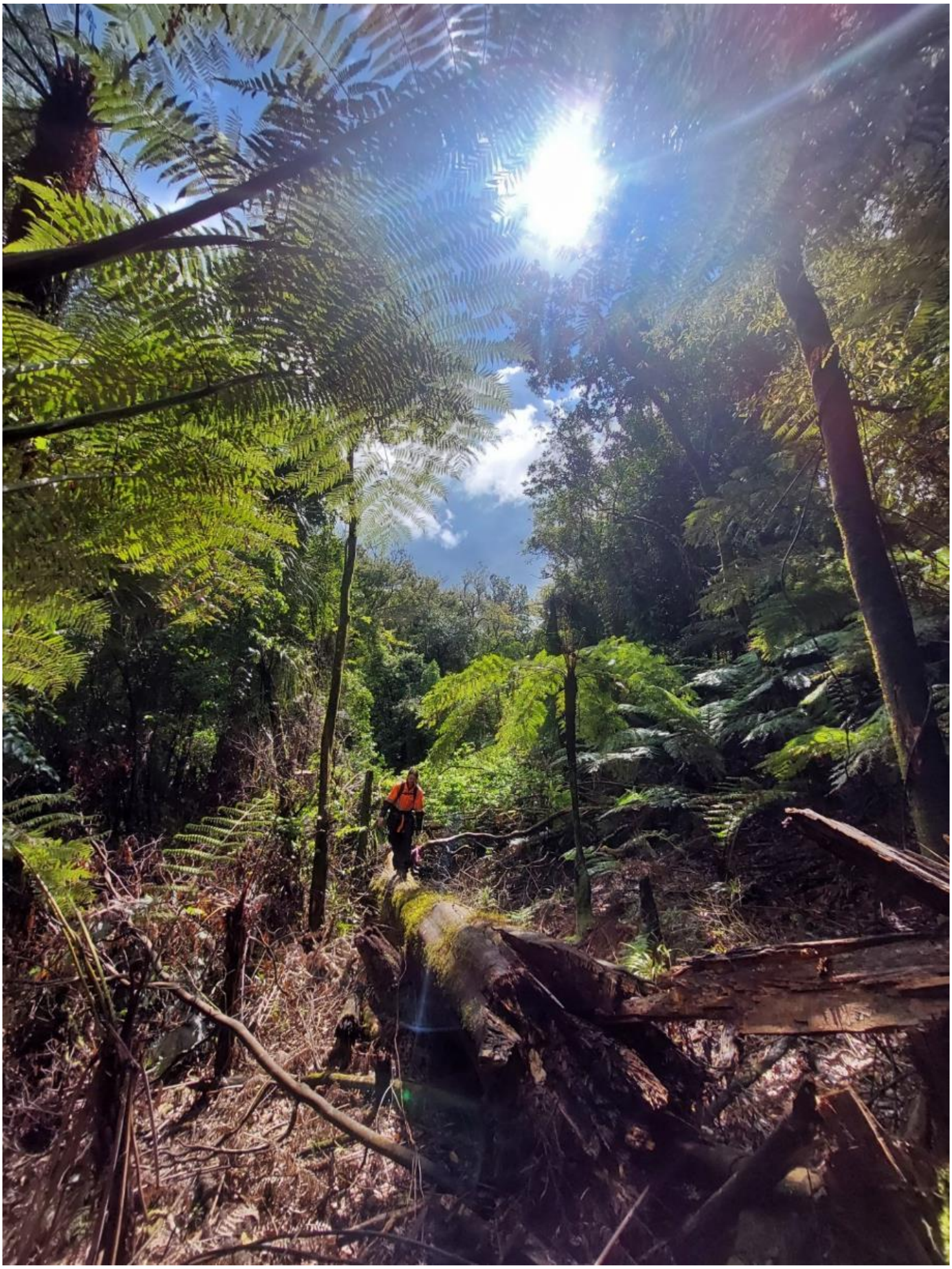


Figure 11. Example of wind fall and resulting canopy light gap at Aongatete forest, Bay of Plenty. (Photo: Warwick Allen)

3 Impacts on naturally uncommon ecosystems and threatened species

3.1 East Coast lowland native forest fragments

3.1.1 Introduction and methods

Hawke’s Bay and Gisborne have few remaining remnants of pre-European lowland forests (Clarkson & Clarkson 1991; MacGillivray 2022). The area was forested before human settlement, shifting to extensive wetland habitat and seral shrublands following Māori burning, then to grasslands after European settlement (McGlone 1978; Wilmshurst 1997). Many of the few remaining forest fragments on the Hawke’s Bay and Gisborne floodplains were affected by Cyclone Gabrielle, with floodwaters washing away the understorey and depositing sediment on the forest floor, in some cases causing tree mortality (Figure 12 and Figure 13).

In addition to the long history of extreme flood events in North Island forests (Martin 2006), more recent pressures such as browsing by feral ungulates and invasion by non-native plants may alter natural forest regeneration processes. Sediment deposition represents another anthropogenic pressure, as land-use change from native forest to more erodible pasture and plantation forest (McMillan et al. 2023) has altered catchment-scale sediment volumes (Wilmshurst 1997; Trustrum et al. 1999).

Redpath and Rapson (2015) previously studied the impacts of a 2004 flood event on tawa (*Beilschmiedia tawa*) in McPherson’s Bush Reserve, Turakina Valley, near Whanganui. They attributed the synchronous mortality of most tawa individuals in flooded areas to prolonged anoxia caused by sediment deposition. High seedling density of tawa and kahikatea (*Dacrycarpus dacrydioides*) was also observed post-flood, but recruitment was poor due to disturbance-facilitated invasion of non-native plants such as *Tradescantia fluminensis* and *Holcus lanatus*. In general, kahikatea is adapted to disturbance, especially on mineral soils such as those that predominate the alluvial floodplain of Gisborne (Duncan 1993; Ebbett & Ogden 1998; Lusk et al. 2009).

Ultimately, the intensity and scale of the flood event will determine the nature of the disturbance and microsites available for vegetation recovery (Duncan 1993). These could become invaded by non-native plants, some of which may be transient, but others may persist and alter the forest successional trajectory (Murphy et al. 2008). It also remains unclear how post-disturbance forest regeneration is influenced by herbivorous mammals, including domestic stock and feral ungulates such as deer and goats. If post-cyclone mortality of mature trees is high and regeneration is altered by invasive plants and herbivores (Wright et al. 2012; Richardson et al. 2014; Allen et al. 2023), then we may suffer the gradual further loss of the few remaining lowland forest fragments in the Hawke’s Bay and Gisborne regions.

We took a two-step approach to better understand the immediate impacts of the cyclone and what it means for the future of these lowland sites. First, we conducted a rapid qualitative assessment of cyclone impacts on six Hawke’s Bay lowland forest fragments, which were all DOC scenic reserves. Observations were conducted along main walking tracks, with 45 to 90 minutes spent in each reserve. Signs of flooding, deposition, landslides, and wind damage from Cyclone Gabrielle were recorded. We observed mostly minor cyclone impacts across the forest fragments (Appendix 2; Table A2.1).

Second, to inform the management of lowland forest fragments we installed permanent monitoring plots at 19 sites in Gisborne. In these plots we will continue to evaluate the impacts of Cyclone Gabrielle, characterise the plant communities that have established after disturbance, and assess whether forest recovery may be improved through management such as fencing and non-native plant removal. By monitoring lowland forest fragments across a gradient of cyclone impacts and management intensity we aimed to answer the following research questions:

- How was the vegetation of lowland podocarp forest fragments affected by Cyclone Gabrielle?
- Does fencing improve outcomes for post-disturbance forest recovery?

Figure 12. Remnant kahikatea (*Dacrycarpus dacrydioides*) forest beside the Hangaroa River, Gisborne, which was severely flooded during Cyclone Gabrielle, showing signs of dieback. This photo was taken on 6 November 2023 and all pictured trees are now dead. (Photo: Malcolm Rutherford)

Figure 13. Remnant mataī (*Prumnopitys taxifolia*) forest beside the Hangaroa River, Gisborne. Signs of flooding were still evident over 18 months after Cyclone Gabrielle, including flattened saplings, hanging debris, and dieback of small trees. However, regeneration was occurring in this stock-fenced site, including seedlings of highly palatable māhoe (*Melicytus ramiflorus*). (Photo: Warwick Allen)

We established 41 permanent monitoring plots across 19 study sites between 26 August and 5 September 2024 (Figure 14). All study sites were fragments of remnant lowland native podocarp forest on the alluvial floodplain between Wairoa in northern Hawke's Bay and Ruatoria in Gisborne, dominated by kahikatea and mataī, with tītoki (*Alectryon excelsus*), tawa, pukatea (*Laurelia novae-zelandiae*), and karaka (*Corynocarpus laevigatus*) as other canopy dominants. Sites were selected to vary along gradients of cyclone impacts (from no impacts to severe flooding and sediment deposition) and mammalian herbivore protection (unfenced to deer-fenced).

In each forest fragment we established two to three permanent 20 × 20 m monitoring plots (Hurst et al. 2022). In each plot we measured cyclone severity and impacts (e.g. sediment depth, height of flood debris, tree mortality, canopy density), characterised the plant community (e.g. plant species identity and percentage cover across different height tiers), and quantified the potential for forest regeneration (e.g. seed bank composition, seedling and sapling counts, signs of mammalian browsers). The frequency and abundance of bird species was also assessed using 5-minute bird counts (Dawson & Bull 1975; Hartley 2012). These data will be used for future analyses that assess cyclone impacts and forest regeneration potential in more detail.

For the purposes of the data presented below, we measured sediment depth at five locations in the plot, arranged in a quincunx design. A spade was used to expose the soil profile, and the depth of the uppermost sediment layer was measured. Where discoverable, the maximum height of flood debris (e.g. sediment and plant material deposited on standing vegetation) was measured at up to five locations around each plot. The number of saplings (i.e. trees taller than 1.35 m with diameter at breast height less than 2.5 cm) of each tree species were tallied in each plot. We categorised tree dieback by assigning each tree a score based on visual estimates of tree health:

- 0 = healthy: no obvious signs of stress
- 1 = unhealthy: clear but localised signs of stress or dieback
- 2 = almost dead: widespread stress or dieback, <10% foliage left alive
- 3 = recently dead: likely post-cyclone death based on lack of wood decay or presence of dead leaves and small twigs
- 4 = decay underway: likely died before the cyclone.

For analyses, we removed trees with a dieback score of 4 because they were dead before the cyclone. Data were summarised at the plot level by calculating mean sediment depth, flood height, and dieback scores for all trees combined and dominant tree species. The sapling data was subset to include only native tree species, the main contributors to native forest regeneration. To test the relationships between tree dieback scores and cyclone impact (i.e. sediment depth and flood height), we used a series of linear mixed-effect models with tree dieback score as the response variable and sediment depth or flood height as the explanatory variable. Forest fragment was included as a random effect to control for non-independence of plots from the same fragment. To test whether native sapling density differed between plots in fenced and unfenced forest fragments, we used a generalised linear mixed-effects model with a Poisson error distribution, sapling number as the response variable, plot fencing status (fenced, unfenced) as the explanatory variable, and a random effect for forest fragment to control for non-independence of plots from the same fragment.

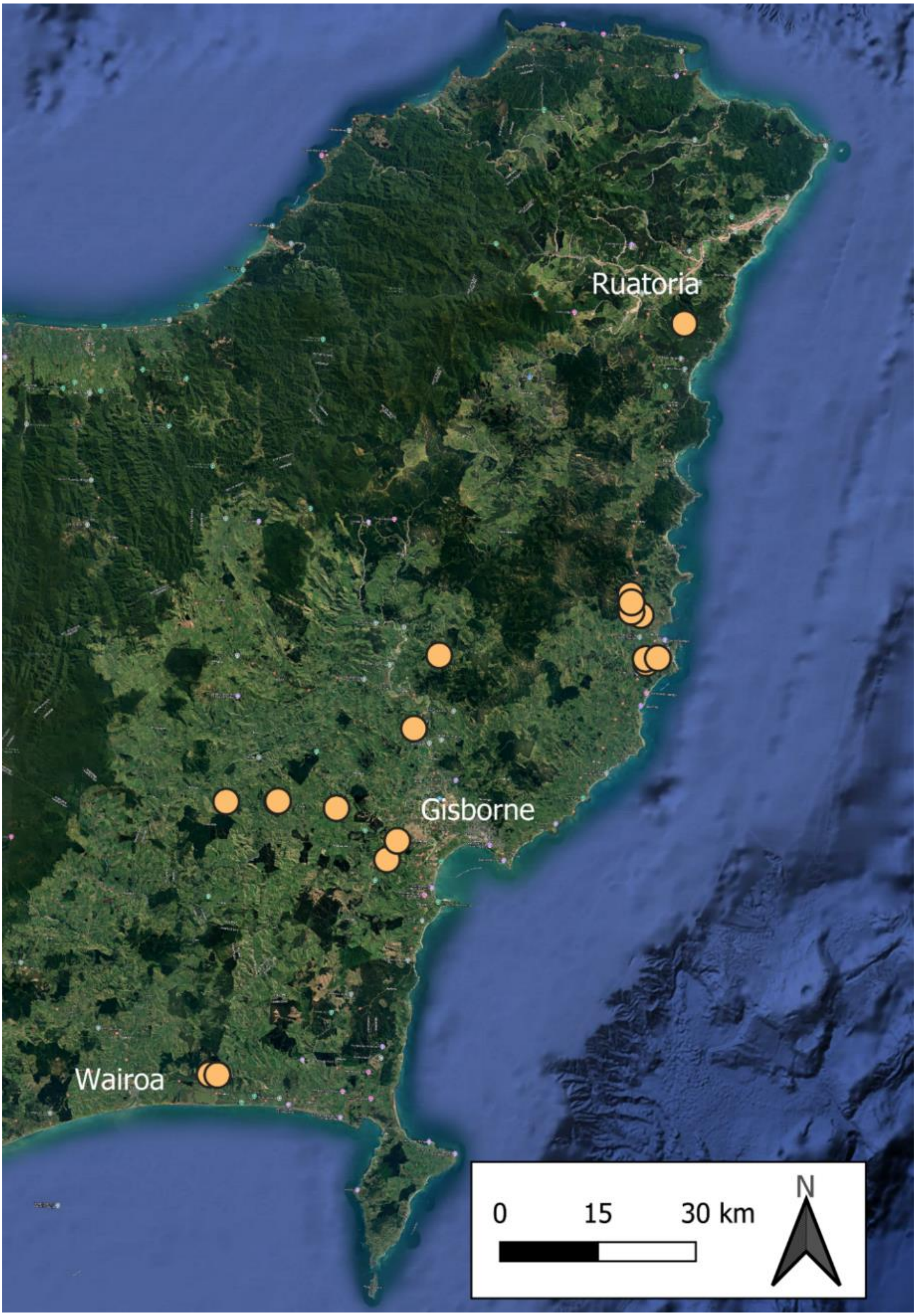


Figure 14. Map showing the 19 study sites where permanent monitoring plots were installed to measure cyclone impacts and recovery of lowland forest.

3.1.2 Results

The maximum sediment depth observed was 66 cm and averaged 7 ± 2 cm (mean ± 1 standard error) across all plots. Flood debris was detected up to 4.10 m above the ground at a site beside the Hangaroa River and averaged 0.67 ± 0.16 m across all plots.

Overall tree dieback (i.e. averaged across all trees within a plot) increased in sites with deeper sediment deposition ($P < 0.001$; Figure 15A) but not flood height ($P = 0.144$; Figure 16A), suggesting that high sediment deposition after flooding may be a greater threat to the persistence of lowland forests than the initial flood event. Dominant tree species varied slightly in their degree of susceptibility to sediment deposition, but all suffered increasing dieback with greater sediment depth (all $P < 0.006$; Figure 15B-F). In contrast, flood height was only related to dieback for some tree species (Figure 16B-F). Tawa, pukatea, and karaka were all susceptible to both sediment deposition and flooding (all $P < 0.018$; Figure 15D-F and 16D-F, respectively), whereas kahikatea and mataī showed some tolerance to flooding (both $P > 0.308$; Figure 156B-C).

Tawa appeared to be the species that was most susceptible to flooding and sediment deposition, suffering from dieback even at low levels of cyclone impact. This pattern could be a result of the unusually high volume of rain in the year leading up to Cyclone Gabrielle (Harrington et al. 2023). Tawa dieback was observed in sites that were unaffected by the cyclone but that had a high water table and saturated soils (Malcolm Rutherford, pers. comm., October 2024). Interestingly, tawa was also the species that was worst-affected by wind damage at Aongatete forest (section 2.3).

Unfenced sites with stock access had almost no forest regeneration occurring, with some plots containing zero saplings. Plots in fenced forest fragments had four times more native saplings than unfenced plots ($P < 0.001$; Figure 17). However, we observed that plots in fenced sites tended to be invaded by non-native plants, including *Tradescantia*, Japanese honeysuckle, hawthorn, and privet (Figure 18).

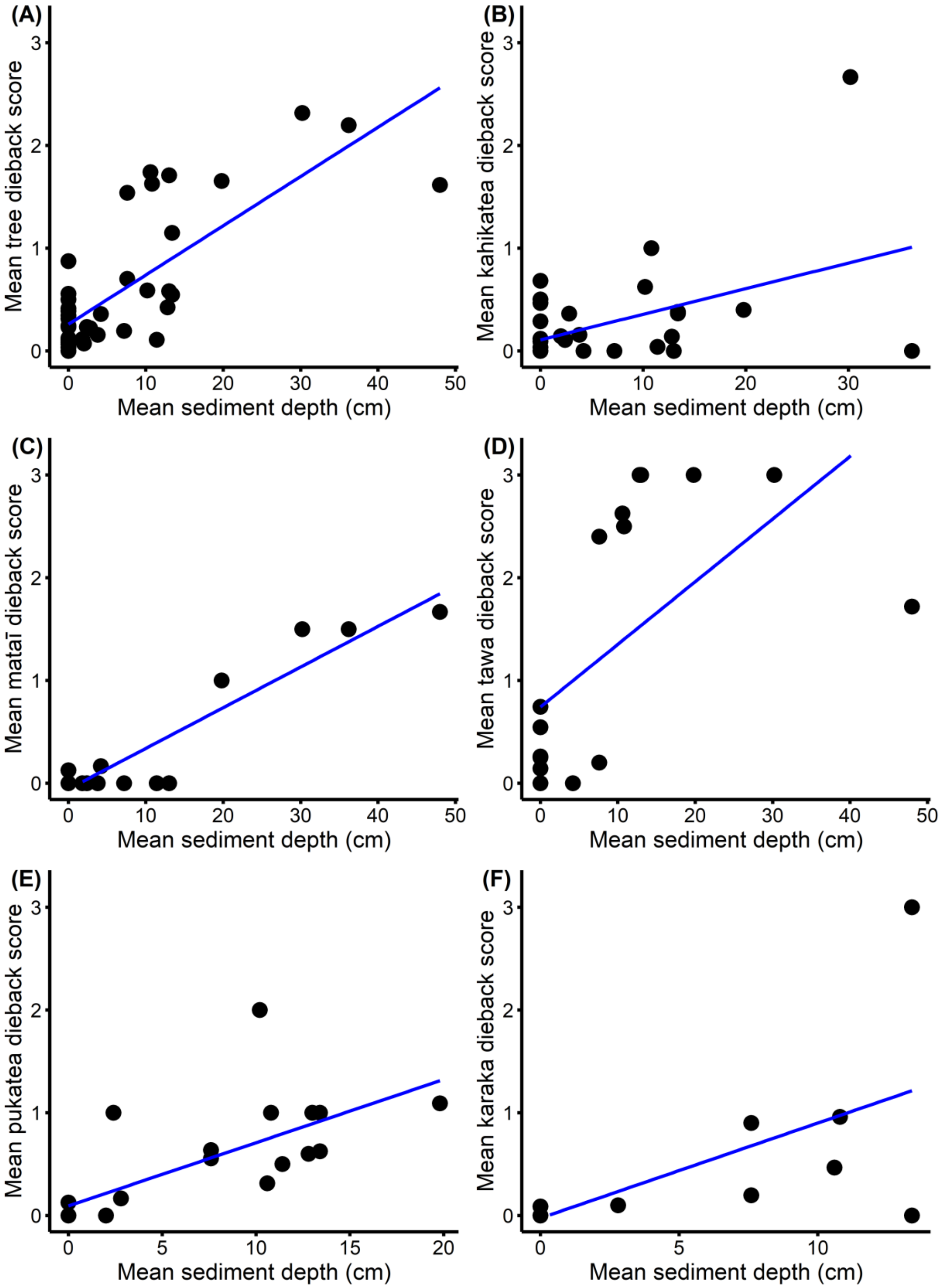


Figure 15. Average dieback score of trees in Gisborne lowland native forest fragment plots along a gradient of sediment depth after Cyclone Gabrielle: A, overall average for all trees; B, kahikatea; C, matai; D, tawa; E, pukatea; and F, karaka.

Note: Solid lines represent significant relationships ($P < 0.05$) and were fitted by least-squares regression.

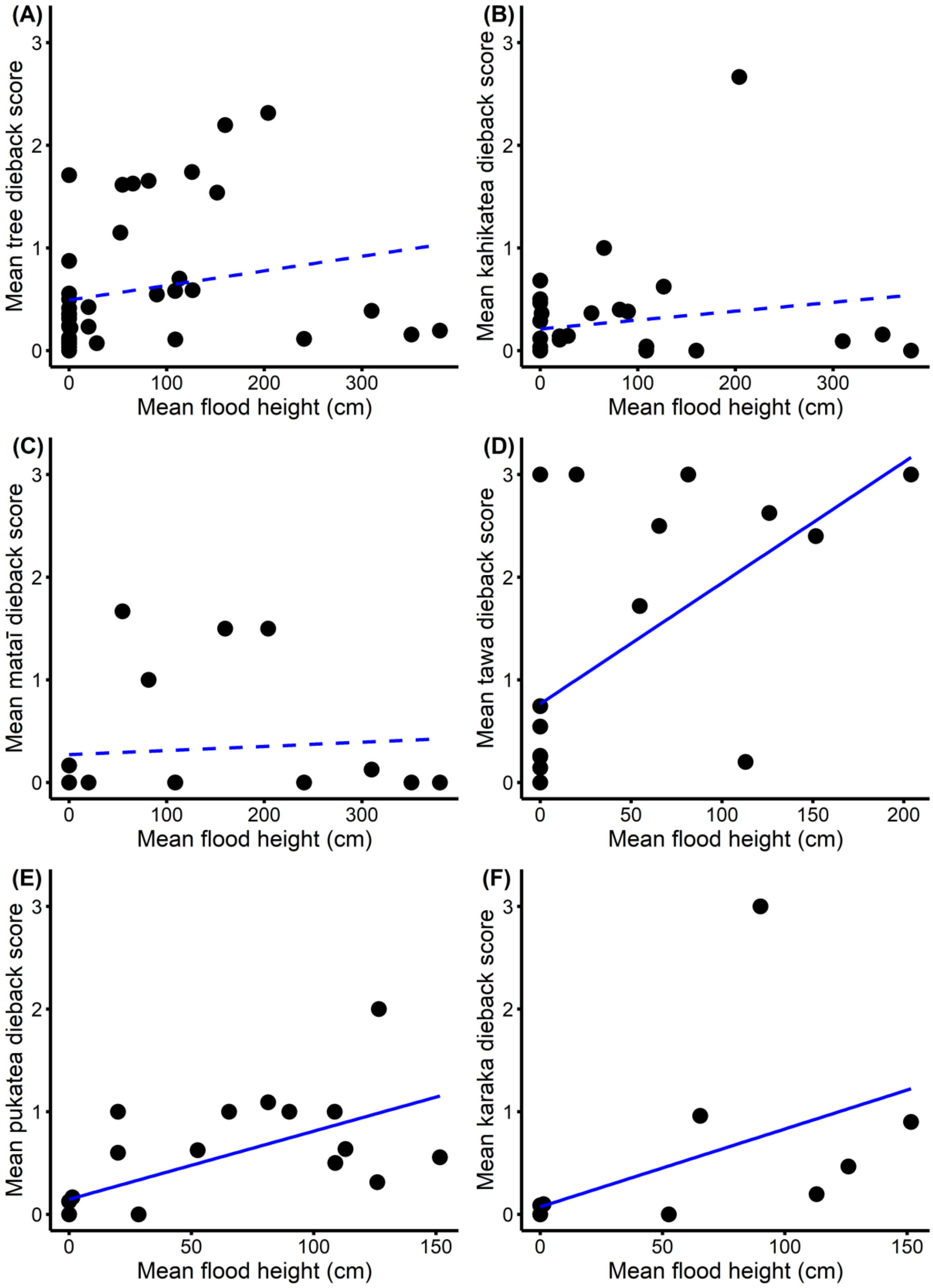


Figure 16. Average dieback score of dominant tree species in Gisborne lowland native forest fragment plots along a gradient of flood height after Cyclone Gabrielle: A, overall average for all trees; B, kahikatea; C, matai; D, tawa; E, pukatea; and F, karaka.

Notes: Solid and dashed lines represent significant (*P* < 0.05) and non-significant (*P* > 0.05) relationships, respectively. Lines were fitted by least-squares regression.

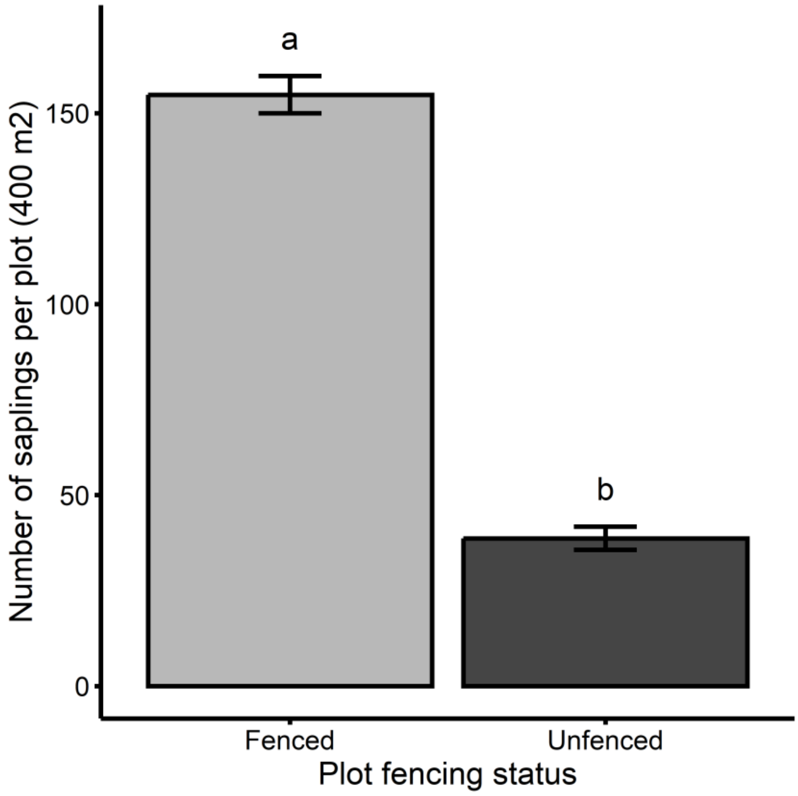


Figure 17. Mean (± 95% CI) native sapling density from plots in fenced and unfenced lowland native forest fragments in Gisborne Region.

Notes: Different lowercase letters indicate a significant difference ($P < 0.05$) between mean native sapling density.

Figure 18. A fenced lowland forest fragment in Tolaga Bay, Gisborne, that was not affected by Cyclone Gabrielle. The canopy is dominated by native trees, including kahikatea (*Dacrycarpus dacrydioides*), tītoki (*Alectryon excelsus*), pukatea (*Laurelia novae-zelandiae*), and tawa (*Beilschmiedia tawa*), but the understorey is smothered by a dense carpet of invasive *Tradescantia fluminensis*, which may inhibit forest regeneration following disturbance. (Photo: Warwick Allen)

3.1.3 Discussion

Flooding, erosion, and sediment deposition are natural geomorphic processes that simultaneously destroy and renew New Zealand lowland forest ecosystems. Sediment deposition deprives tree roots of oxygen, and we found that this phenomenon caused stress, dieback, and mortality to vegetation in many of the remaining lowland native forest fragments that we visited in the Gisborne Region. We found that tree dieback generally increased with sediment depth, which may help with the prioritisation of sites for managing forest regeneration.

This type of large-scale disturbance creates opportunities for recruitment from the seedbank and release of previously light-limited seedlings and saplings. Many native trees are adapted to this type of disturbance regime, with dense seedlings of recently recruited native trees found in some of our study sites. However, these and native tree saplings only occurred at reasonable densities in sites where stock access was prevented through fencing, indicating that domesticated and feral mammalian browsers may alter, delay, or entirely prevent post-disturbance regeneration (Richardson et al. 2014). Furthermore, we observed that fenced sites were often invaded by non-native plants, which also enjoyed release from mammalian browsers. Therefore, land managers should realise that fencing alone will not be enough to reinstate regeneration (Morales et al. 2016), and that invasive plant management may be needed to improve forest regeneration outcomes.

Similar impacts on lowland forest were reported from other regions. Tōtara Reserve Regional Park, Manawatū-Whanganui, received extensive flooding and sediment deposition from the Pohangina River (section 3.5), affecting almost the full extent of tōtara and mataī forest ('WF2' according to the Singers and Rogers 2014 ecosystem classification) left at the reserve and in the catchment (Lorraine Cook, Horizons Regional Council, pers. comm. September 2024; Figure 19). Floodwaters inundated the understorey and deposited large amounts of sediment and non-native plants, which may or may not establish. The river also destroyed almost the full extent of the hebe, wharariki flaxland/rockland (CL6; Singers & Rogers 2014) cliff ecosystem within the reserve (Figure 19), although there are probably other areas elsewhere along the river.

Martiniello et al. (2024) conducted a similar study to ours in riparian rainforest along the subtropical coast of eastern Australia after two consecutive major flood events in March 2022. They found that smaller woody plants were the most affected by flooding, but that the riparian rainforest exhibited high overall resilience to flooding. Finally, our results parallel those of a study conducted on gravel ridge shrublands at Birdlings Flat, near Christchurch, where plant communities exist in states of either 'grazed with no regeneration' or 'fenced and invaded' (Sarah Richardson, pers. comm., September 2024).

The analyses presented in this report represent a first step towards quantifying regeneration potential for these lowland forest fragments. A soil seed bank experiment is currently being conducted to characterise the potential plant community of each forest fragment, while a deeper analysis of the plot data could reveal patterns in regeneration potential across different height tiers, size classes, and plant palatability to mammalian browsers. Furthermore, formal analysis of vegetation composition and structure will provide further insight into invasion by non-native plant species across the range of management approaches. We plan to revisit these plots after 5–10 years to assess any long-term cyclone impacts and to examine how forest recovery is progressing compared to the potential plant community (from seedling and soil seed bank data) and under different management regimes.

3.1.4 Conclusions and recommendations

Here we present answers to our original research questions and provide recommendations for the management of, and future research on, extreme weather impacts on lowland forests.

Conclusions

- How was the vegetation of lowland podocarp forest fragments affected by Cyclone Gabrielle?

Tree dieback consistently increased in sites with deeper sediment deposition but less so with flood height, suggesting that high sediment loading in flood events may be the greater threat to lowland forests. Dominant tree species varied in their susceptibility to sediment deposition and flooding.

- Does fencing improve outcomes for post-disturbance forest recovery?

Unfenced sites with stock access had almost no forest regeneration occurring, while fenced sites generally had more regeneration, but were sometimes invaded by non-native plants.

Recommendations

- Fence lowland forest fragments to limit stock and ungulate access, promoting regeneration.
- Monitor for non-native plant invasions and act swiftly prevent the establishment and spread of new and existing invasive species.

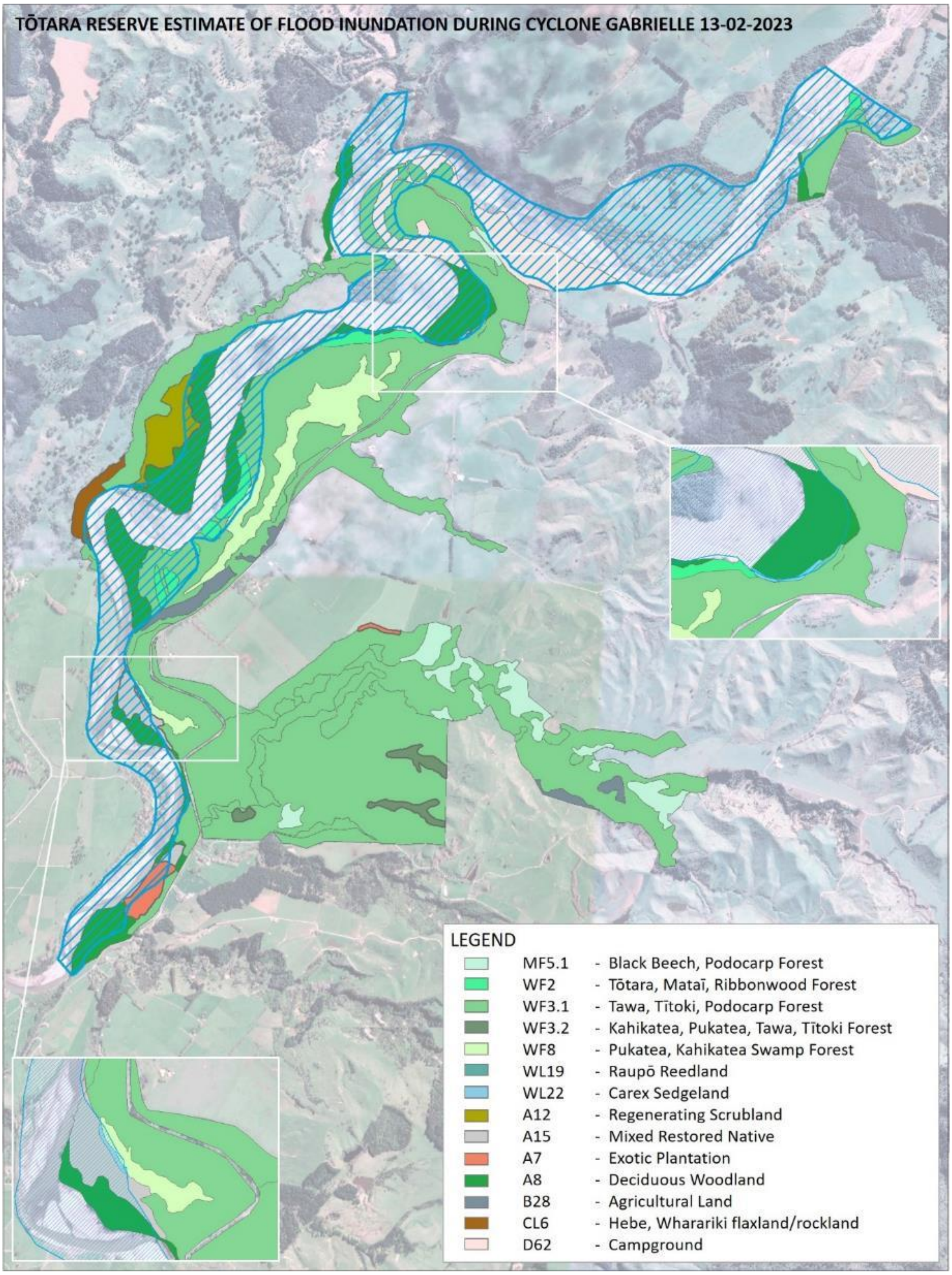


Figure 19. Map showing the estimated areas of flood inundation after Cyclone Gabrielle for different vegetation types at Tōtara Reserve Regional Park, Pohangina Valley, Manawatū-Whanganui. (Source: reproduced with permission from Horizons Regional Council)

3.2 Hawke’s Bay and Auckland wetlands

3.2.1 Introduction

The extent and condition of New Zealand freshwater wetlands have declined significantly since the arrival of humans. More than 90% of wetland area has been lost, with degradation ongoing through drainage, nutrient inputs, and impacts of invasive species (MfE & StatsNZ 2015; Burge et al. 2023).

Auckland and Hawke’s Bay have each lost over 95% of their historical wetlands (Auckland Regional Council 2010; Hashiba & Wu 2020), and those remaining are subject to multiple stressors, including extreme weather events such as tropical cyclones. In 2010 and 2015, respectively, Auckland Council and Hawke’s Bay Regional Council (HBRC) started long-term SoE monitoring programmes to track the state and trend of 52 and 43 freshwater wetlands in their respective regions (Hashiba 2017). These wetlands were selected to represent a random sample of wetland types, baseline conditions, and geographical spread (Clarkson et al. 2004; Clarkson & Bartlam 2017).

Part of the SoE monitoring programme involves measuring the Wetland Condition Index and the Wetland Pressure Index (Clarkson et al. 2004; Clarkson et al. 2014; Clarkson & Bartlam 2017). These indices are semi-quantitative metrics comprising several ecological indicators relating to the major threats and stressors known to degrade wetlands.

The Wetland Condition Index could be considered a measure of wetland ecological integrity (Burge 2024), and its indicators are hydrological integrity, physico-chemical parameters, ecosystem intactness, browsing and predation, and dominance of native plants. These indicators are broken down into components, which are each scored from 0 to 5 against an assumed baseline state before European settlement, when large-scale wetland modification and loss began. The average score across components is calculated for each indicator, and these are summed to give a score out of 25 (high scores indicate good condition).

The Wetland Pressure Index assesses the potential threats to wetlands in the surrounding landscape. Its indicators are modifications to catchment hydrology, water quality decline in catchment, ungulates, lagomorphs and possums, predators, key undesirable plant species, percent of catchment in introduced vegetation, and wetland isolation. Each indicator is given a score of 0 to 5 and the average is taken to give a score out of 5 (high scores indicate strong pressure). Scores for both indices are informed through the full wetland monitoring process of classification and delineation of vegetation types, field reconnaissance, establishment of permanent plots, and field and laboratory measurements (Clarkson & Sorrell 2018).

These long-term SoE monitoring data provide a vital pre-cyclone baseline that can be used to quantify the impacts of Cyclone Gabrielle and associated weather events on wetland condition and pressures in the Auckland and Hawke’s Bay regions. We aimed to answer the following research questions:

- How did Cyclone Gabrielle affect wetland condition and pressures indices?
- Which indicators and components of the wetland condition and pressures indices were affected?

- Did observed changes in wetland condition and pressure indices depend on wetland type, elevation, or land tenure?

3.2.2 Methods

In Auckland the most recent pre-cyclone surveys for each wetland were conducted from 2017 to 2023, between the months of February and April (Figure 20Figure 20, some sites not shown to protect landowner privacy). Post-cyclone surveys were conducted during two periods: 16 sites were surveyed immediately after Cyclone Hale (from 7 February 2023), which severely affected the Auckland Region, and another 36 sites were surveyed between January and March 2024.

In Hawke's Bay the most recent pre-cyclone surveys were conducted between June 2016 (Tukituki catchment), February and March of 2018 (TANK catchment: Tutaekuri, Ahuriri, Ngaruroro, Karamu), and 2020 (MWE catchment: Mohaka, Wairoa, Esk). To capture perishable data from an unbiased sample of wetlands, we conducted post-cyclone surveys at 27 wetlands, including all SoE wetlands in the TANK (13) and MWE (11) catchments, and another three wetlands in the Tukituki catchment (Figure 21). These catchments were selected for resurveying because they held the most recent pre-cyclone data. The wetlands were visited between May 2023 and May 2024. Some surveys were delayed on multiple occasions by difficulties with site access due to standing water or debris, even months after the cyclone.

At each wetland we collected data to quantify wetland condition and pressure indices, plant diversity and composition, and soil and foliar nutrient status (following the wetland monitoring methods outlined in detail in Clarkson et al. 2004, Clarkson et al. 2014, and Clarkson & Bartlam 2017. Briefly, wetland condition and pressure indices were estimated using the methods described above, while vegetation composition and soil and foliar nutrients were measured in established permanent plots. Although Auckland Council and HBRC both followed the overall approach outlined in the Wetland Condition Index and Wetland Pressure Index manuals, each council used slightly different sets of criteria, which means data sets cannot be combined or directly compared. Also, water-level data were obtained from Hawke's Bay wetlands using HOBO U20 water-level data loggers.

To examine the impacts of Cyclone Gabrielle on the Wetland Condition Index, Wetland Pressure Index, and their various indicators and components, we used a series of paired t-tests to compare data from pre- and post-cyclone surveys. To examine how wetland condition and pressure indices, and their pre- vs post-cyclone change, varied with wetland type, elevation, and land tenure, we used linear regression models. All analyses were implemented in R version 4.4.1 (R Core Team 2024).

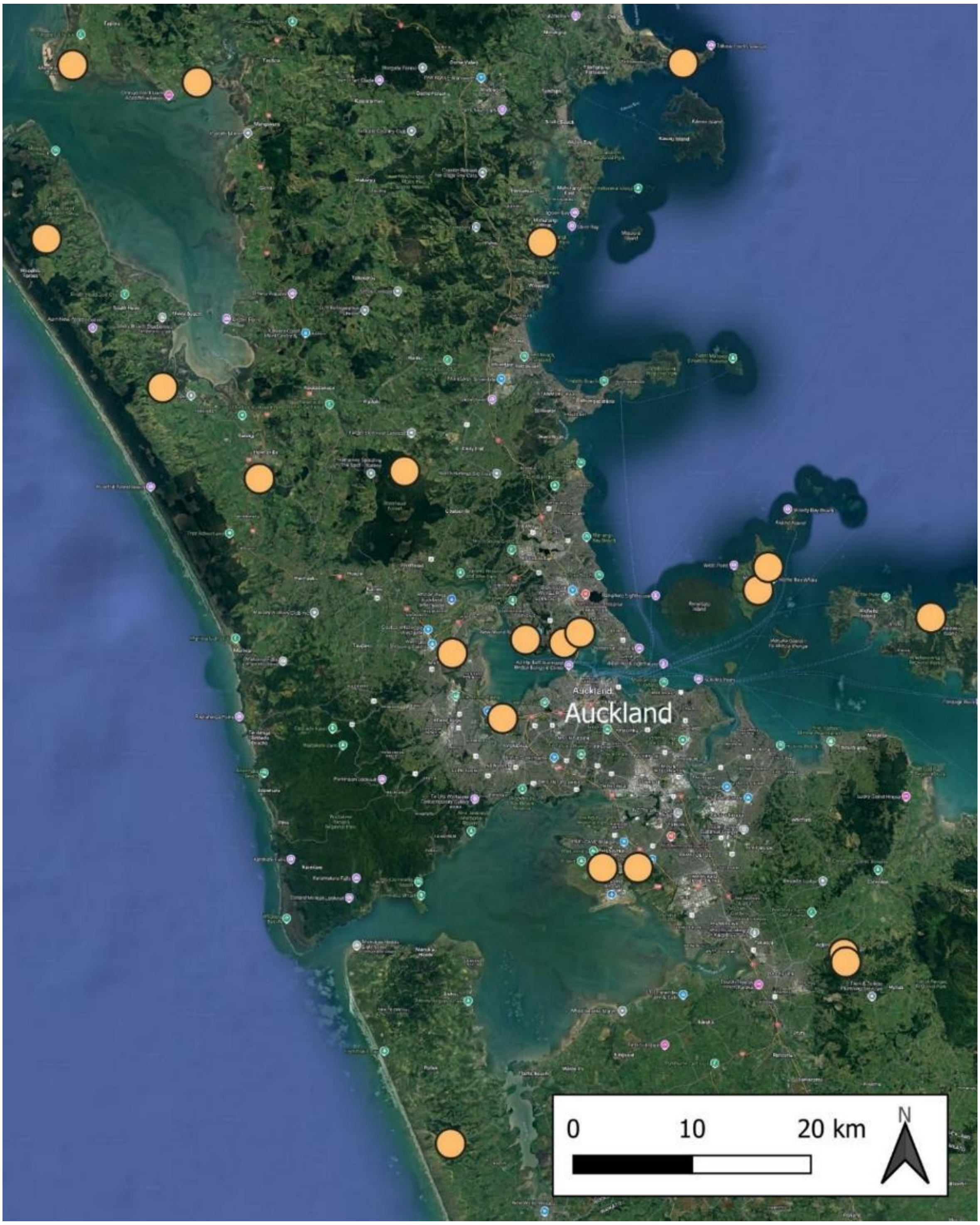


Figure 20. Map showing the 21 Auckland wetlands on public land that were resurveyed after Cyclones Hale and Gabrielle.

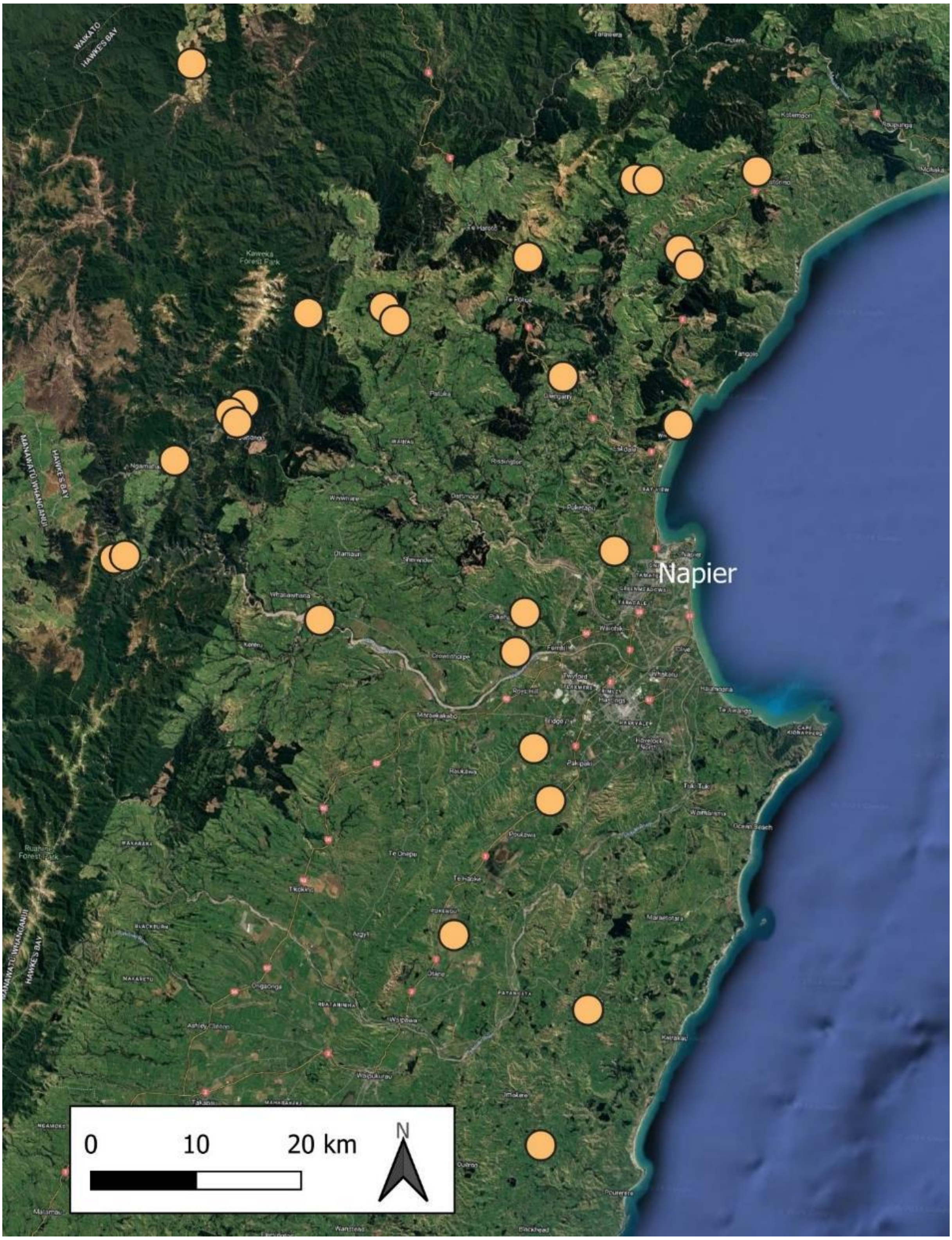


Figure 21. Map showing the 27 Hawke’s Bay wetlands that were resurveyed after Cyclone Gabrielle.

3.2.3 Results

Water-level logger data revealed that wetlands took on large volumes of water during Cyclones Hale and Gabrielle (Figure 22). Some wetlands remained flooded several months after the cyclones (Figure 23).

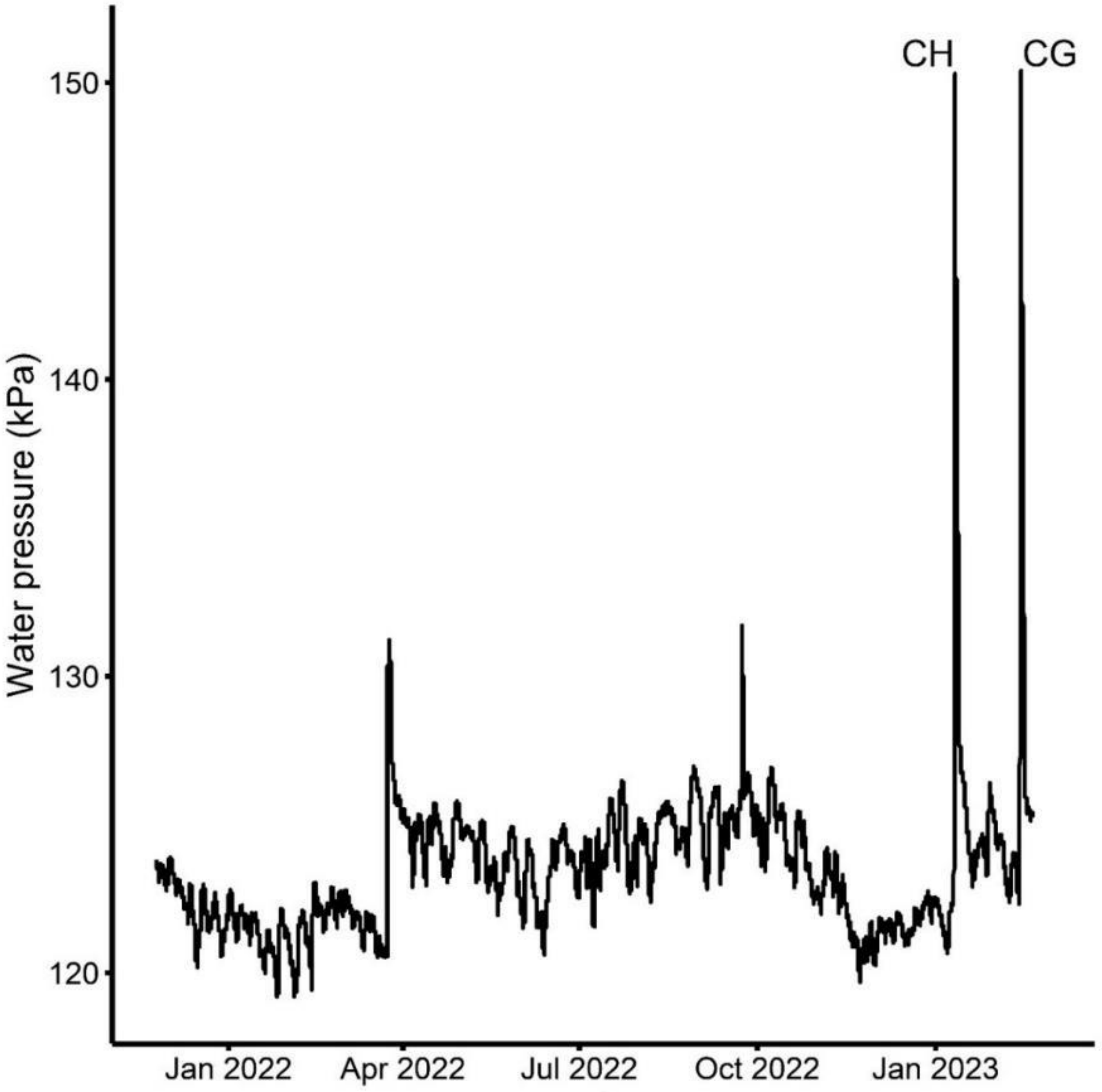


Figure 22. Water-level logger data from a floodplain wetland near Elsthorpe, Hawke's Bay, showing two large spikes in water pressure that correspond to Cyclone Hale (CH) and Cyclone Gabrielle (CG).

Figure 23. Example of a high-elevation, high-condition wetland near the Kaweka Ranges, Hawke's Bay, with flooding still evident over 6 months after Cyclone Gabrielle. (Photo: Warwick Allen)

Auckland

In Auckland, the mean Wetland Condition Index did not differ between surveys conducted before and after the extreme weather events of early 2023 (Figure 24A). Also, wetland condition scores and the change in Wetland Condition Index between pre- and post-cyclone surveys (i.e. post-cyclone condition minus pre-cyclone condition) were unrelated to wetland elevation or land tenure type (private vs public). Sample sizes were insufficient to test for differences among wetland types (i.e. there were 45 swamps, three marshes, and single replicates of saltmarsh, seepage, shallow water, and ephemeral wetlands). No wetland condition indicators were affected by the cyclone (Figure 25A), and the only component that differed between pre- and post-cyclone surveys was a reduction in flora and fauna harvesting levels (Figure 26A), which was unrelated to Cyclone Gabrielle or other extreme weather events.

The mean Wetland Pressure Index also did not differ between pre- and post-cyclone surveys (Figure 27A), and the change in this index between pre- and post-cyclone surveys (i.e. post-cyclone pressure minus pre-cyclone pressure) was also unrelated to wetland elevation or land tenure type. However, pre- and post-cyclone wetland pressures were 26% and 23% higher, respectively, for private compared to public wetlands. Pre- and post-cyclone wetland condition was not related to wetland elevation. Some individual wetland pressure indicators differed between the pre-cyclone and post-cyclone surveys (Figure 28A); specifically, pressure from key undesirable plants and poor water quality both increased, while pressure from wetland isolation declined.

Hawke's Bay

In Hawke's Bay the mean Wetland Condition Index declined after the cyclone at 21 sites and increased at six sites, with an overall decline of 4%, from a mean of 16.5 (out of 25) to 15.7 (Figure 24B). The change in Wetland Condition Index between pre- and post-cyclone surveys (i.e. post-cyclone condition minus pre-cyclone condition) was unrelated to wetland elevation or wetland type (bog, fen, swamp, marsh). Wetland condition was higher at high elevations both before and after the cyclone (Appendix 3; Figure A3.1), while wetland pressure showed the opposite trend (Figure A3.1). Post-cyclone wetland condition differed among wetland types, with swamps having an average condition index 22% higher than that of marshes. Sample sizes were insufficient to test for differences among wetland land tenure types.

Drilling down into the various wetland condition indicators and components, we found that the overall decline in condition was driven by a lower score for physico-chemical parameters (Figure 25B). Specifically, sedimentation, vegetation damage/clearance, and introduced predator impacts all scored worse in post-cyclone surveys compared to pre-cyclone surveys (Figure 26B). This corresponds to the analysis of impacts on wetlands based on spatial layers, which found relatively consistent sediment deposition to mapped Hawke's Bay wetlands at around 2–5% cover (section 2.1).

The mean Wetland Pressure Index did not differ between pre- and post-cyclone surveys (Figure 27B) and the change in this index between pre- and post-cyclone surveys was unrelated to wetland elevation or type. No wetland pressure indicators differed between pre- and post-cyclone surveys (Figure 28B).

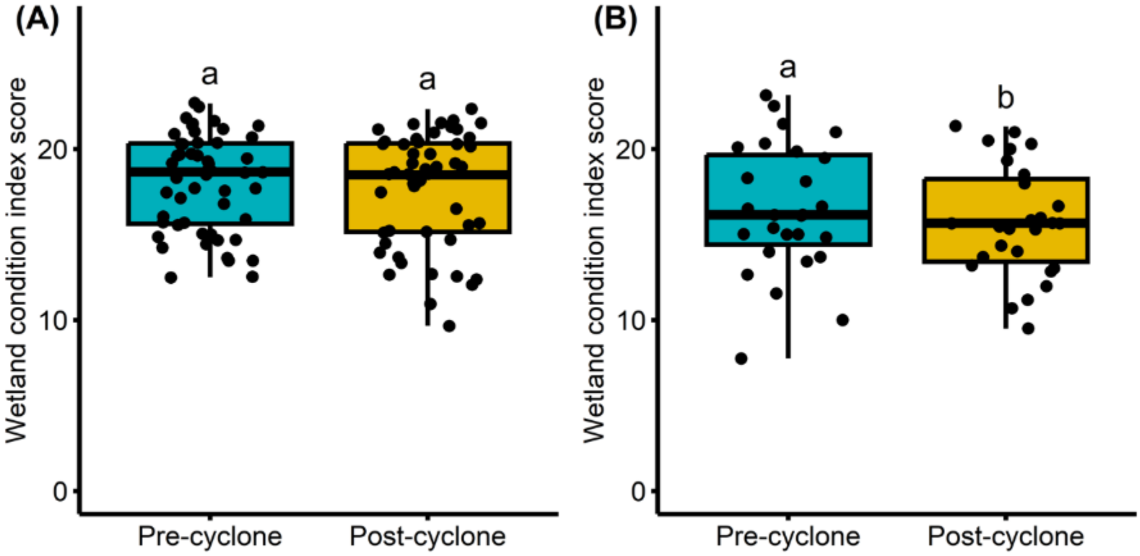


Figure 24. Box plots of Wetland Condition Index scores for Auckland (A) and Hawke's Bay (B) wetlands before and after Cyclone Gabrielle.

Notes: Boxes show the interquartile range, from the first to third quartile, with the slightly thicker line in the middle representing the median. Whiskers indicate variability outside the interquartile range, and points show the raw data. Different lowercase letters indicate a significant difference ($P < 0.05$ using paired t-test) between mean pre- and post-cyclone wetland condition index.

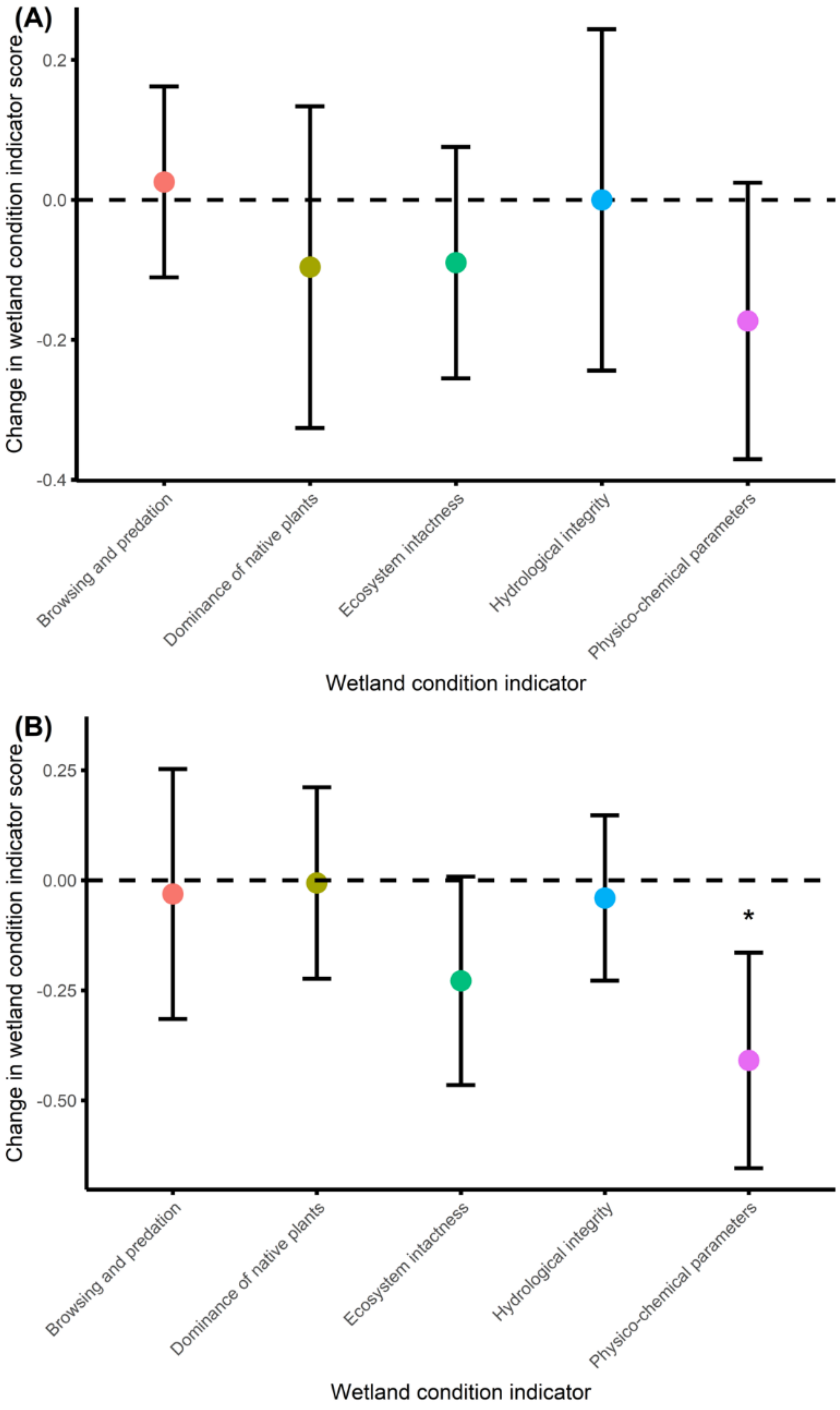


Figure 25. Mean (± 95% confidence interval) change in wetland condition score for the different indicators that combine to make up the overall Wetland Condition Index.

Notes: positive values represent improved wetland condition, negative values represent a decline in wetland condition, and the dashed line at zero represents no change in wetland condition. An asterisk (*) denotes indicators where the mean change in wetland condition score was significantly different from zero (*P* < 0.05 using paired t-tests).

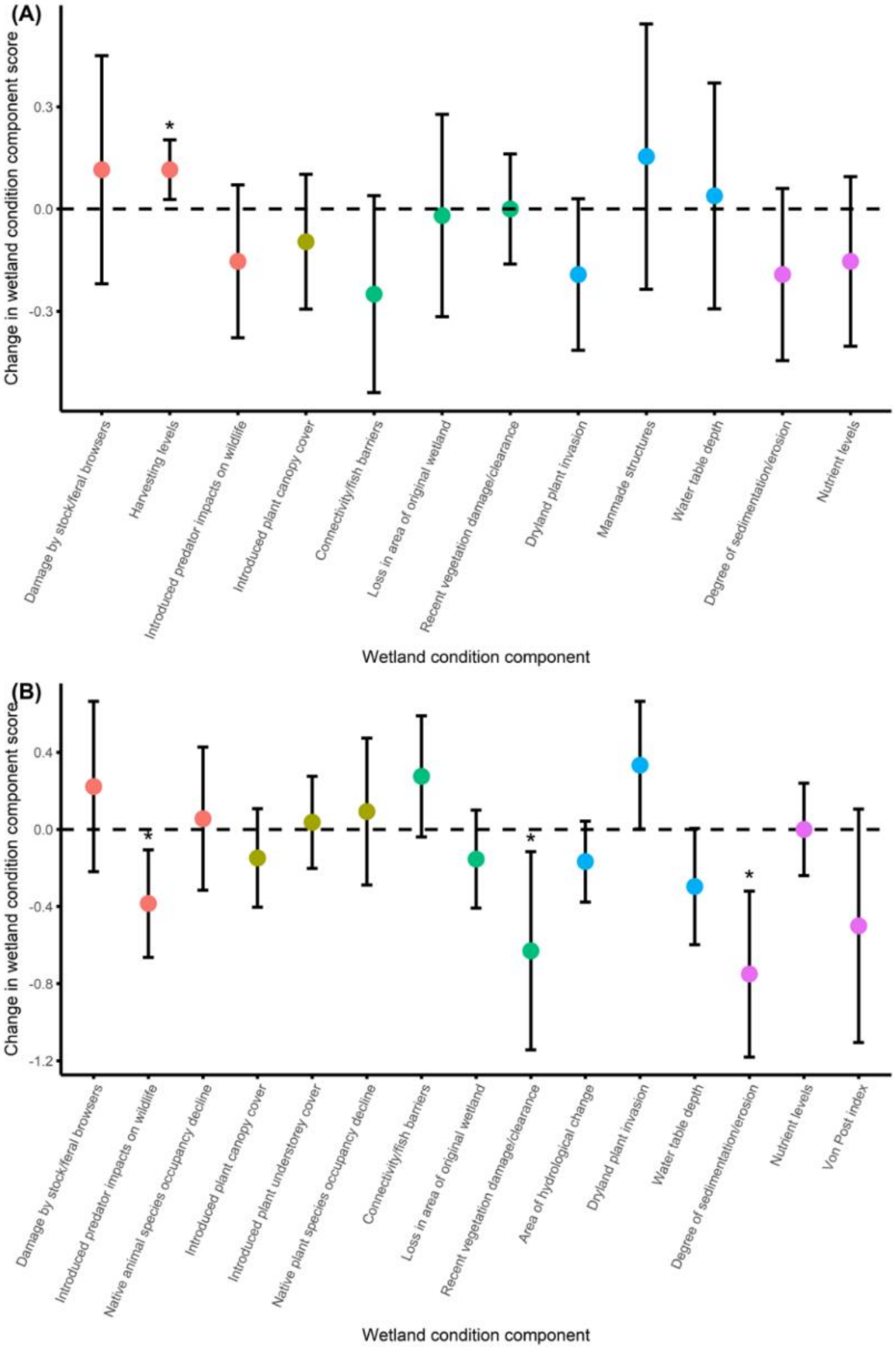


Figure 26. Mean (± 95% confidence interval) change in Wetland Condition Index score for the different components that make up each indicator in Auckland (A) and Hawke's Bay (B), wetlands before and after Cyclone Gabrielle.

Notes: symbol colours correspond to the wetland condition indicator that each component contributes to, as shown in Figure 25 above (e.g. green symbols represent components of the ecosystem intactness indicator). Positive values represent improved wetland condition, negative values represent a decline in wetland condition, and the dashed line at zero represents no change in wetland condition. An asterisk (*) denotes components where the mean change in condition score was significantly different from zero ($P < 0.05$ using paired t-tests).

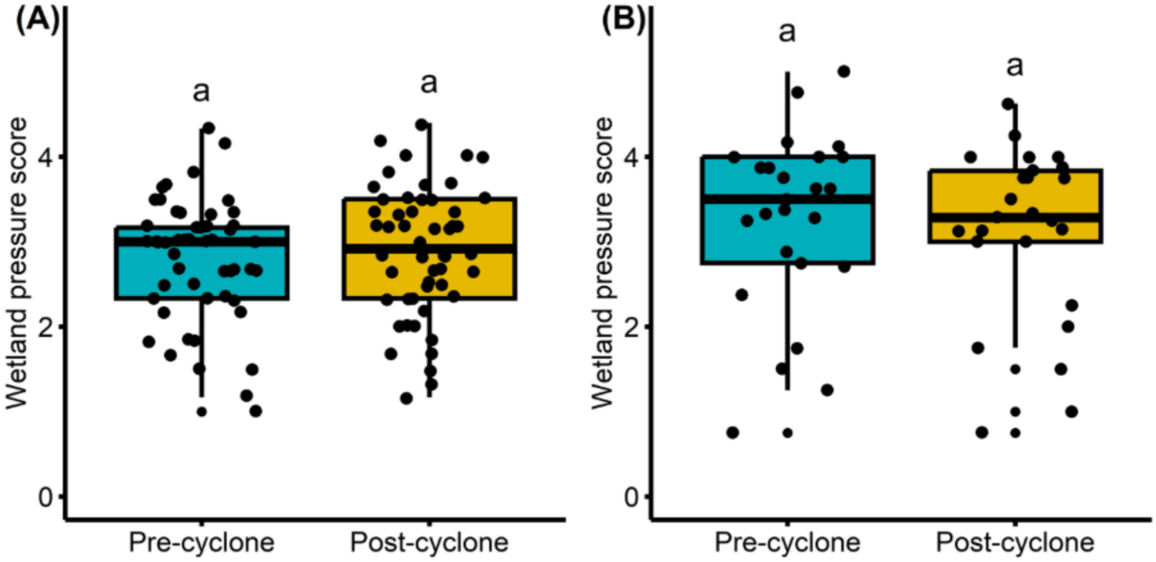


Figure 27. Box plots of Wetland Pressure Index scores for Auckland (A) and Hawke's Bay (B) wetlands before and after Cyclone Gabrielle.

Notes: Boxes show the interquartile range, from the first to third quartile, with the slightly thicker line in the middle representing the median. Whiskers indicate variability outside the interquartile range and points show the raw data. Identical lowercase letters indicate the lack of a significant difference (*P* > 0.05 using paired t-test) between mean pre- and post-cyclone Wetland Pressure Index.

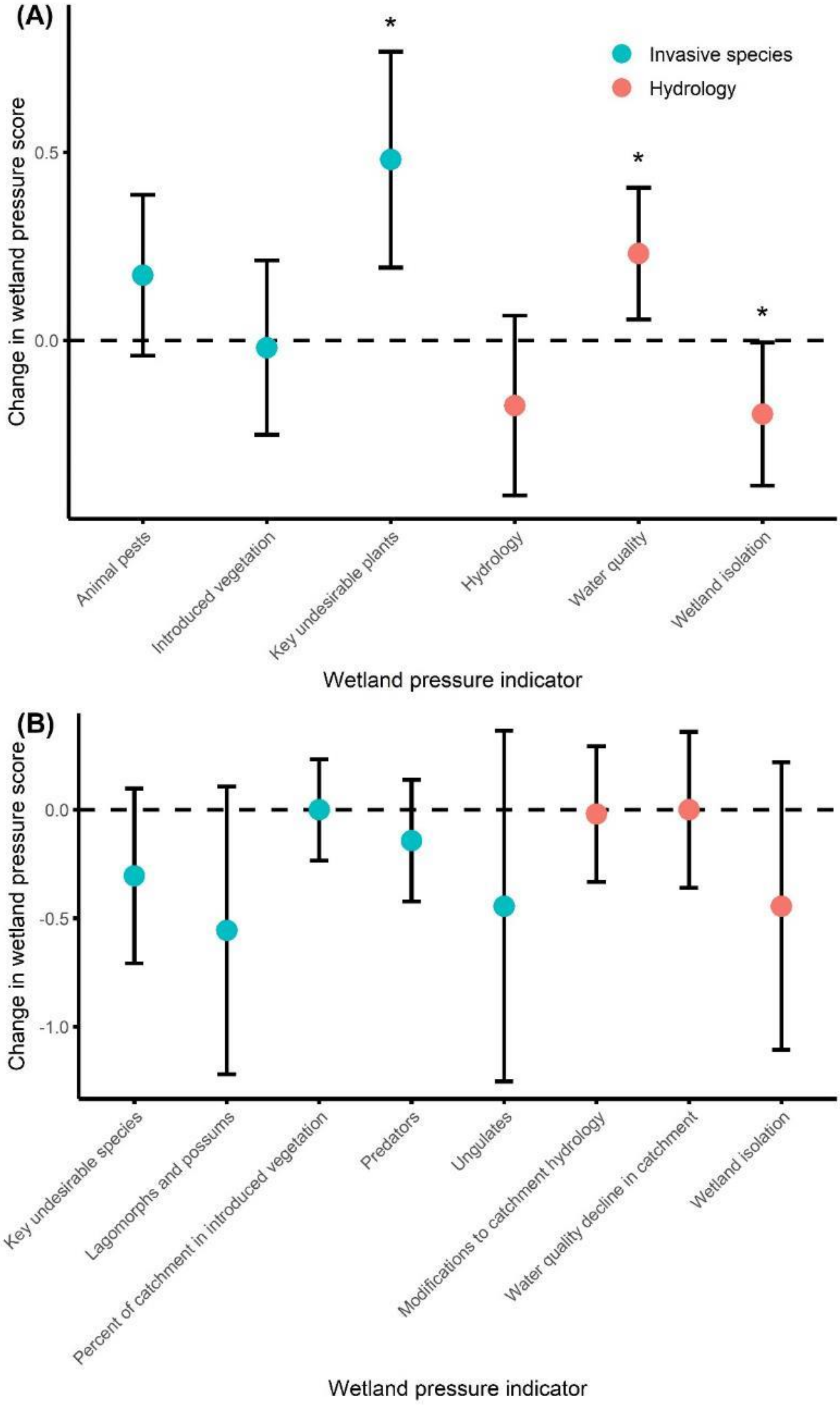


Figure 28. Mean (± 95% confidence interval) change in wetland pressure score for indicators of wetland pressure in Auckland (A) and Hawke's Bay (B) wetlands.

Notes: positive values represent increased pressure, negative values represent decreased pressure, and the dashed line at zero represents no change in pressure to the wetland. An asterisk (*) denotes components where the mean change in wetland pressure score was significantly different from zero ($P < 0.05$ using paired t-test). Different colours denote indicator types: invasive species (blue) and hydrology (red).

3.2.4 Discussion

Although many Auckland and Hawke's Bay wetlands experienced severe flooding during the extreme weather events of early 2023, the immediate impacts on overall wetland condition were relatively minor. Increased sedimentation, damage to native vegetation, and mammalian predator impacts on wildlife all contributed to the 4% average decline in Hawke's Bay wetland condition between pre- and post-cyclone surveys, the last of which was not considered cyclone related. This result indicates that regional-scale wetland condition is largely resilient to the immediate impacts from extreme weather events such as tropical cyclones. However, larger impacts were more frequently observed at the scale of individual wetlands, with some experiencing declines in wetland condition of up to 18%. These sites may require more targeted management to promote recovery to their pre-cyclone state.

As with lowland forest (section 3.1), braided rivers (section 3.3), and freshwater ecosystems (section 4), we identified sedimentation from nearby waterways and slips on adjacent land as a key factor behind the post-cyclone decline in Hawke's Bay wetland condition. Sediment deposition is considered to affect wetland condition through the input of nutrient-rich sediment from pastural land, altering physico-chemical parameters, with potential implications for plant composition and diversity through altered nutrient levels (Burge et al. 2020) and the dispersal and establishment of non-native plants. Analysis of pollen records indicates that historical sedimentation also temporarily altered wetland plant communities, favouring other native species such as raupō (*Typha orientalis*) (Li et al. 2024).

Both Auckland and Hawke's Bay experienced no overall change in the average Wetland Pressure Index, suggesting there are minimal expectations of longer-term cyclone impacts. However, the individual pressure indicators of non-native plants and reduced water quality increased in Auckland wetlands, which could indicate the potential for longer-term impacts that may take time to become apparent in wetland monitoring data. For example, slow turnover of New Zealand plant communities may mean that the impacts of increased nutrients (via sedimentation) may be slow to appear in plant community data (Burge et al. 2020). Likewise, post-cyclone establishment of non-native plant species, including ruderal species that favour disturbance and increased nutrient levels, may take time to spread and become detectable in randomly located vegetation plots.

In any case, it is important to detect and mitigate the potential for the cumulative effects of incremental impacts on wetland condition after subsequent extreme weather events. Therefore, we recommend the continuation and expansion of standardised SoE monitoring programmes by regional councils. This national-scale data set would also facilitate the testing of research questions relating to wetland type and land tenure, which were not able to be tested as part of this study due to insufficient sample sizes at the regional scale.

We note that the observed impacts on the wetland condition and pressure indices, and their indicators and components, may not be wholly attributable to Cyclone Gabrielle. This challenge of direct attribution is due to the amount of time between some pre- and post-cyclone surveys and the multiple pressures faced by wetland ecosystems. However, in many cases there was obvious evidence of cyclone impacts that contributed to the lower Wetland Condition Index score (Figure 29). For example, slips and flooding associated with the cyclone were clearly related to increased sedimentation (and a 21% decline in the component score) of several Hawke's Bay wetlands.

Wetland condition scores in Hawke's Bay increased with elevation, both before and after the cyclone, while wetland pressure declined. This relationship may reflect the presence of more intact upper catchments in Hawke's Bay, which we recommend should be conserved. This relationship was not apparent for Auckland wetlands, but their maximum elevation was only 107 m, compared to 1,060 m in Hawke's Bay. We also note that the two regions used slightly different methods to assess wetland condition (a couple of components differed for wetland condition and pressure scores), which can make it challenging to compare results. We recommend the adoption of standardised monitoring wherever possible to assist with the integration of data across regions after large-scale disturbance events.

Alongside resilience, water retention by wetlands plays an important role in flood and erosion mitigation, and other ecosystem services (Clarkson et al. 2013). For example, one study from the midwestern United States found that flood impacts increased once more than 60% of historical wetlands had been lost (Zedler 2003). Another review found that floodplain wetlands reduced or delayed floods, but that evidence for flood mitigation of other wetland types was mixed (e.g. headwater wetlands) (Bullock & Acreman 2003). A study carried out in Florida found that the number, type, and location of permits to approve loss of wetlands was a significant predictor of flood damages (Highfield & Brody 2006). While these studies suggest that wetlands can mitigate flood damage, future research is needed to better quantify and understand flood mitigation by wetlands and different land-use types in New Zealand.

The analysis in this report only scratches the surface of the questions that could be answered using these long-term SoE monitoring data. We recommend that future work expand on these analyses to assess post-cyclone changes in soil characteristics, and plant diversity and composition. For example, soil nutrients and bulk density could increase with sedimentation, and colonisation by non-native ruderal species that favour disturbed areas with high nutrient levels may portend longer-term changes to wetland condition and biodiversity. Such early indicators of long-term change are important to detect, especially given the slow turnover of New Zealand wetland plant communities (Burge et al. 2020).

Finally, the inherent complexity and semi-quantitative nature of metrics such as the Wetland Condition Index mean they can obscure as much as they reveal. Therefore, future research should explicitly investigate the relationships between index indicators and measures of ecological integrity (e.g. species richness, native dominance, occupancy of vulnerable species; Bellingham et al. 2016). This information will also help to translate changes in wetland condition and pressure indices to potential management actions that can be implemented in the field.

3.2.5 Conclusions and recommendations

Here we present answers to our original research questions and provide recommendations for the management of, and future research on, extreme weather impacts on wetlands.

Conclusions

- How did Cyclone Gabrielle affect wetland condition and pressures indices?

In Auckland, Cyclones Hale and Gabrielle had no overall impact on the mean wetland condition or pressure indices. In Hawke’s Bay, the mean Wetland Condition Index declined by 4% after the cyclone, while the Wetland Pressure Index was unchanged.

- Which indicators and components of the wetland condition and pressures indices were affected?

In Auckland, pressure from key undesirable plants and poor water quality increased after the cyclone, while pressure from wetland isolation decreased. In Hawke’s Bay, the Wetland Condition Index components of sedimentation, vegetation damage/clearance, and introduced predator impacts all scored worse in post-cyclone surveys compared to pre-cyclone surveys.

- Did observed changes in wetland condition and pressure indices depend on wetland type, elevation, or land tenure?

Post-cyclone changes in wetland condition and pressure indices were unrelated to wetland type, elevation or land tenure. However, in Hawkes’ Bay the Wetland Condition Index increased and the Wetland Pressure Index decreased with higher elevations. In the Auckland region, the Wetland Pressure Index was higher for wetlands on private than on public land.

Recommendations

- Enhance current wetlands: cumulative impacts of multiple extreme weather events could further degrade wetland condition over time. To maintain wetland resilience, management should target factors that contributed to the observed decline in wetland condition. For example, sedimentation may be partially mitigated by restoring native vegetation around wetlands to lessen their proximity to highly erodible land, fencing the wetland to reduce stock and feral ungulate access, and connecting waterways to enable the recovery of communities.
- Restore more wetlands: to help mitigate the impacts of future flooding, we recommend the retention and restoration of more wetlands, from high in catchments down to the floodplain. Small wetland restoration may help with regular floods and erosion mitigation at higher elevations, but this must be combined with large-scale lowland wetland restoration to help manage extreme weather events such as Cyclone Gabrielle.

Figure 29. Example of a cyclone-affected wetland (centre) in the MWE catchment, Hawke's Bay, featuring eroded hillside in the foreground and around the wetland. (Photo: Warwick Allen)

3.3 Hawke's Bay braided rivers

3.3.1 Introduction

Braided rivers are naturally uncommon ecosystems (Williams et al. 2007) that are facing multiple threats, including land-use change, pollution, invasive plants and animals, and extreme weather. Cyclone Gabrielle caused record-high flooding in the Tutaekuri, Ngaruroro, and Tukituki River catchments, all which support internationally and nationally significant breeding populations of native shorebirds. This includes 13% of the global breeding population of banded dotterels (pohowera, *Charadrius bicinctus*), around 50% of the national breeding population of black-fronted dotterels (*Elseyornis melanops*), approximately 5% of the national population of pied stilts (poaka, *Himantopus himantopus*), and the only North Island breeding population of South Island pied oystercatchers (tōrea, *Haematopus finschi*) (McArthur et al. 2020, McArthur, Thomas et al. 2021, McArthur et al. 2022).

Between 2019 and 2021 HBRC carried out a 3-year series of annual bird surveys along 292 km of the Tutaekuri, Ngaruroro, and Tukituki Rivers (Figure 30). To generate data with high spatial resolution, each river was divided into sections, varying in length from 220 to 2,170 m. The boundaries of these survey sections were aligned with pre-established river cross-sections from HBRC's river cross-section monitoring network, and surveyed to assess gravel availability and flood control performance since 1990 (Clode & Beya, 2018). The existence of these spatially explicit shorebird data, which were partnered with data on habitat characteristics (i.e. vegetation cover and substrate composition), represented a unique opportunity to quantify the impacts of an extreme weather event on riverbed-nesting shorebird communities. Quantifying these impacts will greatly improve our understanding of how New Zealand's endemic and threatened shorebird species respond to our changing climate, and will also help HBRC to differentiate the impacts of extreme weather events from those of flood mitigation activities.

We partnered with HBRC and ecological consultant Nikki McArthur to carry out a fourth, post-cyclone survey (McArthur, Allen et al. 2024). Using these data we aimed to answer the following research questions:

- How were braided river bird habitat characteristics (vegetation cover, substrate composition) altered by Cyclone Gabrielle?
- How did the abundance and distribution of native shorebirds (banded dotterels, black-fronted dotterels, pied stilts, South Island pied oystercatchers) change after Cyclone Gabrielle?
- Were changes in the abundance and distribution of native shorebirds related to changes in habitat characteristics (i.e. cover of vegetation and substrate size classes)?

3.3.2 Methods

The post-cyclone survey was carried out between 21 October and 18 November 2023. Each river section was surveyed by a team of between one and six experienced observers. The number of observers varied according to the width of the active riverbed in each river section, with observers typically spaced ≤100 m apart across the width of the riverbed. Each team typically walked line-abreast up or down the river, recording the identity and cumulative counts of all adult birds seen or heard in the bed of the river, or in the adjacent riparian vegetation, within each survey section. Special care was taken to systematically search all areas of dry, un-vegetated gravels and all muddy backwaters, temporary pools or minor channels to minimise the risk of missing territorial pairs of banded dotterels, black-fronted dotterels, and pied stilts. Team members maintained regular communication with one another using either hand-held radios, mobile phones, or hand signals to avoid double-counting or missing any individual birds detected.

Observers also collected data describing the extent of vegetation cover, substrate composition, and woody debris at 200 m intervals within each survey section. Both vegetation and driftwood cover were quantified by visually estimating the percentage of dry gravel beaches or islands covered in vegetation >5 cm in height, and in driftwood, within an imaginary box extending 50 m upstream and downstream of the interval, and across the entire width of the active riverbed. These individual vegetation and driftwood cover estimates were then used to calculate mean vegetation cover and mean driftwood cover for each survey section.

Substrate cover was estimated using the same approach, but divided into seven size classes, which together sum to 100%:

- sediment (<0.063 mm)
- sand (0.063–2 mm)
- gravel (2–16 mm)
- pebbles (16–64 mm
- cobbles (64–256 mm)
- boulders (256–4,000 mm)
- bedrock (>4,000 mm).

The area of each survey section was estimated using ArcMap version 10.8.2 to calculate the density of birds per hectare within each section. The calculated survey section areas used in this analysis include the proportion of the active riverbed covered in water. Because these habitats are unoccupied by shorebirds, the densities reported here will underestimate the true densities of adult birds occupying dry gravel habitats within each survey section.

The degree to which shorebird densities have been underestimated within each survey section will also probably vary between one section and another according to the proportion of riverbed within each section covered in water. Unfortunately, we had no way of accurately quantifying the proportion of active riverbed within each survey section under water. However, we observed that this proportion is relatively small (generally <15%), so the degree to which the proportion of the total area of riverbed situated beneath surface water differed from one section to the next was likely to be low.

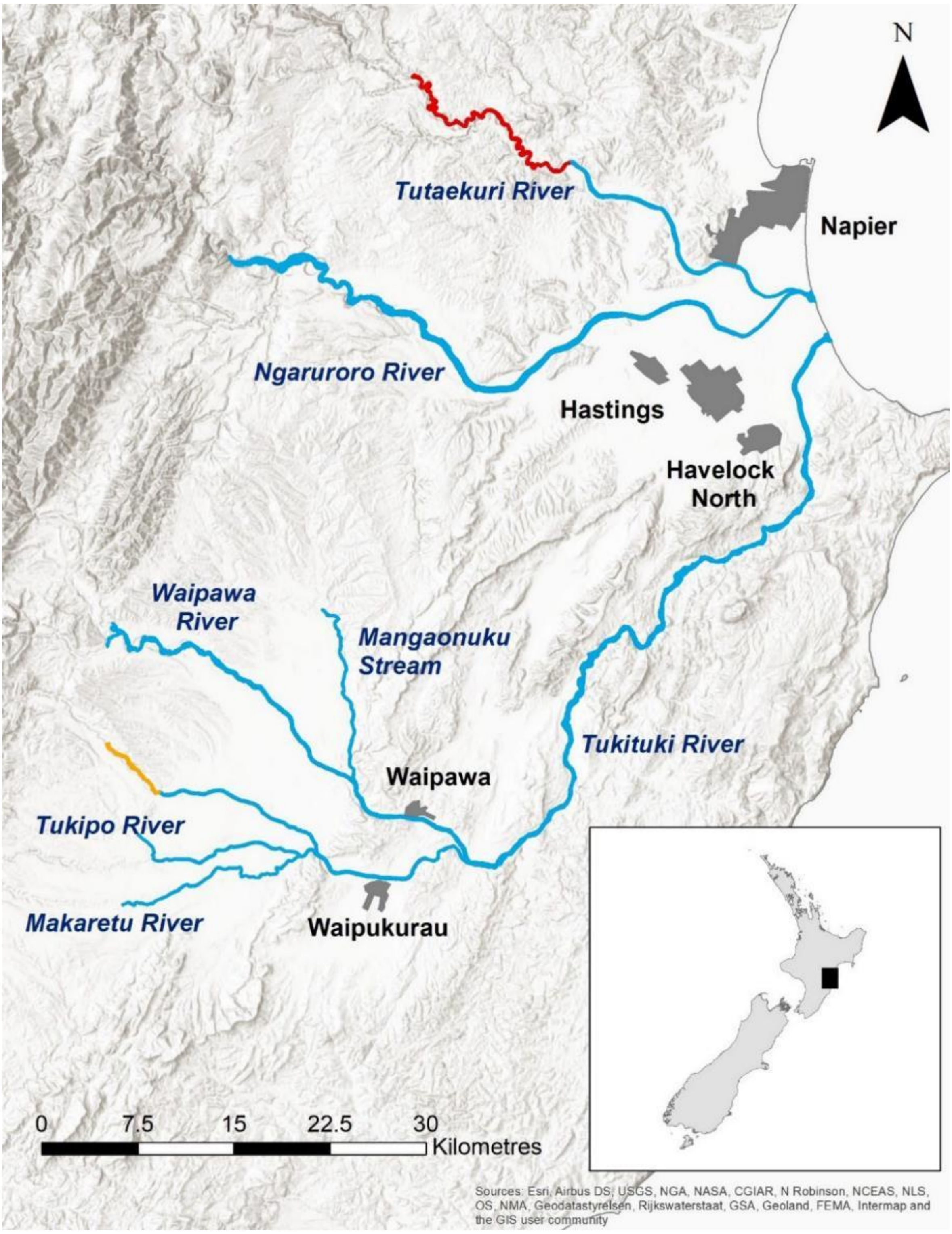


Figure 30. Map showing the spatial extent of bird surveys carried out in the Tutaekuri, Ngaruroro, and Tukituki River catchments, Hawke's Bay, between 2019 and 2023.

Notes: river sections marked in blue have been surveyed during all four surveys carried out between 2019 and 2023. The river section marked in red was surveyed during the 2020, 2021, and 2023 surveys, while the river section marked in orange was surveyed during the 2021 and 2023 surveys. (Reproduced with permission from McArthur, Allen et al. 2024).

To examine the impacts of Cyclone Gabrielle on the percentage cover of vegetation and substrate size classes, and whether cyclone impacts varied among catchments, we used generalised linear mixed models (GLMMs) implemented in R version 4.4.1 (R Core Team 2024) with the package glmmTMB. We used models suitable for non-integer proportion data with a beta distribution (Brooks et al. 2017). Data were transformed to avoid zeroes and ones before analysis, following Smithson and Verkuilen (2006): $[y \times (n - 1) + 0.5] / n$, where n is the total sample size.

Each model contained percentage cover as the response variable, sampling period (pre- vs post-cyclone), catchment (Ngaruroro, Tukituki, Tutaekuri), and their interaction as explanatory variables, and a random effect of river section nested within river to account for the non-independence of observations within the same river section and within the same river.

For significant categorial explanatory variables we conducted pairwise contrasts among means using *post hoc* Tukey tests with Bonferroni correction, restricting contrasts to pre- and post-cyclone comparisons within catchments. Woody debris cover was analysed using the same approach; however, because this variable was only measured after Cyclone Gabrielle, catchment was the only explanatory variable included in the model and river was the only random effect.

To examine the impacts of Cyclone Gabrielle on the density of four focal shorebird species (banded dotterel, black-fronted dotterel, pied stilt, and South Island pied oystercatcher), we again used GLMM implemented in R version 4.4.1 (R Core Team 2024) with the package glmmTMB. All models used a Poisson error distribution to model shorebird abundance per river section as the response variable and included sampling period (pre- vs post-cyclone), catchment (Ngaruroro, Tukituki, Tutaekuri) and their interaction as explanatory variables, an offset to account for river section area, and a random effect of river section nested within river. For significant categorial explanatory variables, we conducted pairwise contrasts among means using *post hoc* Tukey tests with Bonferroni correction, restricting contrasts to pre- and post-cyclone comparisons within each catchment. Because South Island pied oystercatchers were so sparsely distributed, we used data only from river sections where they had been detected.

To test whether post-cyclone changes in shorebird density were related to changes in habitat characteristics, we used linear mixed models implemented in R version 4.4.1 (R Core Team 2024) with the package lme4. To limit the number of explanatory variables in each model, we summed the cover of substrate size classes into three groups: fine (sediment and sand), medium (gravel and pebble), and coarse (cobble, boulder, and bedrock). All models used the change in shorebird density per hectare within each river section (i.e. post-cyclone density minus pre-cyclone density) as the response variable, and included change in cover of vegetation, and in fine, medium, and coarse substrate (i.e. post-cyclone cover minus pre-cyclone cover) as explanatory variables. A random effect of river nested within catchment was used to account for non-independence of observations within the same river and catchment.

3.3.3 Results

Cyclone impacts on substrate composition varied among catchments

Pre-cyclone, the overall substrate composition of Hawke's Bay braided rivers was dominated by pebbles (39% of total cover), followed by gravel (24%), cobbles (23%), sand (6%), sediment (5%), boulders (3%), and bedrock (0%). After the cyclone, cover of both silt and sand doubled to 11%, while cover of pebbles (38%), gravel (20%), cobbles (18%), and boulders (1%) all decreased.

However, the impact of the cyclone on substrate composition depended on the catchment (Figure 31). This was the case for all substrate size classes (GLMM; cyclone × catchment interaction: all $X^2 > 6.47$, $P < 0.039$), except for bedrock ($X^2 = 0.06$, $P = 0.972$).

In the Ngaruroro catchment, sediment cover almost quadrupled after Cyclone Gabrielle, increasing from 5.8% to 22.4% (Figure 32A), while cover of sand, gravel, pebbles, cobbles, and boulders was relatively unaffected (Figure 32Figure 32B–F).

In the Tukituki catchment, sediment cover increased by 33% after Cyclone Gabrielle, from 6.4% to 8.5% (Figure 32A), and pebble cover increased by 9%, from 38.5% to 41.1% (Figure 32D). In contrast, cobble cover decreased by 19%, from 25.0% to 20.3% (Figure 32E) and boulder cover decreased by 11%, from 3.3% to 2.6% (Figure 32Figure 32F). Cover of sand and gravel were both unaffected (Figure 32B, C).

In the Tutaekuri catchment, sediment cover increased by 51% after Cyclone Gabrielle, from 6.1% to 9.1% (Figure 32A), and sand cover increased by 129%, from 7.1% to 16.4% (Figure 32B). In contrast, gravel cover decreased by 28%, from 28.1% to 20.2% (Figure 32C), pebble cover decreased by 32%, from 36.1% to 24.7% (Figure 32D), and cobble cover decreased by 43%, from 14.8% to 8.5% (Figure 32E). Boulder cover was unaffected (Figure 24F). Bedrock was detected in only 6% (71 of 1,162) of river sections, with a mean cover of 0.4%, which was not influenced by Cyclone Gabrielle or catchment (Figure 32G).

Vegetation cover decreased after Cyclone Gabrielle

Vegetation cover decreased in 96% (327 of 339) of river sections, but the magnitude of decline depended on the catchment ($X^2 = 13.21$, $P = 0.001$). In the Ngaruroro catchment, vegetation cover decreased by 39% after the cyclone, from 14.2% to 8.6% (Figure 32H). In the Tukituki catchment, vegetation cover decreased by 64%, from 22.6% to 8.1% (Figure 32Figure 32H). In the Tutaekuri catchment, vegetation cover decreased by 65%, from 21.9% to 7.6% (Figure 32H).

Woody debris was common but had low cover

Woody debris occurred in 96% of river sections (330 of 342) that were surveyed after Cyclone Gabrielle. However, mean woody debris cover averaged just 2.8% across all river sections and did not differ among the three catchments.

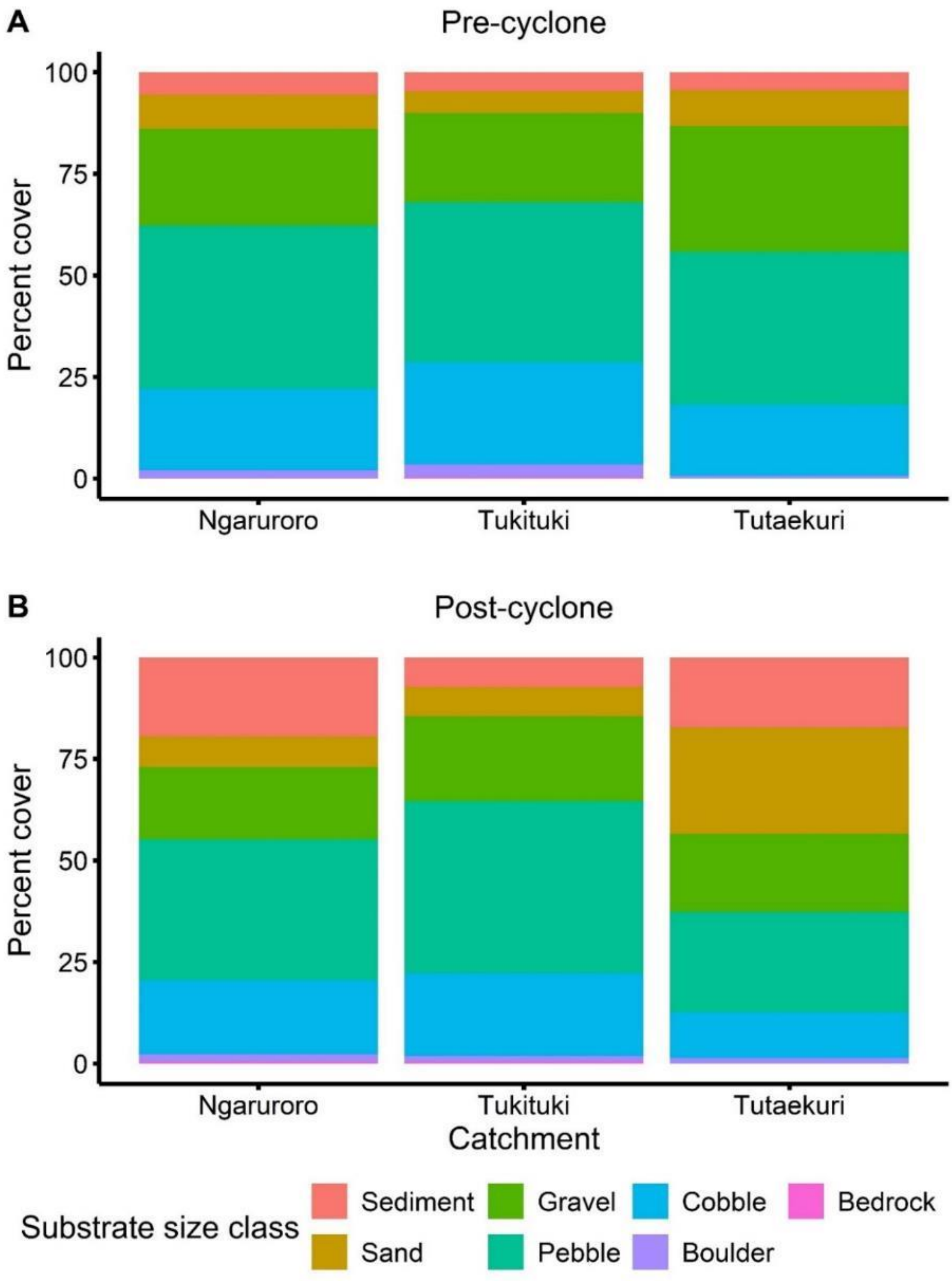


Figure 31. Stacked bar plot showing the substrate composition of Hawke's Bay braided rivers in three catchments, before (A) and after (B) Cyclone Gabrielle.

Note: Each coloured section of the bar plot represents average percentage cover of the corresponding substrate size class.

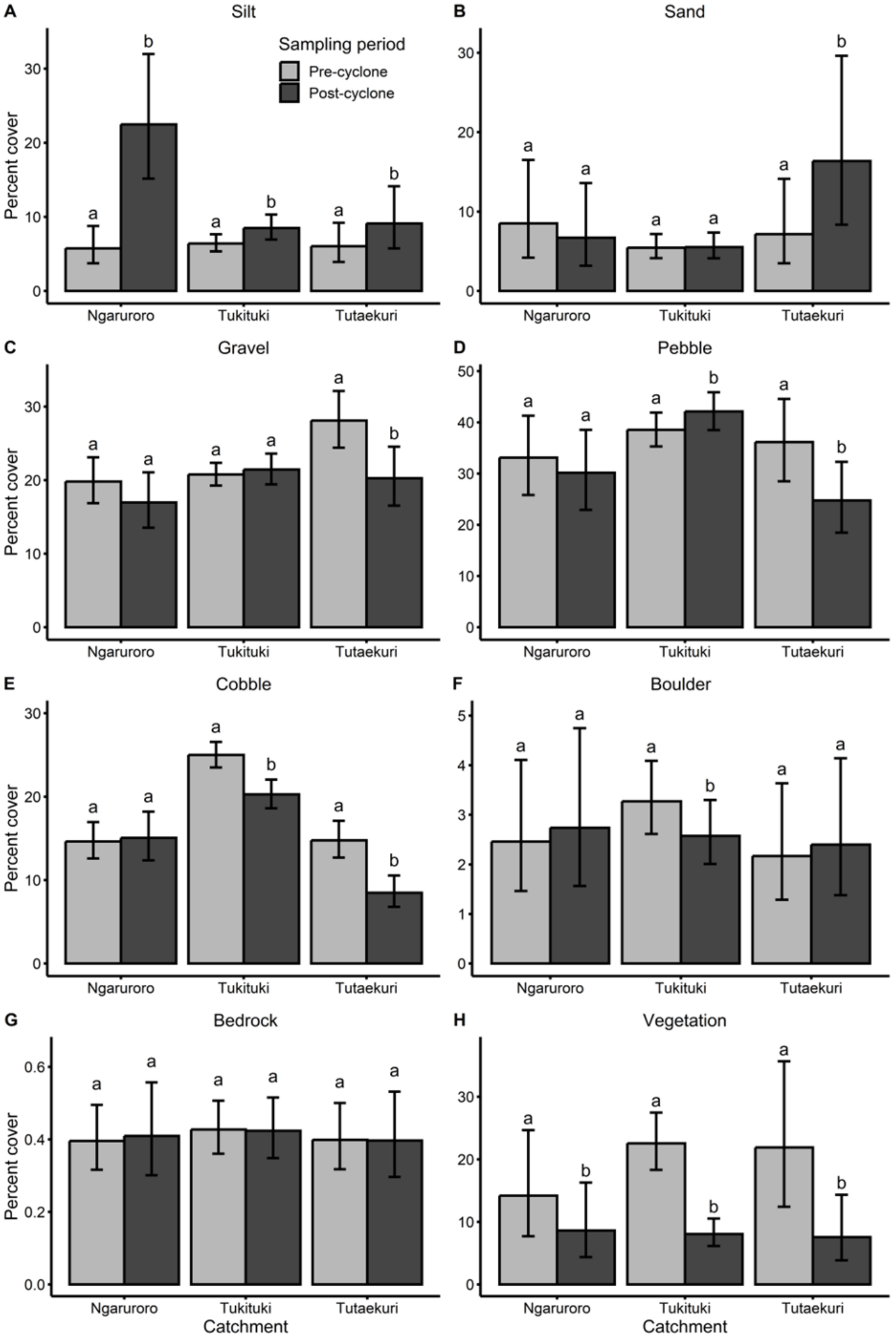


Figure 32. Percentage cover (estimated marginal mean ± 95% confidence intervals) of sediment (A), sand (B), gravel (C), pebbles (D), cobbles (E), boulders (F), bedrock (G), and vegetation (H) for three Hawke's Bay braided river catchments, before and after Cyclone Gabrielle.

Note: Different lowercase letters indicate significant differences between pre- and post-cyclone surveys within each catchment using *post hoc* Tukey tests with Bonferroni correction (*P* < 0.05).

Banded dotterel (pohowera)

A total of 2,066 adult banded dotterels were counted during the 2023 post-cyclone survey, including 162 birds on the Tutaekuri River, 760 birds on the Ngaruroro River, and 1,144 birds on the Tukituki River and its tributaries. The total number of banded dotterels counted during the post-cyclone survey was 15% lower than the 3-year average count of 2,418 birds between 2019 and 2021.

The impact of Cyclone Gabrielle on banded dotterel density depended on the catchment (cyclone × catchment interaction: $X^2 = 19.10$, $P < 0.001$). In the Ngaruroro and Tutaekuri catchments, banded dotterel density decreased by 28% and 56%, respectively (Figure 33A), after the cyclone, whereas no change in banded dotterel density was detected in the Tukituki catchment. Banded dotterel density decreased in 64% (153 of 238) of river sections where they were present during at least one survey and that were surveyed both before and after the cyclone (Figure 34).

Changes in banded dotterel density after Cyclone Gabrielle were not related to the change in vegetation cover, or to fine, medium, and coarse substrate (Figure 35).

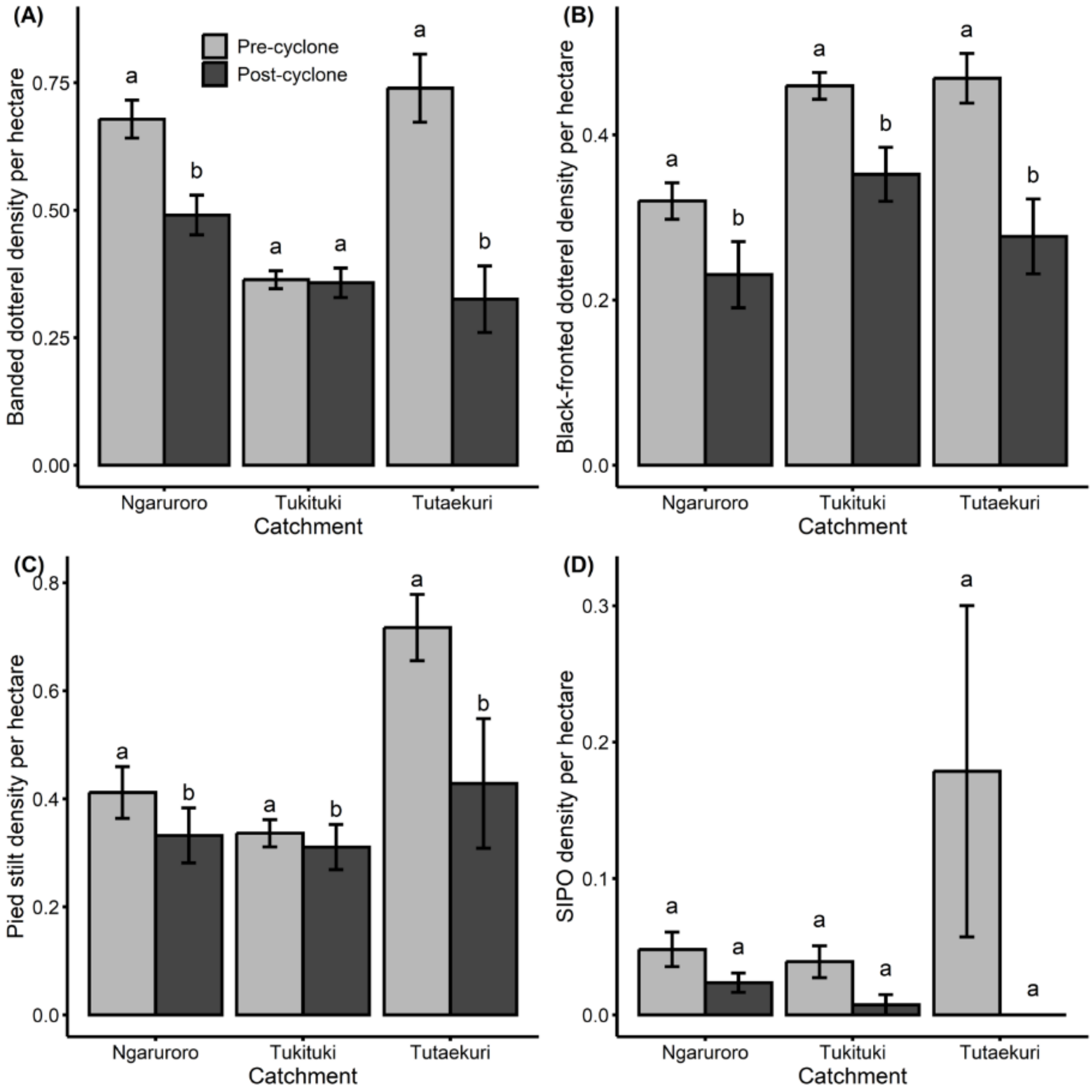


Figure 33. Mean (± 1 S.E.) density of (A) banded dotterels, (B) black-fronted dotterels, (C) pied stilts, and (D) South Island pied oystercatchers (SIPO) in three Hawke's Bay braided river catchments, before and after Cyclone Gabrielle.

Notes: Different lowercase letters indicate significant differences between pre- and post-cyclone surveys within each catchment based on *post hoc* Tukey tests with Bonferroni correction ($P < 0.05$).

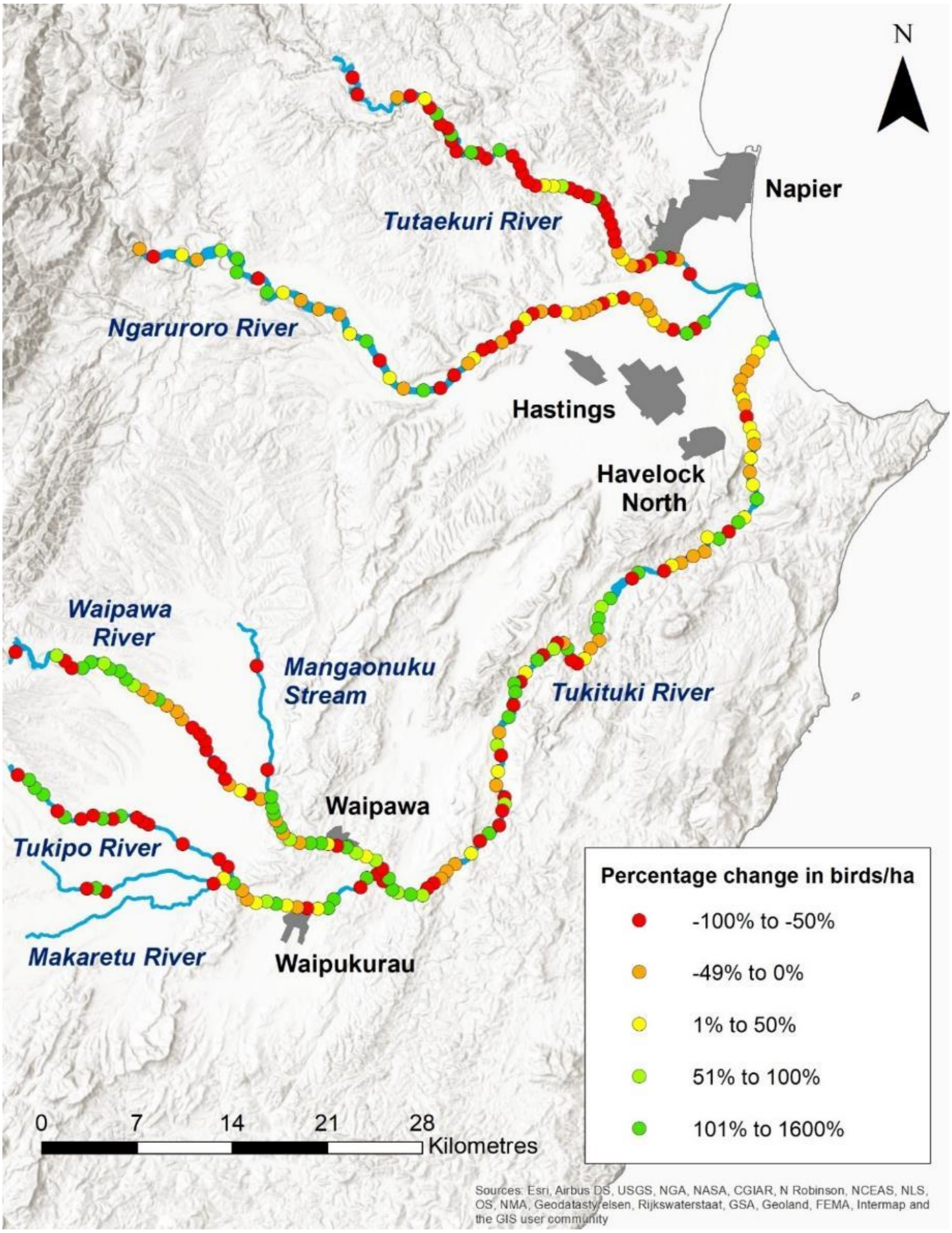


Figure 34. Percentage change in banded dotterel density per survey section on the Tutaekuri, Ngaruroro, and Tukituki Rivers between 2019 and 2021 (before Cyclone Gabrielle) and 2023 (after Cyclone Gabrielle). (Reproduced with permission from McArthur, Allen et al. 2024)

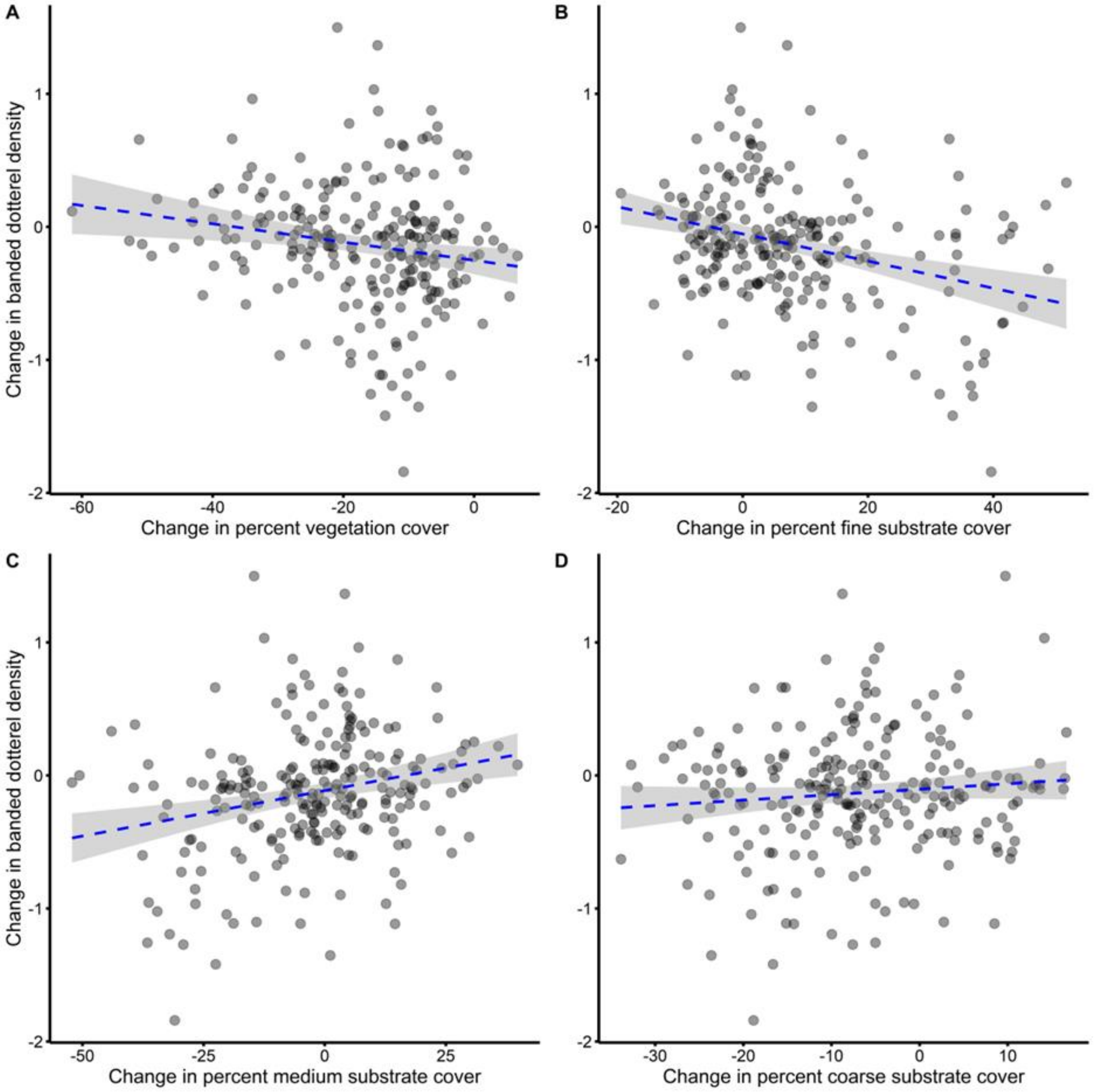


Figure 35. Relationships between the change (i.e. post-cyclone minus pre-cyclone) in banded dotterel density and the change in percentage cover of vegetation (A), and in fine (B), medium (C), and coarse (D) substrate in Hawke’s Bay braided rivers.

Note: Dashed lines represent non-significant relationships.

Black-fronted dotterel

A total of 987 black-fronted dotterels were counted during the 2023 post-cyclone survey, including 118 birds on the Tutaekuri River, 255 on the Ngaruroro River, and 614 on the Tukituki River and its tributaries. The total number of black-fronted dotterels counted during the post-cyclone survey was 30% lower than the 3-year average count of 1,405 birds between 2019 and 2021.

Black-fronted dotterel density declined after the cyclone in all three catchments, but with differing severity (cyclone × catchment interaction: $X^2 = 6.46$, $P = 0.039$), declining by 41%, 28%, and 23% in the Tutaekuri, Ngaruroro, and Tukituki catchments, respectively (Figure 33B). Black-fronted dotterel density decreased in 68% (231 of 338) of river sections where they were present during at least one survey and that were surveyed both pre- and post-cyclone (Figure 36).

River sections with the greatest decreases in vegetation cover experienced the largest increases in black-fronted dotterel density (Figure 37A). However, changes in black-fronted dotterel density after Cyclone Gabrielle were not related to the changes in fine, medium, and coarse substrate cover (Figure 37B–D).

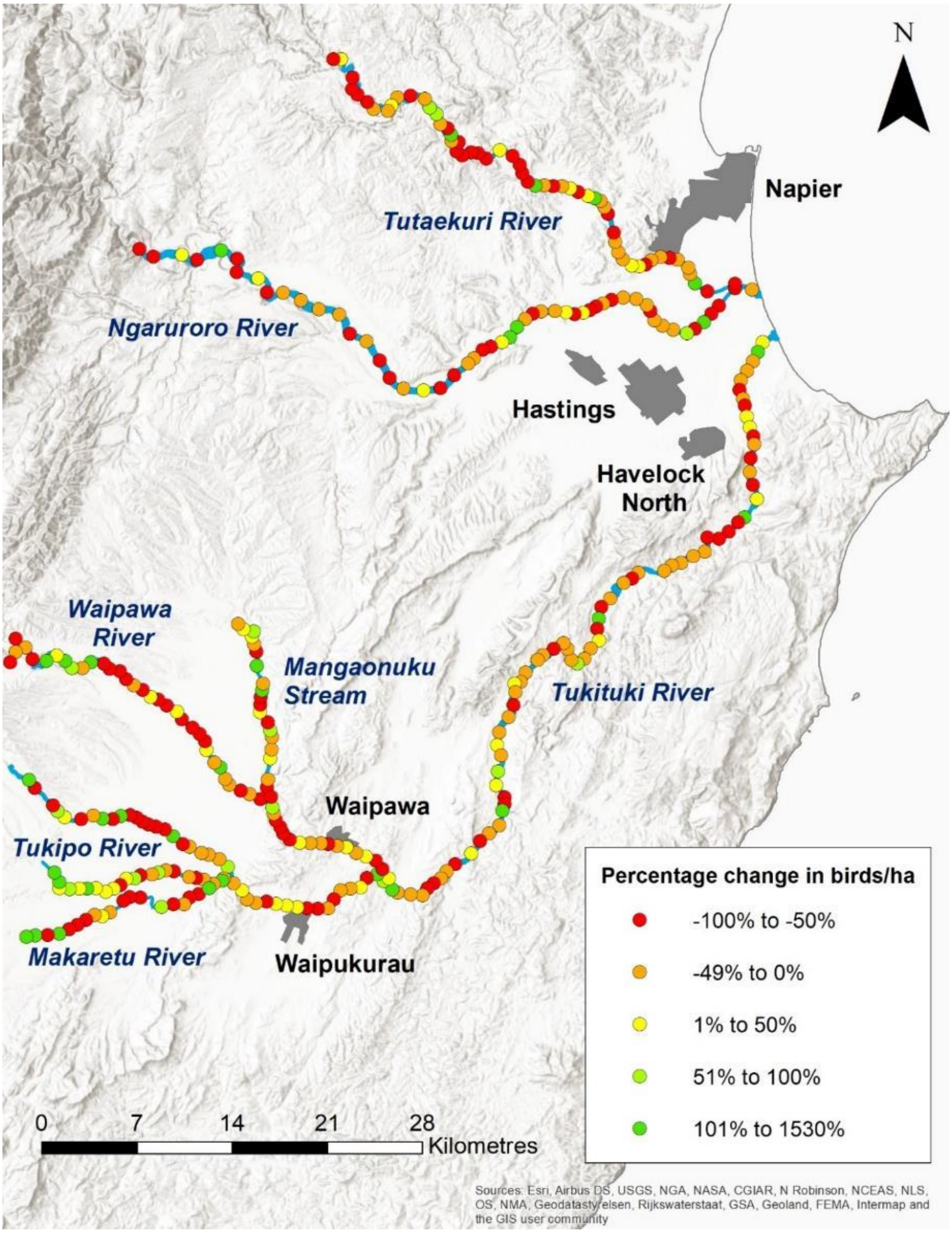


Figure 36. Percentage change in black-fronted dotterel density per survey section on the Tutaekuri, Ngaruroro, and Tukituki Rivers between 2019 and 2021 (before Cyclone Gabrielle) and 2023 (after Cyclone Gabrielle). (Reproduced with permission from McArthur, Allen et al. 2024)

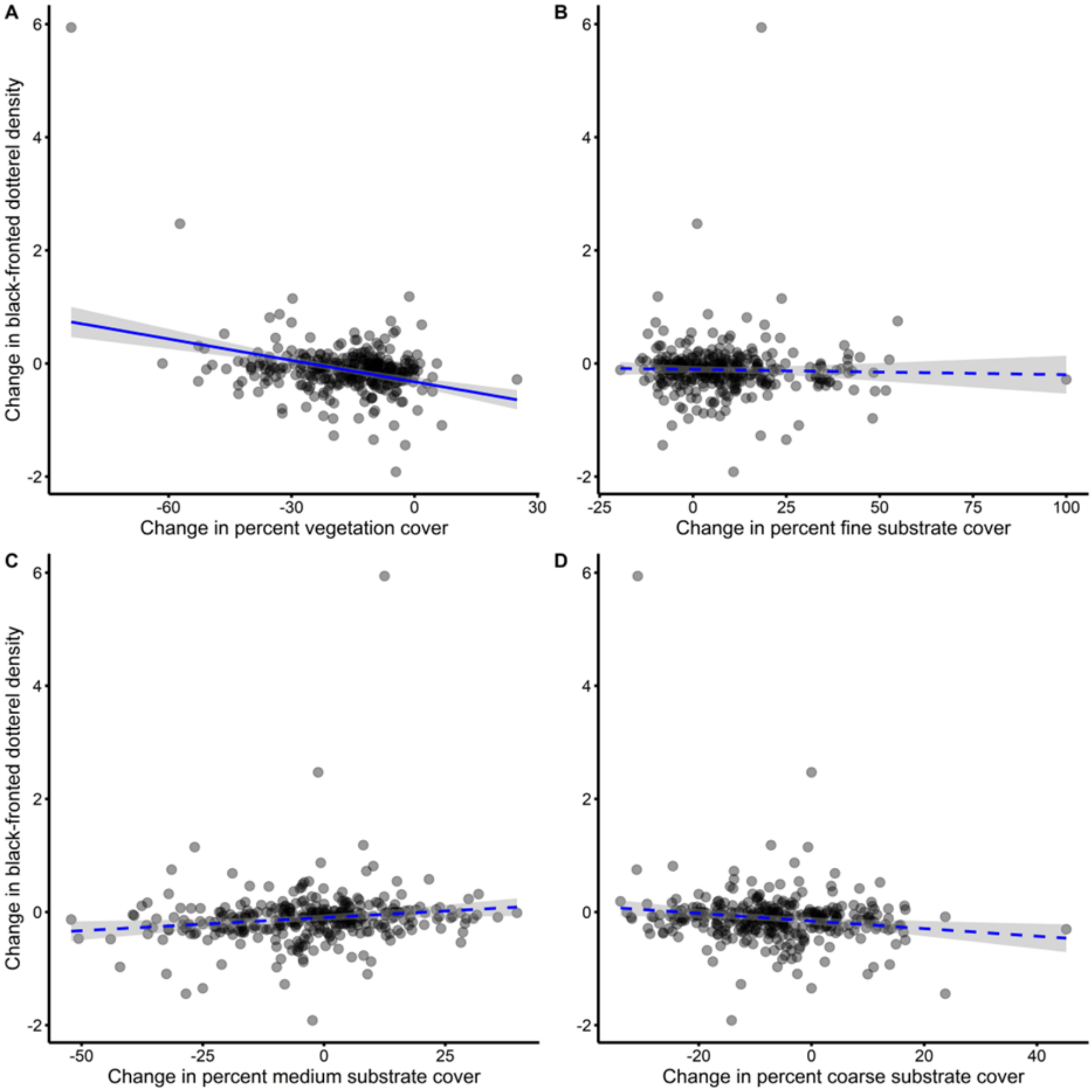


Figure 37. Relationships between the change (i.e. post-cyclone minus pre-cyclone) in black-fronted dotterel density and the change in percentage cover of vegetation (A), and in fine (B), medium (C), and coarse (D) substrate in Hawke's Bay braided rivers.

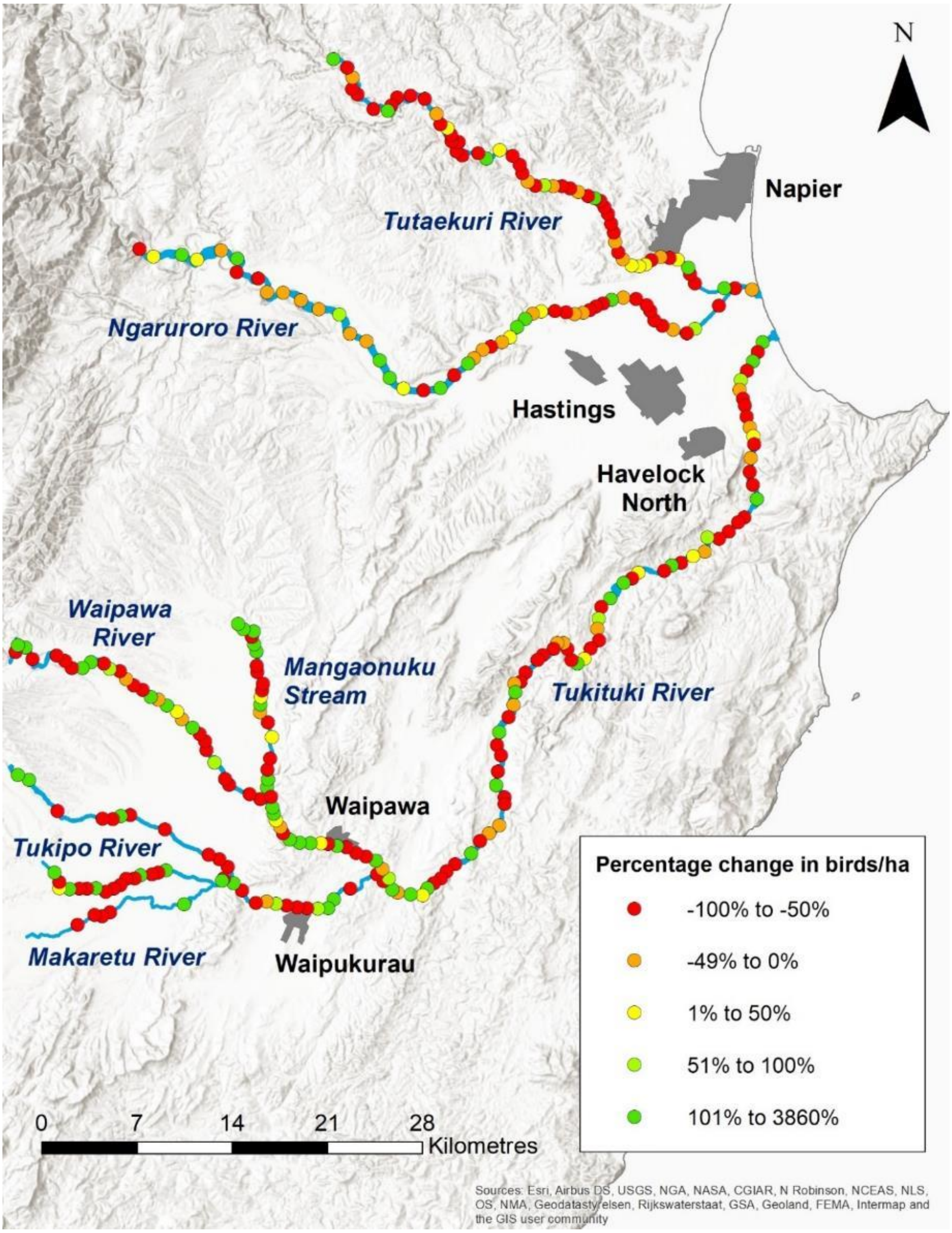
Note: solid and dashed lines represent significant (*P* < 0.05) and non-significant relationships, respectively.

Pied stilt (poaka)

A total of 1,327 pied stilts were counted during the 2023 post-cyclone survey, including 197 birds on the Tutaekuri River, 531 on the Ngaruroro River, and 599 on the Tukituki River and its tributaries. The total number of pied stilts counted during the 2023 post-cyclone survey was 16% lower than the 3-year average count of 1,573 birds between 2019 and 2021.

The impact of Cyclone Gabrielle on pied stilt density depended on the catchment (cyclone × catchment interaction: $X^2 = 62.68$, $P < 0.001$). In the Ngaruroro, Tukituki, and Tutaekuri catchments, pied stilt density decreased by 19%, 8%, and 41%, respectively (Figure 33C) after the cyclone. Pied stilt density decreased in 62% (175 of 282) of river sections where they were present during at least one survey and that were surveyed both before and after the cyclone (Figure 38).

River sections with the greatest decreases in vegetation cover experienced the largest increases in pied stilt density (Figure 39A). However, changes in pied stilt density after Cyclone Gabrielle were not related to the changes in fine, medium, and coarse substrate cover (Figure 39B–D).



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

Figure 38. Percentage change in pied stilt density per survey section on the Tutaekuri, Ngaruroro, and Tukituki Rivers between 2019 and 2021 (before Cyclone Gabrielle) and 2023 (after Cyclone Gabrielle). (Reproduced with permission from McArthur, Allen et al. 2024)

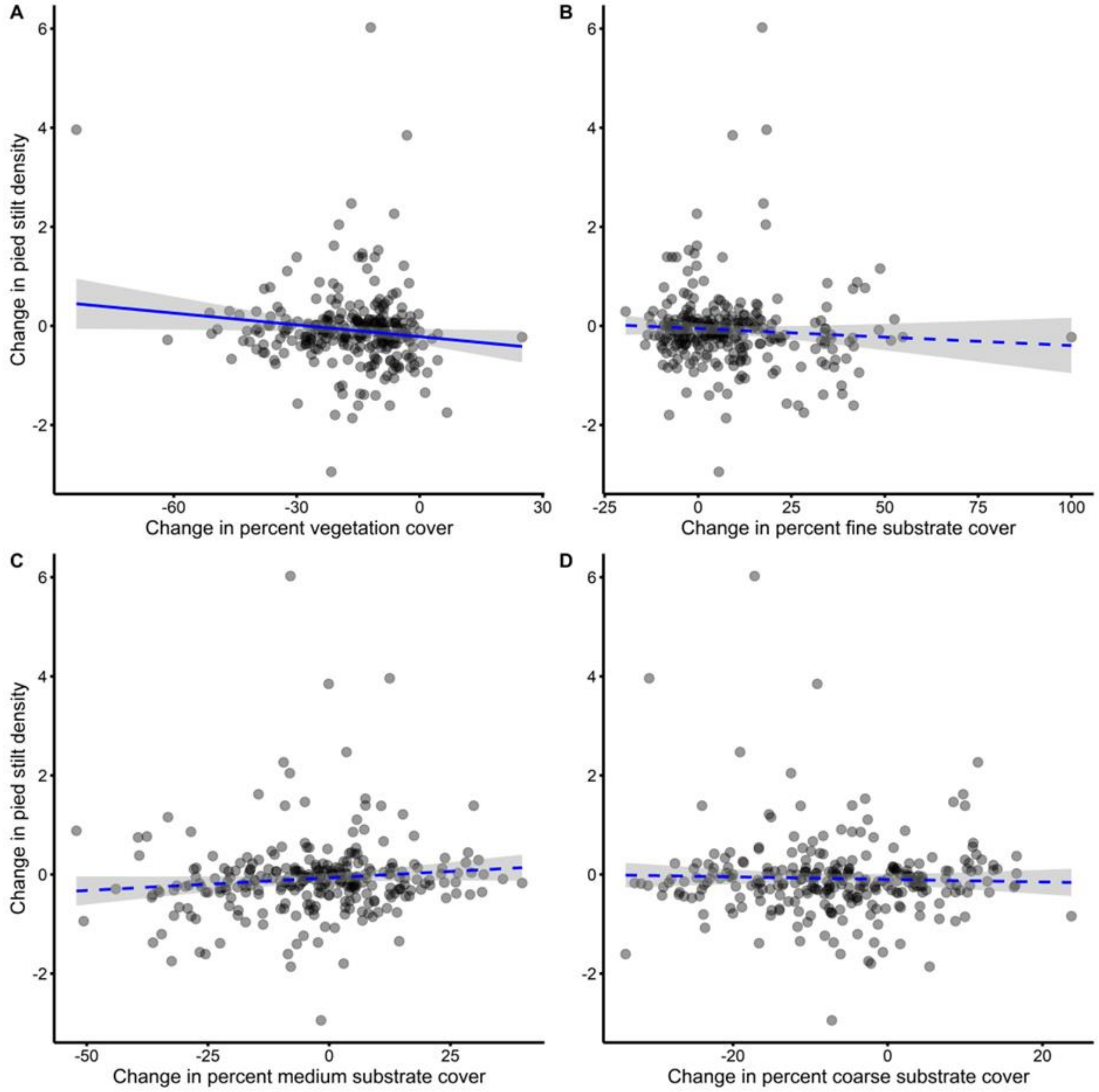


Figure 39. Relationships between the change (i.e. post-cyclone minus pre-cyclone) in pied stilt density and the change in percentage cover of vegetation (A), and in fine (B), medium (C), and coarse (D) substrate in Hawke's Bay braided rivers.

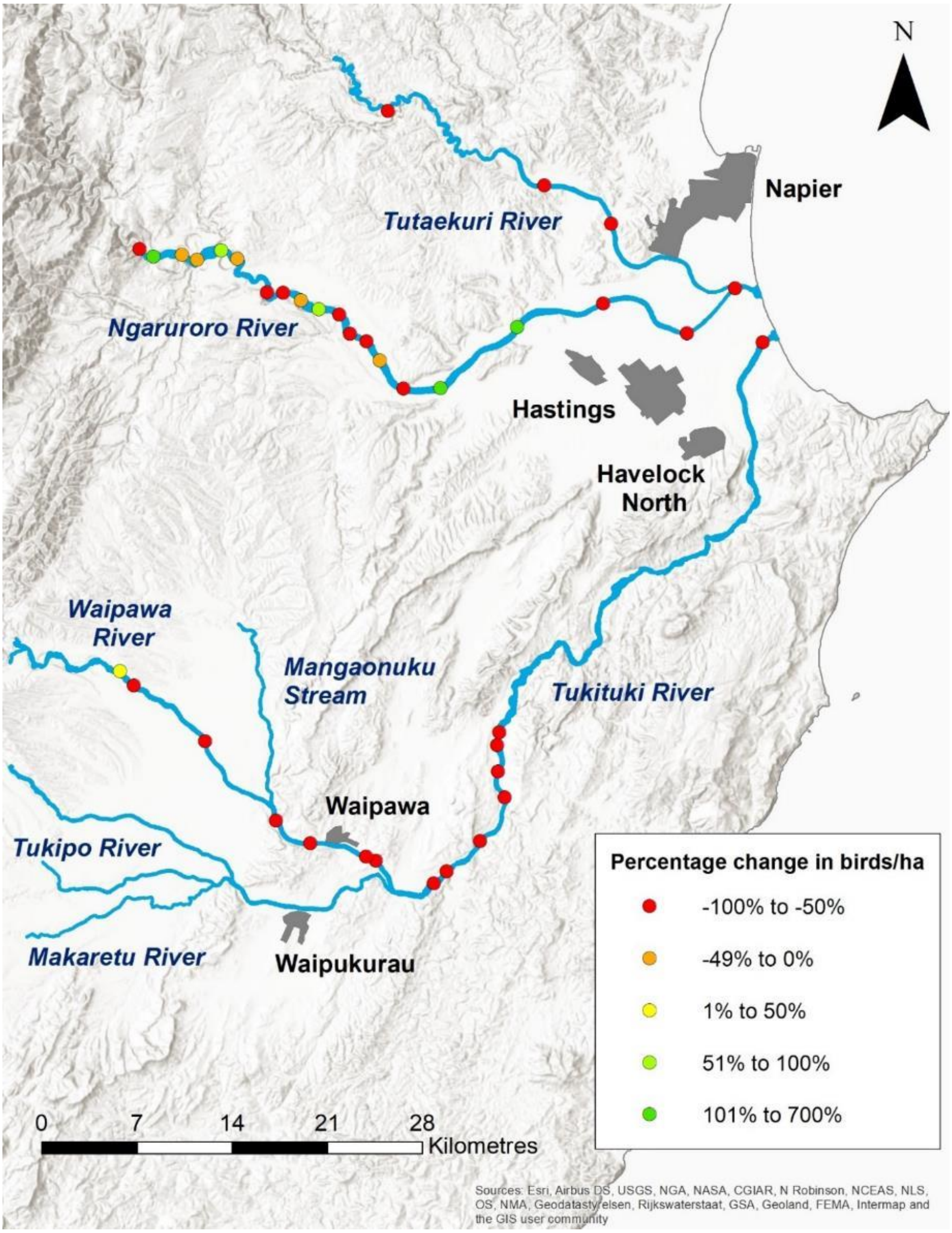
Note: solid and dashed lines represent significant (*P* < 0.05) and non-significant relationships, respectively.

South Island pied oystercatcher (tōrea)

Twenty-six South Island pied oystercatchers were counted during the 2023 post-cyclone survey, including 24 birds on the Ngaruroro River and two on the upper Waipawa River in the Tukituki River catchment. No South Island pied oystercatchers were encountered on the Tutaekuri River during the survey. The total number of South Island pied oystercatchers counted during the 2023 post-Cyclone Gabrielle survey was 43% lower than the 3-year average count of 46 birds between 2019 and 2021.

Probably due to the relatively small sample size (154 observations over 4 survey years), we did not detect a statistically significant impact of Cyclone Gabrielle on South Island pied oystercatcher density (Figure 33D) and were not able to model the cyclone × catchment interaction. However, South Island pied oystercatcher density decreased in 82% (31 of 38) of river sections where they were present during at least one survey and that were surveyed both before and after the cyclone (Figure 40).

Changes in South Island pied oystercatcher density after Cyclone Gabrielle were not related to changes in cover of vegetation, or to fine, medium, and coarse substrate (Figure 41A–D).



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

Figure 40. Percentage change in South Island pied oystercatcher density per survey section on the Tutaekuri, Ngaruroro, and Tukituki Rivers between 2019 and 2021 (before Cyclone Gabrielle) and 2023 (after Cyclone Gabrielle). (Reproduced with permission from McArthur, Allen et al. 2024)

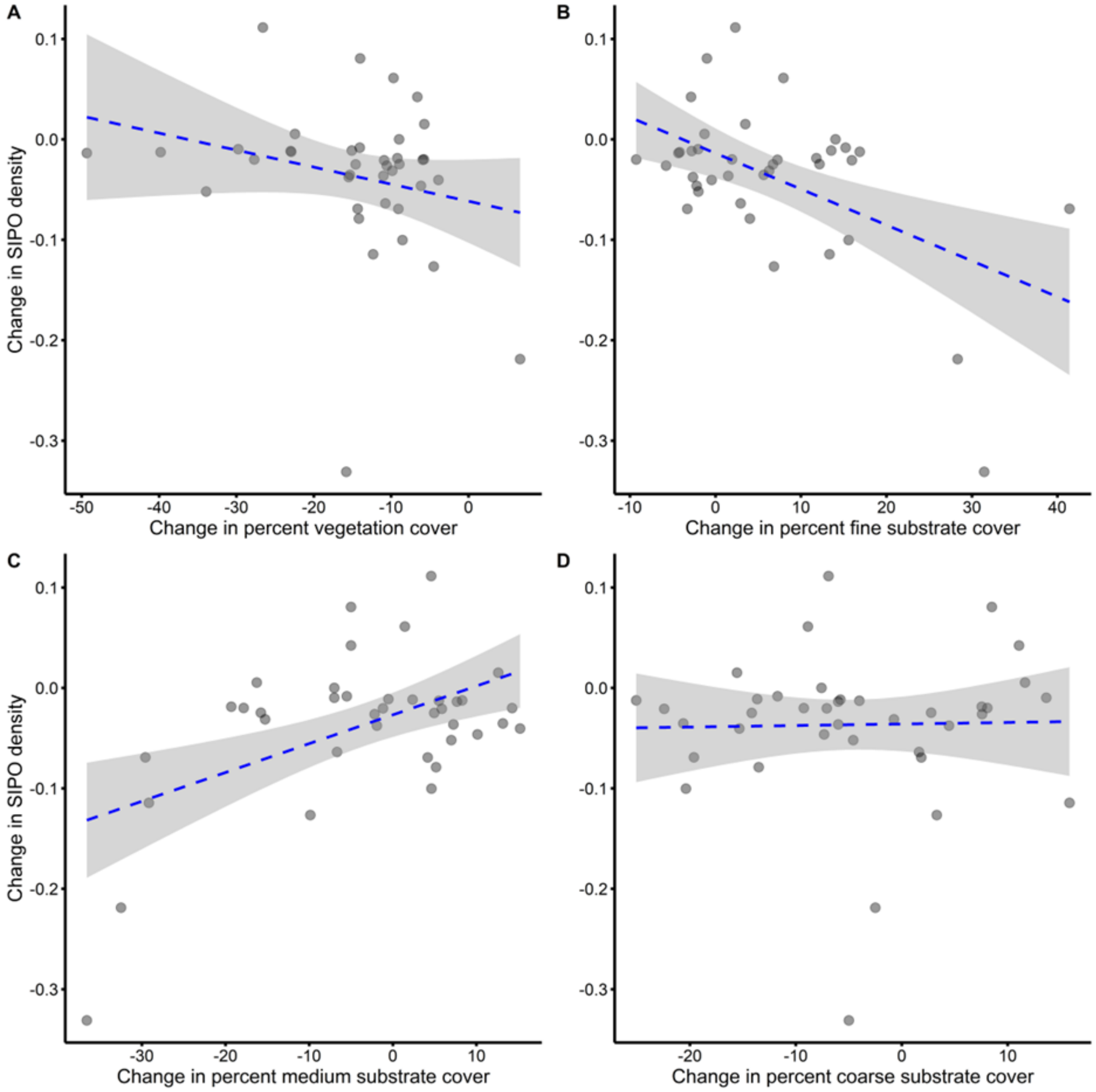


Figure 41. Relationships between the change (i.e. post-cyclone minus pre-cyclone) in South Island pied oystercatcher (SIPO) density and the change in percentage cover of vegetation (A), and of fine (B), medium (C), and coarse (D) substrate in Hawke's Bay braided rivers.

Note: Dashed lines represent non-significant relationships.

3.3.4 Discussion

Cyclone Gabrielle changed the vegetation cover and substrate composition of Hawke's Bay's braided rivers and the communities of birds that inhabit them. Three of the four key shorebird species experienced substantial population declines relative to pre-cyclone surveys, while the fourth species (South Island pied oystercatcher) was already so uncommon that its apparent 43% population decline was statistically non-significant.

These results provide some of the first quantitative evidence that extreme weather events can lead to substantial, catchment- and regional-scale declines in populations of riverbed-nesting shorebirds in New Zealand. Our findings suggest that these species will have high vulnerability to the predicted increases in the severity of extreme weather events over the coming decades. The natural interannual variability of populations of these species does remain poorly understood, and temporary population declines such as those observed may be a normal response to extreme weather events. However, it is likely that additional novel pressures such as habitat loss, increased sediment deposition, and mammalian predators will mean that population recovery may not be as rapid as it once was. Therefore, future research should continue long-term monitoring of these species, from regional to national scale, to better understand temporal and spatial population trends.

Very few other studies have quantified the impacts of extreme weather on native bird populations in New Zealand, and none on a comparable spatial scale. Weston and Fraser (2020) reported that a severe hailstorm caused mass mortality among nesting white-fronted terns (tara, *Sterna striata*) and black-billed gulls (tarāpuka, *Chroicocephalus bulleri*) at the Rangitata River mouth during November 2019. Six hundred and fifty white-fronted terns, representing 16–22% of the total number of adults breeding in one nesting colony, died from injuries sustained during the hailstorm, and 80 black-billed gulls, 95% of the nesting colony, also died.

The New Zealand fantail (pīwakawaka, *Rhipidura fuliginosa*) is another native bird species known to experience severe population declines due to extreme weather events. This species was driven to local extinction on the subantarctic Snares Islands in mid-2001, probably due to a severe north-easterly storm that struck the island group in July of that year (Miskelly & Sagar 2008). Severe local fantail population declines that occurred in the Hutt Valley and in Wellington City in 2011 were likely to have been caused by two unusually severe snowfall events that occurred in July and August of that year (McArthur 2024; McArthur, Flux et al. 2024).

The observed changes in habitat and bird populations were catchment specific. For example, fine substrate increased most in the Ngaruroro and Tutaekuri Rivers, whereas vegetation cover declined most in the Tukituki and Tutaekuri Rivers. However, patterns of change in shorebird populations were consistent across species, with all experiencing the strongest decline along the Tutaekuri River, followed by the Ngaruroro and Tukituki. This result contrasts with those of a study in South Island braided rivers, which showed species-specific responses of shorebirds to changes in river flow and predation by non-native mammals (Cruz et al. 2013). These different results may arise if large-scale impacts from catastrophic disturbance events such as Cyclone Gabrielle overwhelm species-specific responses.

The catchment-scale declines in populations of banded dotterels, black-fronted dotterels, pied stilts, and South Island pied oystercatchers that we detected on these Hawke’s Bay rivers following Cyclone Gabrielle appear to be the first such declines reported for these species in New Zealand. However, it is not clear from our results whether these observed population declines are a result of adult mortality, or a change in shorebird distribution and habitat use in response to local declines in habitat quality. Given the time of year that Cyclone Gabrielle struck New Zealand, differences in the life-history traits of these species may have resulted in species-specific differences in adult mortality or post-cyclone changes in habitat use.

In mid-February most of the banded dotterels that breed on the Tutaekuri, Ngaruroro, and Tukituki Rivers would probably have finished breeding and have already migrated to post-breeding or wintering sites at estuaries, harbours and coastal lagoons in Hawkes’ Bay, the Bay of Plenty, Auckland and Northland (Pierce 1999). This being the case, it appears unlikely that the 15% decline observed in 2023 is a result of a mass-mortality event that occurred on Hawke's Bay rivers during Cyclone Gabrielle. Instead, if these catchment-scale population declines were caused by high rates of adult mortality that occurred during Cyclone Gabrielle, it is perhaps more likely that this mortality occurred at these coastal post-breeding and wintering sites, many of which also experienced severe flooding during Cyclone Gabrielle. Alternatively, this mortality may have occurred over a more prolonged period in the weeks and months that followed, perhaps due to an interruption in food availability in heavily disturbed coastal or riverine habitats.

In contrast to banded dotterels, most of the black-fronted dotterels that breed on Hawke's Bay rivers were likely to have still been present on these rivers when Cyclone Gabrielle struck in mid-February. Most black-fronted dotterels breeding in New Zealand appear to occupy their breeding habitats year-round, with only a small minority migrating to wintering sites at nearby estuaries, coastal lagoons, and lake shores (Heather 1973; Dennison & Robertson 1999; Heather & Robertson 2015). This being the case, it is more likely that the 30% decline observed in 2023 is indeed the result of a mass-mortality event that occurred on Hawke's Bay rivers during Cyclone Gabrielle, or in the weeks or months that followed.

In the case of populations of both pied stilts and South Island pied oystercatchers breeding on Hawke's Bay rivers, the timing of any post-breeding movements, and the locations of post-breeding or wintering sites for these species, are more poorly known, making it less clear where, if any, adult mortality occurred following Cyclone Gabrielle.

It is possible that the catchment-scale declines in populations of banded dotterels, black-fronted dotterels, pied stilts, and South Island pied oystercatchers were caused by a change in habitat use rather than by adult mortality. Local declines in habitat quality caused by Cyclone Gabrielle, such as a reduction or disruption to food availability on Hawkes' Bay rivers, could have resulted in significant numbers of shorebirds relocating to higher-quality breeding habitats elsewhere. However, evidence for this occurring in the aftermath of Cyclone Gabrielle appears to be weak. Each of these four species tends to exhibit a high degree of fidelity to breeding sites, with most experienced breeders returning to the same breeding territories each year (Baker 1969; Pierce 1989; Marchant & Higgins 1993; Sagar et al. 2002; Dowding & Moore 2006).

There is also little published evidence that adult New Zealand shorebirds undertake mass movements between breeding sites from one year to the next in response to local habitat disturbance. Transitory mass movements of shorebirds can occur during the breeding season following a flood event, but in these cases shorebirds typically retreat to nearby refugia habitats before rapidly returning to their breeding territories once floodwaters recede (e.g. Crossland & Crutchley 2020).

Shorebird surveys carried out along the Hawke's Bay coastline showed that the numbers of banded dotterels, black-fronted dotterels, and pied stilts had declined by 31%, 22%, and 34%, respectively, between 2021 and 2024 (McArthur, Thomas et al. 2021; McArthur, Toy et al. 2024). This strongly suggests that the shorebird population declines observed on Hawke's Bay braided rivers cannot be explained by birds relocating to nearby coastal habitats during the following breeding season. One possible exception is that the number of South Island pied oystercatchers counted along the Hawke's Bay coastline increased by 121% between

2021 and 2024 (McArthur, Toy et al. 2024). Some of this increase could be explained by birds relocating from the Hawke's Bay braided rivers.

We found only weak links between changes in bird density and changes in habitat characteristics. It has been known for some time that riverbed vegetation cover and the size-class structure of riverbed substrates has an influence on the local density of riverbed-nesting shorebirds, although this knowledge has largely been based on anecdotal observation rather than quantitative evidence (O'Donnell et al. 2016). Cyclone Gabrielle caused substantial reductions in riverbed vegetation cover in all three river catchments. Percentage cover of fine substrates also increased, essentially covering medium and large substrates. Sections of riverbed with greater reductions in vegetation cover after Cyclone Gabrielle tended to experience the largest increases in black-fronted dotterel and pied stilt densities, but no such relationship was observed for banded dotterel densities.

There were no relationships detected between local shorebird densities and changes in the percentage cover of fine, medium, and coarse substrates. However, it is worth noting that the two catchments that experienced the strongest changes in substrate composition (Tutaekuri and Ngaruroro) also experienced the greatest declines in shorebird density.

The lack of a correlation between changes in local shorebird densities and changes in substrate size-class structure could be due to several factors. For example, disturbance to riverbed habitats caused by Cyclone Gabrielle was unlikely to be confined to changes in riverbed vegetation and substrate. Severe scouring of the riverbed by floodwaters, the extensive deposition of fresh sediments, and a sustained increase in turbidity are all likely to have affected the riverbed invertebrate communities on which these shorebirds rely for food (see section 4 of this report). These changes in potential food availability, and the impacts of these changes on local shorebird densities, may have acted to mask the impacts of local changes in vegetation cover and size-class structure.

Alternatively, if the shorebird population declines observed on these rivers following Cyclone Gabrielle were because of adult mortality that occurred elsewhere (e.g. at post-breeding or wintering sites), this, combined with the high breeding-site fidelity of these species, may also act to mask the impacts of local changes in vegetation cover and size-class structure.

This being the case, monitoring changes in vegetation structure, substrate size-class structure, and local shorebird densities when these rivers are not severely disturbed by an extreme weather event may further improve our understanding of the influence of riverbed vegetation and substrate size-class structure on local shorebird densities. These surveys have created the first catchment-scale data sets capable of quantifying the relationship between shorebird densities, riverbed vegetation cover, and substrate size-class structure, making a significant contribution to our existing knowledge of the ecology of riverbed-nesting shorebirds.

If the catchment-scale declines in the abundance of shorebirds on the Tutaekuri, Ngaruroro, and Tukituki Rivers are indeed a result of adult mortality, then the magnitude of these declines is of regional, national, and global significance. Combining the Hawke's Bay river and coastal shorebird surveys (McArthur, Allen et al. 2024; McArthur, Toy et al. 2024), we estimate a 17% population decline in adult banded dotterels (from 2,813 to 2,337) following the cyclone, equating to an approximate 2.5% decline in the national and global breeding population of banded dotterels (Hansen et al. 2016). Banded dotterel numbers are currently estimated to be declining at an average rate of between 1.4% and 3.7% per annum across their entire New Zealand breeding range (O'Donnell & Monks 2020). An additional decline of 2.5% in the national/global breeding population, attributable to a single extreme weather event affecting just one region of New Zealand, represents an alarming escalation in this declining population trend.

Black-fronted dotterels are largely restricted to stony riverbed habitats in Hawke's Bay, and the Tutaekuri, Ngaruroro, and Tukituki Rivers represent a major stronghold for this species in the North Island and in New Zealand, supporting between 47% and 52% of the national population (McArthur et al. 2022). Combining the Hawke's Bay survey results with recent surveys of Wairarapa rivers (McArthur & Burgin 2017), we estimate that New Zealand supported a national population of between 2,480 and 2,850 black-fronted dotterels before Cyclone Gabrielle, an upwards revision of the previous estimate of 2,000 birds (Heather & Robertson 2015). If the 30% decline in black-fronted dotterel numbers observed in 2023 is indeed a result of adult mortality, this would equate to an approximately 15% decline in the New Zealand breeding population of black-fronted dotterels.

A key remaining question is how rapid habitat and bird population recovery will be – if it happens at all. Vegetation cover is expected to rapidly rebound, but largely through reinvasion by non-native plants such as tree lupin (*Lupinus arboreus*) and willow (*Salix* spp.). The early stages of this process were observed during the 2023 survey, just 8 months after the cyclone. These invasive plants could further compound the cyclone impacts on shorebirds by reducing habitat availability and providing cover for mammalian predators, alongside other impacts such as competition with native plants and changes to river hydrology.

Furthermore, an earlier study of braided rivers in Canterbury showed that cover of invasive plants was higher in rivers with larger maximum flows and in plots with fine substrate texture (Brummer et al. 2016). This suggests that large-scale flood events with sediment deposition, such as Cyclone Gabrielle, may further facilitate plant invasions of braided rivers. Substrate composition may gradually shift back towards medium-sized substrate as sediment continues to wash out of the system with normal river fluctuations, but the rapid re-establishment of invasive plants could stabilise deposited sediment and drive a more permanent change in braided riverbeds.

Due to the uncertainty regarding whether these shorebird population declines on Hawke's Bay rivers have been caused by adult mortality or by changes in habitat use, the fate of native shorebirds is more difficult to predict. It is not clear whether, or how rapidly, these populations will recover from the observed declines, but this would probably depend on recovery of habitat, resources, and breeding success. Although few studies have quantified the adverse impacts of extreme weather on native bird populations in New Zealand, overseas studies have demonstrated large-scale avian mortality after extreme weather events (Wiley & Wunderle 1993; Fairbairn et al. 2022).

The long-term population impacts of these events have proven more difficult to quantify, due to the rarity and randomness of extreme weather events, and to the paucity of long-term population trend data over appropriate time scales (Jenouvrier 2013). When combined with other threats to braided river birds (such as predation by mammalian predators), future increases in the frequency or severity of extreme weather events are likely to negatively affect the population trends of already threatened and at-risk species.

3.3.5 Conclusions and recommendations

Here we present answers to our original research questions and provide recommendations for the management of, and future research on, extreme weather impacts on braided rivers.

Conclusions

- How were braided river bird habitat characteristics (vegetation cover, substrate composition) altered by Cyclone Gabrielle?

Braided riverbeds experienced increased cover of fine substrate after Cyclone Gabrielle, but vegetation cover (mostly non-native species) decreased.

- How did the abundance and distribution of native shorebirds (banded dotterels, black-fronted dotterels, pied stilts, South Island pied oystercatchers) change after Cyclone Gabrielle?

Populations of banded dotterels, black-fronted dotterels, pied stilts, and South Island pied oystercatchers on Hawke’s Bay braided rivers declined by 15%, 30%, 16%, and 43%, respectively, after Cyclone Gabrielle.

- Were changes in the abundance and distribution of native shorebirds related to changes in habitat characteristics (i.e. cover of vegetation and substrate size classes)?

Sections of riverbed with greater reductions in vegetation cover after Cyclone Gabrielle experienced the largest increases in black-fronted dotterel and pied stilt densities. No significant relationships were detected between local shorebird densities and changes in the percentage cover of fine, medium, and coarse substrates.

Recommendations

- Continue to monitor shorebird populations along Hawke’s Bay braided rivers and coastlines, and establish similar monitoring programmes in other regions. This approach will allow us to disentangle mortality from movement and improve our understanding of how shorebird species respond to extreme weather events. Moreover, given that the intensity of tropical cyclones is predicted to increase in the coming decades, understanding whether, and how rapidly, shorebird populations recover from these observed declines will be crucial for improving our understanding of the vulnerability of these species to the impacts of extreme weather events. This will, in turn, assist HBRC, and other statutory authorities, to make better-informed decisions regarding the measures required to mitigate the impacts of extreme weather events on populations of our riverbed-nesting shorebirds.

  For this reason, we recommend that a second multi-year series of shorebird surveys be scheduled for the Tutaekuri, Ngaruroro, and Tukituki River catchments between 2026 and 2029, both to quantify the extent to which these shorebird populations have recovered from the adverse impacts of Cyclone Gabrielle, and to add to this long-term shorebird monitoring data set.

- Implement mitigation measures to reduce the impacts on shorebird populations and braided river ecosystems. Given the risk that extreme weather events pose to the viability of the internationally and nationally significant populations of shorebirds inhabiting Hawke's Bay rivers, climate change adaptation plans should include mitigation measures designed to both reduce and offset the adverse impacts of extreme weather events. These mitigation measures could include implementing landscape-scale mammalian predator control along the Tutaekuri, Ngaruroro, and Tukituki Rivers to increase shorebird breeding productivity during non-flood years, and thereby offset losses of adults, eggs and chicks caused by extreme weather events.

  Climate change mitigation could also include adapting local flood protection and land-use practices to allow more room for rivers to expand across floodplains during extreme weather events, or creating artificial shorebird habitats beyond river corridors to provide alternative nesting habitats and 'flood refugia' with lower risk of being inundated during high-rainfall events.

  The tentative links between changes in habitat and bird density may also point to potential habitat management approaches, such as the periodic removal of woody vegetation to increase breeding habitat and refuge availability, or extraction plans that could be easily modified to minimise impacts on shorebird habitat. In cases where shorebird habitats are being managed for other reasons (e.g. flood protection), disentangling the impacts of extreme weather events on shorebird populations from those caused by flood protection activities will also be increasingly important to ensure the potential adverse impacts of future flood protection activities continue to be adequately managed.

  Continuing to monitor the long-term population trends of riverbed-nesting shorebirds on Hawke's Bay rivers (the first recommendation) will help tease apart the impacts of extreme weather events from flood protection activities.

3.4 Northland coastal active dunes

3.4.1 Introduction

Coastal active dunes (hereafter active dunes) are a naturally uncommon and endangered ecosystem (Williams et al. 2007). They provide important ecosystem services such as protection from storm surges and sea-level rise (Johnston et al. 2023), opportunities for recreation, tourism, and cultural practices (Barbier et al. 2011), and habitat for biodiversity, including threatened species (Holdaway et al. 2012). The area of active dunes in New Zealand declined by around 80% between the 1950s and 2008 (Hilton et al. 2000; MfE & Stats NZ 2018), and the active dune systems that remain are often highly modified and facing multiple threats, including land-use change, invasive species, climate change, and extreme weather (Hilton et al. 2000; Hilton 2006).

Active dunes are the first point of landfall for tropical cyclones and are subject to some of the strongest rainfall, winds, storm surges, and deposition of storm debris. To characterise changes in active dune area and vegetation cover following Cyclone Gabrielle, we used data from the Northland Regional Council coastal dune vegetation monitoring programme, which began in 2016. This monitoring programme consists of surveys conducted along transects at 14 sites. We aimed to answer the following research questions:

- In Northland, to what extent has active dune width changed following Cyclone Gabrielle, and does this vary among sites?
- To what extent has overall vegetation cover, native plant dominance, and percent cover of key plant species on active dunes changed following Cyclone Gabrielle, and does this vary among sites?

3.4.2 Methods

Here we made use of data stored in the Coastal Monitoring Database,[7] administered by the Coastal Restoration Trust. This data set includes repeat measures of sand dunes nationally, with data being collected by a range of agencies and community groups; we restricted our analyses to dunes in Northland. The 14 sites are distributed across 11 locations; three locations have two sampling sites near to one another, and we account for this spatial non-independence by using a nested random effect in our statistical models, reflecting the structure of the monitoring database.

At each site, surveys are conducted along replicate transects established from the back to the front of the sand dunes, which we refer to as the dune width (from our analyses, n = 1–17 transects per site, median = 4). The landward end of each transect has been permanently marked for easy relocation and the transect bearing recorded to facilitate repeat surveys. Vegetation is sampled at each metre along the transect, from the starting point to the dune toe, by placing a pole upright on the dune and recording the uppermost plant species (or bare sand) that is touching the pole, and the identity and height of the tallest plant within a 30 cm diameter.

Key indicator native plant species were identified through conversations with Richard Griffiths and Laura Shaft (Northland Regional Council) and included kōwhangatara (*Spinifex sericeus*), pīngao (*Ficinia spiralis*), wīwī (*Ficinia nodosa*), small-leaved pōhuehue (*Muehlenbeckia complexa*), and tātaraheke (*Coprosma acerosa*). Key non-native plant species included invasive marram grass (*Ammophila arenaria*), buffalo grass (*Stenotaphrum secundatum*), kikuyu grass (*Cenchrus clandestinus*), and ice plant (*Carpobrotus edulis*). Not enough data were available to test for changes in percentage cover for pīngao, tātaraheke, or marram grass, and so these species were excluded from our analyses.

We limited our analyses to transects where data had been collected both before and after the cyclone. We also only used data from the two transect surveys that were closest to before/after 15 February 2023, when the cyclone began to abate and move away from mainland New Zealand (i.e. the closest possible comparison of pre- and post-cyclone dune vegetation). The dates of pre-cyclone surveys ranged from 8 March 2021 to 13 January 2023, with 96% of transects sampled in the year before Cyclone Gabrielle. The dates of post-cyclone surveys ranged from 27 March 2023 to 7 May 2024, with all but two transects (97%)

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[7] https://monitoring.coastalrestorationtrust.org.nz (accessed 11 July 2024).

surveyed during the year following the cyclone. This relatively short temporal scale is important for studying dynamic ecosystems such as coastal dunes and supports the attribution of observed changes to the impacts of the cyclone rather than to more gradual processes. The final data set consisted of 71 transects from 13 sites across 10 locations (Figure 42Figure 42).

To examine the impacts of Cyclone Gabrielle on transect distance (i.e. dune width) and top plant height, we used a linear mixed effects model with transect distance as the response variable, sampling period (pre- vs post-cyclone) as the explanatory variable, and a nested random effect of transect within site within location to account for non-independence of observations. For the model of top plant height, species identity was also included as a random effect to account for variation among species. To examine the impacts of Cyclone Gabrielle on vegetation cover variables, we used generalised linear mixed effects models with a beta error distribution (log link function) suitable for non-integer proportion data (Brooks et al. 2017). Data were transformed to avoid zeroes and ones before analysis, following Smithson and Verkuilen (2006):

$$\frac{y \times (n - 1) + 0.5}{n}$$

where y is the cover value and n is the total sample size.

Each model contained proportion cover as the response variable (converted to percent for reporting results), sampling period as the explanatory variable, and a nested random effect of transect within site within location. All models were implemented in R version 4.4.1 (R Core Team 2024) with the package glmmTMB.

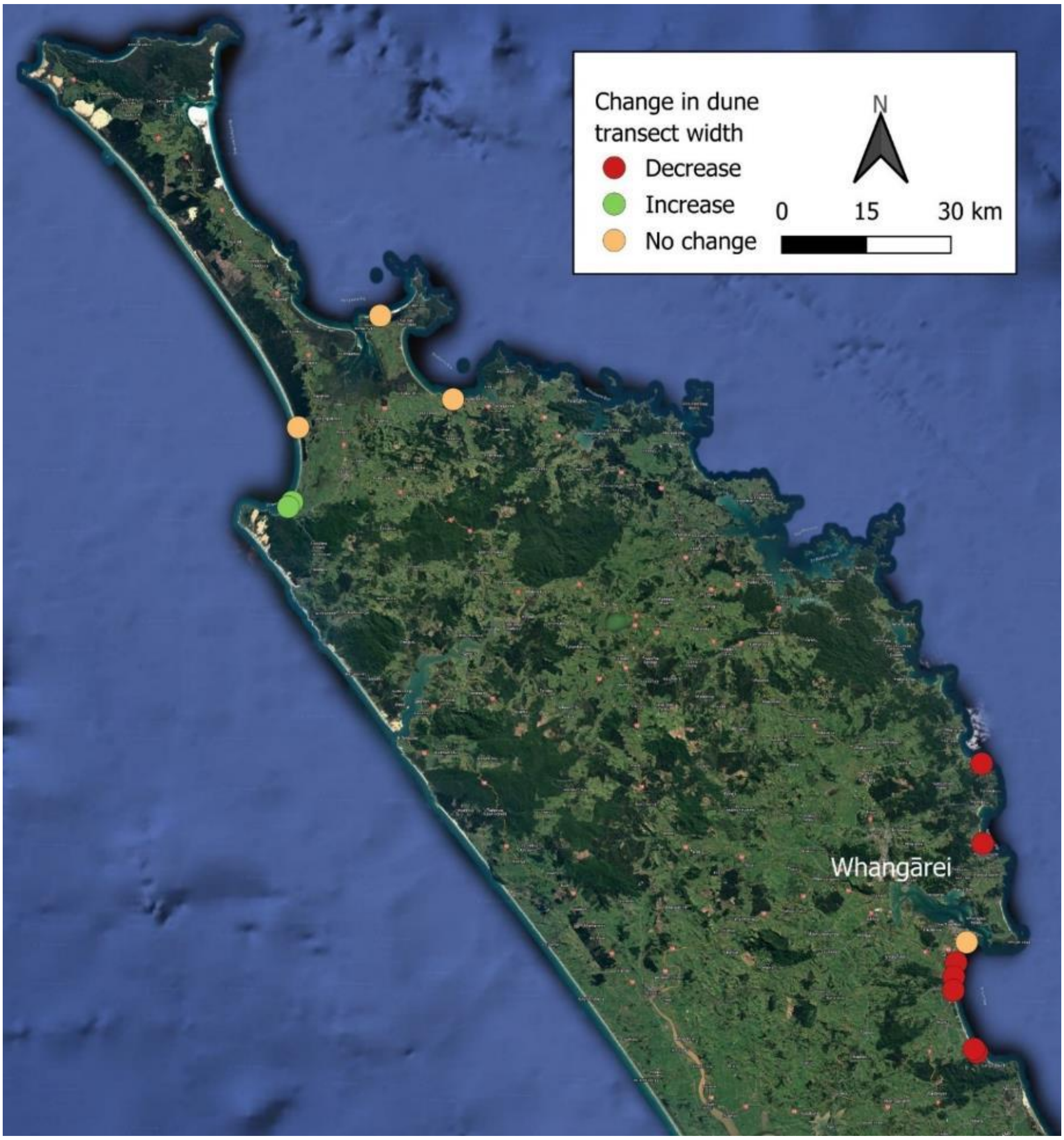

Figure 42. Map showing the 13 Northland coastal active dune monitoring sites for which pre- and post-cyclone data were collected.

Note: different symbol colours represent the change in transect width observed between pre- and post-cyclone surveys.

3.4.3 Results

Overall transect distance (i.e. dune width) declined by an average of 2.1 m (4% of pre-cyclone distance) between pre- and post-cyclone surveys (Figure 43A), indicating that Cyclone Gabrielle probably reduced the overall area of active dunes in Northland. Survey sites showed strong variability in their change in transect distance, ranging from a mean decrease of 9.6 m at Ruakaka Surf Club to a mean increase of 13.7 m at Kaka Street, Ahipara (Figure 44).

Overall dune vegetation cover was unchanged by the cyclone (79% cover before the cyclone and 78% after the cyclone; Figure 43B), as was native dominance (i.e. the percentage of vegetation cover that was native) (61% both before and after the cyclone; Figure 43C). These results indicate that the cyclone had no immediate impact on active dune vegetation cover and did not immediately increase plant invasion of Northland dunes. However, the overall trends obscured strong variability among sites in their change in vegetation cover and dominance of native plant species (Figure 45Figure 45), but no spatial patterns were apparent like those observed for change in transect distance. Vegetation was 6% taller on average after the cyclone (Figure 43D), a small but statistically significant increase.

Small-leaved pōhuehue, buffalo grass, and kikuyu grass all demonstrated a change in their percentage cover between the two survey periods. Cover of small-leaved pōhuehue increased by almost a quarter (22%) between pre- and post-cyclone surveys (Figure 46B), while buffalo grass increased by a third (36%) (Figure 46C). In contrast, cover of kikuyu grass decreased by almost a third (31%) after the cyclone (Figure 46Figure 46D). Cover of kōwhangatara (Figure 46A), wīwī, and ice plant did not change between surveys conducted before and after Cyclone Gabrielle. However, again there was substantial variability among sites in terms of the change in percentage cover of key plant species (Figure 47Figure 47A–F).

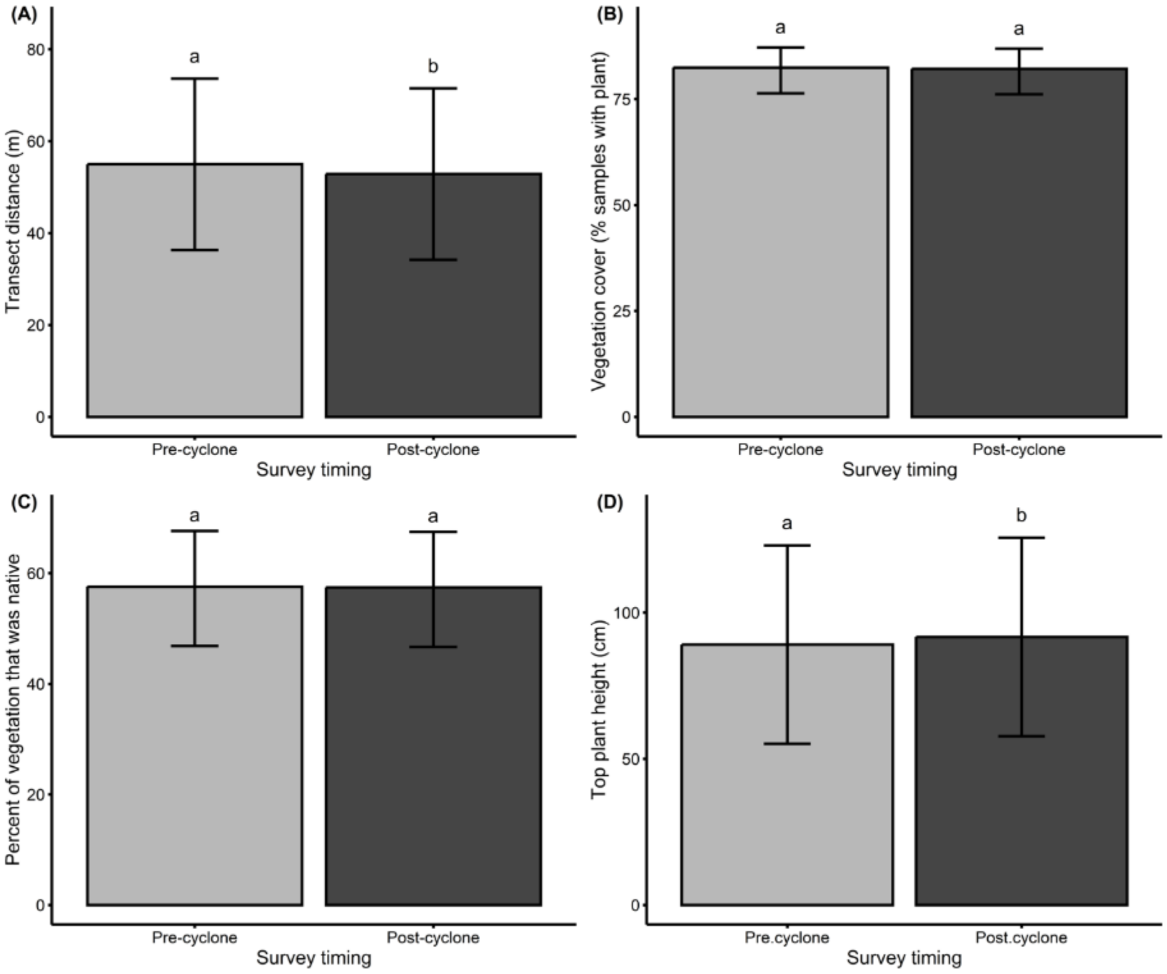

Figure 43. Mean (± 95% CI) transect distance (a measure of dune width) (A), percentage cover of vegetation (B), percentage of vegetation that was native (i.e. native dominance) (C), and maximum plant height (D) of Northland coastal active dunes, before and after Cyclone Gabrielle.

Note: different lowercase letters indicate a significant difference (*P* < 0.05) between pre- and post-cyclone means.

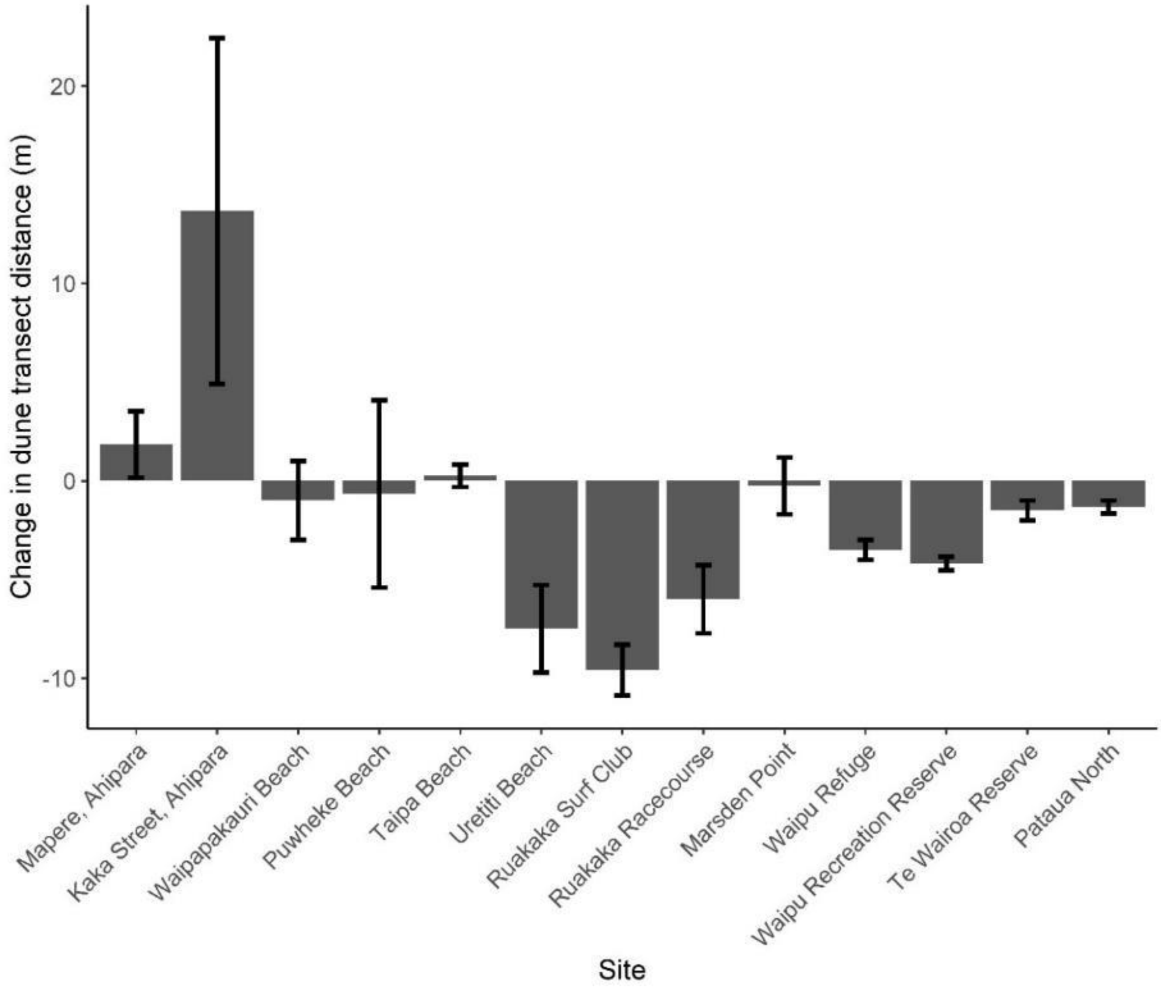

Figure 44. Change in mean (± 1 SE) transect distance (a measure of dune width) at 13 Northland coastal active dune monitoring sites before and after Cyclone Gabrielle.

Note: sites are ordered from west to east.

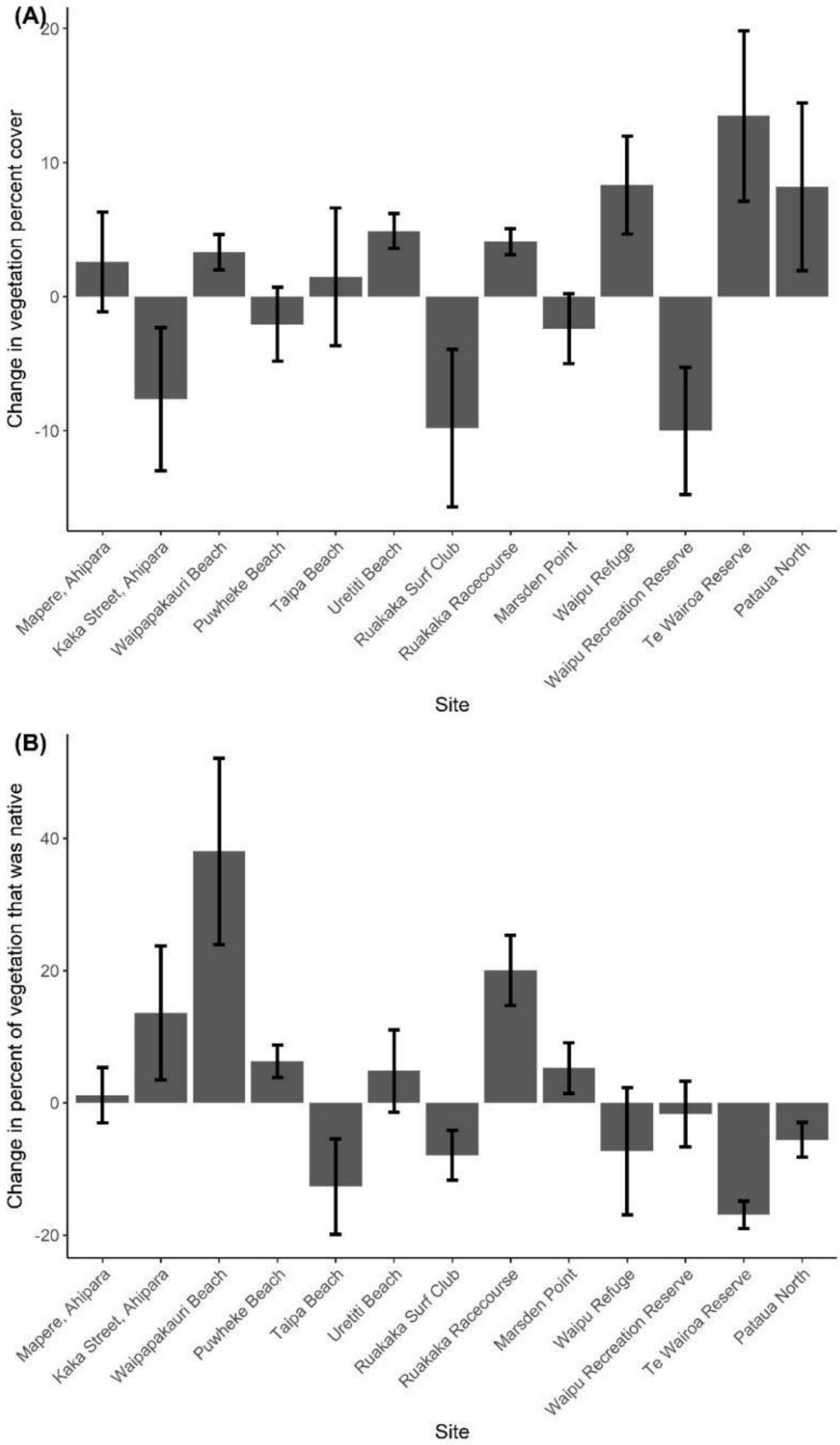

Figure 45. Change in mean (± 1 SE) percentage cover of vegetation (A) and percentage of vegetation that was native (i.e. native dominance) (B) at 13 Northland coastal active dune monitoring sites before and after Cyclone Gabrielle.

Note: sites are ordered from west to east.

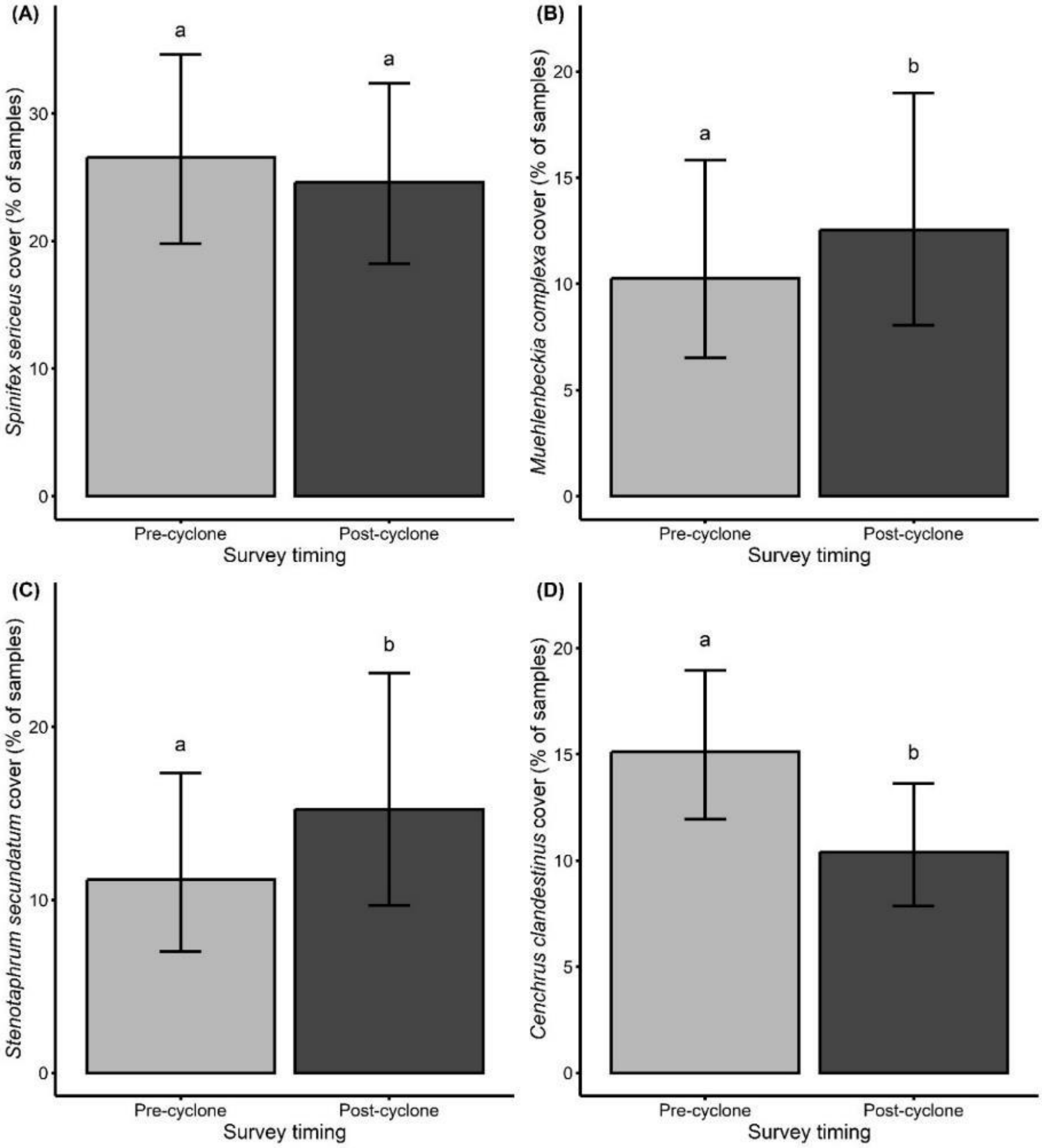

Figure 46. Mean (± 95% CI) percentage cover of kōwhangatara (*Spinifex sericeus*, native) (A), small-leaved pōhuehue (*Muehlenbeckia complexa*, native) (B), buffalo grass (*Stenotaphrum secundatum*, non-native) (C), and kikuyu grass (*Cenchrus clandestinus*, non-native) (D) at Northland coastal active dune monitoring sites before and after Cyclone Gabrielle.

Note: different lowercase letters indicate a significant difference ($P < 0.05$) between pre- and post-cyclone means.

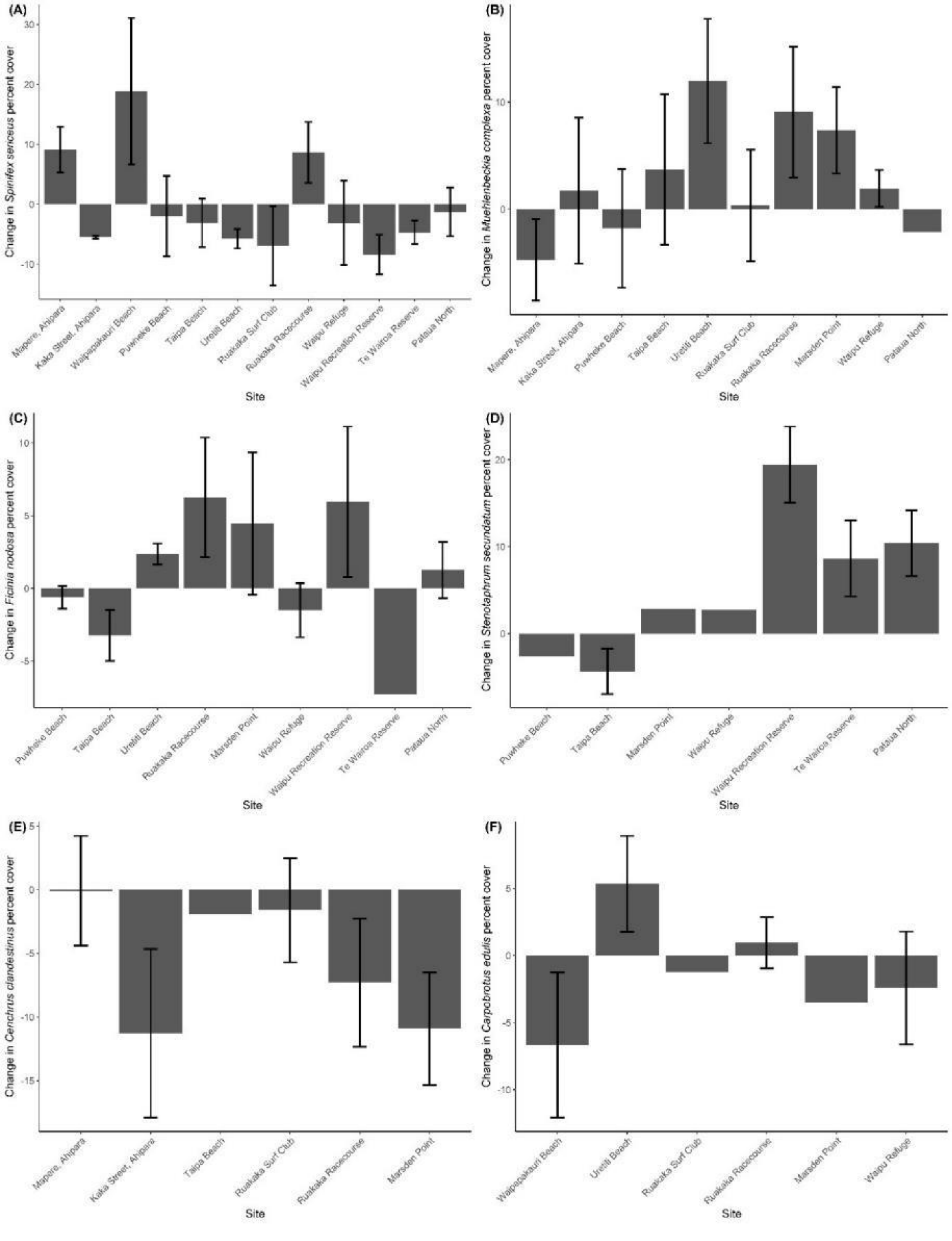

Figure 47. Change in mean (± 1 SE) percentage cover of kōwhangatara (*Spinifex sericeus*, native) (A), small-leaved pōhuehue (*Muehlenbeckia complexa*, native) (B), wiwi (*Ficinia nodosa*, native) (C), buffalo grass (*Stenotaphrum secundatum*, non-native) (D), kikuyu grass (*Cenchrus clandestinus*, non-native) (E), and iceplant (*Carpobrotus edulis*, non-native) (F) at Northland coastal active dune monitoring sites before and after Cyclone Gabrielle.

Note: sites are ordered from west to east.

3.4.4 Discussion

An average of 4% of coastal active dune width was lost at our Northland study sites after Cyclone Gabrielle. Because active dunes are highly dynamic ecosystems, we cannot exclude other causes of the observed loss with absolute certainty, such as gradual erosion. However, multiple lines of evidence support Cyclone Gabrielle as a major contributing factor to the loss of coastal dune width.

For example, the seven sites with the largest decreases in transect distance (i.e. dune width) were all located along a c. 50 km stretch of the east coast between Matapouri and Waipu that was directly facing the path of the cyclone and most exposed to storm surges. Moreover, our findings largely reflect those of another Extreme Weather Research Platform (EWRP) project led by Dr Murray Ford (University of Auckland), who used an existing data set based on high-resolution satellite imagery to assess coastline erosion caused by Cyclone Gabrielle.[8] That study highlighted Ruakaka in Bream Bay as a badly affected location, and this was also the location of the worst-affected site from our study, with the next four also located along the 15 km of coastline south to Waipu Beach. Also, 96% of the data were collected within 1 year either side of the cyclone, facilitating close comparison of pre- and post-cyclone data.

Results of the EWRP coastline mapping project showed that Cyclone Gabrielle typically caused 5–15 m of erosion along the northeastern North Island coastline, but there was strong variability among sites, reflecting the findings of our analysis. The erosion mapping study also suggested that Cyclone Gabrielle may have triggered a state change at some dune locations. For example, previously stable coastlines may have transitioned to eroding coastline after the storm, although ongoing monitoring is needed to confirm this. Although we detected changes in percentage cover for some indicator plant species, future analysis could use the full data set to place the cyclone impacts in long-term context and test for changes in any trends that were triggered by the cyclone. Future monitoring along the same transects will illuminate whether dune width shows signs of recovery or continued loss.

Despite active dune width declining after the cyclone, dune vegetation cover was largely resilient. This ideal combination of resilience and mitigation services (e.g. storm surge protection) is crucial for ecosystems in extreme weather events and is like that observed for flood mitigation by wetlands (section 3.2) and erosion mitigation by native forest (section 2.1; McMillan et al. 2023). To safeguard and augment the ecosystem services provided by coastal active dunes, management actions should aim to minimise dune losses to development, prevent vehicle and stock access, manage plant invasions, and plant native sand-binding species.

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[8] https://resiliencechallenge.nz/project/mapping-cyclone-driven-erosion-of-north-islands-east-coast-beaches/ (accessed 20 September 2024).

3.4.5 Conclusions and recommendations

Here we present answers to our original research questions and provide recommendations for the management of, and future research on, extreme weather impacts on coastal active dunes.

Conclusions

- In Northland, to what extent has active dune width changed following Cyclone Gabrielle, and does this vary among sites?

An average of 2.1 m (4%) of active dune width was lost after Cyclone Gabrielle, with the largest declines observed at sites along the east coast of Northland.

- To what extent has overall vegetation cover, native plant dominance, and percent cover of key plant species on active dunes changed following Cyclone Gabrielle, and does this vary among sites?

Overall cover and native plant dominance of active dune vegetation was unchanged by the cyclone. Cover of small-leaved pōhuehue and buffalo grass increased after the cyclone, while kikuyu grass cover decreased. There was substantial variability among sites in terms of the change in percentage cover of key plant species, but few consistent patterns emerged.

Recommendations

- Continue monitoring of coastal active dunes in Northland and other regions around New Zealand. Care should be taken to identify plants to species level, where possible, to improve the taxonomic resolution of the data and depth of analyses.
- Implement management of coastal active dunes to safeguard and augment biodiversity and ecosystem services. Management actions taken could include preventing vehicle and stock access, controlling non-native plant invasions, and planting native sand-binding species.

3.5 Conservation infrastructure: North Island ecosanctuaries

3.5.1 Introduction

Ecosanctuaries are a vital part of the conservation infrastructure of New Zealand, where they are defined as ‘a project larger than 25 ha implementing multi-species, pest mammal control for ecosystem recovery objectives, and with substantial community involvement’ (Innes et al. 2019). Their overarching goal is to restore ecosystems to a state dominated by diverse and abundant native species and their interactions.

This is generally achieved through the eradication (or near-zero densities) of the full suite of pests (e.g. rats, mustelids, cats, brushtail possums, ungulates, invasive plants), and the reintroduction and protection of species that are directly threatened by pests, which has historically focused on vertebrates. Moreover, by providing a place to observe and connect with endemic and local biodiversity, as well as opportunities to participate in various projects, ecosanctuaries play an important role in linking communities with conservation. In essence, ecosanctuaries protect some threatened species and represent a significant contribution to conservation efforts throughout New Zealand.

A major focus of climate change research has been on the direct effects of a shifting climate or extreme weather events on species populations and ecosystem extent and condition. However, extreme weather events, such as cyclones, have the potential to affect ecosanctuaries in several ways. Cyclone impacts could be direct and immediate, including wildlife death and injury, and habitat destruction. Other impacts may be indirect or occur over a longer time. For example, damage to critical infrastructure or reduced pest management following a cyclone could lead to increased predation pressure on threatened species, or opportunity costs associated with recovery to a previous state instead of advance towards future goals. Further impacts may take time to become apparent, with changes in species abundances lagging resource fluctuations.

To safeguard the hard-won conservation gains of ecosanctuaries against extreme weather events, there is an urgent need to identify the species, ecosystems, and conservation infrastructure that are most at risk. Here we aim to profile how Cyclone Gabrielle affected ecosanctuaries across the North Island of New Zealand. We aimed to answer the following research questions:

- At what frequency were different types of cyclone damage experienced by ecosanctuaries?
- What were the range and frequency of impacts on conservation infrastructure and activities?

3.5.2 Methods

We interviewed representatives from ecosanctuaries across the North Island. Ecosanctuaries were identified based on Innes et al. 2019, the list on the Sanctuaries of New Zealand Inc. website,[9] and word of mouth. Smaller pest-fenced ecosanctuaries (based on Burns et al. 2012) were also included in our study because they often host vulnerable biodiversity and represent significant conservation investment. These criteria resulted in data from 65 ecosanctuaries (Figure 48Figure 48).

Ecosanctuary representatives were prompted with a set of standardised questions. Responses were recorded as presence/absence of each type of cyclone damage or disruption to conservation activities, while notes were taken on the types and magnitudes of impacts that were experienced by each ecosanctuary. If a particular type of conservation activity was not present at an ecosanctuary (e.g. no pest fence present), data were coded as NA. The questions asked were:

> As a result of Cyclone Gabrielle, did your ecosanctuary experience damage from:
>
> a inundation?
>
> b sediment deposition?

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[9] https://www.sanctuariesnz.org/; accessed 25 June 2023.

c erosion?

d wind?

As a result of Cyclone Gabrielle, did your ecosanctuary experience damage or disruption to:

a pest fencing?

b other fencing?

c other infrastructure?

d culturally significant sites?

e native wildlife?

f monitoring of native species?

g pest management?

h restoration plantings?

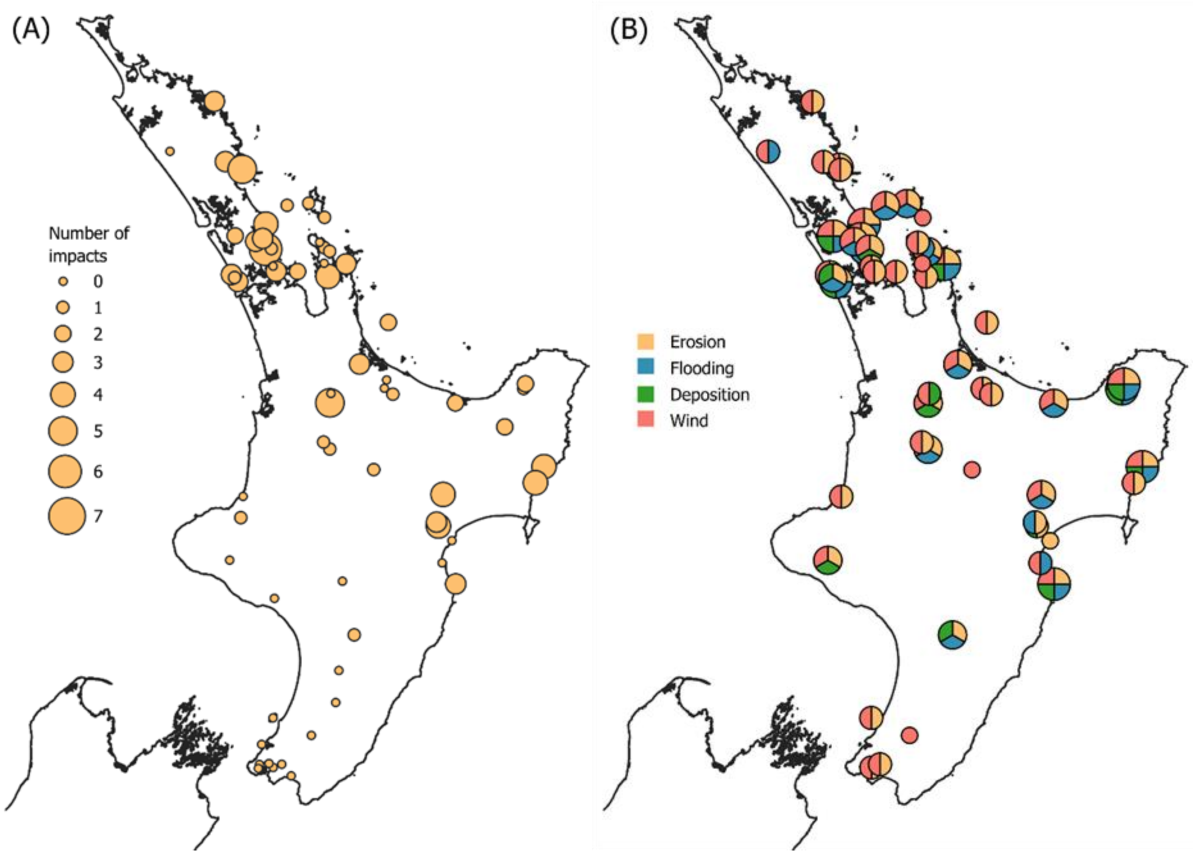

Figure 48. Map showing the 65 ecosanctuaries that were interviewed to assess the impacts of Cyclone Gabrielle. In (A), point size is scaled according to the number of different types of impacts to conservation activities that were experienced by each ecosanctuary. In (B), point size is scaled and coloured according to the number and identity, respectively, of different damage types that were experienced (only ecosanctuaries with recorded cyclone damage are shown).

3.5.3 Results

Prevalence and examples of different types of physical damage

Of the 53 ecosanctuaries that suffered some type of damage from Cyclone Gabrielle, 91% were damaged by wind, 85% by erosion, 47% by inundation, and 32% by sediment deposition (Figure 49A). Only 18% of ecosanctuaries experienced no physical cyclone damage (Figure 49B), with most of these located in the southwest of the North Island (Figure 48A). More than one type of damage was experienced by 74% of ecosanctuaries (Figure 49B), and the median number of types of damage experienced was two.

Wind damage was most frequently reported (Figure 49A), with impacts ranging from minor defoliation to wind throw of hundreds of mature trees. One of the worst examples of wind damage occurred at Bream Head Scenic Reserve in Northland, where the cyclone flattened large stands of naturally regenerating kānuka (*Kunzea ericoides*) forest that were exposed to southwest winds. Significant wind damage was also reported from Mayor Island / Tūhua, where the roofs of buildings were blown off and mature trees were blown down throughout the island. Aongatete Forest Project in the Bay of Plenty also reported wind-thrown trees throughout the forest, resulting in many canopy light gaps up to 0.2 ha in size (section 2.3). At Mahakirau Forest Estate on the Coromandel Peninsula, many trees were blown over by the wind, with movement through the forest requiring a constant clamber around fallen trees and branches or entanglement in fallen kareao (supplejack, *Ripogonum scandens*) vines.

Erosion damage was widespread and occurred in multiple forms (Figure 49A). Landslides were frequently reported, ranging in size from just a few metres to a reported 500 × 100 m (5 ha) slip that affected up to seven trap lines at Ark in the Park in the Waitākere Ranges. Mahakirau Forest Estate experienced numerous landslides, which also deposited sediment into streams and forests, and damaged several tracks used to service pest management lines. Storm surges caused significant coastal erosion, especially in ecosanctuaries around Auckland and Northland, where the ocean washed away active dunes and coastal scrub (section 3.4), and damaged dune restoration plantings, historical midden sites, and coastal trails.

Inundation and sediment deposition were the least reported types of cyclone damage to ecosanctuaries, reflecting the paucity of native forest (and hence ecosanctuaries) in lowland, flood-prone areas where historical clearance has been most comprehensive (Ewers et al. 2006; Allen et al. 2013). Perhaps the most consequential example of inundation occurred at Tōtara Reserve Regional Park in Manawatū-Whanganui, a region that received relatively little attention following the cyclone. Due to its location on the banks of the Pohangina River, Tōtara Reserve Regional Park experienced severe flooding, with campsite facilities completely underwater (Figure 50Figure 49C), and 1–2 m of sediment deposited through buildings and up to 100 m into low-lying parts of the forest. Although sediment may represent fresh substrate and a potential flush of nutrients, it can also spread invasive species, and deposition around the base of trees can starve roots of oxygen, eventually leading to mortality (Redpath & Rapson 2015). Shakespear Regional Park, a peninsula ecosanctuary north of Auckland, also suffered significant flooding: standing water prevented visitor access for multiple days and caused damage to the pest fence (Figure 50B).

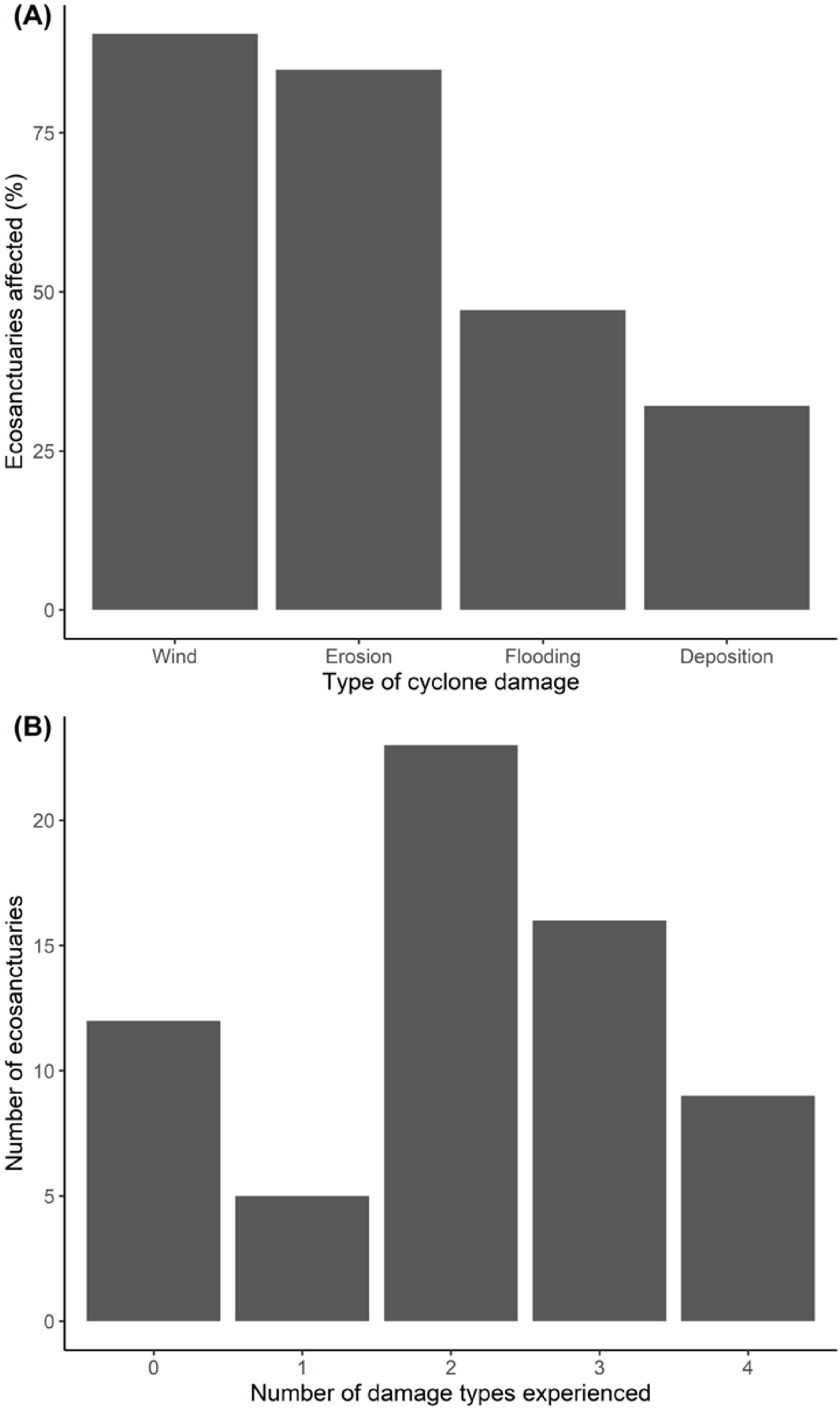

Figure 49. A: the percentage of ecosanctuaries on the North Island of New Zealand that experienced each type of damage from Cyclone Gabrielle, presented from most to least frequent (n = 53 ecosanctuaries that suffered some type of damage) B: frequency of the number of damage types experienced by ecosanctuaries (*n* = 65).

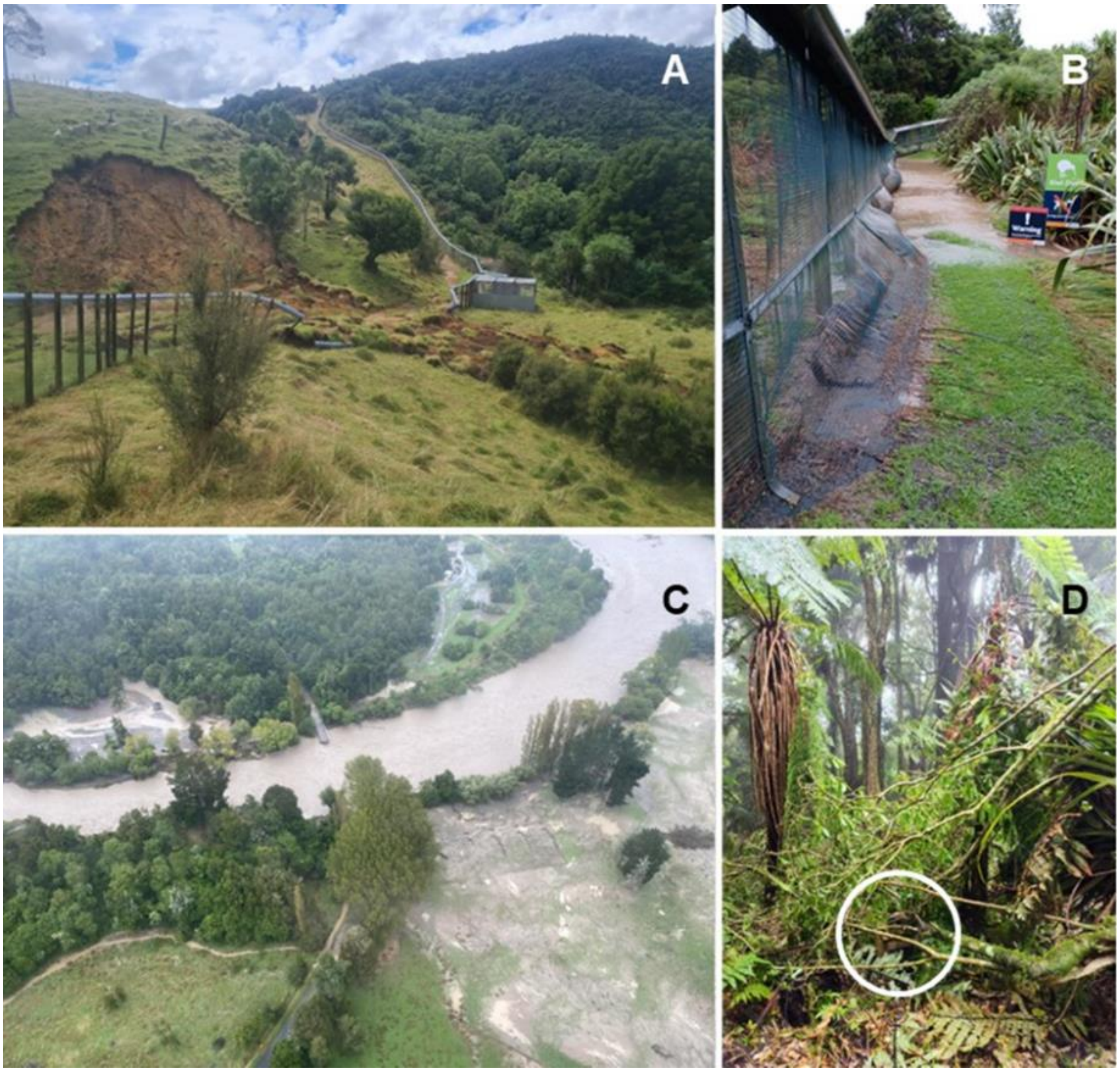

Figure 50. Examples of Cyclone Gabrielle impacts experienced by ecosanctuaries in the North Island of New Zealand: A, landslide damage to the pest fence at Opouahi kiwi crèche, Hawke's Bay; B, flooding damage to the pest fence at Shakespear Regional Park, Auckland; C, impeded access, flooding, and sediment deposition through the forest and camping ground at Tōtara Reserve Regional Park, Manawatū-Whanganui; D, windfall obstructing a trap line and covering a trap (white circle) at Mahakirau Forest Estate, Waikato. (Sources: photo A: Deb Harrington; photo B: Auckland Council; photo C: Horizons Regional Council, photo D: Sara Smerdon)

Conservation infrastructure

Although 23% of North Island ecosanctuaries experienced no impacts on conservation infrastructure or activities, 65% experienced multiple impacts (Figure 51B), with a median of three impacts for affected ecosanctuaries.

Perhaps most crucially, 40% (4 of 10) of surveyed ecosanctuaries that maintain a pest fence and were affected by the cyclone reported that their fence was compromised (Figure 51A). At Opouahi kiwi crèche in Hawke's Bay, which is a predator-free ecosanctuary, landslides flattened the pest fence in two locations (Figure 50A). It took several weeks for the fence to be repaired due to problems with access and availability of contractors, allowing rats (*Rattus* spp.), stoats (*Mustela erminea*), ferrets (*Mustela furo*), and sheep (*Ovis aries*) to enter the ecosanctuary. After several months of intensive trapping, surveillance, and two visits by mustelid detection dogs, staff are optimistic that Opouahi kiwi crèche is once again predator free.

At Sanctuary Mountain Maungatautari in the Waikato, New Zealand's largest mainland predator-free ecosanctuary, the pest fence was damaged by tree falls in six locations. For comparison, there is an average of nine breaches that require fence replacement per year along the 47 km of pest fence maintained by the ecosanctuary. Despite fence repairs being completed within 48 hours, five weasels, seven ship rats and three possums were trapped or detected inside the fence (within 1 year of the cyclone), near to where it was compromised, and are thought to be potentially related to cyclone damage.

At predator-free Wairakei Golf Course, near Taupō, some of the approximately 1,800 tree falls (mostly non-native conifers) damaged the pest fence in two locations. Despite the fence being cleared and fixed within 48 hours, two ferrets were captured following increased trapping efforts.

Finally, flooding caused the pest fence to give way in one location at Shakespear Regional Park (Figure 50B). This damage was repaired the following day, and the fence and other hydrology infrastructure has since been re-engineered to improve drainage in preparation for future flooding events.

Impacts to other fencing, such as that used to exclude stock or feral ungulates, were only reported from 23% of the 26 affected ecosanctuaries that had stock or feral ungulate fencing (Figure 51A), and any impacts on vegetation from browsing mammals could be considered relatively minor. For example, approximately half of the riverside fencing was damaged by flooding at Longbush Reserve in Gisborne. Minor damage to stock fencing occurred at Bream Head Scenic Reserve, Mataia Restoration Project in Kaipara, Shakespear Regional Park, and Boundary Stream Mainland Island near Napier, allowing stock to temporarily access some forested areas. At Boundary Stream, a fenced exclosure protecting the nationally critical ngutukākā (kakabeak, *Clianthus maximus*) from mammalian browsers was also damaged (section 3.6.7), but this was repaired before any plants were browsed.

Damage to other infrastructure was the most widely reported cyclone impact, occurring at 82% of affected ecosanctuaries (Figure 51A), ranging in severity from minor and inexpensive to critically important and costly. Impeded access due to infrastructure damage has been a major and ongoing issue for several ecosanctuaries. Public road closures restricted access for up to several weeks, and hundreds of kilometres of roads and tracks through ecosanctuaries suffered damage, with some areas remaining inaccessible more than a year after the cyclone. In some instances the damage has required hundreds of person-hours to fix, and some tracks will be permanently retired due to wind fall, landslides, logistics of access, and risks to health and safety. Maungataniwha Native Forest in northern Hawke's Bay is one such ecosanctuary: it suffered massive destruction to its road and track infrastructure, with a digger operator still clearing roads over 18 months after the cyclone. Recreational and operational facilities were also affected at many ecosanctuaries, ranging from washed-out walking tracks, boardwalks, and bridges, through to buildings, camping grounds and gates damaged by flooding, wind, or tree falls. Such figures give an indication of the substantial private and community investment in conservation across the affected regions.

Impacts to sites of cultural significance occurred at 32% of the 25 affected ecosanctuaries for which data were collected (Figure 51A). Middens were washed away and buried by landslides at Young Nick's Head (Te Kuri) in Gisborne and Muriwai Penguin Project near Auckland, respectively. Site access was also affected in some ecosanctuaries, such as damage to tracks limiting access to historic pā and whare sites at Maungataniwha Native Forest.

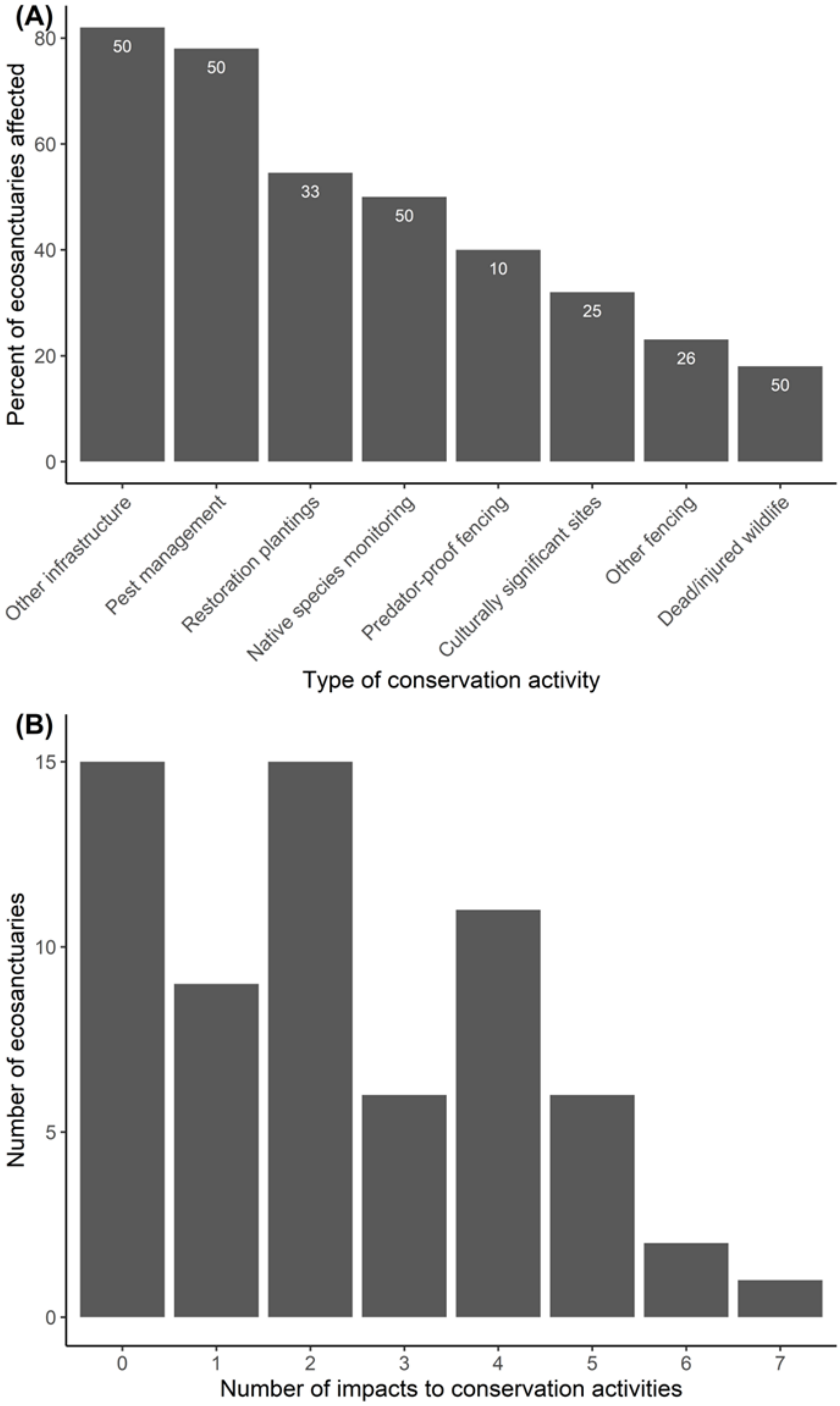

Figure 51. The percentage of ecosanctuaries in the North Island of New Zealand that experienced impacts from Cyclone Gabrielle, by type of conservation activity, presented from most to least frequent.

Notes: In A, sample size of ecosanctuaries that were undertaking each conservation activity before Cyclone Gabrielle are shown at the top of the bar for each category. B shows frequency of how many different impacts to conservation activities were experienced by ecosanctuaries.

Monitoring, pest management, and restoration

Dead or injured native wildlife were not frequently observed, with direct observations reported from only 18% of ecosanctuaries (Figure 51A). Two of the eleven North Island brown kiwi (*Apteryx mantelli*) chicks that were being cared for at Opouahi kiwi crèche were presumed to have died in landslides, and another kiwi was found dead, presumed drowned, at Sanctuary Mountain Maungatautari. Beach-wrecked seabirds (e.g. grey-faced petrel [*Pterodroma gouldi*], fluttering shearwater [*Puffinus gavia*], and little penguin [*Eudyptula minor*]) were observed at multiple coastal ecosanctuaries (e.g. Tāwharanui Regional Park, Shakespear Regional Park), but not in the vast numbers that have been seen after some winter storms (e.g. an estimated 300,000 prions [*Pachyptila* spp.] were thought to have perished in 2011[10]). At Mahakirau Forest Estate and Otawa Scenic Reserve, pepeketua (Hochstetter's frog [*Leiopelma hochstetteri*]) were assumed to have been gravely affected by flooding of and sediment deposition in their favoured streamside habitat during breeding. On a more positive note, the brown teals (*Anas chlorotis*) at Cape Sanctuary were reported to have enjoyed the flooded landscape.

Native species monitoring and pest management were disrupted with varying severity at 50% and 78% of the ecosanctuaries that were affected by the cyclone, respectively (Figure 51A). Impeded access and the slow process of clearing tracks were the primary issues, delaying programmes by anything from a few days to indefinitely. For example, operations at some ecosanctuaries (e.g. Maungataniwha Native Forest, Boundary Stream Mainland Island, and Bream Head Scenic Reserve) had still not returned to full capacity when interviews were conducted more than 6 months after the cyclone, while parts of several ecosanctuaries are no longer considered safe to access due to the ongoing threat of landslides or tree fall.

The cyclone also had broader impacts on the conservation workforce. The loss of full-time staff, contractors, and volunteers put considerable strain on some ecosanctuaries, with disruptions to personal lives (e.g. damage to homes or businesses), competition for contractors, and health and safety concerns all contributing to reduced capacity of the paid and volunteer workforce.

Finally, because many monitoring programmes are seasonal, an entire year of monitoring data was lost for some species and ecosystems, creating gaps in valuable long-term time series that underpin effective conservation management.

Additional disruptions to pest management included damage to or loss of traps, bait stations, and surveillance equipment (Figure 50D). This ranged from the loss of a single tracking tunnel up to entire lines of traps and bait stations that were washed away or are no longer accessible. For example, Te Hauturu-o-Toi / Little Barrier Island lost about half of its 80 surveillance stations around the coastline, while Boundary Stream lost over 100 traps, with more still unable to be assessed. At Cape Sanctuary an entire trap, bait station, and monitoring line was lost in one gully, while another 45 traps and 50 bait stations were washed away when a dam burst after building up behind slash accumulated in a creek. This

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[10] https://blog.tepapa.govt.nz/2011/07/18/riders-of-the-storm-thousands-of-seabirds-perish-on-new-zealand-shores/ (accessed 23 June 2024).

represents several thousand dollars of lost pest management equipment, before even considering the labour cost to re-establish the same level of pest management.

Several ecosanctuaries reported that their traps filled with sediment or were constantly wet, resulting in them rusting more rapidly, being heavier to move, and bait decaying faster. Overall, some of the worst-affected ecosanctuaries estimated their trapping efficiency to be 30–50% of normal up to 6 months after the cyclone.

The direct impacts of Cyclone Gabrielle on pest species are unclear. Some ecosanctuaries reported a decline in pest numbers (e.g. Windy Hill Sanctuary on Great Barrier Island / Aotea Island noted a decrease in numbers of kiore [*Rattus exulans*], hypothesising that this was due to consistent wet weather), while others reported increases, mostly of rats (e.g. Kaikōura Island / Selwyn Island). Predator incursions were also detected for some island ecosanctuaries. For example, rats were presumed to have arrived with floodwaters or flotsam on Limestone Island, while a cat was found on Kaikōura Island / Selwyn Island. Finally, the cyclone caused delays to invasive plant management programmes at several ecosanctuaries, which could become a larger issue in the future as invaders such as mothplant (*Araujia sericifera*) take advantage of disturbed areas.

Of the 33 ecosanctuaries with restoration plantings, 55% reported that they had been damaged (Figure 51A). At an average installation cost of $23,000 per hectare (Forbes 2021), damage to or destruction of restoration plantings is a significant lost investment. However, most reports of cyclone-related damage to restoration plantings at ecosanctuaries involved relatively small areas. For example, approximately 400 m^2 (0.04 ha) of restoration plantings at Young Nick’s Head (Te Kuri) suffered from wind throw, and around 1.5 km of active dune plantings at Shakespear Regional Park were eroded away by storm surges. Limestone Island in the Whangārei Harbour and Waikawau Bay Wetland Restoration Project on the Coromandel Peninsula each lost regenerating mānuka (*Leptospermum scoparium*) and kānuka that had been planted in coastal areas due to windburn and salt spray. However, some ecosanctuaries reported that their restoration plantings were thriving after the cyclone. For example, floodwaters were observed to suppress non-native plants at Tōtara Reserve Regional Park, benefiting several native tree species that were planted 1–2 years ago.

3.5.4 Discussion

The force of Cyclone Gabrielle was widely felt across the network of North Island ecosanctuaries, with 86% suffering at least one type of damage or impact on conservation activities. A range of impacts with variable severity were reported, although damage to infrastructure (e.g. fences, buildings, roads, and tracks) through wind and erosion was widespread and consequential for many ecosanctuaries.

Indirect impacts accompanied the direct and immediate damage, with loss of access, incursions by mammalian predators, and disruption to monitoring and pest management programmes all limiting the ability of individual ecosanctuaries to perform their core functions – sometimes for an extended period. However, with the overarching goal of protecting New Zealand’s most threatened species in mind, it was encouraging that the broader network of ecosanctuaries was resilient to the cyclone impacts. No local extinctions were reported, and there is a steely resolve to rebuild what was lost and keep pushing forward with new and existing conservation projects. Despite this positive collective outcome, the immediate impacts and costs of repairs were significant for some ecosanctuaries, and several lessons can be learnt to better prepare for and respond to future cyclones.

The immediate effects of the cyclone ranged from mild to severe. Most ecosanctuaries experienced multiple types of damage, probably because some damage types are linked, such as heavy rainfall that contributed to flooding, erosion, and sediment deposition. Moreover, the impacts of the cyclone were exacerbated by the preceding weather, which has been described as a low-probability, high-impact 'black swan' event (Macinnis-Ng et al. 2024). For example, many respondents noted that flooding-related impacts were the cumulative result of record rainfall across multiple months for some regions (Harrington et al. 2023; MfE & Stats NZ 2023).

Erosion and wind fall remained an ongoing issue for many ecosanctuaries months after the cyclone, as new and recurring landslides accompanied further rainfall and trees blew down more easily in the saturated soil, requiring clearance whenever access roads or tracks became blocked.

The size, type, and topography of each ecosanctuary also influenced the types and severity of damage they experienced. For example, the time-consuming and expensive clearing of monitoring and pest management lines scaled with ecosanctuary size, with some of the largest ecosanctuaries maintaining several hundred kilometres of roading, tracks, and pest management lines. However, conservation projects of all sizes will have been affected, from national parks maintained by DOC to backyard trapping projects. The combined 245,000 ha area of ecosanctuaries included in this study represents just a small portion of the total land being managed for pests in the North Island, indicating that the impacts of Cyclone Gabrielle would have been widely felt by many conservation projects.

Finally, the general topography of an ecosanctuary was a useful indicator of the types of damage and impacts it was likely to experience. For example, coastal and low-lying ecosanctuaries experienced more flooding and sediment deposition, while ecosanctuaries in steeper landscapes were more likely to suffer impacts from erosion. Thus, cyclone impacts were likely to reflect those more frequently experienced during smaller storms but at a far larger scale, suggesting that ecosanctuaries can predict the most likely types of cyclone damage and where they might occur, thereby helping with preparation, rapid response, and resilience.

Damage to conservation infrastructure was the most significant issue facing ecosanctuaries after Cyclone Gabrielle. Pest fences represent a large investment and were particularly vulnerable to damage from landslides and tree fall. Pest incursions rapidly follow fence damage (Connolly et al. 2009), highlighting the importance of speedy repair and mitigation measures such as temporary fencing and the increased deployment of pest surveillance and management around compromised areas. There was also a significant loss of traps, bait stations, tracking tunnels, and trail cameras, which limited the ability of ecosanctuaries to achieve their core goals, and are expensive and time consuming to replace.

Cleaning up and clearing of tracks has taken over a year in some cases, causing further disruptions to native species monitoring and pest management programmes. Restoration plantings were also lost or damaged in some locations. Although replacement and additional plantings should help to stabilise disturbed land and limit plant invasions, significant further investment will be required.

Conservation is expensive, and in New Zealand it commonly requires active interventions. Infrequent climate events, amplified by ongoing climate change (Harrington et al. 2023), will diminish our capacity to maintain those interventions and incur a substantial lost opportunity cost (Macinnis-Ng et al. 2024). This will leave ecosanctuaries 'running to standstill' without greater investment just to maintain the conservation gains that have been achieved. Financial impacts are challenging to quantify and often involve commercially sensitive information. However, the financial costs of Cyclone Gabrielle were disproportionately distributed across ecosanctuaries based on their size, topography, assets, and the whims of the cyclone, with costs incurred by some of the worst-affected ecosanctuaries estimated at upwards of $1 million per ecosanctuary.

Although dead or injured native wildlife was the least-reported conservation impact, this was likely to be an underestimate of wildlife mortality. For example, slips and flooding potentially affected seabirds breeding on Te Hauturu-o-Toi / Little Barrier Island, such as was observed for seabirds on other nearby offshore islands (section 3.6.4; Bell et al. 2023; Ray & Burgin 2023).

Other impacts of the cyclone on wildlife may not yet be apparent. For example, wind damage to trees may affect flowering or fruiting the following season, altering resource availability for higher trophic levels. In one study on Te Hauturu-o-Toi / Little Barrier Island, Toy et al. (2018) speculated that 69% and 64% lower detection rates of hihi (*Notiomystis cincta*) and tūī (*Prosthemadera novaeseelandiae*), respectively, in 2007 compared to 2006, were because of a particularly severe winter storm in July 2007 that caused widespread defoliation and may have reduced food availability for nectivorous birds.

Overall, there is little known about how pest mammals and invasive plants respond to extreme weather events in New Zealand. Pest densities may decline in the immediate aftermath of a cyclone, temporarily offsetting disruptions to management programmes, although this remains to be tested. The impacts of cyclones on animals are understudied in general (Pruitt et al. 2019), and future research should aim to quantify and understand impacts on species across multiple trophic levels, their interactions, and ecosystem functioning. Our capacity to prepare for future events would be greatly enhanced by focusing on animal responses to cyclone events based on longitudinal studies, replicated across several sites, so that we have pre- and post-event data (e.g. section 3.3).

Tropical cyclones can also facilitate plant invasion at multiple spatial scales. For example, cyclones create disturbed areas where invasive plants can establish (Restrepo & Vitousek 2001; Murphy et al. 2008; Lynch et al. 2009; Catford et al. 2012) and have been implicated in the spread of invaders at the landscape scale (Bhattarai & Cronin 2014). Ultimately, the intensity and scale of any extreme weather event will determine the types of microsites available for vegetation recovery (Duncan 1993). Thus, plant invasions may only become apparent with time, suggesting that monitoring of disturbed areas for invasive species is an important activity for ecosanctuaries for several years after a cyclone.

Some reassuring findings emerged from the mess the cyclone left behind. Primarily, when considering the overarching goal of protecting native biodiversity, the network of ecosanctuaries collectively weathered the storm. It was encouraging that no local extinctions or major animal mortality events were reported, even from the hardest-hit individual ecosanctuaries, let alone across multiple populations of a threatened species. However, there is potential for stronger impacts to occur with future cyclones. For example, if a large ecosanctuary with diverse and high-value species (e.g. Sanctuary Mountain Maungatautari) were to experience pest fence damage and a prolonged lack of access, such as occurred at Opouahi kiwi crèche (Figure 50A), the potential impacts of sustained incursions of multiple pest species could be devastating for some highly sensitive species (e.g. North Island and South Island saddleback [*Philesturnus* spp.]). Even in such a scenario, the distribution of some threatened species across multiple ecosanctuaries provides in-built resilience and an 'insurance policy' against the worst-case scenario of local extinction.

However, species such as New Zealand storm petrel (*Fregetta maoriana*) and Westland petrel (*Procellaria westlandica*), which are both only known to breed in one location in New Zealand (Te Hauturu-o-Toi / Little Barrier Island and Punakaiki, respectively), remain particularly vulnerable to the impacts of extreme weather events (e.g. Waugh et al. 2015), where simple bad luck could lead to their only breeding colonies being destroyed. This vulnerability highlights the urgent need to investigate translocation or enhanced protection of particularly vulnerable and challenging species such as seabirds. Moreover, there is an urgent need to assess the vulnerability and protection status of less charismatic species, such as native invertebrates, plants, and fungi, and to incorporate them into spatial conservation planning.

Another positive discovery from the cyclone was that native forest suffered comparatively less erosion than non-native forest and pasture (McMillan et al. 2023), indicating that the majority of ecosanctuaries – as landscapes primarily covered in native forest – may already have resilience to some impacts of future extreme weather events. However, slips that do occur in native forest may be more damaging than in pasture, leaving a mess that is more difficult to clean up. Along the same lines, although sanctuaries in a forested matrix may provide 'spillover' benefits for the surrounding community (Fitzgerald et al. 2019; Burge et al. 2021), repairs of pest fences and other infrastructure may also be more challenging than in a pastural landscape.

A final positive aspect were the stories of ecosanctuaries working together to solve problems and achieve shared goals. Notably, the rapid deployment of a fencing team to Wairakei Golf Course was assisted by Sanctuary Mountain Maungatautari, where rapid fence repairs had just been completed.

Tropical cyclones will continue to intersect with the growing network of ecosanctuaries and conservation projects throughout New Zealand. With Cyclone Gabrielle a few individual ecosanctuaries took the brunt of the impact, suffering substantial damage to infrastructure and work programmes. However, a general lack of baseline monitoring data for many of their most precious conservation assets (their biodiversity) makes it challenging to assess which species have been harmed and which have emerged relatively unscathed. This is consistent with Binny et al. (2021), who found that long-term monitoring data sets for invertebrates, vegetation, and herpetofauna were under-represented compared to those of birds, limiting their ability to report on the biodiversity outcomes of ecosanctuaries.

3.5.5 Conclusions and recommendations

Here we present answers to our original research questions and provide recommendations for the management of extreme weather impacts on New Zealand ecosanctuaries.

Conclusions

- At what frequency were different types of cyclone damage experienced by ecosanctuaries?

82% of North Island ecosanctuaries experienced physical cyclone damage. Of those affected, 91% were damaged by wind, 85% by erosion, 47% by inundation, and 32% by sediment deposition. Multiple types of damage were experienced at 74% of ecosanctuaries.

- What were the range and frequency of impacts on conservation infrastructure and activities?

77% of North Island ecosanctuaries experienced impacts on conservation infrastructure or activities. Of the affected ecosanctuaries, 40% had pest fences that were compromised, 23% had other fencing that was damaged, 82% suffered impacts to other infrastructure, and 32% had sites of cultural significance that were affected. Native species monitoring and pest management were disrupted at 50% and 78% of ecosanctuaries, respectively, while injured or dead wildlife was observed at 18% of ecosanctuaries. Fifty-five percent of restoration plantings were damaged.

Recommendations

- Ecosanctuaries should create, review, and regularly update their climate adaptation and disaster response plans. These should anticipate individual and collective risks to ecosanctuaries from extreme weather events, with a focus on mitigating impacts. Protocols should also be developed for rapid implementation of post-disturbance monitoring, including early deployment of remote-sensing tools.
- Continue, establish and maintain standardised monitoring programmes for at-risk species and ecosystems. Standardised, long-term monitoring across multiple independent ecosanctuaries is crucial to quantifying change in ecosystem condition and populations of threatened species, so that management responses in the aftermath of extreme weather events can be informed and effective.
- Conduct a spatial conservation risk assessment of threatened species and ecosystems across the ecosanctuary network, under a range of natural disaster scenarios. This analysis would identify gaps in our understanding of which species and ecosystems are being managed and where, so that risk can distributed spatially, and swift action taken when a regional event is forecast.
- To distribute risk, new and additional conservation translocations should be considered, especially for range-restricted and intractable species (i.e. species that continue to decline despite conservation efforts; Hare et al. 2019), including assisted migration beyond a species' historical range.
- Non-charismatic and lesser-known species should be explicitly integrated into the ecosanctuary network. This would help to protect greater taxonomic and functional

diversity, and to restore functioning and resilient ecosystems – a stated goal of many ecosanctuaries.

- Suitable native vegetation should be planted to help stabilise existing landslides and secure areas vulnerable to future erosion. In high-risk areas, species should be carefully selected for resilience to wind, inundation, or deposition.
- A pest management buffer zone should be maintained around the boundary of pest fences to reduce pest densities and limit incursions if fences are damaged.
- A 'disaster response kit' should be assembled to facilitate rapid response and recovery after extreme weather events. This would be proportionate to ecosanctuary size and might include items such as traps, bait stations, tracking tunnels and trail cameras, temporary pest fencing and fencing materials, shovels, machetes, chainsaws, and other tools.
- Ecosanctuaries should use cyclone warning periods to prepare several days in advance of storm arrival. Depending on priorities, resources, time available, safety, and likelihood of impacts, recommended preparation activities could include ensuring drains and slipways are clear, installing sandbags, stowing valuable infrastructure, securing or moving pest management equipment away from waterways and coastlines, establishing monitoring around predator-proof fences to rapidly detect incursions, and relocating species of high value. Human resources are also an important consideration, as many of the people who work in ecosanctuaries are also involved in Civil Defence and other emergency services. This includes alerting contractors to potential damage ahead of time so that critical infrastructure (e.g. pest fences) can be prioritised and rapidly repaired. These operating procedures should be developed and included as part of any project's disaster response plan.
- Monitor for non-native plant invasions and act swiftly to prevent the establishment and spread of new and existing invasive species.
- Continue to improve capability, communication and cooperation across the ecosanctuary network to develop cross-project resilience across large spatial scales. These actions might include the incorporation of Australian and Pacific Island partners, and improving financial security through insurance, corporate sponsorship, and local and central government support for extreme weather preparation and recovery.

3.6 Threatened species

We collaborated with government agencies, ecological consultants, and other stakeholders to collate information on the impacts of Cyclone Gabrielle on some of New Zealand's most threatened species. Case studies range from anecdotal observations to systematic pre- and post-cyclone population surveys.

3.6.1 Whio (blue duck)

Whio (blue duck [*Hymenolaimus malacorhynchos*]) is a nationally vulnerable species, with an estimated population of fewer than 3,000 individuals. They are currently restricted to clean, fast-flowing streams and are generally only found in the forested upper catchments of rivers with high water quality, low sediment loading, canopy cover, stable banks, and healthy invertebrate communities. As a result, whio are expected to be severely affected by extreme weather events that cause flooding and sedimentation of their specialised river habitat.

Regular monitoring surveys of whio in the Mangatera/Waiokotore and Apias/Ikawatea catchments of northern Ruahine Forest Park, Manawatū-Whanganui, allow an assessment of how the cyclone affected their population size, breeding, and distribution. The area experienced intense rainfall and flooding during Cyclone Gabrielle, with the river still discoloured months later and up to 2 m of gravel deposited in some locations.

Surveys have been conducted along the same general stretch of river since 2004. We focused on the surveys from 2019 or 2022 (pre-cyclone), 2023 (3 months post-cyclone) and 2024 (15 months post-cyclone). In 2023, a total distance of 36.1 km of rivers and streams was surveyed with the assistance of Tui and Falco, two certified whio dogs. In February 2024, 39 km of rivers and streams were surveyed over 3 days with the assistance of whio dogs Tui and Charlie.

Whio numbers in the Mangatera/Waiokotore catchment decreased by 65% immediately after the cyclone, from 40 individuals in 2022 to 14 in 2023 (Table 2; Figure 52). We advise caution in interpreting the magnitude of this change, however, as the 40 individuals observed in 2022 was easily the most since the 51 observed in 2009 (Table 2). Numbers were stable in the Apias/Ikawatea catchment, with 18 whio observed in 2023 compared to 17 in 2019 (Table 3). In the 2024 surveys there appeared to be a redistribution of ducks on less-affected waterways, with 19 whio (including one juvenile) observed in the Mangatera/Waiokotore catchment, and 36 in the Apias/Ikawatea catchment. Of concern, there were no signs of attempted breeding in either catchment in both the 2023 and 2024 surveys, other than one juvenile observed in 2024.

By examining faecal sign at the side of the river during 2023 surveys the rangers observed that *Coprosma propinqua* berries were making up a large portion of the whio diet. This is thought to occur when their preferred diet of freshwater invertebrates is scarce and may help to explain why there has been almost no breeding observed over the last 2 years. In 2024 invertebrate communities were observed to be recovering in both catchments, consistent with observations from Hawke's Bay (see section 4). Waterways in the Mangatera/Waiokotore catchment remained scoured, with little cover for whio, while the establishment of non-native plants, notably tree lupin (*Lupinus arboreus*), on gravel deposit terraces could provide cover for predators. The Apias/Ikawatea catchment is showing signs of recovery and improved whio habitat, with deeper pools returning and little remaining evidence of flood impacts, apart from one stretch of rolling shingle and a couple of log jams.

We are grateful to Aimee Stubbs, Luke Easton, and Paul Jansen from DOC for sharing data and other information.

Table 2. Results of whio (blue duck, *Hymenolaimus malacorhynchos*) surveys in the Mangatera/Waiokotore catchment of the northern Ruahine National Park, Manawatū-Whanganui

Survey date	Pairs	Singles	Ducklings	Total
2004	2	7	0	11
1–3 November 2009	12	8	19	51
13–15 December 2016	3	7	11	24
9/10 March 2017 (Waiokotore Stream only)	3	5	0	11
27 February – 1 March 2018	2	3	12	19
19–21 February 2019	5	3	5	18
19–21 February 2021	7	6	2	22
18–20 February 2022	**10**	**8**	**12**	**40**
24–26 February 2023	**5**	**4**	**0**	**14**
27–29 February 2024	**5**	**8**	**1**	**19**

Notes: bolded rows highlight the survey that was conducted in the year before Cyclone Gabrielle and those conducted after, to assess impacts and recovery.

Table 3. Results of whio (blue duck, *Hymenolaimus malacorhynchos*) surveys in the Apias/Ikawatea catchment of the northern Ruahine National Park, Manawatū-Whanganui.

Survey date	Pairs	Singles	Ducklings	Total
1–3 November 2009 (Ikawatea Stream only)	6	1	22	35
November 2010	3	6	0	12
December 2016	7	8	12	34
27/28 February 2018 (Apias Stream only)	4	6	9	23
19–21 February 2019	**5**	**1**	**6**	**17**
24–26 May 2023	**5**	**8**	**0**	**18**
27–29 February 2024	**14**	**8**	**0**	**36**

Notes: bolded rows highlight the survey that was conducted in the year before Cyclone Gabrielle and those conducted after, to assess impacts and recovery.

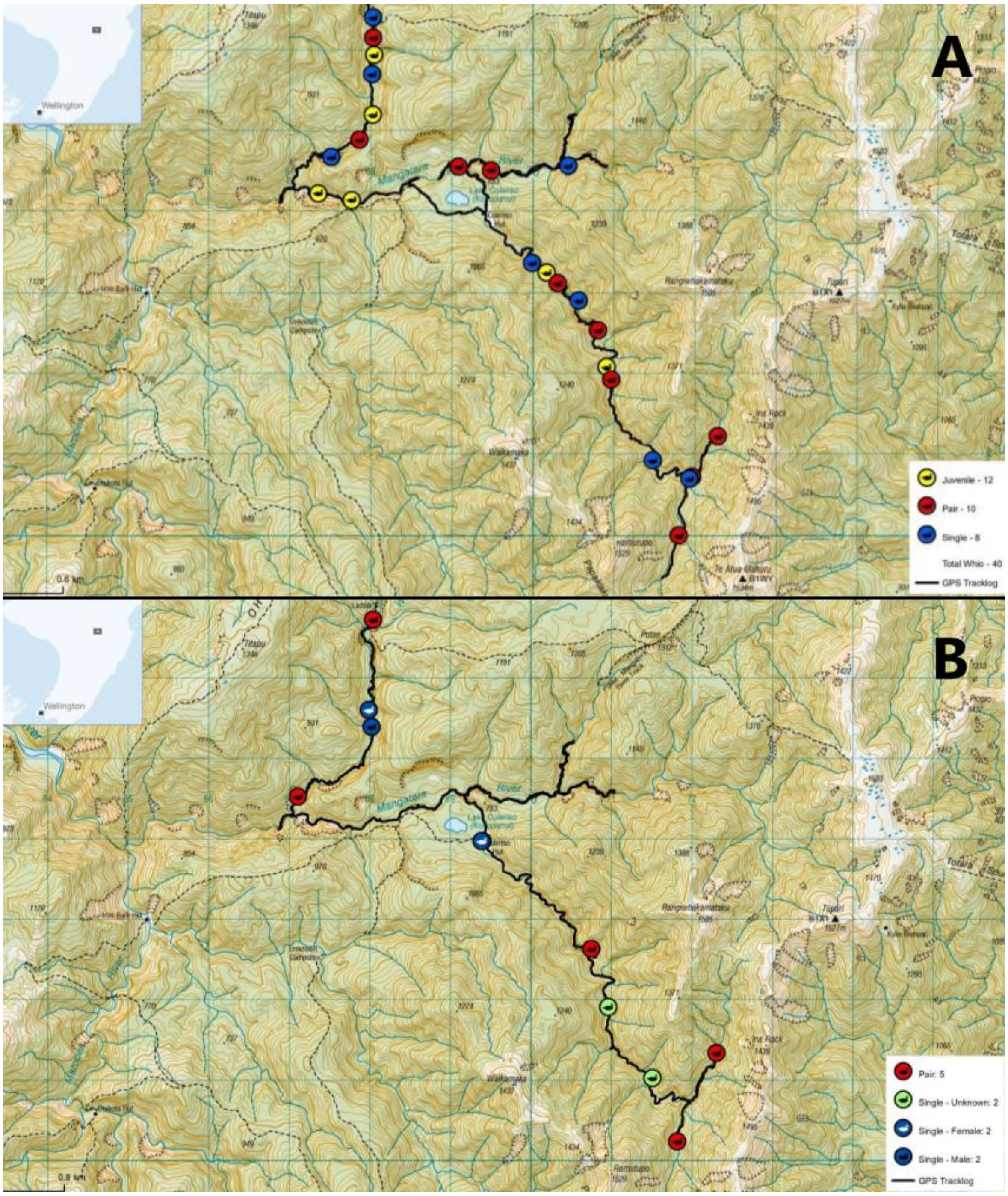

Figure 52. Results of 2022 (A) and 2023 (B) whio (blue duck, *Hymenolaimus malacorhynchos*) surveys on the Mangatera River and Waiokotore Stream, showing locations of pairs (red points), singles (blue and green), and juvenile (yellow) birds. (Reprinted from Bird 2023 with permission)

3.6.2 Shore plover (tūturuatu)

Shore plovers (tūturuatu [*Thinornis novaeseelandiae*]) are a nationally critical species, with an estimated 250 individuals remaining, half of which are found on the Chatham Islands. Other populations are located on Portland Island off Māhia Peninsula, Hawke's Bay, and Motutapu Island in the Hauraki Gulf, near Auckland. Captive breeding populations are also held at Pūkaha National Wildlife Centre in Wairarapa, Isaac Conservation and Wildlife Trust in Christchurch, and Cape Sanctuary in Hawke's Bay. Post-cyclone surveys revealed that the shore plover populations on Portland Island and Motutapu Island were largely unaffected by Cyclone Gabrielle. However, nine individuals (including four breeding adults) reportedly drowned in aviaries at Cape Sanctuary during Cyclone Gabrielle, representing approximately 3% of the total population. This breeding facility was also not able to be used for over a year after the cyclone. This finding highlights a potential risk of maintaining captive breeding populations, where threatened species may be unable to find shelter from extreme weather events or other natural disasters.

We are grateful to Troy Makan from DOC and Aimee Pitcher from Cape Sanctuary for sharing this information.

3.6.3 Fairy tern (tara iti)

Fairy terns (tara iti [*Sternula nereis*]) are considered New Zealand's most critically threatened native breeding bird species, with just 10 breeding pairs remaining in the 2022/23 season. DOC considers storms to be a major threat to fairy tern chicks and adults, but it is challenging to confirm the loss of an adult bird to a storm because they are very seldom recovered dead.

DOC uses recoveries of birds at the Kaipara Harbour spring tide roost sites to assess individual survival at the end of the breeding season. Assessments after Cyclone Gabrielle were carried out by staff and volunteers over 13 high to spring tides between 19 February and 23 April 2023 at Manukapua Island and Papakanui Spit. Regular searches were also carried out at Waipū in the weeks following Cyclone Gabrielle.

There were two almost certain adult losses, two known fledgling losses, and three suspected adult losses around Cyclone Gabrielle, representing over 15% of the total population in New Zealand. The birds that were suspected lost were last seen at the breeding sites before two other tropical depressions that preceded Cyclone Gabrielle, so the exact dates of their fate are not able to be determined. It is extremely unusual for the programme to lose five adults during a breeding season. Overall, the population declined over the 2022/23 breeding season, with Cyclone Gabrielle being a major contributing factor.

- Two parents and their two fledglings were seen at Waipū up until 10 February 2023 but were not seen after Cyclone Gabrielle. The bodies of the two fledglings were recovered near their natal area on 17 February 2023.
- An adult male with high site fidelity was last seen at Papakanui Spit on 6 December 2022.
- A 3-year-old breeding female who laid two clutches at Mangawhai was last seen on 5 January 2023.
- The male from the other Waipū pair was last seen on the breeding site on 7 January 2023.

We are grateful to Tony Beauchamp and Jamie Stavert from DOC for sharing this information.

3.6.4 Seabirds

Seabird colonies in the Hauraki Gulf and Bay of Plenty are frequently surveyed to monitor breeding bird populations and their breeding success. DOC, Wildlife Management International, Northern New Zealand Seabird Trust, and other stakeholders regularly monitor colonies of several species, including flesh-footed shearwater (toanui [*Ardenna carneipes*]), grey-faced petrel (ōi [*Pterodroma gouldi*]), black petrel (tāiko [*Procellaria parkinsoni*]) and New Zealand storm-petrel (takahikare raro [*Fregetta maoriana*]).

During the 2022/23 breeding season 271 flesh-footed shearwater study burrows were monitored on Ohinau Island (Ray & Burgin 2023). The colony was badly affected by the Auckland Anniversary floods and Cyclone Gabrielle, and had a very poor breeding season, with many burrows observed to be flooded or waterlogged. Only 10% of breeding attempts produced a chick that was likely to survive until fledging, far lower than the 59% measured in the 2021/22 season (Burgin & Ray 2022) and the lowest recorded breeding success on the island since monitoring began in 2016. Landslips also destroyed many known flesh-footed shearwater burrows. Breeding was not monitored in the 2023/24 breeding season, so it remains unknown whether breeding success has recovered to pre-cyclone levels (Ray et al. 2024).

During the 2022/23 breeding season, 480 black petrel study burrows were monitored in the Mount Hobson study area on Great Barrier Island (Aotea Island) (Bell et al. 2023). Fledging success was 61%, 11% lower than the 28-year average and the lowest since monitoring began in 1995/96. This decrease in breeding success was largely attributed to the extreme weather events of 2023, specifically the Auckland Anniversary floods and Cyclone Gabrielle. Researchers observed that some burrows had flooded following these extreme weather events, resulting in the loss of eggs, embryonic death, over 20 chicks dying by drowning, and potentially lower foraging success of parents. A further 13 chicks were in poor condition before fledging and were not expected to survive.

The death of some chicks was speculated to be due to the loss of breeding adults during the extreme weather events, but post-cyclone survival of adults has yet to be quantified. In relatively long-lived species, such as black petrel and flesh-footed shearwater, the loss of breeding adults has a far greater impact than variability in breeding success (Sæther & Bakke 2000). Therefore, we suggest that future research also focus on assessing adult survival following extreme weather events.

The grey-faced petrel colony on Mt Maunganui was unaffected by the cyclone (Paul Cuming, Western Bay Wildlife Trust, pers. comm., November 2023).

3.6.5 Pekapeka (long-tailed bat)

Pekapeka (long-tailed bat [*Chalinolobus tuberculatus*]) is one of only two extant endemic terrestrial mammal species in New Zealand and is considered critically threatened. Steve Sawyer (Ecoworks NZ) collected pre- and post-cyclone bat pass data from four sites along the Waimata River in Gisborne using AR4 acoustic recorders. Pre-cyclone surveys were carried out in 2019 and 2021, and post-cyclone surveys were carried out between January and April 2023. Each recorder was placed in trees or shrubs at around head height and set to begin recording at 20:30 and to record for 9 hours.

Bats remained present at all four sites in post-cyclone surveys, although pass rates declined at three sites and by an average of 28% overall (Table 4). However, it is unclear whether this reflects a decline in population or an effect of the cyclone, which could have caused the loss of roost trees (which are also likely to be those most vulnerable to cyclone damage).

We are grateful to Steve Sawyer (Ecoworks NZ) for sharing these data.

Table 4. Pekapeka (long-tailed bat [*Chalinolobus tuberculatus*]) pass rates from 2023 and previous bat surveys within the Waimata River catchment

Site	2023 bat pass rate per hour	Previous bat pass rate per hour (survey year)
Kenway's Bridge	0.50	0.10 (2021)
Lower Paddock / Parsons	0.87	1.16 (2019)
Longbush 3	0.15	0.11 (2021)
Longbush 4	0.39	3.66 (2021)

3.6.6 Pepeketua (Hochstetter's frog)

Pepeketua (Hochstetter's frog [*Leiopelma hochstetteri*]) is New Zealand's most widespread endemic frog species, occurring in discrete populations throughout the upper half of the North Island, from East Cape across to the King Country, and up to Waipu in Northland. However, this species is facing many threats and has a conservation status of At Risk – Declining. Pepeketua are semi-aquatic, typically occurring in the vicinity of forested streams and seepages with rocky or woody debris. They are averse to high sediment loads and are therefore often absent from streams with significant disturbance (e.g. ungulate wallowing, habitat destruction, forestry) (Nájera-Hillman 2009; Easton 2015), suggesting that this species may also be highly susceptible to impacts from extreme weather.

Anecdotal reports indicated that multiple sites with pepeketua were affected by Cyclone Gabrielle and other extreme weather events of early 2023, but there has been nothing quantified yet. For example, one population of pepeketua at an undisclosed Bay of Plenty location was severely affected by the Auckland Anniversary storm, which occurred approximately 2 weeks before Cyclone Gabrielle. At this site frogs inhabit just two tributary streams, one of which supports the bulk of the population, estimated to be only 100 to 200 individuals. During the Auckland Anniversary storm a large slip flowed down the main tributary and destroyed at least 600 m of prime habitat that was densely populated by frogs (Figure 53). The downstream bed was completely gouged out by the slip debris (15–20 m high in some places), so it is assumed that any frogs present in this habitat would have perished, although no monitoring data have been collected.

The slip has split the remaining frog population in two, and the cliff above the site is also now unstable, meaning that any further slips are likely to destroy remaining habitat, putting this frog population at risk of being unable to recover. Floods and other disturbances have probably always redistributed populations of frogs that live in stream courses. However, the current context of fragmented landscapes, novel predation threats, and climate change mean that these populations may be less likely to recover before the next extreme weather event occurs.

At Mahakirau Forest Estate, on the Coromandel Peninsula, pepeketua were assumed to have been affected because they had eggs about to hatch when the cyclone flooded and deposited sediment throughout their streamside habitat. Subsequent surveys in spring 2024 found over 100 frogs, including juveniles, suggesting there are promising signs of population recovery (Sara Smerdon, Mahakirau Forest Estate, pers. comm., October 2024). Pepeketua were also present near the Coromandel Kopu Hikuai bridge slip (Amanda Haigh, DOC, pers. comm., June 2024).

We are grateful to John Heaphy (Ranger / Project Lead, Biodiversity, Protected Species and Islands) and Amanda Haigh (Regional Liaison, Biodiversity, and Leader, Frog Recovery Group) from DOC, Sara Smerdon (Mahakirau Forest Estate), and Jim Dowman (Chair, Te Whakakaha Conservation Trust) for sharing information, data and photos.

Figure 53. A large slip that destroyed prime pepeketua (Hochstetter's frog [*Leiopelma hochstetteri*]) habitat at an undisclosed site in the Bay of Plenty. The impact on the population is currently unknown but is assumed to be substantial and has split the remaining population in two. (Photo: John Heaphy)

3.6.7 Ngutukākā (kākābeak)

Ngutukākā (kakabeak [*Clianthus maximus* and *Clianthus puniceus*]) is simultaneously one of New Zealand's most critically threatened and widely cultivated endemic plant species. Both species are highly palatable to introduced browsing mammals (Shaw & Burns 1997), which has contributed to their current rarity and threat status. *Clianthus puniceus* is currently extinct in the wild but has previously been known from Moturemu Island in the Kaipara Harbour. *Clianthus maximus* currently occurs at a small number of locations across northern Hawke's Bay, Te Urewera, and Gisborne, areas that were hit hard by Cyclone Gabrielle. Most populations in northern Hawke's Bay and Gisborne are monitored annually by DOC for the survival of adult plants and seedlings.

Except for Te Urewera populations, all known sites where wild *C. maximus* plants were present in 2022 have been resurveyed since Cyclone Gabrielle. The number of wild plants detected declined from 62 to 48 individuals between 2022 and 2024, a 23% reduction in population size. Most of the decline occurred at sites in northern Hawke's Bay and at a site near Te Puia Springs in Gisborne.

Only two plants (3% of the surveyed population) were definitively lost because of Cyclone Gabrielle, both from slips at the Ruakituri River and Te Kooti's Lookout sites in northern Hawke's Bay. Other slips resulted in close calls, with plants located right at the edge of the slip face (Figure 54). The remainder of the decline may be explained by a combination of drought in 2022, plants not able to be relocated during the post-cyclone survey in 2024 (plants were not flowering during the aerial resurvey so may have died from unknown causes or not been visible), and observer variability in counting densely interwoven plants from a distance at difficult-to-access sites.

In the absence of browsing, ngutukākā occurs on steep, open, skeletal, and frequently disturbed microsites such as cliffs, slips, lake margins, and riverbanks (Shaw & Burns 1997). A key question for future monitoring is whether the many new landslides created by Cyclone Gabrielle present opportunities for ngutukākā seedlings to establish. This will only be likely to occur in sites with sustained control of browsing animals.

Although only a small number of wild ngutukākā plants were directly affected by Cyclone Gabrielle, there were significant indirect impacts to the ngutukākā recovery programme via damage to infrastructure. These impacts included restricted ground access to several wild sites due to extensive damage to roads and farm tracks, damage to exclosures that protect both wild and planted sites from browsing by feral ungulates, and damage to multiple plant nurseries that grow locally provenanced plant stock for the recovery programme. These factors combined have led to a temporary significant increase in both costs and time for undertaking regular recovery activities for ngutukākā.

We are grateful to Paul Cashmore (Technical Advisor, Flora) and Helen Jonas (Ranger, Biodiversity) from DOC for sharing information, data and photos.

Figure 54. A slip that came perilously close to a wild ngutukākā plant on Panekiri Station, Hawke's Bay, and destroyed one side of the exclosure that protects it. The plant and remaining fence are present in the photo foreground. (Photo taken 12 May 2023 by Helen Jonas)

3.6.8 *Leptinella rotundata*

Leptinella rotundata was originally discovered in 1906 on the coastal cliffs west of the Waitākere Ranges. It has since been found in only a few isolated populations between Te Henga / Bethells Beach and Cape Reinga and is considered regionally critical in Auckland and nationally critical (de Lange et al. 2024). Most patches are less than 2 m^2 in area, consist of a single sex (although male and female plants co-occur at one site), and are declining in size.

There are four known extant (pre-cyclone) natural sites along the coast near the Waitākere Ranges, which were severely affected by slips caused by Cyclone Gabrielle. The site near Muriwai was visited in October 2023 and the plant was still present but much reduced in extent, down from several square metres to just one small clump, approximately 300 × 300 mm. It looked as if it had suffered from too much water washing through the habitat (John Rugis, University of Auckland, pers. comm., October 2024). The other three sites, located along the Te Henga Walkway, have not yet been relocated during post-cyclone surveys, although further searches are warranted (Sabine Melzer, Auckland Council, pers. comm., June 2024).

Anecdotal observations and surveys following up on plants after Cyclone Gabrielle in Northland suggest that there were no major cyclone impacts on these populations (i.e.

populations lost in slips), although wind-blown sand may have covered plants at several sites (Andrew Knock and Andrew Townsend, DOC, pers. comm., October 2024). However, slips near some populations suggest that luck played a part in preventing the loss of known patches. Historically, regular disturbance may have favoured species such as *L. rotundata* by creating new, open substrate for colonisation. However, the consequent lack of seed production with isolated single sex populations severely limits the resilience of this species. Moreover, non-native plants may now rapidly colonise newly available habitat and outcompete native species, highlighting the need for future monitoring of *L. rotundata* and other threatened plants that occur in frequently disturbed habitats.

4 Resilience of resident fish and macroinvertebrate communities, and recolonisation of migratory fish species

4.1 Introduction

Cyclones affect freshwater ecosystems through intensive rainfall and high winds, which causes flooding of rivers and streams, erosion of stream banks, deposition of material from the landscape into waterways and smothering or loss of riparian vegetation (Pratchett et al. 2011; Cyrus et al. 2020; Figure 55). Collectively these impacts can cause localised disruption to habitats and species (Chen et al. 2015; Schutte et al. 2020).

In addition to displacement and direct mortality of freshwater biota during cyclones, critical life-stage habitats for fish and macroinvertebrate species can be smothered or eliminated, connectivity of habitats for migratory species can be reduced, and changes in competition for resources can influence the presence and abundance of species (Makiguchi et al. 2009; Pratchett et al. 2011; McEwan & Joy 2013).

Consequently, changes to freshwater fish and macroinvertebrate communities can occur as the direct result of physical changes to the environment caused by cyclones. To determine the short-term impacts of Cyclone Gabrielle on freshwater biota, we compared pre- and post-cyclone fish and macroinvertebrate species presence and abundance using environmental DNA (eDNA) and physical monitoring data sets.

Figure 55. Aerial image of Mangaone River and Tutaekuri River after Cyclone Gabrielle. (Source: image courtesy of GNS Science)

4.2 Methods

4.2.1 Site selection and overview of data sets

Data from the Sentinel-1 and -2 satellites were used to select sites within the Hawke’s Bay region based on a range of disturbance levels at the catchment and site level. Changes in the extent of sediment and slips at the site and catchment level were used as indicators to represent overall cyclone disturbance. Satellite data were processed by Dragonfly Data Science and consist of before (5 January – 10 February 2023) and after (19–21 February 2023) images of vegetation, based on the Normalised Difference Vegetation Index from Sentinel-2 (Dragonfly 2023).

Site-level extents were calculated by creating a 1 km buffer around available sampling points and calculating the proportion of the area within 30 m of the river on each side covered by sediment and slips after the cyclone (Figure 56). At the catchment level, the extent of disturbance was quantified by taking the proportion of the entire catchment that had changes in sediment and slips landscape cover.

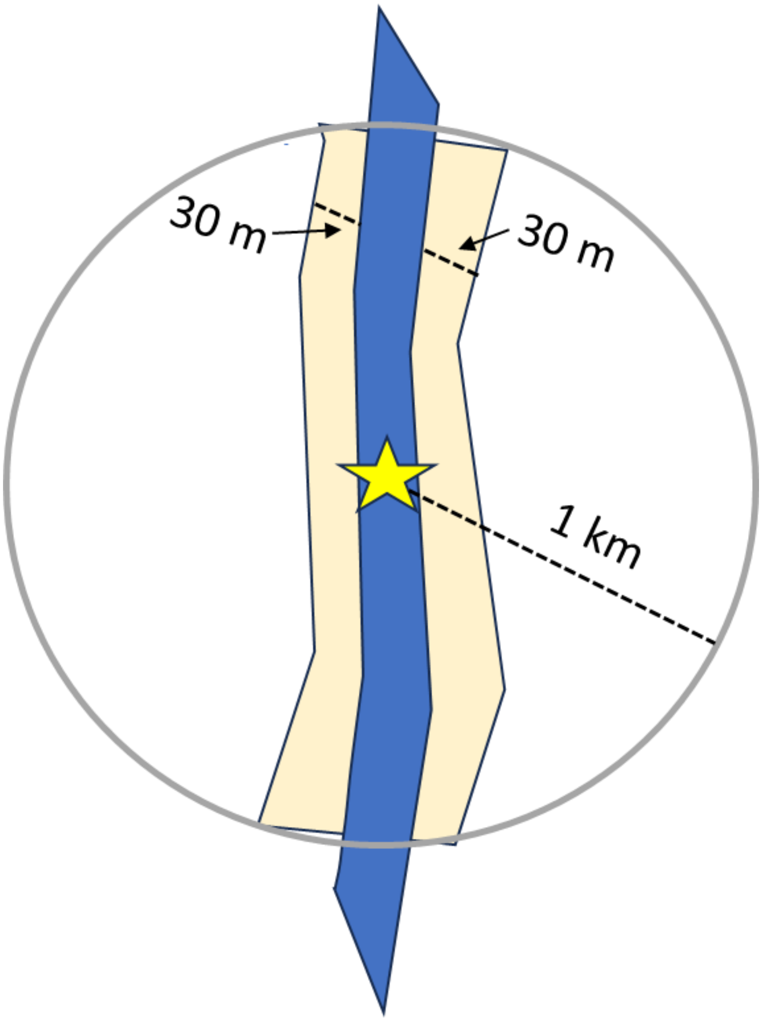

Figure 56. Scheme used to determine the level of disturbance at the site level. The star indicates the sampling location, and the stream is represented by the blue polygon.

Note: distances not to scale.

In conjunction with Hawke's Bay Regional Council (HBRC), 53 sites from HBRC's long-term monitoring network were selected to survey the response of fish and macroinvertebrate populations after Cyclone Gabrielle (Appendix 4; Table A4.1). Sites were selected to represent a range of site and catchment disturbance across the Hawke's Bay region and where existing pre-cyclone data could be used as a control sample (Figure 57). A mix of passive (environmental DNA monitoring) and active (physical sampling) surveys was carried out across the sites. The surveys were undertaken by HBRC and conducted according to standard SoE sampling protocols. They included the following.

- eDNA was resampled at 34 sites affected by Cyclone Gabrielle, using samples from before (January 2021 – January 2023), immediately after (April – May 2023), and the following summer (February–March 2024; Figure 58).
- Macroinvertebrate communities were surveyed at 26 sites routinely sampled by HBRC as part of their SoE monitoring (Figure 58). All macroinvertebrate physical samples were paired with deposited sediment (quorer method; see next section) and eDNA sampling at the same site. Of the 26 sites, 24 had eDNA sampling carried out before Cyclone Gabrielle, 19 had eDNA sampling carried out immediately after the cyclone (March–May 2023), and 21 had eDNA sampling carried out the following summer (January–March 2024). Deposited sediment samples were only collected after the cyclone (April 2023 – May 2024).
- Fish populations were surveyed at six sites previously sampled by HBRC (Figure 58). eDNA sampling was also carried out at each site, although no fishing site had existing eDNA data.

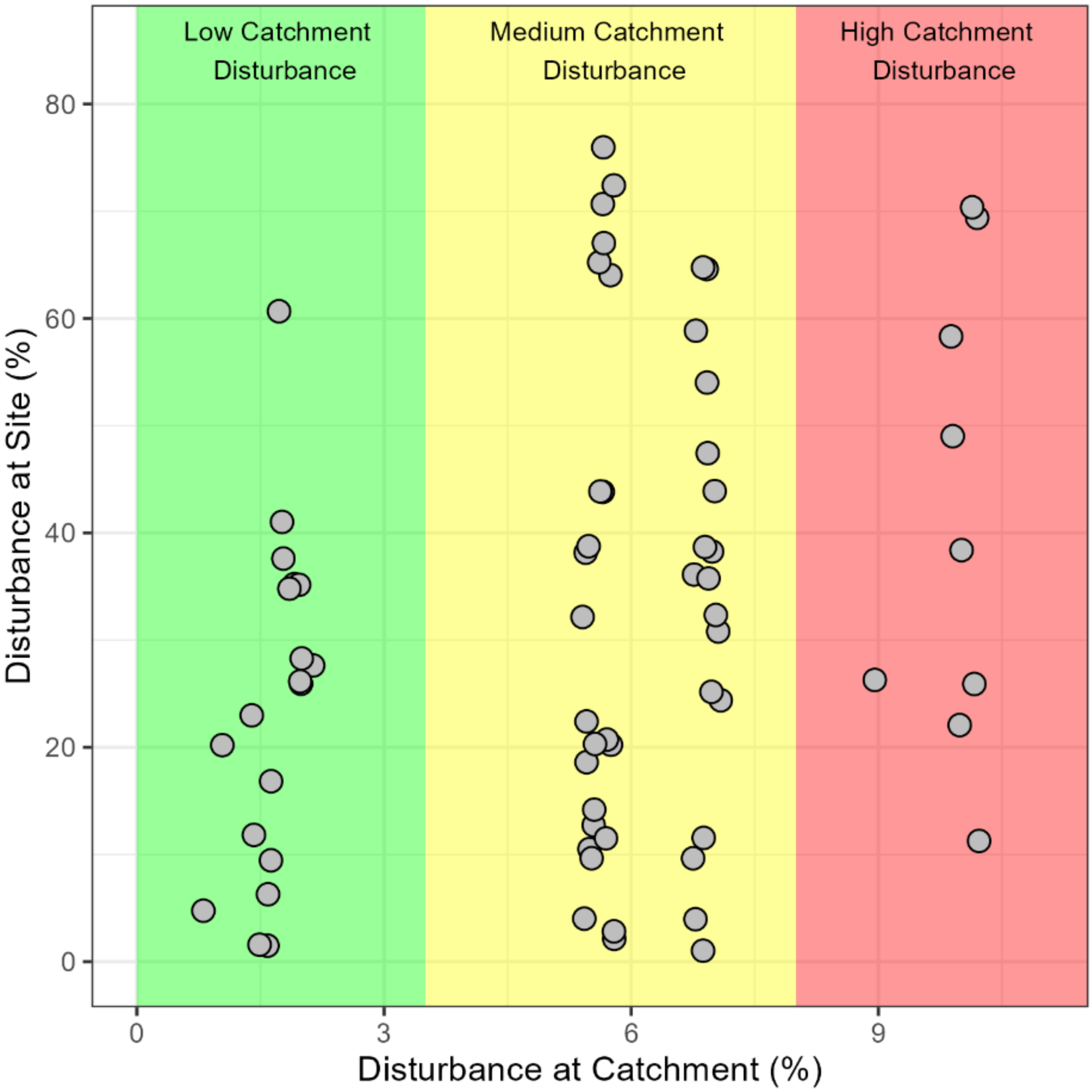

Figure 57. The distribution of Hawke's Bay freshwater sampling sites across catchment, and site-level disturbances after Cyclone Gabrielle.

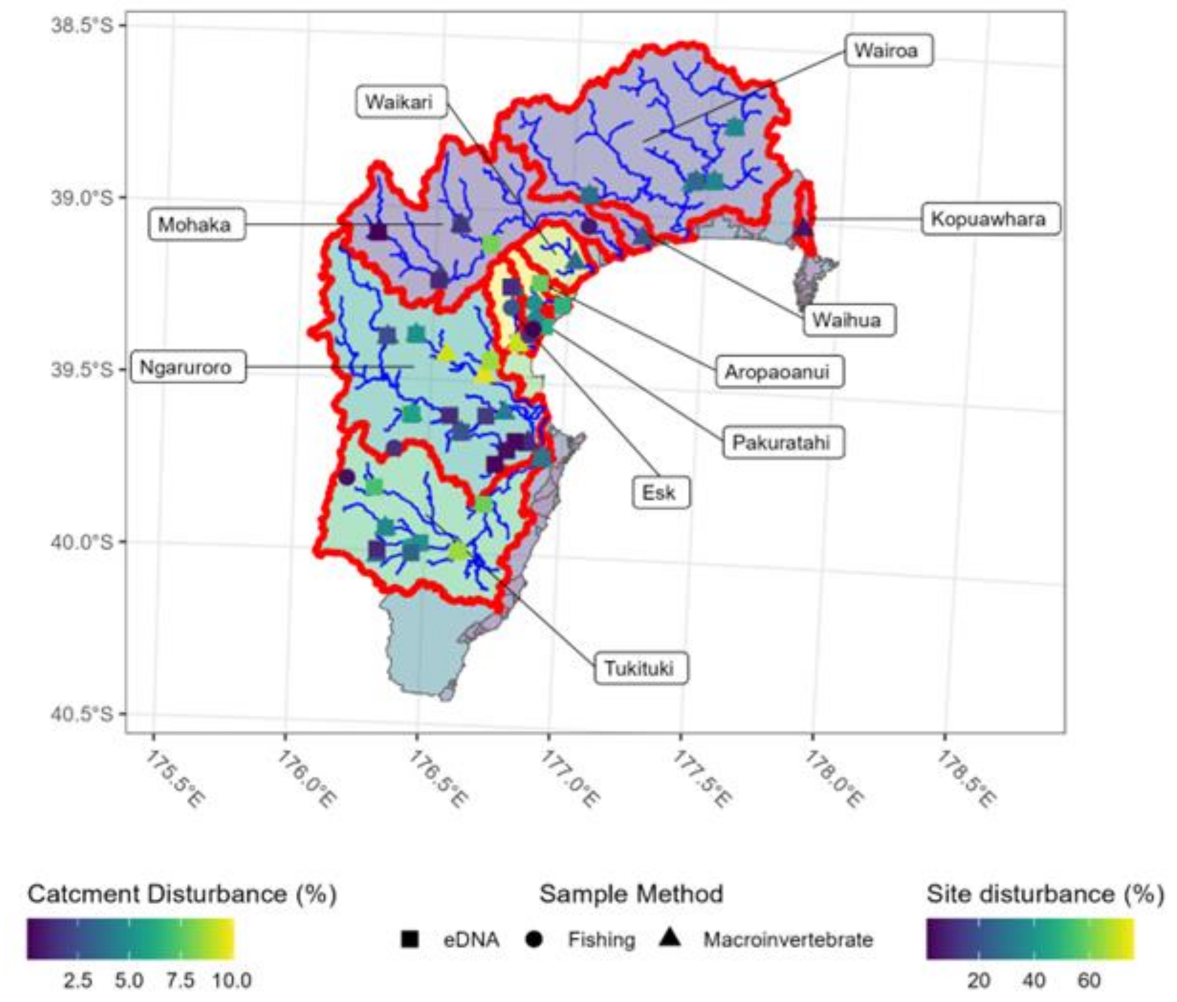

Figure 58. Map of the eDNA, fishing, and macroinvertebrate sampling sites across Hawke's Bay Region.

Notes: red polygons and labels indicate catchments where sampling occurred. Site names with their respective sampling methods can be found in Table A4.1.

4.2.2 Abiotic measures

River flow

To compare the timing and magnitude of the river flow to previous years, flow data were obtained for 11 sites from HBRC[11] for the period 2009 to 2023. Flow duration curves were calculated for each site to assess the flow characteristics of Cyclone Gabrielle compared to previous years.

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[11] https://www.hbrc.govt.nz/environment/river-levels/

River sediment

Deposited sediment was measured approximately monthly between April 2023 and May 2024 (Appendix 5; Figure A5.1) at 25 of the 26 macroinvertebrate sampling sites. The quorer method for resuspendible sediment (Clapcott et al. 2011) was used. Briefly, this method involved placing a 'quorer,' or open-ended container, over the stream bed and pushing it into the sediment to isolate a patch of stream bed. The area of stream bed within the quorer was then stirred to resuspend surface and subsurface sediments in the water column. A sample of the resulting slurry within the tube was collected, along with a background sample from the undisturbed water column outside the tube. The depth of the water within the tube after stirring was measured at five locations and averaged. The samples were processed in the laboratory to determine suspendible inorganic sediment (SIS) and suspendible organic sediment (SOS) (both measured in grams per square metre), standardised against the background sample.

We ran two models to evaluate the influence of disturbances at both the catchment and site levels, testing whether SIS was primarily driven by large-scale catchment factors or by more localised site-specific factors. It was also necessary to account for the temporal trend in suspended inorganic solids (grams per square metre). Thus, each model included an interaction between the date of sample and catchment-level disturbance or site-level disturbance. We included a random intercept (sample site) and slope (date) in the model to account for variation among sites. A gamma distribution was used due to the non-linear nature of the data. In addition, we compared temporal patterns in SIS to rainfall and river flow to investigate whether further increases in SIS occurred during subsequent flow events.

Changes in river connectivity

Directly after the cyclone, NIWA created a list of potential barriers that had previously been surveyed using the fish passage assessment tool (FPAT) to direct follow-up assessments by HBRC. The post-cyclone FPAT assessments tracked how the cyclone may have affected their risk to fish passage and the overall connectivity of the system. The assessments took place from April 2023 to June 2024. Culverts that had additional fish passage structures installed after the cyclone were removed from the data set so that we could better understand the impacts of the cyclone on in-stream barriers in the absence of remediation efforts.

4.2.3 eDNA, fish, and macroinvertebrate sampling

The physical fishing and eDNA sampling were carried out in summer 2024 to ensure both methods were undertaken during the appropriate window (December to March) for sampling fish species. The physical fishing sites incorporated those sampled as part of Hawke's Bay's SoE monitoring programme. HBRC monitors freshwater fish populations at 20 wadeable stream and river sites. Every summer, five of the 'reference' sites are sampled, and the remaining 15 sites are rotated and, therefore, change each year. Consequently, for comparison before and after Cyclone Gabrielle, physical fishing sites surveyed in January 2021 to 2023 were used for pre-cyclone data.

For eDNA analyses, data collected in the summer and autumn months between January 2020 and May 2022 were used as pre-cyclone data. The autumn 2023 eDNA sampling after

Cyclone Gabrielle was carried out between March and June 2023. Although physical fishing data were confined to the appropriate sampling window (December to March), eDNA is less reliant on capture efficiencies, and autumn data provided valuable insights into the presence of fish species immediately after the cyclone. However, a limitation of the eDNA analyses is the temporal difference in sampling between summer and autumn.

HBRC carried out physical sampling for macroinvertebrates at monthly intervals from April 2023 to March 2024, although not all sites were sampled every month (Appendix 5). For the purposes of this project, NIWA processed samples that were taken every 2 months (April/May 2023, July 2023, September 2023, November 2023, and January 2024). Samples were analysed for species identification following the '200+ fixed count with scan for missed taxa' method from the National Environmental Monitoring Standards (NEMS 2020). Briefly, this method involves randomly selecting a representative fixed-fraction subsample using a gridded sorting tray and identifying all the macroinvertebrates present within the subsample. Subsampling is repeated until at least 200 individuals have been identified. Once a subsample (grid square) has been started, all individuals within it must be counted and identified, even if the total exceeds 200 individuals. The remaining sample is then scanned for any additional taxa absent from the subsamples, which are also identified and classified as 'missed' taxa.

4.2.4 Data analyses

Fish responses

Model selection

To evaluate whether Cyclone Gabrielle had an impact on different response variables of the fish community (eDNA Index of Biological Integrity [eIBI], prevalence, species richness of taonga and non-native species, described below), we used a standardised model selection criterion to first control for a range of factors that naturally drive species responses across the landscape (i.e. landscape-level response), and then used a suite of *a priori* models to evaluate the potential impact of Cyclone Gabrielle (i.e. cyclone response).

The first set of candidate models that account for landscape variability incorporated different combinations of elevation, distance to sea (penetration), and size of the catchment area upstream of the sampling location, all of which were derived from the Digital River Network (version 3; Table 5). Then, using only pre-cyclone data, seven landscape models were compared using Akaike Information Criteria (AIC; Akaike 1976), whereby the simplest model (i.e. with the least number of covariates, K) that was within ΔAIC < 2 of the model with the lowest AIC value was selected as the top model (Table 5). In cases where the sample size was small ($n/K \leq 40$), a bias-corrected version of the AIC was used (AIC_c).

Next, using the top model from the landscape model, five additional *a priori* models with different combinations of treatment, site disturbance, and catchment disturbance were selected. Treatment represents the temporal component and has three levels: pre-cyclone, directly following the cyclone (autumn 2023), and 1 year after the cyclone (summer 2023/24). Site disturbance is a continuous measure of local impacts determined from the change in sediment and slips at the site scale (as described in 'Site selection'). Catchment disturbance is a categorial variable with three levels (low, medium, high), determined from changes in sediment and slip landscape cover within 1 km of the sampling site (see Figure 57 for break points). In addition, the models containing site or catchment disturbance also included an interaction term between treatment and the respective disturbance (Table 5).

The following guide was used to determine the level of Cyclone Gabrielle impact based on the model selection criteria.

1 No cyclone impact would be supported by a top model that did not include a measure of cyclone impact (treatment or disturbance; cyclone model 1 in Table 5).

2 Cyclone impact was not driven by site or catchment level disturbance (cyclone model 2; Table 5).

3 Cyclone impact was driven by site or catchment level disturbance (cyclone model 3 or 4 respectively; Table 5).

4 Cyclone impact was driven by both site and catchment-level disturbance (cyclone model 5; Table 5).

Table 5. *A priori* selected models to determine the effects of Cyclone Gabrielle on freshwater fish in Hawke's Bay

Notes: landscape models were selected to control for confounding variables of site placement across the watershed. Cyclone models were selected to determine the level of impact from the cyclone. Disturbance at site and catchment level was determined from aerial imagery. Treatment represents the temporal component (before and after the cyclone). Site and catchment variables were included as random intercepts.

Models
Landscape models
response ~ (1 | Site) + (1 | Catchment)
response ~ Elevation + (1 | Site) + (1 | Catchment)
response ~ Penetration + (1 | Site) + (1 | Catchment)
response ~ Upstream Area + (1 | Site) + (1 | Catchment)
response ~ Elevation + Upstream Area + (1 | Site) + (1 | Catchment)
response ~ Elevation + Penetration + (1 | Site) + (1 | Catchment)
response ~ Elevation + Penetration + Upstream Area + (1 | Site) + (1 | Catchment)
Cyclone models
1) response ~ selected landscape var + (1 | Site) + (1 | Catchment)
2) response ~ selected landscape var + Treatment + (1 | Site) + (1 | Catchment)
*3) response ~ selected landscape var + Treatment * Site Disturbance + (1 | Site) + (1 | Catchment)*
*4) response ~ selected landscape var + Treatment * Catchment Disturbance + (1 | Site) + (1 | Catchment)*
*5) response ~ selected landscape var + Treatment * Site Disturbance + treatment * Catchment Disturbance + (1 | Site) + (1 | Catchment)*

eDNA analyses

Fish eIBI score analysis

The Fish Index of Biotic Integrity (Fish IBI; Joy & Death 2004) is a required metric of the National Policy Statement for Freshwater Management 2020 (NPS-FM). It is computed from species detection using physical fishing methods. Here we calculate a molecular Fish IBI (eIBI; range from 0 to 60) from eDNA results using coding from the Ministry for the Environment fishr package (Bain 2021). Only DNA sequences that matched to species level were used in the analysis. AIC model selection of *a priori* models (Table 5) was used to evaluate the impacts of Cyclone Gabrielle. The glmmTMB models outlined in Table 5 used a gamma distribution with log link. Tukey's *post hoc* analysis was used to test differences between treatment groups.

Taonga and non-native species richness

Species richness of taonga (in this instance, fish species utilised in traditional mahinga kai [food cultivation]) and non-native species was derived from eDNA detections (Table 6). The *a priori* models in Table 5 were used to evaluate the impacts of Cyclone Gabrielle based on AIC selection criteria. For each model a Poisson distribution was used, and Tukey's *post hoc* analysis was used to test differences between discrete variables (treatment and catchment disturbance) if present in the final model.

Table 6. List of taonga and non-native fish species detected using eDNA

Common name	**Scientific name**
Taonga species	
Banded kōkopu*	*Galaxias fasciatus*
Common smelt (pōrohe)*	*Retropinna retropinna*
Giant kōkopu*	*Galaxias argenteus*
Grey mullet**	*Mugil cephalus*
Īnanga*	*Galaxias maculatus*
Kōaro*	*Galaxias brevipinnis*
Lamprey (piharau/kanakana)*	*Geotria australis*
Longfin eel (tuna)*	*Anguilla dieffenbachii*
Shortfin eel (tuna)*	*Anguilla australis*
Shortjaw kōkopu*	*Galaxias postvectis*
Non-native species	
Brook char	*Salvelinus fontinalis*
Brown trout	*Salmo trutta*
Catfish	*Ameiurus nebulosus*
Chinook salmon	*Oncorhynchus tshawytscha*
Grass carp	*Ctenopharyngodon idella*
Gambusia	*Gambusia affinis*

Common name	Scientific name
Goldfish	*Carassius auratus*
Guppy	*Poecilia reticulata*
Perch	*Perca fluviatilis*
Rainbow trout	*Oncorhynchus mykiss*
Rudd	*Scardinius erythrophthalmus*
Sockeye salmon	*Oncorhynchus nerka*
Tench	*Tinca tinca*

* Migratory species

** Marine wanderer

Note: Non-native species were taken from Joy & Death 2004 and include species that are not present in the Hawke's Bay region

Prevalence analysis

Before analysing individual species, we calculated the proportion of each fish species present based on eDNA counts for each replicate (i.e. prevalence index; Melchior & Baker 2023). The prevalence index was calculated for each species by taking the median percentage of eDNA reads for each species across replicates at a site that had positive detections for a given species (Melchior & Baker 2023). The impacts of Cyclone Gabrielle were tested using the model selection criteria outlined above. A beta distribution was used for each model. However, because the response value for a beta distribution is bounded by 0 and 1 excluding the boundaries, it was necessary to apply the following conversion to individual species prevalence:

$$Y_{beta} = (Y_{original} * (N - 1) + 0.5)/N$$

where $Y_{original}$ is the prevalence index and N is the number of samples.

Finally, Tukey's *post hoc* analysis was used to test differences between discrete variables if present in the final model.

Fish abundance analysis

An IBI score was calculated based on the relative abundance data from the electric fishing (EFM) surveys using the same methods as were used to calculate the eIBI. However, due to the limited number of sampling sites with EFM data it was not feasible to evaluate the response of capture data using the AIC model selection criteria. Consequently, the only model assessed tested whether the IBI score differed between before the cyclone and the following summer. Data obtained directly following the cyclone were excluded due to the temporal mismatch of species movements between summer and autumn. The model still included the random intercepts of site and catchment and used a gamma distribution with log link. Like previous analyses, Tukey's *post hoc* analysis was used to test differences between pre- and post-cyclone IBI scores.

A qualitative assessment of general temporal trends in relative abundance was also conducted at the species level. This was because not all species were detected at all six sampling sites, with many species found at only two to four sites, which increases the risk of a single site heavily influencing the quantitative analysis.

Fish spawning surveys

Īnanga is one of the five galaxiid whitebait species, alongside banded kōkopu, kōaro, giant kōkopu, and shortjaw kōkopu. In the Hawke's Bay Region, whitebait mainly comprises īnanga (Figure 59), with a smaller proportion of kōaro and banded kōkopu. Giant kōkopu and shortjaw kōkopu are rare/absent in the Hawke's Bay region, with recent eDNA detections for shortjaw kōkopu but no physical fish documented.

Figure 59. Īnanga whitebait (top) and adult (bottom). (Bottom photo courtesy of S. Moore)

Īnanga are the only whitebait species termed catadromous or marginally catadromous, whereby breeding takes place in tidal estuarine waters, but larvae still rear in the ocean and migrate back to fresh water as juveniles for growth to adulthood. Īnanga are primarily an annual species, with adults maturing in their first year and then most dying after spawning. Unlike the other whitebait species, īnanga do not routinely develop lacustrine populations, whereby their life cycle is completed solely in freshwater. Consequently, tidally influenced spawning habitats are critical for īnanga to successfully produce progeny to support the next generation.

Īnanga spawning and eggs (nests) have been observed in Hawke's Bay in April and May on many occasions (Taylor 2002). There are four known īnanga spawning locations in the Wairoa district (Cheyne & Rook 2016). Two known sites are on small tributary streams of the Wairoa River, Huramua Stream and Awatere Stream, and these sites were assessed as part of the cyclone impact investigation. The spawning sites were visited in September 2023 to observe the stream condition and assess implications for spawning habitat, but no surveys of fish or eggs were conducted because it was not spawning season (Elliott et al. 2023).

To assess the impacts of Cyclone Gabirelle on īnanga spawning habitat, spawning surveys were conducted in the intertidal vegetation of Huramua Stream and Awatere Stream in May 2024. Two other tributaries in the lower Wairoa catchment were also searched for eggs because adult īnanga were observed during the September 2023 site visit.

At each site, spawning habitat was sampled using 3 m-long transects perpendicular to the waterline (Orchard & Hickford 2018). Spawning microhabitat was sampled by placing 10 quadrats along the riverbank in the likely spawning zone. These quadrats were placed within 2 m of the waterline. Within each 100 × 100 mm quadrat, counts of the number of stems originating in five randomly placed 30 × 10 mm squares were conducted. Depth of aerial root mats at five random locations was also measured.

Huramua Stream

Huramua Stream is a known īnanga spawning site and was first identified around 2010. The upstream limit to the spawning site is E 1979075 N 5671374 and the downstream limit is E 1979081 N 5671231, with approximately 150 m of suitable spawning habitat along both banks (Figure 60). The vegetation present in 2016 consisted of banks fringed with marsh club rush (*Bolboschoenus* sp.) and *Carex geminata,* interspersed with the grasses creeping bent (*Agrostis stolonifera*) and tall fescue (*Lolium arundinaceum*; Elliot et al. 2023).

Figure 60. Satellite image of Huramua Stream, Hawke's Bay, with the potential īnanga spawning site marked by the yellow ellipse.

Awatere Stream

Awatere Stream is another known īnanga spawning sites within the Wairoa River catchment, which was first identified around 2010 (Elliot et al. 2023). The spawning site in Awatere Stream is approximately 500 m from the confluence with the Wairoa River. The spawning area extends approximately 300 m along both banks of the river, from E 1983550 N 5670900 upstream to E 1983800 N 5670600, located roughly 100 m upstream of State Highway 2 (Figure 61).

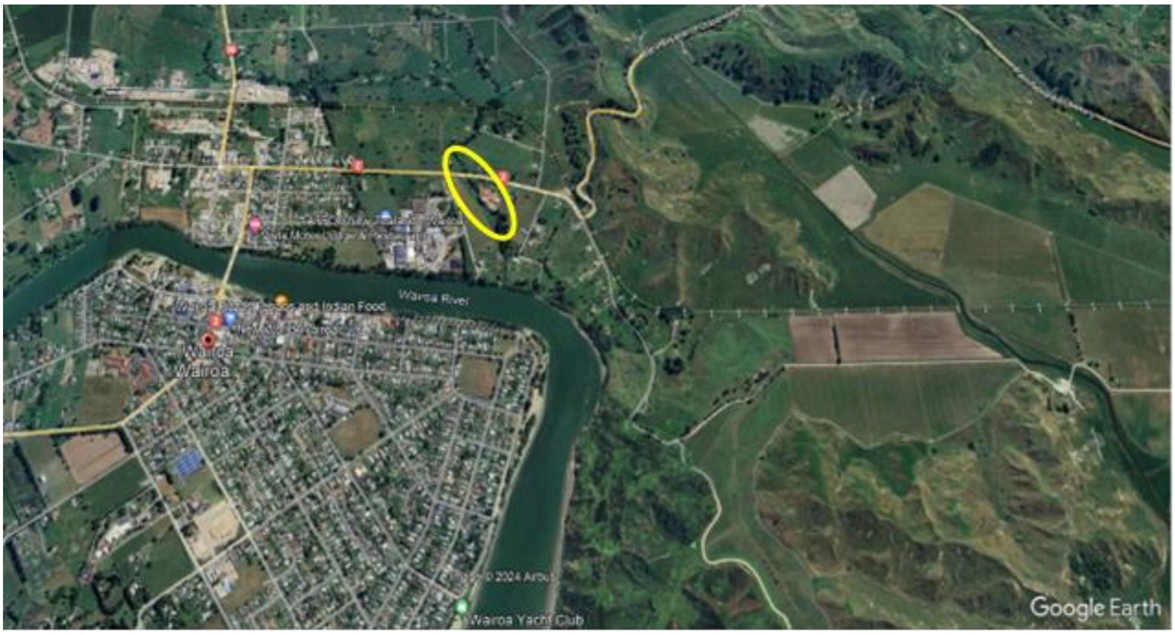


Figure 61. Satellite image of Awatere Stream, Hawke's Bay, with the potential īnanga spawning site marked by the yellow ellipse.

Whakamahi Lagoon tributary

The Whakamahi Lagoon tributary (Figure 62) has not previously been identified as an īnanga spawning site but shows some potentially suitable habitat characteristics. The habitat extending from E 1983760 N 5670577 to E 1983528 N 5670960 was deemed suitable for īnanga spawning, and eDNA analysis indicates the presence of īnanga within this catchment.

Approximately 20 years ago the area above the culvert underwent extensive riparian planting, which has now matured into quite large trees. The well-established riparian vegetation could provide shading and inputs of organic matter beneficial for īnanga spawning habitat. However, further assessment is needed to evaluate the specific conditions along the banks and determine if the habitat requirements for successful spawning are met at this site. The existing fish presence and vegetated riparian zone are positive indicators, but do not guarantee this area currently functions as an active spawning location for the īnanga population.

Figure 62. Satellite image of Whakamahi Lagoon tributary, Hawke's Bay, with the potential īnanga spawning site marked by the yellow ellipse.

Tawhara Stream

Tawhara Stream is not a previously documented īnanga spawning site but exhibits considerable potential habitat characteristics (Figure 63). Based on site visits, the habitat extending from E 1980927 N 5667056 to E 1980871 N 5667111 was identified as potentially suitable and examined for īnanga spawning. eDNA analyses indicate the presence of īnanga in this catchment. Although heavily inundated with driftwood, which can make searching for eggs difficult, such woody debris may not inhibit īnanga spawning. The site also faces threats from invasive plants such as pampas grass (*Cortaderia selloana*) that could degrade spawning conditions if left unmanaged.

Figure 63. Satellite image of Tawhara Stream, Hawke's Bay, with the potential īnanga spawning site marked by the yellow ellipse.

Benthic invertebrate response

Macroinvertebrate metrics

Macroinvertebrate metrics are commonly used to indicate the community composition and ecosystem health of freshwaters. In the National Policy Statement for Freshwater Management (NPSFM 2020), macroinvertebrates are represented by three attribute metrics: the Macroinvertebrate Community Index (MCI), the quantitative variant of MCI (QMCI), and the Average Score Per Metric (ASPM), a multi-metric index that combines MCI and EPT taxa richness and relative abundance. EPT refers to Ephemeroptera – mayflies, Plecoptera – stoneflies, and Trichoptera – caddisflies, which are taxa known to be sensitive to contaminants and changes in environmental conditions.

Macroinvertebrate metrics were calculated for each sample following the methodology of the National Environmental Monitoring Standards (NEMS) for macroinvertebrates (NEMS 2020) (Table 7). For consistency across analyses, all taxonomic data were aggregated to the resolution specified in the NEMS for calculating MCI scores. This is typically genus for most taxa, but family or higher for some groups such as worms, molluscs, and crustacea. Soft-bottomed tolerance values (see Description in Table 7) were used to calculate metrics for sites identified by HBRC as naturally soft-bottomed (greater than 50% fine sediment cover) before Cyclone Gabrielle.

Table 7. Macroinvertebrate metric calculations

Metric	Units	Description	Calculation
Taxa richness		Calculated based on presence data. Taxonomic resolution should be consistent with that used for MCI and QMCI calculations.	The total number of different taxa present in a sample.
EPT taxa richness		EPT (Ephemeroptera – mayflies, Plecoptera – stoneflies, and Trichoptera – caddisflies) are groups known to be sensitive to organic pollution. Caddisflies from the family Hydroptilidae are excluded from EPT metric calculations because they are pollution tolerant.	Number of EPT taxa
Percent EPT taxa richness	%		$\frac{Number\ of\ EPT\ taxa}{Total\ number\ of\ taxa}$
Percent EPT abundance	%		$\frac{Number\ of\ EPT\ individuals}{Total\ number\ of\ individuals}$
Macroinvertebrate Community Index (MCI_{HB}, MCI_{SB})		A measure of stream health based on the tolerance of different macroinvertebrate taxa to organic pollution (Stark & Maxted 2007). Each species is assigned a tolerance score from 1 (very tolerant) to 10 (very sensitive). Tolerance values differ for hard-bottomed (HB) and soft-bottomed (SB) streams. MCI is calculated as the sum of tolerance scores for all species in a site.	$MCI = \frac{\sum_{i=1}^{i=S} a_i}{S} \times 20$ where S = the total number of scoring taxa in a sample and a_i is the tolerance score for the ith taxon.
Quantitative Macroinvertebrate Community Index ($QMCI_{HB}$, $QMCI_{SB}$)		Incorporates abundance of each taxa.	$QMCI = \frac{\sum_{i=1}^{i=S}(n_i \times a_i)}{N}$ where S = the total number of scoring taxa in a sample, n_i is the abundance of the ith scoring taxon, a_i is the tolerance score for the ith taxa, and N = the total abundance for the scoring taxa for the entire sample.
Average score per metric (ASPM)		A multi-metric index calculated as the mean of three metrics: MCI, EPT taxa richness, and percent EPT abundance (Collier 2008).	Each metric is first scaled (normalised) by: $X' = [X - X_{min}]/[X_{max} - X_{min}]$ where X' is the scaled site score, X is the raw site score, and X_{min} and X_{max} are: EPT taxa richness (0–29), % EPT abundance (0–100), and MCI (0–200).

(Source: Adapted from NEMS 2020)

Model selection

A model selection approach like that described for fish responses was used to investigate the impacts of Cyclone Gabrielle on benthic macroinvertebrates using macroinvertebrate community metrics (MCI, QMCI, ASPM, taxa richness, EPT richness, % EPT taxa, and % EPT abundance) as the response variables.

Two sets of candidate models were tested for each response; one set to evaluate landscape drivers and a second to evaluate the cyclone impacts. Given the temporal structure of the data set (samples every 2 months over 1 year), date was included as a fixed effect in all models. The first set of candidate models accounted for landscape variability, including elevation and catchment area upstream of the sampling location as a proxy for waterway size (Table 8).

The four landscape models were fitted to the pre-cyclone data and compared using Akaike Information Criteria (AIC). The simplest model (the model with the least number of covariates, K) within ΔAIC < 2 of the model with the lowest AIC was selected as the top model accounting for landscape variation (Table 8). Next, using the top model from the landscape models, five additional *a priori* models were selected, consisting of interactions between treatment (before and after Cyclone Gabrielle), time (date), and site disturbance (a continuous measure of local impacts) and catchment disturbance (split into low, medium and high).

Models were fitted using a gamma distribution with log link, except for proportional responses (i.e. % EPT), which were fitted with a beta distribution with a logit link. All models included site as a random intercept term to allow for site-level variation. Ideally, the models would have also included a random slope term to allow for different temporal responses between sites, but the additional complexity resulted in convergence issues. A catchment random intercept was not included for the same reason.

A similar guideline to that used to assess fish responses was applied to determine the level of Cyclone Gabrielle impact based on the model selection criteria.

1. No cyclone impact would be supported by a top model that did not include a measure of cyclone impact (treatment or disturbance; cyclone model 1 in Table 8).
2. Cyclone impact was not driven by site or catchment level disturbance (cyclone model 2; Table 8).
3. Cyclone impact was driven by site or catchment level disturbance (cyclone model 3 or 4 respectively; Table 8).
4. Cyclone impact was driven by both site and catchment-level disturbance (cyclone model 5; Table 8).

Table 8. ***A priori*** **selected models to determine the effects of Cyclone Gabrielle on macroinvertebrate communities in Hawke's Bay, from physical sampling every 2 months**

Models
Landscape models
response ~ Date + (1| Site)
response ~ Elevation + Date + (1 | Site)
response ~ Upstream Area + Date + (1 | Site)
response ~ Elevation + Upstream Area + Date + (1 | Site)
Cyclone models
1) *response ~ selected landscape var + Date + (1 | Site)*
2) *response ~ selected landscape var + Date * Treatment + (1 | Site)*
3) *response ~ selected landscape var + Date * Treatment * Site Disturbance + (1 | Site)*
4) *response ~ selected landscape var + Date * Treatment * Catchment Disturbance + (1 | Site)*
5) *response ~ selected landscape var + Date * Treatment * Site Disturbance + Date * Treatment * Catchment Disturbance + (1 | Site)*

Notes: landscape models were selected to control for confounding variables of site placement across the watershed. Cyclone models were selected to determine the level of impact from the cyclone (disturbance at site and catchment level). Disturbance at site and catchment level was determined from aerial imagery. Treatment represents the temporal component (before and after the cyclone). Site was included as a random intercept.

Community analyses

Shifts in community composition following Cyclone Gabrielle were examined using non-metric, multi-dimensional scaling (NMDS) analysis from the 'vegan' package in R (Oksanen et al. 2022). NMDS is a distance-based ordination technique that represents the pairwise dissimilarity between community matrices (species × sample units). Dissimilarities, or distances between community pairs (samples), are mapped into Cartesian space; communities that are closer together in ordination space are more similar than those that are further apart.

The effects of cyclone disturbance on community composition were assessed using permutational analysis of variance (PERMANOVA) and homogeneity of dispersion from the 'vegan' package in R (Oksanen et al. 2022). Pairwise dissimilarities between consecutive samples were used to visualise recovery trajectories for each site.

eDNA analyses

A molecular MCI (eMCI) was calculated using macroinvertebrate species detections from eDNA samples. Data were aggregated to genus-level taxonomic resolution, and any undetermined taxa were excluded.

The Taxon Independent Community Index (TICI), a whole-ecosystem biotic index of riverine organisms (including bacteria, micro-eukaryotes, plants, fungi, and animals; Wilkinson et al. 2024), was provided by Wilderlab with the eDNA detection data for each sample.

Model selection was used to evaluate the impacts of Cyclone Gabrielle on eMCI, TICI, overall taxa richness, EPT richness, and % EPT taxa, following the two-step approach described previously. However, because eDNA samples were only available for three sampling occasions, models included a categorial before/after 'treatment' effect (before the cyclone, directly following the cyclone [autumn 2023], and the following summer [summer 2023/24]) rather than a continuous time series. The candidate set of *a priori* cyclone impact models included combinations of interactions between treatment and site and catchment disturbance (Table 9). All models used a gamma distribution with log link and included site and catchment as random intercepts. Tukey's *post hoc* analysis was used to test differences between treatment groups.

Table 9. *A priori* selected models used to determine the effects of Cyclone Gabrielle on macroinvertebrate communities in Hawke's Bay, based on eDNA sampling

Models
Landscape models
response ~ (1 | Site) + (1 | Catchment)
response ~ Elevation + (1 | Site) + (1 | Catchment)
response ~ Upstream Area + (1 | Site) + (1 | Catchment)
response ~ Elevation + Upstream Area + (1 | Site) + (1 | Catchment)
Cyclone models
1) response ~ selected landscape var + (1 | Site) + (1 | Catchment)
2) response ~ selected landscape var + Treatment + (1 | Site) + (1 | Catchment)
*3) response ~ selected landscape var + Treatment * Site Disturbance + (1 | Site) + (1 | Catchment)*
*4) response ~ selected landscape var + Treatment * Catchment Disturbance + (1 | Site) + (1 | Catchment)*
*5) response ~ selected landscape var + Treatment * Site Disturbance + Treatment * Catchment Disturbance + (1 | Site) + (1 | Catchment)*

Notes: Landscape models were selected to control for confounding variables of site placement across the watershed. Cyclone models were selected to determine the level of impact from the cyclone. Disturbance at site and catchment level was determined from aerial imagery. Treatment represents the temporal component (before and after the cyclone). Site and catchment variables were included as random intercepts

Presence/absence of taxa (genus) × sample unit community matrices of eDNA detections were used to visualise shifts in community composition and recovery trajectories using NMDS, as described previously.

4.3 Results

4.3.1 Abiotic measures

We first present results for abiotic measures to provide essential context for the ecological community responses.

River flow

Peak flows from Cyclone Gabrielle did not show overall higher peak river flows compared to previous years in many of the gauging sites (i.e. 0-5% of the flow duration curve [FDC], Figure 64). However, river flow across the 11 gauging stations in the Hawke's Bay region did show increased sustained flows compared to previous years for many of these gauging stations (i.e. flows between 25% and 75% of time that flow is equalled or exceeded [x-axis]; Figure 64). That said, sustained flows for several sites are noticeably similar to those for previous years (see Hangaroa, Tutaekuri Puketapu, and Waiau Otoi; Figure 64). In addition, the sustained flow seen in many of the sites translated into higher low flows for the year (>95% of the FDC; Figure 64).

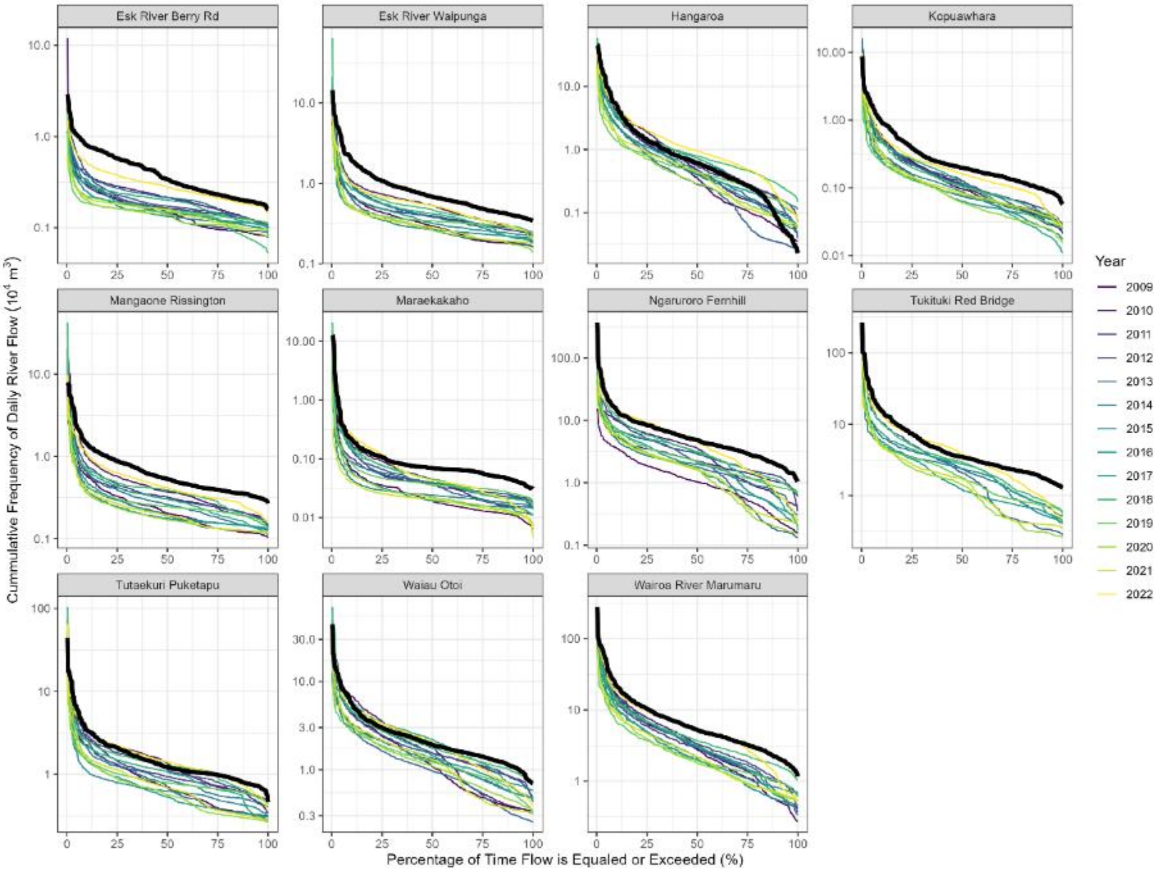


Figure 64. Flow duration curve showing the percentage of time that various flow rates were equalled or exceeded for multiple years across the Hawke's Bay region.

Note: the black line represents data from 2023, when Cyclone Gabrielle occurred.

Sediment

Overall, deposited sediment (measured as suspendible inorganic sediment; SIS) declined across Hawke's Bay, with 17 of the 21 sites showing decreases in deposited (Figure 65) and suspended (Appendix 5; Figure A5.2) sediment over time post-cyclone, although there were short-term increases in SIS associated with subsequent flow events throughout the year (Appendix 5; Figure A5.2). Furthermore, catchments that were classified as high impact showed a greater decrease in SIS through time compared to low-disturbance sites, which displayed little or no change in SIS (Figure 65). At the site level no clear differences in SIS were observed between sites with a high level of disturbance compared with sites with a low level of disturbance (Figure 66).

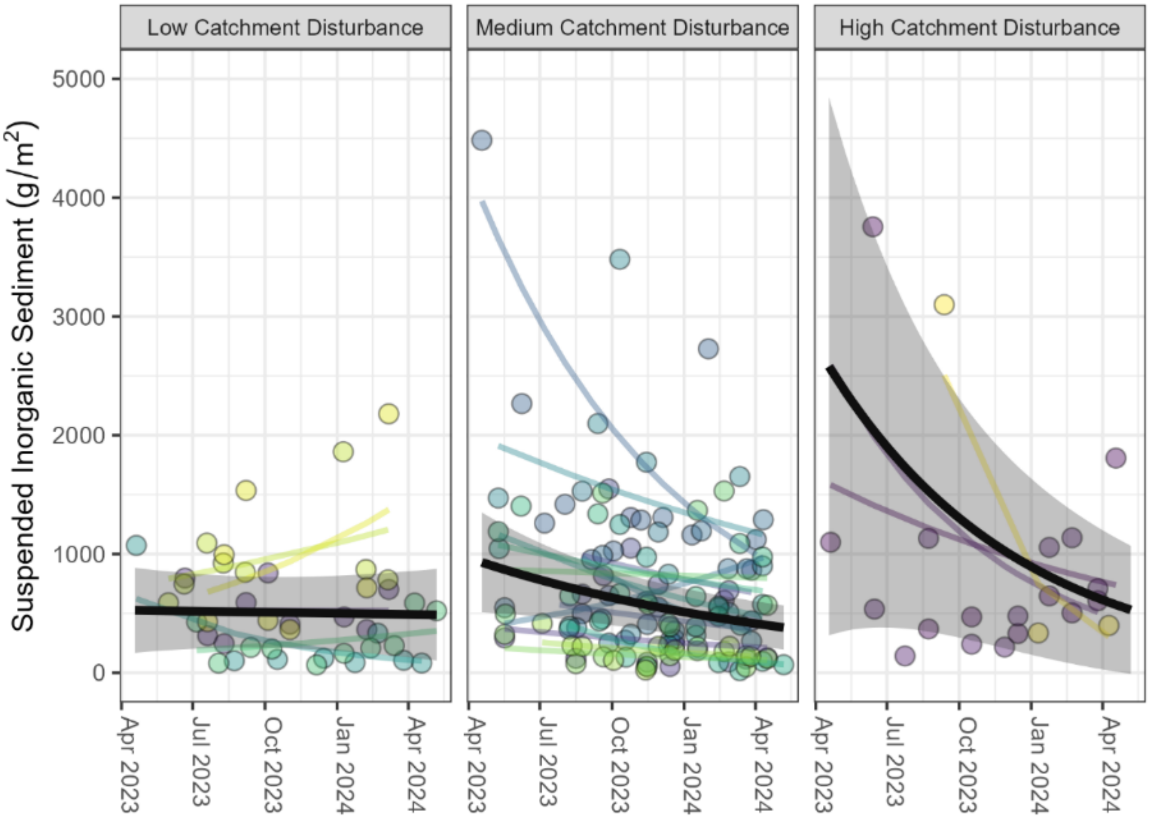


Figure 65. Temporal trend of suspendible inorganic sediment (SIS) in Hawke's Bay streams, based on Cyclone Gabrielle catchment-level disturbance.

Notes: coloured lines are the predicted outputs between SIS and time for each site, and the solid black line is the mean trend of SIS across all sites for a given catchment disturbance level. The grey ribbon represents the 95% confidence interval around the mean fitted line. Point colour corresponds to individual sites.

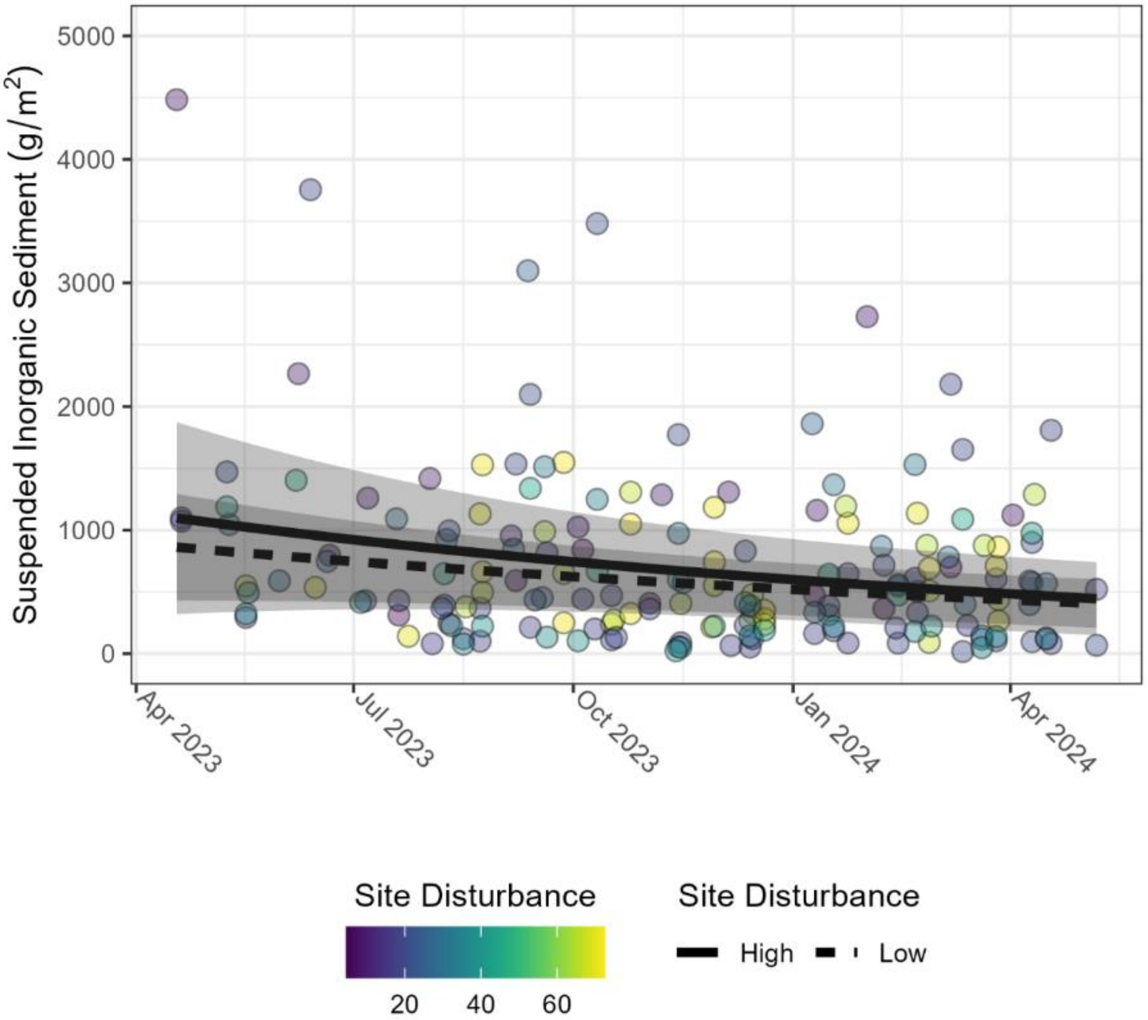


Figure 66. Temporal trend of suspendible inorganic sediment (SIS) across all sampled streams in Hawke's Bay following Cyclone Gabrielle.

Notes: lines are the fitted line for sites with high (64%, solid line) and low (17%, dashed line) disturbance based on satellite imagery (represented by symbol colour). The grey ribbon represents the 95% confidence interval.

River connectivity

A total of 61 culverts were re-assessed following Cyclone Gabrielle. Of these, 13 (21%) had a worsening of their risk assessment, 19 (31%) had an improvement in their risk assessment, and 29 (48%) had no change to their risk score (Figure 67). Of the 19 structures that improved, small changes were observed (e.g. change in risk from high to very high; Figure 67). Structures that had a worsening of their risk assessment had similar trends (e.g. change in risk from very high to high) except for four barriers that went from very low to high- or very high-risk assessments, and consequently are now probably a complete barrier to fish passage (Figure 67).

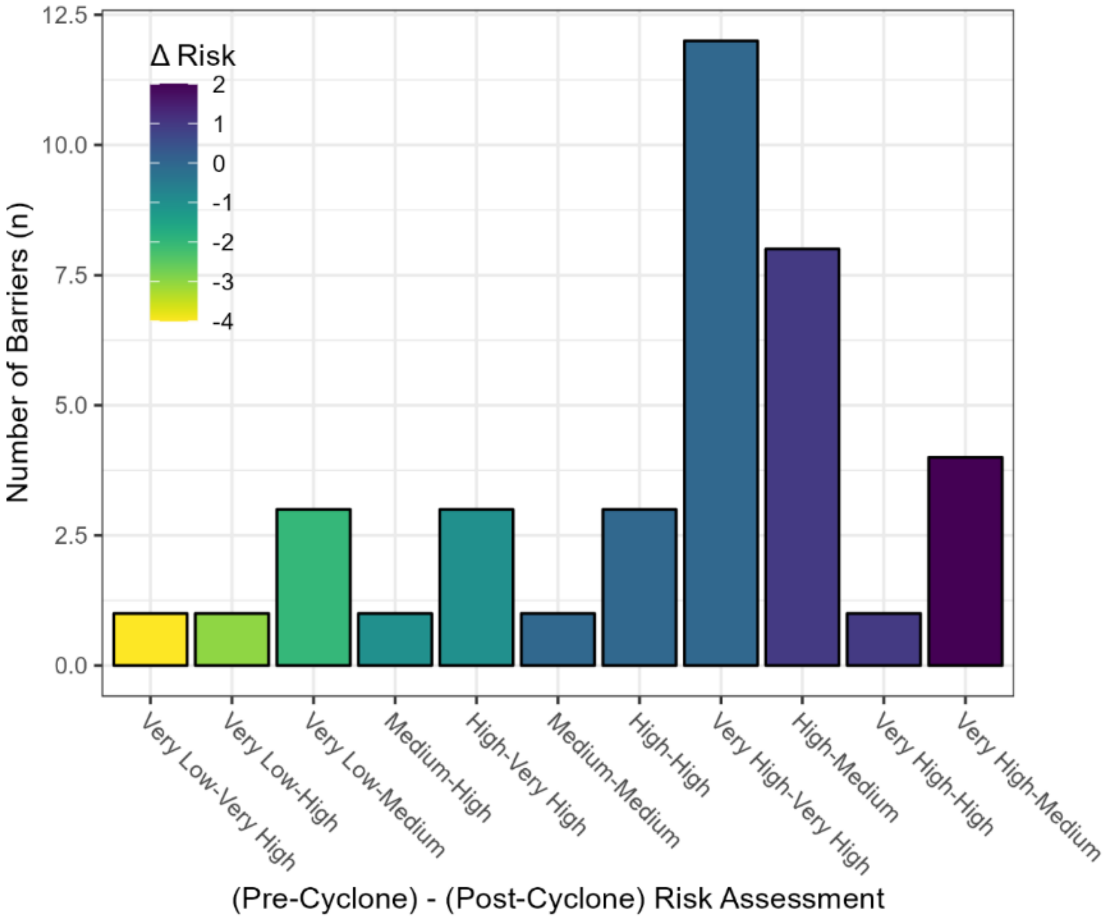


Figure 67. Bar plot showing the frequency of changes in fish barrier risk assessment for 61 culverts across Hawke's Bay after Cyclone Gabrielle.

Notes: positive delta (Δ) risk values indicate improvements in a barrier's risk assessment (cooler colours), negative values indicate worsening of a barrier's risk assessment (warmer colours), and a value of 0 indicates no change.

4.3.2 Fish responses

eDNA analyses

Mean eDNA counts fluctuated across sampling periods (summer months pre-cyclone vs summer 2023/24, Figure 68), with clear increases in autumn 2023, particularly for detections of common bullies. In addition, in some sites where species had low eDNA counts before the cyclone, these species were not detected following Cyclone Gabrielle but were detected again the following summer (e.g. bluegill bullies in Figure 68).

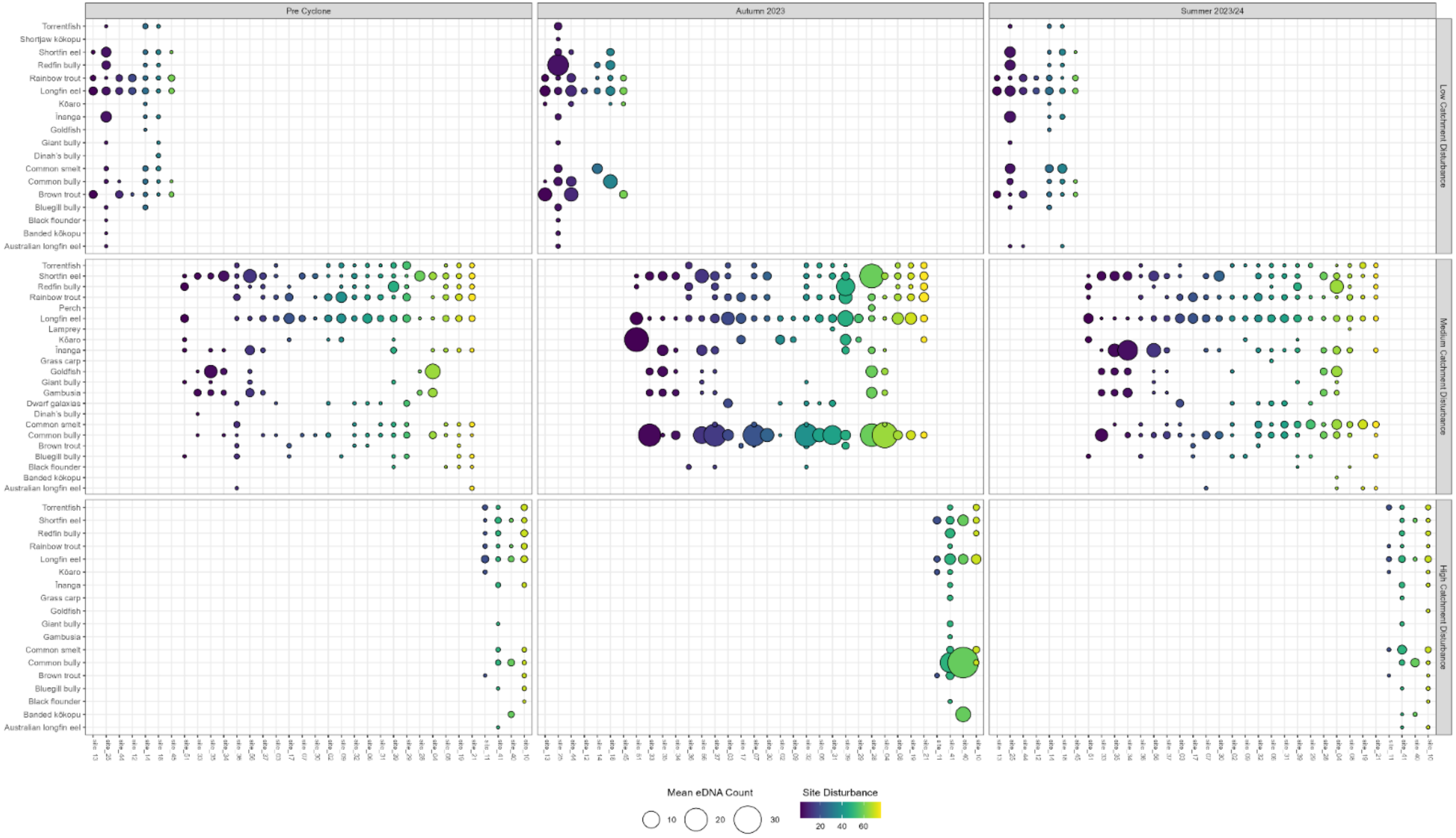


Figure 68. Mean eDNA counts for each site (size of bubble plot), standardised for replicate volume, across site eDNA replicates from before the cyclone (left panel), immediately after the cyclone (autumn 2023; middle panel), and 1 year after the cyclone (summer 2023/24, right panel).

Notes: dark purple points indicate sites with low site disturbance and yellow points indicate sites with higher site disturbance, based on changes in satellite imagery. Site IDs on the x-axis correspond to site names in Table A4.1.

eIBI score

The eDNA Index of Biological Integrity (eIBI) showed a non-significant decrease in eIBI score directly after Cyclone Gabrielle before returning to pre-cyclone levels (Figure 69). The top model assessing the impact of Cyclone Gabrielle on the changes in eIBI score included the interaction between treatment and site (Table 10). However, upon evaluation of the model, a similar positive trend was observed between site disturbance and the eIBI score across treatment groups (e.g. pre- vs post-cyclone), indicating that changes in the eIBI score were related to factors not connected to the cyclone.

This interpretation was further supported by the second-to-top model, which had a ΔAIC of 0.08 (models with ΔAIC < 2 are considered adequate models; Anderson 2002) and did not include any term related to cyclone impacts. Therefore it is unlikely that Cyclone Gabrielle significantly affected eIBI scores (Figure 69). The top model also did not include any landscape terms (e.g. elevation, penetration, or upstream catchment area). This is expected as the eIBI calculation controls for changes in both elevation and penetration (Joy & Death 2004).

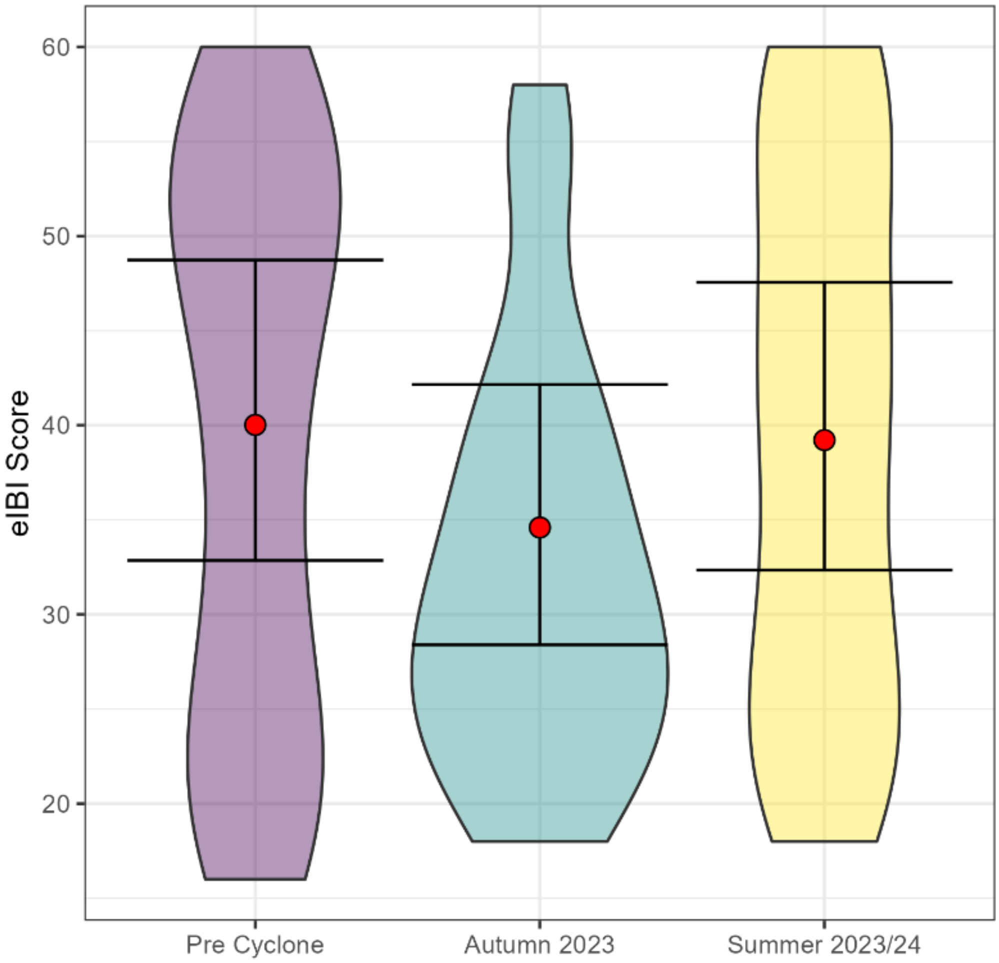


Figure 69. Comparison of the eDNA Index of Biological Integrity (eIBI) scores, based on eDNA samples from Hawke's Bay rivers before and after Cyclone Gabrielle.

Notes: solid red circles are the modelled mean eIBI score for each treatment group boxplot, with the upper and lower 95% CI (error bars).

Species richness

The number of taonga species detected in eDNA sampling increased after the cyclone, especially in sites with high disturbance (Figures 70 and 71). The top model for taonga species richness included the interaction term between treatment and site disturbance (Table 10).

Taonga species richness increased in the summer following Cyclone Gabrielle (Figure 70). The key species driving this increase were īnanga (newly detected at six sites), common smelt (six sites), banded kōkopu (two sites), kōaro (one site), and pouched lamprey (one site), which were not detected before the cyclone or in the autumn following Cyclone Gabrielle, but were detected in summer 2023/24. However, shortfin eels and īnanga were not detected after the cyclone at four and two sites where they were previously detected, respectively. In addition, increased taonga species richness was most evident in highly affected sites (Figure 71).

The top model for explaining variation in non-native species richness was the null model (Table 10), indicating that Cyclone Gabrielle did not affect the presence of non-native species (Figure 70). Like the eIBI analysis, the top model also did not include any landscape variables.

Table 10. Model selection models regressing the eDNA Index of Biological Integrity (eIBI) score, taonga species richness, and non-native species richness relative to spatial (site and catchment disturbance) and temporal (treatment) effects of Cyclone Gabrielle

Model	LogLik	K	AICc	ΔAICc	Weight
eIBI score					
eIBI Score ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance	–471.065	7	957.071	0.000	0.441
eIBI Score ~ (1 | Site) + (1 | Catchment)	–476.529	2	957.155	0.084	0.423
eIBI Score ~ (1 | Site) + (1 | Catchment) + treatment	–475.608	4	959.545	2.473	0.128
eIBI Score ~ (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–472.183	10	966.263	9.191	0.004
eIBI Score ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance + treatment * catchment disturbance	–468.965	13	967.152	10.081	0.003
Taonga species richness					
taonga ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance	–266.603	7	548.147	0.000	0.891
taonga ~ (1 | Site) + (1 | Catchment) + treatment	–272.040	4	552.407	4.259	0.106
taonga ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance + treatment * catchment disturbance	–265.968	13	561.157	13.009	0.001
taonga ~ (1 | Site) + (1 | Catchment)	–278.986	2	562.07	13.922	0.001
taonga ~ (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–270.477	10	562.85	14.702	0.001
Non-native species richness					
non_native ~ (1 | Site) + (1 | Catchment)	–224.569	2	453.234	0.000	0.781
non_native ~ (1 | Site) + (1 | Catchment) + treatment	–223.832	4	455.992	2.758	0.197

Model	LogLik	K	AICc	ΔAICc	Weight
non_native ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance	–223.176	7	461.294	8.060	0.014
non_native ~ (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–220.262	10	462.42	9.186	0.008
non_native ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance + treatment * catchment disturbance	–219.644	13	468.508	15.274	0.000

Notes: LogLik is the log likelihood, K is the number of model parameters, AICc is the Akaike Information Criterion, ΔAICc is the change in AICc relative to the lowest AICc value, and weight is the weight of evidence that the model is the top model

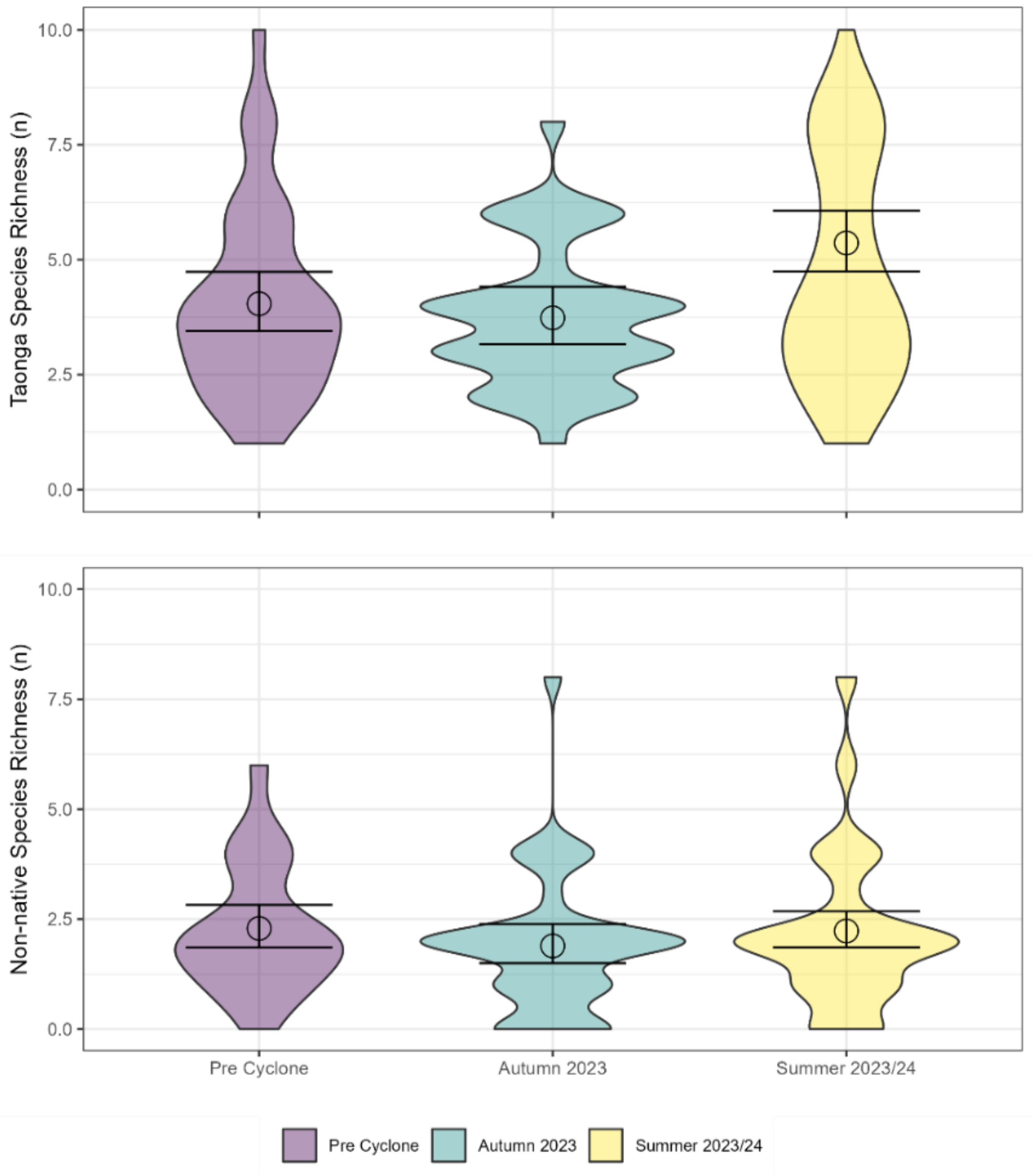


Figure 70. Violin plot of the number of detected taonga (top) and non-native (bottom) fish species using eDNA sampling from Hawke's Bay rivers, before (purple) and after (turquoise and yellow) Cyclone Gabrielle.

Note: Open circles indicate the modelled mean with 95% confidence intervals (error bars).

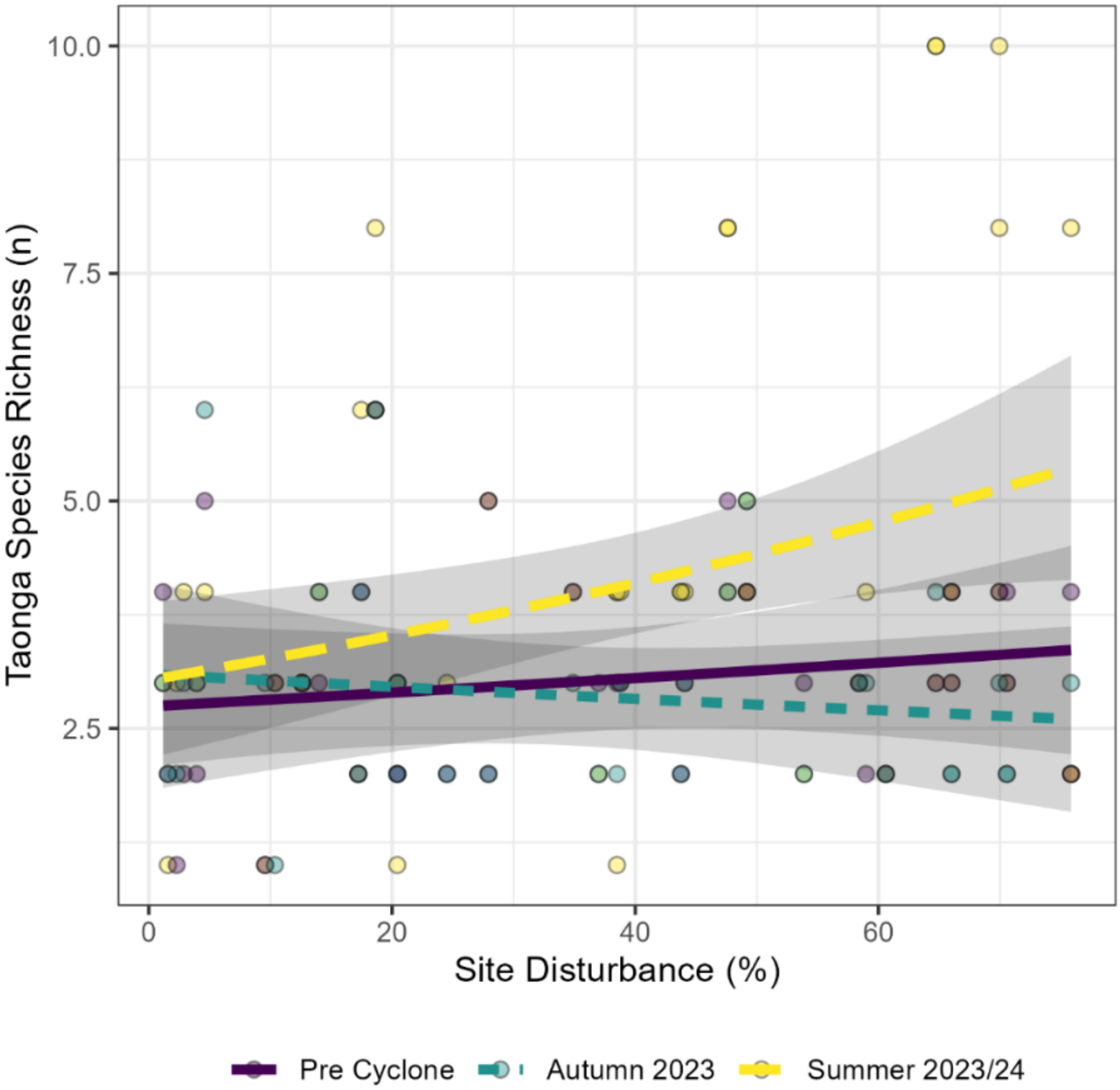


Figure 71. Relationships between taonga species richness and site disturbance, as measured by satellite imagery analysis, before (purple) and after (turquoise and yellow) Cyclone Gabrielle across the Hawke's Bay region.

Note: grey ribbons represent 95% confidence intervals.

Prevalence index

Across the 10 fish species for which prevalences were evaluated, the null model was the top model for four species (kōaro, longfin eel, torrentfish, and redfin bully), with weight of support ranging from 34% (torrentfish) to 74% (kōaro; Table 11). For six species, the top model included only treatment (brown trout, common bully, common smelt, īnanga, rainbow trout, and shortfin eel), with weight of support ranging from 53% (īnanga) to 91% (common bully). Common smelt was the only species with a top model that included an interaction between treatment and site disturbance (Table 11; Figure 72).

Common bully, common smelt, and īnanga showed increased prevalence the summer after the cyclone (Figure 73). Only shortfin eels decreased in prevalence following the cyclone, whereas rainbow trout prevalence decreased immediately after the cyclone and then increased the following summer (Figure 73). In contrast, brown trout had a small decrease in prevalence between autumn 2023 and the following summer.

Table 11. The top model (based on model selection) explaining the prevalence of each freshwater fish species based on eDNA and using data collected from Hawke's Bay streams and rivers before and after Cyclone Gabrielle ('Treatment')

Model	LogLik	K	AICc	Weight
Native species				
Common Bully ~ Upstream Area + (1 | site.id) + (1 | Catchment) + Treatment	110.474	5	–210.324	0.888
Common Smelt ~ (1 | site.id) + (1 | Catchment) + Treatment * Site Disturbance	207.727	7	–400.263	0.799
Īnanga ~ Penetration + (1 | site.id) + (1 | Catchment) + Treatment	223.58	5	–436.536	0.465
Kōaro ~ Elevation + (1 | site.id) + (1 | Catchment)	220.546	3	–434.848	0.692
Longfin Eel ~ Elevation + (1 | site.id) + (1 | Catchment)	46.523	4	–84.633	0.737
Redfin Bully ~ Elevation + Penetration + (1 | site.id) + (1 | Catchment)	195.254	4	–382.096	0.676
Shortfin Eel ~ Elevation + (1 | site.id) + (1 | Catchment) + Treatment	131.484	5	–252.344	0.764
Torrentfish ~ (1 | site.id) + (1 | Catchment)	252.183	2	–500.246	0.336
Non-native species				
Brown Trout ~ Penetration + (1 | site.id) + (1 | Catchment) + Treatment	287.592	5	–564.559	0.668
Rainbow Trout ~ Elevation + (1 | site.id) + (1 | Catchment) + Treatment	141.895	5	–273.164	0.605

Notes: LogLik is the log likelihood, K is the number of model parameters, AIC is the Akaike Information Criterion, and weight is the weight of evidence that the model is the top model (ΔAICc = 0 for all models).

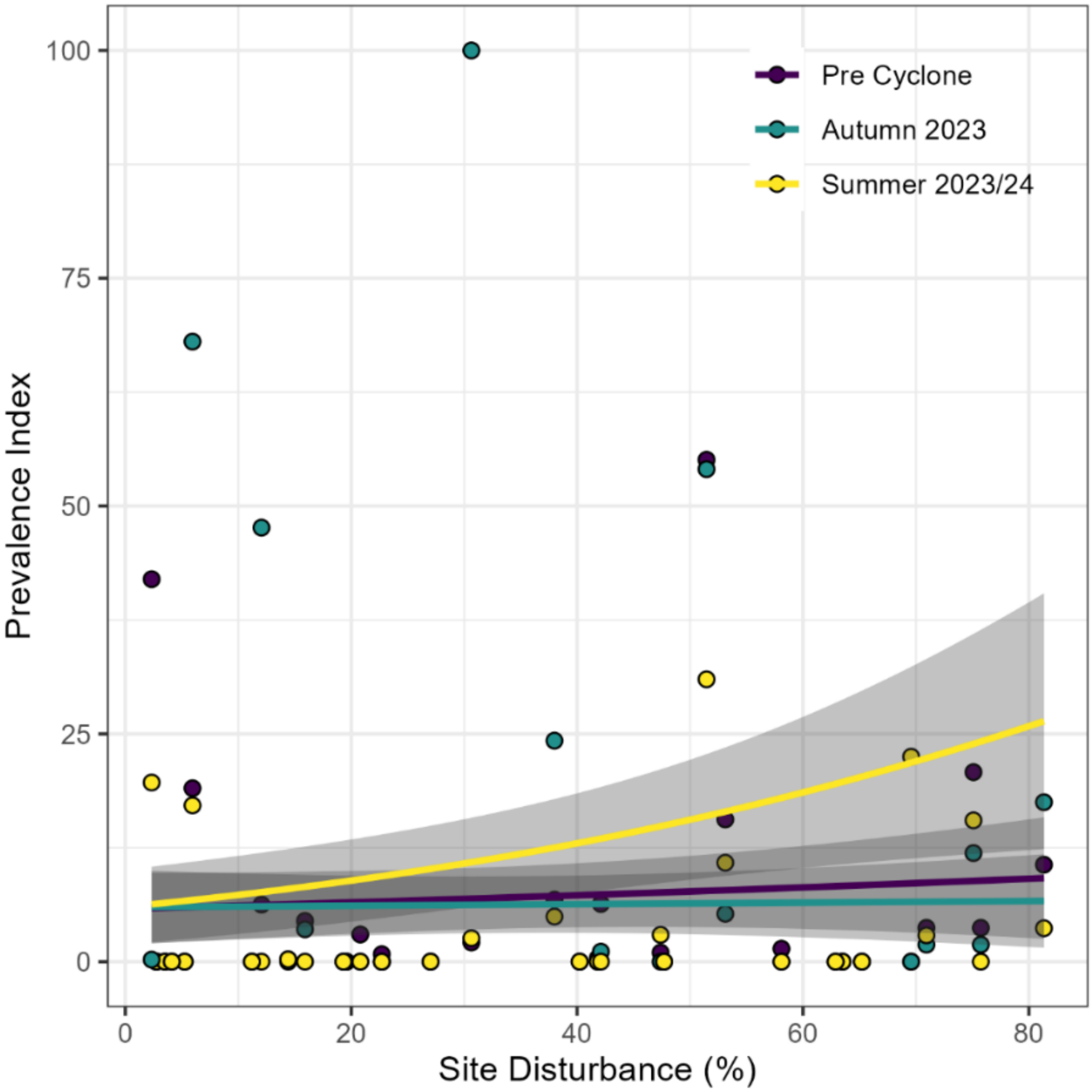


Figure 72. Relationship between prevalence index and site disturbance (based on satellite imagery analysis) for common smelt (*Retropinna retropinna*) in Hawke's Bay rivers before (purple) and after (turquoise and yellow) Cyclone Gabrielle.

Note: trend lines represent the modelled relationships, and grey ribbons represent 95% confidence intervals.

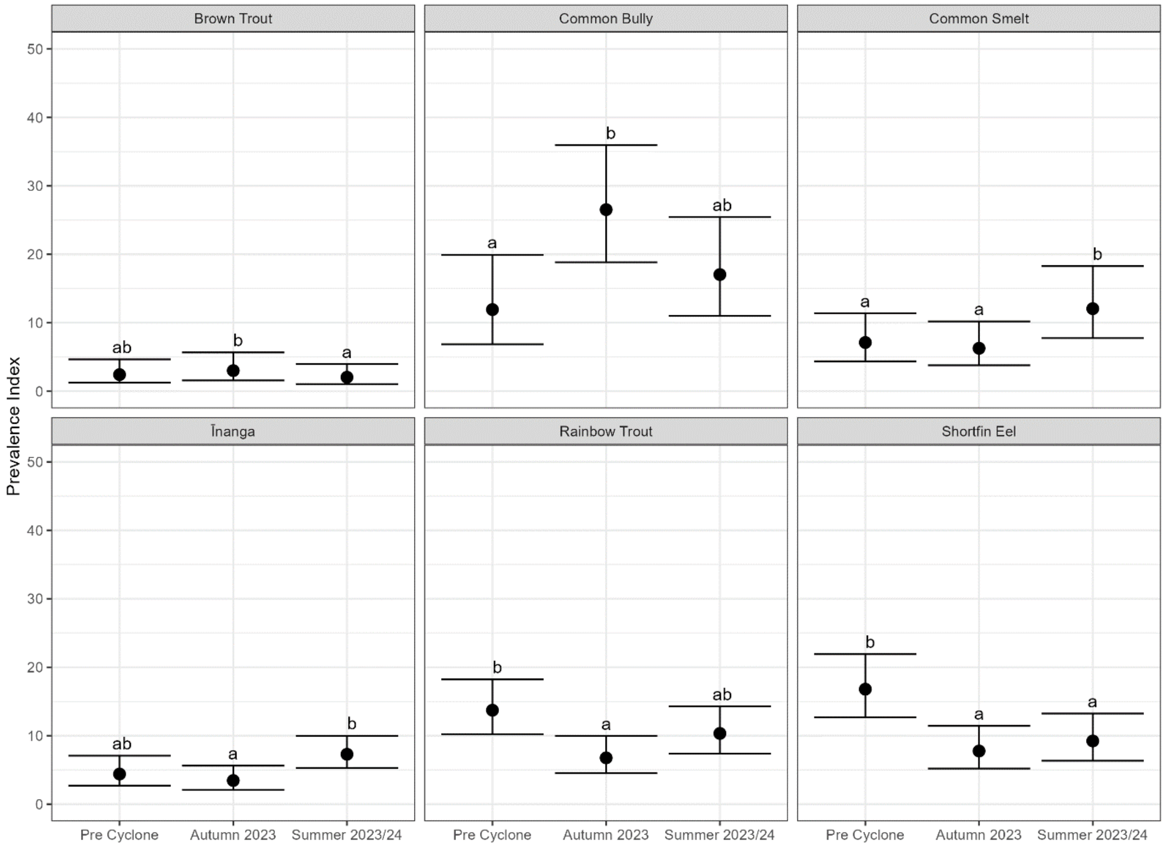


Figure 73. Comparison of eDNA prevalence index before and after Cyclone Gabrielle for six common species across the Hawke's Bay region.

Notes: points represent the modelled mean and error bars are 95% confidence intervals. The same lowercase letters above error bars denotes a non-significant difference between means.

Fish abundance

Electric fishing surveys were less likely to capture several species compared to eDNA detections, with giant and bluegill bullies potentially being identified as unidentified bullies when electric fishing (Figure 74). In addition, Australian longfin eels were detected at three sites using eDNA (nine detections across all eDNA samples; Figure 68), whereas no captures were recorded during physical sampling. The are no records for the occurrence of Australian longfin eels in the New Zealand Freshwater Fish Database for Hawke's Bay, with this species only recorded in three samples across New Zealand. Thus, the increased detection of Australian longfin eels using eDNA relative to historical catch records may indicate an oversensitivity of eDNA to detect them, and their presence in the Hawke's Bay streams needs verification through physical sampling methods.

Like the eIBI score based on eDNA, the Fish IBI score of the physical sample data showed no clear differences before and after Cyclone Gabrielle (Figure 75).

Relative abundance estimates also followed similar general trends to those observed in the species-specific eDNA prevalence index (Figure 76). For instance, the relative abundances of shortfin eels, smelt and common bullies mirrored pre- vs post-cyclone changes in the eDNA-based prevalence index. Conversely, torrentfish and redfin bullies showed consistent changes in abundance after the cyclone (increased and decreased, respectively), whereas they showed no change in prevalence using eDNA data.

A caveat to the qualitative comparisons of fish relative abundance estimates in Figure 76 is the inherent interannual variability known to exist in the abundance of fish species using a single-pass electric fishing reach. In addition, not all fish species were captured across the six sampling sites, with many species only present in two to four sites. Consequently, the low sample sizes limit meaningful comparisons. For all species captured in physical fish surveys, the abundance estimates per 100 m^2 are within the interannual variability previously recorded in the SoE monitoring programme for the Hawke's Bay region.

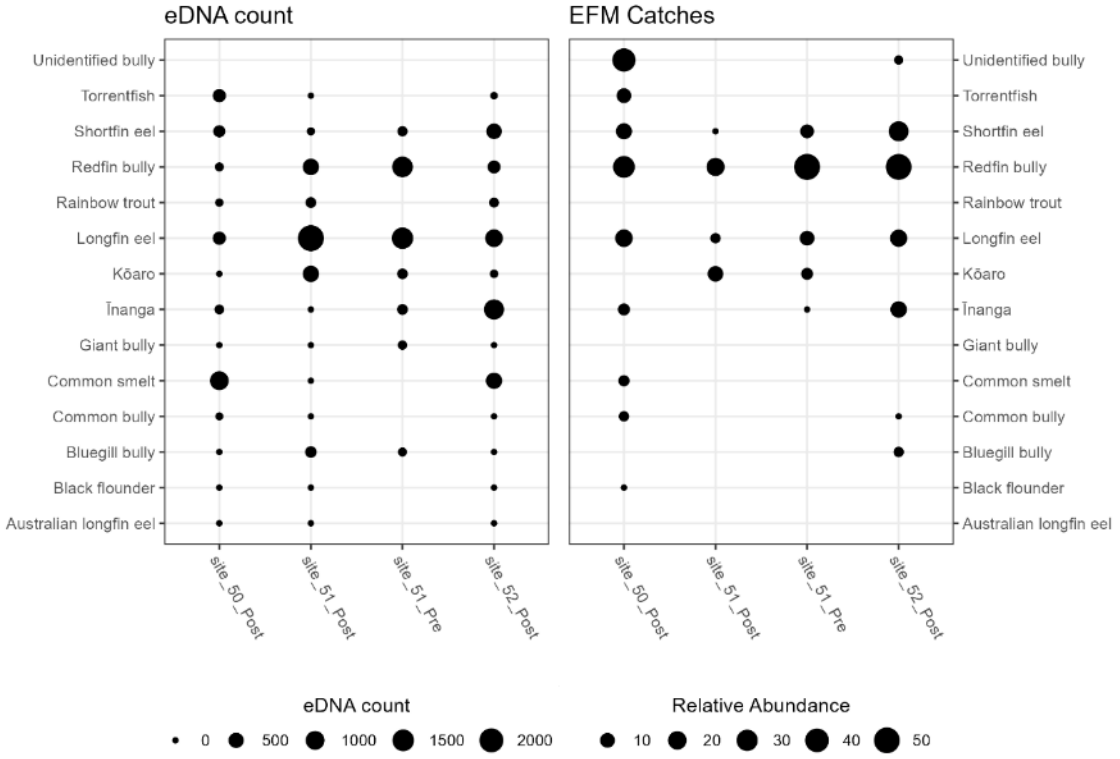


Figure 74. Comparison of mean eDNA counts and electric fishing (EFM) relative abundance of species at four paired Hawke's Bay sampling sites where both methods were used.

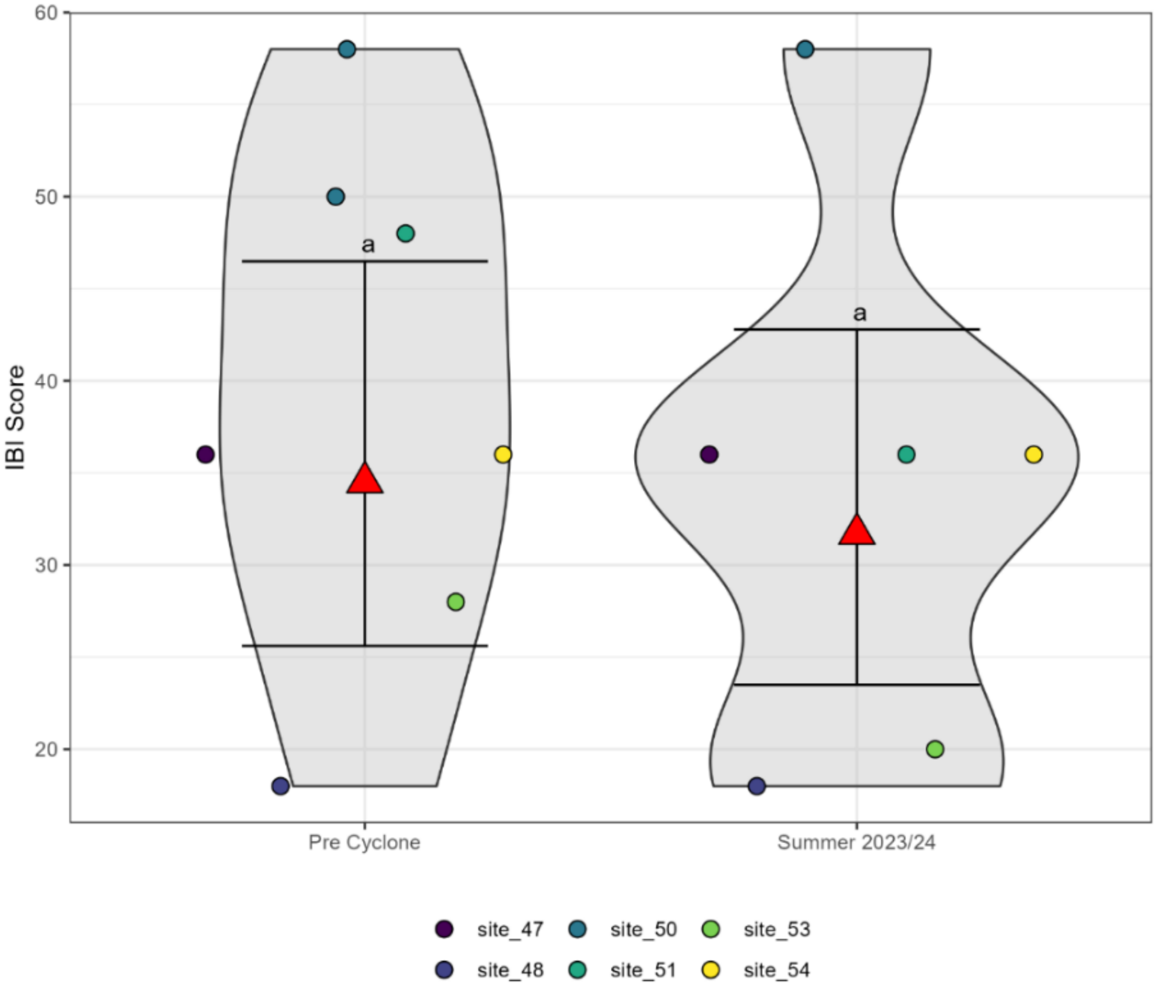


Figure 75. Violin plot of the before and 1 year after Cyclone Gabrielle Index of Biological Integrity (IBI) for electric fishing surveys in Hawke's Bay streams.

Notes: Red triangles represent the modelled means of the IBI scores with 95% confidence intervals (error bars). The same lowercase letter above error bars denotes a non-significant difference between means. Site 50 was sampled on two occasions before the cyclone, and both points are shown on the figure.

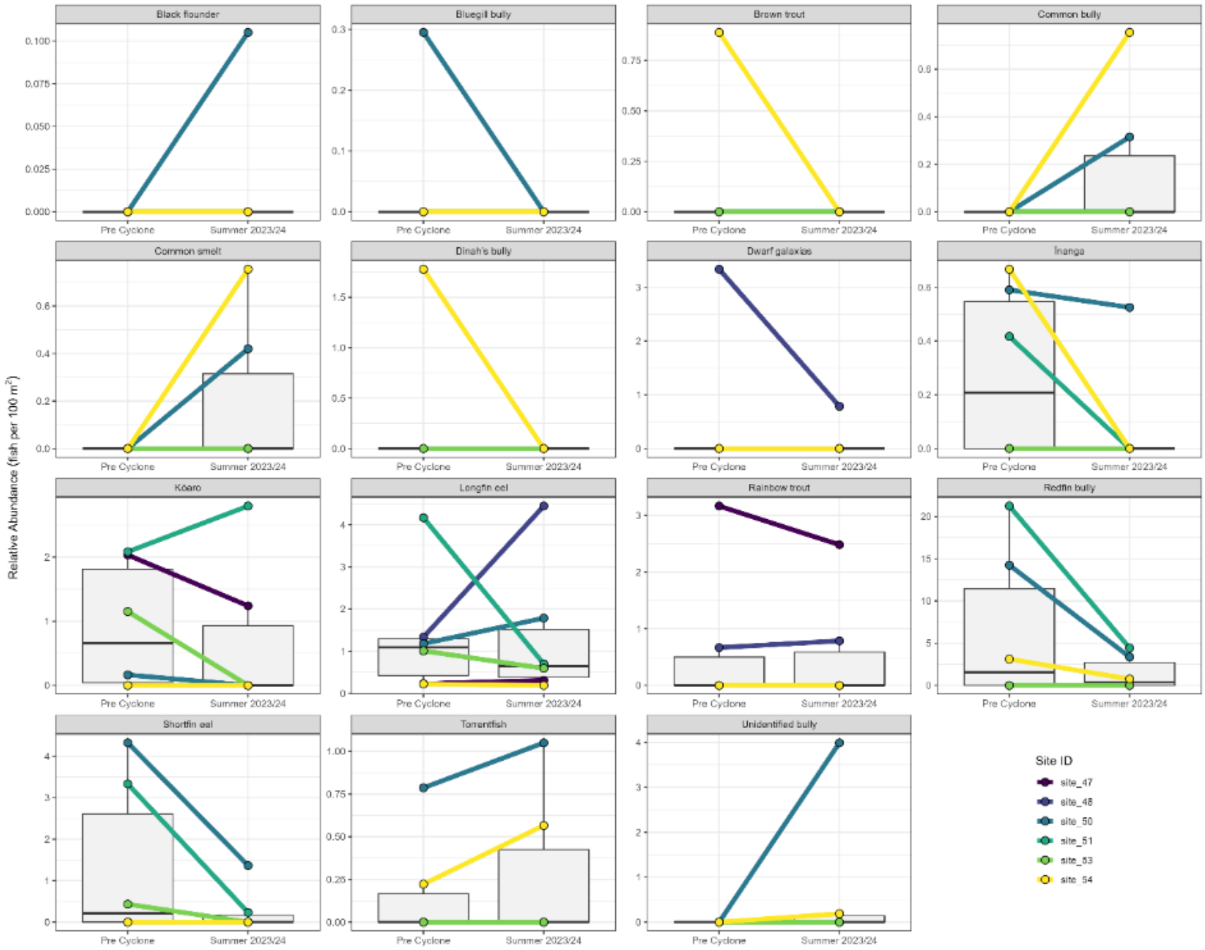


Figure 76. Boxplots showing relative abundances of species sampled using electric fishing surveys in Hawke's Bay streams, conducted before and after Cyclone Gabrielle.

Notes: boxes represent the interquartile range, the black horizontal line is the median value, and whiskers represent 1.5 times the interquartile range. Coloured lines show changes in relative abundance for each site. Site ID corresponds to site ID and names in Table A4.1.

Spawning surveys

Huramua Stream

Riparian vegetation

Figures 77 and 78 show the Huramua Stream riparian vegetation before Cyclone Gabrielle in 2016. Recommendations based on the 2016 assessments called for several measures to improve īnanga spawning habitat conditions along the banks, including upgrading the existing single electric fence to a permanent seven-wire, post-and-batten fence, approaching the owners of the property on the true left bank to install similar fencing along the corresponding length on their side of the river, and controlling invasive pampas grass, willows, and poplars that posed a threat by shading out the desirable spawning grasses growing on both banks (Elliot et al. 2023).

In 2023, protections included permanent fencing on the true right bank crest. However, there was no evidence of fencing on the true left bank. In September 2023, 7 months after the cyclone, the spawning location in Huramua Stream showed major and ongoing impacts from Cyclone Gabrielle. The spawning site is approximately 100 m to the confluence with the Wairoa River, and consequently the site was massively affected by deposited sediment sourced from the main stem (Figure 79). LiDAR measurements revealed the deposition of over 0.5 m of sediment on the true right bank (Figure 79) (Elliot et al. 2023). The true left bank appeared noticeably steeper, with less deposited sediment. While the bank crest fencing on the true right remained intact and some plantings high on the bank had survived, the lower portions of both banks were largely devoid of vegetation (Figure 79).

By May 2024, 15 months after the cyclone, the vegetation on the riverbanks had undergone further changes. On the true right bank the lower section was predominantly dominated by Mercer grass (*Paspalum distichum*), while pasture grasses such as creeping bent were present but sparse. Creeping buttercup (*Ranunculus repens*) was highly abundant on the upper portion of the true right bank. Some regrowth of *Juncus* was also observed (Figure 80). In contrast, the true left bank appeared heavily grazed, and was steeper, with less vegetation due to overgrowing non-native trees (Figure 80).

Figure 77. Huramua Stream īnanga spawning site in April 2016, looking downstream to the confluence with Wairoa River. (Photo: John Cheyne)

Figure 78. Huramua Stream īnanga spawning site in April 2016, looking upstream. (Photo: John Cheyne)

Figure 79. Post-Cyclone Gabrielle sediment deposition at the Huramua Stream īnanga spawning site in September 2023, looking upstream. (Photo: Mike Hickford)

Figure 80. Regrowth of Mercer grass (*Paspalum distichum*) and *Juncus* sp. at Huramua Stream īnanga spawning site in May 2024, looking upstream. (Photo: Mike Hickford)

Īnanga egg search

No eggs were found during the Huramua Stream spawning survey. The spawning habitat was judged as 'poor' due to the low apparent stem density, which would probably result in a high mortality rate for any eggs spawned. There was very little understorey vegetation present in the spawning zone. Although a thick canopy was observed, the stem count was very low, and there was mostly no aerial root mat present (Figure 81). Deposited sediment had smothered riparian vegetation that would normally have supported īnanga eggs and appeared to have affected emergent vegetation that would have provided spawning aggregations of adult fish with cover from avian and eel predators (Figure 81). The lack of suitable vegetation density and structure probably contributed to the absence of eggs found during the survey.

Figure 81. Subcanopy microhabitat in 100 × 100 mm quadrat within Huramua Stream īnanga spawning site in May 2024. (Photo: Mike Hickford)

Note the high level of sediment smothering stems and resulting in the loss of an aerial root mat.

Spawning microhabitat

The mean stem count was 0.17 ± 0.04 stems/cm^2, or approximately 1 stem/5.74 cm^2 (Figure 82). The mean aerial root mat depth was 0.03 ± 0.02 mm (Figure 83). Previous studies by Hickford et al. (2010) found no eggs at stem densities below 0.6 stems/cm^2 or aerial root mats with a depth less than 5 mm. Also, Hickford and Schiel (2011) reported less than 10% egg survival at stem densities below 1 stem/cm^2, and only 50% survival at densities below 2.5 stems/cm^2.

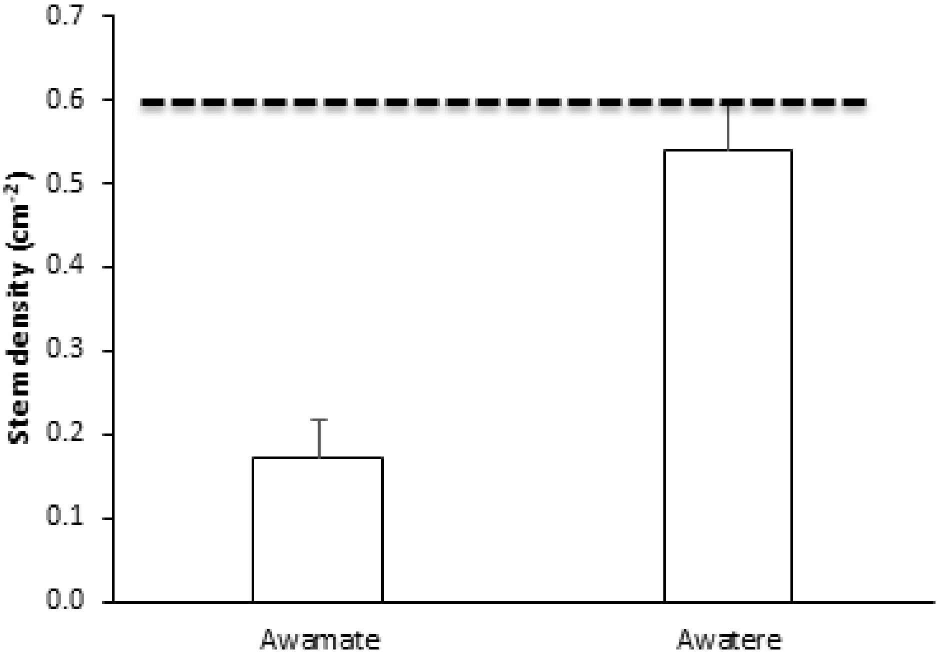


Figure 82. Mean (+SE) stem density within the likely īnanga spawning zone at Huramua (Awamate) and Awatere Streams, Hawke's Bay, in May 2024, 15 months after Cyclone Gabrielle.

Note: the dashed line is the minimum stem density necessary for successful īnanga spawning (Hickford et al. 2010).

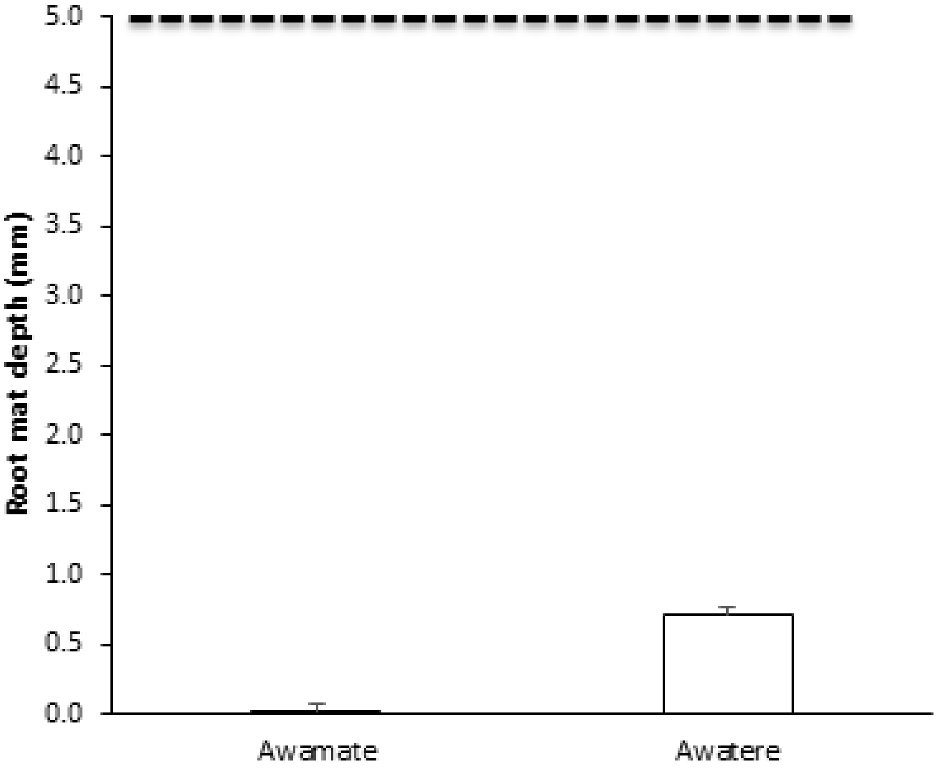


Figure 83. Mean (+SE) aerial root mat depth within the likely īnanga spawning zone at Huramua (Awamate) and Awatere Streams, Hawke's Bay, in May 2024, 15 months after Cyclone Gabrielle.

Note: the dashed line is the minimum root mat depth necessary for successful īnanga spawning (Hickford et al. 2010).

Awatere Stream

Riparian vegetation

Figures 84 and 85 show the Awatere Stream riparian vegetation before Cyclone Gabrielle. In 2016 the vegetation was described as consisting of creeping bent and tall fescue grasses interspersed with patches of flax (*Phormium tenax*), blackberry (*Rubus fruticosus*), Japanese honeysuckle (*Lonicera japonica*), pampas (*Cortaderia selloana*), wild ginger *(Hedychium gardnerianum*), and willows, with the latter invasive plants dominating the desirable spawning grasses in some areas (Elliot et al. 2023). The 2016 recommendations for this site were to maintain the existing fence on the true right bank and control the invasive plant species where they were adversely affecting the spawning grasses (Elliot et al. 2023). Existing protection included fencing on the true right bank crest, but this was in a poor state of repair.

In September 2023, 7 months after the cyclone, there was no evidence of major sediment deposition, based on LiDAR measurements. Heavy grazing was apparent across the entire spawning site, with vegetation cropped very short (Figure 86), and the fence was found to be damaged (Figure 87).

In May 2024, 15 months after the cyclone, grazing was still evident on the true right bank, with livestock present in the previously fenced area during the survey (Figures 88 and 89). However, vegetation had regrown in places, including a mix of creeping bent, tall fescue, and club rush (*Bolboschoenus* sp.) at the waterline (Figures 89 and 90). The true left bank was inaccessible during the May 2024 survey due to a tangihanga at the local marae, but appeared denser with vegetation, although blackberry was prevalent (Figure 90).

Figure 84. Lower section of the Awatere Stream īnanga spawning site in Hawke’s Bay, April 2016, looking downstream. (Photo: John Cheyne)

Figure 85. Upper section of the Awatere Stream īnanga spawning site in Hawke's Bay, April 2016, looking downstream. (Photo: John Cheyne)

Figure 86. Evidence of livestock grazing within the Awatere Stream īnanga spawning site in Hawke's Bay, September 2023. (Photo: Mike Hickford)

Figure 87. Inadequate fencing of the Awatere Stream īnanga spawning site in Hawke's Bay, September 2023. The fence had not been repaired by May 2024. (Photo: Mike Hickford)

Figure 88. Evidence of some regrowth of vegetation within the Awatere Stream īnanga spawning site in Hawke's Bay, May 2024 (compare with Figure 79), despite the fence not being repaired. (Photo: Mike Hickford)

Figure 89. Evidence of ongoing grazing of riparian vegetation on the true right bank within the Awatere Stream īnanga spawning site in Hawke's Bay, May 2024. (Photo: Mike Hickford)

Figure 90. Invasive plants (blackberry [*Rubus fruticosus*] and Japanese honeysuckle [*Lonicera japonica*]) on the true left bank pose a smothering risk to other more suitable vegetation for supporting īnanga spawning within the Awatere Stream, Hawke's Bay, May 2024. (Photo: Mike Hickford)

Īnanga egg search

No eggs were found during the Awatere Stream spawning survey. The spawning habitat was judged 'moderate' due to the low stem density and minimal aerial root mat development observed. There was very little understorey vegetation present in the spawning zone, which is needed to support īnanga spawning. Evidence of sediment deposition was apparent across the site, appearing to have smothered any existing aerial root mats, even at the base of tall fescue (*Lolium arundinaceum*) clumps (Figure 91). Although a thick canopy was present, the stem count was very low, with lots of creeping bent (*Agrostis stolonifera*) stolons, but little aerial root mat development (Figure 92). It is important to note that the stem count represents the number of stems originating per unit area, not the number overlying it, meaning that areas with many stolons can still have low stem counts. The substrate was damp and muddy throughout (Figure 93). The combination of sediment deposition, low stem density, and lack of aerial root mats probably contributed to the absence of eggs found during this survey.

Figure 91. Evidence of sediment deposition at the base of a dense clump of tall fescue (*Lolium arundinaceum*) within the Awatere Stream īnanga spawning site in Hawke's Bay, May 2024. (Photo: Mike Hickford)

Figure 92. Creeping bent (*Agrostis stolonifera*) stolons overlying muddy substrate within the Awatere Stream īnanga spawning site in Hawke's Bay, May 2024. (Photo: Mike Hickford)

Figure 93. Damp, muddy substrate with little aerial root mat within the Awatere Stream īnanga spawning site in Hawke's Bay, May 2024. (Photo: Mike Hickford)

Spawning microhabitat

The mean stem count was 0.54 ± 0.05 stems/cm^2, or approximately 1 stem/1.85 cm^2 (Figure 82). While higher than the very low densities observed at Huramua Stream (0.17 ± 0.04 stems/cm^2), this is still below the 0.6 stems/cm^2 threshold where Hickford et al. (2010) found no eggs present. The mean aerial root mat depth was 0.71 ± 0.31 mm (Figure 83), well below the 5 mm minimum root mat depth associated with finding eggs (Hickford et al. 2010).

Whakamahi Lagoon tributary

Īnanga egg search

While no īnanga eggs were found during the survey, only habitat located c. 10 m downstream of the culvert could be searched due to impenetrable blackberry and scrubby vegetation further downstream (Figure 94). The stream was observed to be quite incised in this area, resulting in relatively little bank area available for potential spawning habitat. The main vegetation likely to provide īnanga spawning habitat was less affected by sediment than the other surveyed sites; however, no eggs could be located (Figure 95). The deeply incised channel and heavy invasive vegetation may be limiting factors that prevent this location from providing suitable spawning conditions for īnanga, despite the well-established upstream riparian planting.

Figure 94. Potential īnanga spawning site in the Whakamahi Lagoon tributary, Hawke's Bay, heavily invaded with blackberry (*Rubus* sp.), May 2024. (Photo: Mike Hickford)

Figure 95. Potential īnanga spawning habitat in the Whakamahi Lagoon tributary, Hawke's Bay, below the Whakamahi Road culvert, May 2024. (Photo: Mike Hickford)

Tawhara Stream

Despite an intensive search of the area between the beach and culvert, no īnanga eggs were found at this location. Although a dense overhanging vegetation canopy was present, there was little microhabitat structure suitable for spawning (Figure 96). The lack of a vegetation layer with stems and aerial root mats appears to be the primary limiting factor currently preventing this site from providing viable spawning habitat.

Figure 96. The potential īnanga spawning site in Tawhara Stream, Hawke's Bay, was heavily inundated with driftwood and invaded by pampas grass (*Cortaderia selloana*) and other undesirable plants in May 2024. (Photo: Mike Hickford)

4.3.3 Benthic macroinvertebrate response

Community composition

Macroinvertebrate community composition diverged between low-, medium-, and high-impact sites following Cyclone Gabrielle (Figure 97). Figure 97 shows greater separation of post-cyclone communities than pre-cyclone communities, although the differences in composition (measured as location of group centroids) were not statistically significant during either time period (pre-cyclone: $F_{2,109} = 2.34$, $P > 0.05$; post-cyclone: $F_{2,94} = 1.94$, $P > 0.05$).

However, there were significant differences in dispersion among sites during both time periods. Before the cyclone, sites that were later classified as low- and medium-catchment-disturbance sites had significantly greater dispersion compared to those later classified as high-catchment-disturbance sites ($F_{2,109} = 6.59$, $P < 0.05$; pairwise comparisons: low-medium $P > 0.05$, low-high $P < 0.05$, medium-high $P < 0.05$). After the cyclone, dispersion of low-catchment-disturbance sites and medium-catchment-disturbance sites was significantly different, but neither had significantly different dispersion compared to high-catchment-disturbance sites ($F_{2,94} = 3.66$, $P < 0.05$; pairwise comparisons: low-medium $P < 0.05$, low-high $P > 0.05$, medium-high $P > 0.05$). Pre-cyclone communities comprised a wide range of taxa, including mayflies, stoneflies and caddisflies (EPT), as well as Diptera, gastropods, and molluscs. Low-impact sites remained associated with EPT taxa after the cyclone, while high-impact sites were dominated by chironomids, microcrustacea (cladocera, copepods, and amphipods), and oligochaetes (Figures 98 and 99).

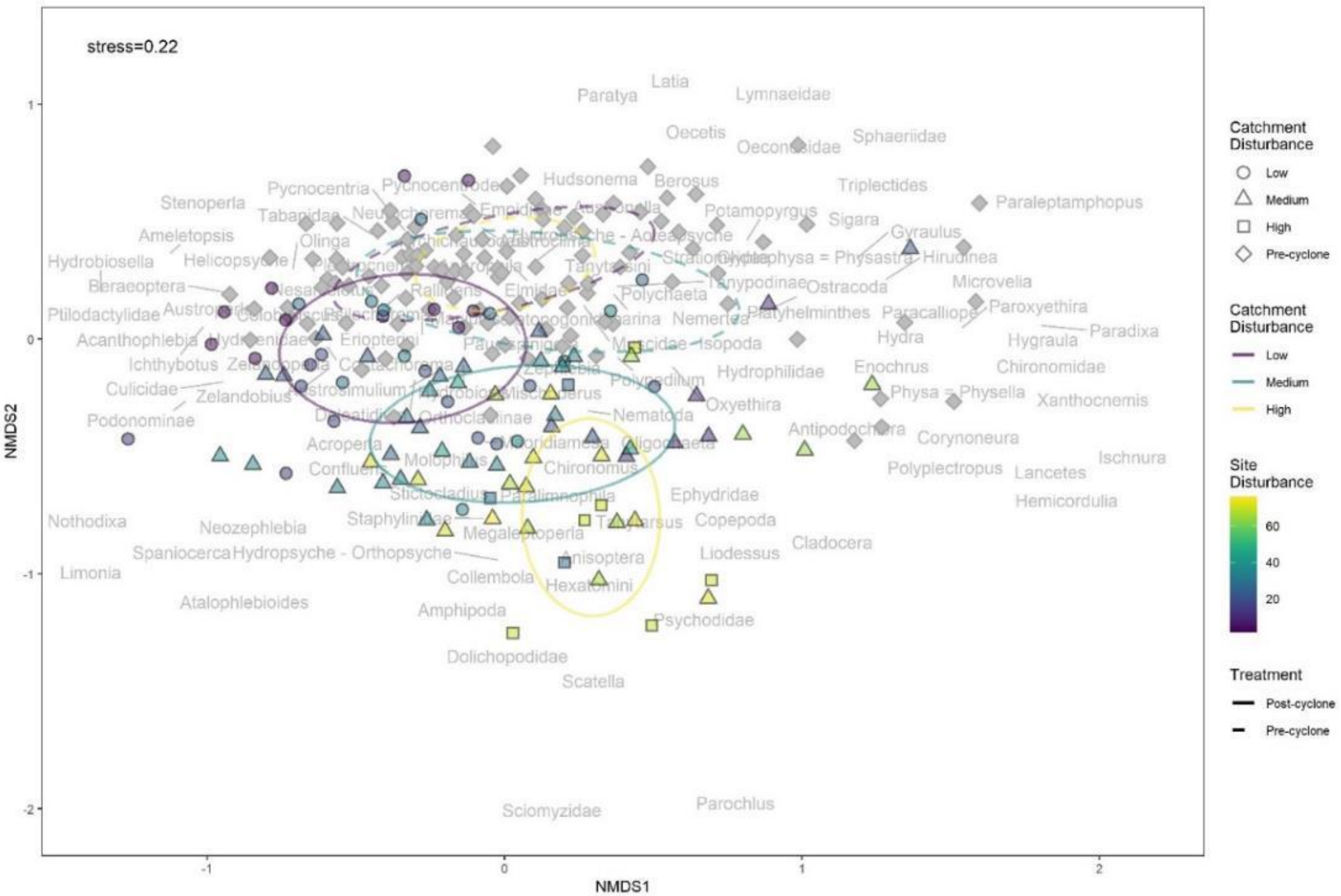


Figure 97. Visual representation of non-metric multi-dimensional scaling (NMDS) analysis showing community composition of freshwater macroinvertebrates across all Hawke's Bay sites before and after Cyclone Gabrielle.

Notes: samples are coloured by site disturbance, while the symbol indicates catchment disturbance category (diamond = pre-cyclone, circle = low, triangle = medium, square = high). Disturbance levels were determined using aerial imagery analysis. Monitoring data from the 5 years before the cyclone are shown as grey diamonds. Ellipses show 1 standard deviation around the centroid for each group: low (purple), medium (turquoise), and high (yellow) catchment disturbance. Ellipses with dashed lines are for pre-cyclone samples, solid lines are for post-cyclone samples. Macroinvertebrate taxa names are shown in grey. The location of taxa names in ordination space relative to sites or other taxa indicates how commonly they are found in a site or with another taxa, respectively.

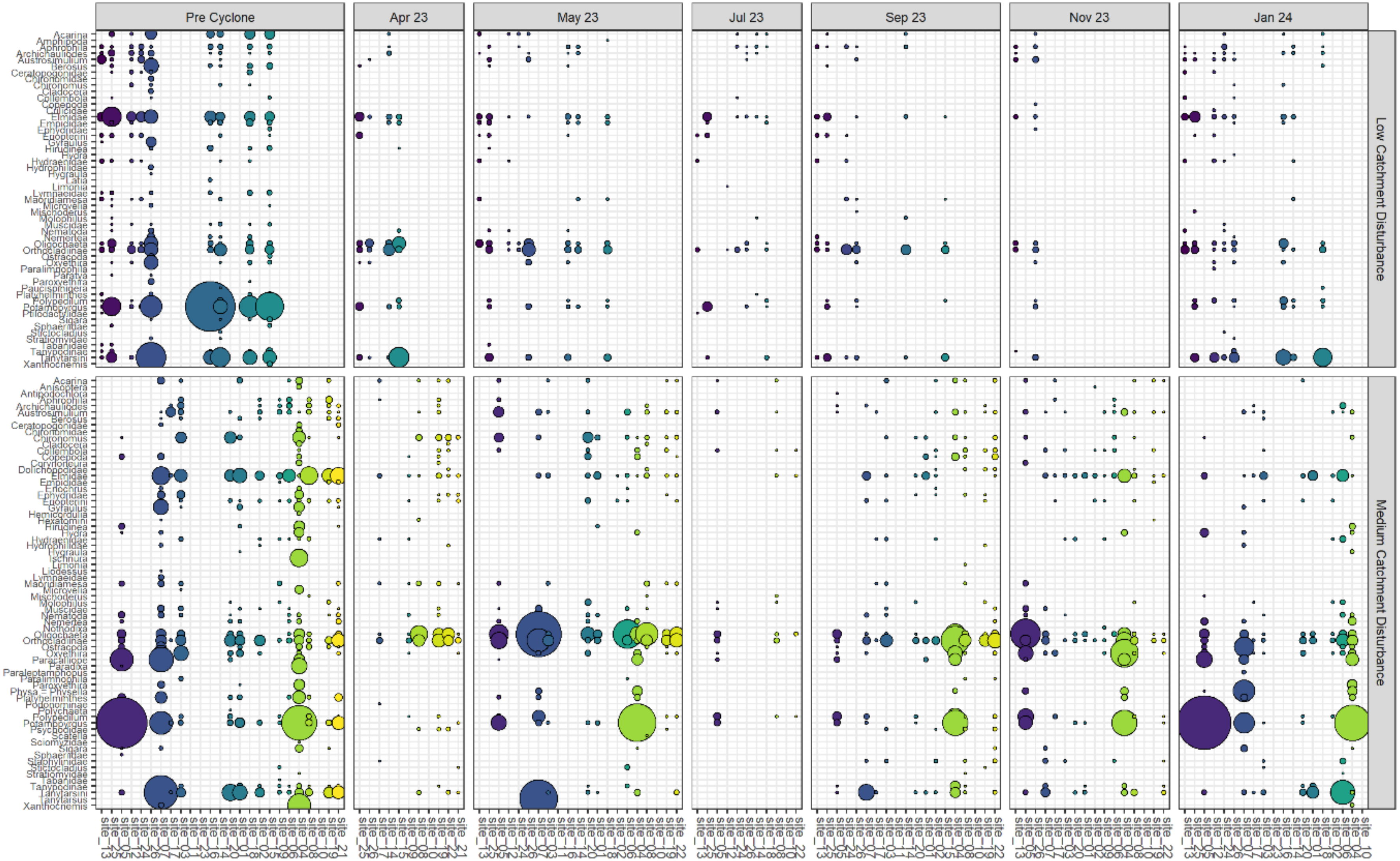
Recovery trajectories

Macroinvertebrate abundance was lower in all sites immediately after Cyclone Gabrielle, in April and May 2023 (Figures 98 and 99). Abundances of taxa in low-impact sites returned closer to pre-cyclone levels over the course of the year, but remained lower than average pre-cyclone abundances in high-impact sites. *Deleatidium* mayflies and Hydrobiosid caddisflies were the most common EPT taxa before Cyclone Gabrielle, and *Deleatidium* was one of the first taxa to recolonise in high numbers at low- and medium-impact sites (Figure 98). In the first 2–3 months after Cyclone Gabrielle there were large increases in the proportion of chironomids, Oligochaetes, and snails, particularly in the sites with medium catchment impacts (Figure 99). These were also the most prevalent taxa in the high-impact sites in January 2024.

Macroinvertebrate communities in rivers and streams with high site and catchment cyclone impacts had greater shifts in composition following Cyclone Gabrielle than communities in rivers and streams that were less affected (Figure 100). The observed changes in composition were larger than the interannual variability observed across 5 years of annual SoE monitoring before the cyclone in all but three low-impact sites (sites 13, 24, 25). However, it is likely that some of the variation observed in the post-cyclone samples, which were collected every 2 months, was due to seasonal fluctuations in community composition, which were not captured by annual summer SoE monitoring. Over 90% of the 2018–22 annual SoE samples were collected between January and March. Consequently, the immediate post-cyclone April 2023 sample and the January 2024 sample should be the closest seasonal equivalents. However, the April 2023 samples were separated from the previous 5 years' SoE monitoring samples in ordination space (Figure 100), reflecting the immediate impacts of Cyclone Gabrielle on community composition.

Figure 98. Mean abundance of EPT (Ephemeroptera, Plecoptera, Tricoptera) taxa in each Hawke's Bay site before Cyclone Gabrielle (left) and every two months after the cyclone from April 2023 to January 2024.

Notes: The size of the points indicates the abundance of macroinvertebrates per sample (scaled up from a 200-fixed count sub-sample), and colour indicates the level of site disturbance (dark purple = low site disturbance, yellow = high site disturbance), based on changes in satellite imagery. Site names on the x-axis correspond to site names in Table A4.1.



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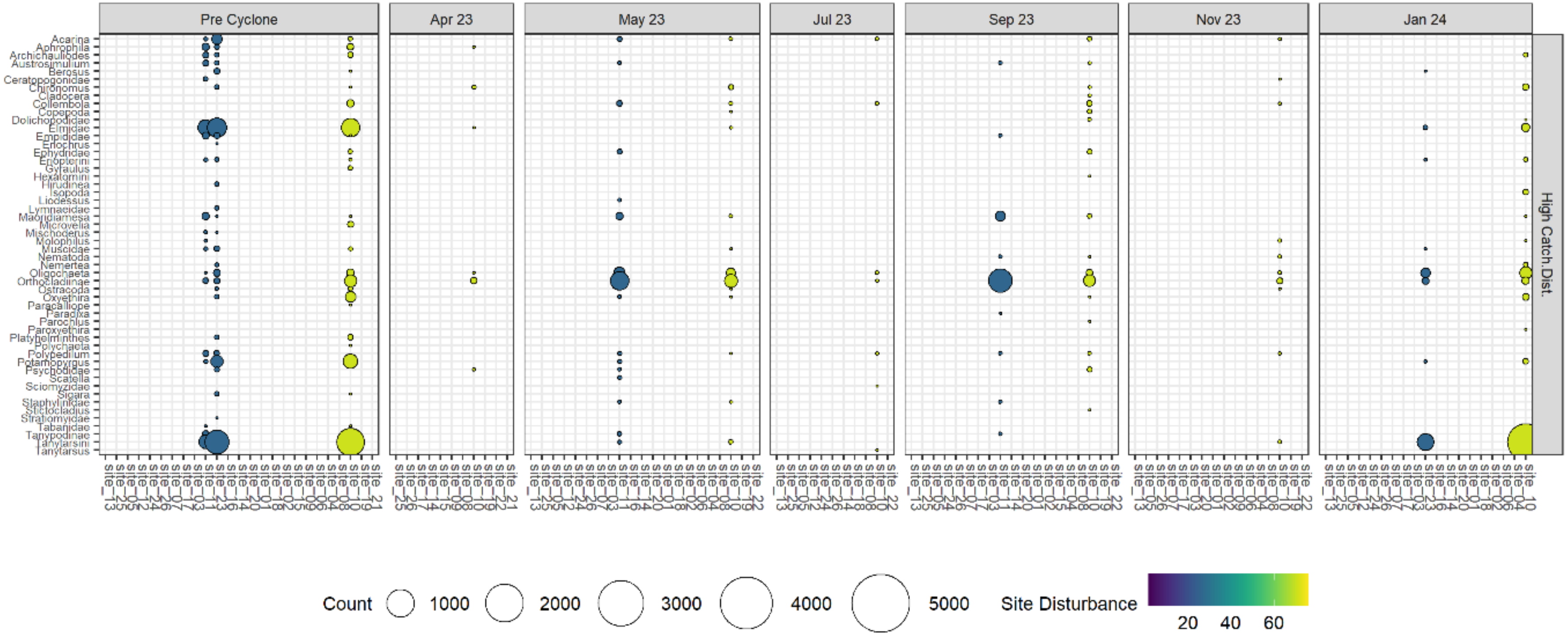


Figure 99. Mean abundance of non-EPT taxa in each Hawke's Bay site before Cyclone Gabrielle (left) and every two months after the cyclone, from April 2023 to January 2024.

Notes: The size of the points indicates the abundance of macroinvertebrates per sample (scaled up from a 200-fixed count sub-sample) and colour indicates the level of site disturbance (dark purple = low site disturbance, yellow = high site disturbance), based on changes in satellite imagery. Site names on the x-axis correspond to site names in Table A4.1.

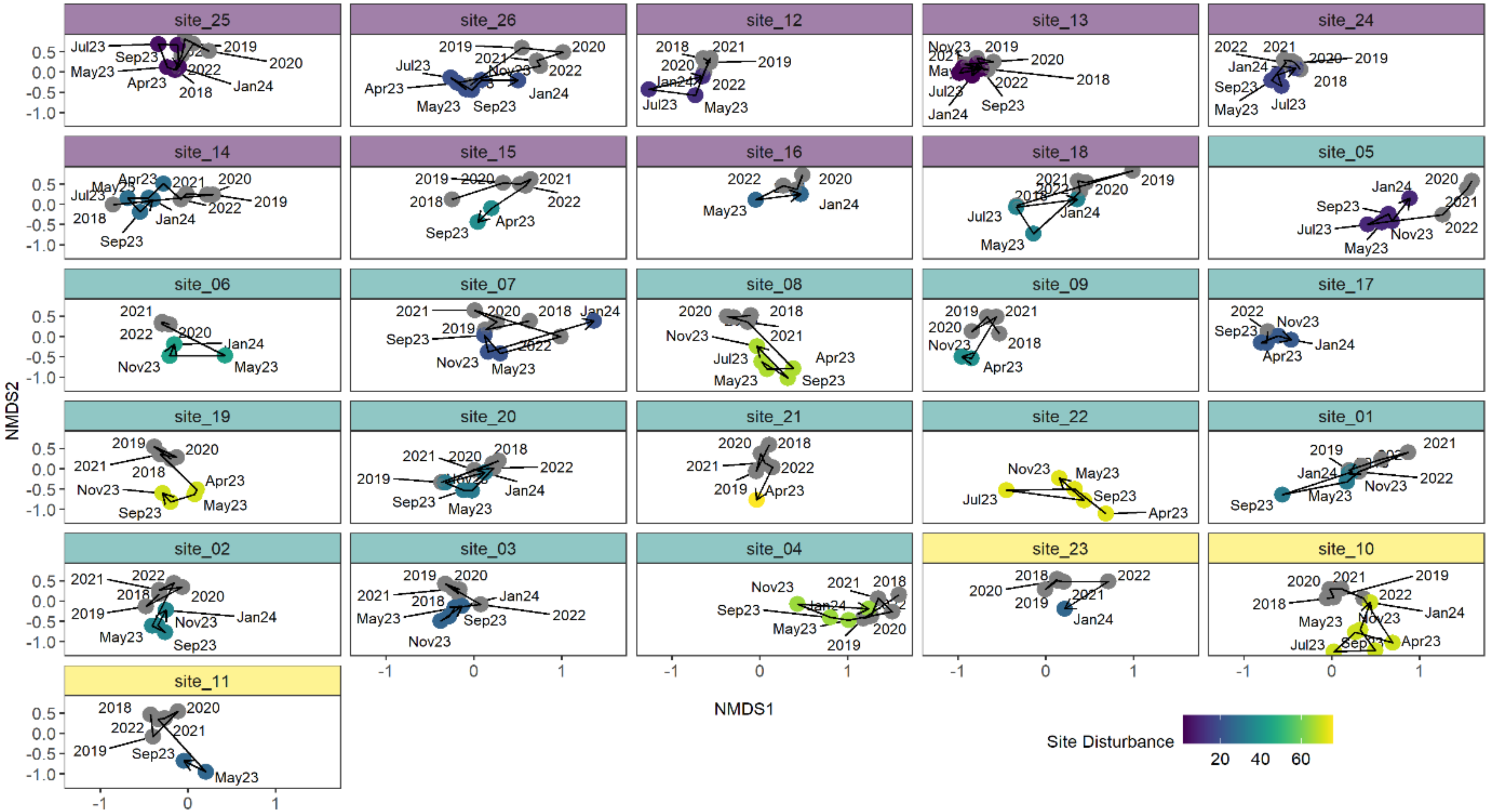


Figure 100. Shifts in community composition at each site over time, from April 2023 to January 2024, compared to annual pre-cyclone community composition.

Notes: the colour of the panel box indicates catchment disturbance categories: low = purple, medium = turquoise, high = yellow. Points are coloured by the level of site disturbance, with grey points representing pre-cyclone samples.

The largest shifts in macroinvertebrate community composition after Cyclone Gabrielle occurred in sites identified from aerial imagery as having high disturbance (Figure 100). Subsequent samples taken every 2 months were more similar to each other than to the previous SoE samples, with distinct post-cyclone clusters evident at many sites, particularly those in catchments identified from aerial imagery as having high disturbance (sites 2, 3, 4, 5, 8, 10, 19). Nevertheless, at most sites the January 2024 sample aligned with previous years' summer samples in ordination space (Figure 100), suggesting that macroinvertebrate communities had recovered within 1 year of Cyclone Gabrielle.

Community metrics

Macroinvertebrate community metric scores reflected the observed changes in community composition before and after the cyclone. Metric scores for samples collected in the months following Cyclone Gabrielle were lower than the typical scores recorded in the previous 5 years of summer SoE monitoring, particularly in medium- and high-disturbance sites. In low-disturbance catchments, scores were often slightly higher following the cyclone, but then declined over the course of the year towards the 5-year pre-cyclone average.

The top model for all macroinvertebrate metrics contained an interaction between date, treatment (pre- and post-cyclone), and cyclone disturbance, based on aerial imagery (Table 12). The top models for taxa richness (number of taxa), EPT (sensitive Ephemeroptera – mayflies, Plecoptera – stoneflies, and Trichoptera – caddisflies) richness, and QMCI (quantitative macroinvertebrate community index) included site disturbance in the interaction, while the top models for % EPT taxa, % EPT abundance, MCI (Macroinvertebrate Community Index), and ASPM (average score per metric) included catchment disturbance.

Table 12. Model selection models regressing macroinvertebrate community metrics relative to spatial (site and catchment disturbance) and temporal (treatment) effects of Cyclone Gabrielle

Model	LogLik	K	AICc	DAICc	Weight
Taxa richness					
Richness ~ (1 | Site) + date * treatment * site disturbance	–594.39	9	1,207.72	0.00	0.77
Richness ~ (1 | Site) + date * treatment	–600.31	5	1,210.92	3.19	0.16
Richness ~ (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	–587.86	17	1,213.05	5.32	0.05
Richness ~ (1 | Site) + date * treatment * catchment disturbance	–593.84	13	1,215.61	7.88	0.02
Richness ~ (1 | Site) + date	–605.74	5	1,221.79	14.07	0.00
EPT richness					
EPT Richness ~ elevation + (1 | Site) + date * treatment * site disturbance	–530.23	10	1,081.60	0.00	0.76
EPT Richness ~ elevation + (1 | Site) + date * treatment * catchment disturbance	–527.06	14	1,084.36	2.76	0.19
EPT Richness ~ elevation + (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	–523.90	18	1,087.53	5.93	0.04
EPT Richness ~ elevation + (1 | Site) + date * treatment	–539.54	6	1,091.51	9.91	0.01
EPT Richness ~ elevation + (1 | Site) + date	–540.51	6	1,093.44	11.84	0.00

Model	LogLik	K	AICc	DAICc	Weight
% EPT taxa					
% EPT taxa ~ elevation + (1 | Site) + date * treatment * catchment disturbance	153.86	14	–277.49	0.00	0.78
% EPT taxa ~ elevation + (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	157.33	18	–274.92	2.56	0.22
% EPT taxa ~ elevation + (1 | Site) + date * treatment * site disturbance	143.75	10	–266.35	11.13	0.00
% EPT taxa ~ elevation + (1 | Site) + date * treatment	127.02	6	–241.61	35.87	0.00
% EPT taxa ~ elevation + (1 | Site) + date	126.73	6	–241.04	36.44	0.00
% EPT abundance					
% EPT abun. ~ elevation + (1 | Site) + date * treatment * catchment disturbance	81.64	14	–133.03	0.00	0.79
% EPT abun. ~ elevation + (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	85.04	18	–130.34	2.70	0.21
% EPT abun. ~ elevation + (1 | Site) + date * treatment * site disturbance	68.72	10	–116.29	16.75	0.00
% EPT abun. ~ elevation + (1 | Site) + date * treatment	54.52	6	–96.60	36.43	0.00
% EPT abun. ~ elevation + (1 | Site) + date	52.77	6	–93.11	39.92	0.00
MCI score					
MCI ~ elevation + (1 | Site) + date * treatment * catchment disturbance	–791.20	14	1,612.64	0.00	0.54
MCI ~ elevation + (1 | Site) + date * treatment * site disturbance	–796.06	10	1,613.27	0.63	0.39
MCI ~ elevation + (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	–788.54	18	1,616.81	4.17	0.07
MCI ~ elevation + (1 | Site) + date * treatment	–806.19	6	1,624.82	12.17	0.00
MCI ~ elevation + (1 | Site) + date	–807.55	6	1,627.53	14.89	0.00
QMCI Score					
QMCI ~ elevation + area + (1 | Site) + date * treatment * site disturbance	–334.81	11	693.01	0.00	0.76
QMCI ~ elevation + area + (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	–326.66	19	695.50	2.48	0.22
QMCI ~ elevation + area + (1 | Site) + date * treatment * catchment disturbance	–333.55	15	699.67	6.66	0.03
QMCI ~ elevation + area + (1 | Site) + date * treatment	–352.96	7	720.50	27.48	0.00
QMCI ~ elevation + area + (1 | Site) + date	–357.85	7	730.27	37.25	0.00
ASPM					
ASPM ~ elevation + (1 | Site) + date * treatment * catchment disturbance	158.88	14	–287.52	0.00	0.52

Model	LogLik	K	AICc	DAICc	Weight
ASPM ~ elevation + (1 | Site) + date * treatment * site disturbance + date * treatment * catchment disturbance	163.52	18	–287.30	0.22	0.47
ASPM ~ elevation + (1 | Site) + date * treatment * site disturbance	149.87	10	–278.59	8.93	0.01
ASPM ~ elevation + (1 | Site) + date * treatment	130.77	6	–249.11	38.41	0.00
ASPM ~ elevation + (1 | Site) + date	130.35	6	–248.27	39.24	0.00

Notes: LogLik is the log likelihood, K is the number of model parameters, AICc is the Akaike Information Criterion. AICc was used if sample size was small ($n/K \leq 40$), ΔAICc is the change in AICc relative to the lowest AICc value, and weight is the weight of evidence that the model is the top model

Taxa richness

The top model for taxa richness included the interaction between date, treatment, and site disturbance (Table 12). However, model predictions only showed an increase in taxa richness over time with high site disturbance in the pre-cyclone data (Figure 101). As no site disturbance had occurred at that time, we conclude that this relationship was due to an additional factor unrelated to cyclone impacts. There was no change in taxa richness over time after the cyclone at either high or low site disturbance. Overall, taxa richness was lower after the cyclone, and lower in high-disturbance sites than in low-disturbance sites.

EPT richness

The top model for EPT richness included an interaction between date, treatment, and site disturbance (Table 12). Species richness of sensitive EPT taxa, on the other hand, did not vary with site disturbance or over time before the cyclone, as would be expected. High disturbance sites had fewer EPT taxa in the months following the cyclone, whereas low-disturbance sites had slightly more EPT taxa immediately after the cyclone, but the number declined over the course of the year to pre-cyclone levels (Figure 102).

% EPT taxa and % EPT abundance

The top model for the percentage of EPT taxa and for the percentage of EPT abundance included an interaction between date, treatment, and catchment disturbance (Table 12). Both metrics showed a similar response, therefore only the figure for % EPT taxa is presented (Figure 103). The relative proportion of EPT was initially higher than the pre-cyclone mean in low-disturbance catchments but declined over the course of the year to pre-cyclone levels, whereas the proportion of EPT in high-disturbance catchments was lower than the pre-cyclone mean immediately after the cyclone, but increased over the course of the year (Figure 103). There was little change in the proportion of EPT taxa in catchments with medium disturbance.

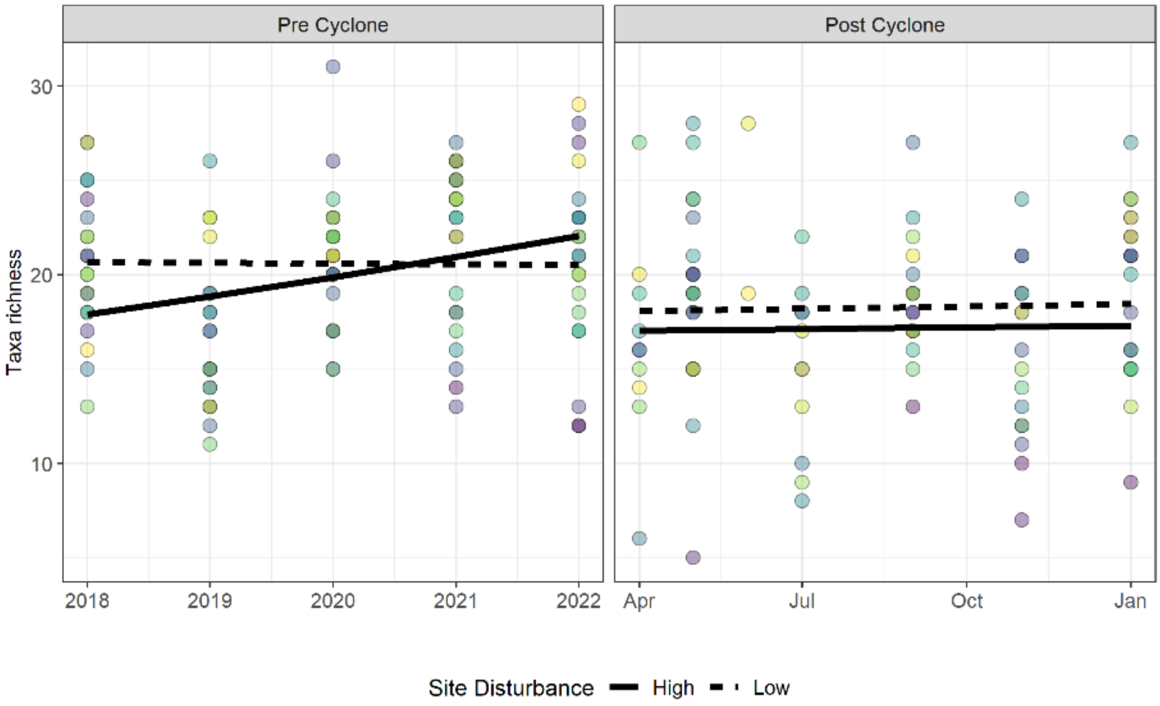


Figure 101. Macroinvertebrate taxa richness at low- and high-disturbance river and stream sites (based on aerial imagery) in Hawke's Bay, before (left) and after (right) the cyclone.

Notes: solid and dashed black lines indicate the overall trend from the best-fitting model for sites of high and low disturbance (75th and 25th quartile, respectively). Points are coloured by site.

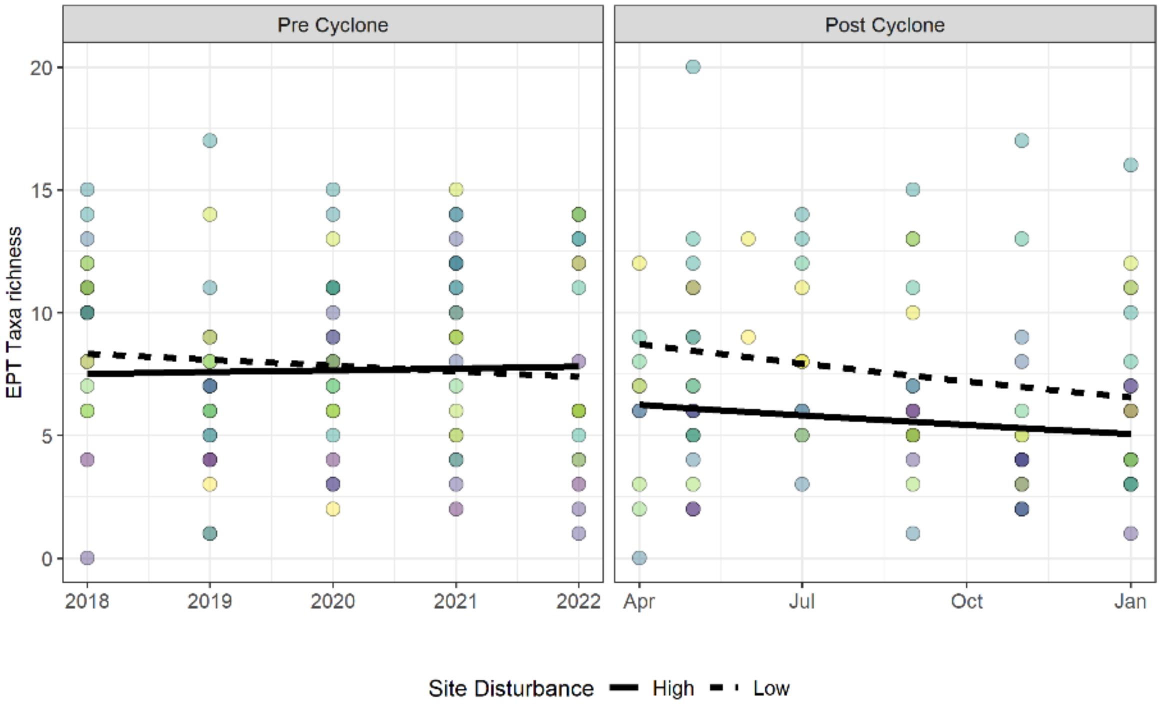


Figure 102. EPT taxa richness at low- and high-disturbance river and stream sites (based on aerial imagery) in Hawke's Bay, before (left) and after (right) the cyclone.

Notes: solid and dashed black lines indicate the overall trend from the best-fitting model for sites of high and low disturbance (75th and 25th quartile, respectively). Points are coloured by site.

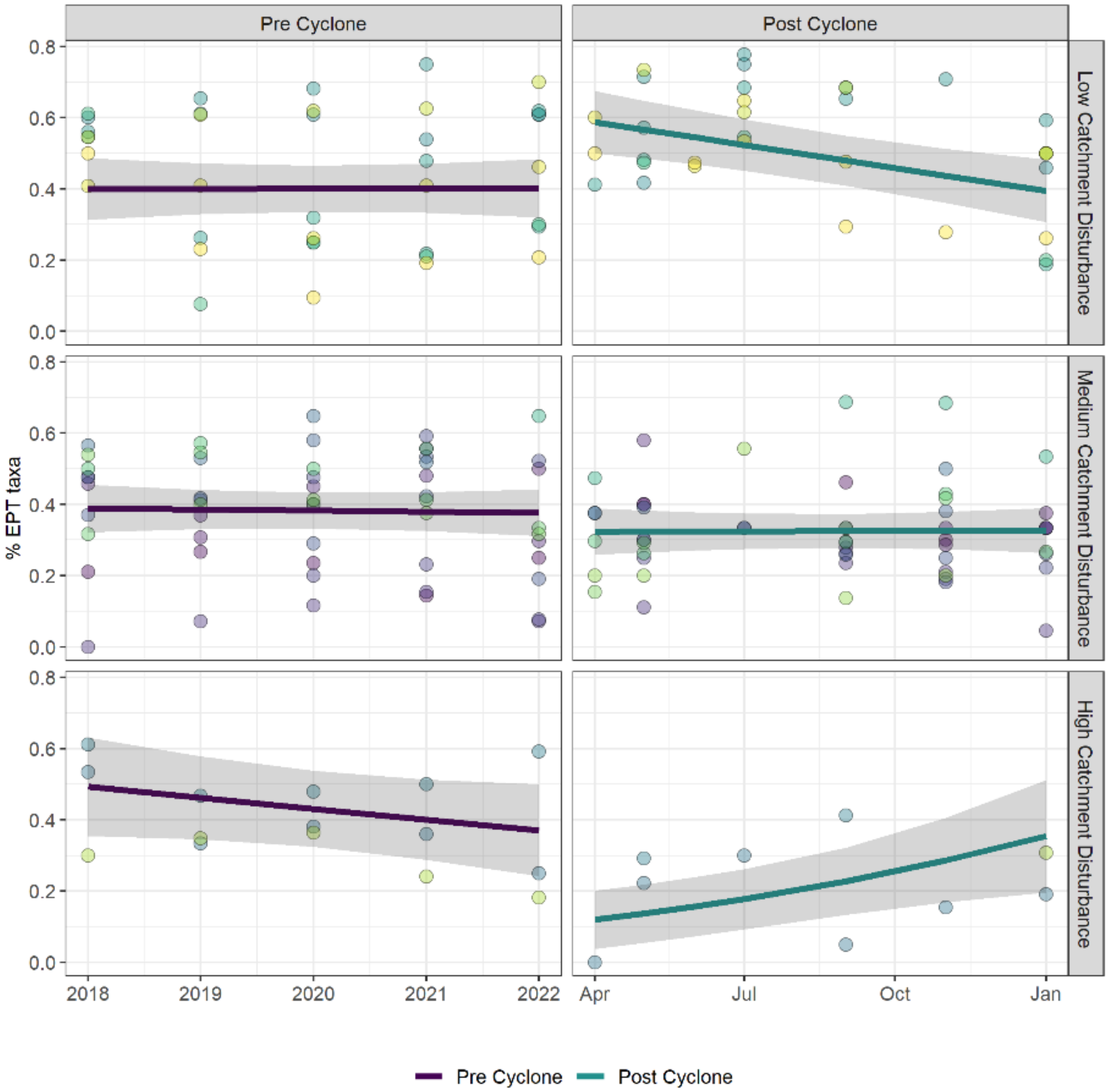


Figure 103. Percentage EPT taxa at sites in catchments with low, medium, and high catchment disturbance (from aerial imagery), before (left) and after (right) the cyclone.

Notes: Coloured lines indicate trends from the best-fitting model over time in pre- (purple) and post-cyclone (turquoise) periods. Points are coloured by site.

MCI

The top model for MCI included an interaction between date, treatment, and catchment disturbance (Table 12). Sites within highly disturbed catchments had lower MCI scores after the cyclone compared to the previous 5 years (Figure 104). Sites within medium-disturbance catchments showed little change, while sites in low-disturbance catchments initially had higher MCI scores in the first few months of samples following the cyclone, which then declined again over the course of the year.

QMCI

The top model for QMCI included an interaction between date, treatment, and site disturbance (Table 12). Before the cyclone, QMCI scores showed a similar slightly declining trend over time across sites, with different post-cyclone disturbance levels based on aerial imagery (Figure 105). After the cyclone, QMCI scores decreased at high-disturbance sites, but then increased again over the course of the year to be similar to those in sites with low cyclone disturbance, which had only demonstrated a slight increase in QMCI over time.

ASPM

The top model for ASPM included the interaction between date, treatment, and catchment disturbance (Table 12). Following the cyclone, ASPM scores increased in low-disturbance catchments but decreased in high-disturbance catchments (Figure 106). Although post-cyclone scores in high-disturbance catchments increased over the course of the year, they still had not returned to pre-cyclone levels by January 2024.

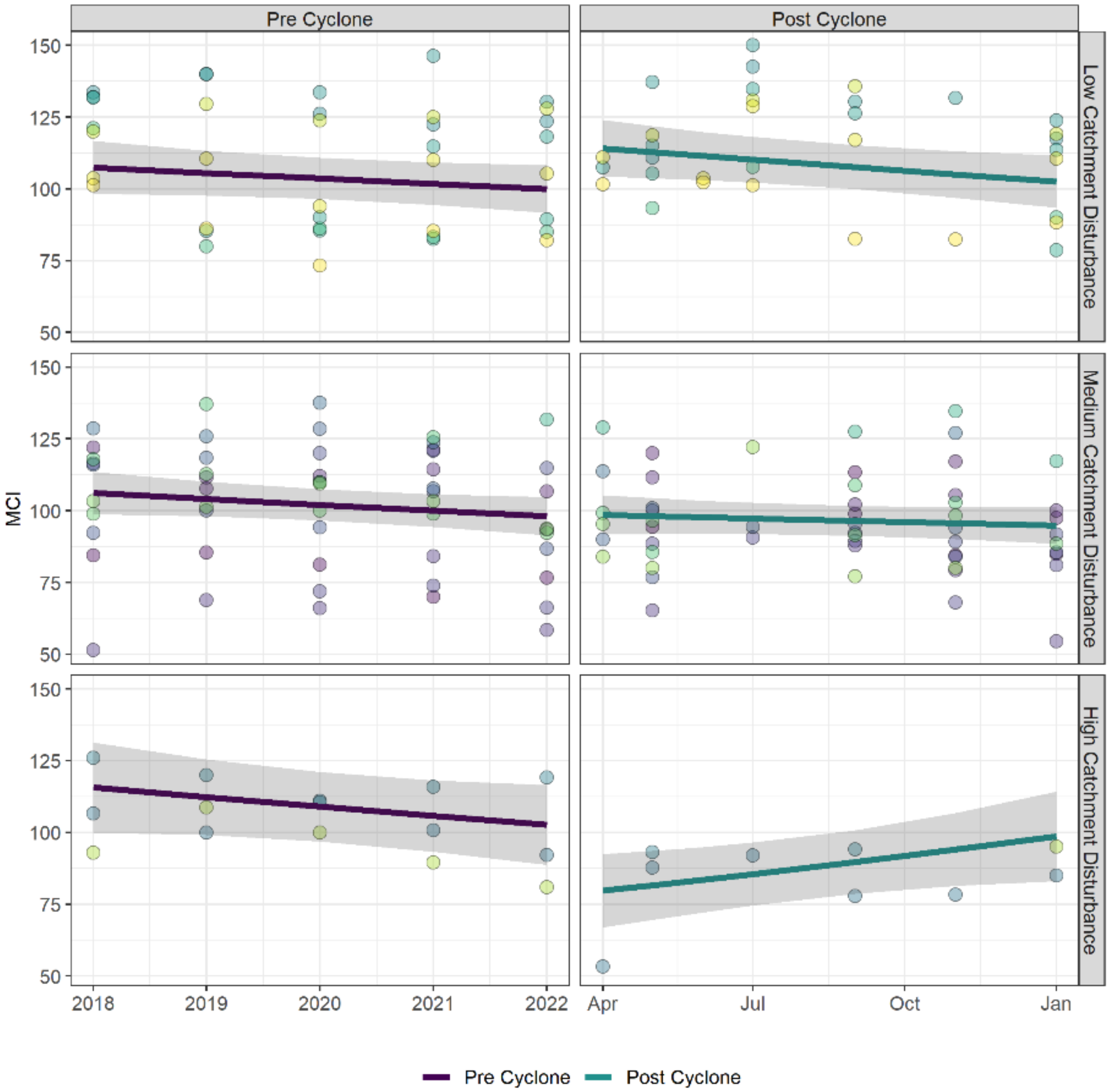


Figure 104. MCI scores at sites in catchments with low, medium, and high catchment disturbance (from aerial imagery), before (left) and after (right) the cyclone.

Notes: coloured lines indicate trends from the best-fitting model over time in pre- (purple) and post- (turquoise) cyclone periods. Points are coloured by site.

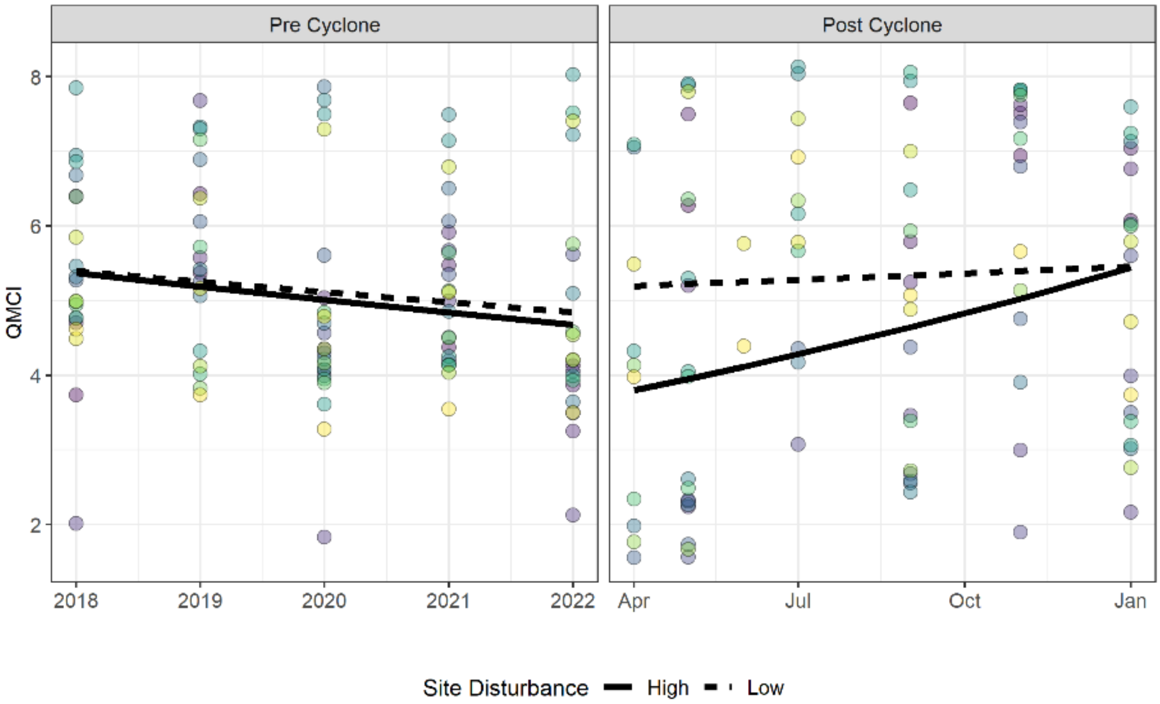


Figure 105. QMCI scores at low- and high-disturbance river and stream sites (from aerial imagery) in Hawke's Bay, before (left) and after (right) the cyclone.

Notes: solid and dashed black lines indicate the overall trend from the best-fitting model for sites of high and low disturbance (75th and 25th quartile, respectively). Points are coloured by site.

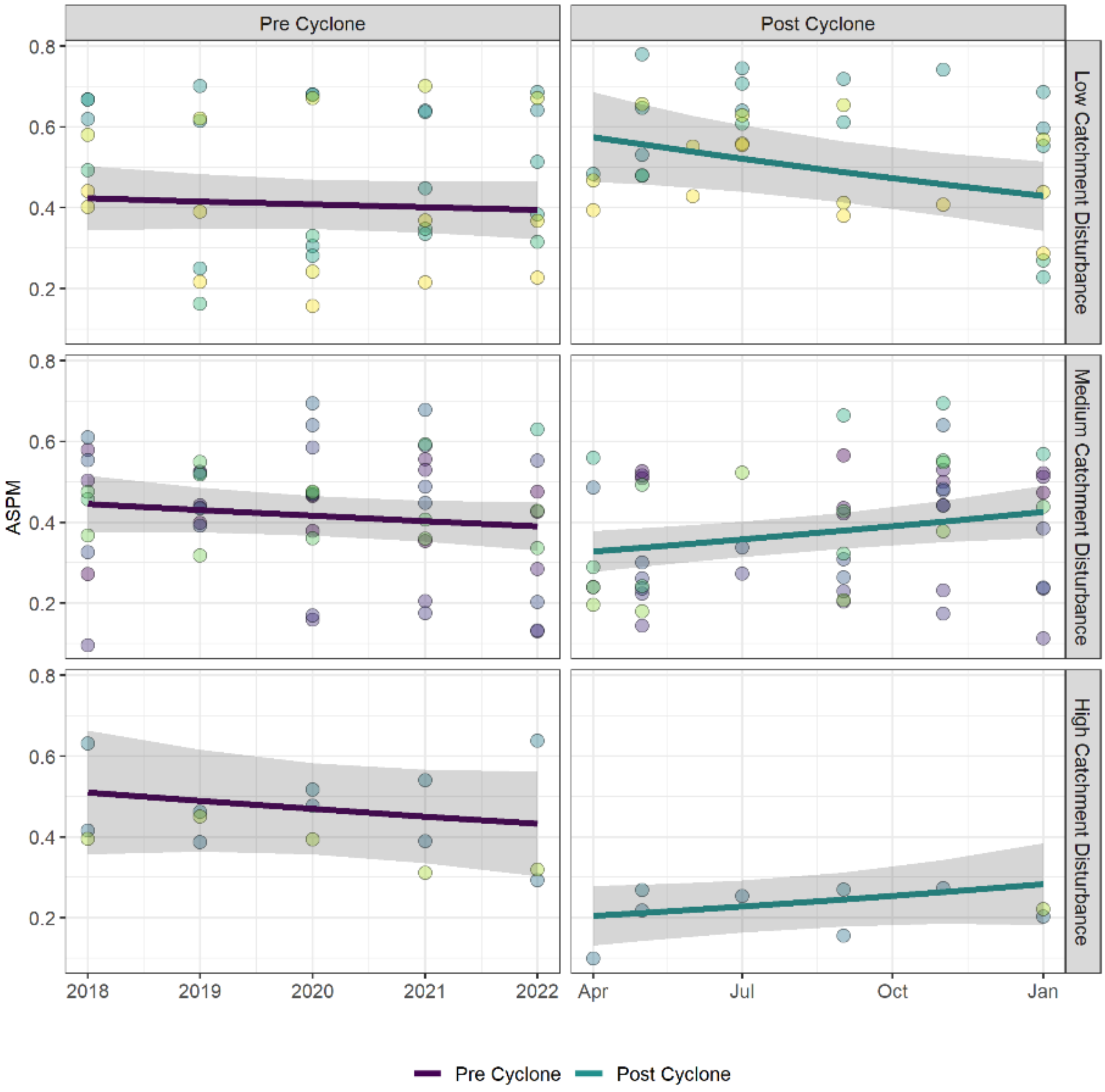


Figure 106. ASPM at sites in catchments with low, medium, and high catchment disturbance (from aerial imagery), before (left) and after (right) the cyclone.

Notes: coloured lines indicate trends from the best-fitting model over time in pre- (purple) and post- (turquoise) cyclone periods. Points are coloured by site.

eDNA analyses

eDNA detected 155 macroinvertebrate taxa identified to genus level, or 91 taxa aggregated to MCI resolution (typically genus, but family, order, or phylum for some taxa). There were 117 unique taxa identified to MCI resolution recorded across all physical samples. The greater taxa richness of the eDNA data set was largely due to finer-scale resolution within groups that are aggregated at higher taxonomic levels in the MCI (i.e. chironomids, oligochaetes, and microcrustacea), rather than detection of additional taxa not found in the physical sampling.

Macroinvertebrate community composition

We observed no statistically significant differences in presence or absence of macroinvertebrate taxa detected by eDNA sampling between site or catchment disturbance categories (determined from aerial imagery), either before or after the cyclone (pre-cyclone PERMANOVA $F_{2,33}$ = 1.25, $P > 0.05$; homogeneity of dispersion $F_{2,33}$ = 0.12, $P > 0.05$; post-cyclone PERMANOVA $F_{2,76}$ = 1.11, $P > 0.05$; homogeneity of dispersion $F_{2,76}$ = 1.96, $P > 0.05$; Figure 107). Overall, there was less separation between eDNA-based communities between pre- and post-cyclone samples, and between levels of site and catchment disturbance, when compared to the physical macroinvertebrate samples (Figure 97).

Before the cyclone the number of eDNA detections was relatively evenly spread across mayfly and caddisfly taxa and large numbers of oligochaetes (Figures 108 and 109). Immediately after the cyclone, in autumn 2023, *Deleatidium* and *Austroclima* mayflies had the greatest number of eDNA detections among EPT taxa (Figure 108), while oligochaetes had the most among non-EPT taxa (Figure 109). In summer of 2023/24, DNA of caddisflies (i.e. net-spinning *Hydropsyche*, cased *Hudsonema*, and free-living predatory Hydrobiosids) had the most detections of all the EPT taxa, while oligochaetes continued to have the most detections of all non-EPT taxa (Figures 108 and 109).

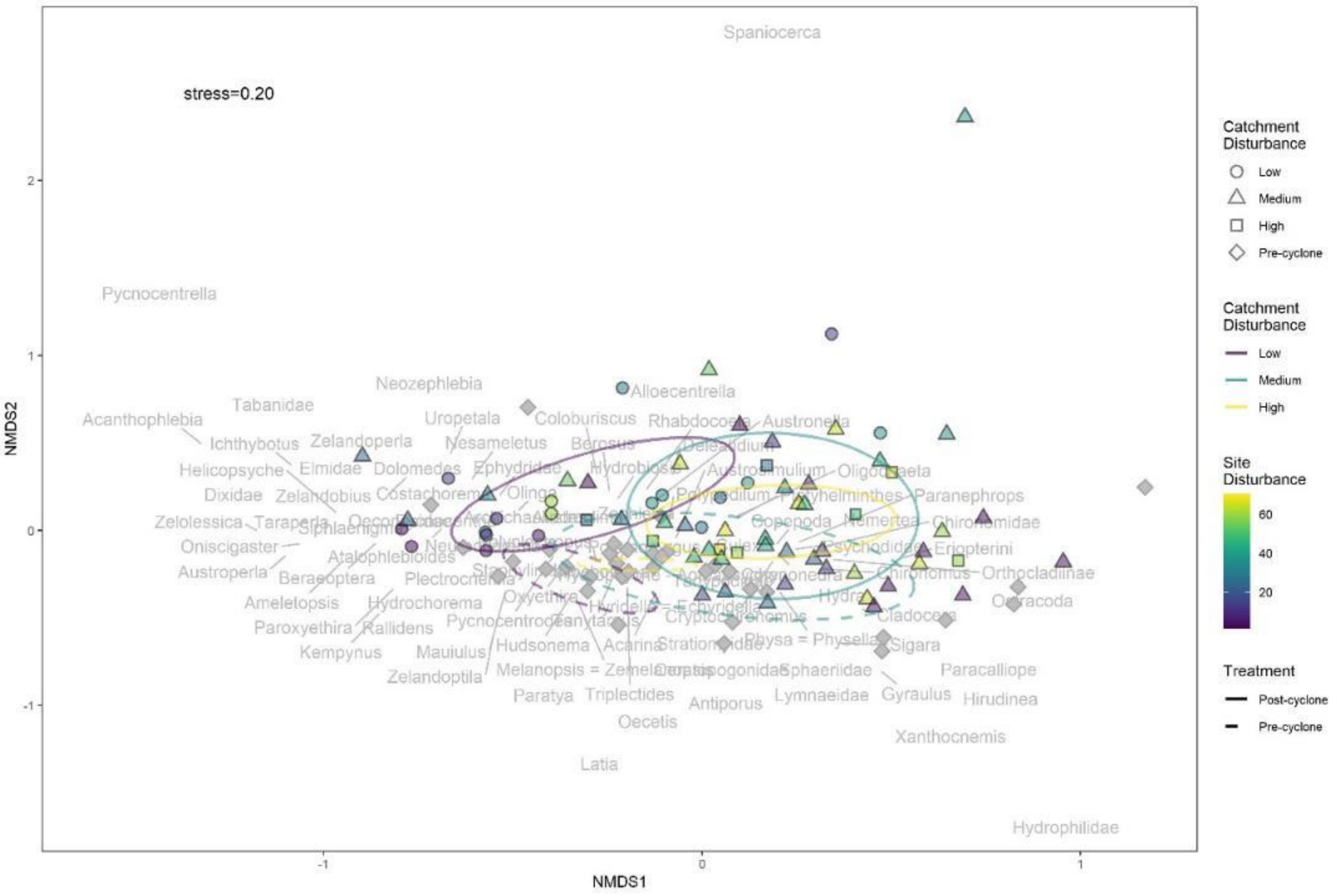
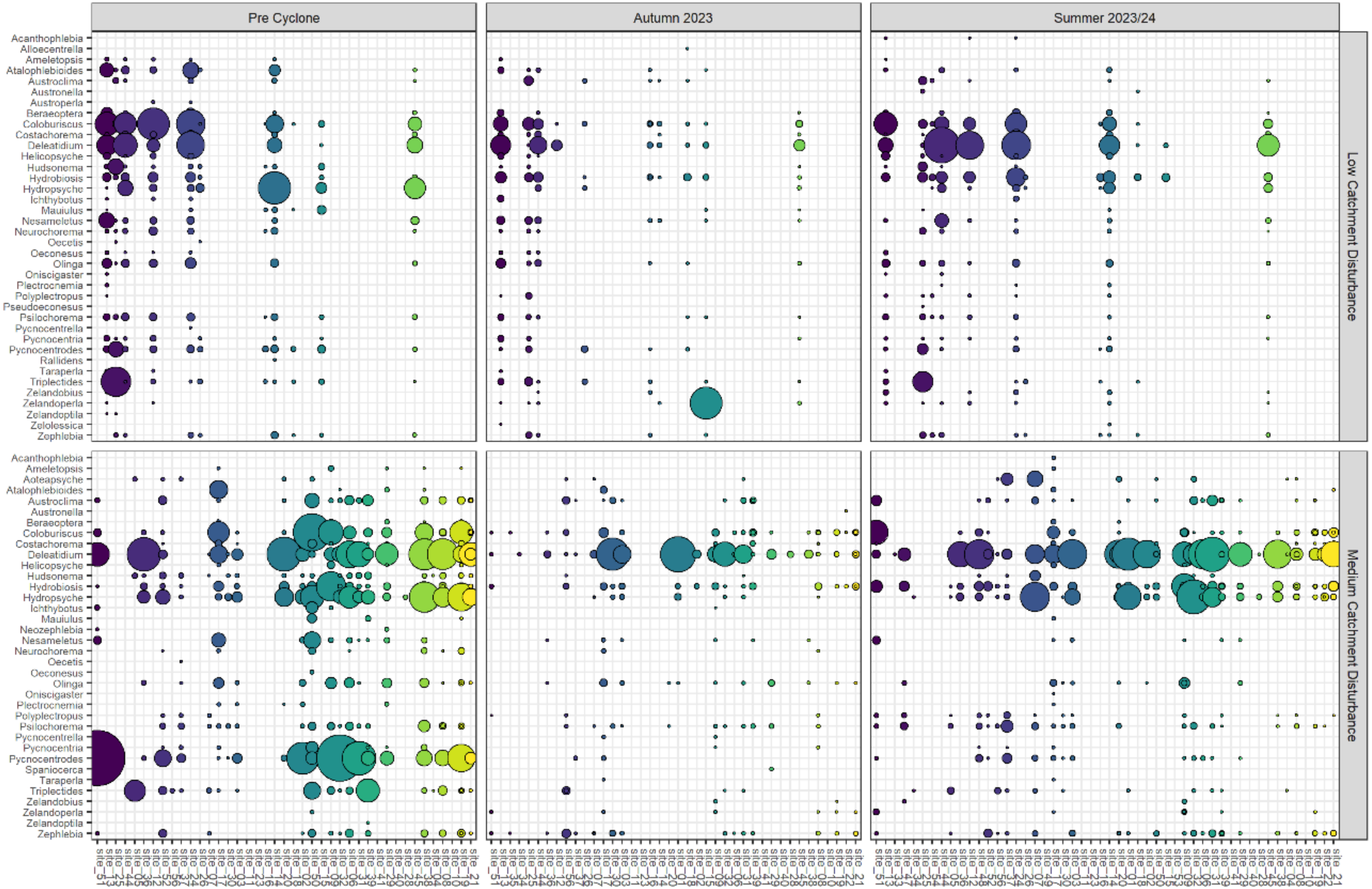


Figure 107. Visual representation of non-metric multi-dimensional scaling (NMDS) analysis showing community composition of freshwater macroinvertebrates from eDNA sampling across all Hawke's Bay sites before and after Cyclone Gabrielle.

Notes: samples are coloured by site disturbance while the symbol indicates catchment disturbance category (diamond = pre-cyclone, circle = low, triangle = medium, square = high). Disturbance levels were determined using aerial imagery analysis. Samples collected in the year before the cyclone are shown as grey diamonds. Ellipses show 1 standard deviation around the centroid for each group: low (purple), medium (turquoise), and high (yellow) catchment disturbance. Ellipses with dashed lines are for pre-cyclone samples; solid lines are for post-cyclone samples. Macroinvertebrate taxa names are shown in grey. The location of taxa names in ordination space relative to sites or other taxa indicates how commonly they are found in a site or with another taxon, respectively.



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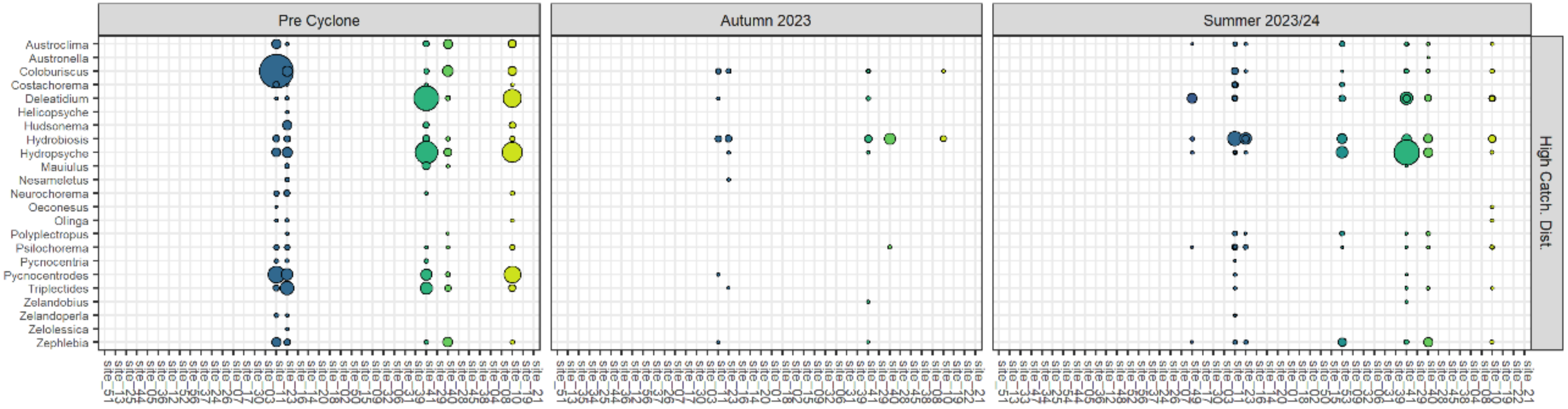
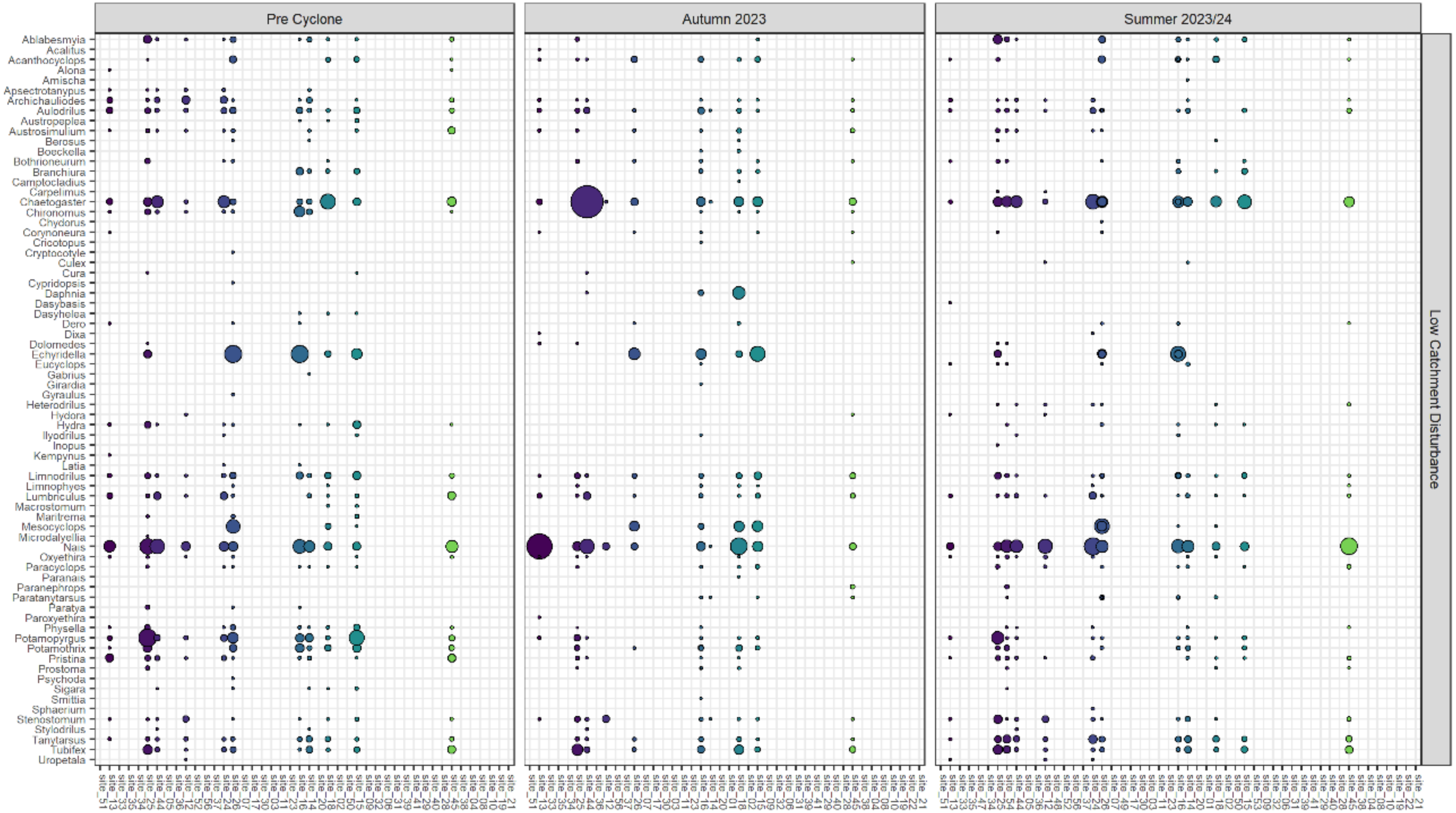


Figure 108. eDNA counts of EPT (Ephemeroptera, Plecoptera, Tricoptera) taxa in each Hawke's Bay site before Cyclone Gabrielle (left) and in autumn 2023 (middle) and summer 2023/24 (right).

Notes: the size of points indicates the total count, standardised for replicate volume, and colour indicates the level of site disturbance (dark purple = low site disturbance, yellow = high site disturbance) based on changes in satellite imagery. Site names on the x-axis correspond to site names in Table A4.1.



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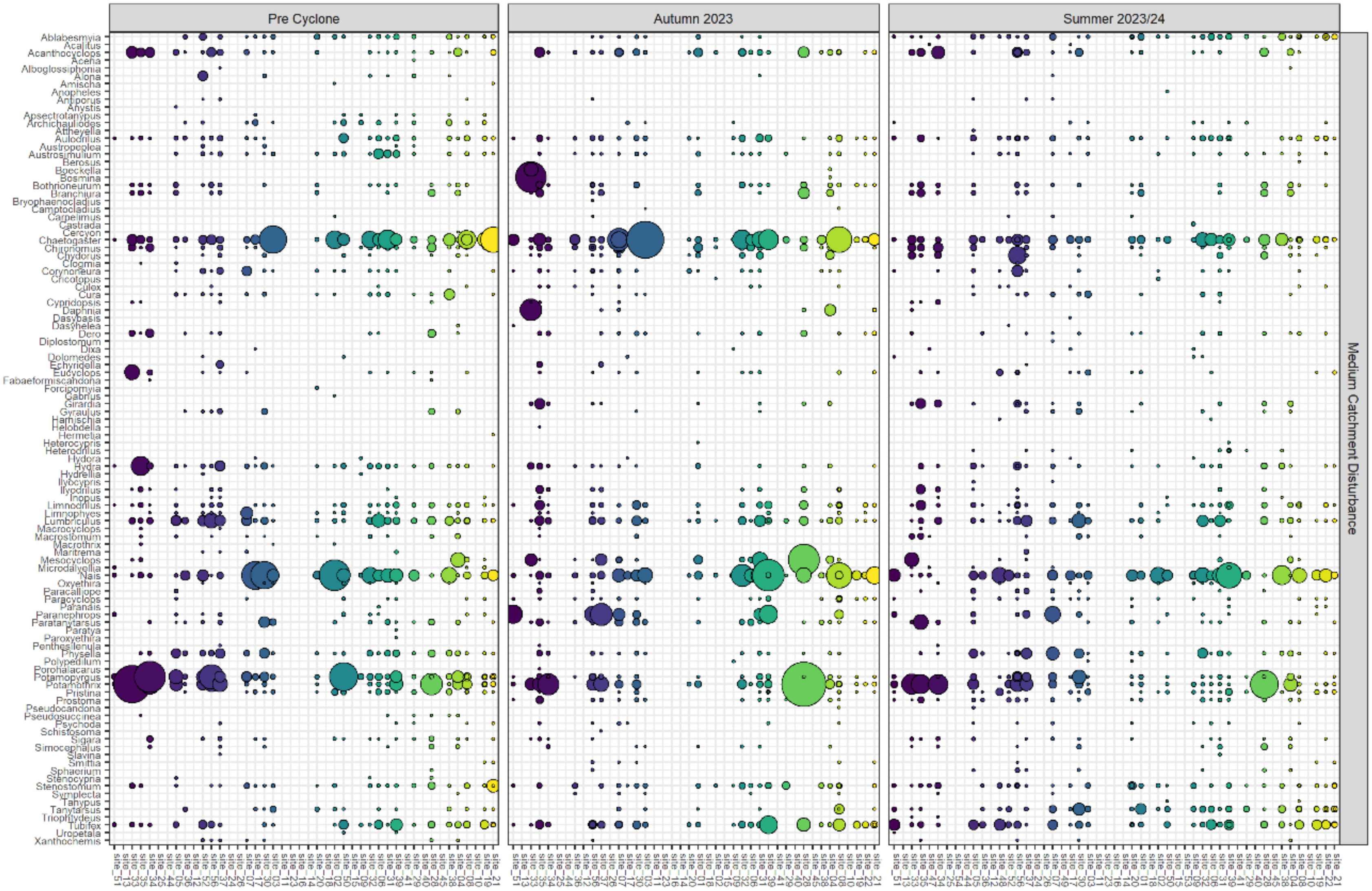

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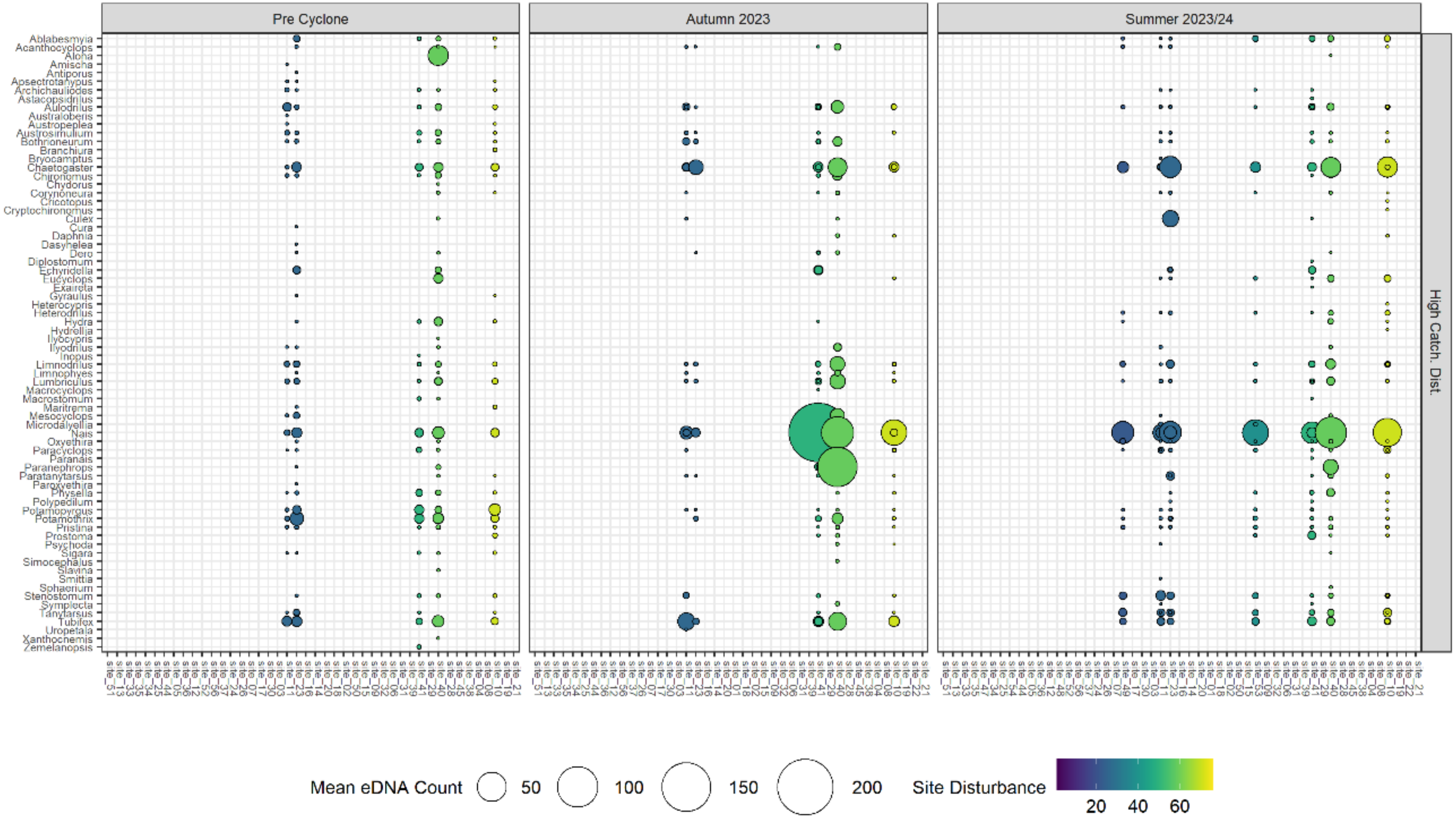

Figure 109. eDNA counts of non-EPT taxa in each Hawke's Bay site before Cyclone Gabrielle (left) and in autumn 2023 (middle) and summer 2023/24 (right).

Notes: the size of points indicates the total count, standardised for replicate volume, and colour indicates the level of site disturbance (dark purple = low site disturbance, yellow = high site disturbance) based on changes in satellite imagery. Site names on the x-axis correspond to site names in Table A4.1

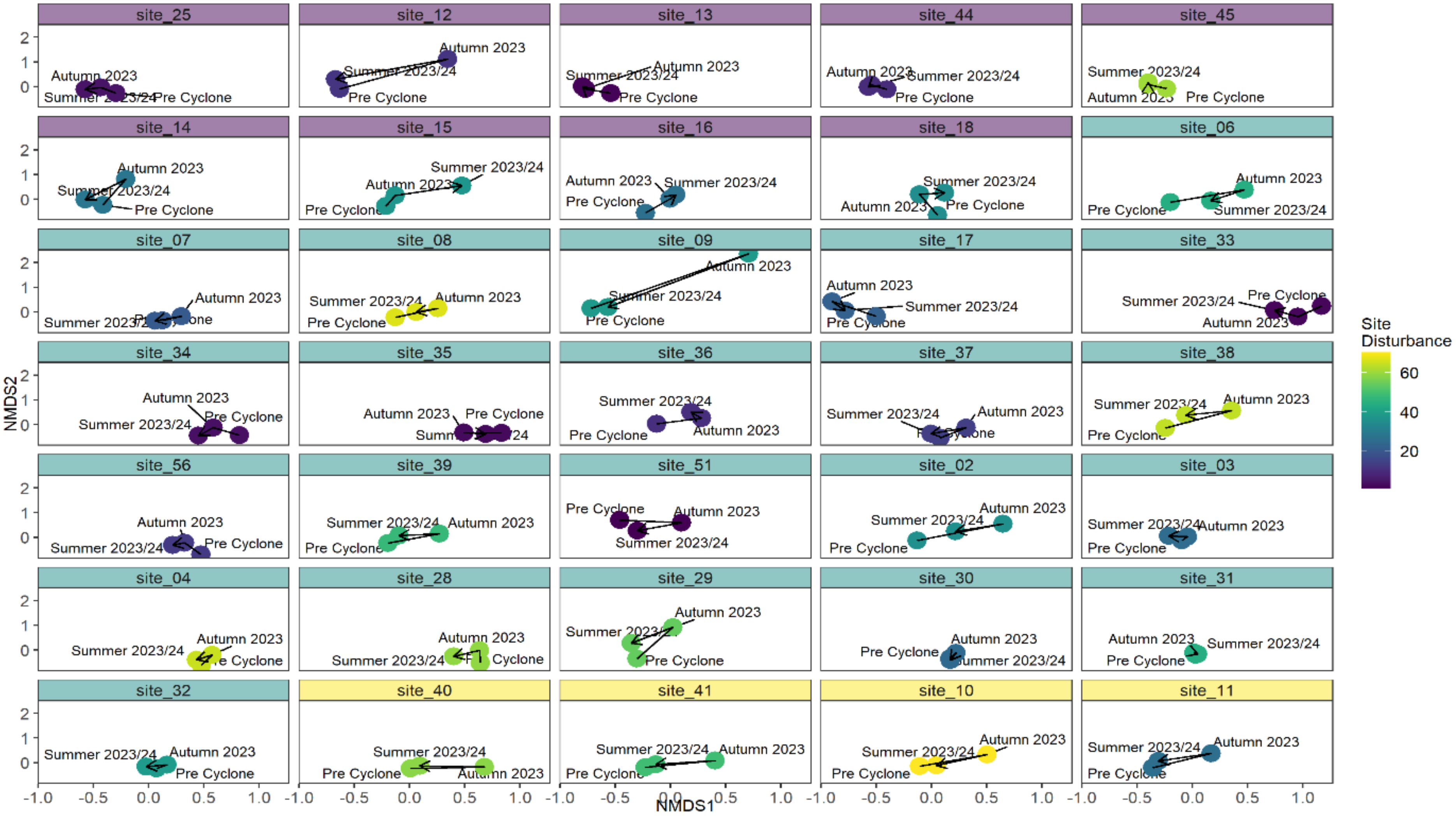

Figure 110. Shifts in community composition between eDNA sampling occasions: one before the cyclone and two after the cyclone.

Notes: the colour of the panel box indicates catchment disturbance categories (based on aerial imagery): low = purple, medium = turquoise, high = yellow. Points are coloured by the level of site disturbance.

Recovery trajectories

Recovery of macroinvertebrate community composition determined using eDNA followed a similar trajectory in most sites across a range of site and catchment disturbance impacts. There was a distinct shift in community composition in autumn 2023 away from pre-cyclone composition (Figure 110). Without further temporal resolution of current or historical samples it was not possible to determine whether this reflects a regular seasonal shift or cyclone impact. However, the magnitude of shift between sampling dates was often smaller in low-impact sites, suggesting that cyclone impacts had an influence on macroinvertebrate community composition. In the summer of 2023/24 community composition at most sites was again similar to the pre-cyclone baseline (Figure 110), indicating that if there had been cyclone impacts, 1 year was a sufficient timeframe for recovery.

Model selection

Taxa richness in eDNA samples was lower in both post-cyclone sampling periods compared to before the cyclone (Figure 111), but the top model did not include site or catchment disturbance (Table 13), indicating that the decline in richness was either temporary or due to an additional non-measured cyclone impact. Likewise, the top model for EPT richness included only a treatment effect (Table 13), reflecting the lower EPT richness in autumn 2023 than either before the cyclone or in summer 2023/24 (Figure 112). The proportion of EPT taxa detected, on the other hand, was unrelated to both treatment and disturbance effects (Table 13).

Table 13. Model selection models regressing eDNA-based community metrics relative to spatial (site and catchment disturbance) and temporal (treatment) effects of Cyclone Gabrielle

Model	LogLik	K	AICc	Δ AICc	Weight
Taxa richness					
Richness ~ (1 | Site) + (1 | Catchment) + treatment	–528.07	4	1,064.44	0.00	0.58
Richness ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance	–525.20	7	1,065.24	0.80	0.39
Richness ~ (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–524.56	10	1,070.83	6.39	0.02
Richness ~ (1 | Site) + (1 | Catchment) + treatment * site disturbance + treatment * catchment disturbance	–521.83	13	1,072.55	8.10	0.01
Richness ~ (1 | Site) + (1 | Catchment)	–534.89	2	1,073.86	9.42	0.01
EPT richness					
EPT Richness ~ elevation + (1 | Site) + (1 | Catchment) + treatment	–427.11	5	864.66	0.00	0.53
EPT Richness ~ elevation + (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–420.89	11	865.84	1.18	0.29
EPT Richness ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance	–425.19	8	867.47	2.81	0.13
EPT Richness ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance +treatment * catchment disturbance	–419.66	14	870.68	6.02	0.03

Model	LogLik	K	AICc	Δ AICc	Weight
EPT Richness ~ elevation + (1 | Site) + (1 | Catchment)	–432.55	3	871.27	6.61	0.02
% EPT taxa					
% EPT ~ elevation + (1 | Site) + (1 | Catchment)	104.58	3	–202.97	0	0.66
% EPT ~ elevation + (1 | Site) + (1 | Catchment) + treatment	104.98	5	–199.51	3.47	0.12
% EPT ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance	108.26	8	–199.43	3.55	0.11
% EPT ~ elevation + (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	111.50	11	–198.94	4.03	0.09
% EPT ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance +treatment * catchment disturbance	113.88	14	–196.41	6.57	0.02
eMCI Score					
MCI ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance	–531.07	8	1,079.24	0.00	0.50
MCI ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance + treatment * catchment disturbance	–524.22	14	1,079.79	0.55	0.38
MCI ~ elevation + (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–529.39	11	1,082.84	3.60	0.08
MCI ~ elevation + (1 | Site) + (1 | Catchment)	–539.51	3	1,085.21	5.96	0.03
MCI ~ elevation + (1 | Site) + (1 | Catchment) + treatment	–538.24	5	1,086.92	7.68	0.01
TICI					
TICI ~ elevation + (1 | Site) + (1 | Catchment) + treatment * catchment disturbance	–428.48	11	881.03	0.00	0.49
TICI ~ elevation + (1 | Site) + (1 | Catchment) + treatment	–435.60	5	881.64	0.62	0.36
TICI ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance	–433.81	8	884.71	3.68	.0.7
TICI ~ elevation + (1 | Site) + (1 | Catchment) + treatment * site disturbance + treatment * catchment disturbance	–426.72	14	884.79	3.76	0.07
TICI ~ elevation + (1 | Site) + (1 | Catchment)	–446.57	3	899.32	18.29	0.00

Notes: LogLik is the log likelihood, K is the number of model parameters, AIC is the Akaike Information Criterion, ΔAIC is the change in AIC relative to lowest AIC value, and weight is the weight of evidence that the model is the top model.

The top model for eMCI contained the interaction between treatment (before and after the cyclone) and site disturbance (Table 13). Before the cyclone there was a positive relationship with eMCI and 'site disturbance' (which was yet to occur) across all sites, whereas in autumn 2023 the relationship was slightly negative (Figure 113). In the summer of 2023/24 there was no relationship between site disturbance and eMCI (Figure 113).

The top model for TICI contained the interaction between treatment (before and after the cyclone) and catchment disturbance (Table 13). *Post hoc* tests showed that the TICI was significantly higher in autumn 2023 than before the cyclone in both the low- and high-catchment-disturbance sites, and also remained higher in the summer of 2023/24 in the high-catchment-disturbance sites (Figure 114). This contrasts with the eMCI and fish eIBI results: eMCI scores were lowest in high-catchment-disturbance sites in autumn 2023. However, the TICI includes a wider range of indicators across multiple taxonomic groups, including aquatic fish, plants, and microbiota, not just macroinvertebrates.

Figure 111. Violin plot of taxa (genus) richness from eDNA sampling of Hawke's Bay streams and rivers, before (purple) and after (turquoise and yellow) Cyclone Gabrielle.

Notes: points are coloured by site. Black circles indicate the modelled mean from the best-fitting model, with 95% confidence intervals (error bars). Different lowercase letters above error bars indicate significant differences between sampling periods.

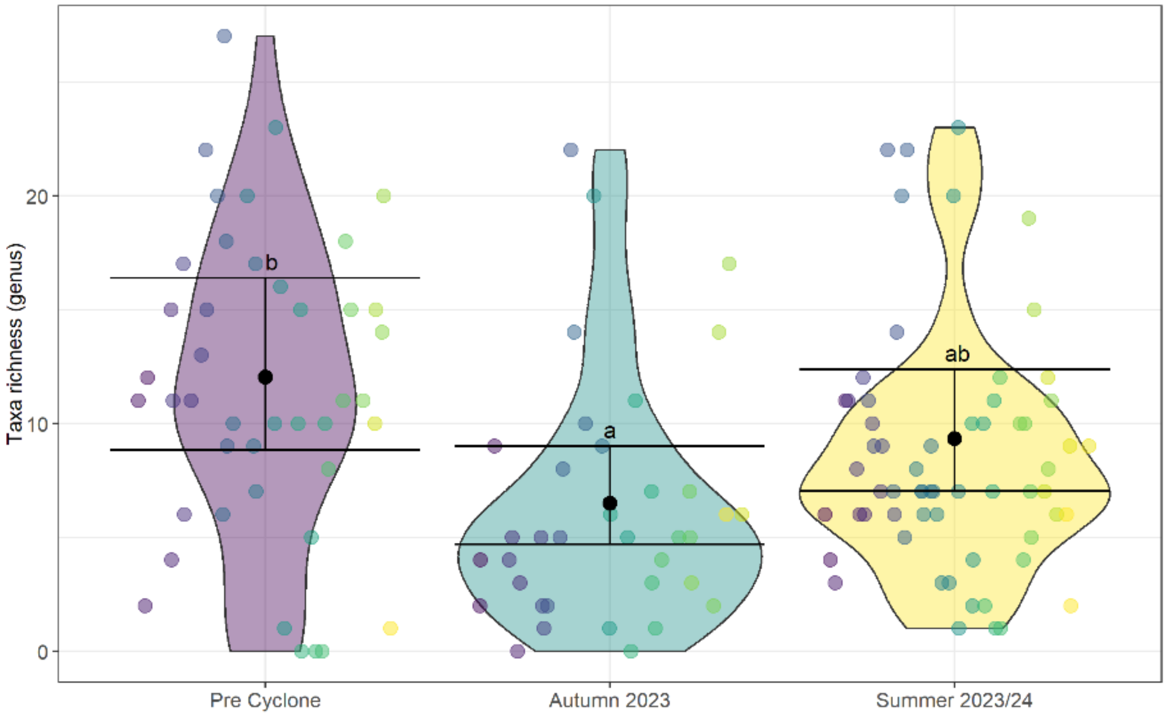

Figure 112. Violin plot of EPT taxa (genus) richness from eDNA sampling of Hawke's Bay streams and rivers before (purple) and after (turquoise and yellow) Cyclone Gabrielle.

Notes: points are coloured by site. Black circles indicate the modelled mean from the best-fitting model with 95% confidence intervals (error bars). Letters indicate significant differences between groups across sampling periods.

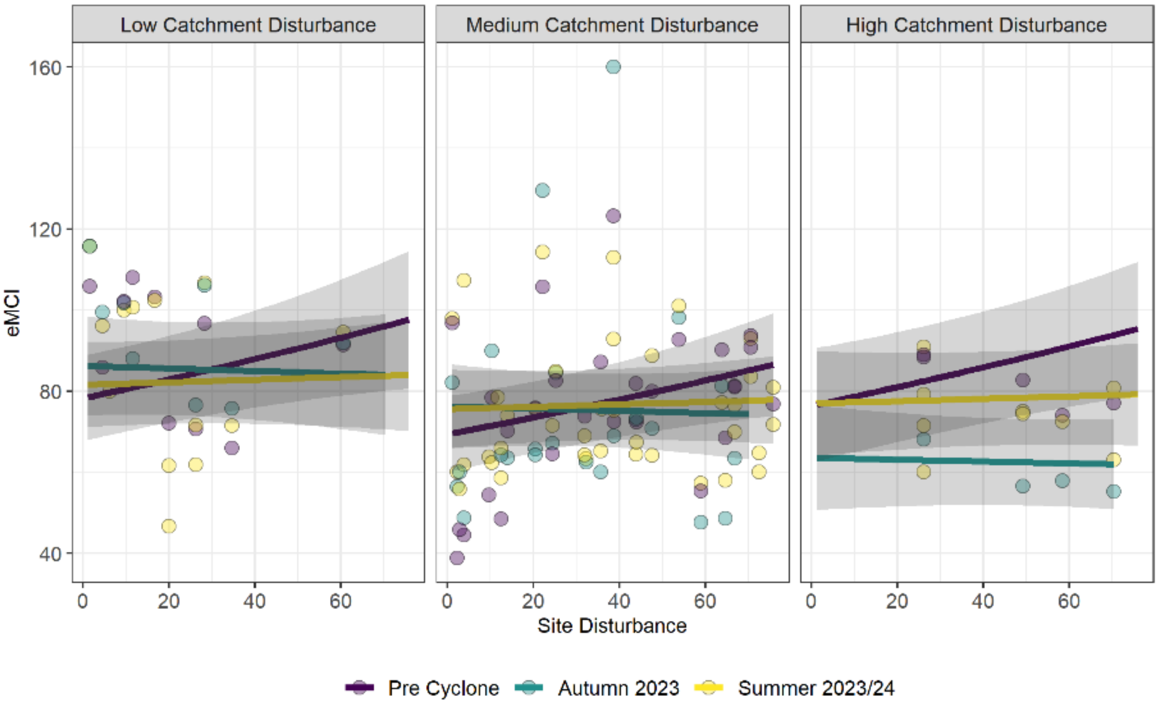

Figure 113. Relationships between eMCI scores and site disturbance in Hawke's Bay rivers and streams (from aerial imagery) before (purple) and after (turquoise and yellow) Cyclone Gabrielle.

Note: points and lines are coloured by sampling period.

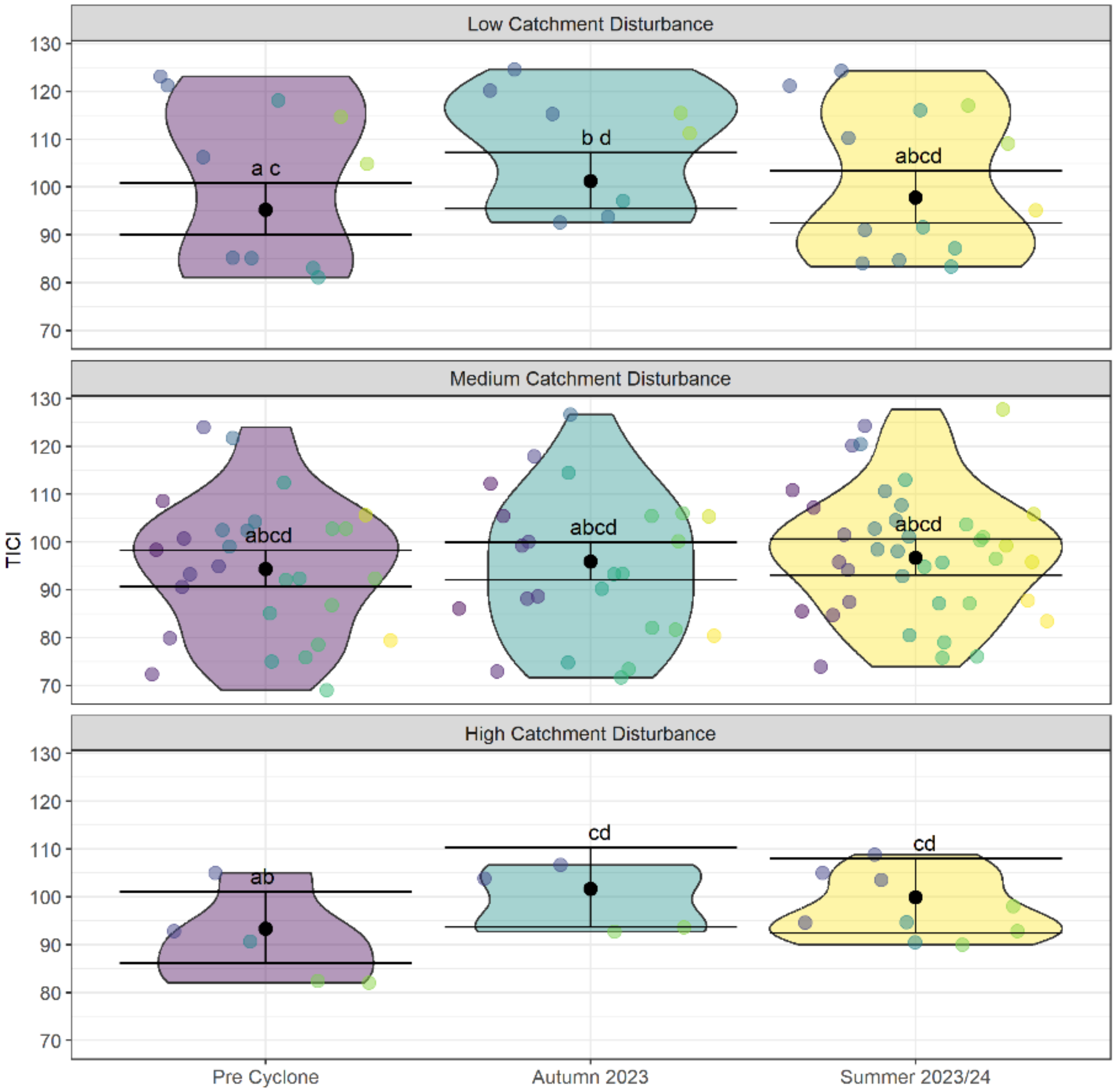

Figure 114. Violin plot of TICI scores from eDNA sampling of Hawke's Bay streams and rivers before (purple) and after (turquoise and yellow) Cyclone Gabrielle.

Points are coloured by site. Black circles indicate the modelled mean from the best-fitting model with 95% confidence intervals (error bars). Letters indicate significant differences between groups across all sampling periods and catchment disturbance categories.

4.4 Discussion

4.4.1 Abiotic response

The flow duration curves from gauging stations in the Hawke's Bay region during the cyclone revealed a significant shift in both the magnitude and timing of river flow, with many stations recording their highest sustained discharges since 2009. Also, the elevated sustained flows contributed to higher low flows for the year. However, sites such as Hangaroa, Tutaekuri Puketapu, and Waiau Otoi exhibited flow patterns consistent with previous high-flow years, indicating localised variability in rainfall related to Cyclone Gabrielle. These findings suggest that Cyclone Gabrielle had a pronounced impact on sustained river flows, with clear extremes across the middle and lower ranges of discharge, but for many sites the rainfall associated with Cyclone Gabrielle was not outside that seen in other years and biota may be adaptable to the disturbances experienced.

On the other hand, flow duration curves do not reflect the intensity of rainfall events; many Hawke’s Bay sites had either the largest volume of rainfall on record or the largest volume over a short duration during Cyclone Gabrielle (Harrington et al. 2023). Furthermore, the peak flows recorded in many sites during the cyclone may be underestimates as the flow recorders were probably damaged before peak flow was reached (Vicki Lyon, HBRC, pers. comm.). Greater intensity of rainfall would likely result in more extreme impacts on river flows and subsequent ecological disturbance.

Deposited sediment (g/m^2 SIS) decreased following Cyclone Gabrielle, with greater decreases in sites located in catchments with medium and high disturbance compared with sites located in catchments with low disturbance. However, decreases in SIS did not appear to be related to site-level disturbance. However, it is important to note that this data set is unlikely to accurately reflect the full sediment inputs from Cyclone Gabrielle, the majority of which occurred during the first 24 to 48 hours of the cyclone (Dr Sandy Haidekker, HBRC, pers. comm.).

Deposited sediment has been shown to negatively affect many species that depend on complex habitats, such as those found in the interstitial spaces of streams. Interestingly, sample sites in catchments with low disturbance showed little or no overall decrease in SIS following Cyclone Gabrielle, indicating that any increase in deposited sediment was probably within the expected variability the rivers routinely experience. However, because pre-cyclone sediment data were not available, it is unknown what ‘typical’ deposited sediment levels in these systems are.

Furthermore, comparison of temporal patterns in deposited sediment against daily flow records shows repeated peaks in deposited sediment associated with small flow events throughout the year. These peaks could indicate flushing of upstream deposits or additional inputs via overland flow in catchments with ongoing erosion or exposed land slips. Because of the importance of deposited sediment to aquatic fauna, continued monitoring and further research are needed to better understand the relationship between changes in aquatic fauna and deposited sediment.

In New Zealand, fragmentation of waterways by anthropogenic barriers that prevent fish accessing critical life-stage habitats (e.g. dams, culverts, and weirs) is one of the most significant causes of the decline in freshwater fish populations (Franklin et al. 2022). We hypothesise that increased sedimentation after Cyclone Gabrielle improved connectivity at some instream structures, which may have enabled the observed rapid recovery of diadromous fish species such as īnanga and smelt. Of the instream structures examined before and after Cyclone Gabrielle, close to a third had an improvement in their risk score. Only 4 of the 61 culverts examined went from very low risk to high or very high risk after Cyclone Gabrielle, indicating extensive restructuring of the culvert and surrounding habitat. Excluding Devil's Elbow, culverts examined in the tributaries of Te Ngarue Stream had deposited sediment that was assessed by the authors as improving passage for fish at those sites. However, if the supply of deposited sediment decreases over time or the deposited substrate is remobilised, some undersized and poorly positioned culverts are likely to become fish passage barriers (C. Baker, NIWA, author's observation).

4.4.2 Fish responses

Fish communities exhibited remarkable resilience to the effects of Cyclone Gabrielle, with eDNA and physical sampling data indicating that community composition the following summer was comparable to that of pre-cyclone samples. Smelt and īnanga, both weak-swimming migratory species, had repopulated affected survey sites by the summer of 2023/24. Strong site fidelity in native fish communities after high discharge events has also been recorded in other regions of New Zealand. For example, David and Closs (2002) found that over 50% of radio-tagged giant kōkopu stayed within their home reach, or moved and returned to their home reach as flows subsided. McEwan and Joy (2013) used passive integrated transponder tags to examine the movements of shortjaw kōkopu, kōaro, and redfin bullies in response to three floods, one of which peaked at more than 200 times base flow. Although they found small changes in the tagged species' abundance after flood events, the three fish species were considered resilient to flood impacts overall.

Some species showed greater resilience, and increased in relative abundance and eDNA prevalence, at survey sites after Cyclone Gabrielle, while other species declined in relative abundance and eDNA prevalence. For example, common bullies and torrentfish showed more persistence at survey sites compared to shortfin eels and redfin bullies. The eDNA of smelt and īnanga also increased in prevalence 1 year after Cyclone Gabrielle compared to pre-cyclone prevalence.

The responses of individual species at the survey sites most likely relates to habitat changes and the availability of refuge habitat. For example, McEwan and Joy (2013) observed habitat changes resulting from increased sediment deposition, which covered cobbles and gravels, reduced the riffle habitats preferred by redfin bullies, and removed their shelter spaces, leading to a decline in their population. Similarly, Jowett and Boustead (2001) demonstrated that the number of upland bullies (*Gobiomorphus breviceps*) decreased as fine sediment filled the interstitial spaces between cobbles. In contrast, common bullies were less affected by increased deposited sediments (Depree et al. 2017).

Torrentfish are often found in fast-flowing riffle habitats among cobble and boulder substrates (McDowall 1990) and are thought to be sensitive to increased sediment deposition because of the infilling of interstitial spaces and a subsequent reduction in refuge habitat (Depree et al. 2017). This implies that torrentfish should be less prevalent after Cyclone

Gabrielle. However, torrentfish are also commonly found along sand banks in swift-moving water within large river systems (Boubée et al. 1986; Baker et al. 2011). Consequently, they may be more adept at coping with habitat changes associated with deposited sediment, but their habitats can often be too deep and swift for sampling, meaning that knowledge of their habitat use is limited and may be biased.

Pelagic species such as smelt and īnanga are also less affected by deposited sediments because they use riparian vegetation, tree roots, woody debris or other complex structures present along stream margins as cover habitats. In this regard, the resilience of fish communities and increased eDNA prevalence of the taonga species īnanga and smelt after Cyclone Gabrielle probably indicates that sufficient refuge (cover) habitats were present the following summer.

This notion is supported by the increased prevalence and relative abundance of smelt, a refuge-seeking species, at sites with high disturbance after Cyclone Gabrielle. Baker and Smith (2015) and David and Closs (2002) found that banded kōkopu and giant kōkopu returned to pre-flood locations if cover habitat remained present, but would recruit elsewhere when cover habitats were lost in high-discharge events.

Internationally, declines in the density and biodiversity of freshwater fish species have been recorded after floods when local habitat has been lost or changed (Matthews 1986; Yoon et al. 2011; Chen et al. 2015). Retaining complex habitat structure after floods is probably a key factor in the resilience of fish populations.

The reduced presence of some fish species at survey sites does not preclude these fish from relocating to suitable habitats in neighbouring tributaries or streams. Flood events can benefit gene flow, enabling stream-resident fish to seek or relocate to new stream systems, redistributing populations and changing population demographics. Across a 2-year study period, Baker and Smith (2015) recorded inter-stream movements associated with flood events in approximately 25% of monitored giant kōkopu and 5% of banded kōkopu. Although David and Closs (2002) recorded high site fidelity in giant kōkopu during high-discharge events, one fish was recorded as having relocated to a neighbouring stream during a large flood.

Increases in suspended sediment after high-discharge events can affect fish community structure. The present study indicated that at the survey sites common bully, smelt, īnanga, and torrentfish presence persisted or increased after Cyclone Gabrielle. An examination of the literature supported these findings. A meta-analysis by Rowe et al. (2009) examined fish presence at 191 sites in New Zealand relative to four measures of suspended sediment. They found that common bully, īnanga, longfin eel, torrentfish, and bluegill bully occurrence was positively correlated with suspended sediment measures and concluded that the presence of these species was unlikely to be adversely affected by increases in suspended sediment. Wright-Stow and Baker (2006) also found that desedimentation of the hydroelectric reservoir impounded by Kourarau Dam (Wairarapa) had no immediate effect on fish communities at four sites surveyed downstream of the dam, of which eels, common bullies, and torrentfish were key biota. As suspended sediment levels continue to decline, we would expect the populations negatively related to SIS to increase (e.g. redfin bullies), while other species (e.g. common bullies and torrentfish) that are more adaptable to habitat changes are likely to remain in similar numbers.

Fish, being mobile, can avoid or move out of areas with high suspended sediment loads. Laboratory experiments by Boubée et al. (1997) examined the avoidance of suspended sediment by the juvenile migratory stage of six native fish species. Banded kōkopu were the most sensitive species, demonstrating a 50% avoidance response at a turbidity of around 25 NTU (nephelometric turbidity units). Īnanga were relatively insensitive to suspended sediment, displaying a 50% avoidance response to 420 NTU. In contrast, redfin bully and shortfin and longfin elvers showed no avoidance behaviour even at 1,100 NTU, the highest turbidity levels examined. The results of these experiments suggest that the reduction in redfin bully presence recorded after flood events by McEwan and Joy (2013), and in the present study, most likely relate to reduced refuge habitat from deposited sediment as opposed to the direct impacts of suspended solids.

We used several eDNA indices alongside electric fishing data to assess the short-term impacts of Cyclone Gabrielle on freshwater fish populations. The eIBI and Fish IBI both indicated no change in the freshwater fish communities before and after Cyclone Gabrielle. The eIBI and the prevalence index have been suggested by David et al. (2021) and Melchior and Baker (2023), respectively, to infer biodiversity and species richness from eDNA data. In general, in this study the eDNA indices have matched the physical electric fishing survey results. Subtle differences in individual species' presence and abundance between physical fishing and eDNA samples is expected because electric fishing solely captures the species that are physically present at a specific site, whereas eDNA sampling can also detect genetic material from species located at an unknown distance upstream (David et al. 2021). Consequently, eDNA can detect additional or rarer/elusive species than conventional sampling methods. However, the indices used in this study provide a simple way to categorise DNA reads to examine changes in species richness and biodiversity.

The recovery of diadromous fish populations after extreme weather events relies heavily on habitat connectivity. Because īnanga and smelt are essentially annual species, with most adults dying after spawning, the presence and abundance of these species after Cyclone Gabrielle requires an intact migratory corridor between the sea and upriver habitats. Thus, continued monitoring of instream structures to assess their risk to fish passage will be important for documenting long-term changes in fish populations relative to temporal changes in deposited sediment as natural river courses become reinstated. This is because migratory fish communities are dominated by species that migrate from the sea to freshwater habitats as small-bodied juveniles (<50 mm). During their upriver migration, vertical drops of as little as 10 cm have been demonstrated to severely restrict passage of some of the most common fish species, such as īnanga and common bullies (Baker 2003).

Ongoing and regular visual observations of instream structures, alongside assessments using the Fish Passage Assessment Tool (FPAT), will be important to determine any temporal increase in the risk to fish passage that each structure presents. Instream structures identified by the FPAT as increasing risk to fish passage can then be prioritised for remediation to mitigate impacts on upriver fish populations.

The short-term presence and resilience of fish communities 1 year after Cyclone Gabrielle does not preclude the occurrence of longer-term impacts that could not be examined in our study. For example, effects from increased suspended or deposited sediment can often be chronic and sub-lethal, but still affect the persistence and/or condition of fish populations.

For example, the direct impacts of deposited sediment on the inter-tidal vegetation used by īnanga as spawning habitat is a key threat to the continued abundance of īnanga in the Hawke's Bay region. Īnanga spawning sites are often in areas of reduced current in the tidal reach of larger rivers (e.g. in backwaters or near the confluence of smaller tributaries) and, as such, are prone to sediment deposition. Smothering of bankside vegetation by sediment because of Cyclone Gabrielle is considered to have increased the likelihood of mortality of deposited eggs by destroying the critical micro-habitat at ground level beneath the vegetation required for egg survival (Hickford et al. 2010; Hickford & Schiel 2011). Stem density and aerial root mat development can take several years to recover from the impacts of sedimentation and grazing (Hickford et al. 2010; Hickford & Schiel 2011).

Although īnanga are regarded as a single species across New Zealand, studies indicate that regional subpopulations (stocks) have developed. Consequently, if spawning habitat is a bottleneck to īnanga completing their life cycle, a population 'sink' develops (Hickford & Schiel 2011) and future generations could decline. McDowall and Eldon (1980) identified differences in fresh-run migrant īnanga size and condition between the Buller River (north Westland) and several rivers in the Haast area (south Westland), which provided anecdotal evidence that īnanga in the Buller River are derived from a different stock to those further south. Subsequently, Rowe and Kelly (2009) found that īnanga in the Mōkau River (Waikato region) were significantly smaller and younger at inward migration compared to those in the Hokitika River (central Westland).

More recently, Egan (2017) used otolith analyses to determine that the marine growth of īnanga in the Canterbury region was different to that of īnanga whitebait captured in the Buller, Golden Bay (Nelson region), and Bay of Plenty regions. Further evidence supporting the notion of discrete stocks of īnanga comes from Chiswell and Rickard (2011). Dispersal modelling of propagules (passively drifting particles) suggested that limited mixing occurs between regions of the North and South Islands. For example, 96% of propagules released between the Bay of Islands and Auckland harbours were recovered in the Bay of Plenty. Collectively, ocean current data indicate that the main source pool of whitebait for the Hawke's Bay region could originate from the east coast of the North Island below East Cape (Figure 115). Even in a widely dispersed species such as īnanga, the development of population sinks in large river systems such as the Wairoa, due to a lack of critical life-stage spawning habitat, could compromise future generations for Hawke's Bay waterways (Hickford & Schiel 2011).

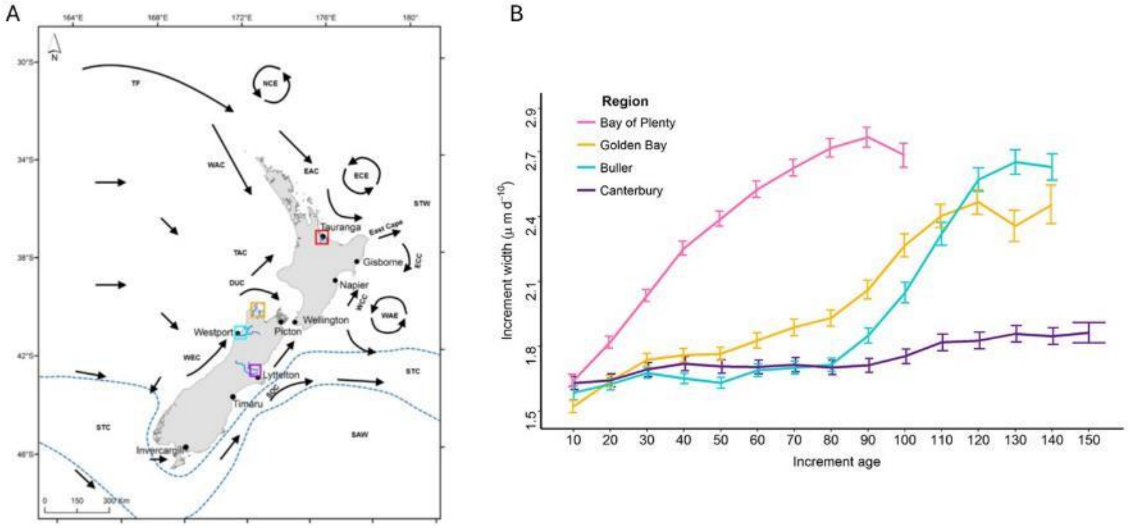

Figure 115. Direction of the major ocean currents around New Zealand (A) and īnanga growth rates identified by Egan (2017) (B). (Figure modified from Chiswell & Rickard 2011 and Egan 2017.)

Notes: the location of the four study regions of Egan (2017) are colour coded in panel A based on the legend in panel B. Error bars represent ± 1 standard error. Growth trajectories in panel B represent the increase in otolith growth per day relative to the age of īnanga, in days.

We could not examine the impacts of Cyclone Gabrielle on the spawning habitat of banded kōkopu and kōaro, the other prevalent whitebait species in the Hawke’s Bay region. Like īnanga, the other four whitebait species have all been observed to use terrestrial egg deposition (Allibone & Caskey 2000; Charteris et al. 2003; Franklin et al. 2015). However, in contrast to īnanga, kōaro and the three kōkopu species spawn in non-tidal parts of rivers, relying on rainfall-driven inundation of the riparian zone for spawning and hatching (Allibone & Caskey 2000; Charteris et al. 2003; Franklin et al. 2015). Consequently, deposited sediment in riparian margins will destroy the critical micro-habitat within the vegetation that is required for successful egg development (Hickford & Schiel 2011).

Deposited sediment within streams can also reduce spawning habitat for fish species that lay eggs in interstitial spaces within the substrate, including redfin bully, common bully, bluegill bully, Dinah’s bully (*Gobiomorphus dinae*), and the non-native species rainbow and brown trout. Kōaro have also been observed to spawn among cobbles and gravels in riffle habitats of rivers (Jane Goodman, Department of Conservation, pers. comm.). Deposition of fine sediment can clog the interstitial spaces used by fish to lay eggs and/or smother the eggs themselves. Smothering by sediment reduces the oxygen supply to the egg and embryo, which can lead to mortality due to hypoxia or physiological impacts such as reduced length and weight (Jensen et al. 2009; Kemp et al. 2011; Kjelland et al. 2015; Sear et al. 2016). Another mechanism whereby deposited sediment can affect breeding success is through the quality of the spawning habitat itself (Kjelland et al. 2015).

Examination of the instream spawning habitats of bullies and other fish species was outside the project’s scope. However, we anticipate that deposited sediments will have reduced the availability of critical interstitial spaces required by fish species that spawn among cobbles and gravels. In contrast, smelt are known to spawn on sand bars within the lower reaches of rivers (Baker & Bartels 2011), and an increase in deposited sediment associated with Cyclone Gabrielle is likely to have increased spawning habitat for this species.

Further chronic effects from increased sedimentation include impacts on the feeding, growth, and condition of fish. Negative impacts of suspended and deposited sediment on the growth and condition of brown trout and rainbow trout are well documented (e.g. Sweka & Hartman 2001; Suttle et al. 2004; Ramezani et al. 2014; Greer et al. 2015, and reviewed by Depree et al. 2017). In contrast, there are few studies on the impacts of elevated sediment levels on the feeding and growth of native fish species. Rowe and Dean (1998) found that the feeding rates of juvenile banded kōkopu, smelt, īnanga, and common bullies in experimental tanks declined as turbidity increased, which may lead to reduced growth if conditions persist. In contrast, Rowe et al. (2002) found no significant trend in feeding rates for smelt over a turbidity range of 0–160 NTU. Rowe et al. (2009) also found no mortality or signs of physiological stress in smelt exposed to suspended sediment levels of 1,000 g/m^3 for 4 hours every 2 to 3 days across a 2- to 3-week period. Presently, there is little knowledge of the chronic effects of increased sedimentation on the health of native fish, meaning that we cannot predict long-term chronic impacts, if any, attributable to Cyclone Gabrielle.

4.4.3 Benthic invertebrate response

Benthic macroinvertebrate communities exhibited resilience to and/or rapid recovery from the effects of Cyclone Gabrielle. While physical sampling data showed significant shifts in community composition immediately after the cyclone and in the intervening year, both eDNA and physical sampling data indicated that community composition was comparable to pre-cyclone composition by the following summer. Similarly, rapid recovery has been reported following extreme flow events in other New Zealand rivers and worldwide, with most assemblages returning to pre-disturbance states within 12 months (Scrimgeour & Winterbourn 1989; Niemi et al. 1990; Suren & Jowett 2006; Death 2008; Mundahl & Hunt 2011; Woodward et al. 2015; Smith et al. 2019; Gholizadeh 2021; Townsend 2024). It has been noted, however, that population densities often take longer to recover than community composition and structure (Mundahl & Hunt 2011).

Floods affect benthic macroinvertebrates in three ways. First, increased shear forces can dislodge invertebrates from the streambed or force them to seek refuge among substrates or in the drift (Bond & Downes 2003; Death 2008). Second, bed movement and overturning of large substrate disrupts habitat and scours macroinvertebrates and periphyton (Death 2008). Third, floods can result in increased suspended and deposited sediment (Wohl et al. 2015). Based on macroinvertebrate sampling, formerly pristine streams have been reported to have water quality indicative of severe pollution immediately following an extreme flood, despite no other disturbance occurring (Smith et al. 2019; Gholizadeh 2021).

Macroinvertebrate community composition in the samples collected immediately following Cyclone Gabrielle had distinctly different community composition compared to the annual monitoring samples from the previous 5 years. Differences in pre- and post-cyclone composition were larger in more disturbed sites, suggesting that the observed changes were associated with cyclone impacts. Macroinvertebrate community composition based on the presence of taxa in eDNA samples varied less between sites that differed in their level of catchment disturbance. This may indicate that the observed differences in composition from the physical samples were primarily due to changes in relative abundance, not species loss or turnover.

Comparison of pre-cyclone eDNA and SoE monitoring data confirmed that communities across all sites had initially been similar across disturbance classes, although sites in low- and medium-disturbance catchments had greater dispersion, or variation in composition among sites, than sites in catchments classified as high disturbance. This is probably attributable, in part, to the smaller number of sites in catchments with high disturbance (three, compared to 14 in catchments with medium disturbance and nine in catchments with low disturbance).

Macroinvertebrate community metric scores were lower after the cyclone in sites and catchments classified from aerial imagery as having high cyclone disturbance (slips and sediment). This indicates that shifts in community composition were associated with losses of sensitive taxa. However, community composition in most sites shifted back towards the pre-cyclone state during the year. Given that only summer data were available from before the cyclone for comparison, it was not possible to discern the proportion of variation observed in the post-cyclone samples that was due to seasonal fluctuations in community composition vs cyclone disturbance.

Strong seasonal effects are common in temperate freshwater systems (Woodward et al. 2002). Seasonality can result from changes in precipitation, flow, habitat size (i.e. cross-sectional area), and temperature (Calderon et al. 2017), all of which serve as cues for growth and development, emergence, and reproduction of many macroinvertebrate species (Calderon et al. 2017). In the Glenfinish River in Ireland, a 13-year study spanning a series of nine extreme flow events, including a 1-in-50-year flood, found that 15.3% of the total variability was associated with seasonal effects and 10.4% related to interannual variability from flooding (Woodward et al. 2015).

By contrast, Suren and Jowett (2006) found that flow had a stronger effect than season on macroinvertebrate densities in the flood-prone Waipara River, although season was also a significant predictor. However, Suren and Jowett (2006) highlighted that many New Zealand macroinvertebrate species do not have clear seasonal life cycles (i.e. distinct cohorts), which may partly explain the reduced influence of seasonal effects in their study. The community composition in the low-impact Hawke's Bay sites remained similar across sampling occasions, which could indicate a lack of strong seasonal effects. This finding indicates that the observed shifts in community composition in high-impact sites are more than likely to be due to impacts from Cyclone Gabrielle rather than seasonal variation.

The eDNA-based MCI (eMCI) scores were generally lower than MCI scores for the same site, due to increased taxonomic resolution of low-scoring taxa in the eDNA-based data, such as oligochaetes, which are aggregated as a single taxonomic group in MCI calculations. As a result, metric values are not directly comparable between the two data sets, although the overall trends can be compared. The eMCI showed the same initial response as MCI: a decline in scores immediately after the cyclone (autumn 2023 sampling) in sites with high catchment disturbance. However, by the following summer of 2023/24, average eMCI scores were like those from samples taken before Cyclone Gabrielle, whereas MCI scores remained low in sites with high catchment disturbance. The eMCI results align with the recovery trajectory analyses for both the eDNA and physical samples, which showed that most communities had largely returned to pre-cyclone composition by January 2024.

Conversely, the TICI (Taxon Independent Community Index, which includes all aquatic organisms, not just macroinvertebrates) increased after the cyclone in both low- and high-disturbance catchments, whereas it showed no change in medium-disturbance catchments. The initial increase in TICI scores in April 2023 could indicate an influx of terrestrial eDNA into rivers and streams in highly disturbed catchments immediately following Cyclone Gabrielle, consistent with high amounts of overland flow and erosion in these sites. However, if that were the case, scores could be expected to decline again under normal flow conditions, whereas TICI scores remained high the following summer. Given the contrasting results of TICI scores with fish and macroinvertebrate responses, other organisms could be driving the TICI response. The TICI is a relatively new index (Wilkinson et al. 2024) and further investigation of results is warranted to understand the drivers of scores before and after the cyclone.

Given the widespread erosion and number of slips and landslides caused by Cyclone Gabrielle, sediment impacts on stream ecosystems and biota were a key concern motivating the freshwater component of this project. Progressive declines in suspended inorganic sediment (SIS) were observed across almost all medium- and high-catchment disturbance sites during the year following the cyclone. In the absence of pre-cyclone sediment data, we assume this indicates that initial post-cyclone SIS levels were above the equilibrium routinely found in these systems, and that the excess sediment was introduced during the cyclone.

Suspended sediment reduces visibility and light penetration, and increases the release of adsorbed contaminants such as nutrients, heavy metals, and pesticides (Bilotta & Brazier 2008). Numerous studies have shown that high suspended sediment concentrations are associated with increased macroinvertebrate drift rates and reduced population densities (Bilotta & Brazier 2008; Depree et al. 2017), but not lethal effects (Suren et al. 2005). Gholizadeh (2021) also reported sharp declines in EPT taxa richness associated with increased suspended sediment loads following extreme floods in the Zarin Gol River in northern Iran.

The effects of deposited fine sediment on macroinvertebrate communities are largely known from studies on sediment inputs from agricultural land, rather than acute effects from flood inputs (Jones et al. 2012; Brooks et al. 2021; Davis et al. 2024). Deposited sediment can smother periphyton, reducing algal growth and biomass and diminishing its quality as a food source (Graham 1990; Izagirre et al. 2009; Brooks et al. 2021). Filling of interstitial spaces reduces access to refugia from predation and high flows (Jones et al. 2012) and buries eggs, reducing hatching success and recruitment rates (Kefford et al. 2010; Brooks et al. 2021). Fine sediment can also clog macroinvertebrate gills and feeding structures (Broekhuizen et al. 2001; Peeters et al. 2006; Larsen & Ormerod 2010; Brooks et al. 2021). Sediment also frequently interacts with or exacerbates the effects of other co-occurring stressors, such as nutrients (Wagenhoff et al. 2012) and temperature (Pigott et al. 2015).

Deposited fine sediment is frequently associated with declines in pollution-sensitive EPT taxa and increased abundance of Diptera, particularly chironomids, as well as oligochaetes and other burrowing taxa (Jones et al. 2012; Wagenhoff et al. 2012; Burdon et al. 2013; Depree et al. 2017). Subsidy-stress or threshold relationships are frequently reported. For example, Burdon et al. (2013) found that the proportion of EPT declined sharply above 20% fine sediment cover, while Wagenhoff et al. (2012) saw an increase in total macroinvertebrate density at low levels of fine sediment, but a decline in EPT when deposited sediment cover exceeded 10%. Wagenhoff et al. (2012) also found a 70% increase in the density of oligochaete worms at c. 90% fine sediment cover.

Effects on macroinvertebrate predators are unclear. Increases in the relative abundance of predatory species were observed in a mesocosm experiment following sediment additions (Pigott et al. 2015), but a field study of macroinvertebrate communities in four streams across a gradient of deposited sediment reported the opposite trend (Rabení et al. 2005).

In our study, losses of EPT taxa and shifts in community composition towards chironomids and worms, but not predators, were observed in the medium- and high-catchment-disturbance sites immediately after Cyclone Gabrielle, supporting the hypothesis that sediment deposition was a key driver of the observed changes in macroinvertebrate communities. EPT taxa richness and relative abundance actually increased in low-disturbance sites immediately following the cyclone, but declined again to pre-cyclone levels over the course of the year. This somewhat surprising result could reflect increased drift from upstream habitats due to high flows during the cyclone, but lack of successful colonisation by drifting organisms due to unsuitable habitat, predation, or competition for resources.

The life histories of the taxa present may also influence community-level responses to disturbance. Woodward et al. (2015) found that small-bodied taxa with short generation times were either less affected, or recovered more rapidly, from a flood disturbance than larger-bodied taxa that reproduce less rapidly. Chironomids typically have two generations per year in New Zealand streams, whereas many EPT taxa only have one (Scarsbrook 2000). Large predators such as Archichauliodes (dobsonflies) and stoneflies have longer life cycles spanning multiple years (Scarsbrook 2000). Thus, the rapid post-cyclone increase in chironomids was probably not only due to their sediment-tolerant status but was also a reflection of their capacity for more rapid population growth.

Recovery of macroinvertebrate communities depends on recolonisation through drift or relocation of adults during emergence and egg deposition (Death 2008; Calderon et al. 2017). Upstream crawling has been shown to contribute little to the recolonisation of newly available habitats by many EPT taxa (Graham et al. 2017). Sources of potential colonists include survivors of the disturbance from within interstitial refugia and headwater refugia (Lake 2013; Bond & Downes 2003; Calderon et al. 2017). In the case of Cyclone Gabrielle, the filling of interstitial refugia with fine sediment may have delayed or hindered recolonisation of highly disturbed sites, so the headwater streams that were less affected by sediment deposition will probably be the main source of colonists for the rest of the region. However, it is important to note that headwater streams also have steeper gradients and will probably have been highly affected by bed movement during the cyclone event, resulting in increased macroinvertebrate downstream drift into potentially less favourable habitats with more sediment deposition.

4.4.4 Summary

Overall, fish communities recovered rapidly, with community composition in the following summer comparable to that of pre-cyclone communities. The resilience of fish communities and increased eDNA prevalence of the taonga species īnanga and smelt after Cyclone Gabrielle probably indicate that sufficient refuge (cover) habitats were present the following summer. In addition, the recovery of diadromous fish populations after Cyclone Gabrielle relies heavily on connectivity of habitats, which means that ensuring connectivity to and availability of refuge habitats during times of high flows is critical to the resilience of migratory species and non-migratory fish displaced during extreme weather events. Here, the replacement or remediation of instream structures (e.g. culverts) to increase their size and conveyance of high flows will help the recovery and resilience of fish populations.

The short-term presence and resilience of fish communities 1 year after Cyclone Gabrielle does not preclude the occurrence of longer-term impacts that could not be examined in the present study. The direct impacts of deposited sediment on the inter-tidal vegetation used by īnanga as spawning habitat is a key threat to the continued abundance of īnanga in the Hawke's Bay region; monitoring and rehabilitation of spawning habitats will be required to ensure long-term persistence of this taonga species.

Macroinvertebrate communities showed distinct shifts in composition over the course of the year following Cyclone Gabrielle, but had largely recovered to pre-cyclone composition in all but the highest-impact sites by the following summer. The sites with the highest site and catchment disturbance based on aerial imagery also showed the largest initial shifts, as well as greater dissimilarity between successive samples. This suggests that compositional changes were at least partially associated with cyclone impacts (i.e. fine sediment deposition), in addition to seasonal variation. Moreover, this relationship also suggests that initial cyclone impacts could be predicted using remote-sensing, which could help direct remediation efforts after future extreme weather events, without the need for intensive field-based sampling. Declines in EPT taxa and increased dominance by sediment-tolerant taxa such as worms, snails, and chironomids in autumn 2023 after Cyclone Gabrielle indicated that increased sediment inputs were likely to be a key driver of the compositional shifts, due to deposited sediment reducing habitat and food availability and quality.

As with fish, the apparent recovery of macroinvertebrate communities by January 2024 does not preclude the possibility of longer-term impacts. If additional sediment inputs from slips and eroded banks in affected sites and catchments continues to occur in subsequent rainfall and flow events, longer-term shifts in composition towards sediment-tolerant communities are likely. Once sediment and/or compositional thresholds are crossed, hysteresis and biological resistance to restoration may inhibit recolonisation by rarer and more sensitive taxa (Lake 2013; Barrett et al. 2021). Impacts on recruitment and recolonisation may not become apparent for several more years, given the 1-year life cycle of New Zealand macroinvertebrates.

Overall, we found that fish and macroinvertebrate communities were resilient to the impacts of Cyclone Gabrielle, with biodiversity recovering by summer 2024. However, the study design was not able to examine chronic, sub-lethal effects that result in long-term changes to fish and macroinvertebrate species' abundance and population structure. Continued monitoring of the study sites will enable abundance data and the size classes of fish species to be examined to ensure consistent recruitment is occurring. In addition, we focused on sediment as a proxy for disturbance impacts from Cyclone Gabrielle because of the importance of sediment in defining fish and macroinvertebrate populations, and because quantitative data on sediment were collected from 25 of 26 macroinvertebrate survey sites. This does not preclude impacts observed in fish and macroinvertebrate populations being driven from bed movement, hydrological changes or other mechanisms. However, quantitative, site-specific data on these variables were not available.

Recovery of aquatic fauna following major disturbances such as Cyclone Gabrielle can be a prolonged process, with full restoration often taking years – if not decades. Continuous monitoring will be critical to understanding how aquatic biota respond to environmental change. This is particularly important in distinguishing the recovery dynamics of different species and ecosystems, including threatened species and uncommon ecosystems. Freshwater monitoring should include a focus on īnanga spawning habitats, as these are vital for the life cycle of the species and may have unique recovery trajectories.

In addition, long-term monitoring should employ both traditional methods (such as electric fishing surveys) to better understand fluctuations in relative abundance along with important community structure metrics (e.g. size classes), and modern techniques (like eDNA sampling and associated eDNA-based metrics such as eMCI and TICI) to provide a comprehensive assessment of aquatic communities.

To better understand the relationship between abiotic conditions and aquatic fauna communities, we recommend continued collection of instream sediment samples alongside sampling of macroinvertebrate and fish communities. Such a comprehensive monitoring and research framework will not only help in the recovery of affected species and habitats, but will also provide valuable data for future conservation and management efforts.

4.5 Recommendations

We examined the recovery of fish and macroinvertebrate community structure in Hawke's Bay streams and rivers 1 year after Cyclone Gabrielle. Freshwater fish communities recovered rapidly, with biodiversity recovering to pre-cyclone levels the following summer. However, habitat alteration may lead to long-term changes in fish community composition and abundance. To reduce the ongoing impacts from Cyclone Gabrielle on fish populations, we recommend the following management interventions:

4.5.1 Connectivity

For fish populations, ensuring connectivity to and availability of refuge habitats during times of high flows is critical to the resilience of migratory and non-migratory fish species displaced during extreme weather events. The replacement or remediation of instream structures to increase their size and subsequent conveyance of high flows will help the recovery and resilience of fish populations. In addition, enhancing instream habitat heterogeneity will lead to increased refuge habitats during extreme weather events. Following are recommended management actions.

- Use the Barrier Assessment Reporting Tool (BART) to prioritise high-risk instream structures for remediation.
- For high-priority structures, carry out regular (annual) visual observations, alongside assessments using the Fish Passage Assessment Tool (FPAT), to determine temporal changes in the risk to fish passage each structure presents as the cyclone's impacts

reduce. Any increase in the risk score should initiate remediation to protect connectivity of upstream habitats.

- Establish riparian buffer zones where they are currently lacking. Inputs of instream woody debris will enhance instream habitat heterogeneity, resulting in the retention of refuge habitat for fish. Emergent large wood can also serve as critical oviposition habitat for several species of caddisflies (Smith & Storey 2018) and accumulates leaf litter to form debris dams, key habitats for recolonisation by drifting macroinvertebrates (Lancaster & Downes 2017). Buffer widths should be at least the maximum tree height to ensure an adequate and ongoing source of wood to the channel; in general, wider buffers will produce greater volumes of wood (Meleason & Hall 2005).

4.5.2 Sediment

Improving land-use practices and management to retain sediment and reduce sediment ingress into streams during extreme floods will increase the long-term resilience of fish and macroinvertebrate populations. Reduction of sediment within streams is important for protecting critical spawning habitats and reducing potential chronic effects from extreme weather events on the feeding and growth of fish species. Reducing sediment deposition along riparian margins is important for protecting refuge habitats and spawning habitats for galaxiids (e.g. īnanga and banded kōkopu). Establishing significant buffer zones of native vegetation around waterways will help reduce the impact of erosion and sedimentation in future extreme weather events. To stabilise banks, plants should be chosen with rooting depths equivalent to or greater than the bank height (Fenemor & Samarasinghe 2020).

4.5.3 Īnanga spawning habitat

Monitoring

Monitoring the recovery time of key īnanga spawning habitats is important for understanding the potential impacts on the Hawke's Bay populations in the medium and long term. The two known īnanga spawning habitats in Huramua Stream and Awatere Stream in the lower Wairoa River should be examined annually in May for īnanga spawning. The critical microhabitat within intertidal vegetation should be surveyed following the methods used in our study. This will determine the timeframe taken for vegetation stem density and aerial root mat depth to recover to the thresholds required for egg survival (Hickford et al. 2010).

Other īnanga spawning habitats were identified in the Tukituki River, Esk River, and Te Ngarue Stream by Rook (1994). These and any other recently discovered spawning sites in the region should also be monitored annually following the methods used in our study, including vegetation and egg surveys, to further document the recovery time of spawning habitats.

Rehabilitation

The documented īnanga spawning habitats in Huramua Stream and Awatere Stream should be protected and rehabilitated as far as practicable. Since 2016, surveys of the Wairoa River sites have identified certain issues that will prolong site recovery and reduce the effectiveness of the vegetation for supporting egg development. Based on the May 2024 survey, the following management actions are recommended:

Huramua Stream. The true left bank is currently not suitable to support īnanga spawning. The primary action required is to improve/install fencing to exclude grazers. The dense non-native vegetation near the waterline reduces the area of grass or rush growth that would provide suitable īnanga spawning conditions. While fencing could allow existing vegetation to recover, non-native plant control may also be necessary to increase the area available for spawning. Along the true right bank the existing fences provide adequate protection, and the site has suitable vegetation that should allow stem density and aerial root mat development to return with time.

Awatere Stream. The true right bank requires fencing and regular maintenance. The dense vegetation clumps currently suitable for spawning are sparse and widely spaced. While the site is heavily affected by sediment deposition, the vegetation was considered to have the potential to recover over time if grazing pressure is relieved through effective fencing.
On the true left bank, management is required to control the invasive Japanese honeysuckle and blackberry that are smothering more desirable vegetation for spawning. Re-establishing native grasses and rushes on the true left bank would create additional suitable spawning habitat.

Artificial spawning substrates. Hickford and Schiel (2013) discovered that īnanga will readily spawn on wheat-straw haybales, which provided the same microhabitat conditions as natural vegetation and resulted in high egg survival. Where natural spawning habitat was degraded, Hickford and Schiel (2013) found that artificial habitats were successful as a temporary means to augment natural egg production. Until vegetation density at īnanga spawning sites has recovered, artificial spawning substrates should be deployed following the guidelines of Hickford and Schiel (2013) to prevent population sinks from developing.

5 Conclusions and recommendations

Extreme weather events are simultaneously a destructive and a rejuvenating force for ecosystems. Cyclone Gabrielle is the first tropical cyclone where there has been a dedicated effort to systematically describe, quantify, and integrate impacts on native ecosystems of New Zealand.

The intense rainfall associated with Cyclone Gabrielle triggered large-scale erosion, especially of pasture and plantation forests (McMillan et al. 2023), while native vegetation experienced relatively minor impacts (section 2.1). Unlike some previous New Zealand cyclones (Martin & Ogden 2006; Platt et al. 2014), strong winds did not inflict extensive blow-down of native forest (section 2.2), although individual tree falls opened many canopy light gaps (section 2.3), providing opportunities for recruitment and release of seedlings and saplings, promoting forest regeneration.

The movement of sediment was one of the more identifiable impacts of Cyclone Gabrielle. Eroded sediment was transported to various ecosystems via floodwaters, threatening the loss of lowland forest fragments (section 3.1), decreasing wetland condition (section 3.2), preventing īnanga spawning (section 4), and altering habitat quality of streams and rivers for native birds (section 3.3 and section 3.6.1), freshwater fish and macroinvertebrates (section 4). Beyond the terrestrial and freshwater realm, other Extreme Weather Research Platform projects found that this massive flush of sediment and woody debris extended out to sea, significantly affecting biodiversity in marine ecosystems (Leduc et al. 2024; Roberts 2024).

Despite these immediate impacts from Cyclone Gabrielle, many of our native ecosystems exhibited resilience, implying underlying adaptation to extreme weather events. For example, vegetation cover of coastal active dunes was largely unaffected (section 3.4), freshwater fish and macroinvertebrate communities demonstrated rapid recovery to pre-cyclone composition after just 1 year (section 4), and flooded lowland forest fragments where stock were excluded showed potential for post-cyclone regeneration (section 3.1).

However, when viewed through the lens of historical and ongoing global change, the path to recovery remains uncertain for ecosystems and species facing a myriad of threats. For example, land-use change, habitat loss and fragmentation, browsing mammals, invasive plants, and other disturbances all have the potential to alter or prevent the recovery of New Zealand's ecosystems and species after extreme weather. A striking example of this was the relative absence of native woody saplings from lowland forest fragments where stock access was allowed (section 3.1). These interactions all occur under the pervasive threat of climate change, which exacerbated the rainfall of Cyclone Gabrielle (Harrington et al. 2023; Stone et al. 2024) and will continue to change extreme weather patterns, affecting species and ecosystems in ways that are challenging to predict (IPCC 2022).

As with several other Extreme Weather Research Platform (EWRP) research projects, our ability to assess the impacts of Cyclone Gabrielle depended on the availability of pre-cyclone baseline data. We used several types of pre-existing monitoring data in multiple ways. These included the use of previously established and newly established permanent forest plots, State of the Environment monitoring data that was collected by Regional Councils, and threatened species monitoring data collected by the Department of Conservation and other stakeholders. A key strength of some data sets was the standardised approach to data collection, which allows for comparisons to be made across sites and regions. It is also worth noting the value of long-term time series, which may allow the separation of 'state change' from 'business as usual' (Allen et al. 1999; Allen et al. 2003). We also highlight the value of monitoring across multiple ecosystems and/or regions, which can help to disentangle mortality from movement along with other spatial patterns in the impacts of large-scale disturbances such as extreme weather events.

Below we revisit our three objectives to summarise key findings and conclusions. We also present a suite of recommendations to be put into practice by the diverse group of stakeholders affected by extreme weather events, including regional councils, politicians and government departments, mana whenua, national trusts, businesses, community groups, schools, ecological consultants, land managers, and private landowners.

5.1 Conclusions

Objective 1: Identify changes in the extent and condition of vegetation cover of native ecosystems immediately after the cyclone.

- Native ecosystems, including forests, wetlands and active dunes, were largely resilient to the extreme weather of Cyclone Gabrielle. Overall impacts from flooding, erosion, and deposition were generally lower than 2% of mapped areas and tended to be higher on flat land and areas close to the lower reaches of river systems. However, localised severe impacts were observed across all ecosystems and their recovery should be monitored and managed.
- Wind impacts to native forest were low overall, mostly restricted to canopy stripping and individual tree falls, rather than widespread wind throw. The NDVI analysis based on satellite imagery showed promise for detecting areas of severe wind fall or canopy discoloration, but was less useful for identifying individual tree falls and requires further development to reduce noise and false positives.

Objective 2: Evaluate impacts on uncommon native ecosystems (lowland forest, wetlands, braided rivers, coastal active dunes), conservation infrastructure (ecosanctuaries), and threatened species.

- Deposited sediment was associated with tree dieback in lowland native forest fragments. Stock access will prevent forest regeneration in affected fragments, whereas fencing will promote regeneration but also non-native plant invasion.
- Wetlands experienced substantial inundation, but their condition remained largely resilient to the extreme weather, although a few suffered severe impacts from sediment deposition and damage to vegetation.
- Shorebird populations on Hawke's Bay braided rivers declined substantially after Cyclone Gabrielle. Braided riverbeds experienced increased cover of fine substrate after the severe flood event, while vegetation cover (mostly non-native species) decreased.
- No īnanga eggs were found in post-cyclone surveys of spawning habitats in Hawke's Bay, which appear slow to recover following extreme weather events.

- An average of 2.1 m (4%) of coastal active dune width was lost to erosion after Cyclone Gabrielle, with the largest declines observed in Bream Bay, Northland. Overall cover and native plant dominance of active dune vegetation was unchanged by the cyclone, although some species-specific changes were observed.
- Conservation infrastructure is vulnerable to extreme weather events. Damage to physical infrastructure was widespread and often associated with loss of access to management areas, disruption to pest control and native species monitoring, damage to restoration plantings, and decreased capacity of the conservation workforce. Of particular concern was widespread cyclone damage to pest fences, with rapid pest incursions detected in most cases. A rapid response is required to prevent the loss of hard-won conservation gains and to avoid ecosanctuaries and other conservation projects 'running to standstill'.
- Uncommon ecosystems and threatened species are especially at risk from extreme weather events due to their limited spatial distribution, low population sizes, and interactions with pre-existing threats such as habitat loss and fragmentation, invasive plants, and mammalian predators and browsers.

Objective 3: Quantify the resilience of resident fish and macroinvertebrate communities and recolonisation of migratory fish species, especially threatened taonga (e.g. īnanga, whitebait).

- Macroinvertebrate communities showed distinct shifts in composition during the year following Cyclone Gabrielle but had largely recovered to pre-cyclone composition in all but the highest-impact sites by the following summer.
- Freshwater fish communities recovered rapidly, with biodiversity recovering to be comparable to pre-cyclone levels the following summer. However, habitat alteration may lead to long-term changes in fish community composition and abundance.
- The short-term presence and resilience of fish communities 1 year after Cyclone Gabrielle indicate that sufficient refuge (cover) habitats were present the following summer.
- eDNA analyses indicated that taonga species richness increased after the cyclone, particularly annual species īnanga and smelt, which suggests that fish migration barriers were not limiting the recovery of populations.

5.2 Recommendations

To best protect New Zealand's ecosystems, species, and conservation assets, we must learn from the experiences of Cyclone Gabrielle, but crucially also embed these lessons into practice. To help guide preparation and response to future extreme weather events, we recommend the following actions be implemented by stakeholders, including regional councils, politicians and government departments, mana whenua, researchers, ecological consultants, land managers, national trusts, businesses, community groups, schools, and private landowners. Although many of these measures will be difficult and costly to implement, this further highlights the diversity and magnitude of challenges that extreme weather events pose to the natural environment:

5.2.1 General recommendations for native ecosystems

- Continue to protect and restore native forest, wetlands, and riparian vegetation, from high in catchments down to the floodplain, to increase the provision of flood and erosion mitigation services. Small wetland restoration may help with regular flood and erosion mitigation at higher elevations, but this should be combined with large-scale lowland wetland restoration to help manage extreme weather events. Buffers of native vegetation around waterways and wetlands can decrease impacts of erosion and sedimentation. Native vegetation should be planted to help stabilise existing landslides and secure areas vulnerable to future erosion. In high-risk areas, species planted should be carefully selected for resilience to wind, inundation, and sediment deposition. As much as possible, catchments should be managed holistically rather than focusing on individual sites.

- Continue to manage the many global change pressures that interact with extreme weather events, such as invasive plants and mammalian browsing. Disturbed ecosystems should be fenced to limit stock and ungulate access, promoting regeneration. Monitor for non-native plant invasions and act swiftly to prevent the establishment and spread of new and existing invasive species. Remove deposited sediment from around trees of threatened species or cultural importance to improve their chances of survival.

5.2.2 Recommendations for freshwater ecosystems

- Maintain and improve connectivity for freshwater species to provide refuge habitat and facilitate recovery and resilience after flood events.
- Deploy artificial spawning substrates to promote īnanga spawning and prevent population sinks from developing before riparian habitat has been restored.
- Continue non-native plant management in braided rivers to improve shorebird habitat.
- Increase predator management efforts along braided rivers, especially in areas known to host breeding native shorebirds, to offset the impacts of extreme weather events.

5.2.3 Recommendations for ecosanctuaries, conservation projects, and threatened species and ecosystems

- All stakeholder organisations should create, review, and regularly update their climate adaptation and disaster response plans. These should anticipate individual and collective risks from extreme weather to a range of terrestrial and aquatic ecosystems and species, with a focus on mitigating impacts. Protocols should also be developed for rapid implementation of post-disturbance monitoring, including early deployment of remote-sensing tools. Planning should consider preparation for ‘black swan events’, whereby multiple, low-probability, high-impact scenarios interact to exacerbate impacts on ecosystems.
- Non-charismatic and lesser-known species should be explicitly integrated into the ecosanctuary network. This would help to protect greater taxonomic and functional diversity, and to restore functioning and resilient ecosystems – a stated goal of many ecosanctuaries.
- To distribute risk, new and additional conservation translocations should be considered, especially for range-restricted and intractable species (i.e. species that continue to decline despite conservation efforts), including assisted migration beyond a species’ historical range.

- The conservation community should continue to improve capability, communication, and cooperation among diverse stakeholders to develop cross-project resilience across large spatial scales.
- A pest management buffer zone should be maintained around the boundary of pest fences to reduce pest densities and limit incursions if fences are damaged.
- A 'disaster response kit' should be assembled to facilitate rapid response and recovery after extreme weather events. This would be proportionate to ecosanctuary size and might include items such as traps, bait stations, tracking tunnels and trail cameras, temporary pest fencing and fencing materials, shovels, machetes, chainsaws, and other tools.
- Land managers should use cyclone warning periods to prepare several days in advance of storm arrival. Depending on priorities, resources, time available, safety, and likelihood of impacts, recommended preparation activities could include ensuring drains and slipways are clear, installing sandbags, stowing valuable infrastructure, securing or moving pest management equipment away from waterways and coastlines, establishing monitoring around predator-proof fences to rapidly detect incursions, and relocating species of high value. Human resources are also an important consideration, as many of the people who work in ecosanctuaries are also involved in Civil Defence and other emergency services. This includes alerting contractors to potential damage ahead of time so that critical infrastructure (e.g. pest fences) can be prioritised and rapidly repaired. These operating procedures should be developed and included as part of any project's disaster response plan.

5.2.4 Recommendations for data and long-term monitoring

- Continue to establish and/or maintain standardised monitoring programmes for at-risk species and ecosystems. Standardised, long-term monitoring across multiple independent sites is crucial for quantifying change in ecosystem condition and populations of threatened species, so that management responses in the aftermath of extreme weather events can be informed and effective. Standardised monitoring is particularly important for distinguishing natural variability from significant ecological changes resulting from the cyclone.
- A centralised, accessible database should be established for the storage and sharing of monitoring data. This will enhance coordination among researchers, conservationists, and policy-makers. Such a database will facilitate long-term monitoring of species and ecosystems, and improve our ability to detect and respond to ecological changes.

5.2.5 Recommendations for future research

- Continue to monitor the long-term impacts on, and recovery of, affected ecosystems. This will provide vital information on how the recovery of various ecosystems is influenced by modern pressures such as invasive plants, feral ungulates, and other disturbances, and under different management regimes.
- Reanalyse data from Sentinel-1 and -2 satellites, initially conducted by Dragonfly Data Science, to monitor the broad-scale temporal recovery of affected sites. This analysis can help link changes in freshwater suspended inorganic sediment levels to changes in landscape cover, offering valuable insights into the effects of sediment redistribution on aquatic habitats, and potentially developing additional remote-sensing tools to help

track recovery. Similar analyses could also be conducted with other remote-sensing data if they are available (e.g. assessing changes in forest canopy height using LiDAR).

- Further develop the spatial analysis methods employed in this report and other Extreme Weather Research Platform projects for rapid deployment following extreme weather events and other natural disasters. These remote-sensed approaches can be used to prioritise where to assess impacts and direct resources towards recovery. This would also necessitate improved coverage, accuracy and availability of maps for various ecosystems and threatened species, alongside planning for systematic ground-truthing following future extreme weather events.
- Carry out research to better quantify and understand the co-benefits and trade-offs of flood mitigation and other ecosystem services provided by wetlands, native vegetation, and other land-use types in New Zealand.
- Aim for future research to inform planning for which types of ecosystems to revegetate, and where, to optimise land-use, future resilience, and mitigation services. For example, maintaining detailed records of restoration activities (location, dates, species composition, spatial extent, etc.) will assist in future assessment of impacts to, and benefits from, riparian revegetation following future extreme weather events.
- Ensure future work investigating wind damage to forests incorporates a larger network of recently measured permanent plots across a broad spatial scale. Applying this approach after cyclones with extreme winds would help to improve future predictions of wind damage to different forest types and across a range of site and species.
- Further analyse lowland forest plot data to characterise forest regeneration potential, based on the soil seed bank and the composition of seedling, sapling, and mature plant communities. The lowland forest permanent plots that we established should be revisited after 5–10 years to assess long-term cyclone impacts and how recovery has progressed under different management regimes, compared to regeneration potential.
- Further analyse wetland State of the Environment monitoring data to assess post-cyclone changes in soil characteristics, and in plant diversity and composition. Future research should explicitly investigate the relationships between wetland condition and pressure index indicators, on the one hand, and measures of ecological integrity. This information will help translate changes in wetland condition and pressure indices to potential management actions that can be implemented in the field.
- Continue to monitor shorebird populations along Hawke’s Bay braided rivers and coastlines, and establish similar monitoring programmes in other regions. This approach will allow us to disentangle mortality from movement, and improve our understanding of how shorebird species respond to and recover from the impacts of extreme weather events.
- Further analyse coastal active dune monitoring data to place cyclone impacts in the context of long-term trends (i.e. by investigating state change across a longer time). Continued monitoring will illuminate whether dune width shows signs of post-cyclone recovery and could direct where active management is required to prevent further loss. While active dunes were one naturally uncommon ecosystem of focus in this report, their inclusion reflects the availability of data rather than where cyclone impacts necessarily occurred. We recommend supporting the work by Regional Councils to implement and maintain consistent and standardised monitoring of naturally uncommon ecosystems.

Such monitoring will provide crucial information on the condition of these ecosystems before and after extreme weather events or other disturbances.

- Conduct a spatial conservation risk assessment of threatened species and ecosystems under a range of natural disaster scenarios. This analysis would identify gaps in our understanding of which species and ecosystems are being managed and where, so that risk can be distributed spatially and swift action taken when a regional event is forecast.
- Carry out studies to understand how spatial connectivity influences recovery rates, including for terrestrial (i.e. lowland forests connected through seed dispersal) and freshwater (i.e. stream connectivity) ecosystems. Differentiating between recovery times for local disturbances and broader catchment-level disturbances will provide insights into the scale-dependent effects of cyclone events. It is anticipated that recovery from catchment-level disturbances may take longer due to the widespread nature of the impacts.
- Investigate the frequency of the monitoring required to disentangle natural variability from post-disturbance change across various ecosystems. For example, ecological monitoring of freshwater ecosystems is typically undertaken once annually over the summer period. This is suitable for SoE evaluations, but we found that the relatively coarse resolution of historical data limited our ability to distinguish between disturbance effects and seasonal influences in some freshwater impact assessments. Collecting more regular seasonal samples at a subset of monitoring sites, including both reference and non-reference sites, for 3–5 years, would help to establish baselines of expected seasonal and temporal variability, especially in highly dynamic freshwater ecosystems.
- Investigate in-stream structures susceptible to becoming fish migration barriers, resulting in long-term changes from extreme weather events. Continue to monitor and re-evaluate instream structures across Hawke’s Bay to assess how the threat of instream structures to fish movement changes as freshwater ecosystems recover from Cyclone Gabrielle, and as sediment levels return to pre-cyclone conditions.

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Appendix 1 – Spatial analysis

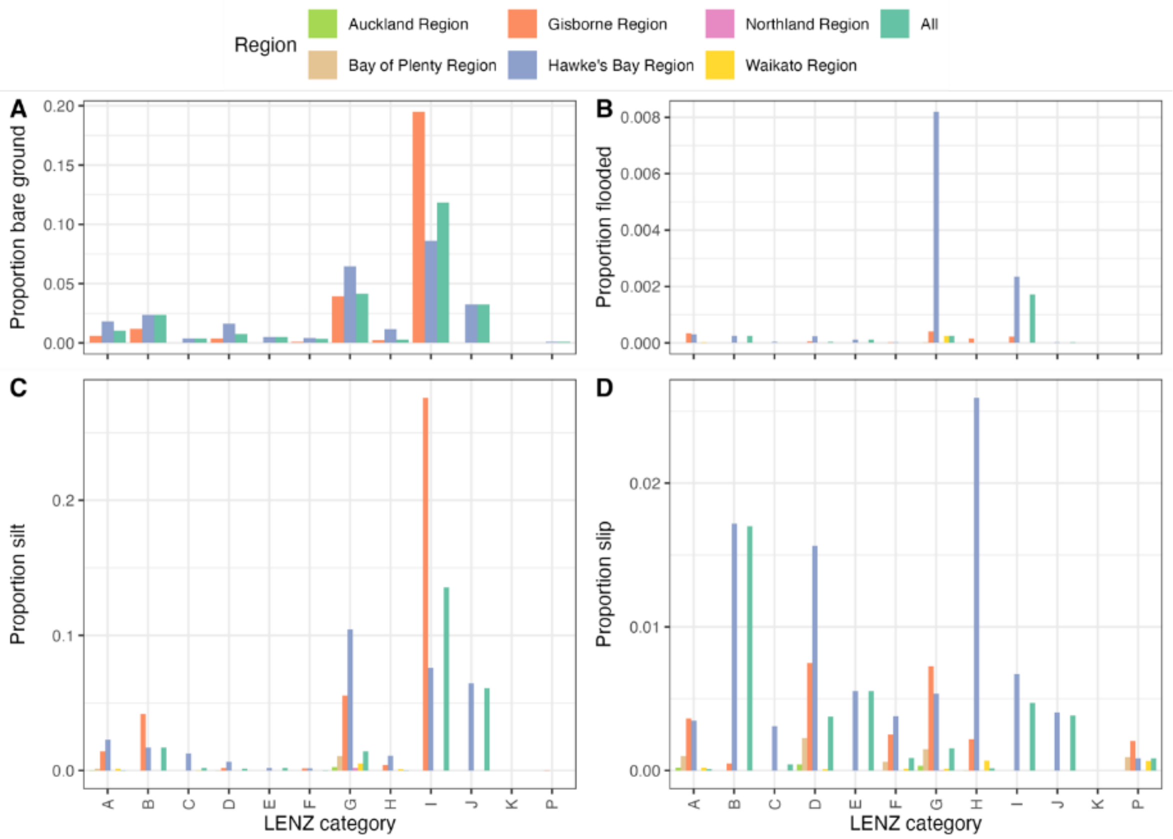

Figure A1.1. Proportion impact on mapped environment types (categories) from the Land Environments of New Zealand (Leathwick et al. 2002), within native woody vegetation from the Land Cover Database (LCDB), across the cyclone-affected regions of the North Island.

Notes: cyclone impact is based on two maps: (A) the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact ([B] flood, [C] silt, and [D] slip), based on the Dragonfly maps (Dragonfly 2023).

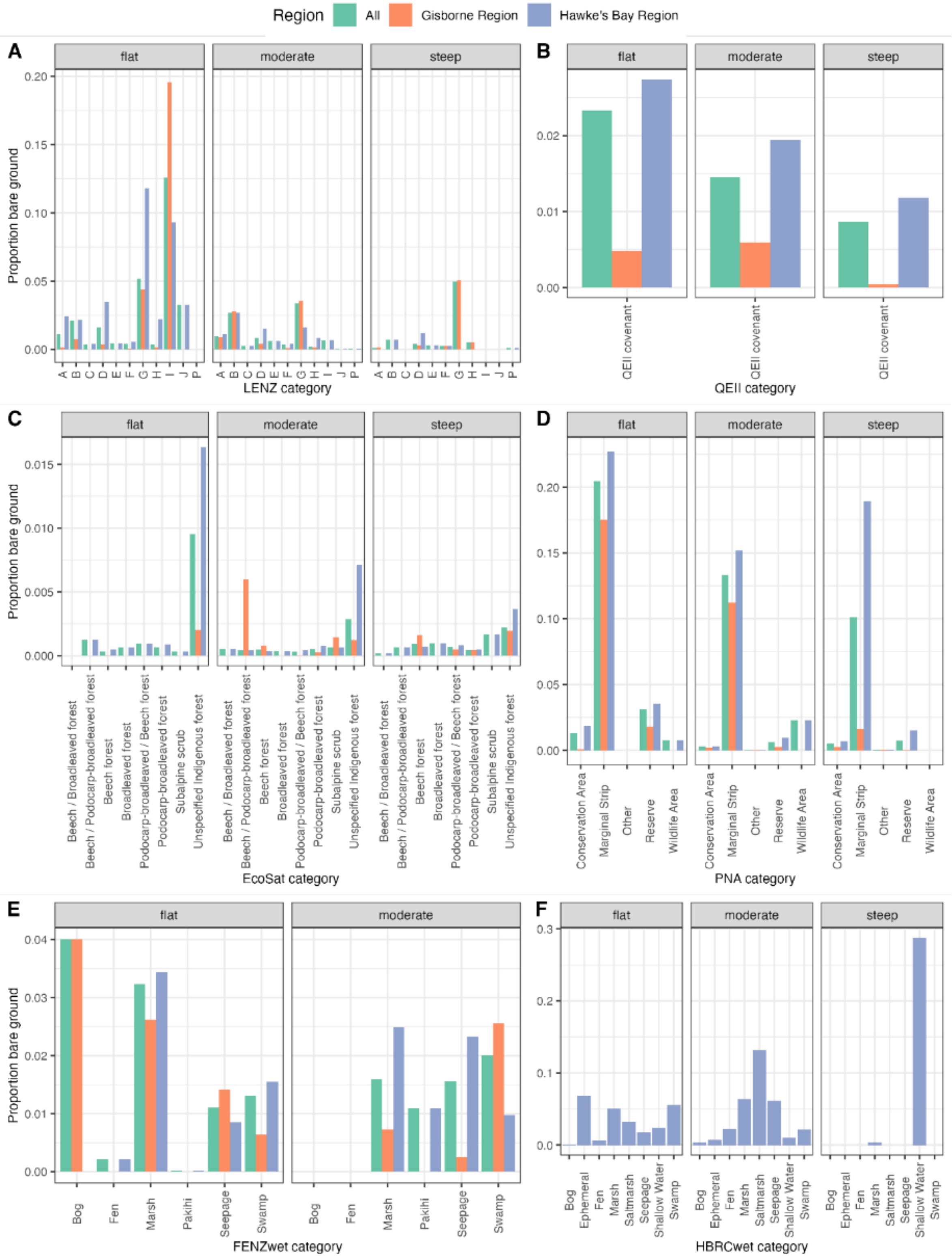

Figure A1.2. Proportion of native vegetation types affected across different slope classes.

Notes: Land Environments of New Zealand (Leathwick et al. 2002) environments (A) are restricted to areas that occur within native woody vegetation from the Land Cover Database (LCDB). Cyclone impact is based on the Manaaki Whenua – Landcare Research map (McMillan et al. 2023).

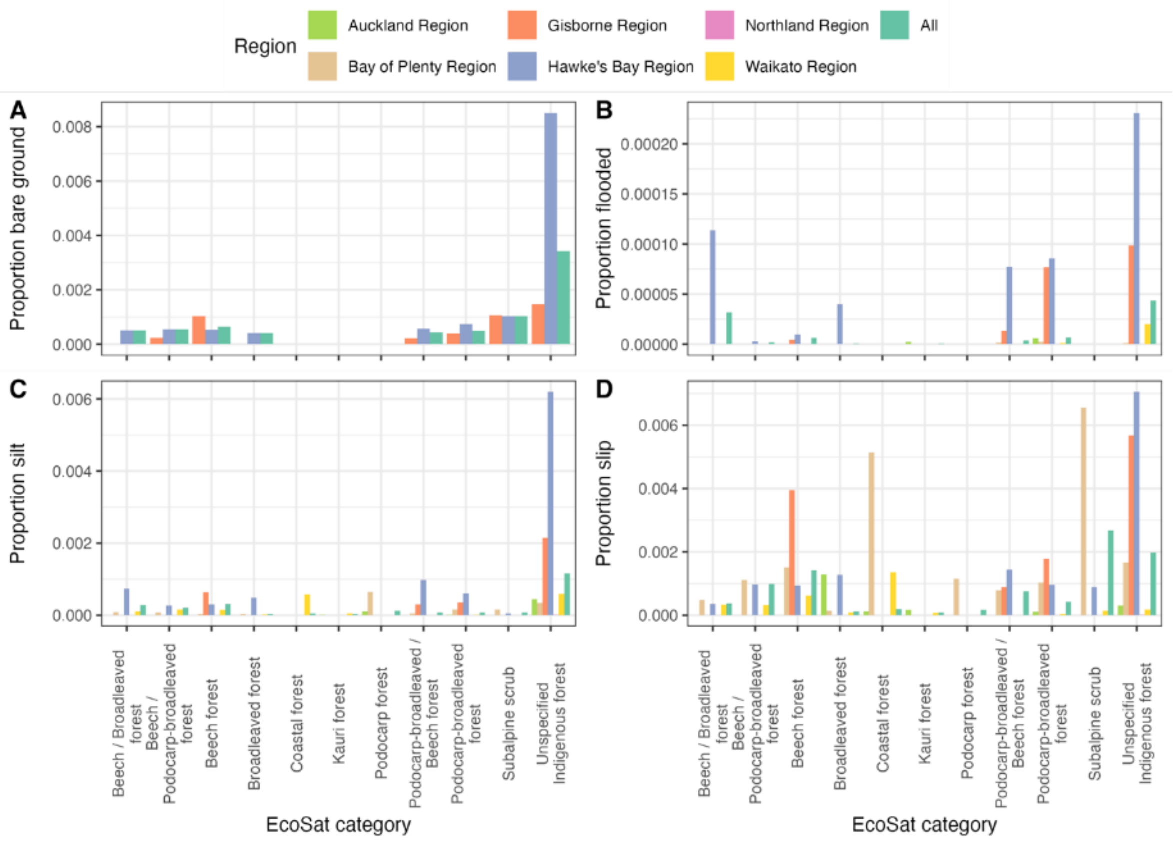

Figure A1.3. Proportion impact on native forest types mapped in EcoSat Forests (Landcare Research 2014) across the cyclone-affected regions of the North Island.

Notes: cyclone impact is based on two maps: (A) the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact ([B] flood, [C] silt, and [D] slip), based on the Dragonfly maps (Dragonfly 2023).

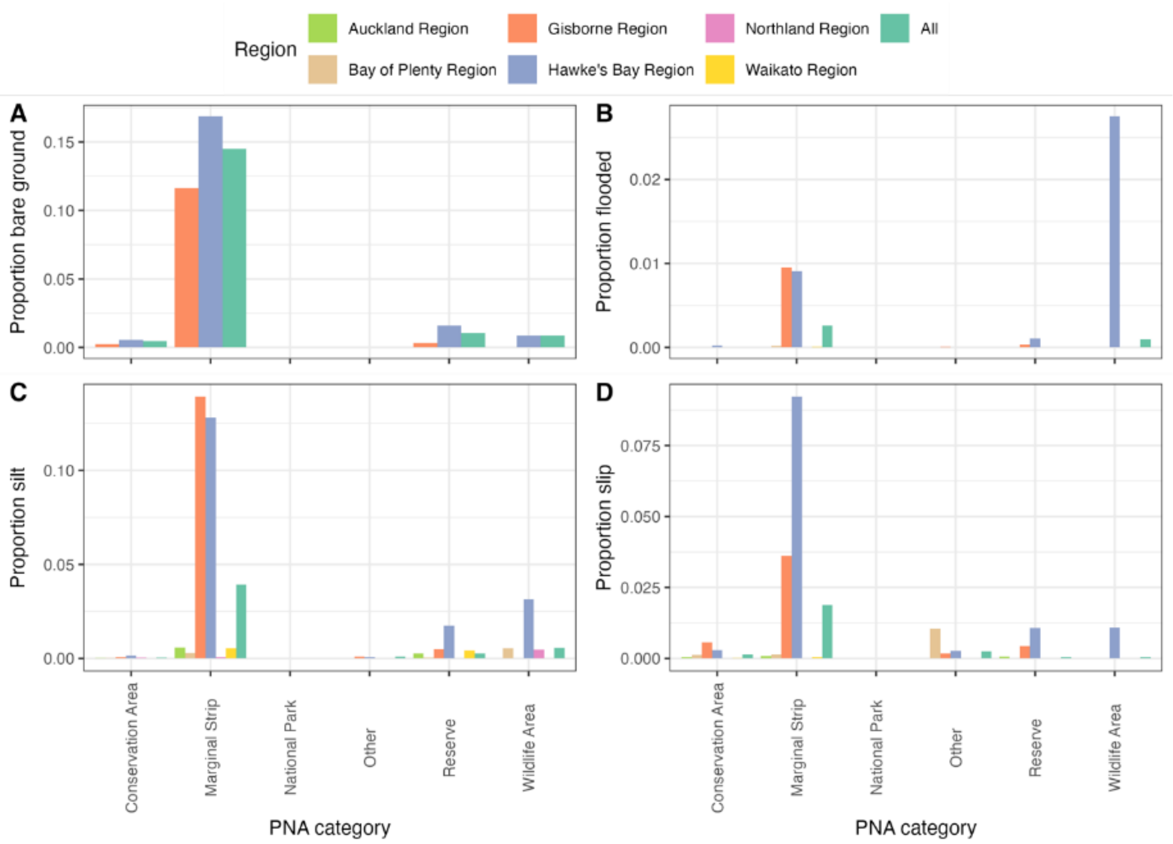

Figure A1.4. Proportion impact on categories from the Protected Areas of New Zealand (Department of Conservation 2023) across the cyclone-affected regions of the North Island.

Notes: cyclone impact is based on two maps: (A) the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact ([B] flood, [C] silt, and [D] slip), based on the Dragonfly maps (Dragonfly 2023).

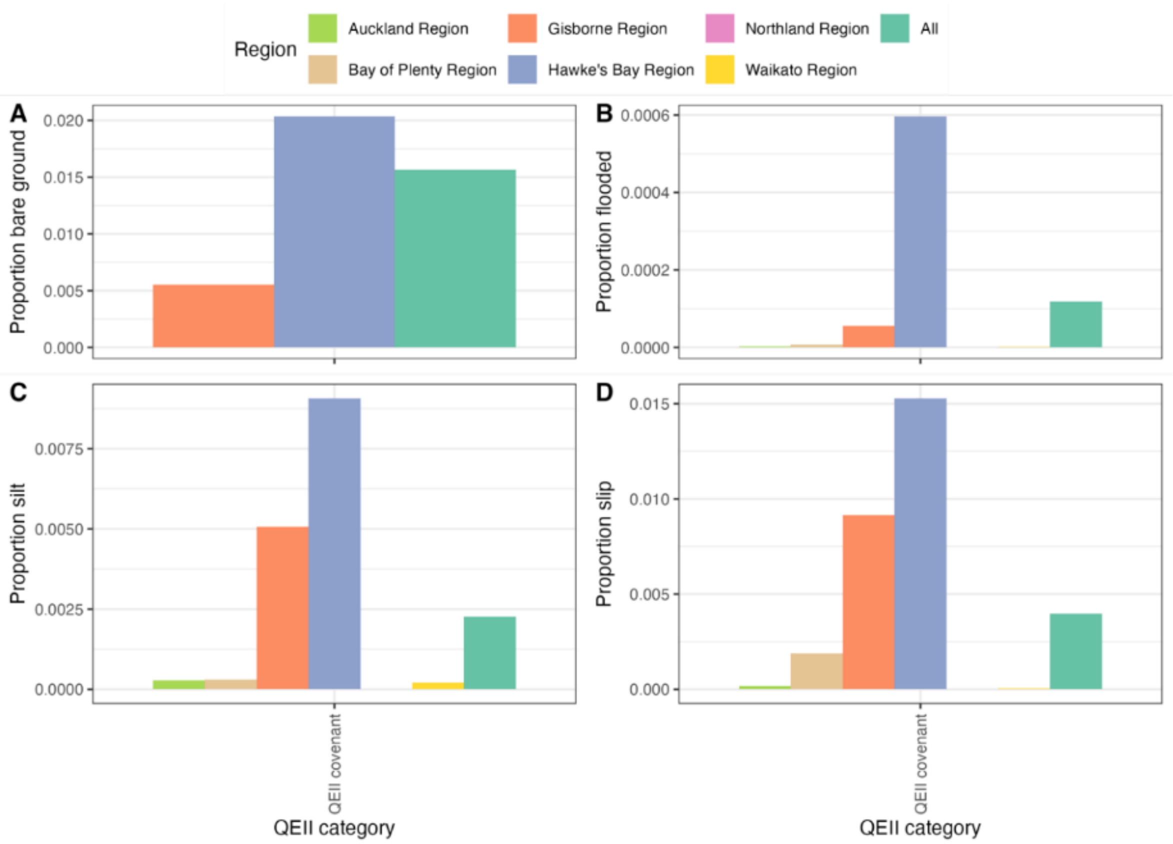

Figure A1.5. Proportion impact on QEII covenants (QEII National Trust 2023) across the cyclone-affected regions of the North Island.

Notes: cyclone impact is based on two maps: (A) the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact ([B] flood, [C] silt, and [D] slip), based on the Dragonfly maps (Dragonfly 2023).

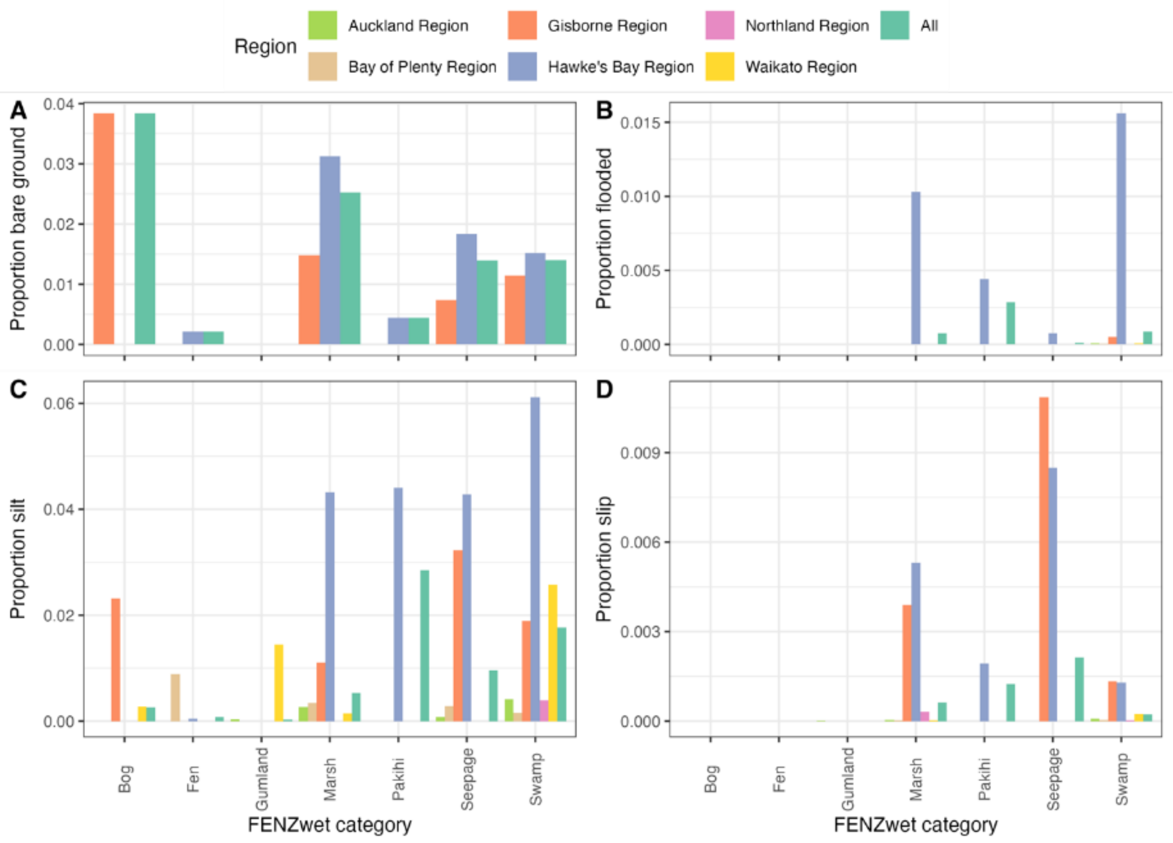

Figure A1.6. Proportion impact on wetlands mapped in the Freshwater Environments of New Zealand (Department of Conservation 2010; Leathwick et al. 2012) wetlands spatial layer across the cyclone-affected regions of the North Island.

Notes: cyclone impact is based on two maps: (A) the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact ([B] flood, [C] silt, and [D] slip), based on the Dragonfly maps (Dragonfly 2023).

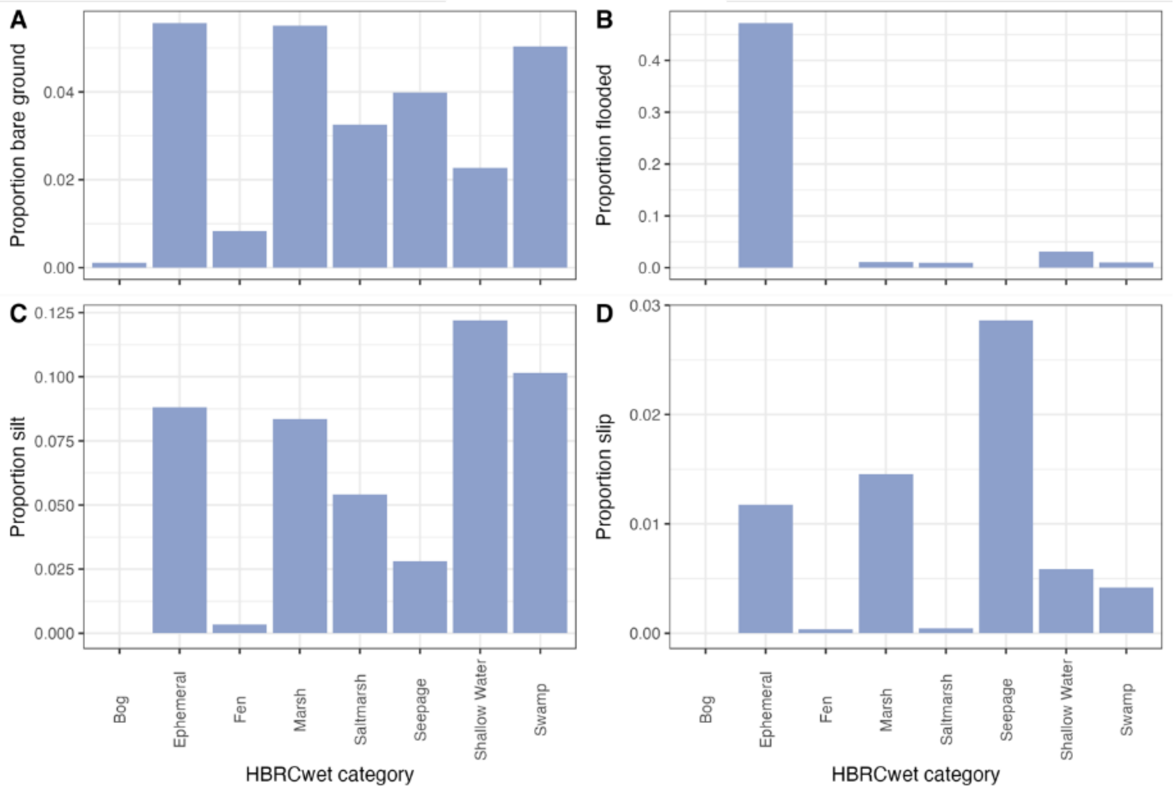

Figure A1.7. Proportion impact on wetlands mapped in the Hawke's Bay Regional Council wetlands spatial layer (Hawke's Bay Regional Council 2023).

Notes: cyclone impact is based on two maps: (A) the Manaaki Whenua – Landcare Research map (McMillan et al. 2023), and three types of impact ([B] flood, [C] silt, and [D] slip), based on the Dragonfly maps (Dragonfly 2023).

Appendix 2 – Hawke's Bay lowland forest rapid assessment

Table A2.1. Observations of Cyclone Gabrielle impacts on Hawke's Bay lowland forest fragments, visited during 3–12 August 2023

Forest fragment	Latitude	Longitude	Observed cyclone impacts
Waipātiki Scenic Reserve	–39.2950	176.9704	Walked out and back along a couple of tracks for a total of 1 hour. The stream running alongside the native forest had burst its banks and sediment was deposited up to a few metres out from each bank. The rapid increase in elevation meant that deposition in the forest was minimal and isolated to lower-lying areas of the reserve. Lots of nīkau palm (*Rhopalostylis sapida*) fronds and general woody debris observed on the forest floor, but no obvious slips or major tree falls.
Māhia Peninsula Scenic Reserve	–39.1248	177.8745	Walked the loop track, which took around 90 minutes. Evidence of minor flooding of a small creek, with some deposition of sediment around banks, but not extending into the forest. One minor slip of around 10 m^2 observed alongside the track. A handful of small to medium trees down, but only a couple of tree falls creating small canopy gaps.
Morere Springs Scenic Reserve	–38.9841	177.7949	Walked the nīkau loop track and part of the ridge track for 1 hour. Observed a couple of uprooted trees and some general small woody debris, but no large patches of wind throw or slips observed. The stream did not appear to have flooded extensively. Mangakawa Track was closed due to tree falls and minor slips that were cleared by September 2023.
Ball's Clearing Scenic Reserve	–39.2715	176.4977	Walked the loop track, which took around 90 minutes. The only obvious cyclone impacts were a couple of large fallen trees, which barely created a canopy gap in the forest. There was minor sediment deposition on the banks of the stream that runs through the reserve, spread up to a few metres along the forest floor and a few cm deep in places. The diversity and abundance of bird life in the forest was notable.
Elsthorpe Bush Scenic Reserve	–39.9188	176.8183	The cumulative rainfall from a particularly wet season had left a few areas of the loop track and forest waterlogged and muddy. Otherwise, there were few cyclone impacts observed during a 45-minute walk along the loop track.
Mohi Bush Scenic Reserve	–39.8575	176.9030	Walked the short loop track, which took 1 hour. The small stream through the reserve had flooded and there was some sediment deposition up to 5 m either side of the stream. One large rimu (*Dacrydium cupressinum*) tree had blown down, creating a significant canopy light gap, but otherwise few wind impacts were observed.

Appendix 3 – Wetland condition/pressure indices and elevation

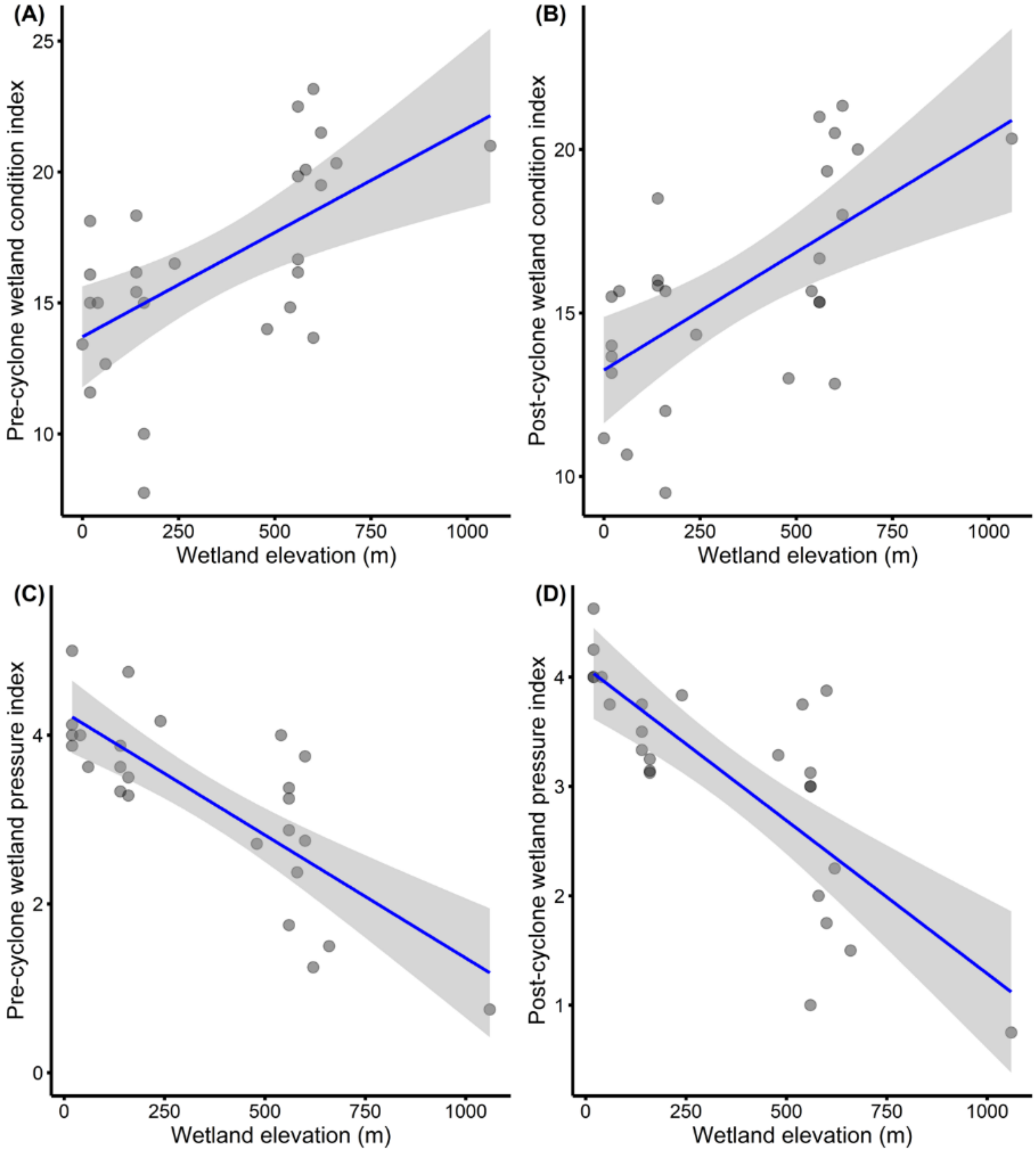

Figure A3.1. Relationships between the elevation of Hawke's Bay wetlands and their wetland condition index score pre-cyclone (A) and post-cyclone (B), and their wetland pressure index score pre-cyclone (C) and post-cyclone (D).

Notes: all lines represent significant relationships ($P < 0.05$) and were fitted by least-squares regression (± 95% CI).

Appendix 4 – Sample locations for freshwater work

Table A4.1. Sampling site names and locations

Sites	Method ID	X	Y	Site ID
Tukituki River at Red Bridge	MCI_28	1936648	5596456	site_01
Tukituki River at Red Bridge	eDNA_33	1936648	5596456	site_01
Tukituki River at SH50	MCI_29	1886242	5573981	site_02
Tukituki River at SH50	eDNA_35	1886242	5573981	site_02
Makaretū Stream at SH 50	MCI_7	1883627	5565246	site_03
Makaretū Stream at SH 50	eDNA_36	1883627	5565246	site_03
Mangatarata Stream at Mangatarata Rd	MCI_12	1909615	5566427	site_04
Mangatarata Stream at Mangatarata Rd	eDNA_40	1909615	5566427	site_04
Mangarau Stream at Te Aute Rd	MCI_38	1932237	5601602	site_05
Poporangi Stream at Big Hill Rd	MCI_24	1894843	5610671	site_06
Poporangi Stream at Big Hill Rd	eDNA_22	1894843	5610671	site_06
Maraekakaho River at Kereru Road	MCI_14	1910656	5604828	site_07
Maraekakaho River at Kereru Road	eDNA_23	1910656	5604828	site_07
Mangaone River at Rissington	MCI_9	1920088	5627758	site_08
Mangaone River at Rissington	eDNA_28	1920088	5627758	site_08
Tutaekuri River at Lawrence hut	MCI_30	1896243	5636419	site_09
Tutaekuri River at Lawrence hut	eDNA_29	1896243	5636419	site_09
Esk Rv River Waipunga Bridge	MCI_3	1929066	5633471	site_10
Esk Rv River Waipunga Bridge	eDNA_4	1929066	5633471	site_10
Esk River at Berry Road	MCI_2	1927755	5650967	site_11
Esk River at Berry Road	eDNA_5	1927755	5650967	site_11
Mokomokonui Stream at Tartraakina Rd	MCI_17	1910660	5671733	site_12
Mokomokonui Stream at Tartraakina Rd	eDNA_3	1910660	5671733	site_12
Mohaka River U/S Taharua River	MCI_16	1883984	5669330	site_13
Mohaka River U/S Taharua River	eDNA_30	1883984	5669330	site_13
Waiau River at Otoi	MCI_32	1952049	5681075	site_14
Waiau River at Otoi	eDNA_41	1952049	5681075	site_14
Hangaroa River at Doneraille Park	MCI_4	1998637	5703026	site_15
Hangaroa River at Doneraille Park	eDNA_42	1998637	5703026	site_15
Wairoa River U/S Mangaaruhe	MCI_40	1986309	5685716	site_16
Wairoa River U/S Mangaaruhe	eDNA_44	1986309	5685716	site_16
Ngaruroro River at Kuripapango	MCI_19	1887046	5635682	site_17
Ngaruroro River at Kuripapango	eDNA_20	1887046	5635682	site_17
Mangapōike River at Suspension Bridge	MCI_10	1992220	5685615	site_18
Mangapōike River at Suspension Bridge	eDNA_43	1992220	5685615	site_18
Mangatutu Stream at Mangatutu Station Bridge	MCI_13	1905836	5629944	site_19
Ngaruroro River at Fernhill	MCI_18	1924648	5611122	site_20

Sites	Method ID	X	Y	Site ID
Tutaekuri River U/S Mangaone	MCI_31	1918337	5623112	site_21
Mangaone River at Dartmoor	MCI_37	1918024	5623397	site_22
Waikari River at Glenbrook	MCI_41	1947507	5659669	site_23
Ripia River U/S Mohaka River	MCI_26	1904044	5655344	site_24
Kopuawhara Stream at Railway Bridge	MCI_36	2020910	5670259	site_25
Waihua River at Waihua Valley Road	MCI_39	1969117	5667507	site_26
Mangaruhe Stream at Riverina Bridge	MCI_11	1984930	5684772	site_27
Papanui Stream at Middle Road	eDNA_32	1917845	5581603	site_28
Makaroro at Burnt Bridge	eDNA_34	1882711	5587199	site_29
Porangahau U/S Maharakeke Confl.	eDNA_37	1894522	5565990	site_30
Makaretu U/S Maharakeke Confluence	eDNA_38	1894348	5567463	site_31
Tukipo River U/S Makaretu Confluence	eDNA_39	1897349	5569138	site_32
Poukawa Stream Te Mahanga Road	eDNA_10	1921508	5594483	site_33
Poukawa Stream at Stock Road	eDNA_11	1925305	5598993	site_34
Irongate Stream at Riverslea Road	eDNA_12	1927999	5601858	site_35
Ngaruroro D/S HB Dairies	eDNA_18	1906939	5610235	site_36
Waitio Stream at Ohiti Road	eDNA_19	1918650	5610077	site_37
Ohara Stream at Big Hill Road	eDNA_21	1894339	5610777	site_38
Te Ngaru Stream	eDNA_49	1937453	5638898	site_39
Sandy Creek at Gauge Station	eDNA_47	1936137	5652892	site_40
Aropaoanui at Aropaoanui Road	eDNA_48	1943269	5645709	site_41
Waipunga at Pohokura Road	eDNA_1	1905420	5682822	site_42
Waiarua Strm U/S State Highway 5 culvert	eDNA_2	1904046	5683539	site_43
Mohaka D/S Ripia River Confluence	eDNA_16	1903485	5653867	site_44
Mohaka D/S Waipunga River Confluence	eDNA_17	1920255	5665678	site_45
Taharua Stream at Red Hut	eDNA_31	1885655	5669847	site_46
Triplex Creek at Triplex Hut	Fish_15	1873886	5590373	site_47
Poporangi Stream at Wakarara Road	Fish_11	1889107	5599813	site_48
Deep Stream at Old Taupo Coach Road	Fish_6	1926784	5645045	site_49
Te Ngarue Stream at DOC Reserve	Fish_2	1934544	5641214	site_50
Pākuratahi Stream U/S Gauging Station	Fish_10	1933841	5638126	site_51
Tamingimingi Stream	Fish_13	1932511	5636099	site_52
Tarere Stream at Devils Elbow	Fish_5	1934323	5646530	site_53
Kakariki Stream	Fish_7	1951879	5671230	site_54
Koaro Stream	Fish_8	1899099	5655484	site_55
Herehere Stream at Te Aute Rd	eDNA_13	1931645	5601484	site_56

Notes: Sites that had the prefix ‘MCI’ in the method ID indicate sites with macroinvertebrate sampling; method IDs with the prefix ‘fish’ were sampled with electric fishing machines; and method IDs with the prefix ‘eDNA’ indicate sites that had environmental DNA taken.

Appendix 5 – Supplemental figures from freshwater ecosystems

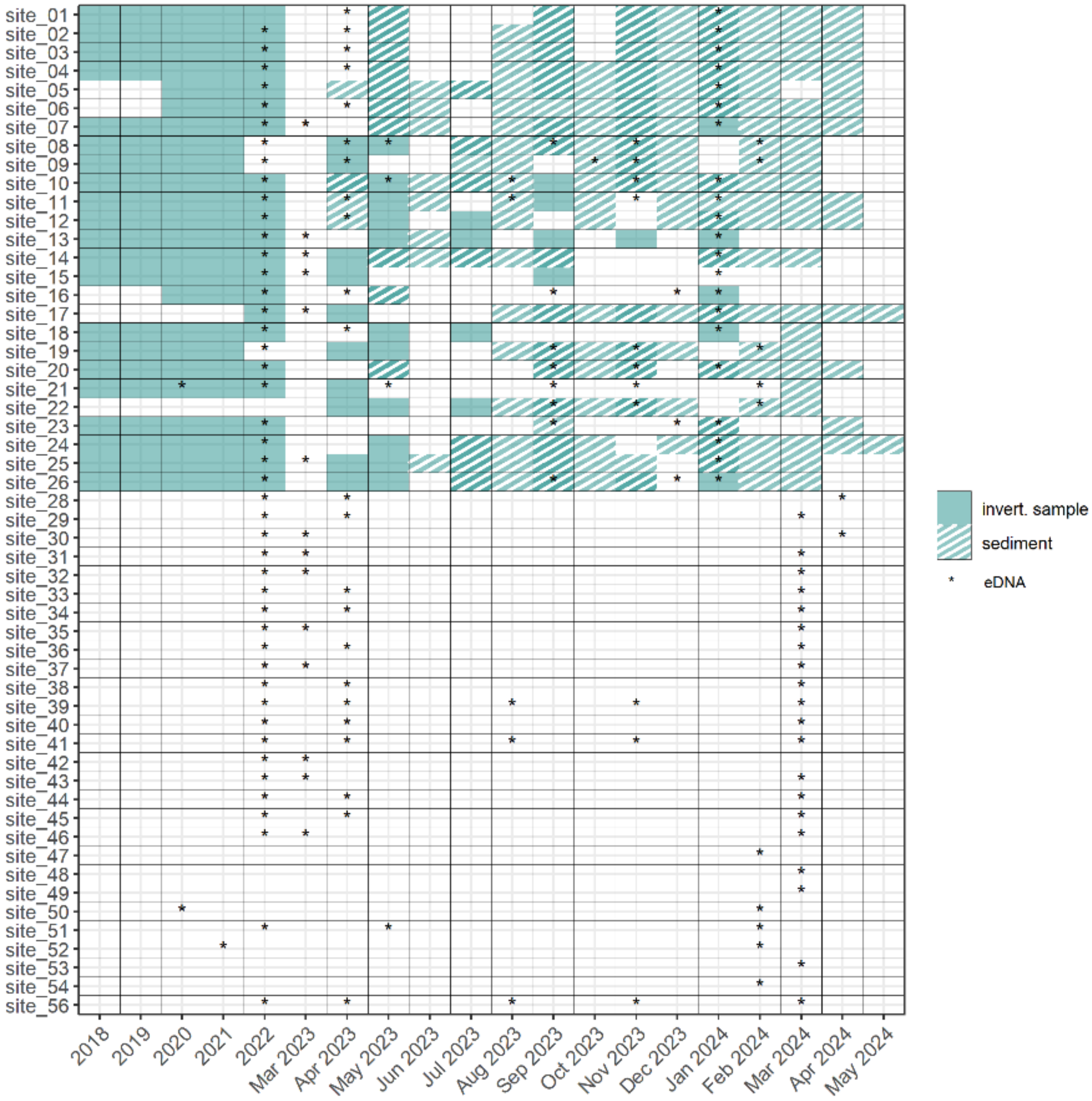

Figure A5.1. Macroinvertebrate and sediment sample collection at Hawke's Bay rivers and streams: annual SoE monitoring 2018–2022; March 2023 onwards post-cyclone sampling, approximately every 2 months for macroinvertebrates and approximately monthly for sediment.

Notes: fill indicates physical sample taken, stripes indicate SIS sample taken, asterisk indicates eDNA sample taken.

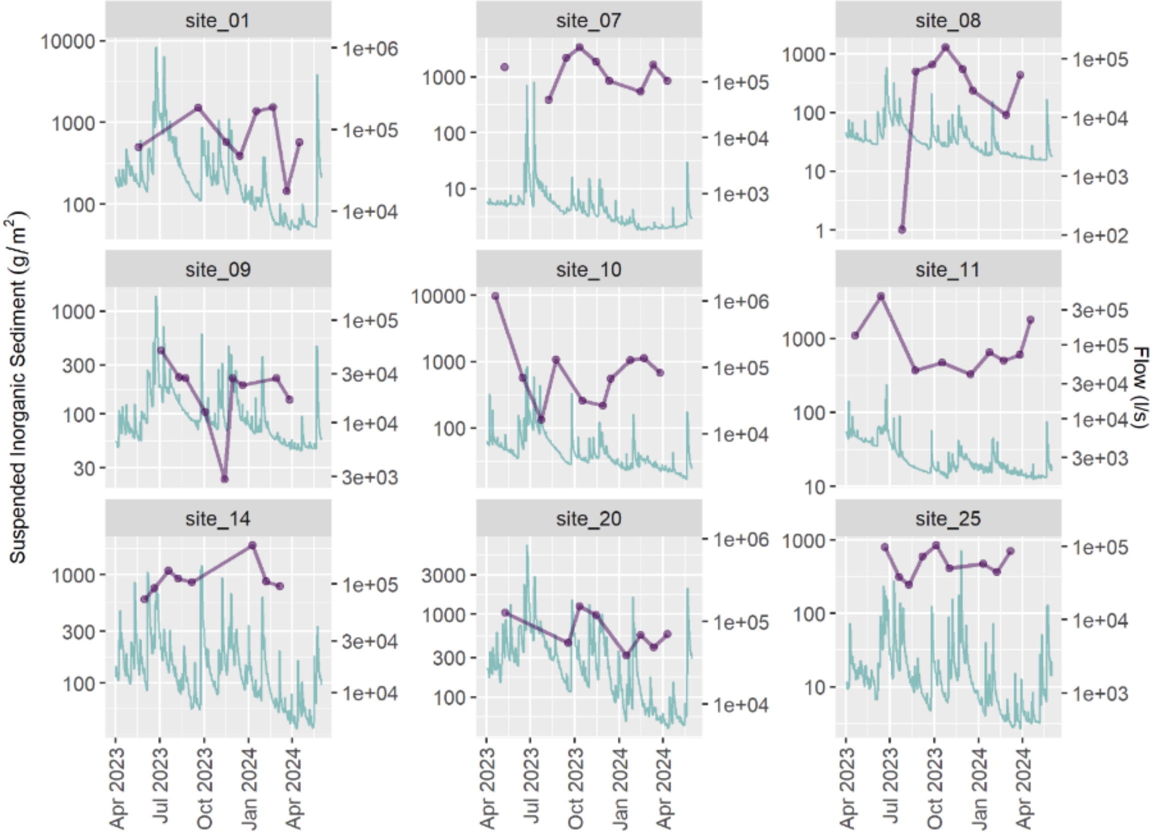

Figure A5.2. Suspendible inorganic sediment (SIS) (purple) and mean monthly flow (turquoise) at nine Hawke's Bay rivers and streams between April 2023 and January 2024.

Note: y-axes are presented on a log scale.