Implications of sediment for fish in the lower Wairoa River, Hawke's Bay

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Background and purpose

The Wairoa River and its tributaries in the Hawke's Bay region are used for mahinga kai, and are of high cultural value for the iwi and hapū of Te Rohe o Te Wairoa. An important threat to the fisheries and general health of the river is from sediment entering the water. The Our Land and Water Science Challenge has commissioned several investigations related to the risks of sediment for fish in the Wairoa catchment, with most emphasis on the lower reaches of the river. This report summarises and synthesises several threads of scientific information related to the risks of sediment for fish in the catchment.

Components of the investigations

The threads of scientific information were:

- Summarising current sediment related water quality attributes, both from observations and national-scale predictive models.
- Summarising observations of freshwater species that have been identified in the Wairoa catchment from past scientific fish surveys.
- Developing fact-sheets for each species summarising information on their sensitivity to sediment considering factors such as life cycle and food sources.
- A coring study to examine sedimentation rates and bed texture in the lower river.
- Examination of river characteristics by a specialist geomorphologist (Prof. Ian Fuller, Massey University) to interpret what the river may have been like before land clearance, especially in relation to the amount of gravel on the river bed. That work is reported elsewhere but summarised here.
- Development of an erosion model to investigate future changes in sediment loading under climate change and erosion control measures, and the implications for water visual clarity. This was a separate study by Manaaki Whenua Landcare Research, which is summarised here.
- Evaluation by a fish scientist of the benefits of erosion control for fish populations.
- Preliminary assessment of changes in bank elevation and sediment concentration following Cyclone Gabrielle.
- Rapid field survey by a fish scientist from NIWA to provide specialist advice on the risks and potential for recovery of fish habitat and īnanga spawning locations following large storm in 2022 and Cyclone Gabrielle in 2023, complementing knowledge of local scientists.

Key findings

Past surveys of fish presence show that:

- Whitebait-net samples below Frasertown found mostly īnanga, which are tolerant of turbid conditions, although kōaro (probably juveniles) were also found.

- Banded kōkopu (*Galaxias fasciatus*) were found only rarely; they tend to prefer small tributaries with good vegetation cover but are not common in whitebait catches in Hawke's Bay.
- Eels were found throughout the river network apart from upstream of the Waikaremoana.
- Torrentfish were found occasionally in the middle reaches; they prefer fast-flowing conditions that could occur in the middle reaches.

Surveys in 1995 of fish abundance at 6 sites in the middle reaches of the catchment show that eels and common bully were present at most sites, īnanga at 4 sites (one site with high density), and there were occasional torrentfish.

General knowledge of fish sensitivity to sediment (as captured in the fact sheets) along with observations of the Wairoa and site-specific knowledge were used to assess the sensitivity of species of interest[1] to sediment in the Wairoa catchment. Sediment may occur in the water column (suspended sediment) or on the river bed (deposited sediment), when referring generically to either of these, we use the term 'sediment'. If It was concluded that banded kōkopu are likely to severely affected by sediment in the lower river. Indeed, they were not observed in the NZFFD (New Zealand Freshwater Fish Database) apart from one site), and they are rare in whitebait catches in the Wairoa. Kōaro are likely to be harmed by sediment in the Wairoa, not so much because of suspended sediment, but because of deposited sediment (adults prefer coarse substrates). Īnanga are likely to be harmed by sediment in the Wairoa due to deposited sediment affecting spawning habitat. While shortjaw kōkopu are potentially affected by sediment, they are regionally sparse; limited by supply of recruits, rather than sediment levels, is likely to be the most important factor limiting their abundance in the Wairoa catchment. Longfin eels are insensitive to suspended sediment but prefer stony substrate. Therefore, if the substrate becomes finer, they could be impacted. Longfin eels were therefore assessed to have a medium to low sensitivity to sediment overall. Giant kōkopu, black founder, kahawai and shortfin eels were assessed to have low sensitivity to suspended? sediment in the Wairoa catchment. These species were found to have low-sensitivity in the mid-catchment to the effects of Cyclone Gabrielle. Yellow-eyed mullet and grey mullet may benefit from the current sediment levels.

Comparison of observed median visual clarity at 8 sites against NOF criteria show that 6 of the sites have visual clarity less than the bottom line. One of these sites is near the estuary mouth where greater turbidity is expected, so the grading is not relevant at that site, and leaving 5 sites that need improvements in visual clarity to reach the bottom line. According to the NOF descriptor of the grading bands, for sites below the bottom line there is expected to be a high impact of suspended sediment on instream biota, ecological communities are significantly altered, and sensitive fish will be lost or at high risk of being lost. Measured visual clarity is less than the value expected for pre-human land use (reference conditions) at most sites. For the 5 sites currently below the bottom line, the reduction of suspended sediment to get the sites into the C band (equalling the bottom line) ranged from a factor of 1.67 to 4.1 (40% to 76% reduction).

[1] aua/yellow-eyed mullet; kanae/grey mullet; tuna (separated into shortfin eel and longfin eel); giant kōkopu; shortjaw kokopu; banded kōkopu; pātiki mohoau/black flounder; kahawai, īnanga; kōaro

Bed sediment adjacent to Wairoa is mud (<63 microns diameter) and very fine or fine sand (63-250 microns), based on analysis of sediment samples. Downstream of Frasertown there is generally soft fine sediment with some papa sills (ledges made of soft mudstone or sandstone) and occasional gravel (based on probing of the bed with a pole). In the Wairoa River upstream of the Frasertown, there is increasing gravel and bedrock, associated with steeper river slopes and higher velocities (based on probing and visual observations of bed morphology). The lower sections of the tributaries are predominantly coarse (less than 15% sediment, based on visual assessment of bed texture) in 1995, but post Cyclone Gabrielle had significantly larger fractions of fine deposited sediment.

A brief and provisional river geomorphology assessment in the lower river downstream of Marumaru (conducted before Cyclone Gabrielle, by Professor Ian Fuller under separate funding) suggested that the Wairoa River had a gravel (or bedrock) bed down to Awamate until about 3000 years ago, but it was unclear whether it was gravel-bed before widespread land cover change around 100 years ago. There was no evidence that the river downstream of Awamate had a gravel bed. We conclude that the lower river (downstream of Awamate) is most likely naturally soft-bottomed. Further work would need to be done to establish the natural state of the bed in the rest of the lower river between Marumaru and Awamate.

Cores (0.6 m deep) take from the Ngamotu Lagoon near the river mouth had layers of mud and fine sand, with indications of large pulses of deposition. Sediment accumulation rates were not able to be established from these cores from radioisotope data due to the blocky nature of the sediment profile. Low concentrations of the fallout radionuclide caesium-137 indicate that the bulk of the deposition was from sub-surface surface sources. The core study was not successful in establishing increases in deposition rates following land clearance, nor changes in sediment texture. This aspect of the work was discontinued. We also assessed that there were not suitable river locations (such as low terraces) to conduct useful shallow coring studies.

Erosion modelling (by Manaaki Whenua, funded separately) indicated that best-effort erosion controls in the catchment would reduce sediment load to the coast by 60%. This would mean that the three out of the 5 sites (out of total of 6 sites overall) would move from having visual clarity worse that the bottom line to better than the bottom line. Climate change will increase sediment loads, so that an additional site would remain below the bottom line after erosion-controls.

Erosion controls are likely to have significant implications for fish in the Wairoa River. The improvement in visual clarity from erosion control would improve conditions for the fish community, especially for banded kōkopu. A likely reduction in deposited sediment accompanying erosion controls would have benefits for Kōaro by improving supply of high-quality food sources and spawning habitat. It would increase the habitat for adult shortjaw kōkopu, but this is unlikely to increase population because there are not recruits. Īnanga are likely to benefit due to reduced risks of sediment smothering spawning sites in the tidally-influence river reaches. The reductions may increase the extent of stony substrate preferred by adult longfin eels, thereby improving their numbers.

Based on limited routine monthly sampling following the storms in March 2022 and Cyclone Gabrielle in February 2023, it was determined that the storms/Cyclone did not increase the suspended sediment concentration for a given flow, although this is a tentative finding based on limited data. Fish survey sites in the mid-catchment inspected after Cyclone Gabrielle in September did not have particularly high turbidity, based on casual observation.

Based on preliminary analysis of LiDAR elevation data and inspection of fish survey sites, Cyclone Gabrielle resulted in erosion of stream banks, removal of riparian vegetation, and stream-bed disturbance. Comparison between 1995 data and post-Gabrielle surveys at 6 stream habitat measurement sites showed: a) degradation of habitat at all sites and b) increases in deposited fine sediment at 4 sites, making them likely to be below the bottom line for deposited fine sediment.

Inspection of two known īnanga spawning sites showed that one site had not been affected much by the Cyclone, while the other had major and ongoing impacts.

These impacts on habitat have implications for fish. The loss of instream cover and overhanging vegetation will affect survival of juvenile and adult īnanga. Riparian grasses will recover fairly rapidly, but full re-establishment of cover will take years. Eels are likely to have been affected by loss of habitat and food sources. Recovery of eels is likely to follow a slow successional process. Smelt are likely to recover rapidly. Torrentfish recovery will depend on exposure of coarse substrate, recovery of food sources, and the supply of recruits from other catchments.

Īnanga spawning habitat at the Awatere stream site, which was not affected by Cyclone Gabrielle, could be improved by management of fencing and bankside vegetation. Recovery of the Huramua Stream site, which was heavily impacted could initially be hastened by planting of grass, but it will take some time for the riparian vegetation to mature and provide full protection for eggs. Artificial spawning habitats could be introduced.

1 Introduction

This report summarises several threads of scientific information related to the risks of sediment for fish in the lower Wairoa River in Hawke's Bay. The Wairoa River and its tributaries are used for mahinga kai, and are of high cultural value for the iwi and hapū of Te Rohe o Te Wairoa. The delivery of fine sediment into the river is an important threat to freshwater fish and general river health.

The Wairoa Tripartite[2] and the Our Land and Water Science Challenge have formed a partnership to jointly guide the direction and delivery of a project focused on understanding cultural values related to the river, the impact of sediment on these values, and implications of land use for erosion and sediment-related aspects of fish health. This report forms part of that larger project.

Investigations by iwi researchers (Galvan and Kawana 2021) under this funding umbrella identified that many aspects of mahinga kai in the lower river have been affected by sediment, including effects on the diversity and abundance of mahinga kai species. They identified several species of particular interest in the lower river. The species of interest were later interpreted as: aua/yellow-eyed mullet; kanae/grey mullet; tuna (separated into shortfin eel and longfin eel); giant kōkopu; shortjaw kokopu; banded kōkopu; pātiki mohoau/black flounder; kahawai, īnanga; kōaro

This report examines several threads of scientific information on how sediment affect these species, including:

- Summarising current sediment related water quality attributes, (suspended sediment concentration, visual clarity, bed sediment texture, and bed cover of fine sediment) both from observations and national-scale predictive models.
- Summarising previous fish survey information from the Wairoa catchment.
- Developing fact-sheets for each species which summarise their sensitivity to sediment, considering factors such as life cycle and food sources.
- A coring study to examine sedimentation rates and bed texture in the lower river.
- Examination of river characteristics by a specialist geomorphologist (Prof. Ian Fuller, Massey University) to interpret what the river may have been like before land clearance, especially in relation to the amount of gravel on the river bed. This work is reported elsewhere but summarised here.
- Development of an erosion model to investigate future changes in sediment loading under climate change and erosion control measures, and the implications for visual clarity. This was a separate study by Manaaki Whenua Landcare Research (MWLR) Vale et al. (2023) , which is summarised here.
- Evaluation by a fish scientist of the benefits to freshwater fish of catchment-scale erosion control.

[2] The Tripartite is the Wairoa District Council, Tātau Tātau o Te Wairoa, Hawke's Bay Regional Council. The relevant project in Our Land and Water is the Whitiwhiti Ora project on land-use suitability.

- Preliminary assessment of changes in bank elevations and suspended sediment concentration following Cyclone Gabrielle.
- Rapid field survey by a NIWA fish scientist to provide specialist advice on the risks and potential for recovery of fish habitat and īnanga spawning locations following large storm in 2022 and Cyclone Gabrielle in 2023, complementing knowledge of local scientists.

Overarching questions are:

- What do we think the river was like before land development (the reference condition), which could inform restoration targets?
- How much are the valued fish affected by sediment?
- What are the restoration prospects in relation to sediment effects, including consideration of climate change?

This report presents or summarises each of these threads of information, and summarise key points in the Executive Summary.

2 Impacts of sediment on selected fish species

This section addresses the impacts of sediment on fish for the current long-term sediment conditions, prior to the recent large storms. The effects of Cyclone Gabrielle are addressed in Section 7.3, and recovery prospects following erosion controls are discussed in Section 8. This section draws on supporting information later in the report, but it presented first due to the primary interest on fish species in the catchment.

2.1 Fish observed in the river from sampling surveys

This aspect of the work summarised existing information on fish distributions in the Wairoa River and its tributaries. This gives a general indication of where different species might be found.

The New Zealand Freshwater Fish Database (NZFFD) was queried (for the period up to December 2021) for information on fish species observed in the Wairoa catchment. The database collates observations of fish species, along with other information such as bed texture. Many observations do not count fish, and varying fish sampling methods are used. A lack of fish observations does not necessarily mean that the species does not exist at the site, rather it may not have been found with the sampling method used. There are other complications such as fish spending different parts of their life cycle in different parts of the river system. Due to limited nature of the observations, the observed distribution of species should be interpreted cautiously. Many of the records were from decades ago (67% before 1997) and current fish distributions (before Cyclone Gabriel) may be different from those recorded in database.

Maps of the observations are show in Figure 2-1 and Figure 2-2. Pātiki mohoao/black flounder and bluegill bully are not included because the observations in the NZFFD were deemed unreliable (very few observations and questionable locations).

It is noteworthy that the eight surveys in the lower Wairoa River below Frasertown used whitebait nets for sampling, which are not likely to catch some species such as adult eels. In contrast, the four surveys in the lower Waiau River area (entering on the right bank at Frasertown) used electric fishing and so found a wider range of species, such as eels.

Of the five galaxiid whitebait species, īnanga (*Galaxias maculatus*) are found in the lower river. Īnanaga are not very sensitive to suspended sediment but they are poor climbers, hence they do not migrate far upstream. In contrast, kōaro (*Galaxias brevipinnis*) are found in the upper catchment (and some lakes) as they prefer relatively coarse substrate and are good climbers. . Kōaro are also observed in the lower catchment while migrating as juveniles. Banded kōkopu (*Galaxias fasciatus*) were rarely found; they tend to prefer small tributaries with good vegetation cover. Banded kōkopu are not common in whitebait catches in Hawke's Bay compared to nearby regions (e.g., Bay of Plenty; Yungnickel et al. 2020). Torrentfish (*Cheimarrichthys fosteri*) tend to occur in faster-flowing clean-substrate areas, which might be found in the mid reaches of the Wairoa catchment. Longfin eels (*Anguilla dieffenbachii*) and shortfin eels (*Anguilla australis*) are found in the mid and upper reaches. Longfin eels prefer cleaner substrate, which is more prevalent in the upper catchment, whereas shortfin eels tolerate muddy substates more. Neither species were found in the lower-most reaches, but that finding reflects the sampling methods. Common bully (*Gobiomorphus cotidianus*) were found throughout the catchment. Redfin bully (*Gobiomorphus huttoni*) are rarely found in unstable, gravelly or sandy streams, preferring rapid flowing bouldery streams, which are more prevalent in the upper Wairoa catchment. Kōura (*Paranephrops planifrons*) occur throughout the catchment, but mainly in the mid catchment. Brown trout (*Salmo trutta*) and rainbow trout

(*Oncorhynchus mykiss*) are more common in the mid and upper reaches of the drainage network. Lamprey (*Geotria australis*) were not observed in the catchment (apart from one questionable observation), although they are known to be difficult to find.

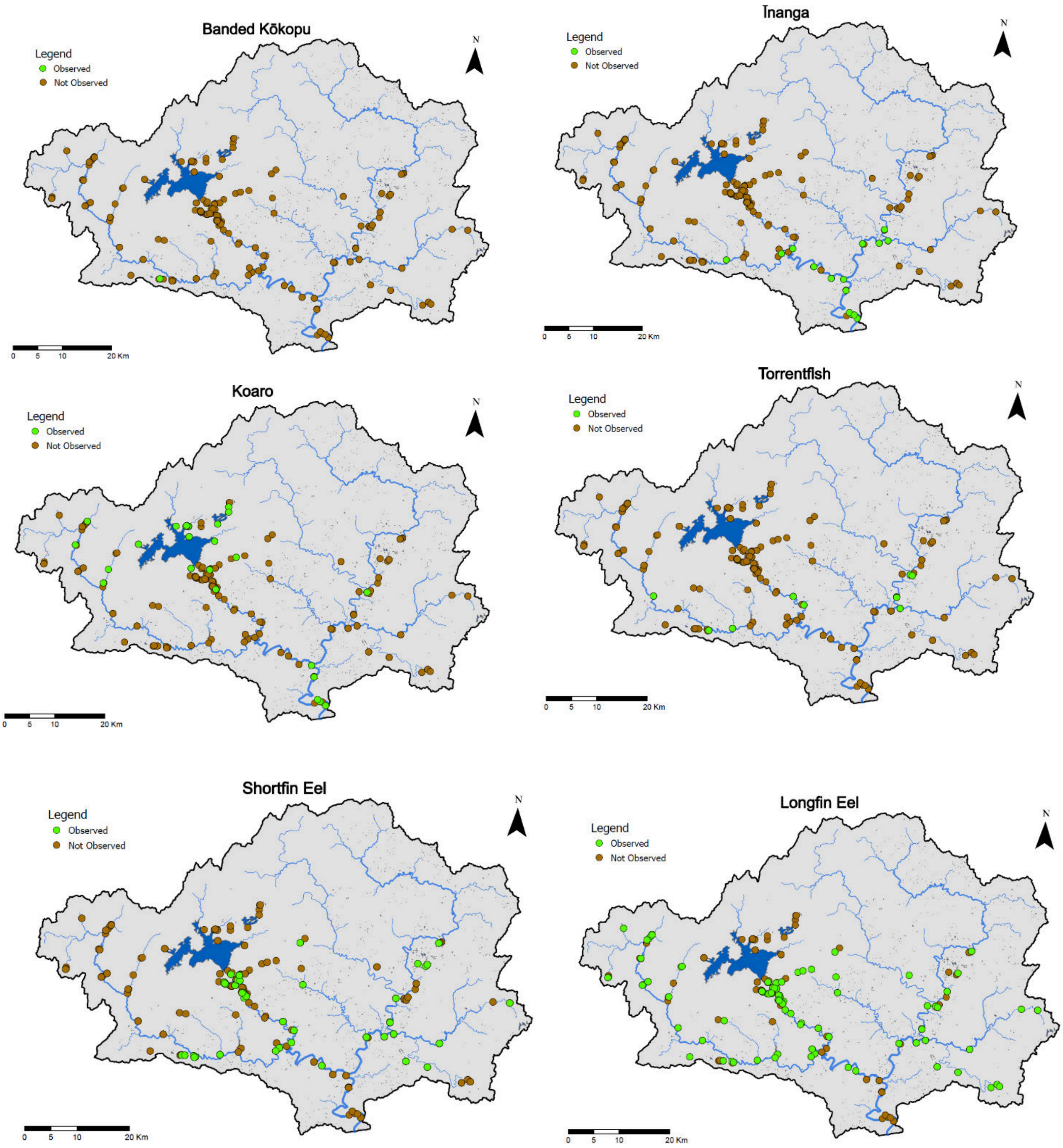


Figure 2-1: Distribution of fish from NZFFD (further species in the next figure).

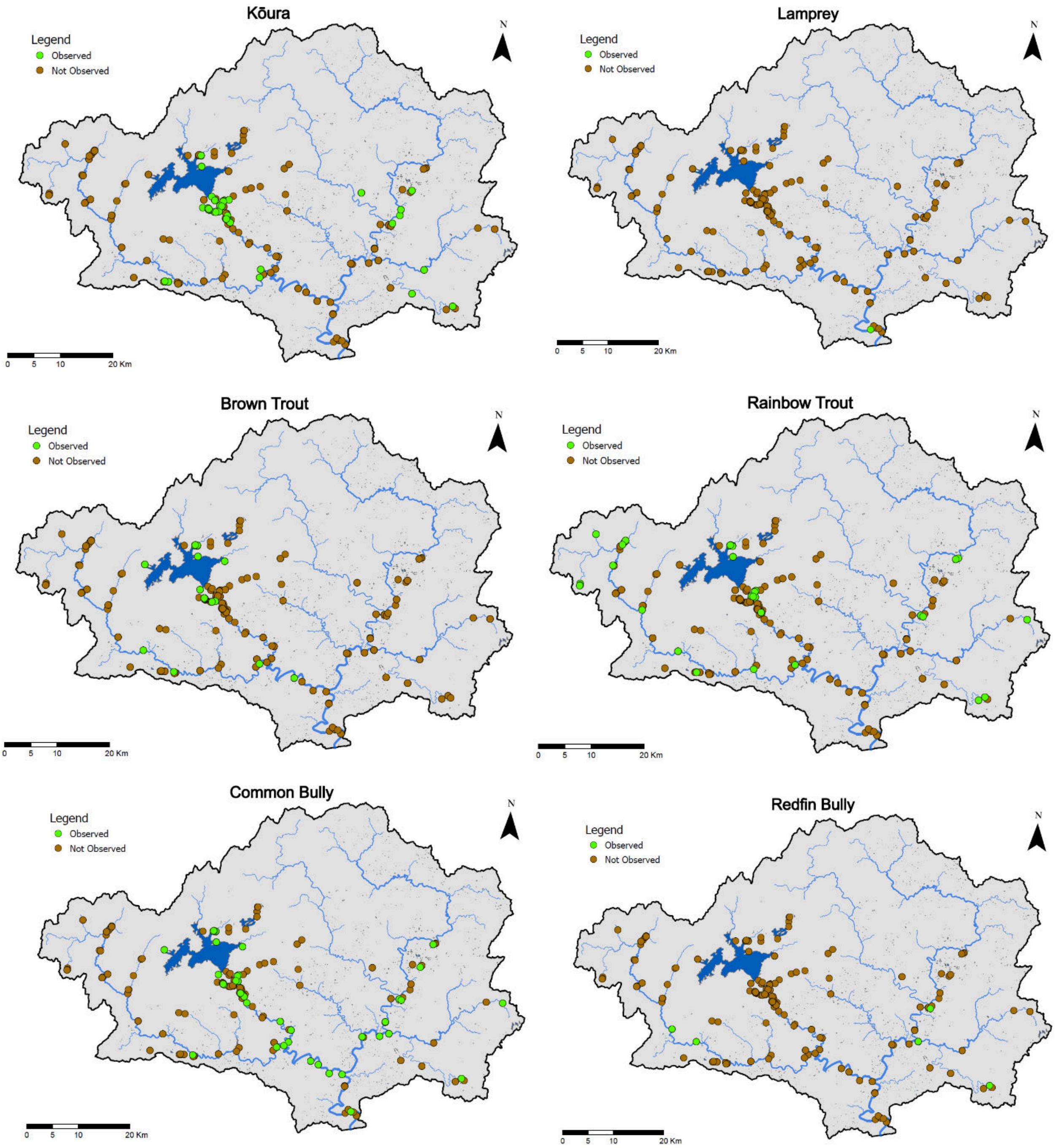


Figure 2-2: Distribution of fish species from the NZFFD. Further species are shown in the previous figure.

Sampling of fish abundance was conducted in 1995 at six sites in the mid Wairoa catchment (which are also sites on the NZFFD presence/absence maps). The sites are discussed in the context of changes following Cyclone Gabrielle in Section 7.3.1, with data in Table 7-2. They show variation of species across sites, with eels at nearly all sites, common bully at most sites, īnanga at 4 sites (one with high density), and occasional torrentfish.

There are two known īnanga spawning locations in the Wairoa catchment (Figure 7-18) (although other spawning sites may exist).

Distributions of selected species from national models (accessed through NZ River Maps[3]) are shown in Figure 2-3. The models are specific to results from electro-fishing from the NZFFD and use a wide range of predictor variables including climate, hydrological, positional (e.g., distance from coast, elevation), geology, and stream characteristics (slope, predicted bed sediment composition) and land cover. They do not consider erosion rates or visual clarity.

The models predict:

- a high presence of īnanga in the lower catchment,
- a low presence of banded kōkopu and kōaro throughout the catchment, and
- presence of longfin eel in the mid catchment, and shortfin eel in the lower catchment.

The predictions are consistent with observations for īnanga, banded kokopu, and in broad terms for eels. The predictions are at odds with observations in some cases. Kōaro were not predicted to be present, but have been observed in the catchment, especially in upper reaches around Waikaremoana.. As noted earlier, the lack of observations of eels in the lower-most river are due to limitations of the sampling method used there.

[3] NZ River Maps (niwa.co.nz)

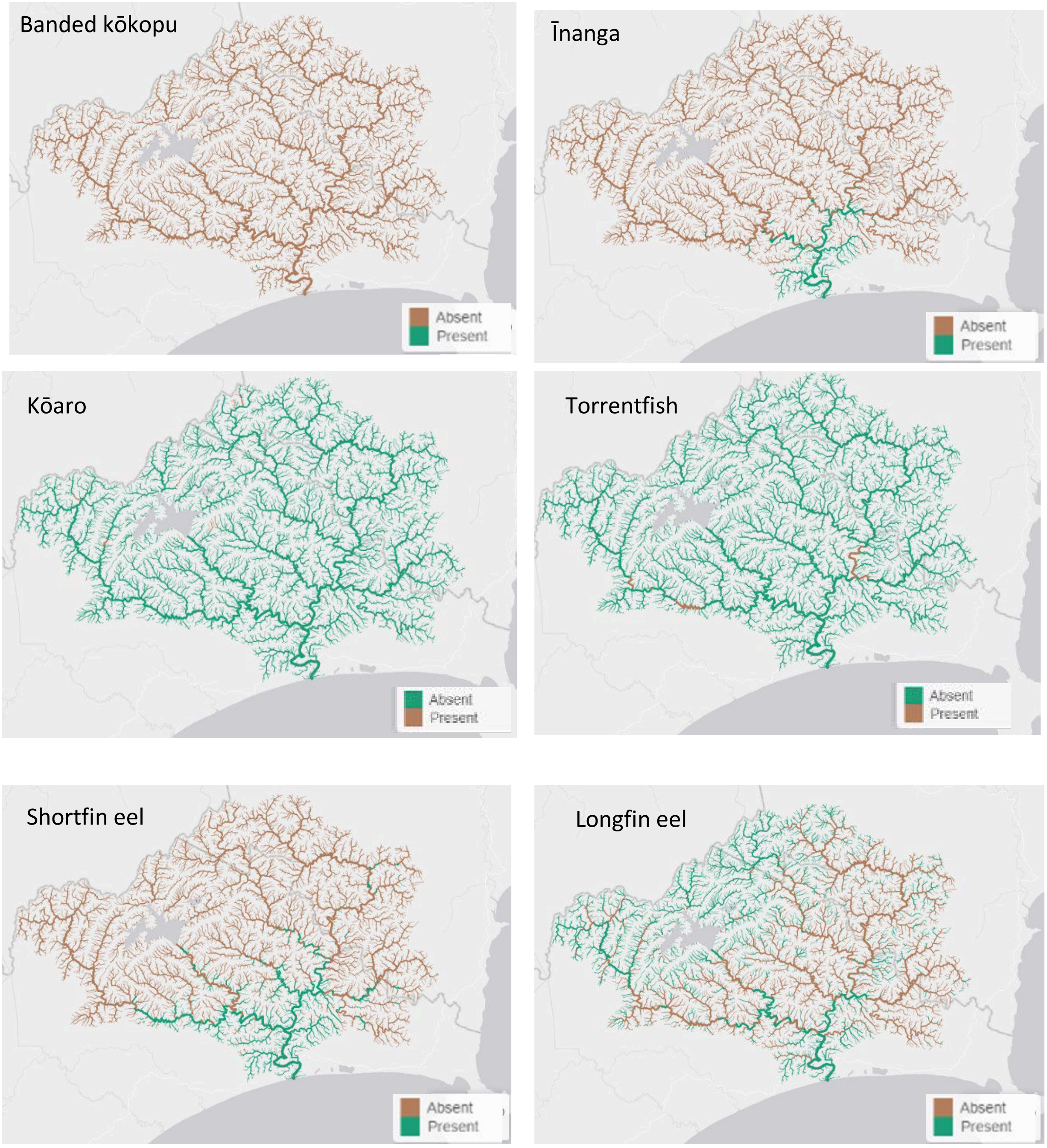


Figure 2-3: Predicted distribution of presence/absence for selected fish species from national fish distribution models, obtained from NZ River Maps. Note that the colour scale reverses between plots.

2.2 Fact sheets on sediment impacts on selected fish species

Information on the sensitivity of fish to suspended and deposited sediment as gathered and summarised in fact sheets[4] for 11 fish species of interest (see Galvan and Kawana 2021; Table 3-1) in the lower Wairoa River (as well as kākahi/freshwater mussels). The sheets were targeted at a general (rather than a scientific or academic) audience, and are designed to be used in any catchment. Application to the Wairoa River is presented in Section 2.3.

For each species, a general introduction provides a commentary on the area where the species occur, the fish life cycle and food sources these can be relevant to the effects of sediment. The effects of sediment were then considered in terms of how suspended and deposited sediment affects habitat, behaviour, feeding, growth, and survival. Citations to scientific papers or reports were provided where they are available.; Expert opinion was used in some cases, and key information gaps were noted. An overall assessment of the sensitivity to sediment was provided in terms of a 'dial' of sensitivity, along with a brief key reason for the sensitivity grading. The overall sensitivity information is collated in Table 2-1. An example of the top-level summary is shown in Figure 2-4.

Table 2-1: Overall summary of sensitivity of 11 fish species to sediment. Māori name is followed by common name.

Species name	Sensitivity	Why
Banded kōkopu	Top of high band	Avoidance and reduced feeding
Kōaro	Middle of medium band	Avoidance, and reduced habitat suitability and growth
Īnanga	Middle of medium band	Reduced feeding and habitat suitability
Shortjaw kōkopu	Middle of medium band	Reduced habitat suitability, but not visual feeders
Tuna/longfin eel	Top of low band	Reduced habitat suitability
Giant kōkopu	Middle of low band	Avoidance and reduced feeding
Pātiki mohoao/black flounder	Middle of low band	Reduced habitat suitability, feeding and growth
Kahawai	Middle of low band	Mobile, pelagic predators
Tuna/shortfin eel	Middle of low band	Few, if any, negative effects on habitat suitability, feeding or growth
Aua/yellow-eyed mullet	Middle of low band	Adapted to turbid water
Kanae/grey mullet	Middle of low band	Depend on fine sediment for feeding

[4] The fact sheets can be obtained online from https://niwa.co.nz/sediment-impacts.

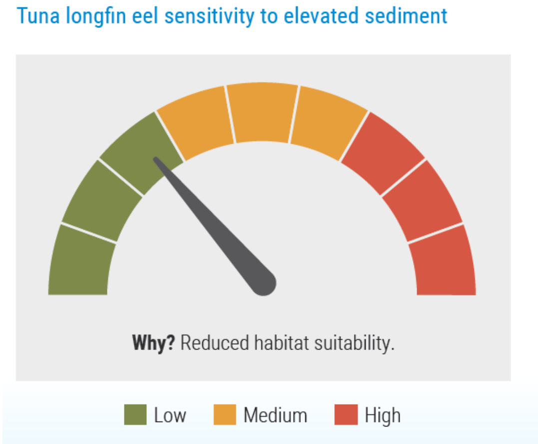


Figure 2-4: An example of the summary pictorial 'dial' of fish sensitivity to sediment, in this case for tuna/longfin eel.

2.3 Implications of sediment for fish species in the lower Wairoa River

For the 11 fish species of interest (Table 2-1), the current levels of suspended and deposited sediment in the lower Wairoa River are likely to be causing harm to four species, having little effect on five species and perhaps enhancing key habitats for two species (Table 2-2). For the 11 fish species of interest, the impact of degraded visual clarity assessed further in Section 3.

Table 2-2: Likely consequences of current sediment levels in Wairoa River on the ecology of 11 fish species.

Species name	Harmful	Some harm	Neutral	Some help
Banded kōkopu	✓			
Kōaro		✓		
Īnanga		✓		
Shortjaw kōkopu		✓		
Tuna/longfin eel		✓	✓	
Giant kōkopu			✓	
Pātiki mohoao/black flounder			✓	
Kahawai			✓	
Tuna/shortfin eel			✓	
Aua/yellow-eyed mullet				✓
Kanae/grey mullet				✓

Banded kōkopu are likely to be severely affected by current levels of sediment in the Wairoa River because of impacts throughout their life history. Across the North Island, banded kōkopu are much less common in turbid rivers than in clear streams (Rowe et al. 2000) and have rarely been observed in the Wairoa River catchment (Figure 2-1). Banded kōkopu comprise a very low proportion (0.7%) of the whitebait catch in the lower reaches of the Wairoa River (Yungnickel 2017) and in Hawke's Bay (1%; Yungnickel et al. 2020). The few banded kōkopu whitebait entering the Wairoa River will be deterred by the turbid water (Boubée et al. 1997). Banded kōkopu migrate slowly (Richardson, J. et al. 2001), therefore fewer juveniles will reach adult habitat in small, bouldery, forested tributaries (Rowe and Smith 2003; West et al. 2005; Crichton et al. 2023). Low recruitment of juveniles into adult habitat has compounding consequences for population replenishment because banded kōkopu whitebait are attracted to water-borne odours released by adults of the same species (Baker, C. F. and Montgomery 2001). Additionally, moderate turbidity disturbs the attraction of banded kōkopu whitebait to water containing the odour of adults (Baker, C. F. 2003). It is likely that the Wairoa catchment supports small, remnant populations of banded kōkopu that are isolated from new recruits (whitebait) by the turbid nature of the lower catchment.

Three fish species are likely to be moderately affected by current sediment levels the Wairoa River because of impacts on at least one life stage:

- Kōaro have been observed throughout the Wairoa catchment (Figure 2-1) with many records from higher elevation streams and tributaries of Lake Waikaremoana. It is likely that at least some of these records are of non-diadromous individuals from lake-limited populations (Rowe et al. 2002a). The presence of kōaro lower in the catchment (Figure 2-1) reinforces observations that kōaro appear relatively insensitive to increases in suspended sediment (Rowe and Dean 1998) and that their occurrence is not related to the duration of turbid conditions (Rowe et al. 2000). However, the habitat and feeding of adult kōaro are susceptible to increases in deposited sediment. Adult kōaro live and feed in micro-habitats with larger substrate particles and more interstitial (between substrate particles) refuge spaces than elsewhere in the reach (McEwan 2009; McEwan and Joy 2014) - deposited sediments will reduce the amount of interstitial space available in streams and cause population decline (Richardson, J. and Jowett 2002). Kōaro reproductive success may also be affected by deposited sediment smothering gravel and cobble substrates on stream banks where kōaro eggs are deposited/develop (O'Connor and Koehn 1998; Allibone and Caskey 2000; Charteris 2002).

- Īnanga have been observed throughout the lower Wairoa catchment (Figure 2-1) and juvenile īnanga dominate the whitebait catch in the Wairoa River (97.9%; Yungnickel 2017) and Hawke's Bay (98.1%; Yungnickel et al. 2020). Īnanga are highly dependent on sight for feeding (Cadwallader 1975; McDowall 1997), but adult (Rowe et al. 2002b) and juvenile (Rowe and Dean 1998) feeding is not reduced until suspended sediment reaches very high levels (>160 NTU equivalent to approximately < 0.1 m visual clarity[5]). The īnanga population in the Wairoa catchment is most likely to be affected by deposited sediment smothering their very-limited spawning habitat in the tidal reach of the river (Hickford and Schiel 2011a). The ground-level micro-habitat that suitable riparian vegetation provides is prone to clogging with sediment. Any reduction in the temperature/humidity/UVB protection that this micro-habitat provides will significantly reduce īnanga egg survival (Hickford and Schiel 2011b).

- Shortjaw kōkopu have not been observed in the Wairoa catchment and are absent from large areas of the east coast (McDowall 1990). Their juvenile stage comprises <0.01% of the whitebait catch nationally and they have only been identified genetically in whitebait catches from the Bay of Plenty, Buller, and south Westland. Shortjaw kōkopu are more abundant in stream reaches with large substrate (cobbles and

[5] https://environment.govt.nz/assets/publications/Files/technical-report-2-comparison-of-clarity-and-turbidity-bottom-lines.pdf

boulders; McEwan and Joy 2014) or plentiful instream debris (Goodman 2002). The debris and interstitial spaces between substrate particles provide refuge spaces during the day, but shortjaw kōkopu often move to pools to feed at night (McEwan and Joy 2014). Current levels of deposited sediment in the Wairoa catchment may have reduced the availability of these refuge spaces with negative effects on any resident shortjaw kōkopu. Supply of recruits, rather than sediment levels, is likely to be the most important factor limiting their abundance in the Wairoa catchment.

The low (or low-moderate in the case of longfin eel) sensitivity to sediment (Table 2-1) of five resident fish species suggests they are unaffected by current sediment levels in the Wairoa River:

- Longfin eels appear to be insensitive to increased suspended sediment concentration in rivers (Rowe et al. 2000). Longfin eels migrate into very turbid waters (Jellyman and Lambert 2003). Longfin elvers do not avoid even extreme turbidity (Boubée et al. 1997) and may even be attracted to turbid tributaries (Schicker et al. 1990). Adult longfin eels mainly use a combination of smell, touch, and taste to feed (Carton and Montgomery 2003) and can feed actively in turbid conditions (Jellyman 1989). The preferred stony substrate habitat (Glova, G. J. et al. 1998) and prey (Jellyman 1989) of longfin eel in the upper Waiau Catchment (Figure 2-1) is unlikely to be affected by deposited sediment. Longfin eels have been observed in most of the Wairoa River network, which covers a range of sediment conditions. Furthermore, while longfin eels have relatively small home ranges they are capable of making extensive movements to occupy more beneficial habitat (Jellyman and Sykes 2003). However, they could be vulnerable to siltation of stream beds in the mid catchment (Section 8.3.1), so they have been allocated a mixture of low and moderate sensitivity categories.

- Giant kōkopu have not been observed in the Wairoa catchment or in Hawke's Bay. However, it appears unlikely that sediment levels in the Wairoa River would negatively impact giant kōkopu. They are generalist feeders (Bonnett and Lambert 2002) that do not rely heavily on sight for feeding (McDowall 1997) so it is unlikely they will be affected by increased suspended sediment. Furthermore, it appears that giant kōkopu may prefer areas with finer substrates, although the association with smaller substrate size may just reflect their strong preference for low water velocity (Bonnett et al. 2002). Supply of recruits, rather than sediment levels, is likely to be the most important factor limiting their abundance in the Wairoa catchment.

- Black flounder are common in the lower Wairoa River and in Hawke's Bay. They are very abundant in highly turbid areas throughout New Zealand (Hardy 1989) where they feed, grow and survive at similar rates to elsewhere (Gorman 1960; Glova, G. J. and Sagar 2000). Black flounder are mobile predators and are equally abundant over a broad range of substrate types (e.g., soft clay, mud and sand) in heavily-sedimented areas (Glova, G. J. and Sagar 2000).

- Kahawai are found throughout New Zealand and feed on small fishes, benthic crustaceans and molluscs in estuaries and at river mouths year-round (Baker, A. N. 1971; Kilner and Akroyd 1978). Kahawai are visual predators (Morgan and Ritz 1983), so turbid water may reduce their ability to school and their feeding effectiveness (Foster et al. 2001). However, kahawai show the ability to switch to preying on benthic organisms when feeding alone near river mouths (Robertson 1982). It is unlikely that deposited sediment will directly impact the coastal habitats of kahawai; juveniles are already uncommon in turbid, upper-estuary areas (Lowe 2013).

- Shortfin eels are common in the lower Wairoa catchment (Figure 2-1) and are found throughout New Zealand in lowland rivers, lakes, wetlands, and estuaries. Shortfin eels are well adapted to cope with, or to avoid, the direct toxic effects of suspended sediment (Hayes et al. 1992). The biomass of smaller shortfin eels is greater in areas with finer substrates (Glova, G. J. et al. 1998), so it is unlikely that an increase in deposited sediment will restrict their habitat.

Two fish species may benefit from current sediment levels in the Wairoa River:

- Yellow-eyed mullet are transient visitors to the estuarine areas of the Wairoa River. They are well adapted to schooling and feeding in the changeable and often turbid water of estuarine areas (Middlemiss et al. 2018) and water visual clarity has very little effect on their occurrence at individual sites within estuaries (Francis et al. 2011). Land-use intensification (e.g., urbanisation or pastoral development) usually results in increased sedimentation in the lower reaches of catchments (Davies-Colley 2013). This sedimentation can degrade critical habitats of some species. However, yellow-eyed mullet are one of the few estuarine fishes that are more abundant in estuaries that have a greater percentage of urban or pastoral development in their catchment (Francis et al. 2011).

- Grey mullet are common in northern New Zealand in sheltered bays and harbours and around the mouths and estuaries of rivers. They can also penetrate long distances inland in larger rivers (Hicks, B. J. et al. 2010). Grey mullet feed on organic material which they sift from sediments sucked from the substrate (Odum 1968). They filter and remove carbon from large volumes of sediment while feeding (Moriarty 1976). Up to half of the gut contents of grey mullet can be comprised of very fine silt, which is important for breaking down food and assisting with digestion (Blaber 2008). Turbidity does not appear to affect the feeding, growth or survival of grey mullet (Wells 1984). It is unlikely that an increase in deposited sediments will affect grey mullet as they are large, mobile fishes that are equally abundant over a range of substrates (Wells 1976).

3 Sediment visual clarity bands and load reduction to meet bottom line

Observations and models of river sediment conditions (such as visual clarity and bed deposited sediment) are useful because they can be compared with attribute state criteria in the National Objectives Framework (NOF) in the National Policy Statement for Freshwater Management (New Zealand Government 2023). Visual clarity of the water is of particular relevance to fish, because fish communities vary more as a function of visual clarity than deposited sediment (Franklin et al. 2019). Relationships between suspended sediment concentration and visual clarity can also be used to estimate the reductions in sediment required to meet a given reduction in visual clarity.

3.1 Visual clarity of water and comparison with NOF bands

Water quality data were provided by Hawke’s Bay Regional Council (HBRC) for all their Wairoa River catchment sites. These data were obtained as part of regular sampling (typically monthly), rather than storm-sampling campaigns. The data cover various periods from about 2010 to mid-2021 (the date of the data request), depending on the site. Sites with less than 20 sampling points were excluded from the analysis.

The median visual clarity values are summarised in Table 3-1and Figure 3-1. The classifications according to NOF bands in the NPS-FM are also shown.

The observed median visual clarity ranged from 0.35 m to 0.99 m. The lowest visual clarity was at the Wairoa River near the river mouth and is likely to be influenced by salinity. Salinity often results in decreased visual clarity due to particle flocculation and recirculation currents. Hence the freshwater visual clarity bands may be less relevant at such locations as they were developed from freshwater site data. Wairoa River at Railway Bridge may also be influenced by salinity.

Most of the sites lie in the D grade, which is below the ‘bottom line’ for median visual clarity. At this level, according to the NOF descriptor of the grading band there is expected high impact of suspended sediment on instream biota, ecological communities are significantly altered, and sensitive fish will be lost or at high risk of being lost. The Mangaaruhe and Mangapoike Rivers, on the other hand, are in the A band despite having similar visual clarity to the some of the other sites. This is a result of these rivers being in a different NOF river class and each class has different thresholds between grading bands. This contrast is surprising given that the sites are of broadly similar character, and the result has implications for reductions in sediment load that may be required to meet visual clarity bottom lines.

Visual clarity at all measured sites can be very low at times, with a minimum value of 5 mm being recorded at the Ruakituri River at Sports Ground site This may have implications for fish if visual clarity is low for extended periods clarity. However, NOF criteria are only for median values, not for infrequent values.

Table 3-1: Summary of visual clarity measurements in the Wairoa catchment n is the number of observations.

Site Name	NZSegment	n	Median visual clarity (m)	Minimum visual clarity (m)	River class for suspended sediment	NOF band
Hangaroa River at Doneraille Park	8143530	133	0.93	0.01	1	D
Mangaaruhe River at Mangaaruhe Station	8155795	22	0.99	0.025	2	A
Mangapoike River at Suspension Bridge	8155822	107	0.95	0.03	2	A
Ruakituri River at Sports Ground	8149195	133	0.83	0.005	1	D
Waiau River at Otoi	8159305	115	0.67	0.01	1	D
Wairoa River at Marumaru	8155540	22	0.71	0.043	1	D
Wairoa River at Railway Bridge	8165291	52	0.53	0.015	1	D
Wairoa River D/S Wastewater Discharge	8170924	25	0.35	0.01	1	D

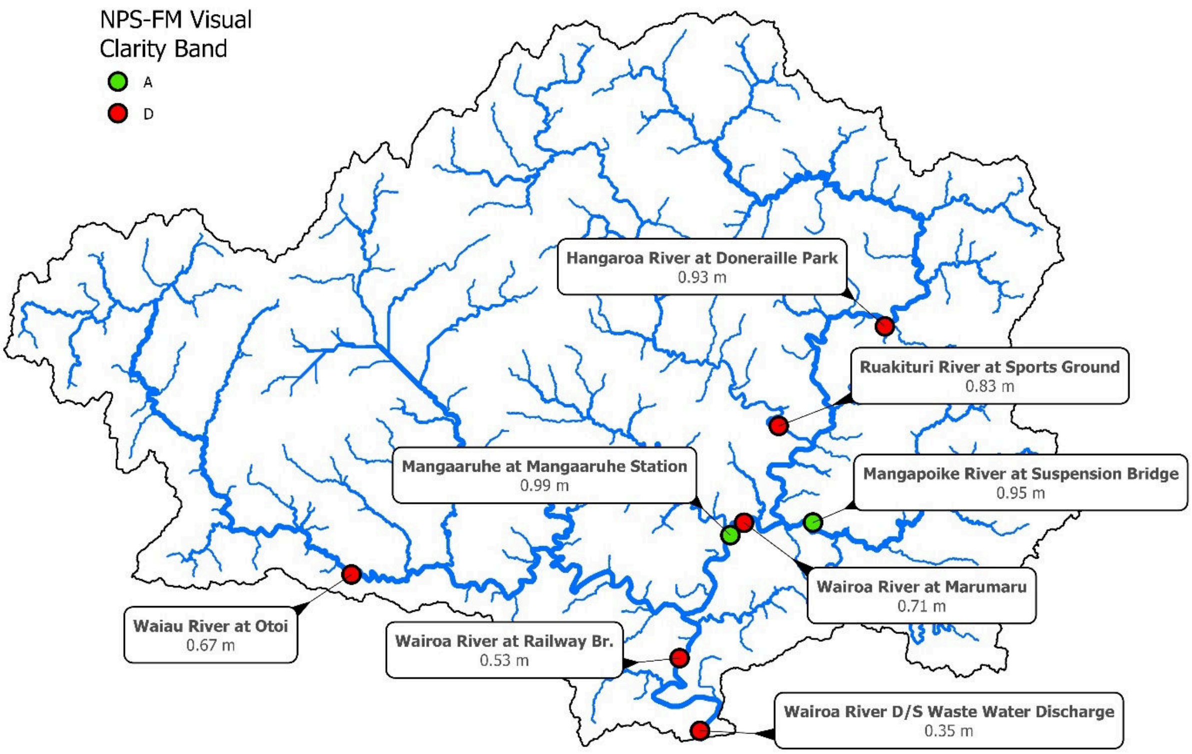


Figure 3-1: Map of observed median visual clarity values (m) and NOF attribute band.

Suspended sediment concentrations (SSC) data are also available for the same sites (but with larger number of samples) (Table 3-2). The median SSC is largest at the site downstream of Wairoa wastewater discharge (D/S Wastewater Discharge). The median SSC is considerably larger than at the Ski Club, River Mouth, or Yacht Club, suggesting the influence of a localised source of sediment (possibly the wastewater discharge itself). Comparing SSC and visual clarity, there is no strong indication of a changing visual nature of the sediment with distance downstream. The median concentrations are larger than the median, suggesting a skewed probability distribution of concentrations, as it typical for water quality data.

Table 3-2: Summary of suspended sediment concentrations (mg/L) from State of Environment monitoring sites.

Site	n	Maximum	Mean	Median
Hangaroa River at Doneraille Park	139	1390	72	5.0
Mangaaruhe at Mangaaruhe Station	24	1280	84	7.7
Mangapoike River at Suspension Bridge	114	1570	98	4.2
Ruakituri River at Sports Ground	139	2300	67	6.0
Waiau River at Otoi	117	1870	126	12.8
Wairoa Estuary at River mouth	48	1320	60	18.2
Wairoa River at Aranui Road	37	1550	99	11.8
Wairoa River at Frasertown Bridge	45	1630	86	9.1
Wairoa River at Marumaru	24	990	76	9.4
Wairoa River at Railway Bridge	192	2900	84	11.0
Wairoa River at Ruataniwha Road	39	1350	70	10.4
Wairoa River at Ski Club	55	520	40	12.8
Wairoa River at Yacht Club	39	730	70	8.9
Wairoa River D/S Wastewater Discharge	90	1280	107	51.0

A National-scale model of visual clarity produced by Whitehead et al. 2022 y predict clearer water in the forested headwaters near Lake Waikaremoana and lower visual clarity in the lower river (Figure 3-2). The measured visual clarity in the lower river is less than the predicted visual clarity., This disparity can probably be attributed to model limitations such as geological influences that are not represented well in the model.

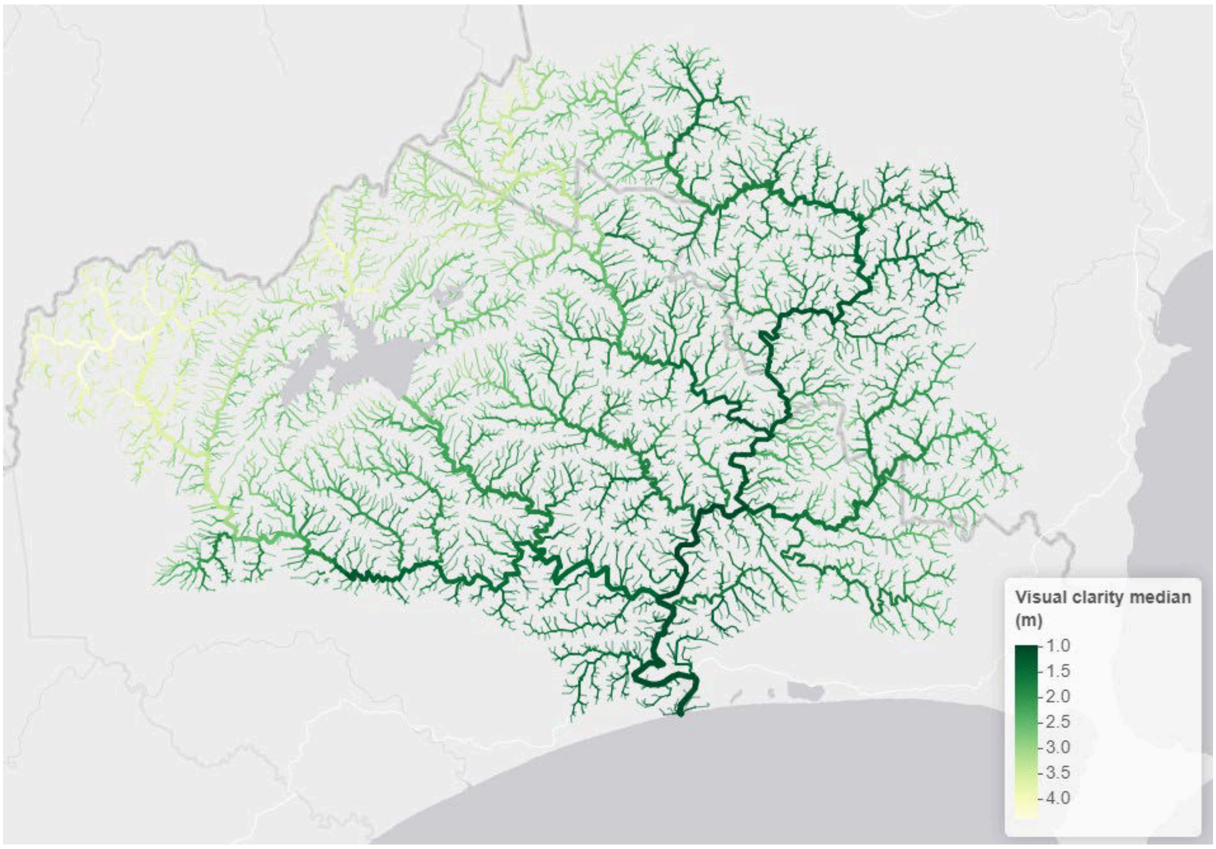


Figure 3-2: Predicted median visual clarity for current conditions from a national model.

3.2 Reference visual clarity

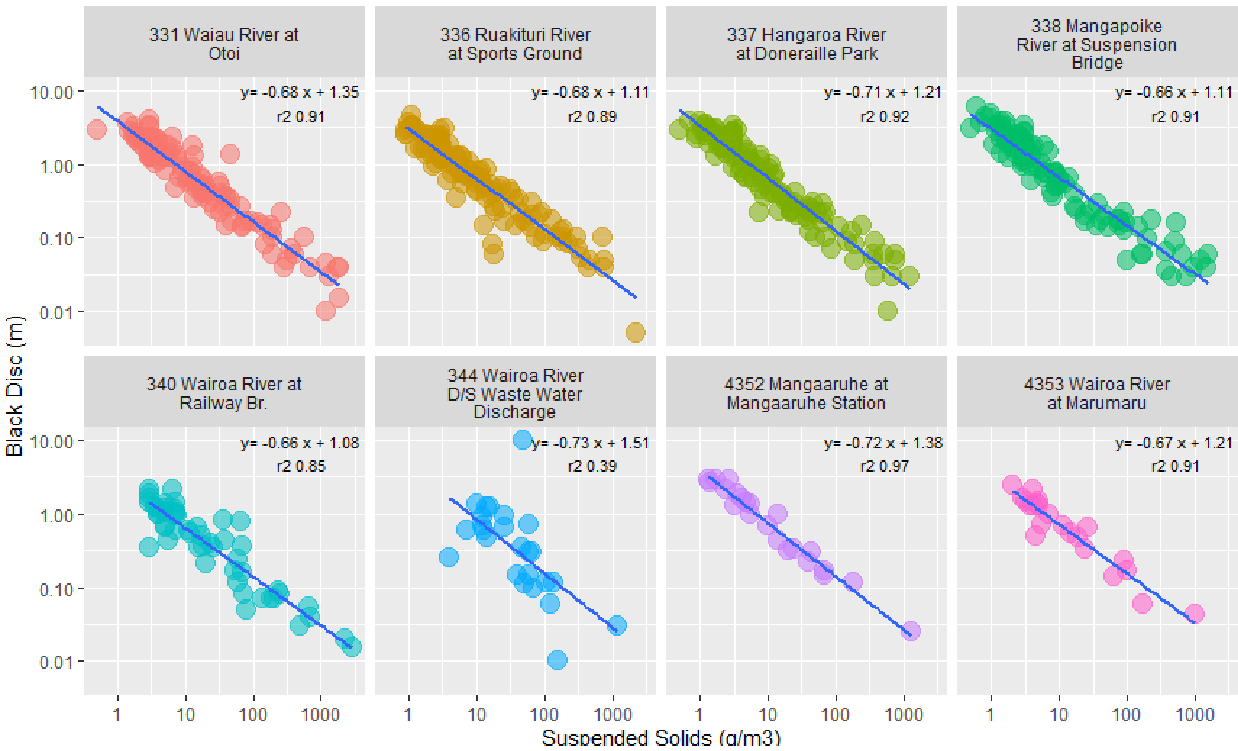
National models predict current and reference visual clarity (that is, the visual clarity expected with pre-human land use) from river suspended sediment class. The suspended sediment class is a classification of rivers into five classes that is relevant to suspended sediment. It is not a classification of the suspended sediment values. Reference values were obtained from Rick Stoffels, NIWA. The source data were from national datasets compile for MfE (Franklin et al. 2019). These reference values give some indication of how much clearer the streams might have been before development of the catchment. These data show that many reaches have a reference visual clarity of 2 m visual clarity, but in some (i.e., Mangaaruhe and Mangapoike) the reference visual clarity is lower because the river class is different. As discussed in relation to the NOF classes (Section 3.1) this is somewhat doubtful given the similar nature of the rivers.

Table 3-3: Measured (current), predicted and reference median visual clarity at monitoring sites.

Site Name	Measured median visual clarity	Predicted median visual clarity	Reference median visual clarity
Hangaroa River at Doneraille Park	0.93	1.30	2.01
Mangaaruhe at Mangaaruhe Station	0.99	1.50	1.11
Mangapoike River at Suspension Bridge	0.95	1.55	1.11
Ruakituri River at Sports Ground	0.83	1.30	2.01
Waiau River at Otoi	0.67	1.10	2.01
Wairoa River at Marumaru	0.71	1.24	2.01
Wairoa River at Railway Bridge	0.53	1.26	2.01
Wairoa River D/S Wastewater Discharge	0.35	1.29	2.01

3.3 Relationship between suspended sediment concentration and visual clarity

The relationship between suspended sediment concentration (SSC) and visual clarity can be used to determine how much change in suspended sediment concentration (OR SSC) might be required to achieve a specific change in visual clarity. This may also give an indication of the required change in suspended sediment *load* (Ministry for the Environment 2020). The relationships are shown in Figure 3.3. The exponent of the power relationship between visual clarity and SSC is the coefficient of the equations in the plots. For example, for the Waiau River at Otoi site, BD ~ $SS^{-0.68}$. The exponents are similar to, but slightly smaller than, the default exponent of -0.76 in the MfE guidance document (Ministry for the Environment 2020).



Suspended Solids Concentration (g/m^3)

Figure 3-3: Visual clarity (as measured by the black disc method) versus suspended solid concentration relationships. The equations are for the logarithm of black disc vs the logarithm of suspended solids.

3.4 Suspended sediment load reduction factor to meet visual clarity national bottom lines

The suspended sediment (SS) load reduction factor (or percentage) required to meet national bottom lines for visual clarity can be calculated from the required change in visual clarity and the exponent of the relationship between visual clarity and sediment concentration (Ministry for the Environment 2020). Vale et al. (2023) conducted such an analysis using the default exponent of -0.76, for a range of attribute band targets. Here we supplement the analysis of Vale et al. (2023) using exponents generated from the bottom line site data. The results are shown in Table 3-4, excluding the site D/S Wastewater. The results show that a considerable reduction in load is required to meet the bottom line at some sites, including a 4.1-fold reduction (76 % reduction) at the Wairoa at Railway Bridge site. The reduction factors from Vale et al. (2023) are smaller because a different exponent was used, but there are many areas of uncertainty in the load reduction analysis so that these discrepancies should not be considered significant.

Table 3-4: Reduction in sediment load to meet national bottom line, expressed as a factor reduction in load. N/A values mean that no load reduction is required.

Site Name	Median visual clarity (m)	Bottom line visual clarity (m)	SSC vs visual clarity exponent	SSC Reduction Factor	SSC reduction %	SS load reduction factor from Vale et al. (2023)	SS load reduction % from Vale et al. (2023)
Hangaroa River at Doneraille Park	0.93	1.34	-0.71	1.67	40	1.61	38
Mangaaruhe at Mangaaruhe Station	0.99	0.61	-0.72	N/A	N/A	N/A	N/A
Mangapoike River at Suspension Bridge	0.95	0.61	-0.66	N/A	N/A	N/A	N/A
Ruakituri River at Sports Ground	0.83	1.34	-0.68	2.02	50	1.89	47
Waiau River at Otoi	0.67	1.34	-0.68	2.79	64	2.50	60
Wairoa River at Marumaru	0.71	1.34	-0.67	2.61	62	2.33	57
Wairoa River at Railway Bridge	0.53	1.34	-0.66	4.10	76	3.33	70

4 Bed sediment characteristics in the lower river

For fish, fine sediment guidelines developed for MfE focus on visual clarity rather than deposited fine sediment. However, deposited fine sediment can affect some fish indirectly through higher-quality food source quality being associated with coarser bed composition as explained in Section 2.3. Therefore, below we consider bed sediment characteristics.

4.1 Estuarine reaches

Sediment texture (particle size distribution) in the lower river was measured annually by HBRC in the estuarine section of the river adjacent to Wairoa[6] (along with chemical parameters). In each sampling year, about 10 samples were taken on one sampling occasion. Results for complete years are summarised in Table 4-1. The results show a predominance of mud (<63 µm) and very fine sand (63–125 µm), with some fine sand (125 – 250 microns) in the sediment in the lower river. There was considerable inter-annual variability, suggesting winnowing of sediment or replacement with sediment from upstream or spatial variability in conjunction with random sampling locations. There was virtually no medium sand (250–500 µm) or coarser sediment (>500 µm). This is consistent with observations of nearshore sediment from visits to the site. In some places, muddy sediment accumulates, which makes river access hazardous. The fine sediment is consistent with soft-rock geology of the catchment erosional areas and low river gradient.

Table 4-1: Sediment particle size distribution percentages from the lower Wairoa River. Mean values across 10 sites by year, and average over all years. Some data were missing from 2020.

Year	Size class (µm)						
	<63	63-125	125-250	250-500	500-1000	1000-2000	>2000
2012	87.87	7.66	3.94	0.51	0.02	0.00	0.00
2013	53.90	38.95	6.03	0.84	0.20	0.07	0.07
2014	27.95	46.94	23.72	0.82	0.15	0.27	0.17
2015	22.50	50.11	24.97	1.79	0.44	0.18	0.00
2016	54.26	30.24	14.66	0.63	0.14	0.09	0.10
2017	63.76	23.63	11.22	0.85	0.37	0.07	0.10
2018	38.92	46.48	13.51	0.78	0.15	0.11	0.05
2019	26.55	47.46	24.36	0.97	0.16	0.24	0.26
2021	24.18	38.43	35.25	0.87	0.18	0.68	0.42
Average over years	43.99	36.69	17.90	0.89	0.20	0.20	0.14

4.2 Lower river and mid catchment

During the boat-based inspection of the lower Wairoa River (see Section 5), the riverbed was probed with a 4m pole. This technique, which is used as part of ecological condition surveys of non-wadeable streams, gives an indication of bed texture. At the rapids about 5 km upstream of Frasertown (the

[6] These data were taken largely in the area (or vicinity) of a grid with the 4 corners:
1) E1982878, N5667891
2) E1982902, N5667870
3) E1982852, N5667834
4) E1982859, N5667819

most upstream location surveyed), there was a hard bed (papa rock, that is soft mudstone/sandstone), with some gravel deposits. Downstream, there was generally soft sediment with little gravel, apart from occasional rock sills and gravel near the railway bridge and in the vicinity of Ruataniwha Marae, and some localised gravel near Awamate Lagoon. There were deep areas (>10 m) downstream of the sills, suggesting that the river can mobilise any deposits in those areas. These sill and scour holes are well known traditional stream features to mana whenua (pers. comm. Katarina Kawana), suggesting that they have persisted and that the riverbed has not built up or scoured down over recent periods.

Some records in the NZFFD include observations of riverbed texture. In the lower Waiau River the mud and sand proportions combined were generally <15%, that is, the sediment was mostly coarse. South of Frasertown, only one of the six sites had observations of sediment texture. That site was near Awamate and had mostly mud and a little gravel. A site at the downstream end of the Mangaaruhe River had <15% mud and sand, the downstream end of the Mangapoike (the river label in the river could be incorrect) had gravel and bedrock, a site on the Wairoa River upstream of that confluence had coarse sediment and bedrock, and a site just downstream of Te Reinga had coarse sediment and bedrock. Aerial imagery from Google Maps clearly shows riffles and bedrock in the upper Wairoa, indicative of coarse sediment. The sampling sites might be biased to coarser sediment areas. Generally, the picture is of coarse sediment in the upper Wairoa River and the lower part of its main tributaries, grading to fine sediment south of Frasertown. This is consistent with the much steeper river in the upper sections and tributaries. For example, by Frasertown (22 km from the mouth) the river surface is about 5 m above sea level, 12 m at Marumaru (10 km further upstream), and 32 m just downstream of Te Reina (a further 18 km upstream).

Five of from six sites in the mid catchment in 1995 had less than or equal to 30% sand and mud (data are presented in fish habitat survey results in Section 7.3.1). This compares with the NOF bottom line for deposited sediment for wadeable rivers of 26% for river classes that predominate in the Wairoa catchment (but note that this is only a rough comparison because fish survey methods). Following Cyclone Gabrielle, all but one of the sites had greater than or equal 30% sand and mud. This level of deposited fine sediment is indicative of a high impact of deposited fine sediment on instream biota, including sensitive fish, according to grade descriptions in the NOF. Four sites had 45% or more of sand or mud. The two upper sites, Mangahohi and Mangaone 2, did not have increases in fine sediment content.

The NOF grading for deposited fine sediment does not apply to river segment that are considered to be naturally soft bottomed. This can be determined by the REC class falling within one of 5 classes. Nearly all of the segments in the Wairoa are of deposited sediment class 3 or 4, and none are classed as naturally soft-bottomed. Under Section 3.25 of the NPS-FM, if a site is currently soft-bottomed, the council must consider whether it is naturally soft-bottomed and whether it can be returned to a hard-bottom condition. From our assessment, nearly all of the river downstream of Frasertown is soft-bottom. The river geomorphology assessment and sediment coring work in the next two sections were intended to shed some light on this question.

5 River geomorphology assessment

A brief and provisional assessment of riverbed sediment characteristics was conducted in January 2023, before Cyclone Gabrielle. The work was led by Professor Ian Fuller (Massey University) and is presented in a separate report (Fuller 2023). The purpose of the work was to establish whether the nature of the river was different before the human induced land disturbance in the early 1900's would have increased erosion rates. If, for example, the river was historically gravel-dominated, then that would provide a reference point for remediation. While identifying historical conditions was the ultimate purpose, the initial survey was designed to obtain preliminary information that might guide further, more-detailed, investigations. The public summary of the report states:

"The Wairoa River carries large quantities of fine sediment (clays, silts and sands). This fine sediment cloaks both the bed and the banks of the river and the river appears to be mainly soft-bottomed downstream from Frasertown. The question this investigation seeks to begin to answer is whether the river has always been characterised by such large amounts of fine sediment, or whether changes in land-use in the catchment may have altered the condition of the river. This investigation used the sediments exposed in the riverbanks as a window back in time. Gravels were seen in the riverbanks as far down the river as immediately below the old river channel at Awamate (now the Awamate Lagoon), but gravels were not seen in the bank where the old Awamate channel has been plugged. Estimates of the age of these riverbank deposits was provided using radiocarbon dating of wood recovered from the base of banks at four locations along the lower Wairoa River. Preliminary findings suggest that the Wairoa River as far as Awamate was gravel-bedded until at least 3000 years ago. Wood underneath thick fines infilling the Awamate channel indicates these deposits are younger than 1365 years old. More work is needed to understand the details of these changes to the sediments in the Wairoa River, but these results are not inconsistent with the idea that land clearance and subsequent escalation of catchment erosion has contributed to the condition of the river as we see it today."

In short, it seems that the upper Wairoa River had gravel bed about 3000 years ago at places where there is now fine sediment. However, it is not yet known how widespread those gravels were, nor whether the transition to fine sediment occurred since land development or whether it occurred prior to land clearance. There is no evidence from preliminary observations in the lower Wairoa River that there was recently a gravel bed.

Follow-up investigations were proposed, including deep coring and dating, to investigate the timing of deposits in the last 3000 years, the extent of the gravels, and more detail on the infilling of the old channel flowing from the Awamate lagoon. This would be a large research project.

6 Sediment coring study at river mouth

6.1 Purpose, site selection, and methods

A sediment coring study was conducted in the lower estuary with the aim of providing information on historical sediment texture (size classes) and changes in deposition rates.

Initially, it was hoped to be able to work in depositional areas in the lower river, such as floodplain deposits or infilled old channels. However, from viewing aerial and satellite images and lidar-based maps, and site inspection and conversations with HBRC, we were not able to identify suitable depositional sampling locations. The lack of suitable sites is because the lower river is often confined in steep banks and deposits within are expected to be fairly ephemeral (remaining for years rather than decades). Higher floodplains were usually well above the river, and may represent deposits from the last interglacial period when the sea came inland to about Frasertown, or are inundated only in extreme events.

Considering the difficulties with finding a suitable location beside the river, it was decided to focus sampling on the river-mouth or estuary areas. Deposition typically occurs in estuarine areas, and changes in sediment composition over time have been observed in estuaries around New Zealand, so there were reasonable prospects for gaining some useful information.

Candidate sites were identified. The southern lagoon (Whakamahi Lagoon) was discarded as a potential site because the estuary mouth is known to shift into that area (from inspection of historical images in Google Maps and as advised by Katerina Kawana) and attention was focussed to the Ngamoto Lagoon side of the river. With assistance from Tatau Tatou, permission for access was granted from Te Ruahina Marae.

The resulting sampling locations are shown in Figure 6-1

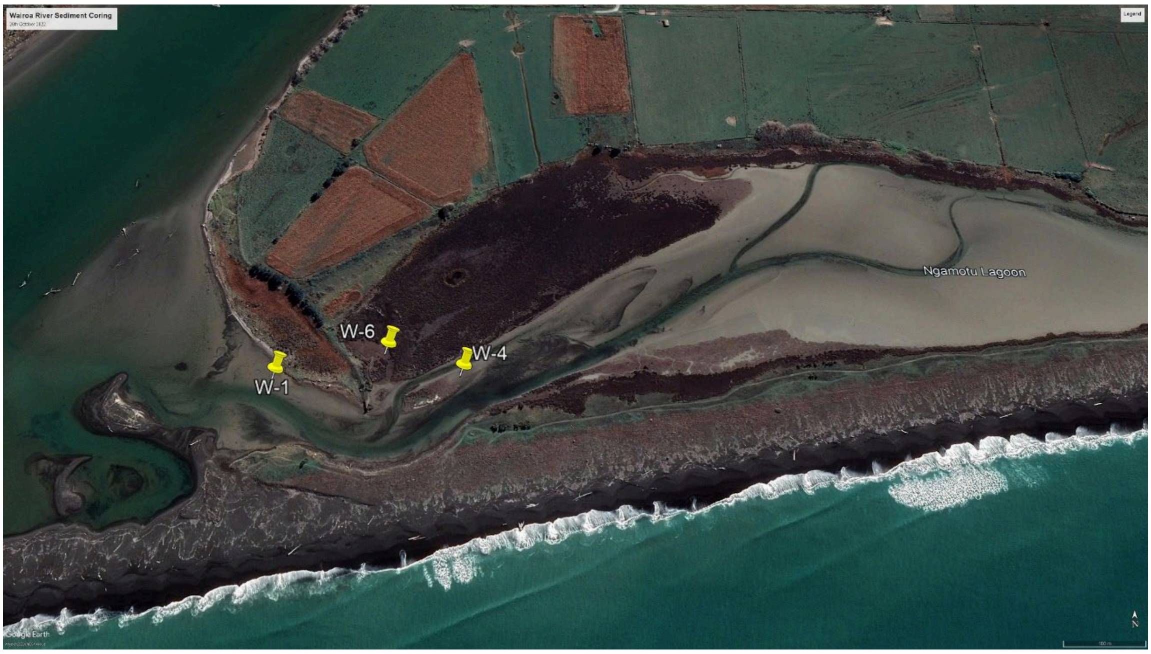


Figure 6-1: Sampling locations at the river mouth and Ngamotu Lagoon.

At each site, cores about 1.2 m in length and 80mm diameter contained within clear plastic casing were taken using a manual percussion corer. An example core is shown in Figure 6-3. Also, slot samples (sediment slabs) about 0.7m deep with clear plastic walls were taken to enable x-ray imaging. One core (W6) was discarded because it was clumpy and more likely influenced by soil.

X-radiographs of the sediment slabs collected in the Perspex-tray sediment corers were made prior to radioisotope dating. The slabs were imaged using a Varian PaxScan 4030E amorphous silicon digital detector panel (Figure 6-2). X-rays were generated using an Ultra EPX-F2800 portable x-ray source with a typical exposure of 25 mAs (milliamp seconds) and 50–60 kiloelectron Volts (keV). The raw x-ray images were post-processed using the Image-J software package.

Figure 6-2: NIWA digital x-ray system with a slap mounted read for imaging. Photo: Ron Ovenden, NIWA.

Following inspection of the images, the sediment cores were sub-sampled at selected depths for gamma spectrometry analysis to obtain the activities of radioisotopes commonly used for sediment dating (i.e., Cs-137, Pb-210, Ra-226 and Ra-228). This was to guide further sampling, and possible application of methods such as radiocarbon dating of shells and pollen analysis. Samples were analysed by ESR National Radiation Laboratory. Appendix A provides a description of lead-210 and caesium-137 dating.

Figure 6-3: Example sediment core in the Perspex coring tube. This sample from site W1.

6.2 Results

X-radiographs from core site W1 are shown in Figure 6-4. The image shows the intact (i.e., minimal mixing) stratigraphy of the sediment column (which is not evident from visual examination). The x-radiographs indicate that the sediment depositing at this site is primarily composed of interlayered sequences of fine-grained muds and sand, of centimetre to decimetre thickness. There is minimal evidence of burrows associated with the feeding and/or burrowing activities of animals. There are several ~2-3 cm diameter bivalve shells below 30cm depth. The x-radiograph indicates that sedimentation at site W1 is dominated by physical processes associated sedimentation with minimal mixing of the sediment after deposition. This is consistent with a river-mouth lagoon environment with large pulses of sediment delivered during periods of high discharge.

Table 6-1 below summarises the radioisotope data.

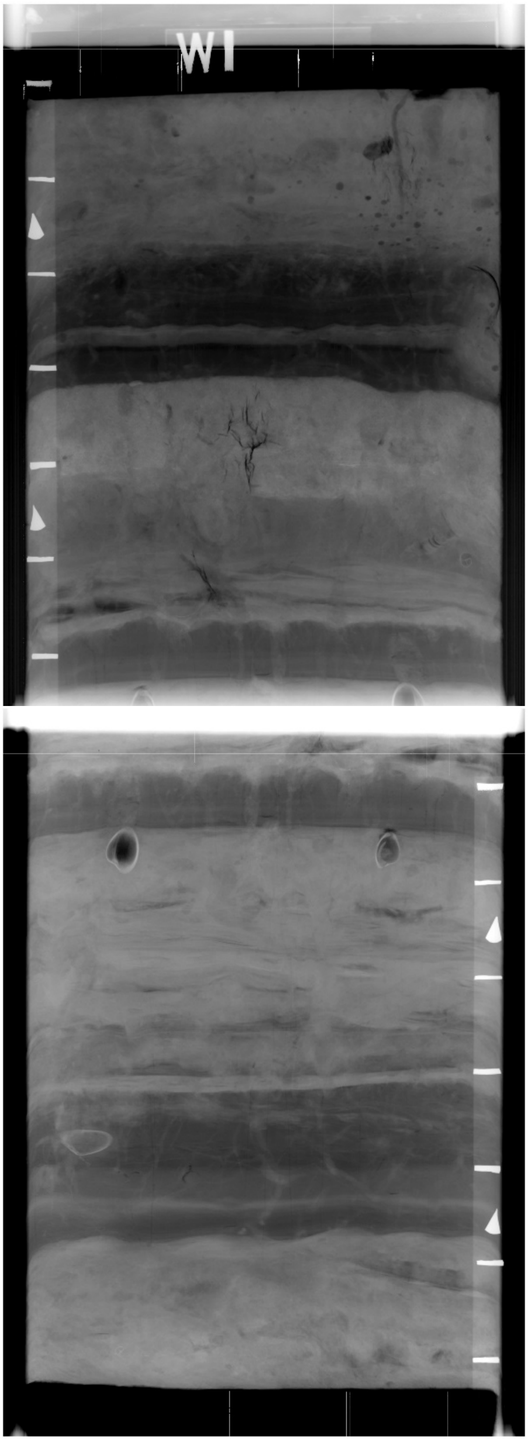


Figure 6-4: X-Ray image of the core from site W1. The top image was from 0 to approximately 32cm depth, while the bottom image was from 28 to 60 cm deep below the ground surface (with some . The scale markers on the LHS of the top image and RHS of the lower image have a 5-cm increment.

Table 6-1: Summary of radioisotope data from cores W1 and W4.

		Pb-210		Cs-137	
Sample ID	**Depth (cm)**	**Activity**	**Uncertainty**	**Activity**	**Uncertainty**
Site W4					
W1 0-1cm	0.5	29.2	6.5	< 0.72	N/A
W1 5-6 cm	5.5	24.9	5.8	< 0.68	N/A
W1 10-11 cm	10.5	30.3	9	< 0.93	N/A
W1 15-16 cm	15.5	27.3	6.6	< 0.78	N/A
W1 20-21 cm	20.5	24.1	5.3	< 0.64	N/A
W1 30-31cm	30.5	27.6	8.5	< 0.95	N/A
W1 40-41cm	40.5	24.9	4.5	< 0.39	N/A
W1 50-51cm	50.5	28.7	7.6	< 0.54	N/A
Site W4					
W4 0-1cm	0.5	31.6	5	< 0.72	N/A
W4 5-6 cm	5.5	31.3	5	< 0.78	N/A
W4 10-11 cm	10.5	30.7	4.7	< 0.67	N/A
W4 15-16 cm		31.9	5.1	< 0.72	N/A
W4 20-21 cm		30.7	4.9	< 0.79	N/A
W4 30-31cm		26	4.4	< 0.71	N/A
W4 40-41cm		30	4.8	< 0.80	N/A
W4 50-51cm		32	4.2	0.46	0.21

6.3 Interpretation

The excess Pb-210 profiles observed in cores W1 and W4 are complex. The usual basis for dating is the fitting of a natural log-linear regression to the excess Pb-210 activity in the zone of sediment accumulation, often below a surface mixed layer (SML). The SML is typically up to several-cm thick indicated by constant excess Pb-210 activity. The zone of accumulation is observed as an exponential decline in excess Pb-210 activity with depth. As can be seen in Figure 6-5 to Figure 6-7, the excess Pb-210 activity profiles in the core vary substantially from an exponential profile. The intact nature of the stratigraphy (i.e., minimal mixing) suggests that these profile data represent natural variation in excess Pb-210 activity within discrete event layers (e.g., top 10 cm muddy sand), deposited over time scales of days. In comparison, the rather than years-decades assumed by the steady state Pb-210 SAR (Sediment Accumulation Rate) model (Appendix, Pb-210 has a 22 year half-life). In this case the variability in excess Pb-210 activity with depth may represent differences in catchment sources (e.g., topsoil vs subsoil).

Caesum-137 (post-1950s) was also absent from all but one sample analysed in the two cores. The low initial excess Pb-210 along with absence of Cs-137 (Cs-137 usually indicates topsoil erosion) suggests that the bulk of this sediment is largely composed of eroded subsoil.

The calculated apparent Pb-210 SAR for sections of the profiles in both cores are:

- Core W1, depth 0-11 cm: 3.0 mm/year.
- Core W1, depth 15-31 cm: 14.5 m/year.
- Core W4, depth 5-21 cm: 145 m/year.

The apparent high SAR, due to the steep excess Pb-210 activity profiles area again consistent with event deposition layers. There is high uncertainty with these SAR estimates because the slopes of the depth data are uncertain, to the point that they are only useful as coarse indicators of high episodic deposition.

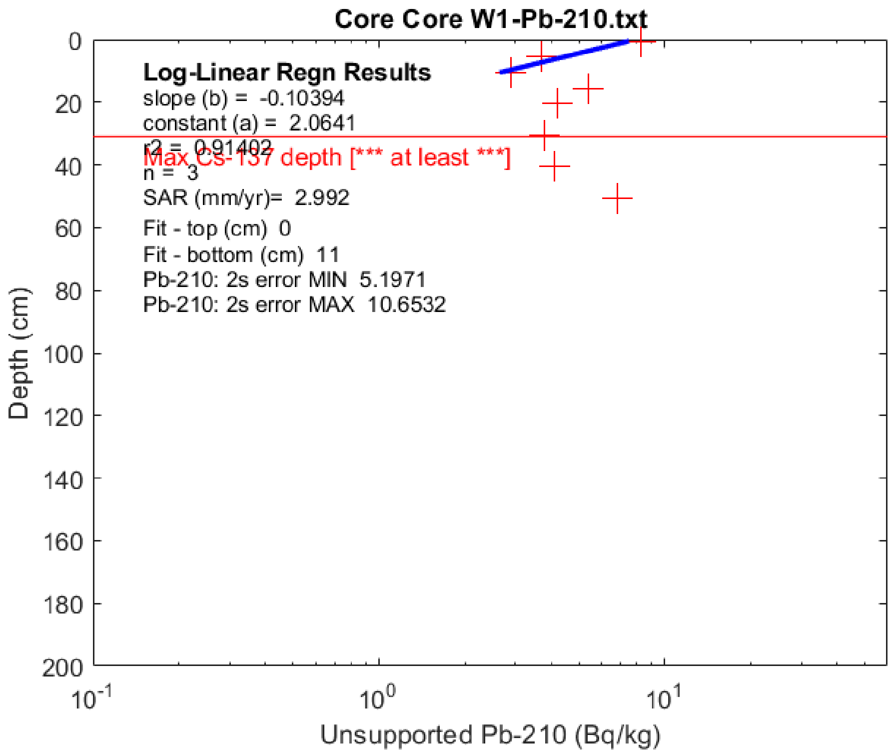


Figure 6-5: Core W1 –sediment accumulation rates (SAR) 0-11 cm depth. Excess ^{210}Pb activity profiles. Time-averaged SAR (mm yr^{-1}) derived from regression fit to natural log-transformed ^{210}Pb data.

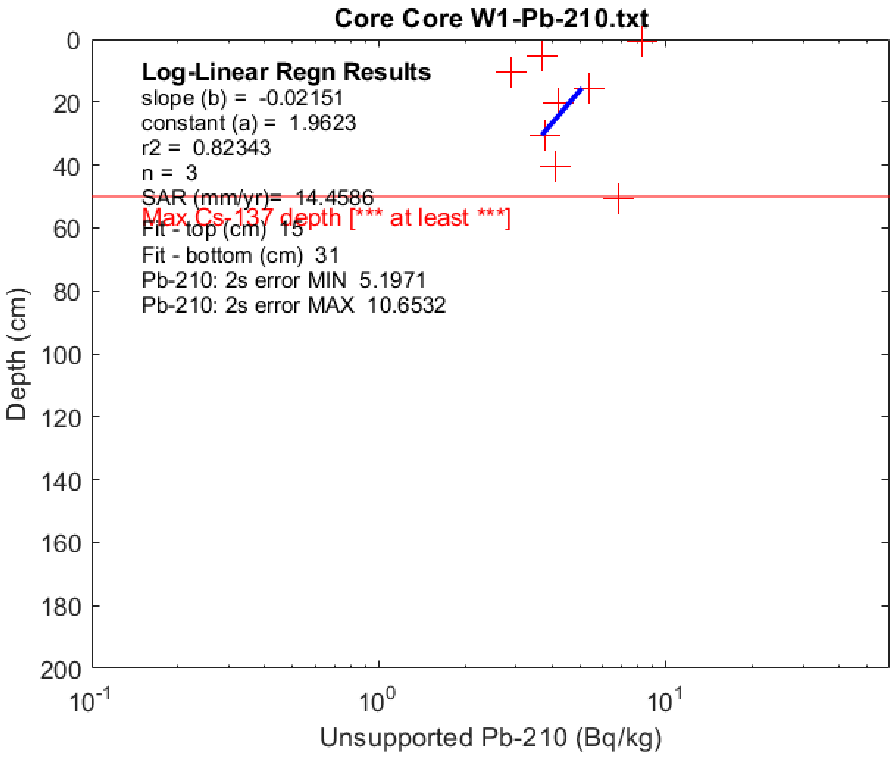


Figure 6-6: Core W2 –sediment accumulation rates (SAR) 15-31 cm depth. Excess ^{210}Pb activity profiles. Time-averaged SAR (mm yr^{-1}) derived from regression fit to natural log-transformed ^{210}Pb data.

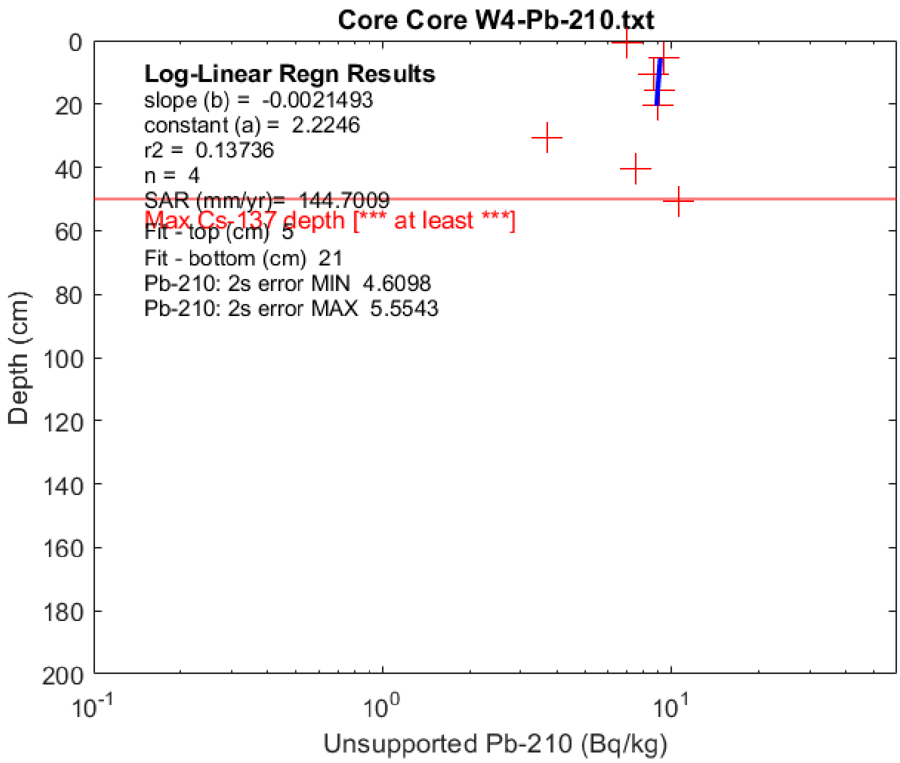


Figure 6-7: Core W4 –sediment accumulation rates (SAR). Excess ^{210}Pb activity profiles. Time-averaged SAR (mm yr^{-1}) derived from regression fit to natural log-transformed ^{210}Pb data (5-21 cm depth).

7 Impacts from recent large storms including Cyclone Gabrielle

Cyclone Gabrielle had massive effects on flows in the Wairoa River catchment in mid-February 2023. Eastern areas of the catchment received more than 500mm of rain during the weather event. This resulted in massive increases in water levels and flow rates at gauging stations in the catchment (Table 7-1). The consequences for fish habitats in the mid-catchment appeared very different to those in the lower catchment.

There was also a large flood in March 2022, which had significant impacts on the catchment and rivers (from personal observations and pers. comm. Katerina Kawana).

Table 7-1: Maximum river level and flow at six sites in the Waiau catchment before (12 February 2023) and because of Cyclone Gabrielle (14 February 2023). Data sourced from Hawke's Bay Regional Council.

Site	12 February		14 February	
	Maximum level (m)	Maximum flow (m^3/s)	Maximum level (m) and time	Maximum flow (m^3/s)
Waiau River at Otoi	1.1	16.7	5.0 (0415)	838
Waiau River at Ardkeen	3.1	87.1	14.1 (0815)	1,654
Ruakituri River at Tauwharetoi Climate	1.0	16.0	10.9 (0400)	989
Mangapoike River at Gorge	0.8	-	9.4 (0400)	-
Wairoa River at Marumaru	0.4	19.9	18.5 (0600)	4,962
Wairoa River at Railway Bridge	11.1	-	22.5 (0915)	-

7.1 Changes in sediment concentrations following recent large storms

One of the potential changes following large storms is an increase in sediment concentration for the same flow rate. It takes years for sediment concentrations to return to pre-storm levels following large storm disturbances, as observed in the Motueka catchment in Nelson (Hicks, DM et al. 2008).

Sediment concentration data before and after the two recent large storms (March 2022 and Gabriel in 2023) are show in Figure 7-1 and Figure 7-2, based on regular monthly sampling and data provided by HBRC[7]. There is no sign of increased concentrations for the same flow rate after the storms, which is surprising given the large amounts of catchment erosion. This analysis is only based on monthly sampling, so the result is only tentative and does not indicate what is happening in storm flows or to sediment loads. However, it is an indication that fish that are sensitive to water visual clarity may not have a protracted 'hangover' from elevated suspended sediment concentrations.

Flow is not measured at Wairoa River at Railway Bridge, but using daily flow from Marumaru, it seems that the Railway Bridge site also does not have an increase in concentration (for a given flow rate).

[7] The provided data started in July 2019 for Marumaru, and January 2019 for Railway Bridge.

Despite the apparent lack of increase in suspended sediment (and likely lack of reduction in visual clarity), there are geomorphic disturbances and sediment deposition that could have impacted fish, as discussed in the following sections.

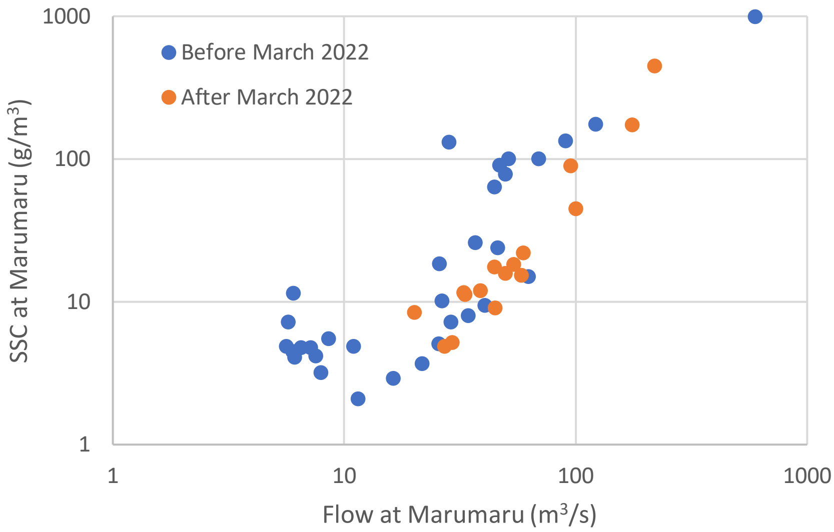


Figure 7-1: Comparison of sediment-versus-flow relationship for the Wairoa River at Marumaru before and after the two large recent storms. Flow rates are hourly flows.

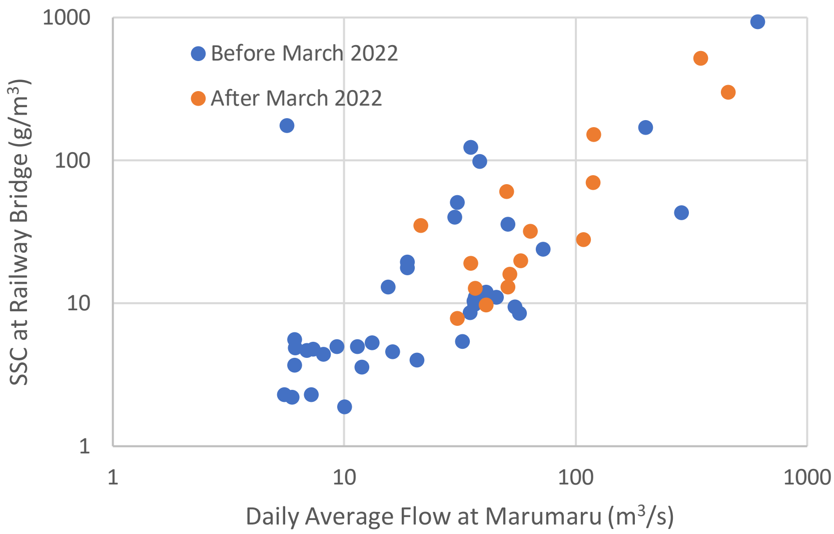


Figure 7-2: Comparison of sediment-versus-flow relationship for the Wairoa River at Railway Bridge before and after the two large recent storms. Flows are daily flows at Marumaru because flow is not measured continuously at the Railway Bridge.

7.2 Geomorphic change in the lower Wairoa River from Cyclone Gabrielle

Following the devastation of Cyclone Gabrielle, rapid response efforts were needed to map stop-bank breaches, infrastructure damage, and geomorphic change. NIWA, University of Canterbury, and Christchurch Helicopters mobilised to collect LiDAR data of impacted rivers and floodplains in Te Matau-a-Māui (Hawkes Bay) and Tairāwhiti (Gisborne). LINZ also mobilised light aircraft to capture aerial imagery for disaster response and assessment of flood extents.

7.2.1 Geomorphic change data acquisition and processing

LINZ aerial imagery was flown from the 19th to 21st of February 2023. Helicopter LiDAR flights were conducted from the 23rd of February to the 15th March 2023, with the Wairoa River covered on the 9th of March. The LiDAR point cloud data were processed by University of Canterbury to generate Digital Elevation Models (DEMs) and publicly released via the LINZ data portal[8]. The LiDAR DEM was then differenced from the HBRC Regional LiDAR, which was collected from the 11th November 2020 to the 24th of January 2021 by Ocean Infinity, to generate a Digital Elevation Model of Difference (DOD). This was performed for the purpose of qualitative assessment of bank erosion in the Wairoa River at key locations of interest such as the confluence with the Huramua Stream. Additional vertical control checks of elevation accuracy were not performed (beyond those undertaken by the University of Canterbury when processing the LiDAR point cloud to generate the original DEM). These checks are recommended if further work quantifying bank erosion and sediment inputs to the river is required. Since the Ocean Infinity LiDAR was collected in 2020/21 it should also be noted that the geomorphic change detected is cumulative between this time and the 15th March 2023 when the helicopter LiDAR surveys took place. Thus, it may include some geomorphic change from storm events other than Cyclone Gabrielle.

7.2.2 Geomorphic change in the Wairoa River

The LINZ aerial imagery, helicopter LiDAR DEMs, and DODs provide an excellent source of information for identifying bank erosion and geomorphic change in the Wairoa River. There was extensive bank erosion throughout the Wairoa River and its tributaries, based on observations of the LiDAR DEMs and field observations. This is likely to have serious impacts for fish habitat and bed substrate. Examples are shown in Figure 7-3 to Figure 7-7, which include the Huramua Stream confluence and Awatere Stream (locations of interest for whitebait spawning, see Section 7.3.2), Ngamotu Lagoon (of interest for deposition and coring analysis, Section 6), and changes at a relict (historical) oxbow lake (Awamate lagoon which is infilling, Section 5). The data underpinning these figures and analysis only became available near the end of this project and should be treated as preliminary.

These preliminary results show:

- elevation reductions (apparent erosion) around the Waiau-Wairoa confluence,
- variable erosion and deposition on the lower Haramua Stream,
- some erosion along the lower Awatere Stream,
- little change in the main body of Ngamotu Lagoon but some apparent erosion around the fringes, and
- some infilling of the Awamate oxbow.

Some of the results are questionable. For example, visual inspection of the Awatere Stream did not show erosion (see Section 7.3.2) which contrasts with the apparent erosion from the LiDAR data. This could be related to changes in vegetation rather than ground surface elevation. Further work is therefore needed to confirm whether the LiDAR elevations are ground surface rather than vegetation.

[8] https://data.linz.govt.nz/layer/114544-gisborne-and-hawkes-bay-cyclone-gabrielle-river-flood-lidar-1m-dem-2023/

Detailed analysis of these datasets would be needed to quantify bank erosion volumes, bank retreat, and changes in riparian vegetation. This is recommended future work, which will give a better understand of the impacts of Cyclone Gabrielle, the effectiveness of riparian vegetation in mitigating erosion, the potential impacts of future extreme weather events, and how to prepare better to mitigate these impacts.

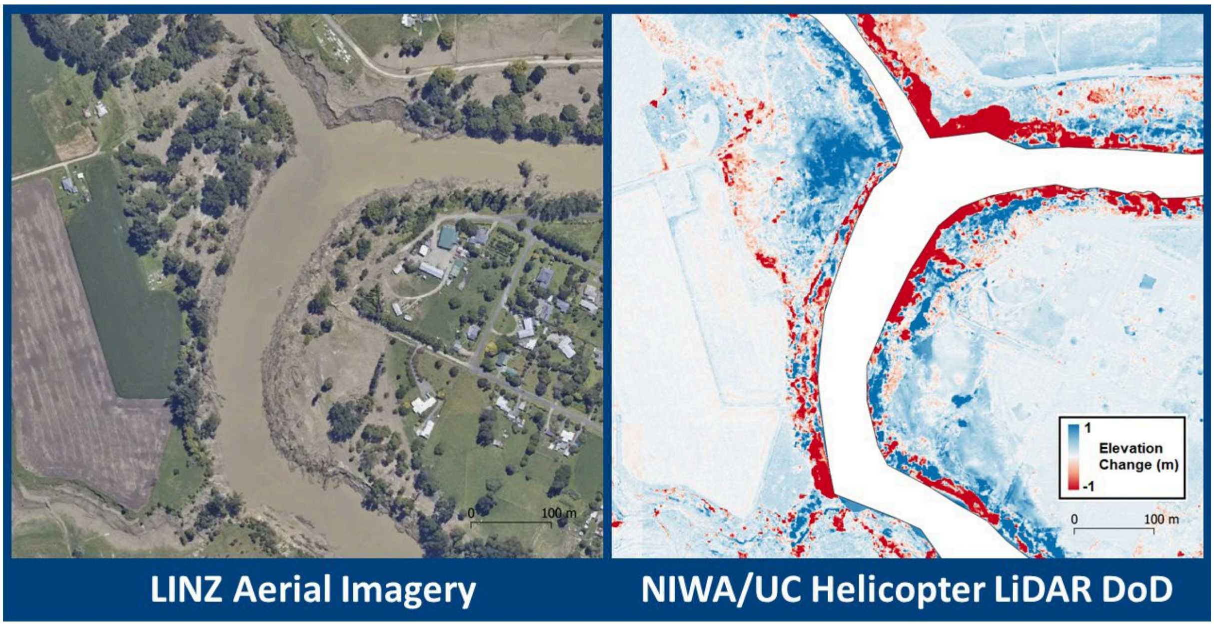


Figure 7-3: Change in elevation for the Waiau River confluence with Wairoa River. Red indicates erosion, blue deposition.

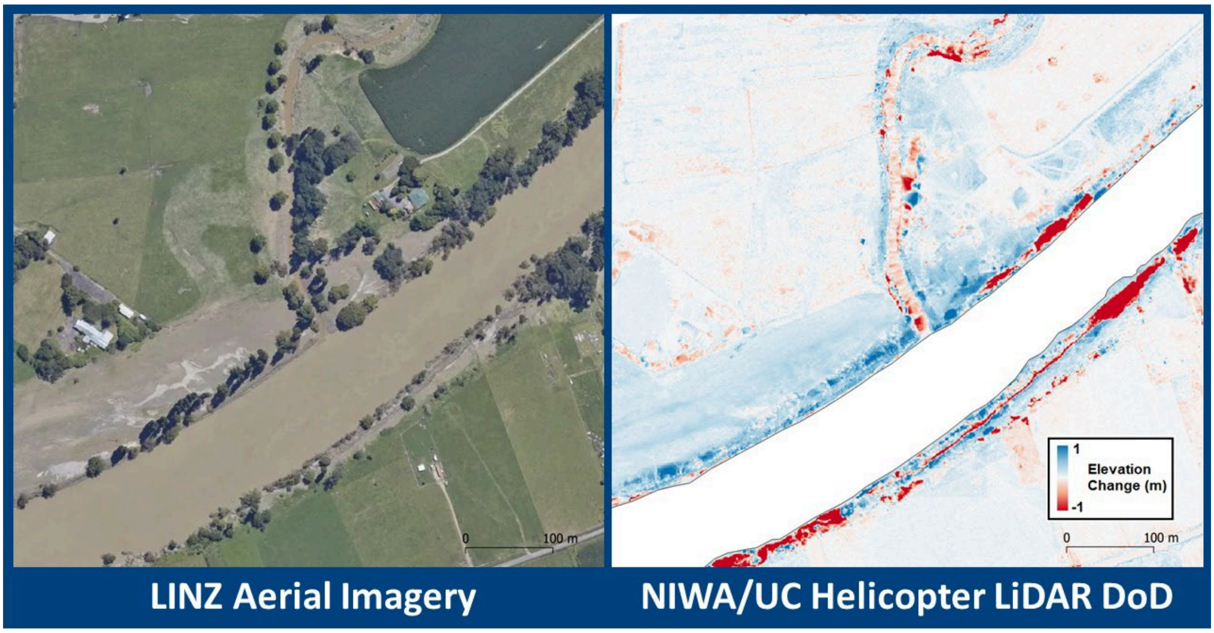


Figure 7-4: Change in elevation for the Huramua Stream confluence with Wairoa River. Red indicates erosion, blue deposition.

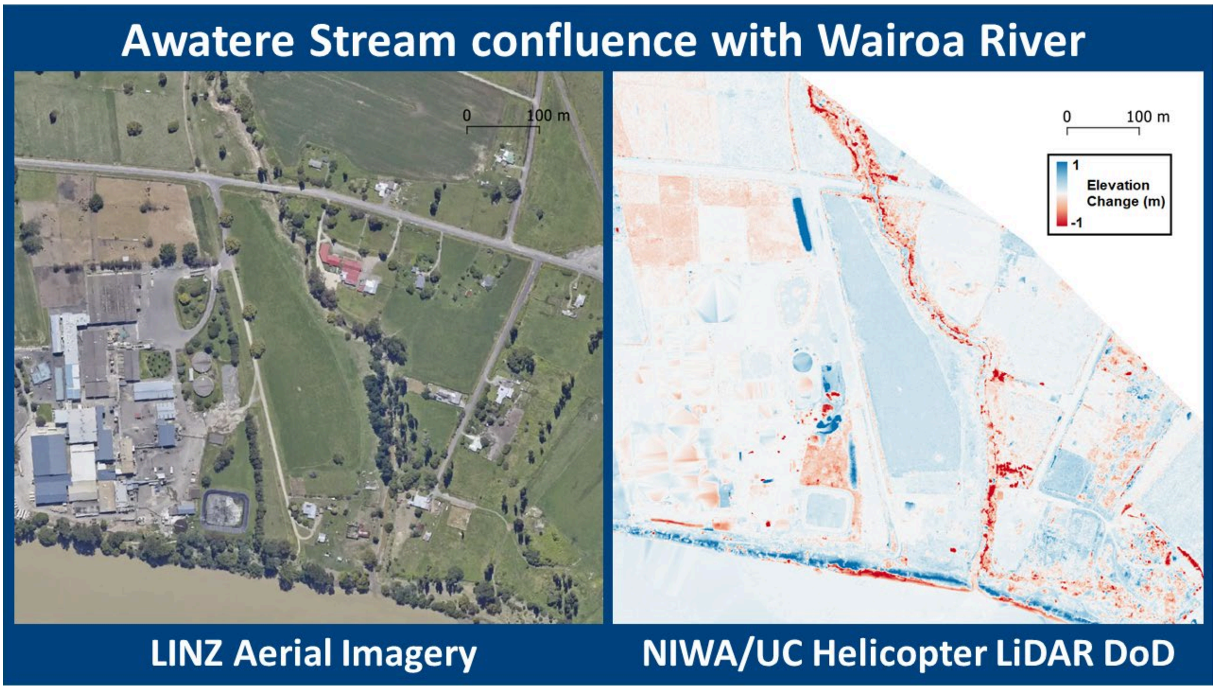


Figure 7-5: Change in elevation Awatere Stream. Red indicates erosion, blue deposition. The whitebait spawning site is south of the road towards the top of the diagram.

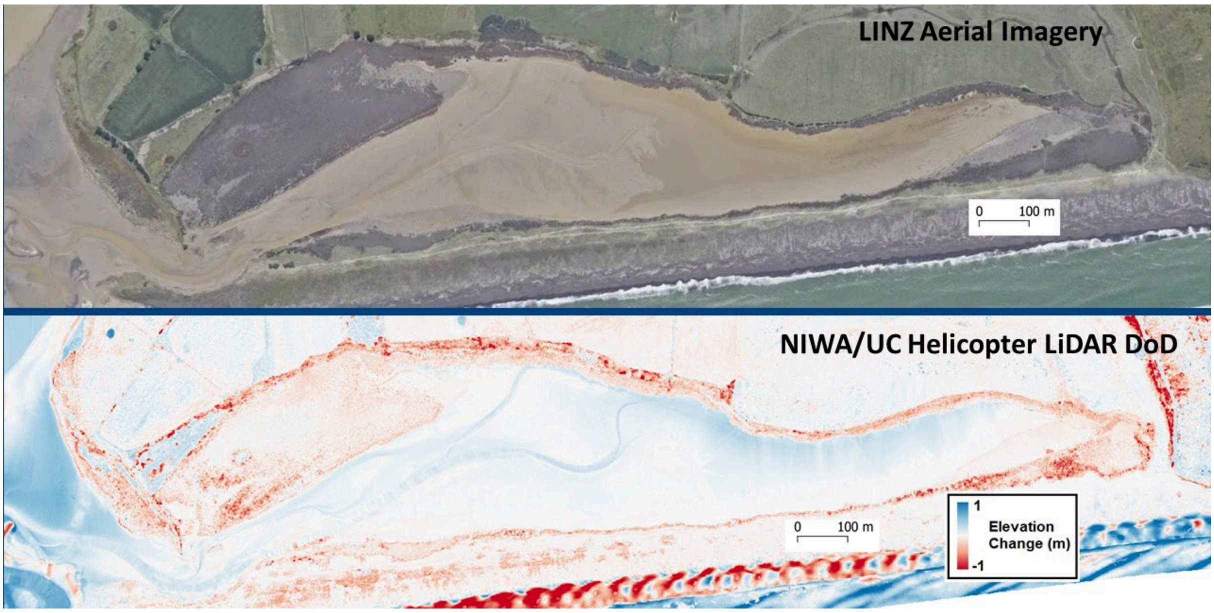


Figure 7-6: Change in elevation Ngamotu Lagoon – Wairoa River. Red indicates erosion, blue deposition.

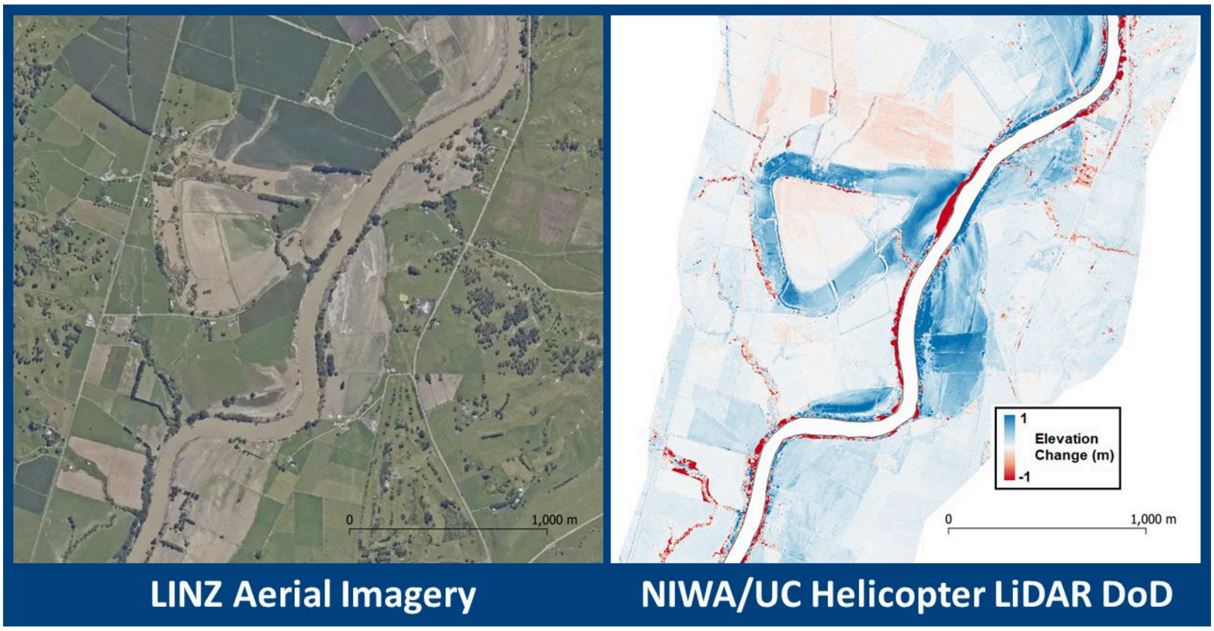


Figure 7-7: Change in elevation Wairoa River at the historical oxbow lake around Ngamotu Lagoon. Red indicates erosion , blue deposition.

7.3 Preliminary assessment of mid-catchment fish habitat and īnanga spawning site impacts from Cyclone Gabrielle

7.3.1 Mid-catchment fish habitat

Methods

Six streams in the mid-catchment, that had been surveyed for resident fish in December 1995, were revisited in September 2023 (seven months after Cyclone Gabrielle) (Figure 7-8). This was to get an indication of changes that might have occurred due to Cyclone Gabrielle, although we cannot rule out the possibility that changes occurred before Cyclone Gabrielle, because there is no intervening survey.

At each of the streams instream habitat was assessed using a Rapid Bioassessment Protocol (RBP). The RBP, which was developed by the U.S. Environmental Protection Agency provides a qualitative evaluation of the structure of the surrounding physical habitat that influences the water quality and the condition of the resident aquatic community (Barbour et al. 1996). For streams, the RBP assesses the habitat by looking the quality of the substrate, channel morphology, bank structure, and riparian vegetation. All parameters are evaluated and rated on a numerical scale of 0 to 20 (highest) for each sampling reach. The ratings are then totalled and compared to a reference condition to provide a final habitat ranking.

Each of the six streams was surveyed in December 1995 using the New Zealand Freshwater Fish Database (NZFFD) habitat criteria and fish sampling protocols. The same criteria were used to re-assess instream habitat in September 2023. However, the fish communities were not resurveyed.

Fish surveys were not completed in 2023. However, using changes to key habitats (described above) as a guide it is possible to comment on the effects of Cyclone Gabrielle on fish communities. The prospects for recovery and rehabilitation are addressed in Section 8.

In 1995, the fish communities in most of the six streams were numerically dominated by īnanga, eels and bullies. Torrentfish and common smelt were only present at some sites. Analysis of the impacts of Cyclone Gabrielle on the mid-catchment focusses on these fish species. Kōaro are excluded as they are expected to occur only in the upper catchment.

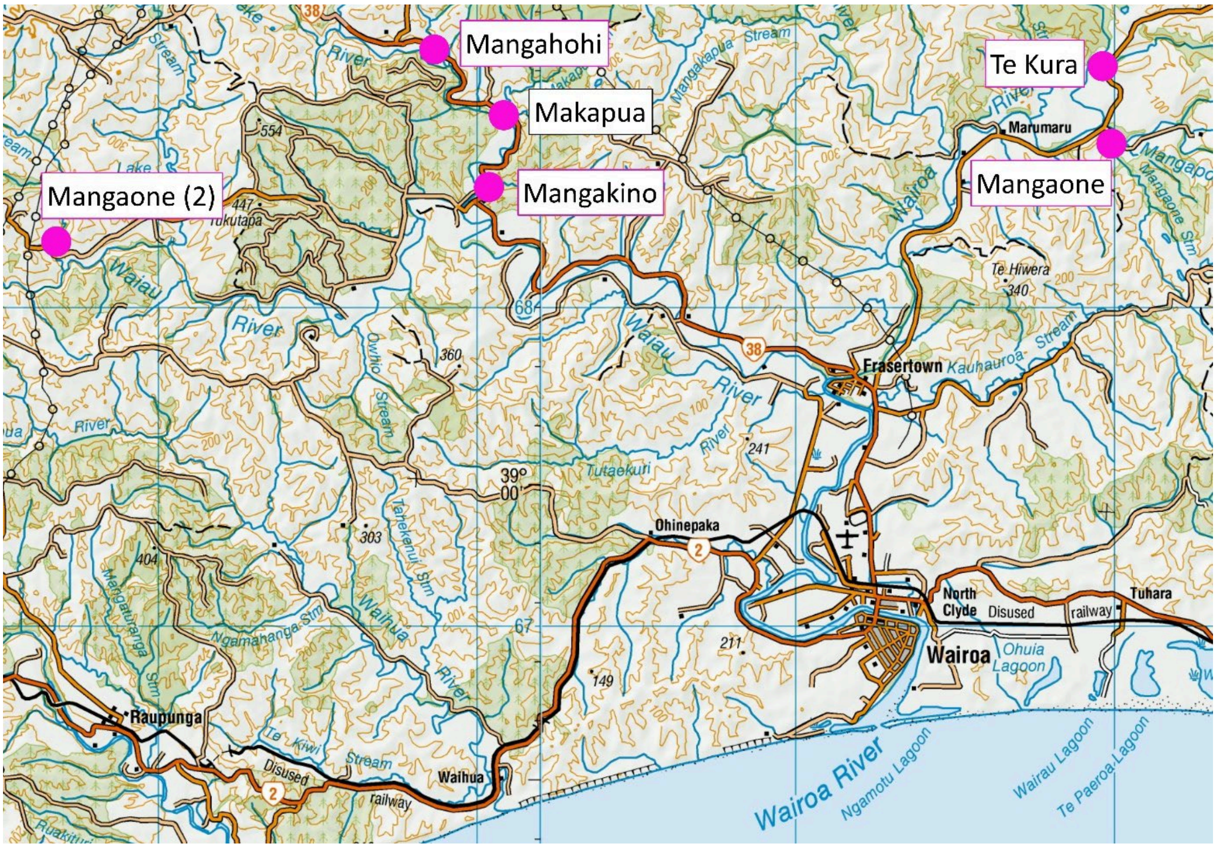


Figure 7-8: Six mid-catchment streams that were assessed for fish habitat quality in September 2023 following previous surveys in December 1995. Note that there are two Mangaone Streams in the Wairoa catchment.

Changes to stream habitat

The six stream sites were between 41 and 69 km from the ocean (Table 7-2) and ranged in elevation from 15–60 m. Generally, the average width of the sample reaches had not changed markedly from that recorded in 1995. The average depth of most streams appeared to have decreased from that recorded in 1995, but it had not rained in the Wairoa catchment for 10 days prior to the September 2023 surveys. There were increases in the mud content in the bed sediment for most sites, with a maximum of 45% increase at Makapua.

Mangaone, Mangakino and Makapua Streams were all ranked in a 'marginal' state by the Rapid Bioassessment Protocol (see BPR ranking in the top section of Table 7-2. These low rankings were mainly caused by the unstable condition of the substrate (Figure 7-9), the amount of deposited sediment (Figure 7-10) and poor bank stability (Figure 7-11). Sites that were higher in the catchment (e.g., Mangahohi and Mangaone 2 Streams) were ranked more highly. Although relatively low in the catchment, Te Kura Stream ranked relatively highly because of extensive riparian vegetation and more-stable instream substrate (Figure 7-12).

In the photographs (Figure 7-9 to Figure 7-17) the visual clarity appears high, despite large disturbances to the stream beds and banks. This aligns with the observation of little change in concentration in the mainstem for a give flow rate (as discussed in Section 7.1), based on monthly observations. These observations are tentative, but suggest that any impacts of the storms on fish could be related more to changes in bed composition and riparian conditions rather than visual clarity.

Table 7-2: Comparison of fish habitats in six mid-catchment streams before (1995) and after Cyclone Gabrielle. Instream habitat was quantified using a Rapid Bioassessment protocol (RBP) and the categorisation tools from the New Zealand Freshwater Fish Database. Fish abundances from 1995.

Site Name		Mangaone		Te Kura		Mangakino		Makapua		Mangahohi		Mangaone 2	
REC segment		8156071		8154086		8157206		8155521		8153505		8159144	
Distance to ocean (km)		41.4		43.5		47.5		52.5		56.7		68.4	
Site elevation (m)		15		18		40		40		60		60	
RBP ranking, 2023 (%)		**Marginal (37)**		**Suboptimal (75.5)**		**Marginal (33)**		**Marginal (36)**		**Suboptimal (75)**		**Suboptimal (67.5)**	
Detailed data													
Date surveyed		1995	2023	1995	2023	1995	2023	1995	2023	1995	2023	1995	2023
Average stream width		2	2	2	3	3	2	2	3	3	3	5	6.5
Average stream depth		0.5	0.3	0.6	0.3	1	0.4	0.4	0.5	0.3	0.1	0.5	0.3
Habitat (% cover)	Backwater					40	10						
	Pool	40	60	50	70	30	40	40	85	40	25		30
	Run	50	10	40	10	20	5	40	10	30	10	50	30
	Riffle	10	10	10	20	10	30	20	5	30	65	50	30
	Rapid		20										10
Substrate (% cover)	Mud	10	25	50	65	20	55	20	65	30		30	15
	Sand		20	5	15				30		10		15
	Gravel	20	20	15	10	15	5	60	5	30	15	20	
	Cobbles	5	20	10	10	20	10	20		30	70	30	30
	Boulders	5	15	20		45	10			10	5	20	25
	Bedrock	60					20						15
Instream cover	Instream debris	N	Y	N	Y	N	Y	Y	Y	N	Y	N	Y
	Undercut banks	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
	Bank vegetation	Y	N	Y	N	Y	N	Y	N	Y	Y	Y	N
Riparian vegetation (% cover)	Native forest				65								35
	Exotic forest						10				10		
	Grass/tussock	70		80	10	60	75	80	100	80	75	80	25
	Exposed bed		100										
	Scrub/willow	30		20	25	40	15	20		20	15	20	40
Fish abundance (m^{-2})	Dinah's bully[1]	Y[2]		0.05						0.15		0.15	
	Common bully	0.03		0.45		Y		0.13		0.04			
	Torrentfish							0.01		0.01		0.05	
	Shortfin eel	0.02		0.08		Y		0.04		0.12		0.03	
	Longfin eel			0.05				0.06		0.10		0.33	
	UID eel	0.13		0.93		Y		0.35		0.19		0.28	
	Common smelt											0.10	
	Īnanga	0.33		0.50		7.93						0.05	

[1]In 1995, these fish were recorded as Cran's bully (*Gobiomorphus basalis*) in the NZFFD. A subsequent revision of the systematics of that species (Thacker et al. 2023) has established that these were Dinah's bully (*Gobiomorphus dinae*).
[2]'Y' designates that this species was observed but not quantified.

Figure 7-9: Unstable substrate within the Mangakino Stream. Photograph taken on 7 September 2023 looking upstream from above the Lake Road (SH38) crossing.

Figure 7-10: Photo of the Mangaone Stream after Cyclone Gabrielle. Note the fine deposited sediment on the stream bed. Photograph taken on 6 September 2023 looking downstream from above the Kotare Road crossing.

Figure 7-11: Photo of the Makapua Stream after Cyclone Gabrielle. Note the unstable stream banks and almost complete absence of scrubby riparian vegetation. Photograph taken on 7 September 2023 looking upstream from above the Lake Road (SH38) crossing.

Figure 7-12: Photo of the Te Kura Stream after Cyclone Gabrielle. Note the mature riparian vegetation and stable substrate. Photograph taken on 6 September 2023 looking downstream from the Tiniroto Road crossing.

A comparison of the current instream habitat at the six stream sites with those recorded in the NZFFD in 1995 shows a noticeable increase in pool habitat and associated reduction in run habitat at most sites (Table 7-2). For example, at the Makapua Stream site the spatial coverage of pool habitat has increased from 40 to 85% (Table 7-2) with associated reductions in run and riffle habitat (see Figure 7-13).

Figure 7-13: Photo of the Makapua Stream after Cyclone Gabrielle, showing pool habitat with very fine substrate. Photo taken on 6 September 2023 above the Lake Road (SH38) crossing.

The two highest streams in the catchment (Mangahohi and Mangaone 2) were the only sites that did not have a large increase in the amount of mud and sand substrate, and an associated decrease in gravel or larger substrates (see Table 7-2and Figure 7-13). Mangahohi (Figure 7-14) and Mangaone 2 (Figure 7-15) had a broad mix of substrate types but were dominated by cobbles and boulders (Table 7-2).

Figure 7-14: Photo of the Mangahohi Stream after Cyclone Gabrielle Note the cobble substrate dominating the stream bed. Photo taken on 7 September 2023 looking upstream above the Lake Road (SH38) crossing.

Figure 7-15: Photo of the Mangaone 2 Stream after Cyclone Gabrielle. Note the dominance of cobble and boulder substrate. Photo taken on 8 September 2023 looking upstream from the Ruapapa Road crossing.

An important habitat feature for fish communities is the provision of instream cover to provide refuge from predation and high flow events. Most of the six streams showed a positive change in the availability of instream debris (Table 7-2 and Figure 7-16), which was already acting to diversify flow structure and substrate types. However, many streams that previously had undercut banks, which also provide refuge habitat particularly for nocturnal species (e.g., longfin and shortfin eels), showed changes from erosion or deposition that had had removed or smothered these key habitats (Figure 7-17).

Figure 7-16: Photo of the Mangaone Stream after Cyclone Gabrielle showing instream debris. Instream debris diversifies instream habitats by altering flows and substrate types.

Figure 7-17: Photo of the Mangahohi Stream after Cyclone Gabrielle showing undercutting and sediment smothering of banks.

There was evidence of modifications to the riparian margins of most of the six streams since 1995, with all but Te Kura and Mangaone 2 showing a reduction, or absence, of scrubby riparian vegetation (Table 7-2 and Figure 7-11).

Implications for Īnanga

The main consequences of Cyclone Gabrielle for īnanga populations in the mid-catchment area will arise from reductions in/removal of overhanging riparian vegetation, based on our observations and knowledge of īnanga. This vegetation provides refuge from avian predators (e.g., matuku moana and kōtare) for this diurnal, schooling species. After Cyclone Gabrielle, all the streams where īnanga were abundant in 1995 had lost instream cover provided by the combination of overhanging vegetation and undercut banks through bank erosion and sediment smothering. Hence most juvenile īnanga recruiting into these areas will succumb to avian predation.

Īnanga have a very broad diet (McDowall 1968), but modifications to the riparian and stream bed conditions due to Cyclone Gabrielle may limit their diet. This is due to the absence of overhanging riparian vegetation, which normally provides a rich subsidy of terrestrial insects to īnanga diet (Richardson, J et al. 1997), coupled with disturbance to stream beds may limit some stream-derived sources of food. Chironomid (midge) larvae will still be abundant in streams with fine sediment beds, but mayfly and caddisfly larvae may be significantly reduced and slow to recover. This will persist until rocky/cobbly habitat re-emerges in these streams.

The consequences of Cyclone Gabrielle on īnanga spawning habitats are discussed in Section 7.3.2.

Implications for Eels

Longfin and shortfin eels are nocturnal predators that use their sense of smell to detect food and prey (Sagar and Glova 1998). They spend most daylight hours sheltering under banks or amongst macrophytes (Jellyman and Sykes 2003). Cyclone-induced reductions in overhanging vegetation and undercut banks, and reductions in the size of sub-stratum will have significantly reduced the abundance of eels in many of the mid-catchment streams (Glova, G. J. et al. 1998). Furthermore, the reduced biomass of potential prey species (i.e., crustaceans and aquatic insect larvae for small eels and fish for larger eels; Jellyman 1989) will have major consequences for eel growth and survival.

Implications for Bullies

The two bully species that were found in the 1995 stream surveys (i.e., common bully, *Gobiomorphus contidianus*, and the newly described Dinah's bully, *Gobiomorphus dinae*) have probably faced similar challenges to īnanga and eels as a result of Cyclone Gabrielle. Fining of the bed substrates will have reduced/removed important food resources, and decreased instream cover will have increased the risk of predation. Furthermore, because these species also spawn in adult habitat (McDowall 2000) the cyclone-induced smothering/removal of suitable spawning substrates (e.g., cobbles, boulders or macrophytes) will have impacted their ability to complete their life cycle.

Torrentfish

Torrentfish are found mostly in gravelly/bouldery rivers with broad open beds and outside of any forest canopy (Davis et al. 1983). These rivers are often unstable with the coarse substrate loose and mobile during elevated flows. Torrentfish are much less prevalent in areas where the substrate is consolidated with silt and sand deposits. Adults are found in the swift, tumbling white water rapids where they live in the gaps between boulders (Glova, Gordon J and Duncan 1985). Their diet is comprised exclusively of the aquatic invertebrate larvae (Scrimgeour 1986).

Torrentfish were observed at the three most inland stream sites during the 1995 surveys (Table 7-2). After Cyclone Gabrielle, Mangahohi Stream (Figure 7-14) and Mangaone 2 Stream (Figure 7-15) retained suitable habitat for torrentfish (>70% of the streambed substrate was gravel or larger). However, Makapua Stream appeared completely unsuitable for torrentfish with mud and sand substrates dominating the streambed (Figure 7-13). Widespread fining of streambed substrates lower in the catchment caused by Cyclone Gabrielle may have impacted some torrentfish populations.

Smelt

Common smelt (*Retropinna retropinna*) inhabit the lower reaches of most New Zealand rivers (Ward, F.J. et al. 2005). However, they were only observed at the most inland (upstream) stream site during the 1995 surveys (Table 7-2). Although well inland, these are likely to have been diadromous individuals that would eventually move downstream to spawn on sand bars in the lower reaches of the river (Ward, Fredrick J et al. 1989). The deposition of fine sediments during Cyclone Gabrielle is unlikely to have disturbed these spawning habitats.

Common smelt feed on a broad range of primarily invertebrate animals ranging from small zooplankton to insects and occasionally small fishes (Northcote and Chapman 1999). Water visual clarity has little effect on the feeding ability of adult common smelt (Rowe et al. 2002b), but suspended and deposited sediment may alter the prey species that are available to them (Hayes et al. 1992). It is difficult to predict the likely consequences of Cyclone Gabrielle on common smelt populations in the Wairoa catchment. This is because they were only observed at one site in 1995, and in 2023 that site was the least impacted of the six visited sites.

7.3.2 Īnanga spawning habitat

Īnanga spawn among tidally-inundated vegetation on stream banks (Hickford and Schiel 2011a). Spawning sites are often in areas of reduced current - in backwaters or near the confluence of smaller tributaries in the tidal reach of larger rivers (Taylor 2002) – and as such are prone to sediment deposition. Smothering of bankside vegetation by sediment reduces the survival of deposited eggs by destroying the critical micro-habitat at ground-level beneath the vegetation (Hickford and Schiel 2011b).

There are two known īnanga spawning locations in the Wairoa catchment (Figure 7-18). These 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.

The spawning site in Awatere Stream is approximately 500 m from the confluence with the Wairoa River. When visited on 6 September 2023, the Awatere Stream spawning site did not appear to have been impacted by Cyclone Gabrielle. There was clear evidence that bankside vegetation had been recently grazed by livestock (Figure 7-19), but there was little deposition of sediment on the stream banks (Figure 7-20). There was also still plenty of instream cover for īnanga spawning aggregations from undercut banks, debris (logs) and macrophytes (Figure 7-22).

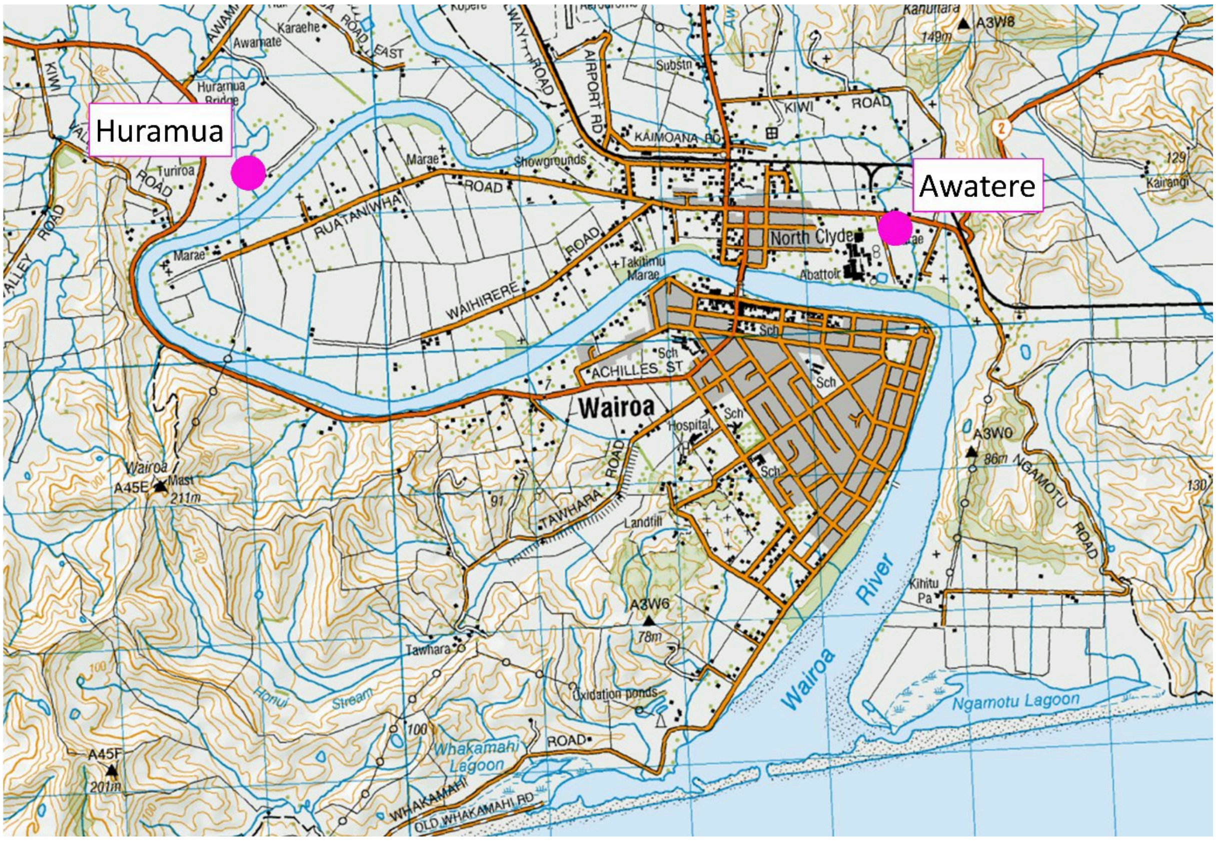


Figure 7-18: Two lower catchment streams that were assessed for īnanga spawning habitat in September 2023

Figure 7-19: Photo of the Awatere Stream spawning site following Cyclone Gabrielle showing evidence of livestock grazing.

Figure 7-20: Photo of the Awatere Stream spawning site following Cyclone Gabrielle. Note that there is no evidence of sedimentation from Cyclone Gabrielle

Figure 7-21: Photo of the Awatere Stream spawning site following Cyclone Gabrielle. Note that damaged protective fencing is allowing livestock access to the īnanga spawning site.

Figure 7-22: Photo of the Awatere Stream spawning site following Cyclone Gabrielle. Note that instream cover at the īnanga spawning sites is provided by overhanging banks, debris and macrophytes.

When visited in September 2023, the known īnanga spawning location in Huramua Stream showed major and ongoing impacts from Cyclone Gabrielle. The spawning site in this stream is much closer (approx. 100 m) to the confluence with the Wairoa River than the spawning site in Awatere Stream (Figure 7-18). Consequently, the spawning site was massively impacted by deposited sediment sourced from the mainstem. The lower banks were covered with up to 0.5m of sediment (Figure 7-4). The sediment had smothered riparian vegetation that would have supported īnanga eggs (Figure 7-

23) and appeared to have impacted emergent vegetation that would have provided spawning aggregations of adult fish with cover from avian and eel predators.

Figure 7-23: Photo of the Haramua Stream spawning site following Cyclone Gabrielle. Not note the evidence of significant deposited sediment at the īnanga spawning site. Photo taken on September 2023.

Figure 7-24: Photo of the Haramua Stream spawning site following Cyclone Gabrielle. The known īnanga spawning site is still well fenced and some bank crest plantings have survived the sedimentation from Cyclone Gabrielle. Photo taken on 6 September 2023.

8 Recovery and rehabilitation prospects

Here we address how fish habitat may respond to changes in visual clarity that may occur due to climate change and catchment erosion control measures. This includes predictions of changes in visual clarity and the implication of those changes for fish. We also address how habitat and fish populations may recover following Cyclone Gabrielle, including potential rehabilitation of one of the īnanga spawning sites.

8.1 Visual clarity changes with erosion controls and climate change

A model of sediment sources in the Wairoa catchment was developed by researchers at MWLR (Vale et al. 2023). They applied the model to assess the potential of a 'best-efforts erosion mitigation scenario' to achieve visual clarity targets at seven monitored sites (see Table 3-4 for the sites and targets). The model also included the implications of predicted climate change (six climate change models, four greenhouse gas emissions trajectories; Vale et al. 2023). The mitigation scenario involved natural reversion on the most erodible pastoral land (Land Use Classification class 7e and 8e corresponding to steep erodible areas), space-planting of trees on remaining hilly pastoral land, and fencing and riparian planting on streams of order 3 and above.

MWLR also assessed the suspended sediment load reduction that would be required to meet visual clarity targets. The method for relating changes in suspended sediment load to changes in visual clarity is based on the assumption that a given percent reduction in sediment load will achieve the same reduction in sediment concentration., This concentration reduction can then be related to visual clarity using a power law relationship (suspended sediment is a power function of visual clarity)(see also Section 3.4 for sediment-visual clarity relationships).

Here we summarise some key results from the MWLR reports:

For the current climate:

- Mitigation would reduce suspended sediment loads delivered to the coast by 60%.
- Five sites need to reduce suspended sediment load to meet the visual clarity bottom line (ranging from 38–70% reduction). For three of these sites, the mitigations would move visual clarity above the bottom line. The remaining sites (Waiau River at Otoi and Wairoa River at Railway Br.) would not achieve the national bottom line for visual clarity with the mitigations; they would need additional suspended sediment load reduction of 48% and 26%, respectively, to achieve the bottom line.

With climate change:

- Climate change was predicted to increase suspended sediment loads.
- Mitigation would more than offset the increase of suspended sediment load from climate change.
- The increase in suspended sediment loads from climate change means that larger reductions would be needed to meet the visual clarity targets compared with no climate change.
- For the five sites that are currently in the D band, load reductions to meet the bottom line range from 43–83%, depending on the site, period (mid or late century), climate

model, and concentration pathway. This is greater than the 38–70% without climate change.

- To meet the bottom line, additional mitigation beyond the best efforts would range from 0–58%, compared with 0–48% without climate change. Three sites would require additional mitigation, compared with two without climate change.

8.2 Implications of erosion control for fish

The visual clarity changes that could result from the 'best-efforts erosion mitigation scenario' (Vale et al. 2023) would have significant implications for fish populations in the Wairoa River. The significantly reduced suspended sediment loads required for downstream monitoring sites to meet NOF band C visual clarity criteria would have positive effects on recruitment, critical habitats, and feeding, growth and survival rates of resident fishes:

1. Improved visual clarity in the lower Wairoa River is likely to produce improved migration rates of banded kōkopu post-larvae (whitebait) through lower reaches. It is likely that more potential banded kōkopu recruits will arrive at suitable adult habitat. The abundance of banded kōkopu is limited by the quality and quantity of adult habitat (West et al. 2005). If deposited sediment does not smother instream refuges, the risk of predation and displacement during floods will decrease (Rowe and Smith 2003). An added benefit of an increase in the resident population size of banded kōkopu in the Wairoa catchment is the potential for their pheromones to attract whitebait recruits to the river mouth (Baker, C. F. and Montgomery 2001).

2. A reduction in deposited sediment in the lower Wairoa River is likely to enhance the food supply and spawning habitat of kōaro. High suspended sediment loads can reduce the density and biomass of benthic invertebrates (Newcombe and MacDonald 1991), which numerically are the greatest food source for kōaro (Main 1988). It is likely that a reduction in suspended sediment loads will improve the feeding and growth rates of resident kōaro.

3. Īnanga spawning sites are generally restricted to the tidally-influenced reaches of major rivers (Taylor 2002). The critical micro-habitat beneath riparian vegetation that īnanga use for spawning (Hickford and Schiel 2011b)and īnanga eggs are very vulnerable to smothering by deposited sediment with consequent mortality of eggs (Hickford and Schiel 2011a). A reduction in suspended sediment loads in the lower Wairoa River will reduce the risk of these obligate habitats being smothered by deposited sediment.

4. A reduction in suspended sediment loads in the Wairoa catchment will likely improve <u>potential</u> adult habitat for shortjaw kōkopu (McEwan and Joy 2014). However, it is important to remember that the rehabilitation of any diadromous fish species (e.g., giant kōkopu) is dependent on an ongoing supply of new recruits. In the case of shortjaw kōkopu (and giant kōkopu), it appears that recruits are currently absent from whitebait influxes.

5. There is some experimental evidence to suggest that a reduction in deposited sediment is associated with substantial increases in longfin eel densities (Ramezani 2014; Ramezani et al. 2014). A widespread reduction in suspended sediment loads in

the Wairoa catchment may increase the extent of the preferred stony substrate habitat of small and medium-large longfin eels (Main et al. 1985; Glova, G. J. et al. 1998). Furthermore, given the territorial nature of longfin eels (Jellyman and Sykes 2003), any increase in the availability of suitable habitat may improve the feeding/growth of resident eels by easing density-dependent effects.

8.3 Implications of Cyclone Gabrielle for fish and post-cyclone recovery prospects

8.3.1 Mid-catchment fish

Īnanga

All the streams where īnanga were abundant in 1995 had lost instream cover after Cyclone Gabrielle. This was caused by the combination of loss of overhanging vegetation and undercut banks through bank erosion and sediment smothering. It is expected that most juvenile īnanga recruiting into these areas will succumb to avian predation until the bank vegetation is re-established. At the six streams most of the 1995 riparian vegetation was exotic pasture grasses (Table 7-2). These grasses will re-establish rapidly and naturally on disturbed banks without any intervention. This will provide some cover, but īnanga are mid-channel schoolers, so full riparian protection will require re-establishment of larger vegetation or overhangs. Re-establishment of larger vegetation will be a more long-term process. Recovery of īnanga habitat is addressed in Section 8.3.2.

Eels

Eel populations are likely to have reduced as a result of reductions in overhanging vegetation and banks, fining of the streambed (for longfin eels), and reductions of the species they feed on. As with the species they feed on, the recovery of eel populations relies on a slow successional process that begins with stabilisation of substrates followed by periphyton growth and finally colonisation by aquatic invertebrates and fish. It is very difficult to short-circuit this process or accelerate its pace.

Bullies

Bullies are likely to have faced challenges due to reduction of food resources associated with bed fining and reduction of cover. Common bully are facultatively diadromous, that is, they can be diadromous or non-diadromous, depending on circumstances (Closs et al. 2003). So even if there are no adults remaining within the catchment, which is most unlikely, new recruits sourced from other rivers will enter the mouth of the Wairoa River after completing their marine larval phase. This improves the prospects for recovery. Dinah's bully are non-migratory (Thacker et al. 2023) so they will be dependent on the spread of larvae from surviving populations within the Wairoa catchment to replenish/re-establish populations in severely impacted areas.

Torrentfish

One of the three streams that held torrentfish in 1995 became unsuitable in 2023 due to siltation of the stream bed. In these areas, the re-establishment of torrentfish will be dependent on exposure of coarser substrates and the recolonisation of invertebrate prey species. The timescale for this is uncertain. Torrentfish are believed to be obligately diadromous (Warburton et al. 2021), so the sustainability of Wairoa River populations is dependent on the supply of recruits from other rivers. If such supplies are available, recovery can be rapid provided that there is suitable substrate.

It is likely that common smelt will recover rapidly from any cyclone-related perturbations because they are a short-lived and often-diadromous.

8.3.2 Īnanga spawning

The Awatere stream spawning site appears to have not been affected by Cyclone Gabrielle. There was little deposition on the stream banks and there was instream cover for spawning īnanga. The fences were damaged with subsequent grazing-related damage to the bankside grass. Repairs to damaged protective fencing (Figure 7-21) will initiate regrowth of bankside vegetation. It can take years for critical micro-habitat near the ground recover following damage (Hickford and Schiel 2014), but in this case the damage seems to have been light and recovery should be rapid.

The Huramua Stream īnanga spawning site was heavily damaged by Cyclone Gabrielle. Despite this, it is still well fenced and there is already some regrowth of bankside grasses and *Juncus* species. Pasture grasses (e.g., *Schedonorus phoenix* and *Agrostis stolonifera*), which are important for īnanga spawning, will re-establish naturally. The process could, however, be hastened by the application of seed. Regardless, deposition and survival of īnanga eggs will not be maximised for several years (Hickford and Schiel 2014) until the understory of the bankside vegetation has thickened enough to buffer temperature extremes and maintain high humidity for developing īnanga eggs (Hickford and Schiel 2011b). In the interim, artificial spawning habitats (see Hickford and Schiel 2013) could be deployed to restart spawning and to support successful egg development.

8.4 Recommended further work on fish recovery

A further survey of potential īnanga spawning locations and assessment options is recommended in a season when locations can be inspected for eggs and fish abundance. This is expected to be conducted in April 2024 as part of other investigations being conducted by NIWA in Hawkes Bay and Tai Rāwhiti as part of cyclone recovery programmes.

New fish abundance and macroinvertebrate studies are also recommended to monitor the recovery of fish in the mid catchment following Cyclone Gabrielle (the macroinvertebrate component give an indication of food sources for fish). These surveys could be done at sites that were surveyed previously (Section 7.3.1), including quantification of fish abundance, bed substrate, and riparian condition. Two sites are being monitored for macroinvertebrate species under other funding. The fish and additional macroinvertebrate surveys would need additional funding.

Simple rehabilitation measures of fence reinstatement and vegetation protection should be undertaken for the Awatere site. Grass seeding and establishment of artificial spawning habitat should be considered for the Huramua Stream site.

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Appendix A Radioisotopes as geological clocks

Radioisotopes are unstable atoms that release excess energy in the form of radiation (i.e., gamma rays, alpha particles) in the process of radioactive decay. The radioactive-decay rate can be considered fixed for each type of radioisotope and it is this property that makes them very useful as geological clocks. The half-life ($t_{1/2}$) of a radioisotope is one measure of the radioactive decay rate and is defined as the period taken for the quantity of a substance to reduce by exactly half. Therefore, after two half-lives only 25% of the original quantity remains.

The $t_{1/2}$ value of radioisotopes also defines the timescale over which they are useful for dating. For example, ^{210}Pb (naturally occurring radioisotope) has a half-life of 22 years and can be used to date sediments up to seven half-lives old or about 150 years. Dating by ^{210}Pb is based on the rate of decrease in unsupported or excess ^{210}Pb activity with depth in the sediment. Excess ^{210}Pb is produced in the atmosphere and is deposited continuously on the earth's surface, where it falls directly into the sea or on land. Like other radioisotopes, ^{210}Pb is strongly attracted to fine sediment particles (e.g., clay and silt), which settle out of the water column and are deposited on the seabed. ^{210}Pb also falls directly on land and is attached to soil particles. When soils are eroded, they may eventually by carried into estuaries and the sea and provide another source of excess ^{210}Pb. As these fine sediments accumulate on the seabed and bury older sediments over time, the excess ^{210}Pb decays at a constant rate (i.e., the half-life). The rate of decline in excess ^{210}Pb activity with depth also depends on the local SAR. Slow declines in ^{210}Pb activity with depth indicate rapid sedimentation whereas rapid declines indicate that sedimentation is occurring more slowly. More details of ^{210}Pb dating are described below.

Although radioisotopes can occur naturally, others are manufactured. Caesium-137 ($t_{1/2}$ = 30 yr) is an artificial radioisotope that is produced by the detonation of nuclear weapon or by nuclear reactors. In New Zealand, the fallout of caesium-137 associated with atmospheric nuclear weapons tests was first detected in 1953, with peak deposition occurring during the mid-1960s. Therefore, caesium-137 occurs in sediments deposited since the early 1950s. The feeding and burrowing activities of benthic animals (e.g., worms and shellfish) can complicate matters due to downward mixing of younger sediments into older sediments. Repeated reworking of seabed sediments by waves also mixes younger sediment down into older sediments. X-ray images and short-lived radioisotopes such as ^{7}Be ($t_{1/2}$ = 53 days) can provide information on sediment mixing processes.

^{210}Pb dating

^{210}Pb ($t_{1/2}$ = 22.3 yr) is a naturally occurring radioisotope that has been widely applied to dating recent sedimentation (i.e., last 150 yrs) in lakes, estuaries and the sea (Figure A-1). ^{210}Pb is an intermediate decay product in the uranium-238 (^{228}U) decay series and has a radioactive decay constant (*k*) of 0.03114 yr^{-1}. The intermediate parent radioisotope radium-226 (^{226}Ra, half-life 1622 years) yields the inert gas radon-222 (^{222}Rn, half-life 3.83 days), which decays through several short-lived radioisotopes to produce ^{210}Pb. A proportion of the ^{222}Rn gas formed by ^{226}Ra decay in catchment soils diffuses into the atmosphere where it decays to form ^{210}Pb. This atmospheric ^{210}Pb is deposited at the earth surface by dry deposition or rainfall. The ^{210}Pb in estuarine sediments has two components: supported ^{210}Pb derived from *in situ* ^{222}Rn decay (i.e., within the sediment column) and an unsupported ^{210}Pb component derived from atmospheric fallout. This unsupported ^{210}Pb component of the total ^{210}Pb concentration in excess of the supported ^{210}Pb value is estimated from the ^{226}Ra assay (see below). Some of this atmospheric unsupported ^{210}Pb component is also incorporated into catchment soils and is subsequently eroded and deposited in estuaries. Both the direct and indirect (i.e., soil inputs) atmospheric ^{210}Pb input to receiving environments, such as estuaries, is termed the unsupported or excess ^{210}Pb.

The activity profile of unsupported ^{210}Pb in sediments is the basis for ^{210}Pb dating. In the absence of atmospheric (unsupported) ^{210}Pb fallout, the ^{226}Ra and ^{210}Pb in estuary sediments would be in radioactive equilibrium, which results from the substantially longer ^{226}Ra half-life. Thus, the ^{210}Pb activity profile would be uniform with depth. However, what is typically observed is a reduction in ^{210}Pb activity with depth in the sediment column. This is due to the addition of unsupported ^{210}Pb directly or indirectly from the atmosphere that is deposited with sediment particles on the bed. This unsupported ^{210}Pb component decays with age (k = 0.03114 yr^{-1}) as it is buried through sedimentation. In the absence of sediment mixing, the unsupported ^{210}Pb activity decays exponentially with depth and time in the sediment column. The validity of ^{210}Pb dating rests on how accurately the ^{210}Pb delivery processes to the estuary are modelled, and in particular the rates of ^{210}Pb and sediment inputs (i.e., constant versus time variable).

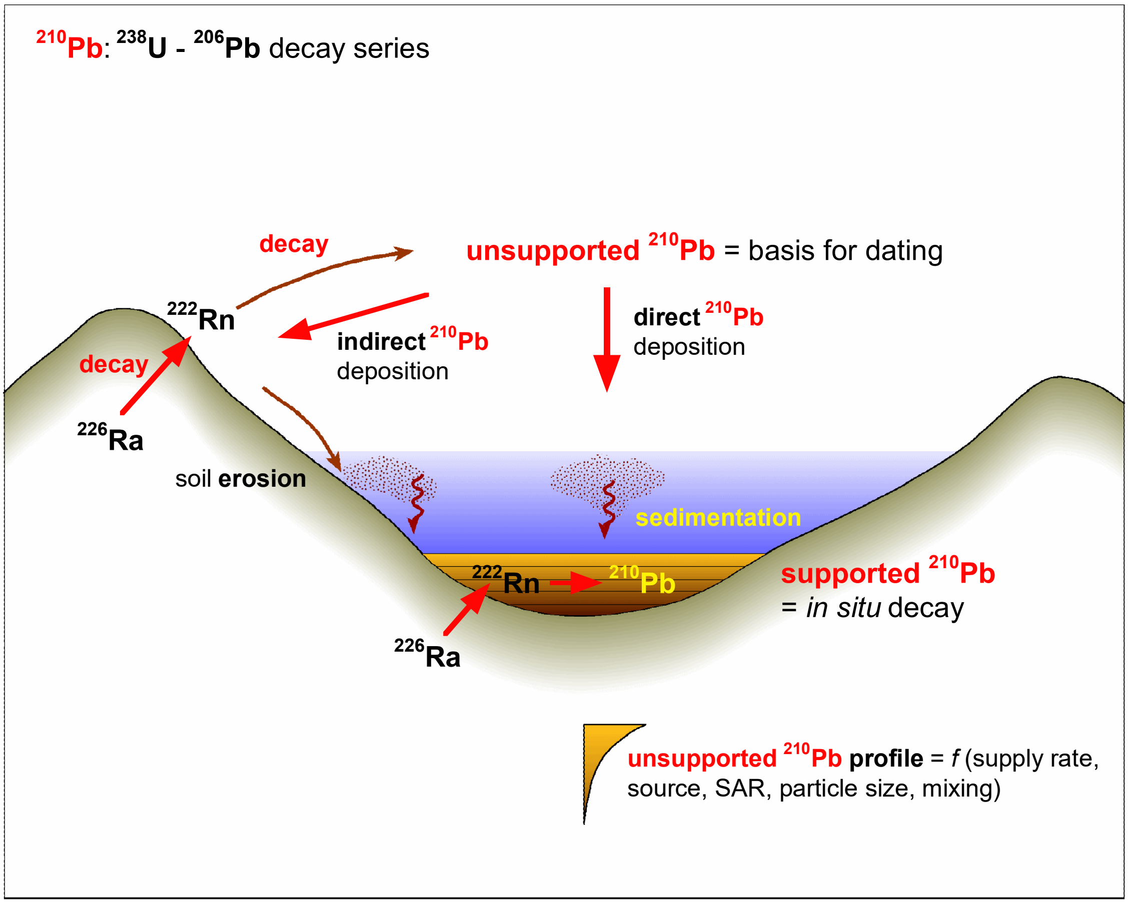

Figure A-1: ^{210}Pb pathways to estuarine sediments

^{137}Cs dating

^{137}Cs was introduced to the environment by atmospheric nuclear weapons tests in 1953, 1955–1956 and 1963–1964. Peaks in annual ^{137}Cs deposition corresponding to these dates are the usual basis for dating sediments (Wise, 1977, Ritchie and McHenry, 1989). Although direct atmospheric deposition of ^{137}Cs in estuaries is likely to have occurred, ^{137}Cs was also incorporated into catchment soils, some of which have been eroded and deposited in estuaries (Figure A-2). In New Zealand, ^{137}Cs deposition was first detected in 1953 and its annual deposition was measurable at several locations until 1985. Annual ^{137}Cs deposition can be estimated from rainfall using known linear relationships between rainfall and Strontium-90 (^{90}Sr) and measured $^{137}Cs/^{90}Sr$ deposition ratios (Matthews, 1989). Experience in a number of NZ estuaries shows that ^{137}Cs profiles measured in estuarine sediments bear no relation to the record of annual ^{137}Cs deposition (i.e., 1955–1956 and 1963–1964 ^{137}Cs-deposition peaks absent), but rather preserve a record of direct and indirect (i.e., soil erosion) atmospheric deposition since 1953 (e.g., Swales et al. 2002a,b, 2012).

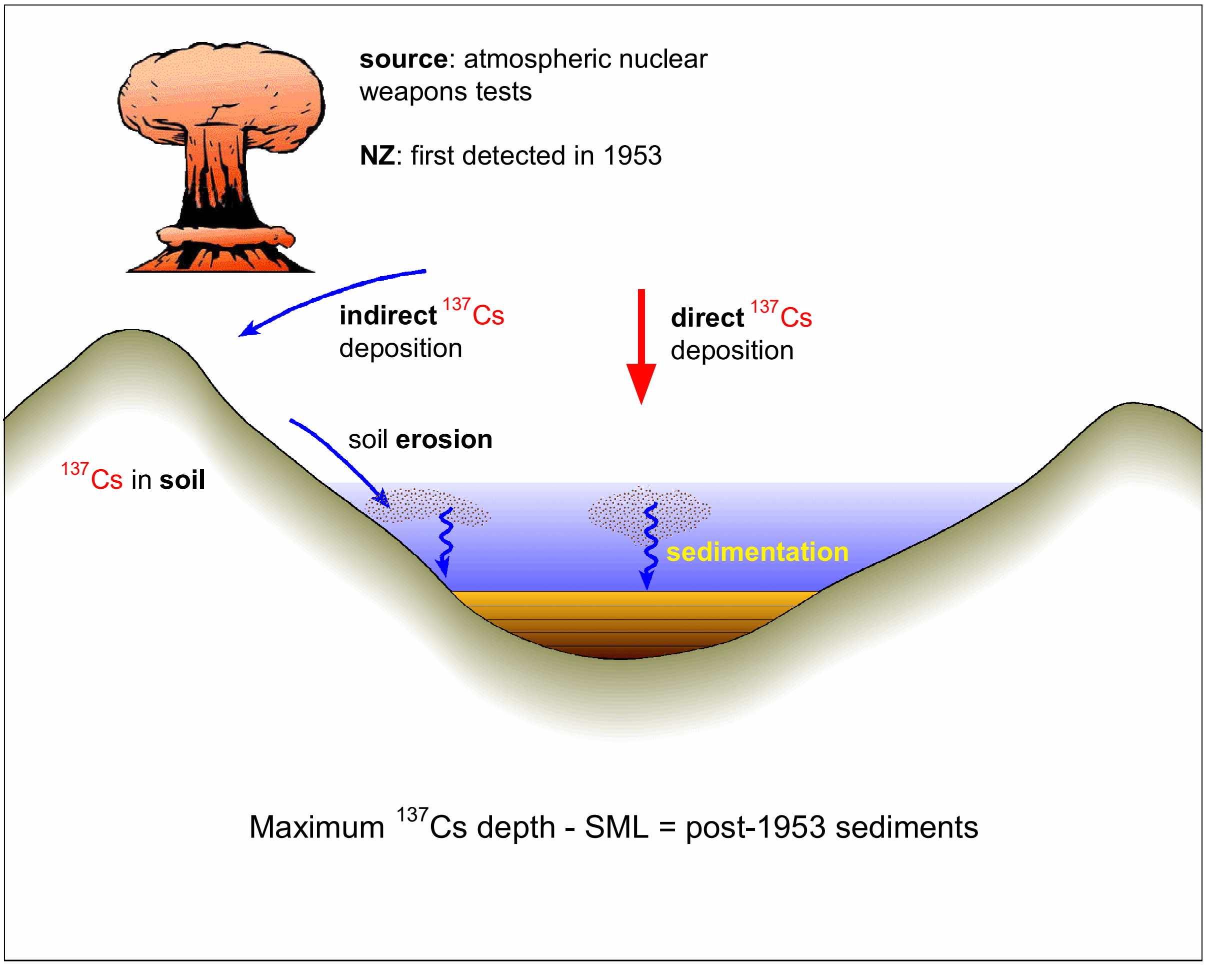

Figure A-2: ^{137}Cs pathways to estuarine sediments.

The maximum depth of ^{137}Cs in sediment deposits is the usual basis for dating in New Zealand estuaries as ^{137}Cs is derived from eroded catchment soils as well as direct atmospheric deposition.

The maximum possible depth of ^{137}Cs occurrence in sediment cores (corrected for sediment mixing) is taken to coincide with the year 1953, when ^{137}Cs deposition was first detected in New Zealand. This assumes that there was negligible delay in initial atmospheric deposition of ^{137}Cs in estuarine sediments (e.g., ^{137}Cs scavenging by suspended particles), whereas time-lag in ^{137}Cs input to estuaries associated with topsoil erosion are likely.

Due to the low initial ^{137}Cs activities in the 1950s and subsequent radioactive decay since that time (i.e., ~2 half-life's, [$t_{1/2}$ = 30 years]), the detectable maximum ^{137}Cs depth will date to sometime during 1952–1963 period, and more likely towards the end of this period. Uncertainty in the maximum depth of ^{137}Cs also results from: (1) the depth interval between sediment samples and (2) minimum detectable activity of ^{137}Cs, which is primarily determined by sample size and counting time. If a surface mixed layer (SML) is evident in a core, as shown by an x-ray image and/or a tracer profile (e.g., ^{7}Be, ^{210}Pb) then ^{137}Cs is likely to have been rapidly mixed through the SML. Therefore, to calculate time-averaged sedimentation rates, the maximum depth of ^{137}Cs occurrence is reduced by the maximum depth of the SML.

Sediment accumulation rates

Time-averaged SAR were estimated from the unsupported ^{210}Pb ($^{210}Pb_{ex}$) concentration profiles preserved in cores. The rate of $^{210}Pb_{ex}$ concentration decrease with depth can be used to calculate a net sediment accumulation rate. The $^{210}Pb_{ex}$ concentration at time zero (C_0, Bq kg^{-2}), declines exponentially with age (t):

$$C_t = C_0 e^{-kt} \qquad (1)$$

where k is the radioactive decay constant for ^{210}Pb (k = 0.03114 yr^{-1}). Assuming that within a finite time period, sedimentation (S) or SAR is constant then $t = z/S$ (where z is depth in the sediment column) can be substituted into Eq. 2 and by re-arrangement:

$$\frac{\ln\left[\frac{C_t}{C_0}\right]}{z} = -k/S \qquad (2)$$

Because $^{210}Pb_{ex}$ concentration decays exponentially and assuming that sediment age increases with depth, a vertical profile of natural log(C) should yield a straight line of slope $b = -k/S$. We fitted a linear regression model to natural-log transformed ^{210}Pb concentration data to calculate b. The SAR over the depth of the fitted data is given by:

$$S = -(k)/b \qquad (3)$$

An advantage of the ^{210}Pb-dating method is that the SAR is based on the entire $^{210}Pb_{ex}$ profile rather than a single layer, as is the case for ^{137}Cs. Furthermore, if the ^{137}Cs tracer is present at the bottom of the core then the estimated SAR represents a minimum value.

The ^{137}Cs profiles were also used to estimate time-averaged SAR based on the maximum depth of ^{137}Cs in the sediment column, corrected for surface mixing. The ^{137}Cs SAR is calculated as:

$$S = (M - L)/T - T_0 \qquad (4)$$

where S is the ^{137}Cs SAR, M is the maximum depth of the ^{137}Cs profile, L is the depth of the surface mixed layer (SML) indicated by the ^{7}Be profile and/or x-ray images, T is the year cores were collected and T_0 is the year (1953) ^{137}Cs deposition was first detected in New Zealand.