



Channel Morphology and Sediment Transport Regime of the Lower Waikanae River

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Executive Summary

Purpose

This report examines the geomorphic condition and sediment transport regime of the lower Waikanae River, from the Water Treatment Plant weir to the estuary, to support management decisions that balance flood protection, ecological resilience and long-term sustainability. It was commissioned by the Department of Conservation (DOC) as part of the Ngā Awa river restoration programme, in which the Waikanae is one of the partner rivers under Waikanae ki Uta ki Tai, the partnership of Ātiawa ki Whakarongotai, DOC, Greater Wellington Regional Council (GWRC) and Kāpiti Coast District Council (KCDC). The report asks why the lower river behaves as it does, how 70 years of management have shaped that behaviour, and what options exist to recover more of the river's natural capacity to regulate its own sediment and habitat.

Overall Condition of the River

The lower Waikanae is an active gravel-bed river that carries bedload from forested headwaters across a coastal alluvial fan to the sea. By national standards the river is in good ecological condition: water clarity, deposited sediment and periphyton sit in the top attribute bands at the regional monitoring sites, and the riparian corridor has been substantially restored. Flood flows continue to mobilise gravel, reshape bars and maintain dynamic in-channel habitats, particularly in the upper reaches, and the largely forested headwaters offer good prospects for rehabilitation.

The river is nonetheless in long-running geomorphic disequilibrium: its present form and behaviour are not aligned with the adjustment processes expected of a range-front fan river, and are held in place by engineering rather than by a balance between sediment supply, transport capacity and channel adjustment. That condition reflects management history rather than a lack of geomorphic or ecological vitality, and it has had two distinct phases:

- **A sediment deficit, c. 1955–1990.** The 1955 Erosion and Flood Control Scheme replaced a multi-thread channel with a single channel on an “improved” alignment, and gravel was extracted at rates well above the river's supply. Archive records indicate about 260,000 m³ was removed in 1960–75, against published supply estimates of roughly 1,000–7,600 m³/yr. By 1986 the bed below the State Highway 1 bridge had degraded by an average of 2 m over 2 km, and a sequence of grade-control weirs was needed to protect the bridges.

- **A sediment surplus, c. 1990–present.** With extraction curtailed, grade control in place and the channel fixed within a 35 m design alignment, the upper reaches continue to lose bed material while the reaches below Jim Cooke Memorial Park accumulate it. GWRC's 2020 survey analysis puts the net gain at about 4,600 m³/yr, with about 69,000 m³ stored above 1991 bed levels.

Key Findings

Historical aerial photography (1942–2022), repeat cross-section surveys (1991–2020), LiDAR differencing (2013–2022), grain-size sampling, geomorphic unit mapping and 1D and 2D morphodynamic modelling give a consistent picture:

- **The channel is shorter, steeper and narrower than the historical river.** The 2022 centreline is about 9% shorter than the 1952 course. For a near-threshold gravel bed, a first-order calculation shows that this steepening alone raises bedload capacity by roughly 20–60%, and confinement to a single narrow channel further impacts trends of erosion and deposition.
- **The upper reaches (below Main Rd) are incising and armouring; the lower reaches are aggrading.** The transition sits near Jim Cooke Memorial Park (about XS 340), and aggradation is concentrated below the natural slope break near the Kāpiti Expressway bridge, where the bed grade falls from about 1:260 to 1:1500.
- **Much of the aggradation zone is a natural depositional setting.** The 1D model deposits sediment there under 1952 conditions as well; the modern configuration deposits more, over a shorter reach.
- **Habitat diversity is low where the river is most constrained.** Automated geomorphic unit mapping shows that rapids, cascades and freely formed riffles are largely absent below the railway bridge; the lower river is dominated by glide-runs, and most pools are forced by groynes and rock work.
- **The estuary responds mainly to river flow.** Sediment plates show a long-term mean accretion of about 10 mm/yr in the upper estuary, but little net change over the last five years, with erosion during recent floods. A gravel front has advanced toward the estuary over several decades.

Interpretation

In its natural state the Waikanae would function as a laterally active fan river, redistributing sediment through channel migration, avulsion and floodplain storage. Confinement within a fixed corridor and shortening of the channel have removed most of these adjustment pathways. As a result, the sediment imbalance is expressed internally - as upstream degradation and downstream aggradation - rather than being dispersed across a broader floodplain.

Gravel extraction and engineering works have maintained conveyance and protected the community, and the river remains attractive and ecologically valuable. These measures help to manage the consequences of the sediment imbalance rather than its causes, and the present configuration depends on continued intervention: weirs to hold the upper bed, extraction to maintain flow conveyance in the lower reach, and bank protection to hold the alignment. Rising design flood levels, climate change and sea-level rise will increase the cost of holding that configuration.

Opportunities and management implications

The Waikanae retains the ingredients for recovery: a reliable supply of mobile gravel, intact headwaters, restored riparian margins, public land in parts of the corridor, and repeat cross-section surveys dating from 1991, with earlier surveys back to 1957. The findings point to a managed-adjustment approach that guides, rather than suppresses, geomorphic change:

- Provide room for the river to store sediment laterally in the aggradation zone (about XS 155–300) by widening the managed corridor and reconnecting former channels, so that deposition builds bars, side channels and floodplain rather than raising the bed.
- Investigate a longer, lower-gradient course between the old State Highway bridges and Jim Cooke Memorial Park to reduce the energy that drives upstream incision.
- Use gravel extraction as a transitional tool to create space and balance the budget, rather than to hold bed levels at a 1991 baseline.
- Adopt geomorphic objectives - corridor width, sediment continuity and geomorphic unit diversity - alongside bed levels in the next Floodplain Management Plan review, developed with Ātiawa ki Whakarongotai through Waikanae ki Uta ki Tai.

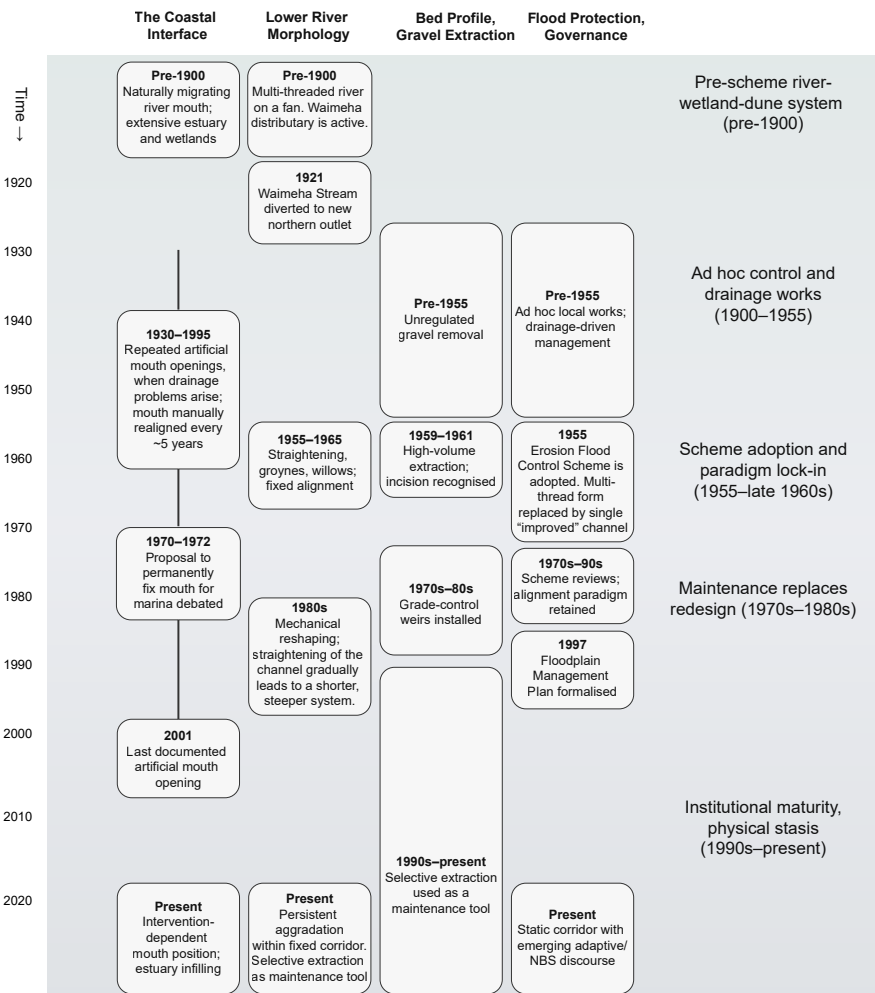


Figure 1-1 Timeline of management of the lower Waikanae River and its coastal interface, pre-1900 to present, grouped into five phases.

Selectively relaxing confinement, restoring longer flow paths where feasible and accommodating controlled lateral change offers a way to reduce long-term maintenance dependence while enhancing ecological and cultural values. The approach is consistent with contemporary understanding of gravel-bed rivers, with nature-based solutions to flood risk, and with the Waikanae ki Uta ki Tai value of te ao tūroa - respect for the natural patterns of the river.

ENABLING RIVER ADJUSTMENT AND FLOODPLAIN EVOLUTION



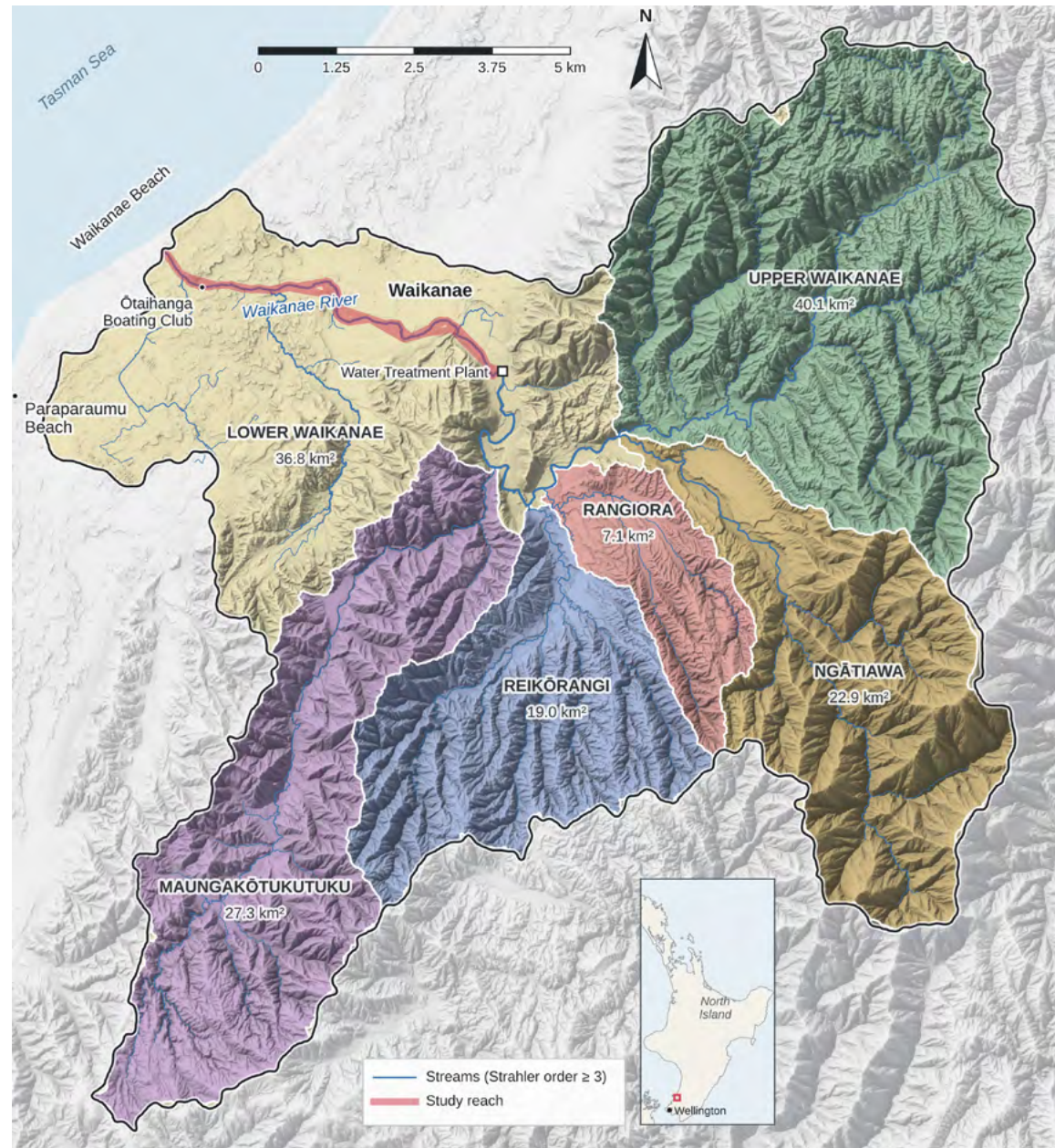
Figure 1-2 The Waikanae River in 1947 (left; Whites Aviation) and 2022 (right). In 75 years the river has changed from a bifurcating channel with a mosaic of bars and floodplain surfaces to a single, straightened and confined channel. This report examines the processes and decisions behind that change.

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Catchment Map

Figure 1-3 The Waikanae catchment and study area. The study focuses on the piedmont and coastal-plain reaches downstream of the Reikorangi Gorge and the Water Treatment Plant.



1. Introduction



Purpose and context

This study was motivated by a need to understand sedimentation problems in the lower Waikanae River and the prospects for diversifying and enhancing riverine habitat on the coastal plain. It was commissioned by DOC within the Ngā Awa river restoration programme. On the Waikanae, Ngā Awa works through Waikanae ki Uta ki Tai, a partnership established in 2019 between Ātiawa ki Whakarongotai, who hold mana whenua over the river and its surrounding environment, and the kāwanatanga agencies DOC, GWRC and KCDC (DOC 2026). The partnership's aim is waiora - healthy water - and its values include mauri (vitality), whakapapa (connection), māramatanga (shared understanding) and te ao tūroa (the natural patterns of the environment).

Flood risk on the Waikanae floodplain is managed by GWRC under the Waikanae Floodplain Management Plan (WRC 1997; reprinted with addendum 2013). The river corridor is also managed as a “mountains to sea” ecological corridor under the Waikanae River Environmental Strategy (GWRC and KCDC 2014), and DOC administers the Waikanae Estuary Scientific Reserve at the river mouth. The present report sits between these frameworks: it explains the physical behaviour of the river that each of them depends on.

Report objectives

The study was designed to inform management options that would improve outcomes for conservation and community priorities, including:

- a more dynamic and diverse suite of riverine habitats (riffles, runs, pools, side channels) to support aquatic and avian biodiversity and ecological resilience;
- enhanced biodiversity values within the estuary;
- protection of culturally important sites, including mahinga kai;
- recreation, including boating in the lower river and whitebaiting; and
- robust flood protection and protection of key infrastructure under climate change.

Research questions

1. What is the nature of the sediments and deposits along the lower river?
2. How geomorphically diverse is the river and floodplain? What is the distribution of geomorphic units (pools, riffles, cascades and bars) along the system, and what range of hydraulic environments, shade and connectivity does this offer riverine fauna?
3. What has caused degradation (bed lowering) in the upper study reach and coarse gravel accumulation in the middle and lower reaches? What has been the trajectory of change, and what are the prospects for stabilising it?

Problem statement

The lower river has been managed to a static channel alignment. Its geomorphic setting - an alluvial gravel fan downstream of a steep, sediment-supplying mountain catchment - suggests that it would otherwise be a dynamic river with multiple channel pathways. A history of degradation in the upper study reach and excess sedimentation in the lower reaches is consistent with a system that has been confined (non-erodible banks), steepened (reduced sinuosity) and fixed at its upstream end (grade control), and that has not been allowed to adjust to these altered boundary conditions.

Hypothesis and predictions

A graded river in the sense of Mackin (1948) adjusts its slope, width and planform so that, over the long term, it transports the sediment supplied to it. On an alluvial fan this adjustment takes the form of channel migration, avulsion and floodplain storage. The working hypothesis is that the lower Waikanae, if free to adjust, would be more sinuous, would store more sediment laterally and would have a more complex channel configuration. If the hypothesis holds, the evidence should show:

- a steepened and shortened channel relative to the pre-scheme river;
- a longitudinal pattern of upstream bed loss and downstream bed gain, concentrated where the transport gradient changes most;
- surface grain size and geomorphic units consistent with excess capacity upstream and excess supply downstream; and
- model results in which the modern configuration produces more pronounced upstream incision and downstream deposition than the pre-scheme configuration.

Approach and data

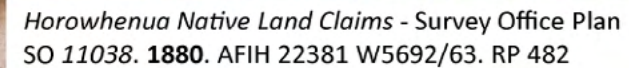
The study combines archival, survey, field and modelling evidence (Table 1-1). Throughout, locations are referenced to the GWRC cross-section numbering established in 1991 (XS 10 at the coast to XS 550 at the Water Treatment Plant; Figure 2-1).

Table 1-1 Data sources used in this study.

Evidence	Period	Source	Used for
Historical aerial photographs	1942, 1947, 1952, 1957, 1961, 1968, 1973, 1979, 1986, 1991–2022	Crown aerial photography; Whites Aviation; GWRC	Planform change, channel length, former channels
Management archive	1945–1991	Easther (1991); Williams (1992)	Works history, extraction records, bed levels, mouth openings
Cross-section surveys	1991, 1995, 1999, 2004, 2010, 2014, 2020 (earlier sets 1957, 1975, 1983, 1987)	GWRC	Mean bed level and volume change by reach
LiDAR	2013, 2020, 2021 (topographic); 2022 (bathymetric)	GWRC; LandPro	Topographic change, geomorphic units, model grids
Bed-material sampling	2022	This study (16 Wolman surface samples; 3 bulk subsurface samples)	Grain-size trends, model substrate
Flow record	1975–2021	GWRC gauge 58902, Water Treatment Plant	Flood frequency, model hydrographs
Morphodynamic models	-	GRATE 1D (Tunnicliffe and Church 2015); Delft3D-FM (Deltares 2020)	Testing 1952 vs 2022 configurations and future trajectory

Structure of the report

Chapter 2 sets out the physical setting and the history of management, from the pre-scheme river to the present. Chapter 3 assembles the sediment budget: supply, extraction and measured change in storage. Chapter 4 examines the form of the modern channel - bed material, channel geometry, geomorphic units - and uses a first-order calculation and two morphodynamic models to test the hypothesis. Chapter 5 draws the evidence together and sets out recommendations.



Horowhenua Native Land Claims, Survey Office Plan SO 11038 (1880), showing the Waikanae and Waimeha (Waimea) channels across the coastal plain. Archives New Zealand AFIH 22381 W5692/63, RP 482.

2. Setting and Management History

To interpret present river behaviour, or anticipate future states, we need to understand the boundary conditions that have shaped the system and the disturbances that have changed them. This chapter describes the catchment and its coastal fan setting, the flood regime, and the history of management from the pre-scheme river to the present, using aerial photography back to 1942 and the management archive compiled by Easter (1991).

The catchment and its coastal fan

The Waikanae River drains the western foothills of the Tararua Range. Its catchment above the Water Treatment Plant is about 125 km², of which about 60% is old-growth or regenerating native forest and 40% pasture (GWRC and KCDC 2014). The main tributaries - the Ngatiawa and Rangiora rivers and the Reikorangi and Maungakotukutuku streams - join in the steep upper catchment (Figure 2-2A). The bedrock is Triassic sandstone and mudstone of the Rakaia Terrane. Landsliding has not been pronounced, but the major valleys contain extensive terrace, fan and hillslope deposits, with terrace sequences 25–30 m thick beside the river, and these are a ready source of gravel when the river erodes its banks.

Below the Reikorangi Gorge the river crosses its own alluvial fan to the coast (Figure 2-1). Alluvial fans form where steep mountain channels meet a lower-gradient plain. As the gradient falls, the river's capacity to carry coarse grains declines rapidly downstream, so fans characteristically show strong downstream fining

and build up through repeated deposition and channel switching (avulsion) that redistributes sediment across a broad apron (Davies and Korup 2007; Davies and McSaveney 2008; Reitz and Jerolmack 2012; de Haas et al. 2018). Gravel may build up in lesser floods and be remobilised in larger ones, and transient phases of storage follow episodes of high sediment delivery from the catchment. Where a fan channel is confined, it has little option for lateral adjustment and must instead build vertically. The Waikanae fan has also been shaped by post-glacial sea-level change, a prograding coastline and Holocene dune building, which have confined and diverted its channels, so that the modern river is inset within its ancestral deposit (Figures 2-9 and 2-10).

Sediment supply has been relatively subdued since European settlement in the 1860s. Forest clearance between about 1886 and 1930 probably produced a pulse of sediment (Easter 1991), but the headwaters have remained largely forested. The river carries gravel almost to the estuary, but most is deposited upstream of the tidal reach; no gravel is observed at the river mouth, and the river's gravel load is effectively retained on the coastal plain (Smith 2018). Coarse material deposited along the profile may remain in floodplain storage until it breaks down and is carried further downstream.

The river is in good ecological condition. At GWRC's monitoring sites water clarity, deposited sediment and periphyton sit in the top (A) attribute bands, and macroinvertebrate communities are healthy, with somewhat lower scores in the lower reaches (GWRC and KCDC 2014; Aquanet Consulting 2023).

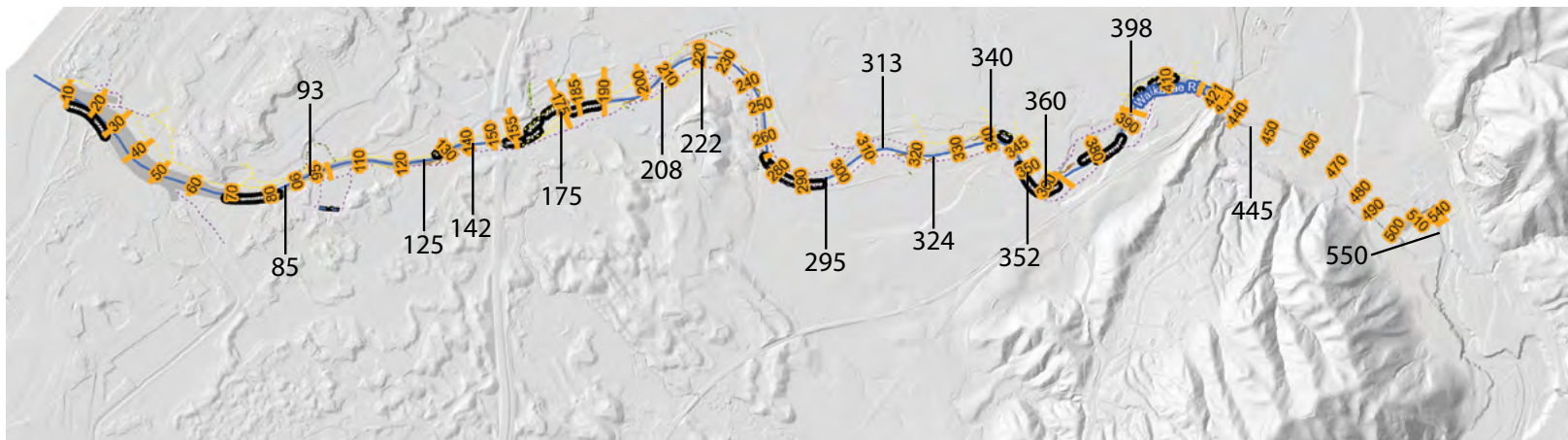


Figure 2-1 Study area, showing the GWRC cross-section numbering used throughout this report. Cross-sections run from XS 10 near the coast to XS 550 at the Water Treatment Plant, about 7.5 km along the present channel (Flanagan 2021). Bed-material sampling sites (this study) carry intermediate numbers.

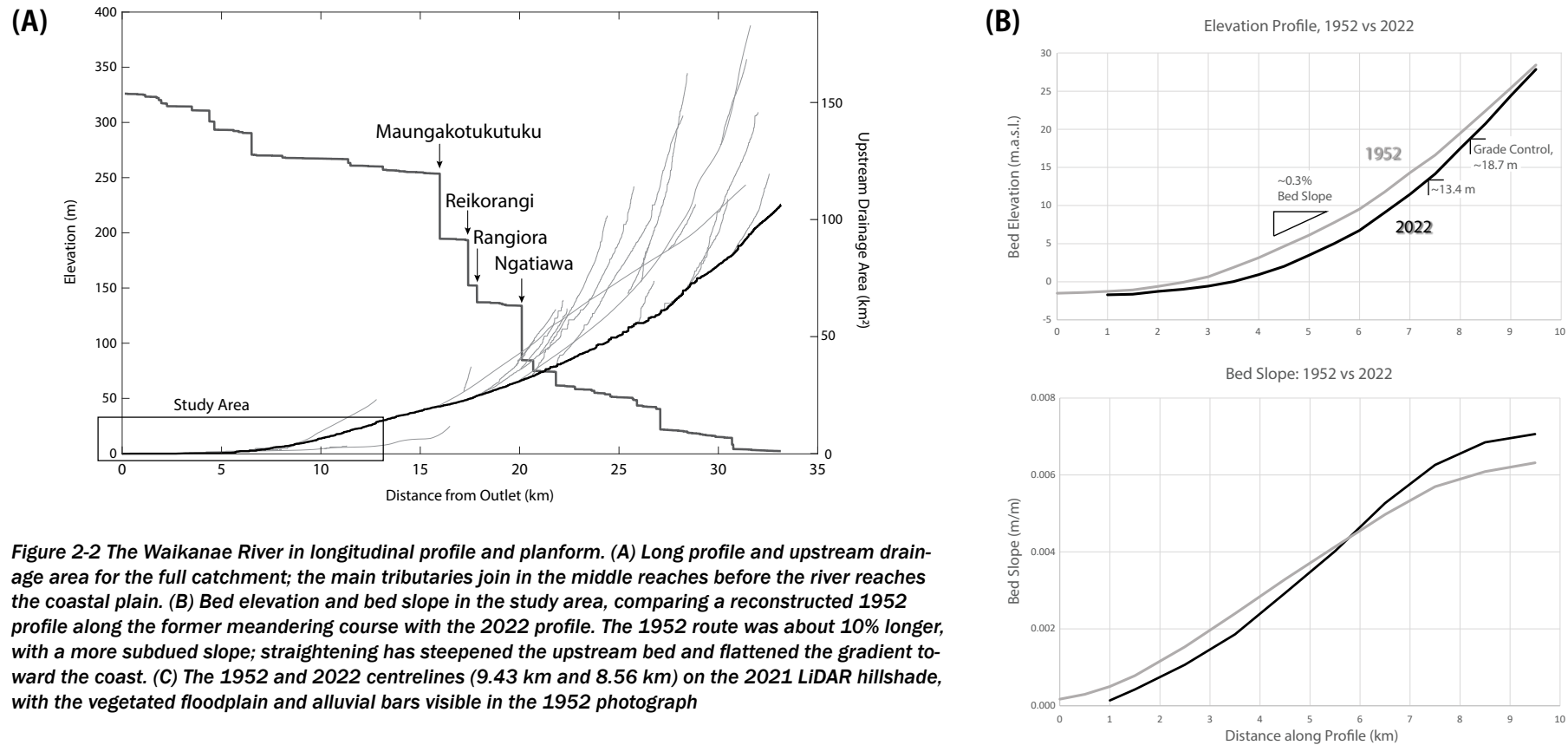
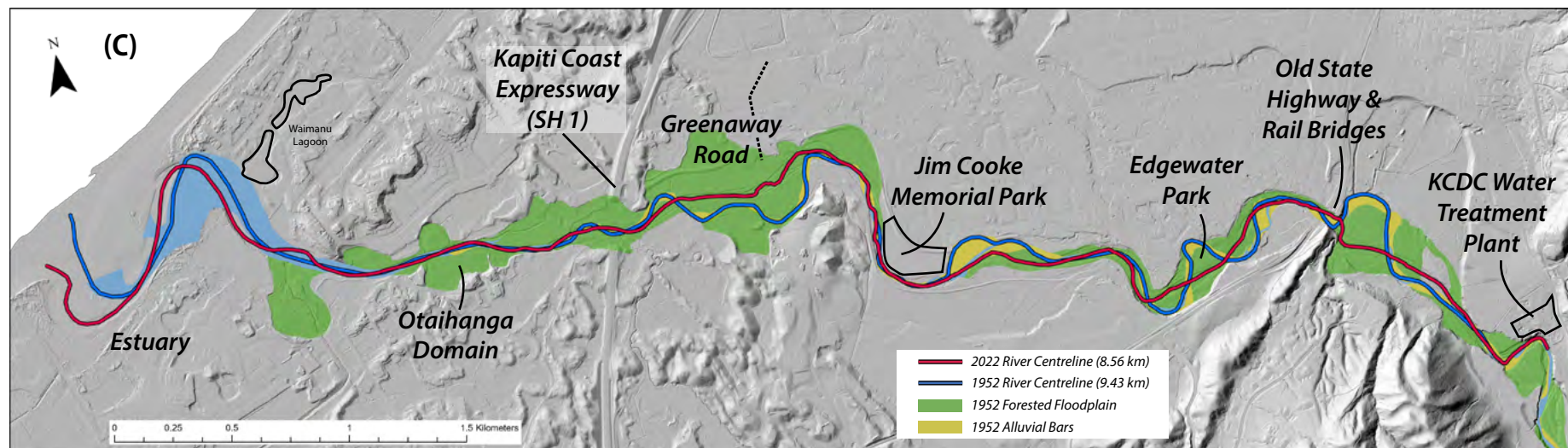


Figure 2-2 The Waikanae River in longitudinal profile and planform. (A) Long profile and upstream drainage area for the full catchment; the main tributaries join in the middle reaches before the river reaches the coastal plain. (B) Bed elevation and bed slope in the study area, comparing a reconstructed 1952 profile along the former meandering course with the 2022 profile. The 1952 route was about 10% longer, with a more subdued slope; straightening has steepened the upstream bed and flattened the gradient toward the coast. (C) The 1952 and 2022 centrelines (9.43 km and 8.56 km) on the 2021 LiDAR hillshade, with the vegetated floodplain and alluvial bars visible in the 1952 photograph



Climate, flow regime and floods

The Kāpiti Coast is exposed to high-intensity rainfall from westerly storms crossing the Tasman Sea, and the steep, convergent upper catchment produces rapid flood rises. Because the catchment is small, floods also recede quickly. Mean flows are highest between June and October (Figure 2-3).

The 1955 flood, estimated at the time at 680 m³/s - about 50% more than later provisional estimates (Easter 1991), damaged houses on the floodplain and led directly to the Erosion and Flood Control Scheme. Significant later floods include October 1998 (peak 304 m³/s on 21 October; WRC 2005) and January 2005, the largest in the gauged record, with a peak of about 381 m³/s. Estimates of the 2005 event's return period range from about 80 to 100 years (WRC 2005; Opus 2012a). Floods in 2015, 2016, 2017, 2021 and 2022 all rank in the ten largest annual peaks since 1975 (Figure 2-4), a disproportionate share for a single decade.

The design standard for urban areas is the 1% annual exceedance probability (AEP) flood, about 395 m³/s (Tonkin + Taylor 2016). The river corridor is defined as the minimum area able to contain that flood and let it pass safely to the sea (Figure 2-5). The 10-year review of the Floodplain Management Plan found that updated 100-year channel flood levels had risen by up to 600 mm above El Rancho and up to 900 mm below it compared with the 1992 estimates, and that the Ōtaihangā floodwall now provided protection against only about a 1-in-20-year event (GWRC 2010). For mid-range climate projections the same review estimated further increases in flood levels below SH1 of up to 200 mm by 2040 and 400 mm by 2090, largest in the tidal reaches at Ōtaihangā and Waikanae Beach. GWRC's design criteria allow for a 16% increase in rainfall intensity and 0.5 m of sea-level rise by 2100 (GWRC 2010).

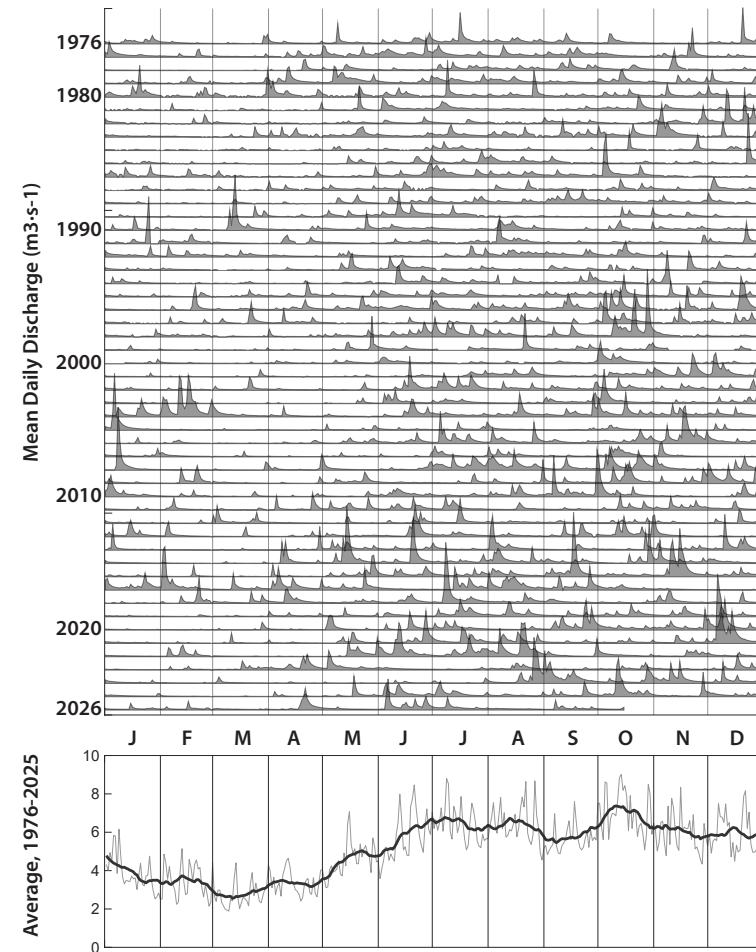


Figure 2-3 Daily mean discharge of the Waikanae River at the Water Treatment Plant (GWRC gauge 58902), 1976–2026, showing the distribution of flows through the year.

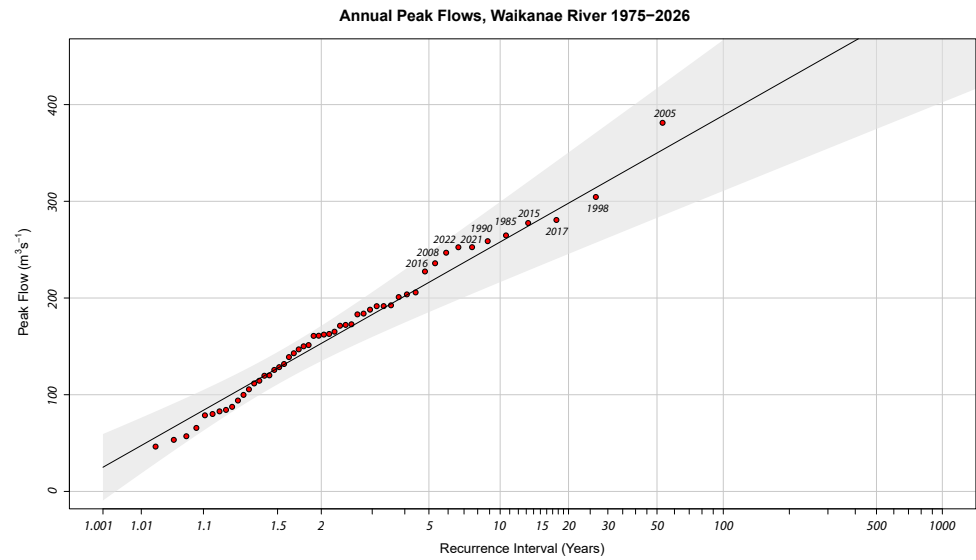
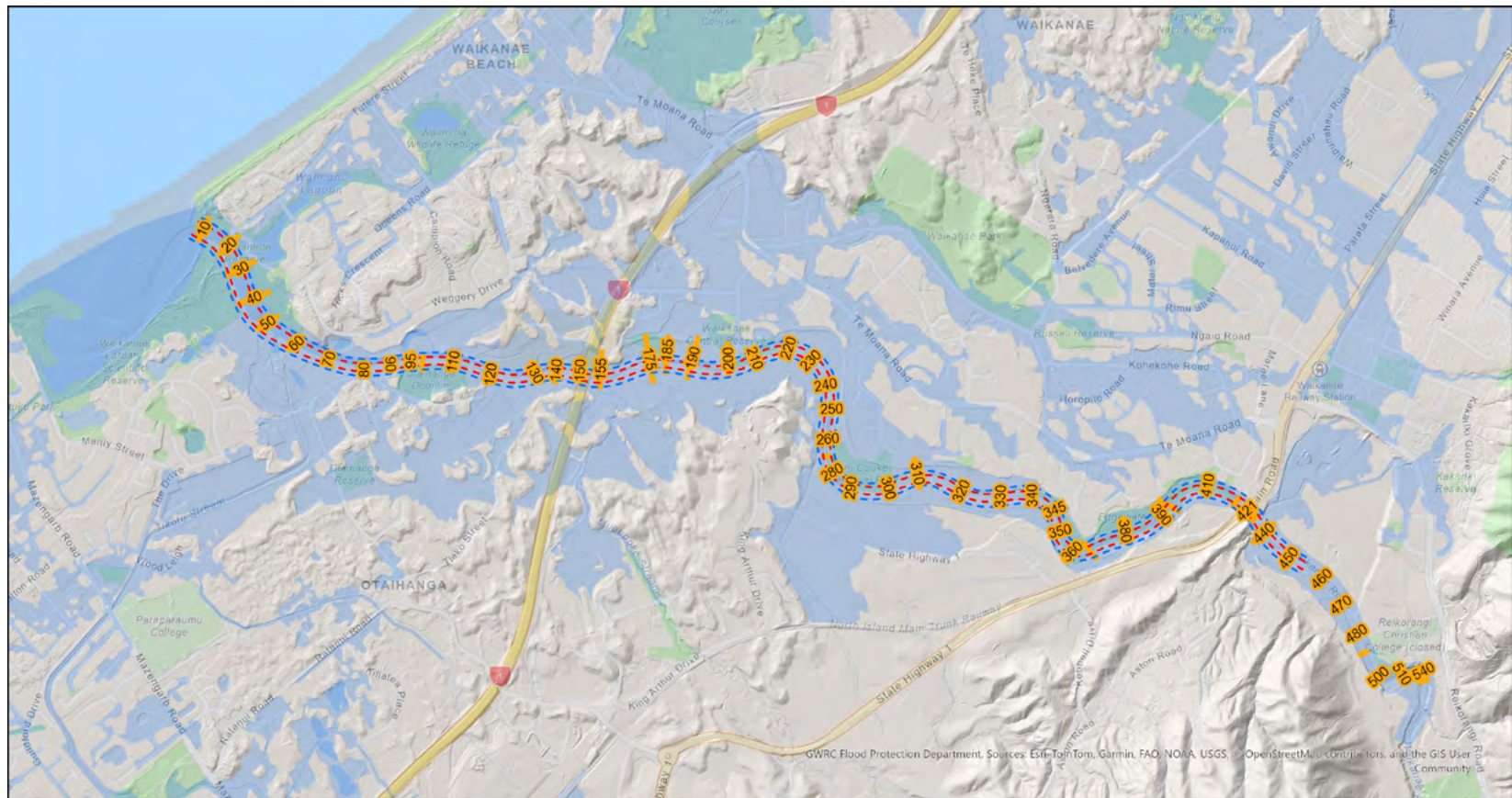


Figure 2-4 Annual peak flows at the Water Treatment Plant (gauge 58902), 1975–2026, plotted as recurrence intervals on a Gumbel distribution with 95% confidence bounds. The catchment is about 125 km² at the plant and larger at the estuary, so flows there are somewhat higher.

Figure 2-5 (below) Modelled 1% AEP flood hazard extent for the Waikanae River, adjusted for potential future climate change and combining river and local stormwater flooding (GWRC 2025). The cross-section network along the lower river is shown - this coordinate system is referred to throughout the report.



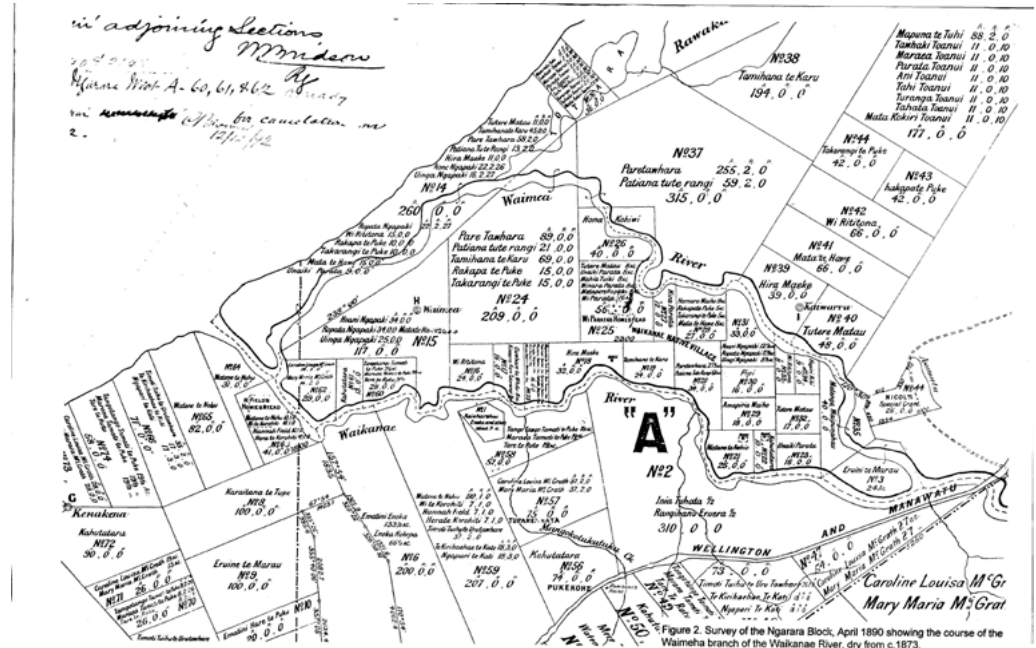
The pre-scheme river

Before the settlement period the coastal plain carried dense lowland forest, swamp forest, wetlands and salt marsh (Easter 1991; GWRC and KCDC 2014). The 1880 and c.1890 survey plans show the river bifurcating about 500 m downstream of the present road and rail bridges, near Edgewater Park, into the Waimeha (Waimea), which ran north across the floodplain, and the Waikanae, which followed approximately its present course. The two rejoined near the present Waimanu Lagoon (Figure 2-6). The Waimeha branch was a dry bed by the early 1890s. Easter (1991) points to forest milling, the railway embankment and floods in 1893–94; the Environmental Strategy to forest clearance and land drainage (GWRC and KCDC 2014). In 1921 the Waimeha Stream was diverted through the foredunes to a new mouth to allow subdivision at Waikanae Beach (Easter 1991; McLean and McLean 2010). The loss of the Waimeha distributary removed a pathway by which gravel had been spread across the fan, so that more of it is now carried down the main channel (Opus 2012b).

The earliest photographs show a river very different from today's. Near the coast, the 1942 photographs show a broad floodplain and, near Greenaway Road (XS 200), anabranching channels within a wide active bed (Figure 2-8, top). The 1947 oblique photographs show wide gravel floodplains and multi-thread channels (Figure 2-7), and the 1952 photographs, the first complete coverage of the study reach, show a narrower but still sinuous river with extensive vegetated floodplain, wetlands and oxbows. The large oxbow at Ōtaihangā dates from a flood in 1927 or 1928 that cut through a dune (GWRC and KCDC 2014). Willow planting had already begun; Williams (1992) suggests that early willow plantings spread uncontrolled across the floodplain and contributed to narrowing of the active channel.

Figure 2-6 (A) Cadastral survey of c.1890 showing the course of the Waimeha (Waimea) River (Easter 1991). **(B)** LiDAR hillshade of the fan, detrended to a surface fitted to the modern Waikanae River. Numerous palaeochannels and fluvial features are evident; sand dunes have variously confined and diverted the channels through the Holocene Epoch.

(A)



Phase 1: the scheme and a sediment deficit, c.1955 - 1990

1955 Erosion and Flood Control Scheme

The scheme was built by the Manawatu Catchment Board between 1956 and 1964, with stopbanks constructed over the 1956/57 to 1958/59 financial years (Easter 1991). Its philosophy was that of many New Zealand schemes of the time. In Easter's (1991, p. 14) summary, it was "*based on the assumption that the existing form of the river could be redefined to a more stable course that would be substantially cheaper and simpler to maintain than the unimproved channel. Multiple channels and uncontrolled 'meandering' were replaced with a single channel on an improved alignment.*" Diversion cuts, removal of vegetation, groynes, willow plantations and bank protection were used to hold the new alignment. The design adopted a bankfull width of 30-40 m (from Lacey's regime formula), meander lengths of 380-460 m and bend radii of about 160 m (Easter 1991). The approach reflected engineering practice of the period; Easter (1991), with the benefit of hindsight, observed that "the wisdom of these measures can be questioned."

Figure 2-8 shows the transition at Greenaway Road: an anabranching river with a mosaic of bar and floodplain surfaces in 1942, a channel widened by gravel extraction in the 1950s and 1970s, and a narrow, rock-lined managed channel today. Upstream, between the Water Treatment Plant and the bridges, the alignment is controlled by rock outcrops and bluffs, extended with rock and rubble linings (Williams 1992).

Gravel extraction and bed degradation

Gravel extraction was administered by the Lands Department until the late 1950s, and no records survive before 1957 (Easter 1991). From 1957 the river was worked for scheme construction, road and rail works and commercial aggregate, including extraction in the Reikorangi valley upstream of the study reach, which reduced supply to the lower river. The archive records 15,000 m³ removed for scheme works in 1957–58, 13,400 m³ taken at Reikorangi in 1958–59, an estimated 28,000 m³ in 1959–60 and 16,000 m³ in 1962–63, and estimates 8,000–13,000

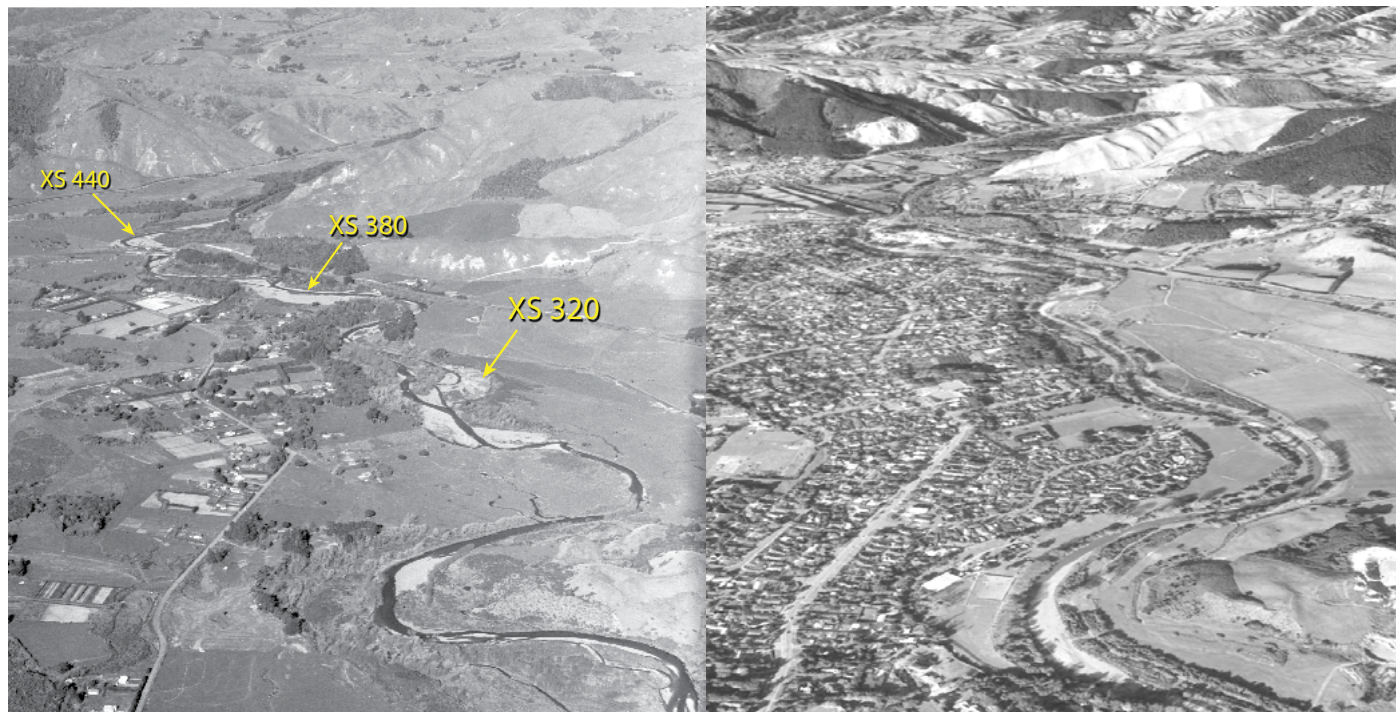


Figure 2-7 The Waikanae River in 1947 (Whites Aviation WA-08815-F, left) and 2022 (right). Before the 1955 scheme the river had wide gravel floodplains and a multi-thread configuration, particularly in the highlighted reaches near XS 320–440. Development has since left little room for the floodplain to evolve.

m³/yr through the 1960s, with a total of about 260,000 m³ for 1960–75, although the compiler flags the attribution of that total as uncertain (Easter 1991). A later GWRC compilation puts the average take at about 10,000 m³/yr from 1957 to 1987 (Kutta 2016, in Smith 2018). These rates exceeded every published estimate of the river's gravel supply (Chapter 3; Figure 3-1).

The bed responded, over time. Railway records show the low-water level at the rail bridge falling 1.53 m between 1930 and the winter of 1959 (Easter 1991). When the Ministry of Works proposed a weir to protect the SH1 bridge piles in December 1959, the Catchment Board resisted a permanent structure because "it would prevent the upstream reach from degrading". A temporary weir was built in the early 1960s and removed in 1966, but degradation continued. At a site meeting in April 1971 the Ministry of Works attributed the degradation to over-extraction, while the Board considered "degradation an objective of their river management to increase flood capacity"; the National Water and Soil Conservation Organisation then declined to subsidise a new weir because "the works are due to over extraction" (Easter 1991). A 1986 Catchment Board report recorded that from 1975 "all reaches of the river [were] severely depleted of shingle", that extraction had deepened the active channel "in most areas including the mouth by up to 2m", and that extraction had since been permitted only for river-control purposes (Easter 1991). A 1986 investigation estimated that the bed had degraded by an average of 2 m over 2,000 m downstream of the SH1 bridge and 1.5 m over 800 m upstream of it, a loss of about 126,000 m³ of bed material (Easter 1991).

Figure 2-8 - The same extent near Greenaway Road (XS 200) in 1942, 1957, 1973 and 2022 (photograph bounds are identical). The 1942 river has a broad floodplain with anabranching channels; dashed lines show the approximate bounds of the bed and the active alluvial surface. A gravel extraction operation (lower left) is visible in the 1973 photograph and in 1968 imagery (not shown). The managed channel is now held in a static alignment by riprap and rock lining.



(A)



(B)



(C)

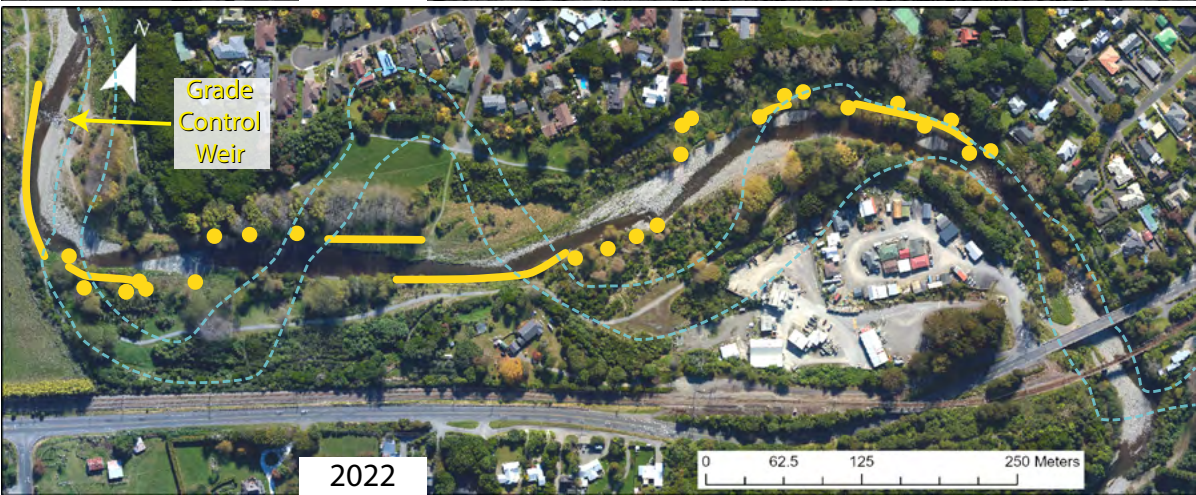


Figure 2-9 - The reach near Edgewater Park (old SH1 and rail bridges at lower right). (A) In 1952 the valley floor holds wetlands, oxbows and low-lying riparian terrain. (B) In 1961, during intensive gravel extraction, bedrock is exposed in the middle point bar and stockpiles are visible on the left bank. (C) By 2022 the river is set in a straight, simple alignment between grade-control weirs at the upper and lower ends of the photograph.

Grade Control

A sequence of weirs was built to arrest the degradation around the road and rail bridges (Figure 2-10A). Rock was dumped across the river in 1971 to form a sill 200 ft (about 60 m) downstream of the SH1 bridge; it was reinforced with concrete blocks in 1972, partly breached in the 1973 Labour weekend floods and reinstated after flood damage in 1980. In 1985 it was replaced by the rock weir that is largely still in place (Figure 2-10B; Easter 1991). A second weir, the Kebbels grade-control structure near XS 350, lies about 1 km downstream (GWRC 2010; Flanagan 2021). Further bank protection and bed-level controls were installed after the October 1998 floods, and these reduced the supply of gravel from the upper reaches (WRC 2005).

The weirs now mark a transition between the steeper, armoured reach upstream of the bridges and the reach below. The bed is armoured for about 150 m downstream of the upper weir, with mobile bar deposits forming in the lee of groynes along the right bank. Bed degradation has direct consequences for bank stability, the foundations of flood protection structures and bridge piers, and the weirs have become permanent infrastructure.

(A)



(B)



Figure 2-10 (A) The weir below the SH1 and rail bridges in November 1979, then a concrete-block structure; it was replaced by the present rock weir in 1985 (Crown aerial photograph 5614 F 27). (B) The heavy rock ballast of the weir, looking upstream, April 2022.



Figure 2-11 Bulldozer tracks where material has been pushed back and forth across the bed to set the river's course, 1986, near XS 370, about 800 m downstream of the old SH1 bridge.

Channel Shaping

Mechanical reshaping of the channel continued through the 1980s, particularly after floods in 1980, 1983 and 1985 (Williams 1992). Figure 2-11 shows bulldozer tracks near XS 370 in 1986, where material was pushed back and forth to set the course and concentrate the flow. After the March 1990 flood the bend at the upper end of Jim Cooke Memorial Park (XS 300–310) was reshaped and a power pylon at the channel edge was protected with concrete rubble, and banks at El Rancho were lined with large gravel from the Ōtaki River (Williams 1992). The cumulative effect of these works is visible in Figure 2-2C: between 1952 and 2022 the centreline shortened from 9.43 km to 8.56 km, about 9%.

Phase 2: the Floodplain Management Plan and a sediment surplus, c.1990 - present

A complete set of 59 cross-sections was surveyed in 1991 and has been resurveyed in 1995, 1999, 2004, 2010, 2014 and 2020 (Flanagan 2021). The 1991 survey became the baseline for management. The Waikanae Floodplain Management Plan (WRC 1997) set out to maintain the flood-carrying capacity and alignment of the river while minimising effects on landscape, cultural, heritage, ecological and recreational values, retaining a range of habitats and enhancing public access. It fixed three management parameters that remain in force:

- a preferred channel alignment, maintained as a 35 m design channel with a 20 m vegetated buffer on each side (Tonkin + Taylor 2016);
- a target of maintaining mean bed levels at or about 1991 levels (GWRC 2010; Tonkin + Taylor 2016); and
- an extraction allowance of about 3,000 m³/yr, reviewed after each survey, to keep the gravel balance at the status quo (WRC 1997, Section 3.3.4).

Under this regime the river was further trained. The 1997 Kauri/Puriri works (about XS 150–260) added a stopbank, a realignment that shortened the reach by 45 m, and grade control (WRC 2005). Bank protection and bed control followed the 1998 floods, and a major realignment was completed at Jim Cooke Memorial Park in 2006 (GWRC and KCDC 2014). By 2010 about 80% of the channel lay within the preferred alignment, and some 400 willows were being planted each year (GWRC 2010).

Extraction in this period was far lower than before 1990, but it was irregular and the record is incomplete. GWRC's compilation shows none in 1995–1999 (Kutta 2016, in Smith 2018), but about 11,000 m³ was removed during the 1997 Kauri/Puriri works, and reported totals of 38,000 m³ for 1991–2004 (WRC 2005) and 78,900 m³ for 1991–2012 (Opus 2012a) exceed the sum of the compiled period averages. 19,243 m³ was taken in 1999–2004 (WRC 2005); a consent for wet extraction behind bunds allowed 35,000 m³ over 2002–2007, of which 30,815 m³ was removed, mainly in the Pukekawa reach (GWRC 2010; Tonkin + Taylor 2016 gives 33,998 m³); and after 2007 only dry-beach extraction above the water line was permitted, averaging 1,770 m³/yr in 2007–2010 (GWRC 2010). A further 11,200 m³ was taken between 2014 and 2020 (Flanagan 2021). The resource consent applications lodged in 2013 and revised in 2016 proposed a one-off removal of 43,700 m³ between XS 50 and XS 300 to restore 1991 bed levels, followed by maintenance extraction of about 6,000 m³/yr (Tonkin + Taylor 2016).

Two recent developments point to a shift in practice. First, construction of the Kāpiti Expressway bridge (opened 2017) was followed by aggradation at El Rancho; in 2020 GWRC modified a partly completed widening there (XS 130–155), after consultation with stakeholders, "to adopt a more natural, meandering shape" (Flanagan 2021; Christensen Consulting 2018). Second, GWRC has adopted a general policy for the western rivers of allowing some meander freedom within stopbanked reaches (Williams 2013, reported in Smith 2018), and has closed a riverside track near XS 250 to allow bank erosion to proceed (Figure 4-6). The 2014 Environmental Strategy also recommends bringing privately owned corridor land on the north bank (XS 217–258) into public ownership (GWRC and KCDC 2014), and the 10-year review recommended investigating options for purchasing the remaining privately owned corridor land (GWRC 2010).

Figure 2-12 (facing page) Airphoto timeseries of the lower river, estuary and sand spit. The accumulation of sand and gravels at the upper tidal limit occurred sporadically in the past (white arrows). Tide levels make it difficult to discern precisely, but some initial signs of the buildup appear in 1991; the buildup was removed in 2005. Since 2013, the accumulation seems to be well-established, with minor reworking by flood flows.

The lower river, river mouth and estuary

The Waikanae Estuary is a moderate-sized tidal river-mouth estuary (40–50 m wide, 1–2 m deep and about 2 km long) that drains onto a broad, flat beach north of Paraparaumu. Much of the estuary is a long, shallow lagoon running behind the beach parallel to the coast (Robertson and Stevens 2012, in Cameron 2016). Tidal influence extends up the river to about XS 120 (GWRC and KCDC 2014). Longshore drift from the north builds a sand spit that pushes the mouth southward; the outlet ranges over about 900 m of shoreline, and floods break through the spit and restart the cycle (GWRC 2024). High spring tides and storm surges also occasionally overtop or erode the spit. Before settlement the estuary was about twice the area of the present reserve; Easter (1991) notes that much of the lost area is "euphemistically termed 'natural accretion', although the term reclamation would be a more proper description." Since the 1960s the land around the estuary has changed from coastal wilderness to a densely populated urban area, with hundreds of residential sections north of the river, and since 2017 the Kāpiti Expressway has crossed the centre of the plain.

The mouth has been cut mechanically 11 times between 1930 and 2001, most recently on 10 December 2001 (GWRC 2003, 2024). Under the regional plan a cut may be triggered when the outlet migrates more than 500 m south or 200 m north of the line of the training groyne, or when river levels at the Ōtaihan-ga footbridge rise 300 mm or more above normal. Each cut now requires the approval of the Minister of Conservation (GWRC 2024). In the early 1970s a marina development excavated the Waimanu Lagoon as a boat harbour and built a rock-lined point on the south side of the mouth; the development failed, but the lagoon, now controlled by a floodgate, and the rock point remain (Easter 1991; Williams 1992). Forming the lagoon drained and blocked the Waimeha Swamp, and traditional whitebait spawning grounds were lost (Easter 1991). The river continues to form natural channels around and south of the point, which has had little influence on mouth behaviour (Williams 1992). Gibb (2002, quoted in GWRC and KCDC 2014) advised that the migration cycle of the mouth should be allowed to continue "as a natural process ... as it rejuvenates the Waikanae Estuary", and DOC has indicated a preference for natural estuarine dynamics and against hard edge protection in the mouth reach (GWRC and KCDC 2014).

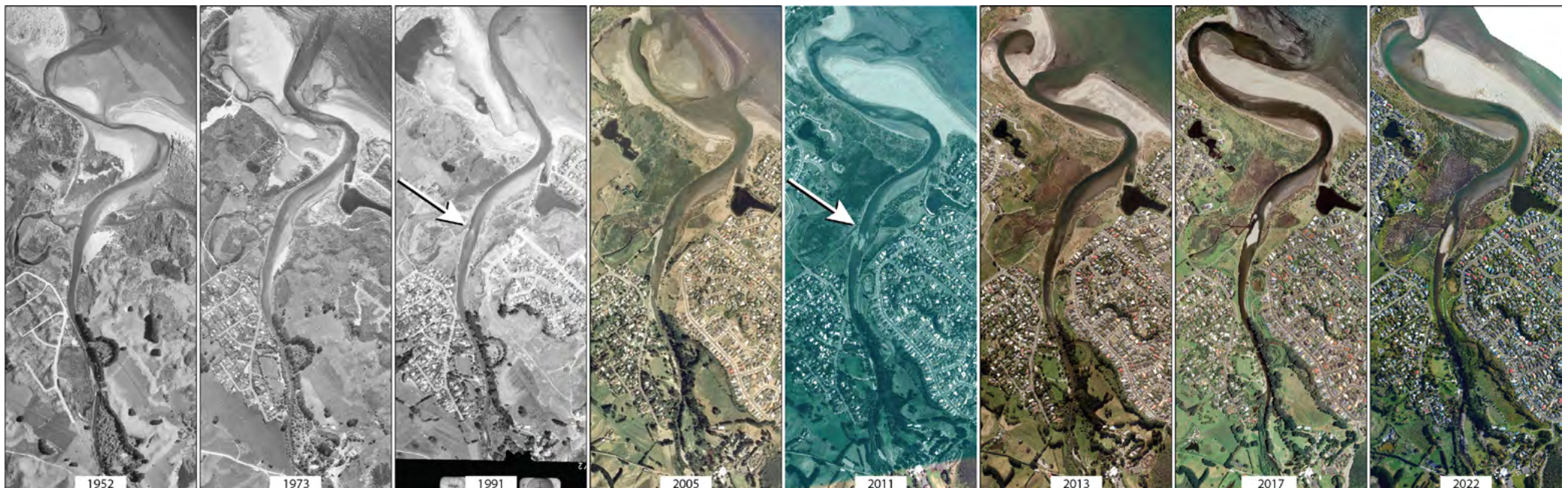




Figure 2-13 View of the sediment accumulation between GWRC cross-sections 60 and 70, looking downstream.

The Waikanae Estuary Scientific Reserve (58.5 ha) was established in 1987 and is administered by DOC. It protects a mosaic of freshwater lakelets, saltwater lagoons and marshes, tidal sand flats and beach, and is a nationally significant wetland (Cameron 2016). The estuary supports one of only two known populations of North Island fernbird in the Wellington region, one of the region's largest pied shag nesting colonies, and at least twelve threatened or at-risk bird species (Cameron 2016); more recent reviews record 13 threatened or at-risk species and 95 bird species at the estuary (DOC 2022). The nationally endangered Centipeda minima subsp. minima and the regionally rare sedges Carex litorosa and C. dipsacea are recorded in the reserve (Cameron 2016). Sixteen fish species are recorded in the river and its tributaries, including the threatened shortjaw kōkopu and lamprey (Cameron 2016), and the tidal reach below Ōtaihangā provides inanga spawning habitat.

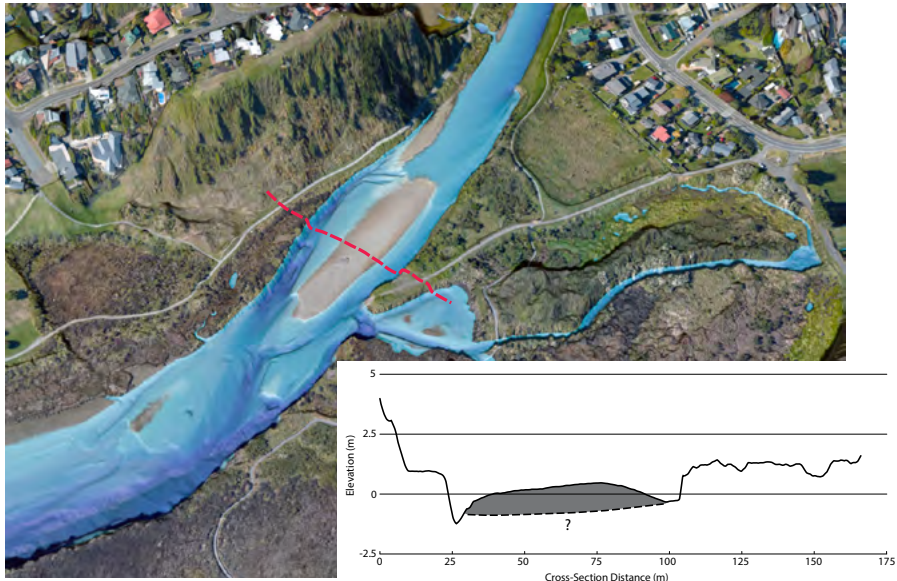


Figure 2-14 Cross-Section of the sediment accumulation near XS 40 in 2022.

Sediment in the estuary

Sediment plates in the upper estuary recorded rapid accretion early in the monitoring record, a mean of 26.4 mm/yr over 2010–2014 with 31.7% mud (Stevens and Robertson 2014, in Cameron 2016). Robertson (2021) reported a mean of +12.9 mm/yr for 2012–2021 at Site A. The most recent monitoring shows a more variable picture: the long-term mean is about 10 mm/yr, but net change over the last five years has been close to zero, with erosion in the most recent surveys during high flows, and mud content has fallen (Stevens 2022; Forrest and Stevens 2023). Forrest and Stevens (2023) conclude that strong variability is "an inherent characteristic of the estuary, and is determined mainly by flow conditions in Waikanae River". The upper estuary is therefore flow-regulated: moderate floods deliver sediment and large floods flush it.

Coarser sediment is a separate issue. A body of gravel and sand has built up at the tidal interface upstream of the estuary, near the Ōtaihangā Boating Club (Figures 2-12 to 2-17). Campbell (2002) estimated that the gravel front had advanced

about 1 km over the preceding 40 years and was about 1.3 m deep adjacent to the boating club; assuming that depth over the whole deposit gave a volume of about 39,000 m³, advancing at about 1,000 m³/yr (Campbell 2002, in Opus 2012a). The accumulation was partly removed in 2005 and has been well established since 2013 (Figure 2-15). The 2013–2022 LiDAR comparison shows only modest growth and some incision and reworking. Flanagan (2021) identifies the gravel island downstream of the boating club and the opposite point bar as the main sites of aggradation in the Ōtaihangā reach.

Sea-level rise will extend the tidal backwater and the zone of low bed shear stress further upstream; Opus (2012b) estimated that a 0.8 m rise would shift deposition several hundred metres upstream. Cardno (2014, in Smith 2018) warned that, as sea level rises, the groyne on the south side of the mouth will act increasingly like a breakwater, altering flow through the estuary and potentially leading to infilling.

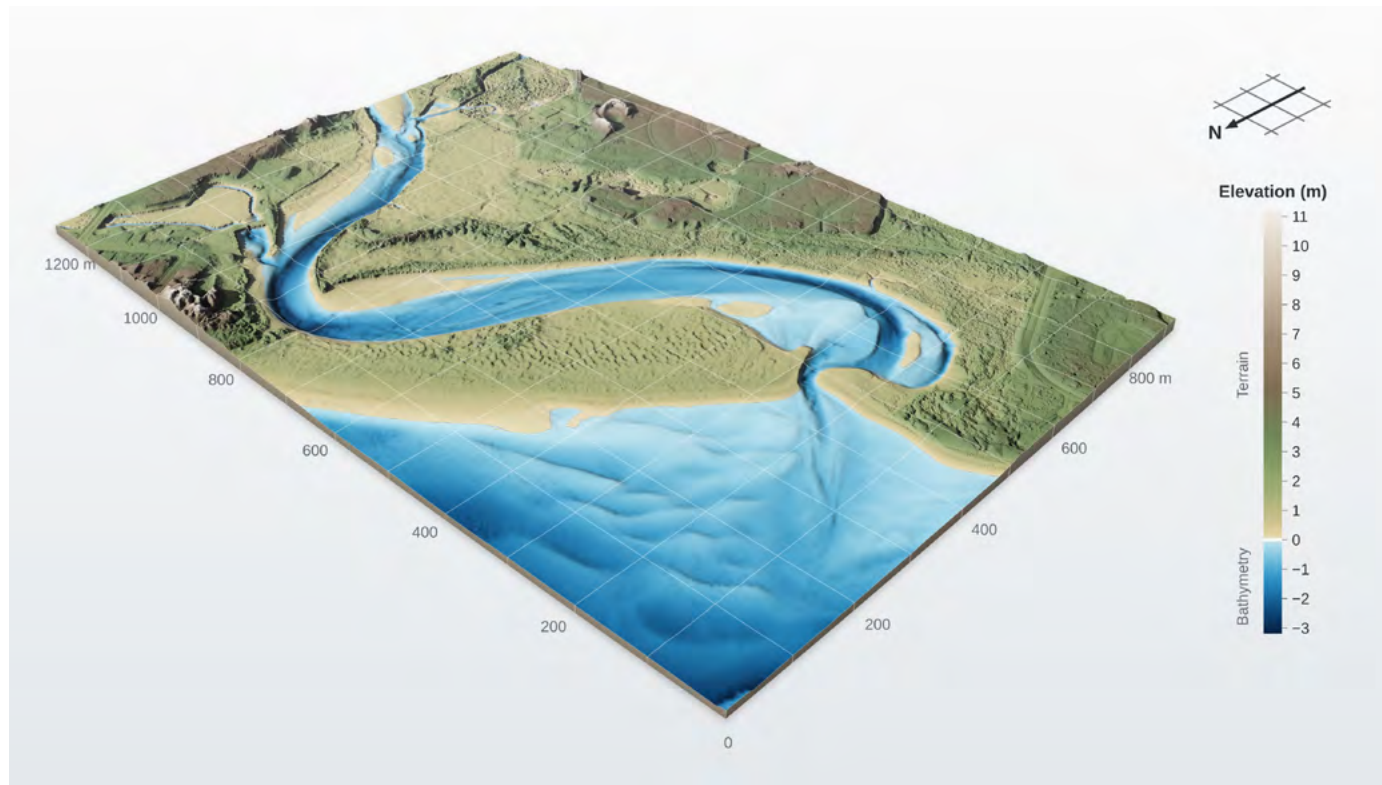


Figure 2-15 Bathymetric LiDAR reveals the contours of the Waikanae estuary and the subaqueous fan beyond the mouth of the river.

3. Sediment Budget



Figure 3-1 Upstream-most gravel sampling site, upstream of Reikorangri Rd bridge.

A sediment budget balances what enters a reach, what leaves it, and what changes in storage. For the lower Waikanae, gravel enters at the Water Treatment Plant from the upper catchment and from erosion of the bed and banks within the study reach; almost none leaves through the river mouth (Smith 2018; Flanagan 2021); and storage changes through deposition, erosion and extraction. This chapter assembles the estimates of each term, sets the history of extraction against them, and uses the cross-section and LiDAR records to locate where the river is gaining and losing sediment.

Gravel supply

No physical measurements of bedload or suspended-sediment transport have ever been made in the Waikanae catchment (Opus 2012b). Estimates of gravel supply to the lower river have been derived indirectly, by scaling from the Ōtaki, from transport equations, or from repeat surveys combined with extraction records (Table 3-1). They range from about 1,000 to 7,600 m³/yr. Most of the spread reflects method and period: transport-equation estimates depend on grain size and calibration - for 2005–2010 the modelled bedload past Edgewater (1,614 m³/yr) was less than a third of the survey-and-extraction estimate for the same site (5,862 m³/yr; Opus 2012a) - while survey-based values include gravel eroded from the bed and banks within the study reach as well as gravel supplied from upstream.

Table 3-1 Published estimates of gravel supply to, or accumulation in, the lower Waikanae River.

Estimate (m ³ /yr)	Period	Basis	Source
960–2,240	-	Scaled from Ōtaki bedload supply by 100-year peak flow	MCB 1986 investigation, in Easter (1991)
c. 5,000	-	Williams' assessment for the Floodplain Management Plan	Williams (1992), in Opus (2012a)
3,000	-	Extraction allowance assumed equal to the rate of accumulation	WRC (1997)
7,605	1999–2004	Survey volume change plus extraction, less bank-derived material	WRC (2005)
1,614 (bedload); 2,388 (total)	1991–2010	BAGS (Wilcock–Crowe) past Edgewater (XS 380); lower bounds	Opus (2012a)
6,000	1991–2010	Input to the reaches below Jim Cooke Memorial Park	Opus (2012a)
≥ 4,600	1991–2020	Net accumulation in the monitored reach, with extraction added back	Flanagan (2021)

Extraction against supply

Figure 3-2 sets the history of extraction against the range of supply estimates. From 1957 until the late 1980s, extraction averaged about 10,000 m³/yr (Kutta 2016, in Smith 2018), with individual years reaching 22,000–28,000 m³, and the archive total for 1960–75 implies about 17,000 m³/yr (Easther 1991). These rates exceeded even the highest supply estimate, and for most of the period exceeded the more conservative estimates several-fold. The river's bed was, in effect, being mined, and the 1.5–2 m of degradation recorded near the bridges (Chapter 2) is the expected result; gravel mining has driven comparable incision on other gravel-bed rivers (Martin-Vide et al. 2010).

Since 1991 extraction has mostly been below supply. GWRC's compiled averages are about 2,000 m³/yr in 1991–1995, nil in 1995–1999, 3,600–7,040 m³/yr in 1999–2010 (including the 2002–2007 wet-extraction consent) and less than 2,000 m³/yr since 2010 (Kutta 2016, in Smith 2018; Flanagan 2021). These averages understate the 1990s: about 11,000 m³ was removed during the 1997 Kauri/Puriri works (WRC 2005), and the reported total for 1991–2012 is 78,900 m³, about 3,600 m³/yr (Opus 2012a). The budget has therefore reversed sign. The lower river now receives more gravel than is removed, and the surplus goes into storage in the reaches below Jim Cooke Memorial Park.

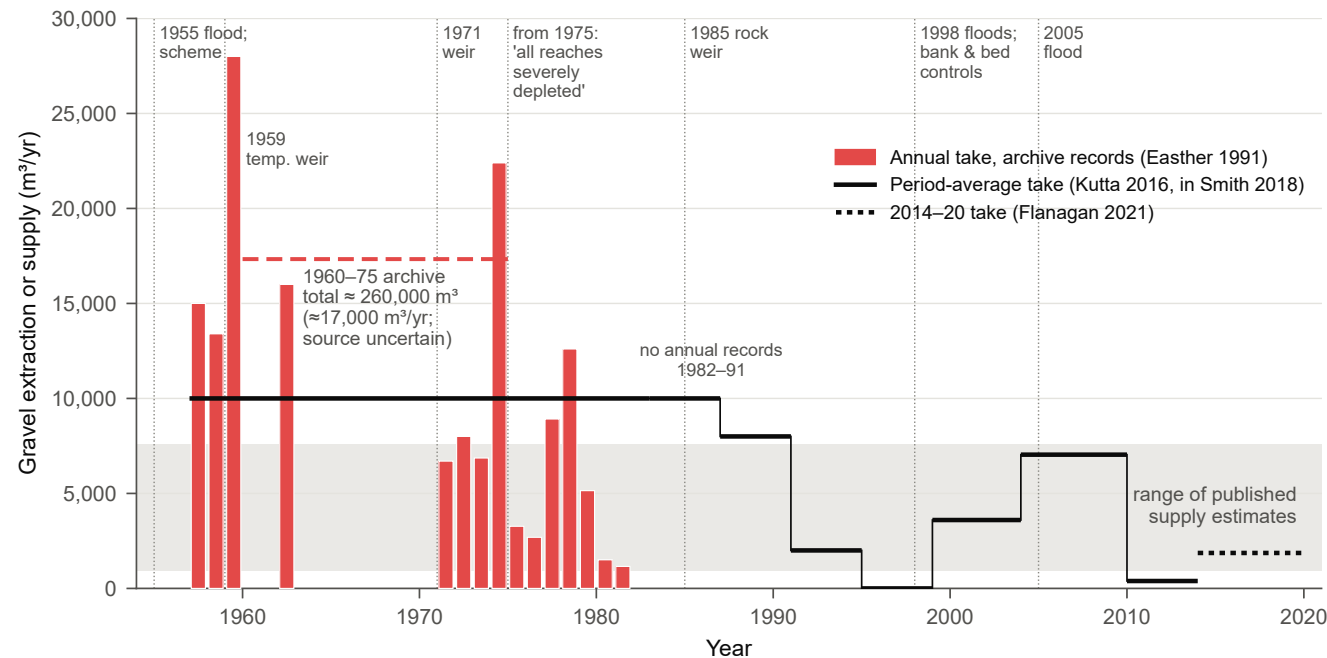


Figure 3-2 Gravel extraction from the Waikanae River, 1957–2020, compared with published estimates of gravel supply. Red bars: annual takes recorded in the management archive (Easther 1991), plotted by financial year; dashed red line: the archive total for 1960–75 expressed as an annual rate (attribution flagged as uncertain in the source). Black steps: period-average extraction compiled by GWRC (Kutta 2016, tabulated in Smith 2018); dotted: 2014–2020 (Flanagan 2021). Grey band: published estimates of supply or net accumulation (Table 3-1). Extraction exceeded supply through the scheme era and has mostly been below it since 1991.

Cross-section budget, 1991 - 2020

Volumetric change between successive surveys of the 1991 cross-section set gives the pattern of gains and losses along the river (Figure 3-4). The errors in such estimates can be significant - probably 10% or more - because the channel varies between the surveyed sections and because compensating erosion and deposition between surveys is not captured, which biases net change towards zero (Lane et al. 1994; Ashmore and Church 1998; Lindsay and Ashmore 2002; Brasington et al. 2003). Volumes derived in this way are therefore minima, but they are a good indication of the direction and location of change. Earlier surveys (1957, 1975, 1983 and 1987) used different section positions and spacing, and only some can be compared directly with the present set (Williams 2015).

Most of the change occurred in the earlier surveys (1991–2004), with more incremental change since. The cumulative change at each cross-section between 1991 and 2020 (lower panel of Figure 3-3) shows net loss in the upper study reach and gain in the lower reaches, with the transition just upstream of Jim Cooke Memorial Park (about XS 340–345). GWRC's own analysis of the same surveys (Flanagan 2021) gives the same pattern at reach scale:

- the reach above SH1 (XS 420–550) is losing about 1,000 m³/yr and its mean bed level has fallen by more than 1.3 m in places since 1991, except immediately below the Water Treatment Plant structure;
- the reaches below SH1 and at Jim Cooke Memorial Park (XS 270–410) are close to balance or slightly degrading, with local deposition upstream of the Kebbels weir;
- the Kauri/Puriri, El Rancho and Ōtaihangā reaches (XS 10–260) are each gaining about 1,900–2,000 m³/yr, with mean bed levels up to 0.8 m above 1991 levels near the Equestrian Centre and 0.3–1.4 m higher at El Rancho.

Summed over the monitored reach, and with extraction added back, the river is accumulating about 4,600 m³/yr, and about 69,000 m³ now sits above 1991 levels downstream of Jim Cooke Memorial Park (Flanagan 2021). GWRC's analysis also locates the principal grade breaks: the mean bed grade falls from about 1:175 upstream of Jim Cooke Memorial Park to about 1:260, and again to about 1:1500 immediately downstream of the Kāpiti Expressway bridge (Flanagan 2021). GWRC's 2017 gravel review noted that aggradation below the bridge predates its construction (quoted in Flanagan 2021), which points to the grade break rather than the bridge as the primary control.

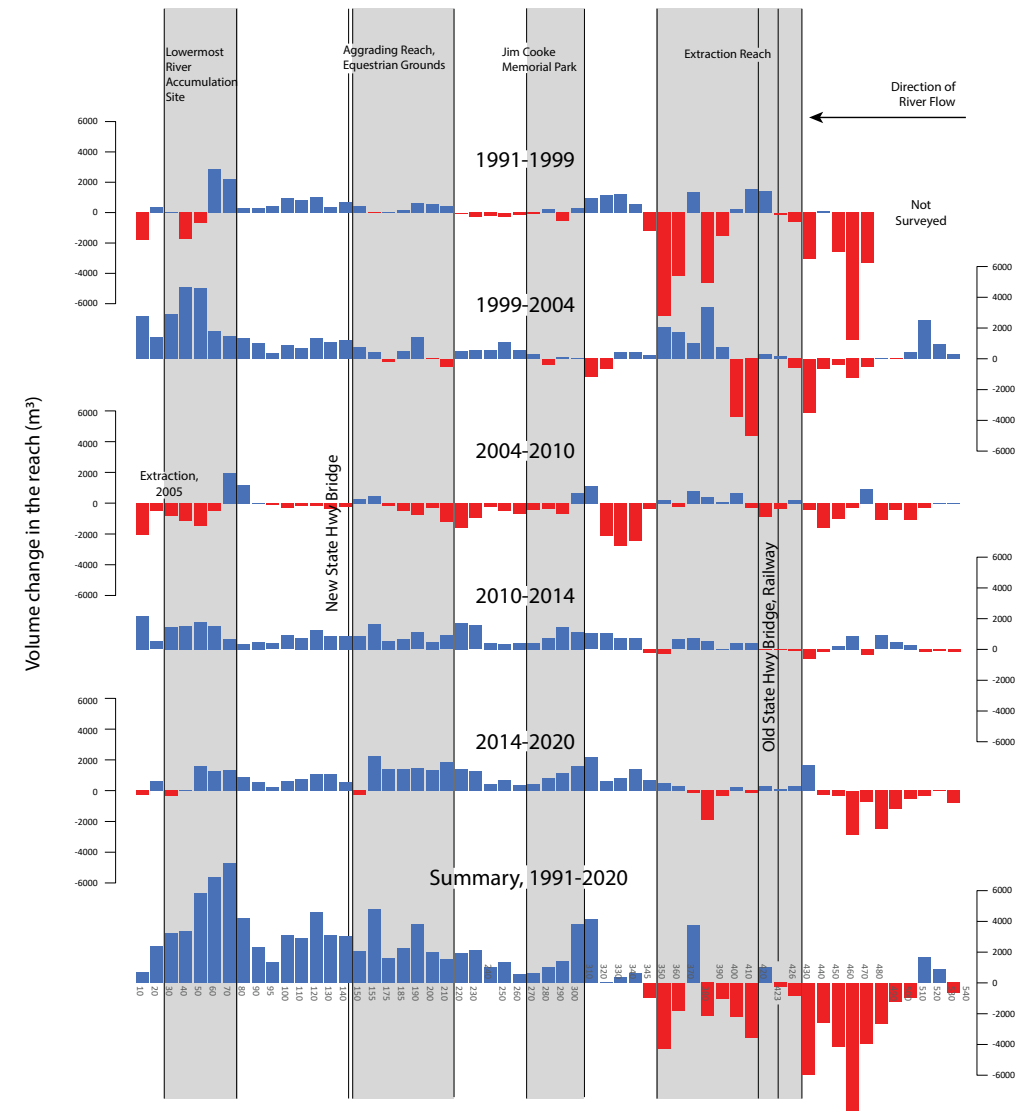


Figure 3-3 Estimated volumetric change at each cross-section between survey epochs, 1991–2020, from mean bed level changes, with the cumulative 1991–2020 change in the lowest panel. Deposition in blue, erosion in red.

LiDAR change, 2013 - 2022

Two LiDAR difference models show erosion and deposition across the whole corridor (Figure 3-4). The river's planform has been generally stable over this period: the principal changes are aggradation in the middle reach and minor bank erosion throughout, consistent with the cross-section record. Change around the Kāpiti Expressway construction site stands out in the 2013–2021 model. A distinct zone of deposition lies between Jim Cooke Memorial Park and

the expressway bridge, including the locus of deposition near Greenaway Road. The accumulation upstream of the estuary shows modest growth, and the cut and fill of the shifting channel behind the spit is clear. The 2021–2022 model shows apparent channel erosion, some of which is likely to be an artefact of comparing conventional (near-infrared) LiDAR, which records the water surface, with bathymetric (green) LiDAR, which records the submerged bed.

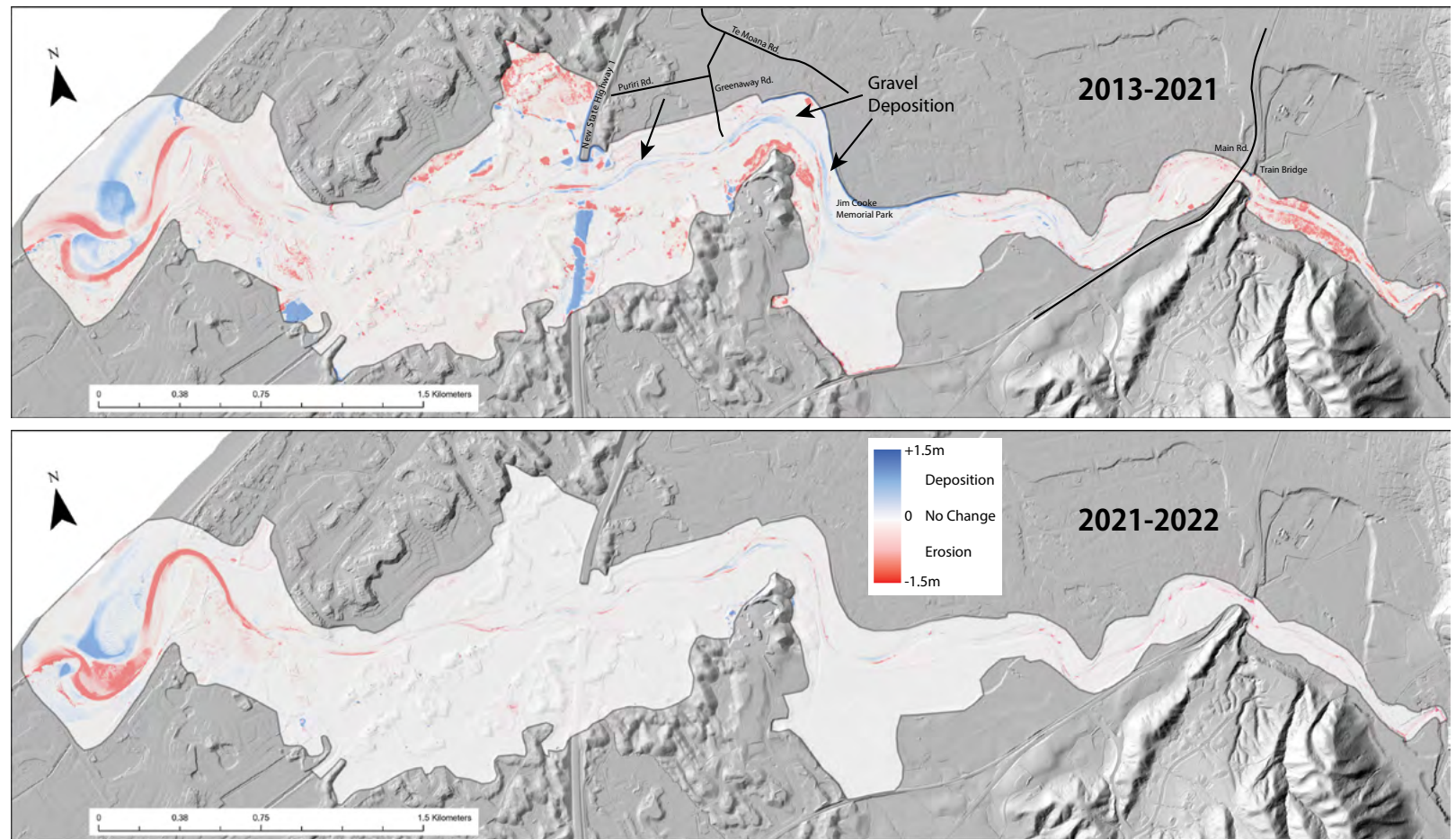


Figure 3-4 LiDAR difference models showing erosion (red) and deposition (blue) across the lower river.

Budget synthesis

The cumulative downstream sum of volume change for each survey interval (Figure 3-5) shows the tendency of the system as a whole: a rising curve indicates build-up, a falling curve indicates degradation, and a flat curve indicates a balance of gains and losses. Earlier epochs show a strong negative trend in the upstream reaches, a flat or subdued trend in the middle reaches and a positive trend in the lower reaches. The positive trend strengthens in the later surveys; in the latest (2020) epoch the lower river shows a moderate aggrading trend from about XS 345 downstream. The upper reaches retain high transport capacity and deliver material through the intervening reaches, which have been engineered to convey it, to the zone of storage below Jim Cooke Memorial Park.

The reach budget has three parts, with deposition concentrated at the grade break below the expressway bridge and at the tidal interface near Ōtaihanga:

1. **Storage.** About 5,800 m³/yr is deposited in the reaches below Jim Cooke Memorial Park (Flanagan 2021), consistent with the Opus (2012a) estimate of about 6,000 m³/yr entering those reaches.
2. **Supply from the local river bed or banks.** The degrading reaches above Jim Cooke Memorial Park contribute about 1,200–1,600 m³/yr from bed and bank storage (Flanagan 2021) - roughly a quarter of the gravel deposited downstream. The contribution was much larger before the post-1998 bed controls: about 28,000 m³ was lost above Jim Cooke Memorial Park in 1995–1999, but only about 10,000 m³ in 1999–2004 (WRC 2005).
3. **Supply from the catchment.** The remainder, about 4,200–4,600 m³/yr, enters the study reach from the catchment above the Water Treatment Plant, matching GWRC's net accumulation for the monitored reach (Flanagan 2021). With negligible export at the mouth, this is a minimum estimate of catchment supply; the survey-based estimate for 1999–2004 was higher, at about 7,600 m³/yr (WRC 2005).

Two conclusions emerge from this. First, the present aggradation is sustained partly by continuing incision upstream, the legacy of the scheme-era deficit; as the upper bed armours and is held by weirs, that contribution should decline and the rate of aggradation with it. Second, most of the surplus is catchment supply arriving at a natural depositional setting - the toe of the fan, where the grade flattens and the tidal backwater begins. A river on an unconfined fan would spread this sediment laterally; the confined Waikanae must store it in the bed.

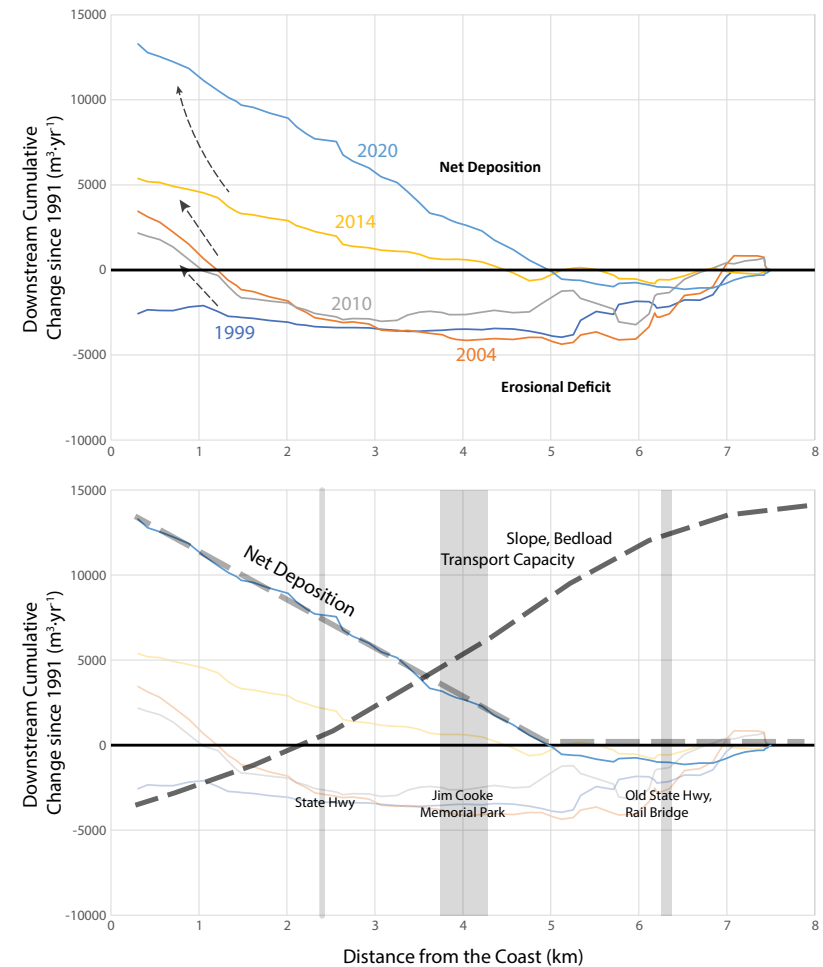


Figure 3-5 Downstream cumulative volume change since 1991, by survey epoch (upper), and the same curves with the schematic downstream decline in slope and bedload transport capacity (lower). A rising curve indicates net deposition and a falling curve net erosion.



Figure 4-1 The reach in the Reikorangi Gorge shows an abundance of loose gravelly material, and relatively deep pools layered with sandy material.

This chapter examines the form of the modern river and the processes that maintain it. It describes the bed material and channel geometry, distinguishes forced from freely formed channel morphology, and maps geomorphic units along the study reach as a measure of physical habitat diversity. It then uses a first-order calculation and two morphodynamic models to test whether the steepened, confined configuration can explain the observed pattern of incision and aggradation.

Bed Material

Surface grain size was measured every few hundred metres along the river to characterise habitat, hydraulic conditions and the gravel transport regime (Figure 4-2). Wolman counts were made at 16 sites, averaging 277 clasts (≥ 8 mm) per site, and three bulk subsurface samples (up to 525 kg each) were taken from beneath the armour layer in the upper, middle and lower reaches and sieved (Figure 4-3).

Bed material in the upper reach extends into the boulder range, with a well-sorted and relatively mobile surface fabric - not strongly imbricated or compacted. Clasts are well rounded, indicating fluvial reworking and little fresh input from landslides. Surface gravels are clast-supported, reflecting high flow competence

without an over-supply of fine sediment. Silt and finer material are notably scarce, and low-flow water clarity is very good. Surface median size (D_{50}) falls from about 64 mm in the upper study reach to about 20 mm near the estuary, over just over 6 km, and the surface becomes progressively better sorted downstream (Figure 4-4). The subsurface becomes progressively richer in sand towards the estuary; although the slope is lower, sandier mixtures are more easily mobilised. The bed changes from gravel to sand at about the Ōtaihangā boat ramp (Opus 2012a). Dynamic gravel bars are plentiful in the upper river, relatively scarce in the degrading section, and reappear as lateral and mid-channel bars in the lower river, where surplus sediment has accumulated.

Downstream fining in fans and other aggrading systems can arise from abrasion, preferential transport of finer grains, selective deposition of coarse clasts in bars and floodplain, addition of material at confluences or by bank erosion, and in-situ weathering. Of these, selective transport and deposition are considered the main controls on fining rates (Allen 2017), and the concave profile of a fan reinforces them as the slope flattens toward its distal end. Williams (1992) estimated that the armour layer is entrained at about $25 \text{ m}^3/\text{s}$ and the whole bed at about $4 \text{ m}^3/\text{s}$, flows exceeded about 2% and 35% of the time respectively (Opus 2012a). The surface is therefore mobilised by moderate floods several times a year, and the gravel supply is not limited by the frequency of competent flows.

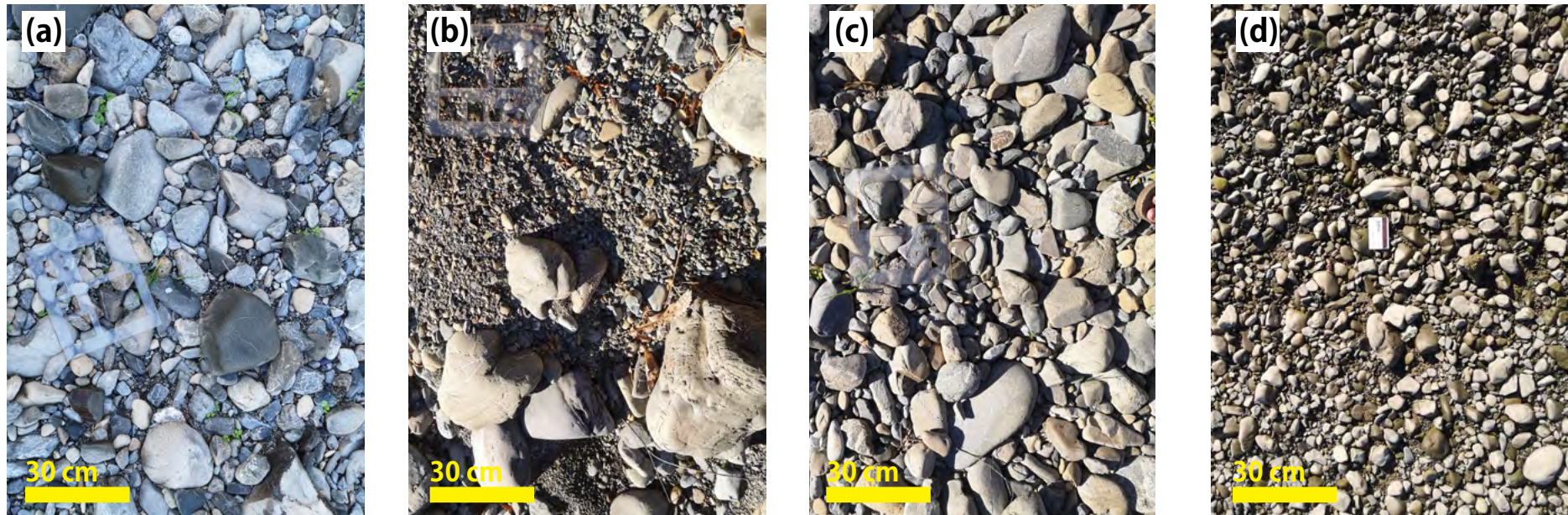


Figure 4-2 Surface grain size variation from the upstream-most sampling site (a) to the lowermost bar upstream of the estuary (d). (b) shows a mobile sheet of pebble-gravel mixture that has deposited on top of a stable cobble-boulder bar in the mid-reaches. Surface materials are generally mobile, and generally do not show much silt content. The material in the lowermost river tends to be quite narrowly graded, relative to the middle and upper reaches (Figure 4-3).

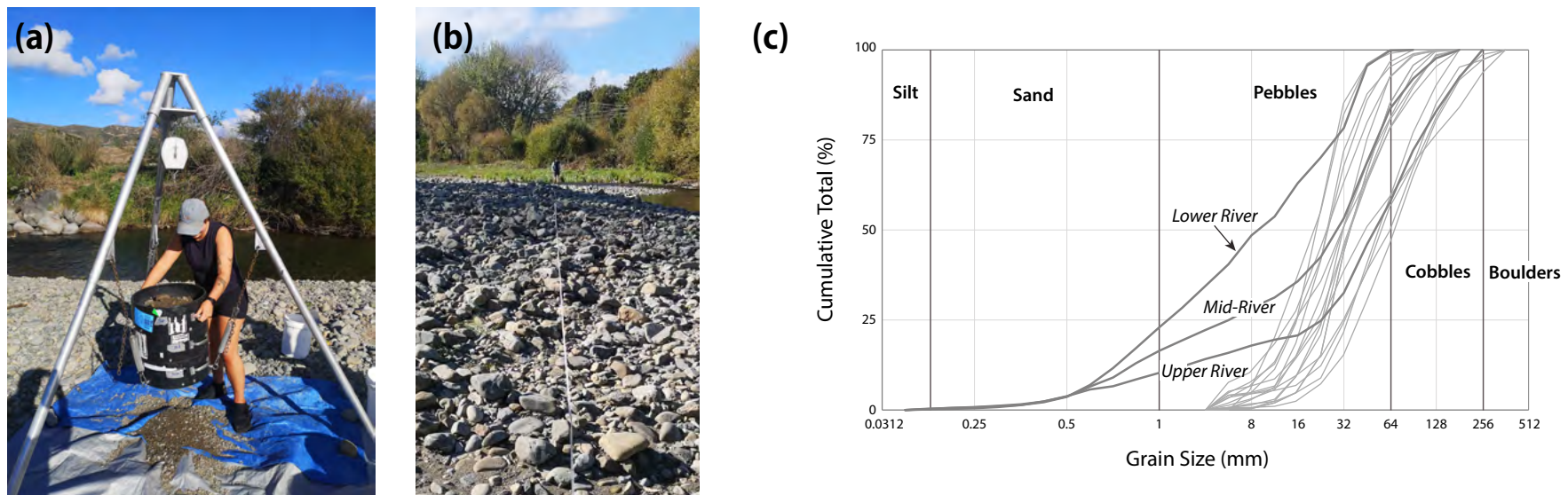


Figure 4-3 Grain size sampling on the Waikanae River. (a) Tripod sieve system for bulk sampling of the subsurface; assessing fractions under the surface armour layer. A measuring tape is used to set the sampling interval along each transect. (b) Sampling results: grain size distribution for 16 surface (Wolman) samples and 3 subsurface (bulk) samples.

Channel geometry and gradient

Bankfull width and depth change systematically downstream, with more pronounced change as the channel approaches the estuary (Figure 4-4). The bed grade falls in steps rather than smoothly: from about 1:175 upstream of Jim Cooke Memorial Park, to about 1:260 through the Kauri/Puriri reach, to about 1:1500 below the Kāpiti Expressway bridge (Flanagan 2021). The two breaks coincide with the transition from degradation to aggradation and with the start of the main zone of storage.

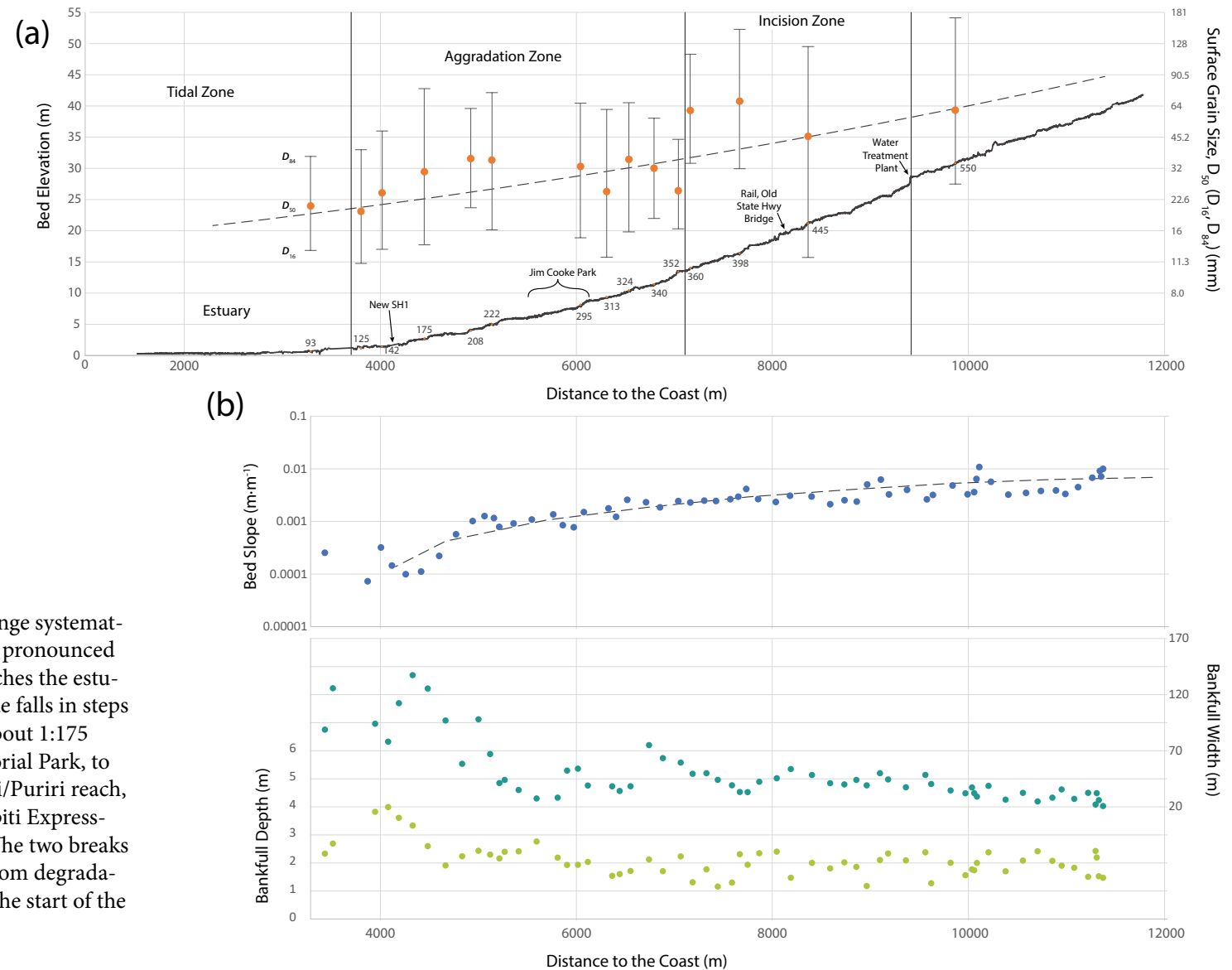


Figure 4-4 Longitudinal variation in (a) surface grain size (D_{16} , D_{50} , D_{84}), (b) bed slope and (c) bankfull width and depth. Aggradation and incision zones follow the 1991–2020 cross-section record (Figure 3-3). Most variables change smoothly from the upper river to just downstream of Jim Cooke Memorial Park; below this the gradient flattens and the channel widens, coinciding with the reach that is aggrading.

The Floodplain Management Plan's 35 m design width for a bankfull discharge of about 160–175 m³/s sits within the envelope of bankfull widths for natural rivers compiled by Phillips et al. (2022) (Figure 4-5), and is close to the 30–40 m bankfull width adopted in the 1955 design (Easter 1991).

Rivers vary widely about such relationships according to sediment supply and bank material (Eaton and Millar 2017). The design width is a width for conveyance. It does not provide the erodible corridor - the meander belt - through which an alluvial river adjusts its planform over time, which can be many times the channel width (Piégay et al. 2005; Biron et al. 2014). For the Waikanae, the 1952 photographs and the relative elevation model (Figures 2-6 and 2-9) indicate the width of the channel belt before confinement. GWRC's closure of a riverside track near XS 250 to let bank erosion proceed (Figure 4-6) is a step in this direction. Systematic mapping of erosion and deposition over successive surveys would show where the river needs more room to adjust its cross-section and planform to carry its sediment load under the present flood regime.

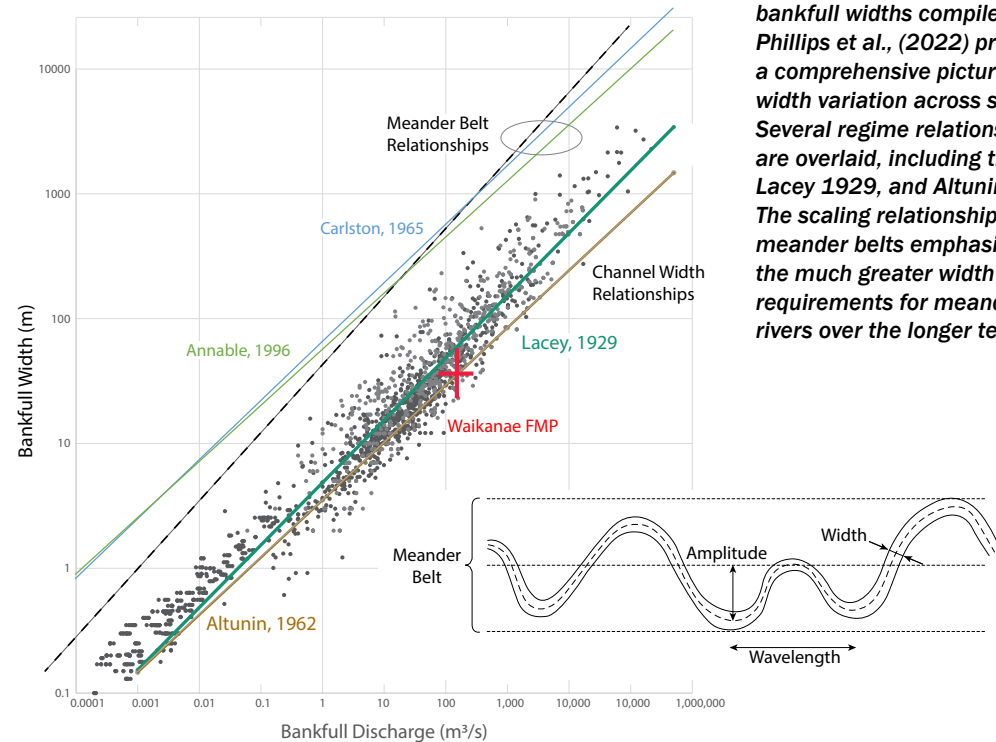


Figure 4-5 A database of natural and laboratory river bankfull widths compiled by Phillips et al., (2022) provides a comprehensive picture of width variation across scales. Several regime relationships are overlaid, including those of Lacey 1929, and Altunin 1962. The scaling relationships for meander belts emphasise the much greater width requirements for meandering rivers over the longer term.

Figure 4-6 Erosion on the left bank of the Waikanae River near XS250, downstream from Jim Cooke Memorial Park. The erosion is evident in the 2013-2021 LiDAR change map (Figure 3-4).



Forced and freely formed morphology

Much of the morphological variation along the Waikanae is currently created by fixed obstacles in the channel - groynes, rock linings, weirs and large wood (Figure 4-7, 4-8). These are forced morphologies, as distinct from freely formed units that arise from the interplay of flow, sediment transport and bank erosion in an actively adjusting channel (Lisle 1986; Montgomery et al. 1995; Buffington et al. 2002). Forced pools and bars are common in natural rivers, where wood, boulders and bedrock induce flow convergence and scour, and they provide good variation in depth and velocity; the scour pool at the groynes near XS 345 exceeds 2 m depth at low stage (Figure 4-8). Freely formed pool-riffle sequences, by contrast, depend on channel meandering, secondary flow and sediment sorting, and require an active alluvial corridor wider than the bankfull channel. A river whose pools exist only where structures force them has lost much of its capacity to create and renew habitat by itself.

Figure 4-7 Forced morphologies. (A) Three rock groynes near XS 345 anchor pool formation. (B) Woody debris near XS 390 has caused local scour and deposition on the right bank.



The Natural Character Index assessment of the western rivers supports this reading. It recorded a pool ratio of zero for XS 240–300 and among the greatest departures from natural character in the scheme between XS 175 and XS 300 (Williams 2013, in Cameron 2016). Cameron (2016) concluded that training the river to a design alignment "could result in restriction or reduction of habitat diversity unless the design alignment also provides for preservation of habitat diversity", and that bed recontouring used to straighten the channel is "likely to result in loss of channel complexity and a reduction in aquatic habitat diversity".

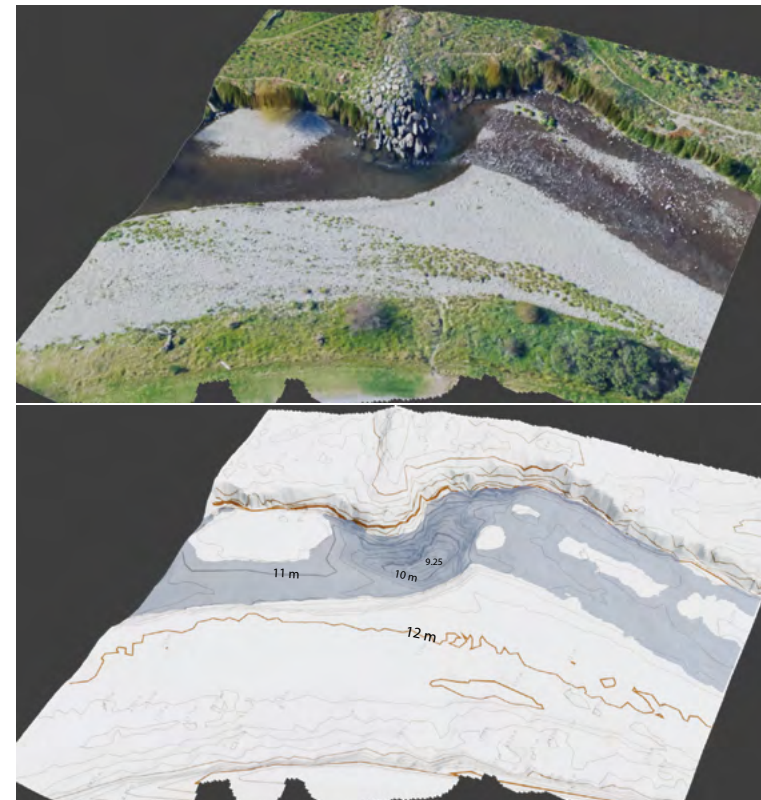


Figure 4-8 (left) Bathymetric LiDAR of the pool at the groynes near XS 345 (flow right to left). Scour at the upstream edge of the groyne exceeds 2 m depth at low stage.

Geomorphic units and habitat diversity

The high-resolution bathymetric LiDAR allows geomorphic units - landforms at the 1–10 m scale with characteristic form and hydraulics, such as pools, riffles, bars and cascades - to be mapped objectively across the whole study reach. We used the Geomorphic Unit Tool (GUT; Bangen et al. 2017), which applies the hierarchical taxonomy of Wheaton et al. (2015) to classify units by stage, shape (concave, convex or planar) and attributes such as position and orientation (Figures 4-9 and 4-10). The tool has seen little use in Aotearoa New Zealand, but it performs well on the Waikanae.

From a conservation perspective, each riverine species has a range of hydraulic environments in which it thrives. A greater diversity of geomorphic units generally means greater physical habitat diversity - more refugia, foraging areas and gradients of temperature, oxygen and velocity - and hence greater richness of macroinvertebrates, fish and macrophytes. Geomorphic unit diversity can therefore serve as a practical proxy for physical habitat diversity (Williams et al. 2020).

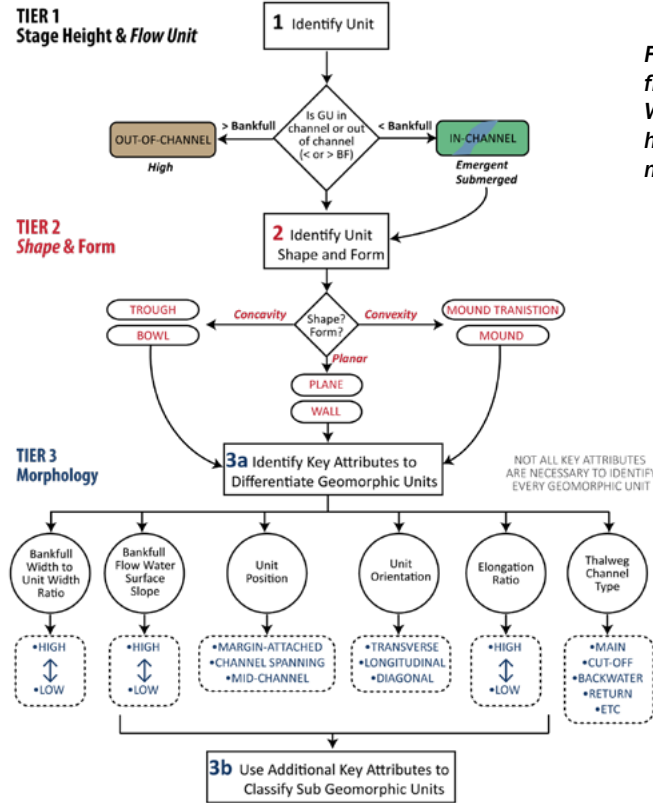


Figure 4-9 Hierarchical framework adapted from Wheaton et al (2015). See: <https://gut.riverscapes.net/background>

The upper study reaches have the greatest diversity of units, including rapids, cascades and riffles (Figure 4-11). These higher-energy units are scarce or absent downstream of the railway bridge. The lower river is dominated by glide-runs (simple, low-gradient troughs) and transitional units, pools correspond to groynes and other structures, and freely formed riffles are largely missing. There are relatively few units associated with lateral migration and channel dynamism - cut banks, bank-attached bars and riffles at bar heads - and a surplus of stable forms. Other than aggradation in Reach 3, the river shows few signs of dynamic morphological adjustment.

Williams et al. (2020) used the same tool before and after the removal of embankments and bank protection from a straightened gravel-bed river in Scotland. Once bank erosion was allowed, the area of in-channel units grew by 23% in two years and 31% in four, the share of glide-run and transition units fell from 80% to about 50%, and the Shannon diversity of geomorphic units rose from 1.40 to 2.05, largely through bank erosion supplying sediment for new lateral, point and diagonal bars. The Waikanae results can be placed on the same scale.

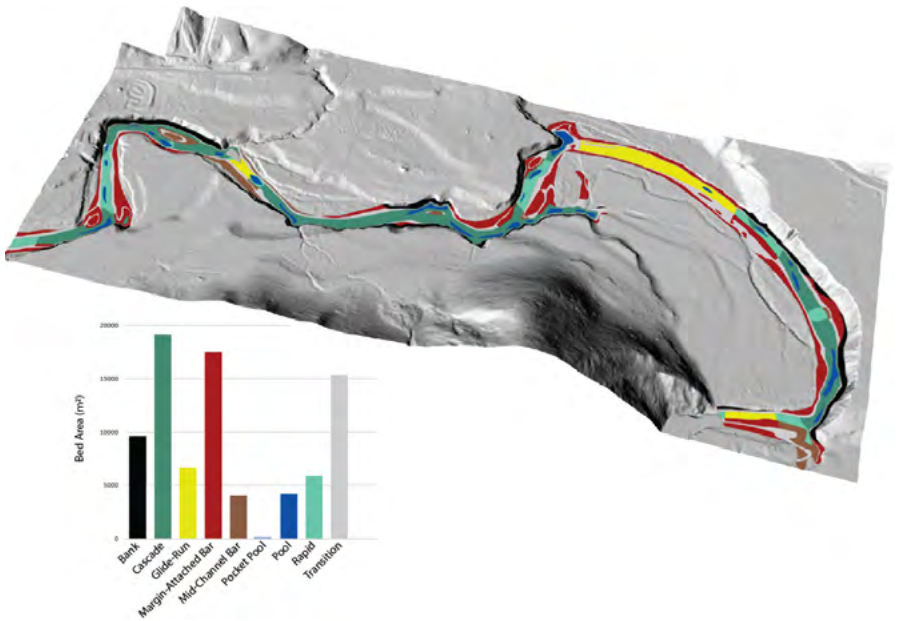


Figure 4-10 GUT analysis of the upper study reach in the Waikanae River (2022 LiDAR).

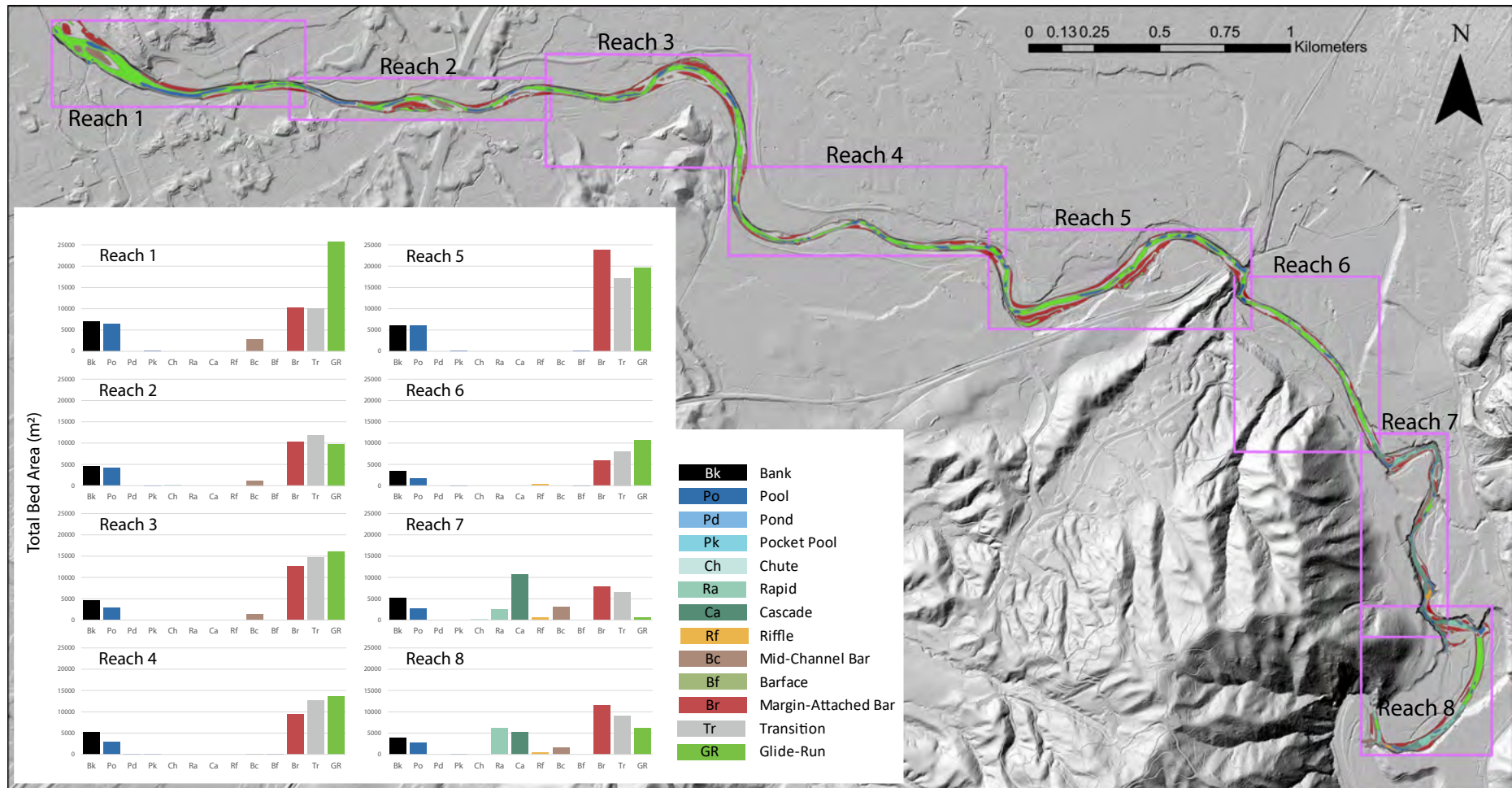


Figure 4-11 Results from the GUT tool identification of geomorphic units along the full study river section.

One-dimensional model (GRATE)

A 1D sediment transport model, GRATE (Tunncliffe and Church 2015), was used to compare the equilibrium longitudinal profile and transport regime of the river between the Water Treatment Plant and the coast for 1952 and 2022 conditions (Figure 4-12). Cross-sections were simplified to trapezoids based on the aerial photographs and surveyed sections. The 1952 model is 9.5 km long and the 2022 model, with reduced sinuosity, 8.3 km. The reach below the railway bridge was held fixed to represent the existing grade controls, preventing upstream propagation of the knickpoint that would otherwise occur. A uniform flood discharge of $250 \text{ m}^3/\text{s}$ and a bedload feed of $0.014 \text{ m}^3/\text{s}$ were applied at the upstream boundary, with tributary inflows neglected, and each model was run until the profile stabilised, generally after 24–48 hours of continuous flood flow.

Both configurations deposit sediment in the middle reaches, but the 2022 model deposits more, and over a reach that corresponds well with the present zone of aggradation and some distance upstream of it. The downstream profile of bedload transport shows why (Figure 4-12c). On a fan the transport gradient tapers abruptly at the distal end, producing deposition. In the 2022 model the steepened upper channel has greater erosive capacity and delivers more sediment downstream, and the steeper transport gradient concentrates deposition over a shorter distance. That the 1952 configuration also deposits in this zone confirms that it is a natural depositional setting; the modern configuration intensifies deposition there and removes the lateral pathways by which the river once spread it.

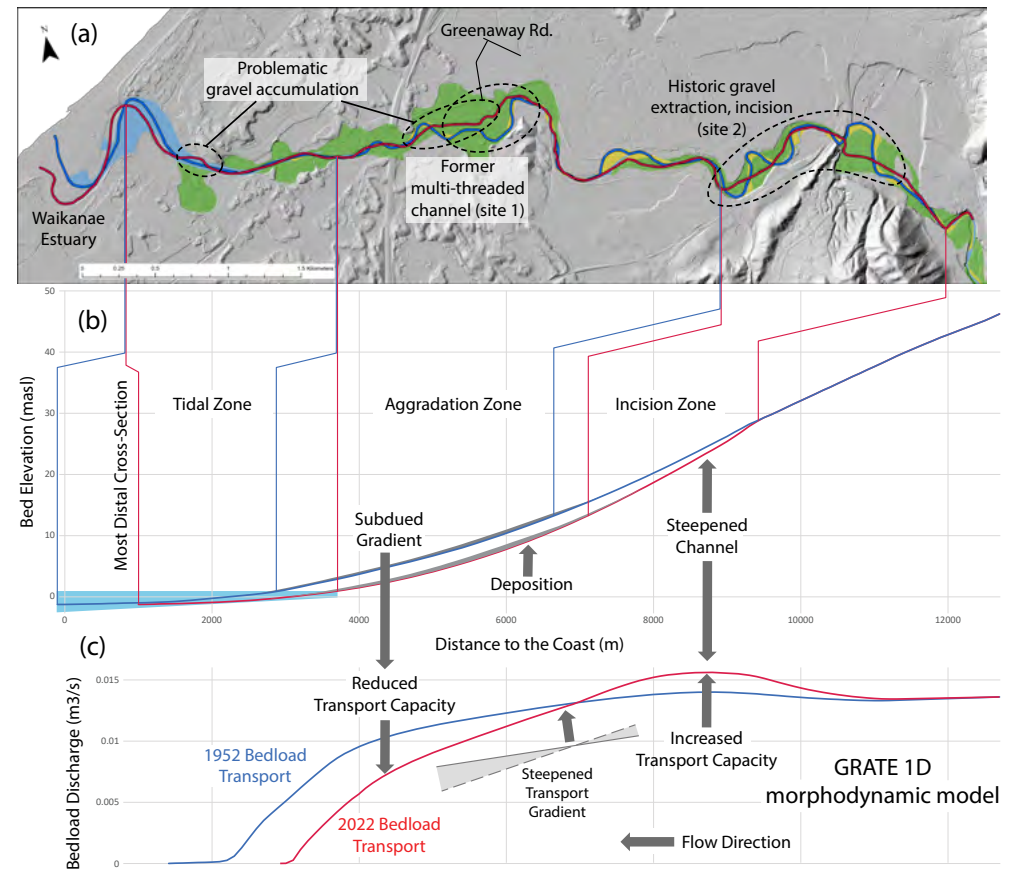


Figure 4-12 GRATE 1D model of the 1952 (9.5 km) and 2022 (8.3 km) configurations: (a) planform and key sites; (b) modelled long profiles, showing the steepened incision zone, the aggradation zone and the tidal zone; (c) bedload discharge along the profile. With reduced sinuosity and a steeper gradient, the 2022 model shows greater erosive capacity in the incision zone and greater deposition in the aggradation zone.

Two-dimensional model (Delft3D-FM)

Delft3D-FM (Deltares 2020) was used in depth-averaged 2D morphodynamic mode to explore the evolution of the lower river under the present discharge and sediment regime, starting from the 2022 bathymetric LiDAR surface. The unstructured grid has an average cell area of 2.7 m^2 (Figure 4-13). A hydrograph peaking at $350 \text{ m}^3/\text{s}$ was cycled four times over 48 hours, spanning partial transport below bankfull to full bed mobility, with a morphological acceleration factor of 2. A tidal boundary was applied at the coast, de-synchronised from the flood cycle so that peak flows met a range of tide levels. Eight bedload fractions from sand (1.4 mm) to large cobble (181 mm) were assigned from the surface and subsurface sampling, with a 20 cm active layer over 1 m storage layers and the Gaeuman et al. (2009) fractional transport formulation. Banks were fixed to the present configuration, so little channel migration occurred. Sediment thickness was assigned by substrate: coarse alluvium for banks and adjacent plains, finer material towards the estuary, and thin or no erodible sediment for hard banks and bedrock.

The model is uncalibrated for flow depth and inundation extent and is exploratory. It is useful because its behaviour arises from physics and measured substrate rather than from fitting to the observed pattern, and it reproduces that pattern:

- the upper reaches coarsen and armour as finer material is winnowed from the steepened bed, and a coarsening front migrates downstream (Figure 4-14);
- finer gravel sheets from upstream move into the aggradation zone below Jim Cooke Memorial Park, and the finest material reaches the zone above the estuary;
- there is net scour through the upper reaches and marked aggradation near Greenaway Road (Figure 4-15), although the transition from degradation to aggradation lies further downstream than in the surveys, possibly reflecting downstream migration of the sediment wedge; and
- the persistent gravel accumulation above the estuary is planed off, or at least incised and reworked, during the highest flows, consistent with a deposit that builds in moderate floods and is washed out in large ones, and with the flow-regulated behaviour of the upper estuary (Chapter 2).

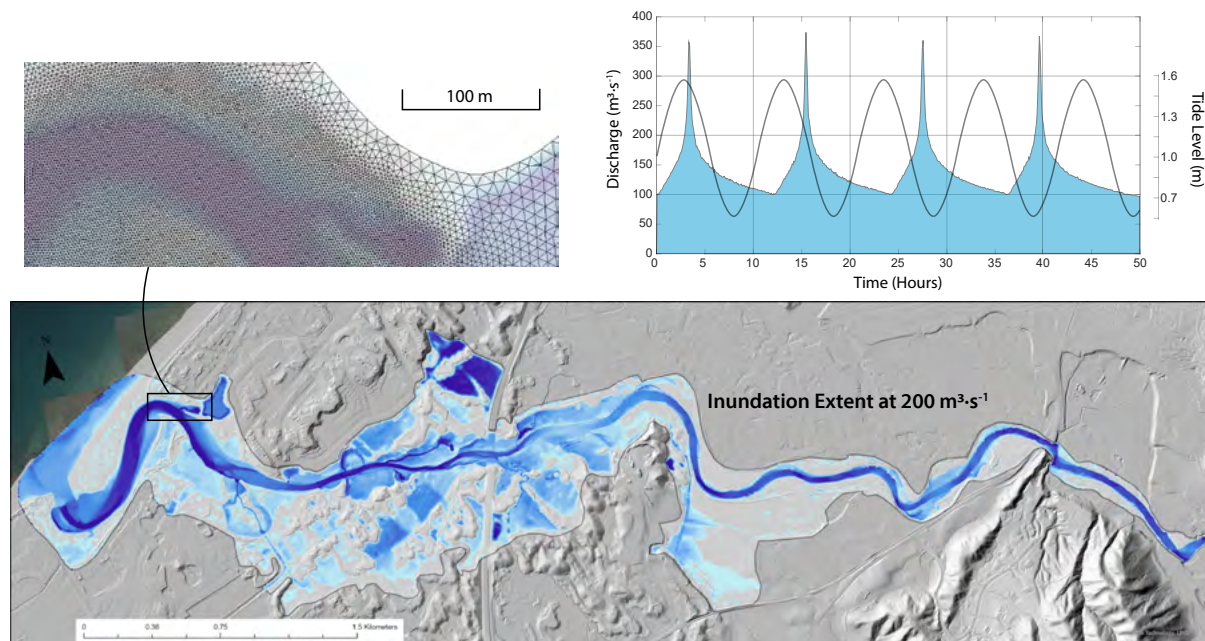


Figure 4-13 Delft3D-FM boundary conditions: the variable-resolution grid, the combined inflow hydrograph and tide, and the inundation extent at about $200 \text{ m}^3/\text{s}$. The model does not represent stormwater drainage or infiltration; its purpose is to simulate sediment transport and morphological change along the river corridor.

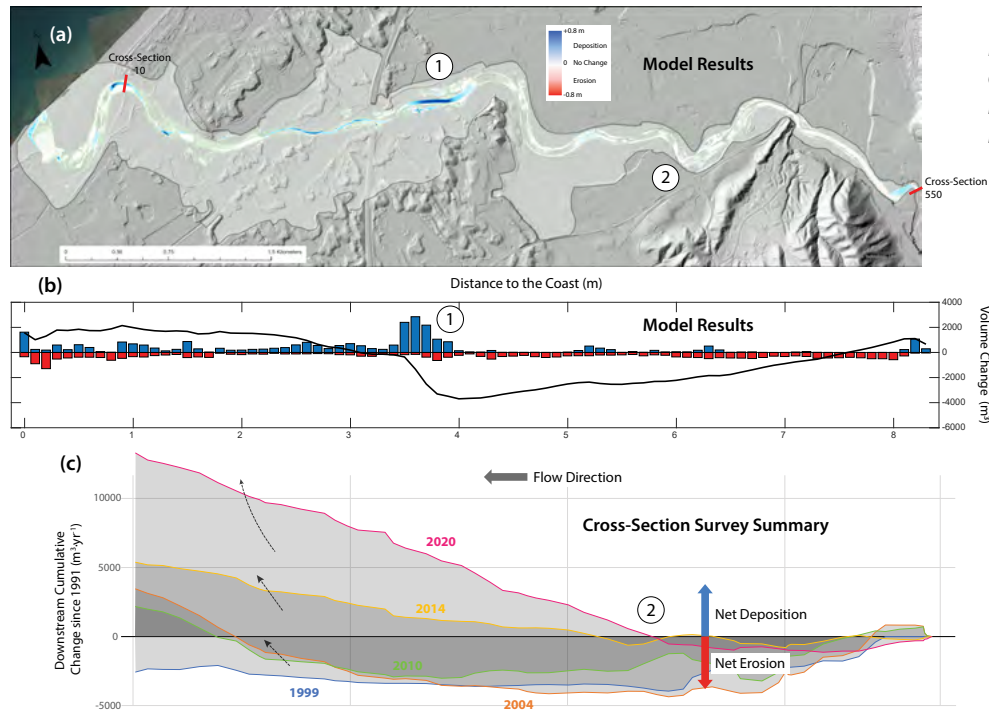


Figure 4-15 Changes in channel configuration over time, both in the model (above, middle) and in the historical cross-sections (bottom).

As aggradation continues, the lower accumulation zone becomes increasingly dynamic, while the upper reach armours because transport capacity on the steepened bed exceeds local supply. Holding the present configuration therefore depends on maintaining stable grade control in the upper river.

The results are strongly conditioned by the upstream boundary and by the assumption that there is little storage or bank erosion in the upper reach; a model can give a reasonable answer for the wrong reasons, and the source of sediment needs to be constrained carefully. Consistent results from two model types with different assumptions nevertheless strengthen confidence in the interpreted trajectory, and the 2D model provides a platform for testing management scenarios (Chapter 5).

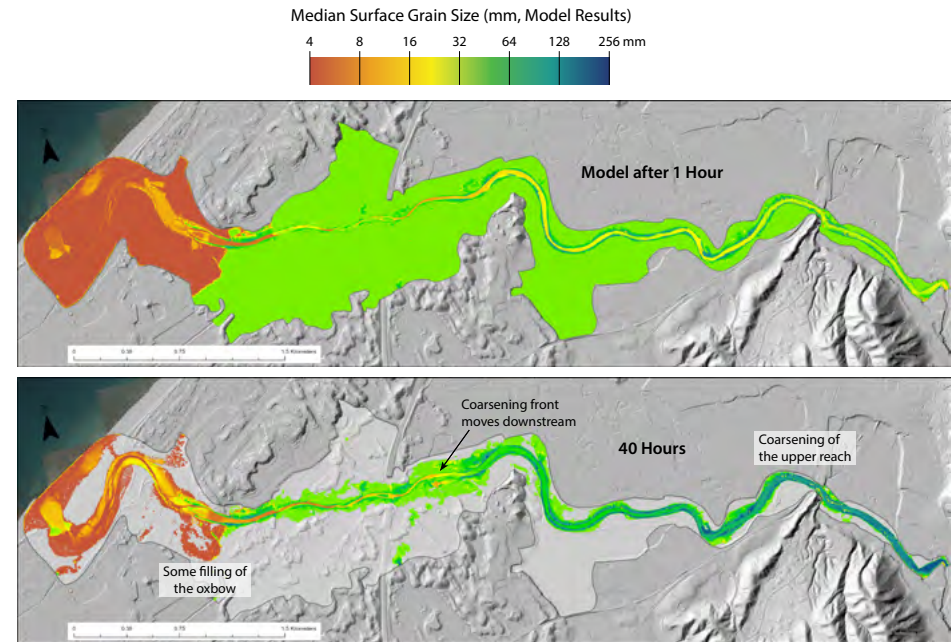


Figure 4-14 Evolution of the bed substrate from the first timestep to 40 hours into the model run. Only the cells activated in the model are plotted in (b). There are several observations of note in the results, namely the coarsening of the upper domain and the migration of a coarsening front further downstream.

The present river as a process system

Taken together, the evidence divides the lower Waikanae into three process zones and an estuary:

- Transfer and incision zone (XS 350–550). Steepened by straightening and lowered 1.5–2 m by scheme-era extraction, and now held by the SH1 and Kebbels weirs. The bed is coarse and armoured, capacity exceeds supply, and the reach still loses about 1,000–1,400 m³/yr. It has the greatest diversity of high-energy geomorphic units.
- Transition zone (XS 270–350). Close to balance, with a grade break near Jim Cooke Memorial Park. Pools are largely forced by groynes and rock work.
- Storage zone (XS 10–260). Below the grade breaks and, from about XS 120, within the tidal backwater. The reach gains about 5,800 m³/yr and its bed has risen up to 1.4 m since 1991. Glide-runs dominate and freely formed riffles are scarce. A gravel front is advancing towards the estuary.
- Estuary. Receives fine sediment and some sand; its condition varies with river flow, with deposition in moderate floods and flushing in large ones.

This is the structure of a confined fan river. The storage zone is where a fan naturally deposits, and would do so under any management. What management has changed is the energy delivered to it and the space available to it: a steeper, narrower channel delivers gravel efficiently to the grade break, and a fixed alignment forces it to accumulate in the bed rather than across bars, side channels and floodplain.

5. Conclusions and Recommendations

Diagnosis

A river in morphodynamic equilibrium can adjust its planform and cross-section freely in response to changes in sediment supply and flood regime. Rivers have several “degrees of freedom” with which to rebalance their sediment budget: a river with excess transport capacity can lengthen its meander path and reduce its slope, or coarsen its bed and increase its resistance; a river with excess supply can widen, split into multiple channels, avulse, or store sediment on its floodplain. When individual components of this system are altered without regard to the whole, the resulting imbalance propagates elsewhere, and the altered components must then be held in place indefinitely. Management decisions made under that paradigm tend to become entrenched - a form of path dependency.

The lower Waikanae shows this sequence clearly, and its trajectory resembles that reconstructed for channelised gravel-bed rivers elsewhere (Scorpio et al. 2018). Its history has two phases of disequilibrium, of opposite sign:

1. **A sediment deficit (c. 1955–1990).** The 1955 scheme replaced a multi-thread fan channel with a single channel on a shorter, narrower alignment. Over the same period gravel was extracted at about 10,000 m³/yr and in some years more than 20,000 m³, several times the river’s supply. The bed near the bridges fell by 1.5–2 m, grade-control weirs became necessary to protect infrastructure, and the managers of the day regarded bed lowering as a means of increasing flood capacity.
2. **A sediment surplus (c. 1990–present).** With extraction reduced and the bed held by weirs, the steepened upper reach still delivers gravel efficiently to the grade breaks near Jim Cooke Memorial Park and the Kāpiti Expressway. There the fan naturally deposits, but the fixed alignment forces sediment to accumulate in the bed. The lower reaches gain about 5,800 m³/yr, about a quarter of it eroded from the river’s own bed upstream, and about 69,000 m³ now sits above 1991 levels.

The evidence for this interpretation is consistent across independent sources:

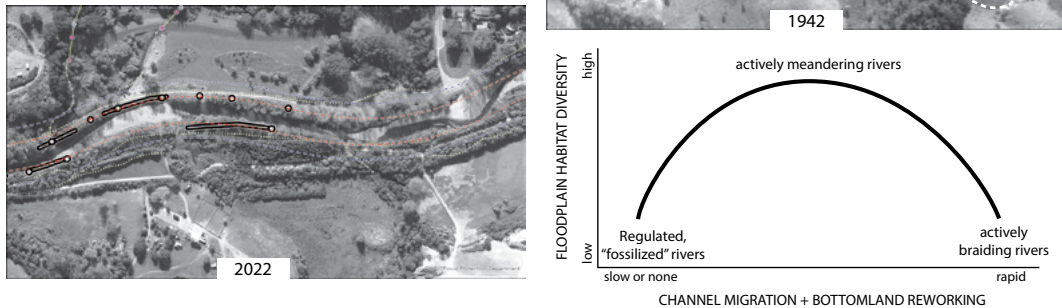
- the planform record (a 9% shorter, single-thread channel);
- the archive (extraction far above supply, and 2 m of degradation);
- the cross-section and LiDAR records (upstream loss, downstream gain, with the transition at about XS 340);
- the bed material (coarse-grained upstream, fining sharply to the storage zone);
- the geomorphic units (few freely formed units below the railway bridge); and
- two morphodynamic models (the modern configuration incises more upstream and deposits more downstream than the 1952 configuration).

GWRC’s own analyses reached a similar diagnosis: “The degradation is a result of the increased erosion capacity of the river now that is confined to a single channel and flood flows no longer spread over the floodplain” (WRC 2005), and “in response to their confinement rivers have a long term tendency to aggrade as their lateral movement is restricted” (Smith 2018).

What present management does, and does not do

Present management maintains flood conveyance through three interlocking controls: weirs hold the upper bed, extraction holds the lower bed at about 1991 levels, and bank protection holds the design alignment. These have protected the community and, with the restoration effort of the last 25 years, have produced a river that is valued and ecologically productive. But they treat the consequences of the imbalance rather than its causes. Scheduled extraction of the lower channel (e.g. Hooker 2013; Tonkin + Taylor 2016) removes the surplus without changing the conditions that create it. The 1991 bed-level target anchors management to a single survey taken within a period of disequilibrium, not to a condition the river can sustain, and the static 35 m design channel is inconsistent with how a range-front river operates on its fan.

Figure 5-1 Conceptual relationship between floodplain habitat diversity and the rate of channel migration and floodplain reworking, from regulated, "fossilised" rivers (low) through actively meandering rivers (high) to rapidly braiding rivers (adapted from Kondolf, 2011). The 2022 reach near Gre-enaway Road sits within the static realm, which the historic river shows evidence of more active channel dynamics.



The costs of holding this configuration are rising. Design flood levels were revised upwards by up to 900 mm between 1992 and 2010, reflecting updated survey information, recalibration to the 2005 flood, revised storm surge and design sea level, adjusted free-board and an assumed southerly mouth position, and the Ōtaihangā floodwall now provides protection against only about a 1-in-20-year event (GWRC 2010). Climate projections add up to 400 mm to flood levels in the tidal reaches by 2090, and sea-level rise will extend the zone of deposition upstream (GWRC 2010; Opus 2012b). Recent floods - four of the ten largest annual peaks on record fell between 2010 and 2017 - give no sign that the demand on the system is easing. Changes in bed level driven by sediment transport are themselves a significant and often under-recognised component of changing flood hazard (Vázquez-Tarrió et al. 2024).

The ecological literature is consistent that actively migrating, flooding rivers support the greatest habitat diversity, because disturbance continually creates and renews habitat (Tockner and Stanford 2002; Stanford et al. 2005; Kondolf 2011). The Waikanae's gradient, discharge and gravel supply are sufficient to sustain riffles, bars, side channels and freely formed pools, and these appear in the oldest aerial photographs. Their absence from the lower river today is a consequence of confinement, not of any lack of geomorphic energy.

Principles for managed adjustment

Process-based restoration aims to re-establish the physical and biological processes that create and maintain river habitat, rather than to construct a fixed form (Beechie et al. 2010). Allowing a river to adjust its form is not in conflict with robust flood protection under the Resource Management Act 1991; a river with room to store water and sediment laterally is better buffered against inundation, erosion and aggradation than one confined to a narrow channel (Piégay et al. 2005; Biron et al. 2014). A resilient river has multiple pathways for responding to disturbance: channel division and active exchange with the floodplain provide many places to absorb the effects of a flood or a sediment pulse, and create a dynamic, complex environment with rich ecosystem values. Three principles follow from the diagnosis:

- **Work on both ends of the imbalance.** The upstream lever is to reduce the energy that drives incision and delivers gravel to the grade break, by restoring length and relaxing confinement where the corridor allows. The downstream lever is to provide room for sediment that arrives at the fan toe to be stored laterally - in bars, side channels, backwaters and floodplain - rather than vertically in the bed. Widening the storage zone will not flush gravel through it; it will change where the gravel is stored, so that deposition builds habitat and floodplain rather than raising flood levels.
- **Treat extraction as a transitional tool.** Extraction will remain necessary while the river adjusts. Its purpose should shift from holding bed levels at a 1991 baseline to creating space and balancing the budget: lowering berms, opening side-channel inlets and removing gravel where it most constrains flood capacity, at volumes tied to measured supply.
- **Manage adaptively, with the river's partners.** The river's response will unfold over decades - longer than most planning timeframes - and cannot be predicted precisely. Interventions should be staged, monitored and treated as experiments from which management learns (Parsons and Thoms 2018), within the Waikanae ki Uta ki Tai partnership and with Ātiawa ki Whakarongotai as kaitiaki. The partnership's value of *te ao tūroa* - respect for the natural patterns of the environment - is a direct statement of this approach.

Recommendations

The recommendations are long-term and incremental. They are summarised by zone in Table 5-1 and shown spatially in Figure 5-2.

1. **Adopt geomorphic objectives in the next Floodplain Management Plan review.** Alongside bed-level and conveyance targets, set objectives for corridor width, sediment continuity (supply, storage and extraction in balance over a defined period) and geomorphic unit diversity by reach. The 35 m static design channel should be replaced, where the land allows, by a managed-adjustment corridor within which the river may migrate.
2. **Define a managed-adjustment corridor in the storage zone (about XS 155–300).** The present zone of aggradation between Jim Cooke Memorial Park and the expressway bridge was a multi-branched channel complex in the 1940s and 1950s, with several side channels visible in the photographs and the relative elevation model. Channel division and avulsion are a fan river's natural response to excess sediment. Widening the managed corridor here, and reconnecting former channels and backwaters at their inlets, would let the river store sediment laterally and build habitat while maintaining flood conveyance through a wider section. Priority areas are land already in public ownership, the private corridor land at XS 217–258 identified for purchase in the Environmental Strategy (GWRC and KCDC 2014), and the former wetland and oxbow sites in the Pukekawa and Kauri/Puriri reaches. The corridor width should be based on the 1942–1952 channel belt, using established methods for delineating erodible or morphodynamic corridors (Piégay et al. 2005; Brenna et al. 2024), and tested hydraulically for its effect on flood levels.
3. **Investigate a longer, lower-gradient course between the old SH1 bridges and Jim Cooke Memorial Park (about XS 300–420).** Straightening and extraction left this reach steeper and lower than its pre-scheme course, and the weirs that now hold it are permanent maintenance liabilities. A feasibility study should test how much meander length can be restored within the constraints of the stopbanks, Transpower pylons, the Te Arawai bridge and adjacent housing, and what reduction in slope, incision and downstream sediment delivery would result. Even a modest increase in sinuosity would offset part of the steepening.
4. **Protect the river–estuary connection.** The upper estuary's condition depends on river flow, and large floods flush it (Forrest and Stevens 2023). Management should maintain flushing flows and the natural migration cycle of the mouth (Gibb 2002) within the triggers set in the regional plan (GWRC 2024), avoid measures that increase fine-sediment delivery during moderate flows, and track the gravel front above the estuary. A memorandum of understanding between DOC and GWRC on the mouth reach, recommended in both the 10-year review and the Environmental Strategy (GWRC 2010; GWRC and KCDC 2014), should be completed.
5. **Strengthen monitoring and modelling.**
 - Repeat bathymetric LiDAR at five-year intervals and after major floods, with DEM-of-difference analysis that reports uncertainty.
 - Report geomorphic unit diversity by reach alongside mean bed levels.
 - Measure bedload directly at one or more sites, since no measurements exist (Opus 2012b).
 - Calibrate the Delft3D-FM (or other morphodynamics-capable) model against the 2013–2022 change record and use it to test scenarios: corridor widening, meander extension, extraction options, and sea-level rises of 0.5 m and 0.8 m.
6. **Co-design with mana whenua and the community.** Develop the corridor and meander options with Ātiawa ki Whakarongotai, including mahinga kai and wāhi tapu considerations in the Ōtaihangā and estuary reaches, and with the landowners, recreation groups and restoration groups that use the corridor.

Table 5-1 Summary of recommended management directions by process zone.

Zone	Present behaviour	Management lever	Candidate actions	Key constraints and tests
Transfer and incision (XS 350–550)	Steepened, armoured, degrading; held by weirs	Reduce energy; restore length where feasible	Meander-extension feasibility (XS 300–420); no extraction; allow bank erosion where assets permit	Bridges, weirs, stopbanks, pylons, housing; weir performance
Transition (XS 270–350)	Near balance; forced pools	Relax alignment locally	Extend meander freedom (e.g. XS 250 track closure model); retain groyne pools as habitat	Jim Cooke Park stopbank, Te Arawai bridge
Storage (XS 10–260)	Aggrading ~5,800 m ³ /yr; glide-run dominated; gravel front	Provide lateral storage; balance budget	Managed-adjustment corridor XS 155–300; reconnect side channels and backwaters; space-making extraction; land purchase XS 217–258	Flood levels (hydraulic testing); private land; inanga spawning and wāhi tapu near Ōtaihangā
Estuary	Flow-regulated fines; mouth migration	Maintain flushing and natural mouth dynamics	Mouth management within triggers; monitor gravel front; DOC–GWRC MOU	Sea-level rise; groyne effects; housing

Closing

The Waikanae is not a degraded river in the conventional sense. Its water is clean, its headwaters are forested, its gravel is mobile, and its corridor and estuary have been transformed by 25 years of restoration. It is a constrained river: its capacity to regulate its own sediment and renew its own habitat has been removed by decisions made for a different era of river management, which treated rivers as conveyance channels rather than as living systems. The opportunity now is to guide the river towards a configuration it can sustain - one that stores sediment where it builds habitat rather than raising flood levels, reduces the long-term cost of maintenance, and continues to protect the community. This is not a return to a pre-human river. It is an informed, staged adjustment, grounded in the river's own history and consistent with the aspiration of Waikanae ki Uta ki Tai for a river whose mauri is restored.

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