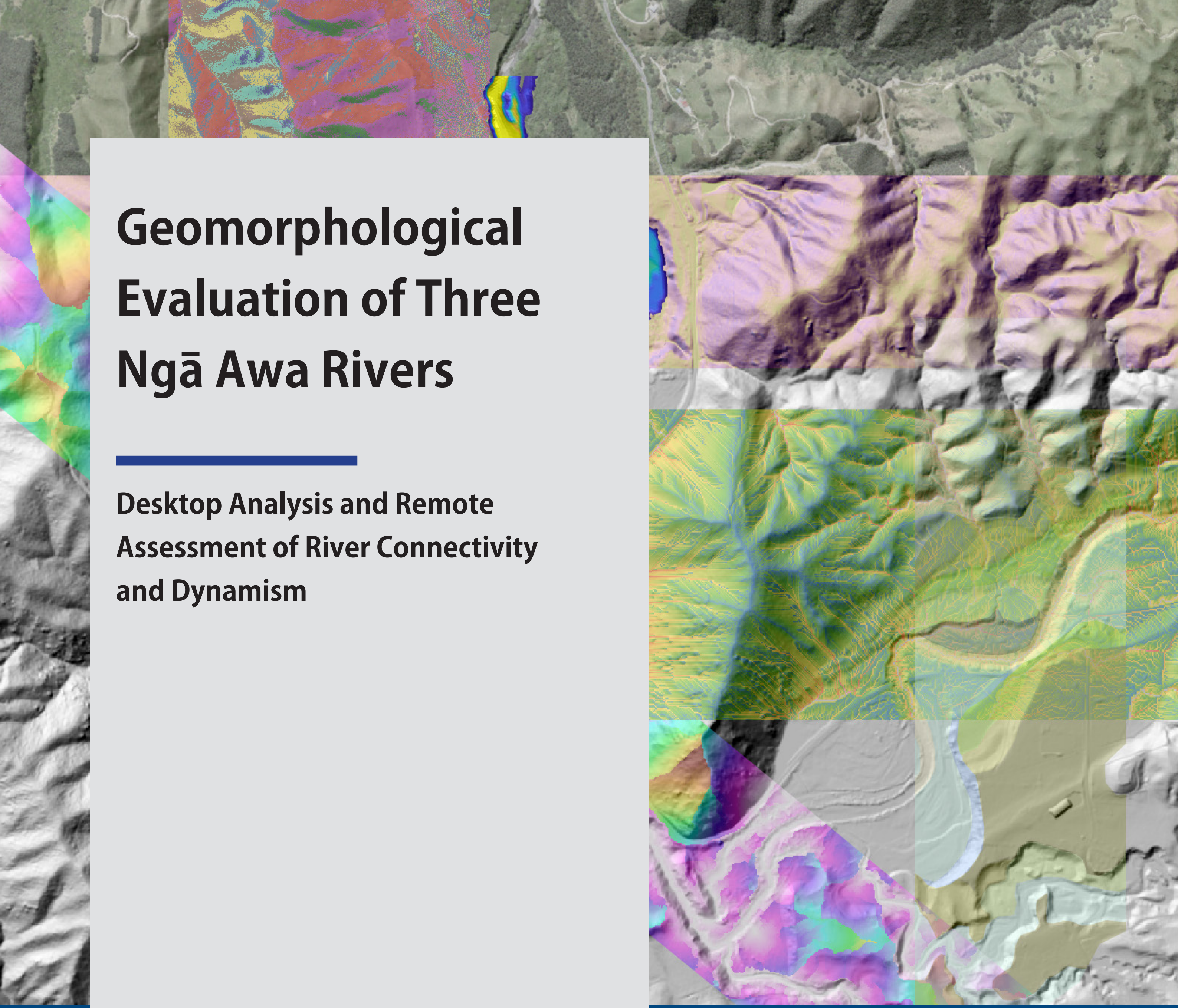

Geomorphological Evaluation of Three Ngā Awa Rivers

Desktop Analysis and Remote Assessment of River Connectivity and Dynamism

Nov 3, 2021

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Executive Summary

REPORT OBJECTIVES

- The *things that matter* - habitat diversity, productive ecosystems, and other attributes we seek to protect in aquatic river systems - arise through a delicate equilibrium between water discharge and sediment supply throughout the year. Sediment budgets, connectivity analyses and sediment routing can be used to assess potential impacts and cumulative effects arising from perturbations such as urbanisation, farming, forestry and shifting climate, and to guide management.

- Analysis of river sensitivity and predisposition to geomorphic change can be assessed with new GIS mapping tools and sediment routing models. Conservation goals for catchments and river systems can be greatly assisted by characterising the distribution of stream power throughout the river network, sites of erosion and sediment storage, connectivity of the sedimentary system, and the longitudinal sequence of river morphologies.

- Three exemplar rivers have been selected for geomorphic analyses, with a view to supporting decision-making for river restoration strategies that will identify opportunities to improve habitat diversity and connectivity within the catchments. This outline of desktop techniques for geomorphic river analysis is intended to enhance analytical capacity within the Department of Conservation's Ngā Awa Programme.

- The study catchments are the ***Mahurangi (Warkworth)***, the ***Waikanae (Kapiti Coast)***, and the ***Pelorus/Te Hoiere (Marlborough Sounds).*** These are among fourteen Ngā Awa rivers under study that were selected on the basis of recovery potential and local support among community and Iwi to progress the aims of river restoration. The three rivers selected for this work represent a broad sampling of physiographic settings, river morphologies, ecological values, and restoration aims.

- A new era of high-resolution survey techniques and analyses has made it possible to extract more refined landscape details and to integrate static and dynamic modelling more easily into GIS analyses. An overview of river processes and landforms is interwoven with some common key questions regarding riverine systems and applicable techniques for providing insights. By showing the initial results of these workflows, this work offers a sampling of what can be applied to a range of conservation problems in a variety of different physiographic and ecological settings.

- There are a variety of approaches that can be used to clearly and consistently identify, classify and name particular river settings and morphologies. This is helpful for quickly identifying propensity for change, sensitivity to disturbance, and habitat regimes within a river network. A River Styles analysis is provided as a synthesis of the governing variables affecting river form in the three study catchments.

SUMMARY AND CONCLUSIONS

- Each river in the study has a unique set of opportunities and constraints for conservation and restoration efforts. The effects of urbanisation, farming and forestry affect various aspects of river connectivity, sedimentary character, the balance of water and sediment supply, and erosional regime. By establishing a clear vision for the future river trajectory, it may be possible to improve and restore various aspects of the river environment, keeping in mind the diverse requirements for the river types and their diverse settings.

- Past disturbances will be of varying extent in time and space, and will often be superimposed. Efforts to restore river functionality may not come to fruition if they are not approached using a whole-of-catchment philosophy. If there are continuing impacts within one part of the catchment, this will invariably frustrate efforts to restore river processes in other connected parts of the network.

- New Zealand is particularly well-endowed with GIS data, environmental time-series data, web-based models, and other resources from LINZ, Landcare, MfE, NIWA and other CRIs, agencies and academic institutions. With the judicious use of these datasets and models (being mindful of limitations), there is excellent scope for developing predictive models of river response to catchment disturbance or restoration initiatives, and longer-term response to variation in climate.

- The resolution and precision of the underlying topographic dataset is essential to many of these analyses. 1-m LiDAR elevation models appear well-suited to the task, whereas the national 8-m dataset lacks much of the precision and resolution necessary to generate more detailed assessments of river form and connectivity. Within the LiDAR datasets there remain issues of canopy cover and hydrological pathways in developed areas (for example), but these can generally be handled with some additional processing. Bathymetric LiDAR is coming online in New Zealand, and holds much promise for improved river and estuary modelling possibilities.

- A pattern that emerges within the three study rivers is that potential for dynamic behaviour is found at sites with (1) high stream power and (2) a low degree of confinement, (3) at confluence points where one or more steep headwater streams converge on the mainstem channel. Some of these sites exhibit past signs of dynamic channel change, although they are now largely being held in place with embankments, stop banks and other reinforced boundaries.

- Climate change will almost certainly play some role in the future evolution of these river systems. The heightened incidence of extreme floods, coupled with a highly altered runoff regime in drained and canalled lowlands, may lead to enhanced erosion potential in lower river sections. Prolonged periods of drought can lead to more complex changes in ecosystem structure, groundwater recharge, and riparian vegetation growth.

Acknowledgments

Thanks to Sue Clearwater (DoC) for engaging us in this project. It has been a great conversation, and a valuable exercise in bridging evolving theory and practise in river restoration and management.

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The catchment and river characteristics of three study sites are considered in this review. The sites represent a diverse sampling of physiographic settings, river morphologies, ecological values, and restoration aims.

	Mahurangi	**Te Hoiere/Pelorus**	**Waikanae**
Catchment Area (km^2)	76	890	153
Relief (m.a.s.l.)	357; Moir Hill, 336; The Dome	1760; Mt Richmond	1102; Kapakapanui
Mean annual and 50-yr flood (m^{3}s^{-1}, approx)	83.7; 235	1100; 1950	170; 380
Rainfall (mm·a^{-1})	1400-1500	1500-2000	1100-2000
Land Environments NZ (LENZ) Category (Climate & Landforms)	Northern Lowlands	Mainly Central Mountains, varied valley-bottom environments.	W/S NI Lowlands, Central Hill Country and Volcanic Plateau, Central Mountains

1. Fluvial Geomorphology for Restoration Planning

Geomorphological processes occur at a range of scales, and while river restoration activities may sometimes occur at a small scale, it is important to take into account the many factors that govern river form and process operating at catchment scale in order to support enduring restoration, and to “work with the river”. While the Ngā Awa initiative is focused on improving conditions within the channel and across the riparian zone, it also considers catchment-scale initiatives (*e.g.*, land use changes) where necessary. This report addresses some of the emerging tools and datasets that can be used to help managers and stakeholders understand and visualise the governing factors that dictate river form and shape their responsiveness to disturbance. These tools are helpful for characterising network connectivity, sediment transport potential, and cumulative response to environmental change. They can help to explore "what-if?" questions by developing scenario-based simulations of change.

Catchment management requires integrating scientific knowledge of ecological relationships within a complex framework of cultural values, local history, and stakeholder perspectives to provide socio-environmental integrity (Naiman *et al.*, 1999). Approaches to management must also address the inherent uncertainty of future change. Given various unique conditions, important hydrological, sedimentary and ecological processes of rivers in Aotearoa New Zealand are not always reflected in international literature: a unique geological makeup, a landscape shaped by active tectonic and volcanic processes, and recent history of land clearance and landuse. Ex-tropical cyclonic storms and multiple-occurrence regional landslide events (Crozier, 2005) can lead to significant cumulative impacts. The potential longer-term effects of climate change in New Zealand add another layer of uncertainty and complexity. The Te Mana o te Wai framing of the most recent National Policy Statement for Freshwater Management (2020) lends a distinctive Māori perspective to managing issues, understanding the river as a living, indivisible entity that requires care and engagement from the local population.

1.1 The Role of Geomorphology in River Conservation

Freshwater systems are among the most threatened ecosystems on Earth (Albert *et al.*, 2021; Birk *et al.*, 2020; Dudgeon *et al.*, 2006; He *et al.*, 2019; Strayer & Dudgeon, 2010; Reid *et al.*, 2019; Su *et al.*, 2021; Vörösmarty *et al.*, 2010). Development and application of proactive and precautionary measures to conserve aquatic ecosystems requires insights into key values (*things that matter* - attributes that we seek to protect), their condition (and controls upon them), their trajectory of adjustment (and associated understandings of threatening processes), seeking to prioritize protection of remnant attributes/populations before degradation pressures become insurmountable (Abell *et al.*, 2008; Hermoso *et al.*, 2016; Nel *et al.*, 2009; Tickner *et al.*, 2020). These are 'no-compromise' deliberations, and lowest common denominator management outcomes do not work: for example, life cycles can only be broken once, there is no such thing as half a habitat, and the weakest link in any chain determines the functionality of the system as a whole (Brierley, 2020).

As geomorphic considerations are key determinants of aquatic ecosystem condition (*e.g.* Best, 2019), conservation and restoration practices are unlikely to be successful unless appropriate regard is given to place-based understandings of process relationships in a given catchment (Brierley and Fryirs, 2005; Brierley *et al.*, 2013).

Rivers adapt to changing flow/sediment conditions over a wide range of timescales and with profoundly variable responses and consequences (Wohl *et al.*, 2015). Once a river establishes a regime condition, predictable adjustments occur in response to changing sediment inputs. Different physiographic settings and sediment supply conditions give rise to different river morphologies with marked variability in their capacity for adjustment (sensitivity) and their range of variability (Brierley and Fryirs, 2005; Fryirs, 2017; Reid and Brierley, 2015). Sensitive rivers have different predisposition to adjust in response to forcing factors such as storm climate, landslide regime, or biotic influence. Geomorphological approaches involve working *with* river process to help build ecological networks, enhance nutrient exchange, and foster habitat development for diverse river fauna (Beechie *et al.*, 2010; Fausch *et al.*, 2002).

Connectivity of the river system has become an important research focus, as the functioning of river ecosystems depends very much on linkages with the adjacent riparian and terrestrial components including overhanging canopy, riparian forest, floodplains, as well as deep and shallow groundwater systems (*e.g.* Boulton *et al.*, 2004; Brierley *et al.*, 2006; Kondolf *et al.*, 2006; Fuller and Death, 2018). New Zealand native fish require longitudinal connectivity to migrate between freshwater and marine environments at different lifestages (*e.g.* larva, juvenile, adult, and breeding stages).

FIGURE 1-1 *RIVERS REQUIRE A BALANCE OF SEDIMENT SUPPLY AND FLOOD DISCHARGE TO DEVELOP AND MAINTAIN ACTIVE INSTREAM GEOMORPHIC UNITS SUCH AS RIFFLES, POOLS, AND LATERAL AND MID-CHANNEL GRAVEL BARS. DEMANDS FROM WATER AND GRAVEL EXTRACTION, THE PRESENCE OF INVASIVE VEGETATION AND THE EFFECTS OF LONG SUMMER DROUGHTS ARE SOME OF THE CHALLENGES FOR MAINTAINING HEALTHY RIVER ECOSYSTEMS.*

Diminished flood magnitude, through progressive shifts in climate for instance, can lead to gradual metamorphosis from braided to meandering river morphology by altering the flow regime relative to the sediment supply. On the other hand, systematic removal of sediment supply through aggregate extraction, if not carefully managed, may similarly lead to changes in river morphology by altering this equilibrium. In a similar vein, changes to riparian vegetation and loading of wood alter the balance of impelling and resisting forces in a reach. Morphological changes alter the distribution and availability of river habitat and modify ecological relationships. River restoration works often focus on restoring the balance between upstream supply and the transporting characteristics of the river, seeking to rehabilitate the dynamic physical habitat mosaic of river systems (*e.g.* Wheaton *et al.*, 2019).

Lane's balance (Figure 1-2) provides a helpful heuristic picture of the ever-evolving balance between the supply of sediment and water, and the resulting river adjustments that may occur. An increase in sediment load, for instance, will push the system toward aggradation, or buildup of the bed. The river can be counterbalanced by steepening of the stream slope, more effectively transferring the load, and bringing the system back into balance. This conceptual picture has physical laws behind it, and sophisticated GIS analysis and numerical modelling can be used to determine the trajectory of a river system based on catchment history and physiographic setting. These tools can be used to assess management scenarios and plot potential pathways into the future. It may also be possible to infer the result of multiple disturbances, at different timescales, through careful observation and analysis. For instance, high rates of sediment accumulation from historic land clearance (late 1800s) may have filled the lower valley with additional alluvium (called legacy sediments). Subsequent realignment of the channel may induce rapid evacuation of this material through enhanced erosion, followed by upstream knickpoint migration. Mapping of sediment stores and monitoring of erosion underpins modelling of system responses to disturbance and their management (mitigation).

Different river settings (Table 1-1) support a range of dynamic and fragile habitats, where valued biodiversity is linked closely to specific geomorphological processes (past and present) that should be understood in developing management plans (Gordon *et al.*, 1998, 2002). Catchment-scale mapping of geomorphic forms (*e.g.* river types) informs analysis of potential risks and stressors, helping to set priorities for recovery and rehabilitation.

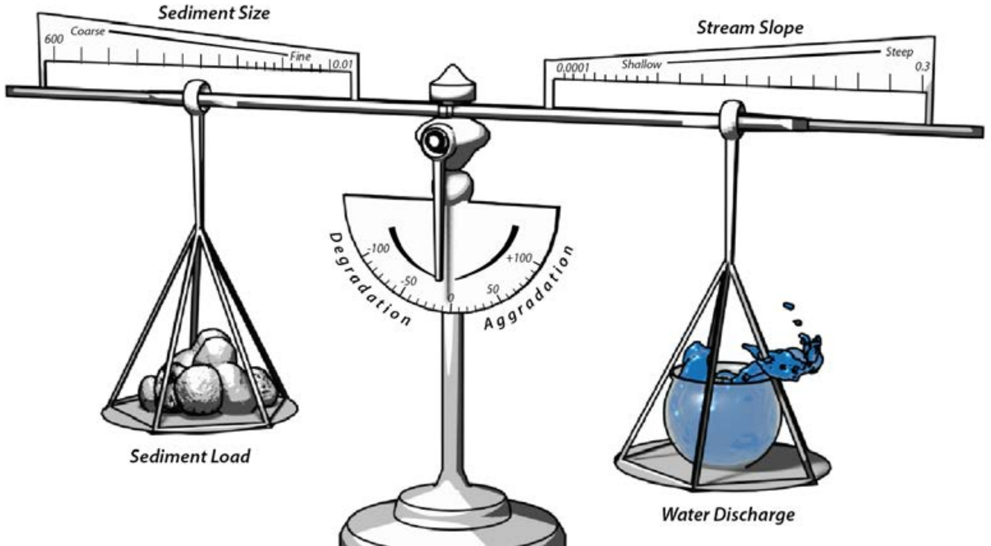


Figure 1-2 *Lane's Balance: The supply of water and sediment, the size of the supplied sediment, and the imposed valley slope will dictate the form of the channel. As catchment area grows larger and slope diminishes, the character and connectivity of the river system will change systematically.*

Catchment Zone	River Asset	Management Issues
Source Zone: headwaters and 'zero-order' catchments	*Habitat diversity and complexity*	*Careful management of landuse in the upper drainage; promoting stability in the steep contributing headwater areas; maintaining a diversity of headwater river environments.*
	Canopy shade, temperature regulation, nutrient flux, oxygenation of water in turbulent flows.	*Riparian protection via buffers and other protective restrictions in headwater areas. Connectivity with colluvial source areas: the supply of coarse debris and wood from headwaters provide important structure and stability elements.*
	Episodic release of sediment to the lower river network is mediated by staged storage along the system, buffering delivery downstream.	*Bed structure (including woody debris) enhances sediment storage and habitat. Land clearance, forestry works and development should not impinge on these riverine environments*
Transfer Zone: montane rivers and alluvial fans.	*Clean gravels, with balanced fine sediment loads, and appropriate levels of periphyton, algal mats, etc.*	*Managing nutrient loads from runoff* *Minimised erosion from disturbed terrain*
	Bars, braids, oxbows, backwater and riparian environments	*Stopbanks can isolate the river from floodplains and other off-channel habitat.*
	Floodplains	*Channelization, which invariably involves straightening of the channel, increases channel gradient, potentially leading to channel-bed scour and reduction of aquatic habitat diversity*
	Groundwater, low-flows	*Improved interception and infiltration through managing forest cover; gravel extraction and in-channel works disrupts flow pathways.*
Deposition Zone: lowland rivers and the parafluvial environment	*Flow of nutrients to parafluvial environments and floodplains*	*Industrial gravel extraction can alter groundwater gradient and pathways. Stopbanks can isolate the river from floodplains and other off-channel habitat.*
	Laterally active channel	*Bank hardening interferes with normal staging downstream of bed material sediments since it prevents the lateral movement associated with bed material deposition and re-entrainment: it thereby interferes with floodplain (and habitat) renewal.*
	Coastal and estuarine environments	*Cumulative impacts, such as nutrient loading or excess sedimentation from the catchment.*

TABLE 1-1 *RIVER 'ASSETS' FROM THE PERSPECTIVE OF GEOMORPHIC PROCESSES THAT SUSTAIN BIOTIC COMMUNITIES AND ECOLOGICAL SYSTEMS WITHIN THE RIVER NETWORK. DIFFERENT SUITES OF GEOMORPHIC PROCESSES OCCUR AT DIFFERENT SCALES WITHIN THE CATCHMENT. HERE WE IDENTIFY A FEW TYPICAL EXAMPLES. MANY OTHERS ARE POSSIBLE, DEPENDING ON THE UNDERLYING GEOLOGICAL, CLIMATIC AND ANTHROPOGENIC FACTORS.*

Although geomorphology by itself isn't the answer, conservation planning will not be effective unless geomorphic considerations are integrated into management plans. An inventory of sediment sources, such as hillslope mass wasting, eroding river banks, or human-induced erosion can help to determine sites where Lane's balance may be moving (or have the potential to move) out of equilibrium, and some corrective action (or prescriptive inaction) can be taken, either passive buffering/isolation (to allow system recovery) or more active intervention such as fencing, planting or engineering structures.

Observations of system change over time are vital in scoping prospective (realistically achievable) river futures. In New Zealand the aerial photograph archive goes back at least eighty years, providing the opportunity to map changes in hillslope condition, timescales of storm response, and the rate of river adjustment on valley floors. The timescale can extend further with careful mapping of old landslide scars and remnant evidence of channel switching (avulsion) and progressive lateral erosion and deposition in scroll plains. Importantly, evolutionary traits must be framed in relation to analysis of legacy effects, as many river systems respond to a layer-upon-layer effect of human disturbance.

In this paper we will look at some techniques for analysing river gradient, confinement, stream power and morphology, as well as determining sediment pathway connectivity and simulating sediment routing. These can help to determine the behaviour and responsiveness of the larger system, or to examine the potential effectiveness of various rehabilitation scenarios

1.2 Desktop Analyses

The study of river process naturally entails quantitative study of landscape form, a field known as *geomorphometry* (cf. Hengl and Reuter, 2007). This field has undergone significant growth in the past two decades associated with the wide availability of digital elevation models and remotely-sensed landscape metrics, including hydrology pathways. Analysis varies from relatively simple calculation of land surface parameters such as local gradient, texture or curvature, to more sophisticated assessments of flow tracing and river transport capacity. With renewed interest in quantitative aspects of sediment transfer, various GIS techniques have evolved to characterise and quantify sediment linkages, pathways and transport capacity. The techniques range across scales, from river bed texture to full catchment extents.

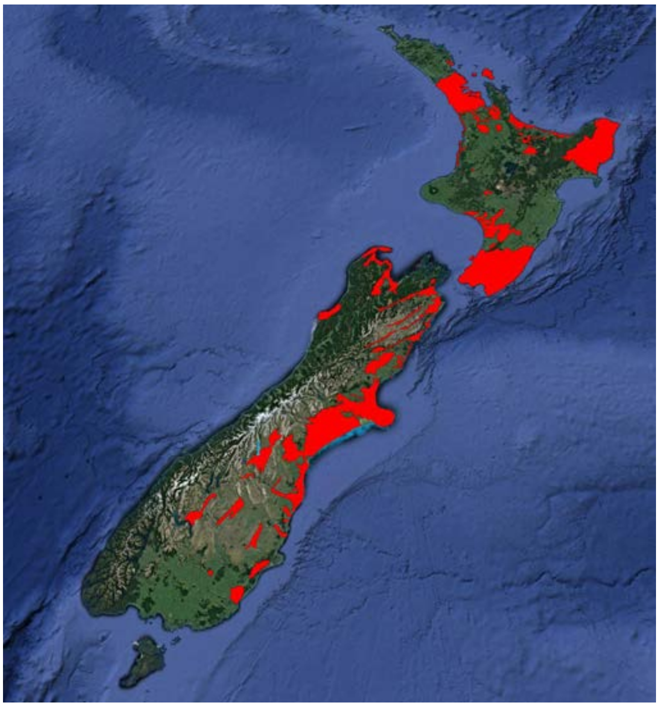


Figure 1-3 *LiDAR coverage within New Zealand (opentopography.org, 2021; LINZ Data Service, 2021). The availability and extent of high-resolution elevation models is growing annually. Two of the three rivers examined in this report have full LiDAR coverage, greatly extending the sophistication and detail of analyses that can be carried out.*

High-resolution digital landscape survey data have changed the way that we can quantify landscape form, from laser (LiDAR) scanning of landforms via theodolite, drone or aircraft, to photogrammetry from satellite, drone or consumer-grade mobile phone. Accordingly, it is becoming increasingly feasible to quantify formerly abstract notions such as landscape 'roughness', 'sensitivity' or 'connectivity'. Regional Councils and LINZ have supported extensive airborne LiDAR surveys since the mid-2000s, and coverage is growing throughout New Zealand (Figure 1-3). Repeat surveys over the same terrain provide highly detailed information on process rates and quantities. Digital Elevation Models (DEMs) generated from LiDAR typically require cleaning and processing to minimise issues related to vegetation, human-made structures, and other artefacts that influence the numerical representation of landscape flow paths.

A key challenge in catchment geomorphology is understanding the cumulative response to disturbance. Different tributaries may be responding at different times as effects of upland disturbance, for example, migrate through the system. With the evolution of network-based river models, the effect of these complex interactions and dynamic adjustments can be explored in increasingly tractable ways, with intuitive visualisation of network interactions.

Key Datasets

The River Environment Classification (REC) is a database of catchment spatial attributes, summarised for every segment in New Zealand's network of rivers (Snelder and Biggs, 2002)

https://niwa.co.nz/freshwater-and-estuaries/management-tools/river-environment-classification-0
https://niwa.co.nz/static/web/REC2_12Feb2014/nzRec2_v5/REC2_geodata_version_5.zip

RetroLens (retrolens.co.nz) provides access to more than 493,000 photos (as of July 2020) that have been digitised and are made available via a user-friendly map interface.

NIWA's NZ River Maps
https://shiny.niwa.co.nz/nzrivermaps/

LUCAS: The Land Use Carbon Analysis System Map is composed of New Zealand-wide land use classifications for 4 historic epochs (1990, 2008, 2012, 2016)
https://data.mfe.govt.nz/layer/52375-lucas-nz-land-use-map-1990-2008-2012-2016-v008/

NIWA Suspended-sediment yield estimator
https://niwa.co.nz/freshwater/management-tools/sediment-tools/suspended-sediment-yield-estimator

NIWA Fish Passage Assessment Tool
https://fishpassage.niwa.co.nz/

LINZ Data Service
https://data.linz.govt.nz/

MfE Data Service
https://data.mfe.govt.nz/

Landcare Research
https://lris.scinfo.org.nz/

koordinates
https://koordinates.com/

Land Air Water Aotearoa
https://www.lawa.org.nz/

Regional Data Sources
https://localmaps.nrc.govt.nz/LocalMapsGallery/
https://www.aucklandcouncil.govt.nz/geospatial/geomaps/
https://maps.waikatodistrict.govt.nz/
https://gis.boprc.govt.nz/
https://maps.trc.govt.nz/LocalMapsGallery/
https://www.hbrc.govt.nz/services/maps-and-gis/
https://mapping.gw.govt.nz/
https://www.topofthesouthmaps.co.nz/app/
https://maps.marlborough.govt.nz/smartmaps/
https://gis.westcoast.govt.nz/WestMaps/
https://canterburymaps.govt.nz/
https://maps.orc.govt.nz/OtagoMaps/
https://maps.southlanddc.govt.nz/Maps3/

Open Topography
https://opentopography.org/

1.3 The River Continuum, and vital quantities for ecosystem function

River systems can be broadly subdivided into source areas, transfer zone, and the terminal deposition zone (Schumm, 1977). The goal and means for improving river conditions differ in these zones, as river character, substrate, and associated habitat conditions change systematically from source to outlet. An important focus of river geomorphology in recent years has been ‘coupling’ and ‘connectivity’ of water, sediment, wood and nutrient pathways between hillslopes and the river network (see Wohl *et al.*, 2017; Heckmann and Vericat, 2018; Nafaji *et al.*, 2021). Good management requires quantitative understanding of the collective influence of various system components. The nature of these connective linkages changes systematically between headwaters and the lowermost river domain. Steep headwater areas convey large quantities of coarser material episodically to the mainstem channel, while further downstream, hillslopes are increasingly de-coupled from the river owing to sediment storage in lateral terrace, fan and floodplain deposits (Church, 2002; Figure 1-4). Thus, the river system is increasingly buffered from hillslope contributions and disturbance, and increased sediment storage regulates the supply of sediment to the channel. This study of pathways from source area to outlet is important for understanding the dynamics of various materials in transport, such as sediment, nutrients, pollutants, contaminants and organic material.

Fluvial forms such as bars, floodplains and fans evolve as a function of water discharge, sediment supply, sediment calibre (particle size; *c.f.* Lane's balance) as well as vegetative cover. These governing variables change systematically from the hillslope to the outlet. The left-hand side of Figure 1-4 shows the change in substrate composition along the system, from a poorly sorted, generally coarse-grained mixture in the slopes and headwaters, to increasingly finer and better-sorted mixture towards the outlet. Because of variations in runoff timing between tributaries, flows become relatively less variable downstream. The ability of the stream to move large material declines as gradient declines, so large material is left behind – even as the capacity of the river to move volumes of sediment increases. The grain size distribution of substrate in steep and active New Zealand catchments typically reflects the legacy of past disturbances, such debris flows or landslides that deliver boulder- or cobble-sized material to reaches where the ambient bed material is typically much finer. These lag fractions tend to accumulate in these reaches, and contributes to varied morphology, bed stability and diverse aquatic habitat.

In order to manage river systems for ecological vitality and habitat diversity, it is important to have a good understanding of the catchment context for the site(s) of interest, and to develop analyses that will highlight the trajectory of the system with respect to these governing factors. With high-resolution imagery, accurate and detailed topographic models and dynamic simulation software, the analyst has greater capacity to explore catchment interactions, and consider disturbance and recovery in progress, relative to the channel's 'sensitivity' or capacity for change.

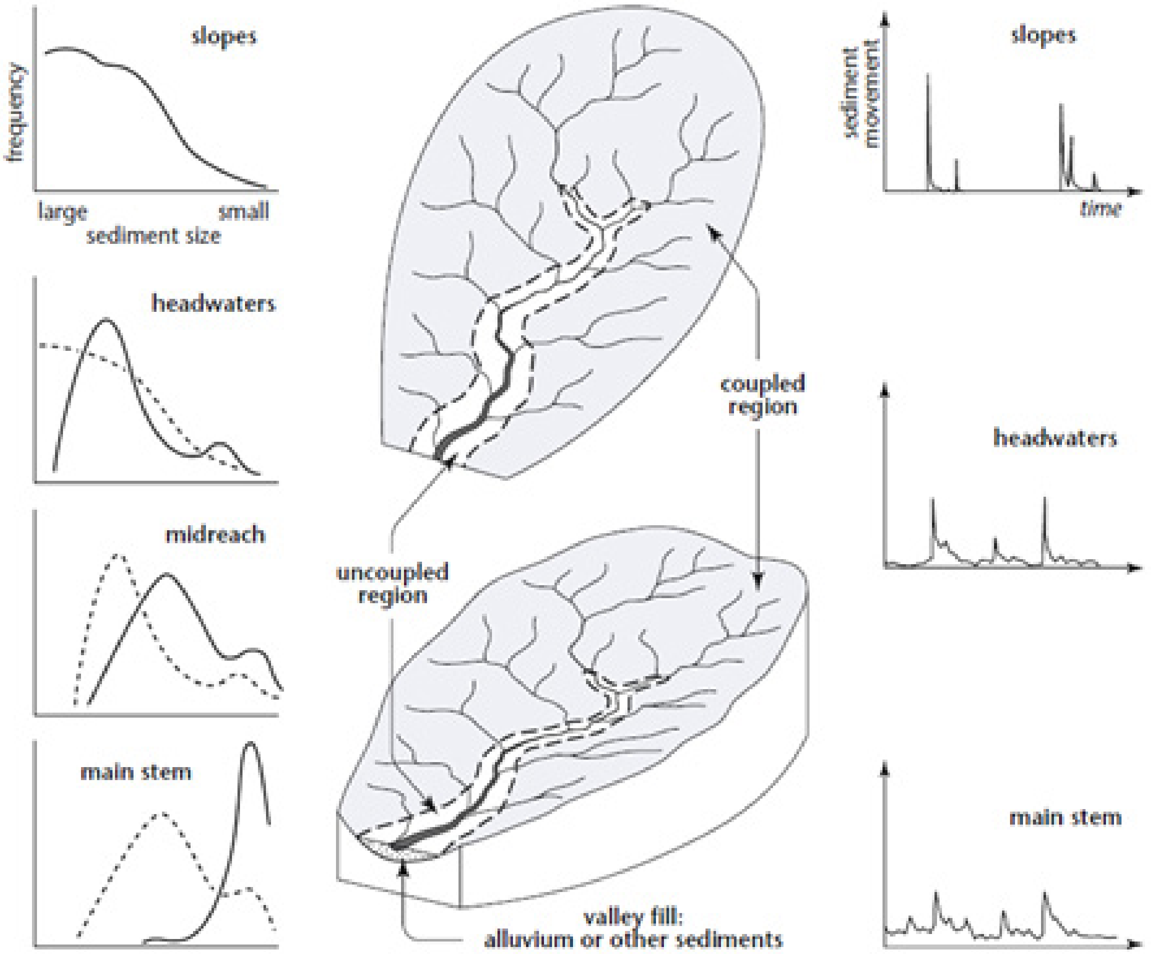


Figure 1-4 *Map and schematic views of a drainage basin to illustrate the concept of "coupling" between a stream channel and adjacent hillside slopes. On the left side of the diagram are schematic graphs of characteristic grain size distributions of channel bed material through the system. On the right side of the diagram are seasonal hydrographs to illustrate the attenuation of variations in flow down the system. In each grain size graph, the next upstream distribution is shown (dashed line) so the intervening modification by stream sorting processes may be directly appraised. Church and Ryder, 2001.*

In the following sections, we review some typical source, transfer and depositional river environments, and the factors that sustain and evolve morphological form in each of them. It is important to emphasise that, much in the manner that rivers have different 'styles', there is also a diversity of catchment form. A 'headwater' environment in an active, volcanic landscape may be quite different to one in a low-relief basin. A river emptying into a subsiding estuarine environment will have a different morphologic character to one that deposits onto an actively building fan. Drainage network pattern (configuration) and drainage density (landscape dissection) vary markedly in differing landscape settings. The principal distinctions involve the elements in Lane's balance: sediment supply and calibre, and the magnitude of annual flood discharge all vary from the upper catchment to the lower valley. Accordingly, connectivity relationships and patterns of geomorphic hotspots vary from catchment to catchment.

Hillslopes and 'Zero-Order' Basins

Zero-order basins are common features of soil-mantled landscapes, defined as unchanneled basins at the head of a drainage network (Benda and Dunne 1997; Istanbulluoglu *et al.* 2004; Grieve *et al.*, 2018; Sidle *et al.*, 2018). These sites mediate transfer between hillslope environments and the river network. Approximately 95% of runoff reaching the drainage network is generated within this process domain (Knighton, 1998; McDonald and Coe, 2007). Water from the hillslopes is delivered primarily by subsurface storm flow (McGlynn *et al*, 2004, McNamara *et al.*, 2005) and secondarily by saturation overland flow. The overall shape of the catchment flood hydrograph may be strongly influenced by this delivery process; increased storage can delay the arrival of the flood wave in the channel, and subdue the peak in discharge.

Sediment is delivered by surface processes, typically by shallow landsliding and debris flows. The delivery of sediment to stream channels can be discrete (*e.g.*, debris flows) or relatively chronic (*e.g.*, soil creep or the storm-by-storm delivery of sediment from roads). The geometry and volume of the zero-order basin (also known as colluvial hollows) control how quickly sediment may re-accumulate after landslide evacuation, staging material for the next event.

Plotting the upstream catchment area versus gradient for every cell in a digital elevation model (Figure 1-5), it is possible to identify trends of diminishing slope with increasing upstream area. This corresponds to the point of incision on the landscape where the river network begins. With high-resolution LiDAR surveys, it is possible to map out the sensitive areas at the channel 'head', where the transition from undissected hillslope begins. The location of the channel head is estimated on theoretical grounds, using slope-area models (see Tarboton *et al.*, 1991). To date, the implications for ecological function and ecosystem organisation are not yet well-established.

Where forestry and roading cross steep and convergent terrain above first-order drainages, there is increased potential for triggering instabilities that deliver sediment to the network. For this reason, establishment of buffer zones is a common best practice to minimise sediment delivery to the system downslope. Because of the steep terrain and direct pathway to the fluvial system, connectivity analysis typically reveals high potential for transfer between hillslopes and the river system via these zero-order basins.

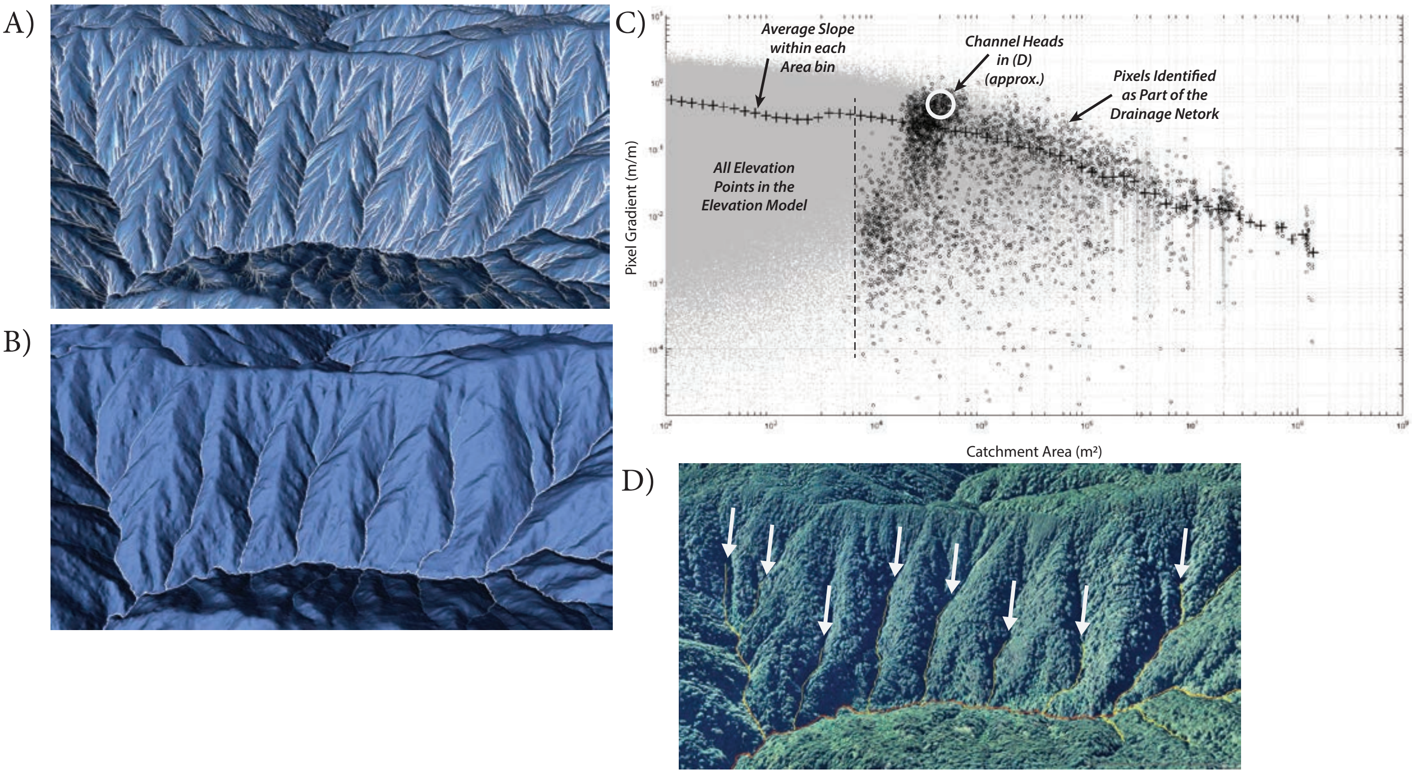


Figure 1-5 *Digital representation of the drainage network begins with discrimination amongst hillslope and channelised topography. A 2.5m LiDAR elevation model from the upper Waikanae River catchment shows the detailed, automatic delineation of drainage features. The TauDEM routine uses the Peuker-Douglas algorithm to find a hinge point in the slope-area relationship of pixels within the digital elevation model. The 'head' of each first order drainage, denoted by arrows in (D), is circled in (C). In steepland terrain, these are vital connective linkages between the hillslope and fluvial systems.*

Headwater Channels

Headwater streams comprise 60 to 80 percent of the cumulative length of river networks and directly connect the upland and riparian landscape to the rest of the stream ecosystem (Meyer & Wallace 2001; May and Gresswell., 2002; Bishop *et al.*, 2007; Freeman *et al.* 2007). As with zero-order basins, disturbance of headwater streams can have a disproportionate effect on riverine systems, owing to the cumulative effect of many smaller branches feeding the trunk stream. They provide key habitats for biological diversity (Finn *et al.*, 2011), yet recent studies imply that they are largely neglected during forestry planning and management (Richardson *et al.*, 2012, Kuglerová *et al.*, 2020). Small channel size and closed canopy give rise to strong local microclimate gradients, higher input rates of organic matter, and low primary production. In some areas, the absence of fish may provide a predator-free, or at least predator-reduced environment. This can provide important habitat elements for some species that are not tolerant of predation by fish (Richardson and Danehy, 2006). Changing landuse and deforestation within their contributing catchment can change fluxes between uplands and downstream river segments, impacting these distinctive habitats. Increasing interest in the stability and evolution of these rivers reflects their major role in moderating sediment and nutrient delivery to the lower valley.

Various stream morphologies found in headwater channels have been summarised in classification schemes. Figure 1-6 shows the system from Montgomery and Buffington (1997), capturing key typologies from the Pacific Northwest, USA. Steepland rivers in New Zealand show quite similar forms. Headwater streams are ultimately exporters of colluvial material, but in the short run, substantial accumulations of sediment and wood may occur along steep channels. Accumulations may be particularly prominent at the break in slope where they meet the mainstem channel, creating fans. Once in the channel, coarse debris may remain for a long time, since ordinary stream flows are incapable of moving it (Figure 1-7). The result is a relatively stable cascade or step-pool structure, prevalent in channels with gradient greater than about 4% (Grant *et al.*, 1990; Chin 1999), often supplemented by wood in the channel (Zimmerman and Church, 2001; Church, 2010). These accumulated materials are periodically evacuated by debris flows, debris floods or gully erosion on a scale of decades to centuries.

Given their important role in promoting biodiversity and diverse habitat, assessing impacts to headwater streams is a key part of New Zealand conservation efforts. Internationally, it is considered best forestry practise to leave an unmanaged strip of vegetation (riparian buffer) around steep headwater streams (*e.g.* Finland, Sweden, and Canada; Richardson *et al.*, 2012; Jyväsjärvi *et al.*, 2020). In New Zealand, however, buffers are only required for perennial streams greater than 3 m in width (NES-Plantation Forestry, 2017). Headwaters streams have sometimes been specifically defined as having a width of *less than* 3 m (Richardson and Danehy, 2007), but definitions range widely. The point being that these systems are difficult to protect in the current policy framework. Retention of headwater riparian buffers reduces nutrient losses and sediment erosion, maintains natural in-stream thermal and light regimes and provides terrestrial resource subsidies to stream food webs (Kreutzweiser *et al.*, 2009, Richardson and Sato, 2015).

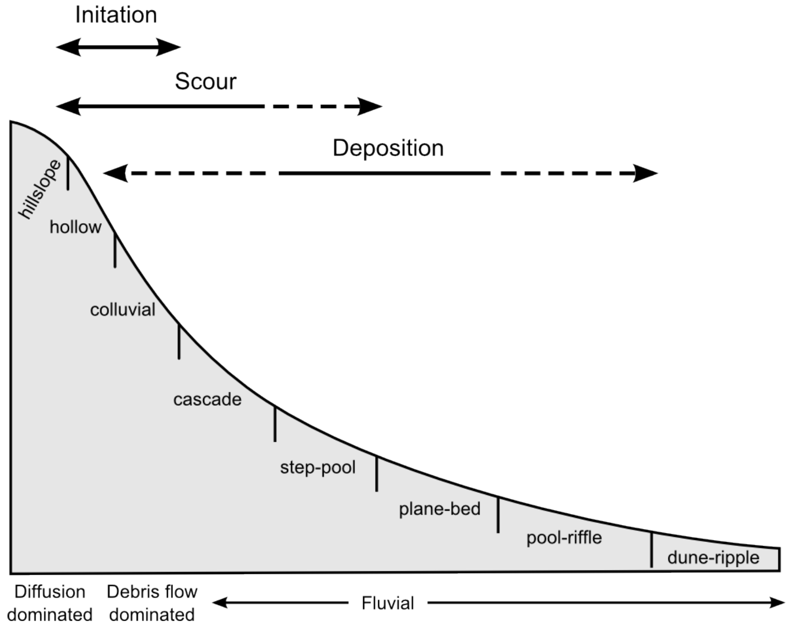


Figure 1-6 *Classification of mountain streams along a longitudinal profile, according to Montgomery and Buffington (1997). These distinctive river morphologies reflect changing sediment supply conditions, and the recruitment of coarse (cobble, boulder) materials and wood that add important structure to streams in very steep settings. The systems provide unique habitat, and nutrient flux from these many headwater systems sustains ecological communities in the larger river system.*

Figure 1-7 *A bedrock gorge in the Haast River catchment (left), exhibits active recruitment of very large bouldery materials from closely coupled colluvial sources. The largest of these provide quasi-stable morphology elements in cascade and step-pool systems. Moss on the rocks in a small step-pool stream on the flanks of Mt Pirongia (right) attests to the enduring stabilising role of these elements, delivered long ago by mass-wasting processes upstream.*

The Transfer Zone: Upland and Montane Channels

Rivers are ultimately a product of their geologic and tectonic setting. Landscape gradient dictates the regime of sediment production and delivery, and therefore the resultant river form. Imprinted upon this is the signature of long-term climate forcing, which further modulates rates of weathering and sediment movement through the system. The frequency and magnitude of landslides and debris flow deliveries dictates many aspects of sediment storage (or bedrock exposure), evolution of the valley fill, and the textural character of the river system.

Montane systems have a shallower slope than headwater streams (roughly 0.003 to 0.03 gradient). If they are not confined by bedrock, these rivers deposit their load of cobble, gravel and sand, forming a variety of different depositional forms (lateral, mid-channel bars) that are the basis of essential riverine habitat. While the channel pattern generally remains relatively stable over time, ongoing erosion and deposition of materials creates and reworks bars and bedforms with varying residence times and probability of onward transfer. The channel is, at best, ‘pattern stable’, meaning that its geometry, including planform, retains the same average character (Church, 2015).

It is impossible to reliably determine the behaviour, sensitivity or resilience of a river system without understanding its longer-term trajectory, and its response state from past disturbances. Reviewing past aerial imagery, looking at remnant terrace surfaces adjacent to the river, and gathering local knowledge all contribute to a fuller picture of the longer-term behaviour of the system.

Schumm (1972), Kellerhals *et al* (1976), Wolman (1982) and Church (1992, 2006, 2015) and others have outlined the links between channel gradient, sediment calibre, and sediment supply. Using these guides, changing conditions can be conceptualised over time or along a longitudinal gradient, as gradient and sediment conditions change (Figure 1-9). The classification also has evident links to broadly evaluating habitat potential, or assessing the potential behaviour of the channel under changing sediment and flooding regimes.

Figure 1-8 *A montane channel confined by bedrock valley walls. There is little opportunity for deposition and storage in these relatively steep systems, however the river exhibits a diversity of in-channel fluvial forms such as pools and riffles.*

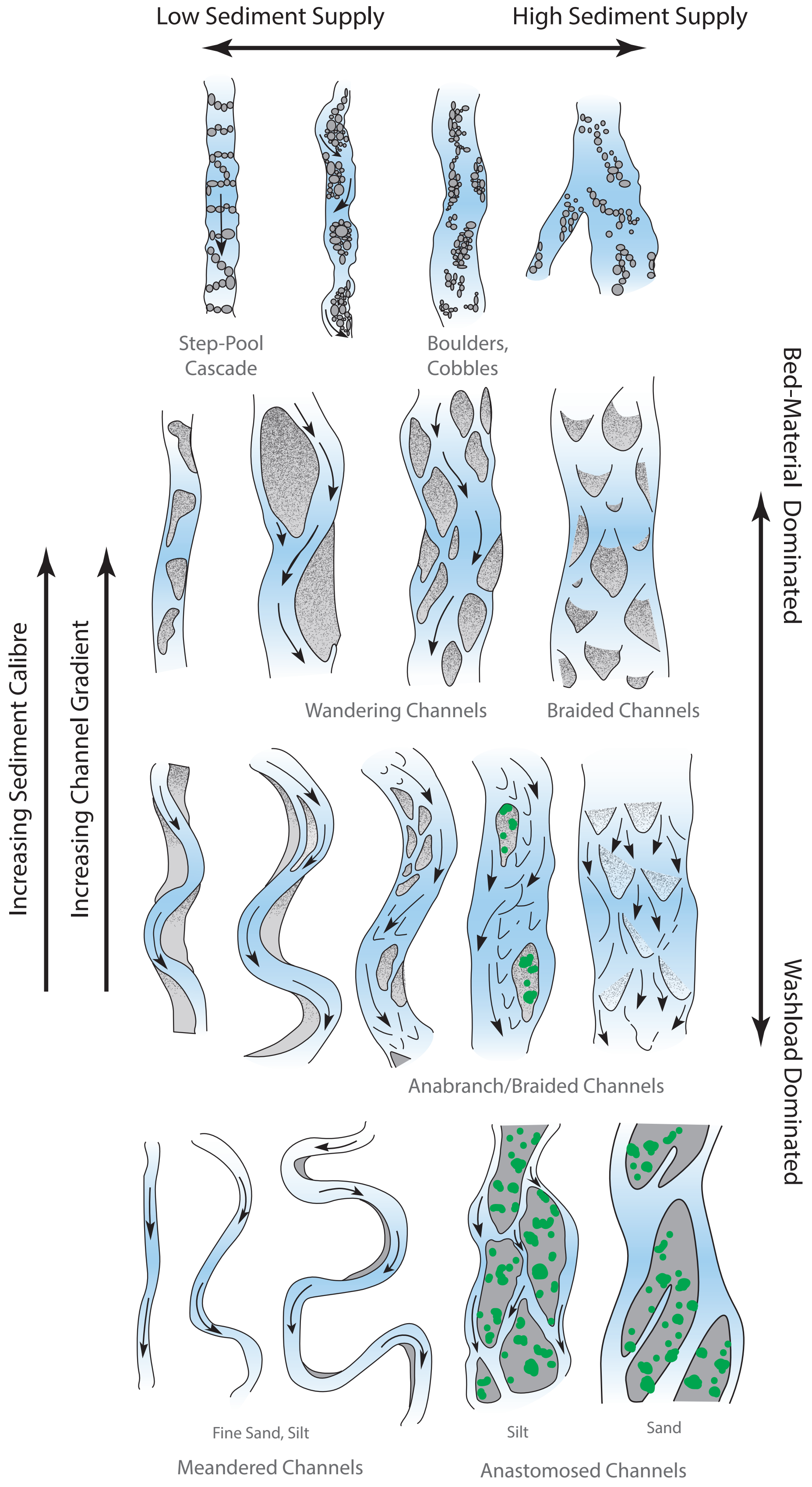


Figure 1-9 *Morphological channel types according to channel gradient, sediment calibre and sediment supply conditions. The planform stability of these channel types decreases with higher sediment supply (right-most, in diagram) and coarser sediment calibre (uppermost - braided and very steep coarse-grained systems; Modified from Church, 2015).*

The Deposition Zone: Lowland Alluvial Systems and Terminal Deposits

As major river systems leave valley confines, they typically move over very low gradients. Bank erosion becomes an important mode of sediment delivery. In some cases, this can equal or exceed contributions from headwater systems (Florsheim *et al.*, 2008; Williams *et al.*, 2020). Residence times of alluvium may be very long, given the slow lateral migration rates and large historic floodplains. These deposits are often favourable for human agriculture and development. Accordingly, these alluvial rivers tend to be subject to major engineered constraints, limiting or arresting their evolution.

Because of their significant habitat complexity and diversity, alluvial rivers are very important biodiversity reservoirs, with varied ecological communities. At the marine interface these systems interact with long shore, beach, lagoon and dune sedimentary systems. Groundwater interactions in many large floodplain systems recharge from subsurface reservoirs in the 'parafluvial' zone (Tonina and Buffington, 2011) at the margins on the principal channel systems. The low gradient setting favours the development of wetlands, marshes and discontinuous channel systems which host a number of important but sensitive ecological systems.

Given New Zealand's dynamic tectonic setting, and interactions with coastal sediment transfer, the depositional zone may be subject to low-energy, subsiding conditions, an actively building environment, or some intermediate balance of these (Figure 1-10). Long-term subsidence has resulted in 'drowned' topography in many areas, with shallow tidal estuaries accumulating fine-grained material from the catchment (Figure 1-10A). More actively uplifting regions, as well as glaciated catchments, give rise to coarse-grained systems with broad floodplains, and more active interplay with fan building and erosion/transfer by coastal currents. Active mass-wasting regimes, and periodic seismic events contribute to an actively building deposition zone (*e.g.* Clarence River, Figure 1-10C, on the South Island).

Figure 1-10 *Lower river dynamics are strongly conditioned by the tectonic and coastal setting, from protected estuarine environments, to graded equilibrium with longshore processes, to active building of fan-deltas in geologically dynamic environments. (A) Waiwawa River, Coromandel Peninsula, has a subsiding, estuarine terminus to the river system; (B) the Waipaoa (Gisborne District) in Poverty Bay, shows a stable to gently prograding late Holocene equilibrium with coastal transfers; (C) the Clarence River shows an active regime of constructive fan-delta building over time.*

Anthropogenic Channels

It is estimated that roughly 20% of New Zealand's land area has, or is suitable for, drainage such as canals, ditches or drains (Manderson, 2020). Drainage is generally necessary to prepare soils for agriculture or horticulture; the roots of pasture or crops will not survive in waterlogged soil. Even partly drained soils can be problematic for cultivation. Drainage lowers the water table below the level of plant roots.

Surface agricultural drains are often highly modified, straightened waterways with trapezoidal or U-shaped cross-section (Figure 1-11). In many parts of New Zealand, surface drains are also connected to subsurface tile drains. Artificial drainage can strongly alter the arrangement of Lane's balance by conveying runoff in straight conduits without the accompanying lateral channel evolution (width, sinuosity) along drainage pathways or graded adjustment of channel slope. Disruption to the longitudinal continuity of sediment transport creates "hungry water" (Kondolf, 1997): the river cuts into its bed and erodes material. While these channels may sometimes occupy the depression that was their ancestral alluvial bed or wetland, the modern morphology bears little semblance to 'self-formed' and naturally adjusted conditions. Combined with common practices of flow abstraction and retention, there is a growing imperative to link river restoration efforts with broader consideration of hydrologic manipulation on the landscape (Whipple and Viers, 2019). It is also important to consider the impacts of altered hydrologic conveyance on the erosion characteristics of river morphologies downstream, as the river adjusts to higher peak storm flows.

From a hydrology and river geomorphology perspective, ancestral wetlands (bogs, fens, marshes, swamps) played an important role in storing and releasing water gradually, reducing the impact of flooding downstream. The presence of natural vegetation, trees, root mats and other wetland vegetation slows the velocity of flood waters, reducing flow depth and erosive capacity, and diffusing flows across the floodplain. Effects vary with position in the landscape. Water supply in headwater systems is dominated by rainfall supply, so enhanced delivery to the lower system alters the timing and intensity of flooding downstream. In transfer and deposition zones, altered flow pathways affect groundwater and floodplain interactions. From an ecological perspective, wetland and vegetated waterways are important for the organisms that form the base of the food web and feed many species of fish, amphibians, shellfish and insects. Wetlands help to regulate pH, solute and sediment content, and help to diversify habitat in the catchment.

There is currently experimentation underway with 'two-stage' channels: artificially created floodplains designed to lower the power of water by dissipating its energy during flooding (Nature Conservancy, 2018; Holmes *et al.*, 2019). This also helps absorb nutrients like phosphorous and nitrate and trap fine sediment. This is a small but important step toward regaining some geomorphic functionality in these highly modified hydrological systems. Broader efforts to restore 'room for the river' and re-establish ancestral river floodplains (Fokkens, 2006; Biron *et al.*, 2014; Massé *et al.*, 2020) are gaining popularity world-wide; there is important scope for bringing this practice to New Zealand, to nurture river habitat, foster riparian wetlands connectivity, improve flood resilience and restore functional morphology processes (lateral migration, channel avulsions).

Figure 1-11 *Drainage channels are designed for optimum conveyance; steep banks allow deep and fast flows in flood events, effectively flushing sediment and debris on relatively low slopes. Canals are straight, taking the most efficient route and typically directing water to the margins of productive land. They bear little resemblance to their ancestral 'self-formed' channels.*

Figure 1-12 *A network of canals (gaps among the rectangular fields) draining water from fields in a lowland estuarine environment. The sinuous Araparera River is situated within a corridor among the drained fields, Kaipara Harbour (c) 2021 Google Earth.*

2. Desktop Geomorphic Analyses

Based on the principles outlined in the previous section, there are numerous important linkages among landuse/landcover, catchment sediment production, disturbance regime and resultant channel form. Perhaps inevitably, the science of catchment 'restoration' is inexact, as attributes and relationships play out in distinctive ways in each river system; hence Brierley and Fryirs' (2005) key imperative to 'Know your Catchment'. Forcing factors such as storm incidence and mass-wasting regime are highly variable. Unfortunately, some key relationships between land use and sediment yield are poorly characterised. However, many tools can be used to explore linkages between river process, the configuration of connected landforms and the river network, the potential for sediment delivery, and the potential responsiveness of the river system (e.g. Fryirs *et al.*, 2019; Piegay *et al.*, 2020; Reichstein *et al.*, 2019; Rou *et al.*, 2015).

In this section we look at tools for (1) inferring fluvial process via channel form and morphology, (2) network configuration including hydrologic (and thus sedimentary) routing and connectivity in a GIS environment; (3) plotting longitudinal (downstream) characteristics of the river network, and (4) assessing sediment transport potential and interactions amongst responsive pathways in the network. Lastly, we look at the potential for reach-scale simulation of river response to disturbance and sediment transfer (Figure 2-13).

With the availability of high-resolution topographic data, it is now possible to resolve many river characteristics (channel definition and gradient, most importantly) that were previously difficult to quantify reliably across catchment scales. The addition of satellite/airphoto time-series and uniform landuse classification coverage helps the analyst to further determine morphological style, bed texture, channel condition, and attributes of the adjacent terrain that influence/control river character and behaviour.

Many of these tools are based on proprietary software platforms, namely ESRI's ArcGIS and MathWorks' MATLAB. These are commonly - but not always - available within major research institutions, CRIs, government agencies (DoC), as well as regional and local Councils. Open Source workflows for most of these tools are also available (e.g. QGIS, Octave), albeit with possible minor compatibility issues.

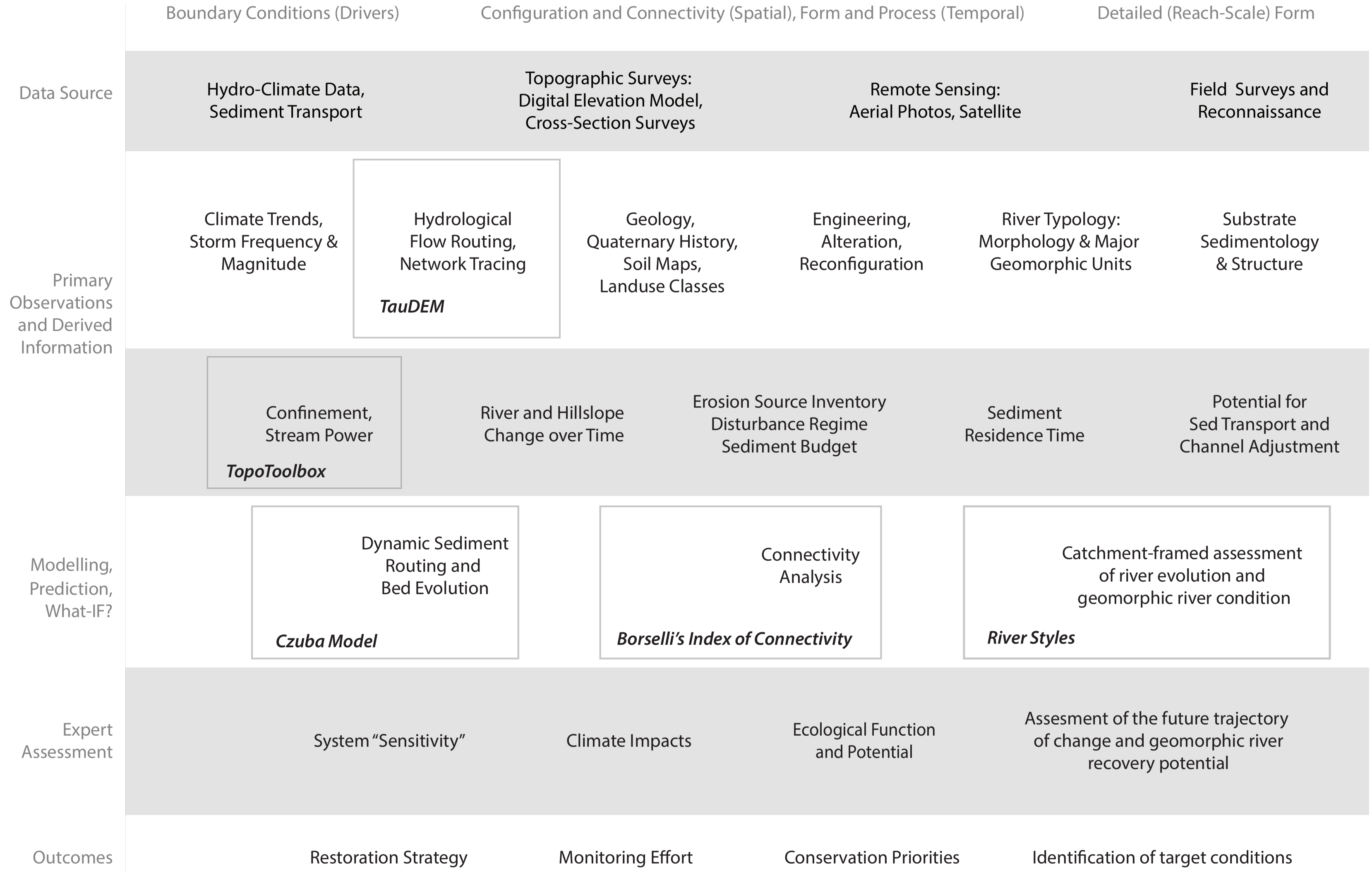


Figure 2-13 *Generalised workflow used for assessing catchment characteristics, connectivity and predisposition to change. Evaluating the drivers of geomorphic change, the historic pace of change, and the arrangement of landscape elements is essential to understanding the potential for restoration success and possible future trajectories of the system. The present study did not proceed to field surveys, but this is recommended for future work. Key desktop tools used in the present study are highlighted, and discussed in the following pages.*

2.1 Hydrological Flow Routing (TauDEM)

Hydrological flow routing is an essential first step in defining the river network based on a Digital Elevation Model (DEM). This is a relatively standard procedure and can be accomplished by using numerous different software packages, including for instance, ArcGIS (Hydro Toolbox), QGIS, SAGA GIS, Whitebox GIS and others. The TopoToolbox also provides a library for this procedure. We have employed David Tarboton's (2016) TauDEM software, which is optimised for use on very large grids, and generates a vector layer with important connectivity information for further GIS processing.

Flow direction is established for the DEM, and then the model is "filled", such that there are no internal sinks and all pixels drain toward the trunk channel. Following this, the accumulation area (upstream catchment area) for every pixel in the model can be calculated, providing the basis to estimate flow at any point in the drainage network.

Further analyses involve definition of Strahler order, and assessment of the distance from any point to the nearest channel. A list of more analyses is provided in Tarboton (2016).

Numerous issues must be addressed to bridge this virtual construct of the drainage network and the real world. Depending on the resolution and elevation fidelity of the DEM, the real river channel may take a substantially different course from the modelled one. Forest canopy and other landscape elements that obscure the river form are not always cleanly removed from 'bare earth' models used to construct the network. Subsurface drainage pathways, particularly in urban areas, are obscured, and require special treatment for inclusion in the drainage model. 'Burning' of the drainage into the model (by subtracting some appreciable depth along the drainage line) is one such technique.

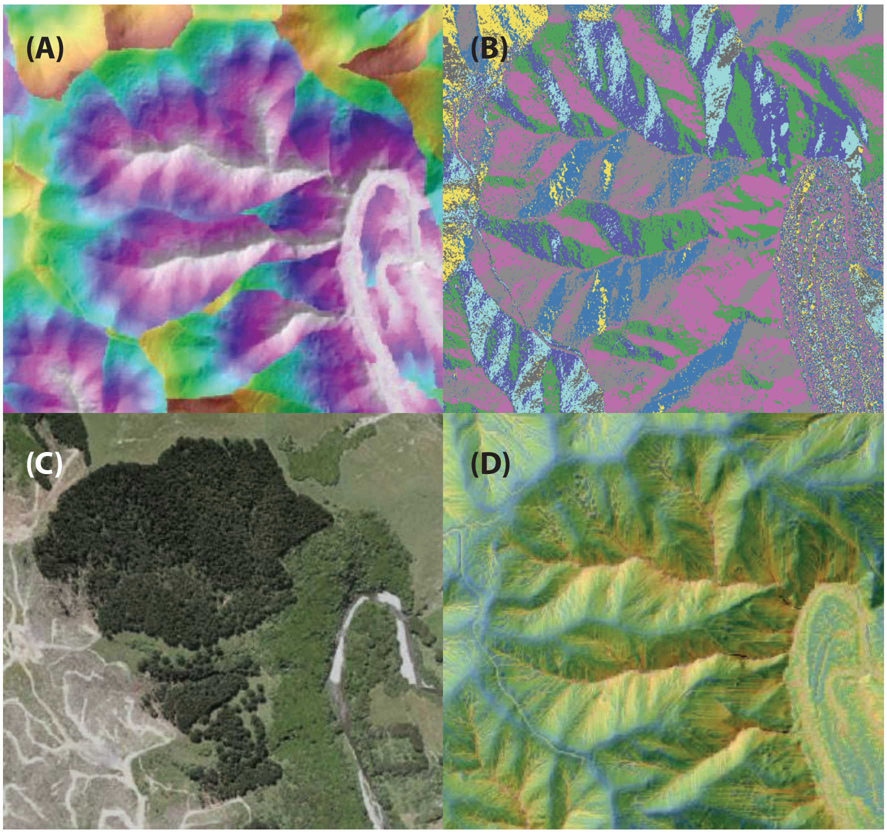


Figure 2-14 ***A modelled sub-basin within the Waikanae catchment: (A) distance to the main channel, (B) flow direction, (C) satellite photo, (D) flow accumulation raster.***

2.2 The TopoToolbox

TopoToolbox (Schwanghart and Scherler, 2014) is a comprehensive function library for digital elevation model (DEM) analysis. The main strength of TopoToolbox lies in the handling of gridded DEMs, flow and stream networks, and connective information. The tools have been implemented within an object-oriented MATLAB class hierarchy. Many of the analyses can be achieved through GIS tools, but the command interface, display and memory management in TopoToolbox is particularly efficient.

TopoToolbox provides a set of Matlab functions that support the analysis of relief and flow pathways in digital elevation models. The major aim of TopoToolbox is to offer helpful analytical GIS utilities in a non-GIS environment in order to support the simultaneous application of GIS-specific and other quantitative methods. The software is perhaps designed with more exploratory and theoretical analyses in mind (e.g. knickpoint identification, Chi analysis, topographic prominence), but it is quite powerful for quickly delineating the long profile, relative confinement (e.g. valley bounds), and stream power within the river system, and easily moving between profile view and planform maps.

The TopoToolbox supports other emerging software tools such as CASCADE (Schmitt *et al.*, 2016, Tangi *et al.*, 2019), which simulates sediment transport and connectivity. River network extraction, reach segmentation and assignment of hydromorphologic and geomorphic attributes is carried out using TopoToolbox routines.

This toolset is not intended to replace more traditional GIS analyses, but it does show the strong potential of embedding river network attributes and transport characteristics in a numerical engine such as MATLAB. Higher-order assessment of network behaviour and cumulative impacts within a catchment can be explored in more sophisticated ways and communicated more clearly.

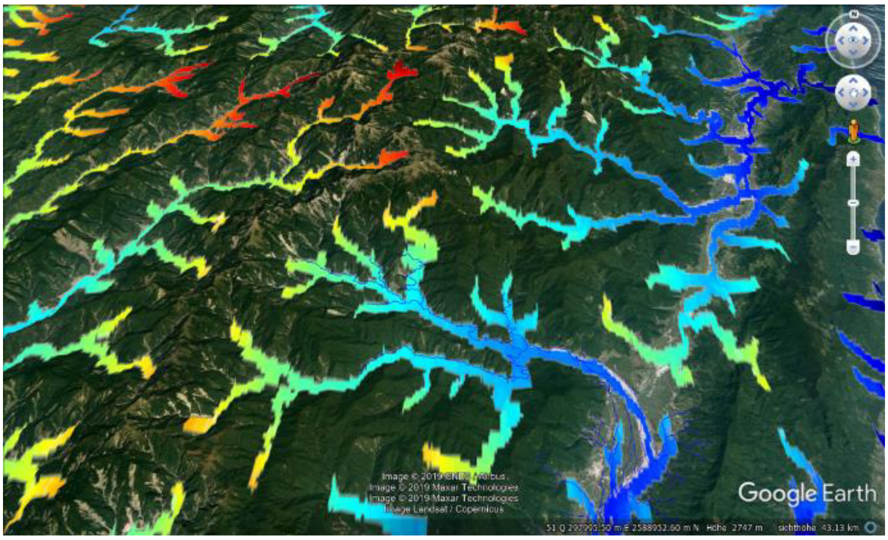


Figure 2-15 ***TopoToolbox results (river 'χ' metric) exported to Google Earth. Colours indicate the relative capacity (or susceptibility) of river basins to gain catchment area (or lose it), as erosion proceeds over geologic time scales and drainage divides migrate. See Willett et al. (2014) for more details. Source: https://topotoolbox.wordpress.com/2019/10/30/colored-stream-networks-in-google-earth/***

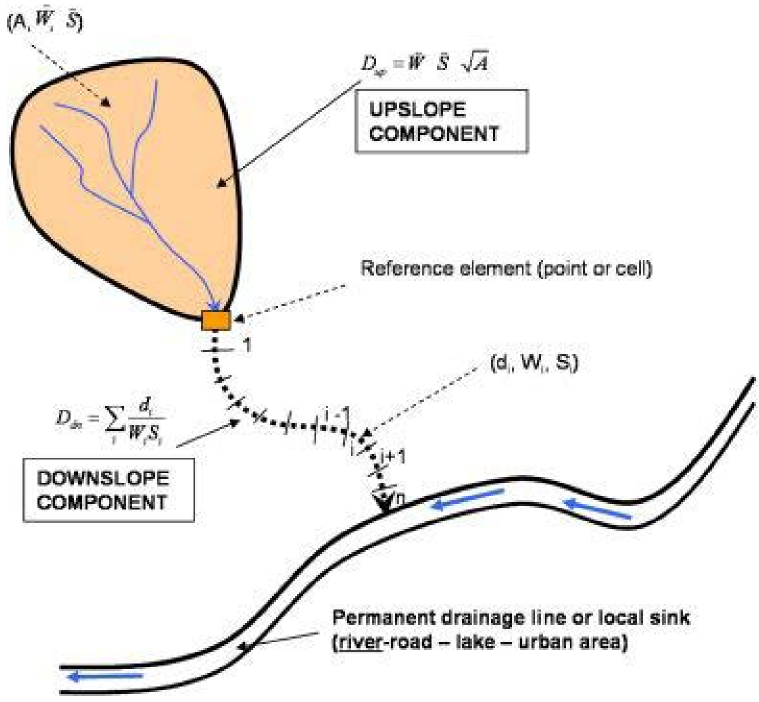


Figure 2-16 *Borselli et al's conceptualisation of sediment connectivity is embodied in the balance of upslope factors driving sediment movement (slope, discharge) and the downslope distance to the trunk stream and the transport capacity (d, slope). This is computed for each DEM cell or pixel on the landscape. A weighting factor, reflecting the effect of landuse or landcover on sediment production and transport, can be assigned to each cell.*

2.3 Assessing Sediment Connectivity

Connectivity describes the efficiency of material transfer between geomorphic system components such as hillslopes and rivers, or longitudinal segments within a river network (Harvey, 2001, 2002). Water and sediment connectivity (distinct from ecological connectivity) are key issues in the study of hydrological and geomorphic processes and associated transfer pathways (*e.g.* Bracken *et al.*, 2013, 2015; Brierley *et al.*, 2006; Fryirs, 2013; Parsons *et al.*, 2015; Wohl, 2017; Wohl *et al.*, 2019). The many components within the hillslope and fluvial system exhibit connectivity at differing temporal and spatial scales. Explicit mapping of these connections generates a better appreciation of how disturbance may transit through the catchment: what source areas contribute to a site, and what receiving areas the site contributes to, over what timeframe.

Assessment of connectivity entails consideration of lateral, longitudinal and temporal linkages within the drainage basin. Though a variety of field techniques and monitoring strategies can be used, an initial investigation can begin with a desktop GIS analysis. Given the availability of a high-resolution elevation model and an established hydrological connectivity framework (*e.g.* via TauDEM, Section 2.1), it is possible to map connections based on attribution of the relative production and transfer potential from various landscape compartments. The scheme developed by Borselli (2008; Figure 2-13) generates important insights into landscape connections, requiring an appropriately detailed elevation model and landuse designation within the catchment. Borselli's Index is essentially the ratio between factors that drive sediment flux from upslope (slope, discharge) and the factors governing the evacuation of those materials (distance to the channel, slope).

Connectivity changes systematically throughout the drainage network. Figure 2-17 shows examples of variable connections to the fluvial system, ranging from disconnection arising from a floodplain buffering the main channel (A), to partial transport and reworking of landslide material, partly stranded on an alluvial fan (B), to highly connected terrace deposits feeding directly to the channel (C). In (A) and (B), finer materials likely reach the channel in greater proportion than coarser ones, emphasising that connectivity can vary by size fractions. As landslides and other mass wasting processes vary in time, temporal shifts in connectivity are inevitable.

An example of a map showing Borselli's Index of Connectivity is show in Figure 2-18. The units are relative, and depend on various parameters and landscape setting. Points close to the river system score high, while points in the upper drainage and ridges score low. There are a number of undefined points on the ridges and in rough terrain, where calculation of the index results in a zero, and is undefined in the final logarithmic result. Different landuse types in the landscape are assigned different weightings, according to some relative sediment production factor, such as the USLE-RUSLE ‘C-factor’ or similar index of relative erodibility.

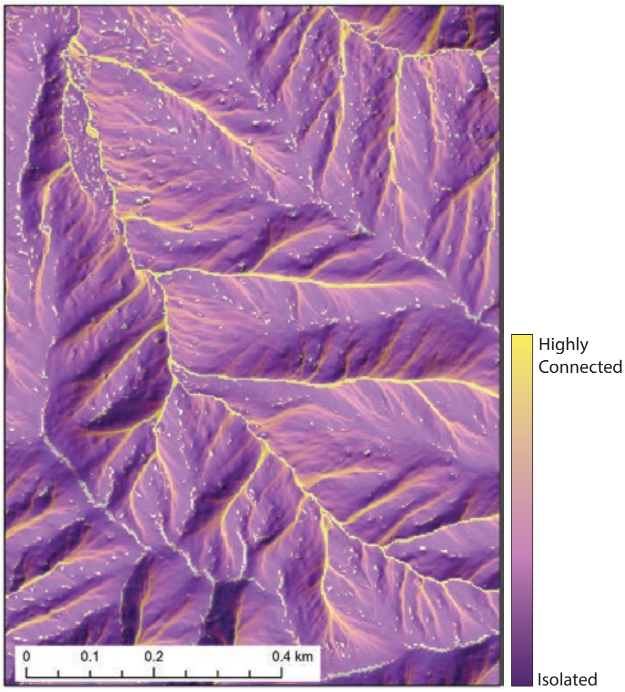
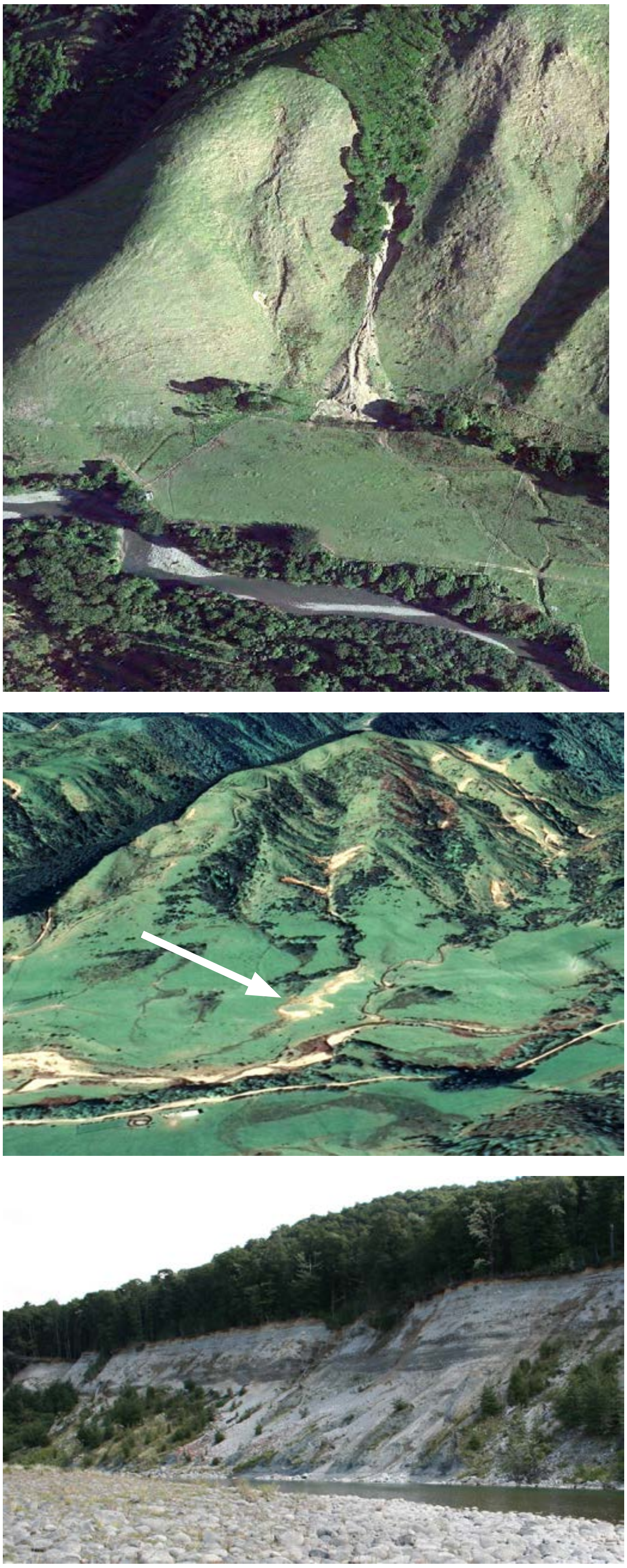


Figure 2-18 *An example of a connectivity map in a mountain drainage (Waikanae catchment).*

Figure 2-17 *Degrees of coupling within fluvial systems: (A) a landslide in the lower Waikanae River is mostly disconnected from the river; the great majority of the load is deposited on the floodplain, with some diffuse fine sediment washing out. (B) A fan provides intermediate storage between sites of active landsliding and delivery to the river. (C) A Quaternary terrace in the mid-reaches of the Waiau River sheds sediment directly to the channel.*



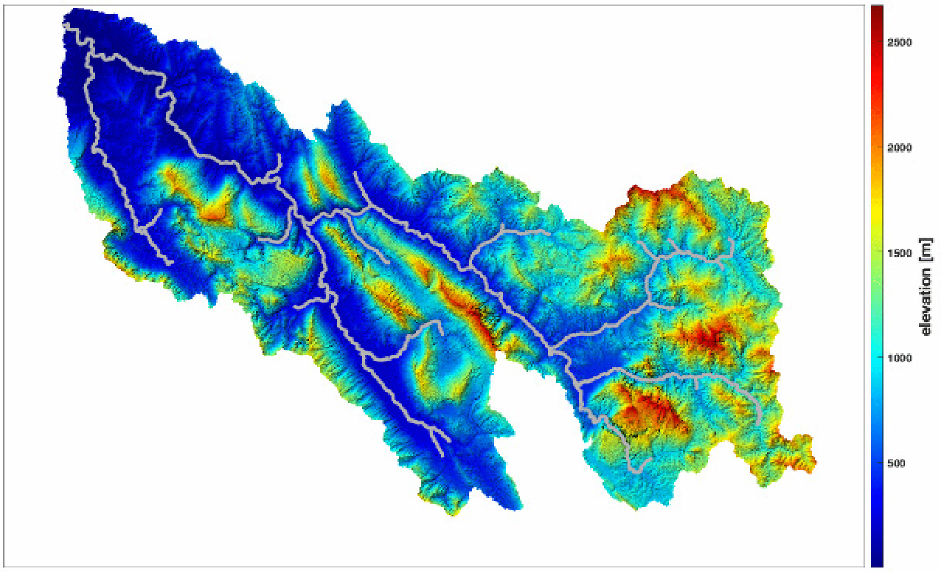


Figure 2-19 *The* CASCADE model has been applied to quantify basin-scale connectivity in poorly monitored rivers (Schmitt *et al.*, 2018; Bizzi *et al.*, 2021). The Aoös or Vjosa River (northwestern Greece and southwestern Albania) provides a good test case for the CASCADE algorithm. (topotoolbox.wordpress.com)

2.4 Dynamic Simulation of Network Behaviour

Network Connectivity, Coupling and 'Hotspots'

Different parts of the system will have different arrangements of 'Lane's Balance', and therefore different morphologies and river types result. The last part of this section we examine different characteristic morphologies and sediment dynamics observed at different scales within the catchment. It has long been supposed that, much like the hydrologic network, the response of the sedimentary network is shaped by the topology of connecting branches (e.g., Rodriguez-Iturbe and Valdes, 1979; Gupta *et al.*, 1980). Given that the rate of transfer of sedimentary materials may be modulated with changing morphological character of the river, the signal (time series of sediment yield) at the outlet will be a function of these upstream conditions. Concepts of coupling and connectivity between network links has long been understood in the static, local sense; it is only relatively recently that simulations of the cumulative effect of these variable and varying linkages have been developed for relatively large river networks, casting some light onto impact of network arrangement on channel dynamism in response to various forms of disturbance. CASCADE (Schmitt *et al.*, 2016; Tangi *et al.*, 2019) and SeRFE (Gilbert and Wilcox, 2020) are two recent models that can generate sophisticated dynamic simulations of catchment response to sediment loading.

In this work we employ Czuba and Foufoula-Georgiou's (2014) River Network Bed Material Sediment routing model to explore the role of network structure on sediment evacuation in the three study catchments. As with TopoToolbox, this model is based in MATLAB, although active development has switched to Python, and the code has been incorporated into the LANDLAB codebase (Barnhart *et al*, 2020). The model takes a Lagrangian perspective of sediment transport, tracing the fate of individual 'parcels' of sediment through the drainage network. Each parcel responds to local conditions in the network link, including discharge, channel gradient and sediment calibre.

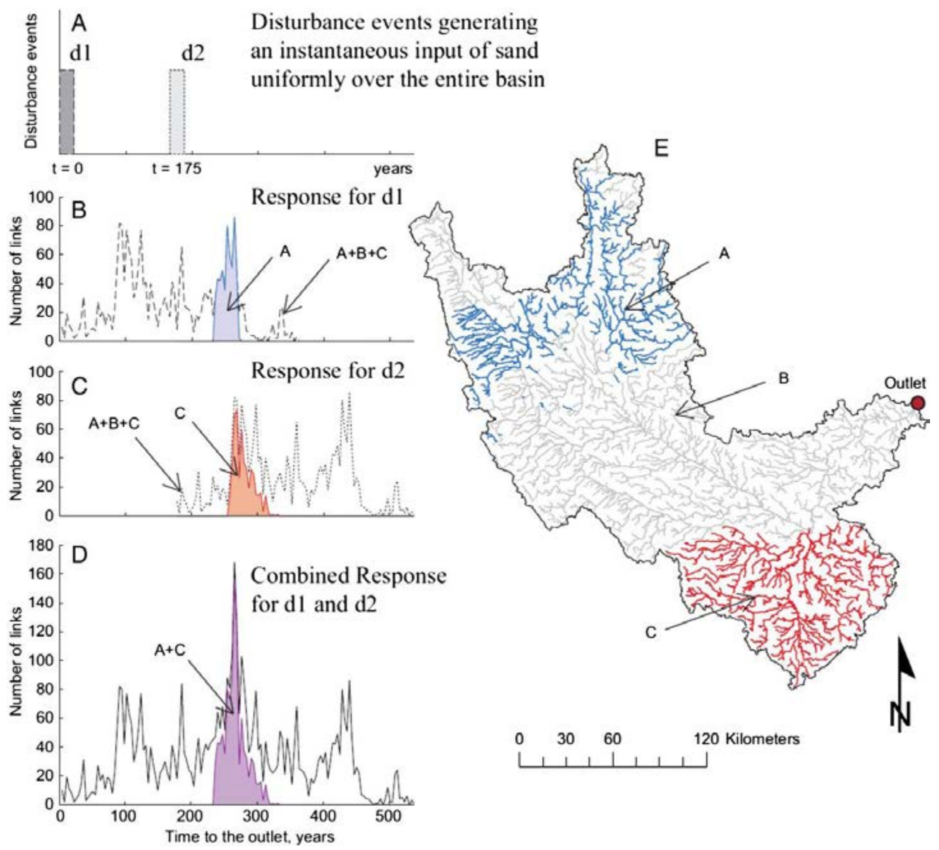


Figure 2-20 *An example of output from Czuba and Foufoula-Georgiou's (2014) River Network Bed Material Sediment, simulating sediment transfer dynamics in the Minnesota River catchment. The model response time-series at the outlet can be interrogated to reveal which components of the network are contributing to the total discharge. This particular example shows the superposition of two disturbance events in time (sand parcels liberated to every first-order link in the network), leading to a complex, cumulative outcome downstream. These insights into the synchronisation and amplification of sediment fluxes within the network are helpful for managing potentially active source areas, and developing a strategy for aligning landuse and rehabilitation efforts.*

From a conservation standpoint, such simulations of network behaviour offer important insights into the likely sites of sediment overloading, buildup and thus dynamic channel behaviour. The model offers highly idealised representations of system response, but combined with other information on changing land use, historic sediment sources and past channel change in the study catchment, it becomes possible to develop more sophisticated hypotheses regarding future system behaviour. It may also guide fieldwork and monitoring efforts, hinting at likely sites of change. The 'hotspots' identified in the model are sites where parcels of sediment tend to accumulate; certain network arrangements lead to disproportionate loading of the system. This offers insight into likely residence time of sediments in a given link, capacity for buffering delivery to links downstream. All of this information is helpful for gauging habitat potential and working out the consequences of changes to river connectivity in different parts of the catchment.

2.5 River Styles Classification

Numerous geomorphic classification systems have been developed over time, with early approaches focusing on the genetic structure and evolution of rivers as influenced by tectonics and geologic structure of the landscape (*cf.* Buffington and Montgomery, 2013). Many of the classifications that have been developed are inherently regional, imposing order on different suites of river types and associated landforms to address regional questions.

The River Styles Framework (Brierley and Fryirs, 2005) was initially developed in the context of Australian rivers, but the principles have proven readily transferable, globally (Fryirs and Brierley, 2018). Recent application of the process to the Waipā River catchment (Marson *et al*., 2021) has shown that it functions well in the distinct New Zealand riverscape. The essential outcome of the naming process is that a common understanding of river character and behaviour can be established, which has clear advantages for developing catchment management strategies and setting conservation priorities. It is also helpful from a connectivity perspective, as we consider the longitudinal linkages within the river system: where materials are stored, where the river is more likely to respond to disturbance, or where distinct habitat may be found, for instance.

The identification, naming and presentation of River Styles is a four step process:
1. The problem: correctly differentiate and interpret river reaches at the outset.
2. The procedure: the framework and measures used to distinguish and differentiate river types, allowing for characterisation of new types if required.
3. The convention: the sequence of steps used to name different river types in a consistent manner, irrespective of landscape setting.
4. The product: a standard approach for assigning full (verbose) and abbreviated names for different river types that can be applied across the spectrum of river diversity.

The approach to identify and analyse River Styles uses three key measures: river planform, geomorphic units and bed material. These measures are ordered on the River Styles procedural tree under each valley-setting (Figure 2-21). The measure used to determine valley setting is lateral confinement of the channel. This entails analysis of the position of the channel relative to a valley bottom margin, and the extent to which either bank (not both) abuts a valley bottom margin. Three valley settings cover the full spectrum of river diversity; confined, partly confined and laterally unconfined

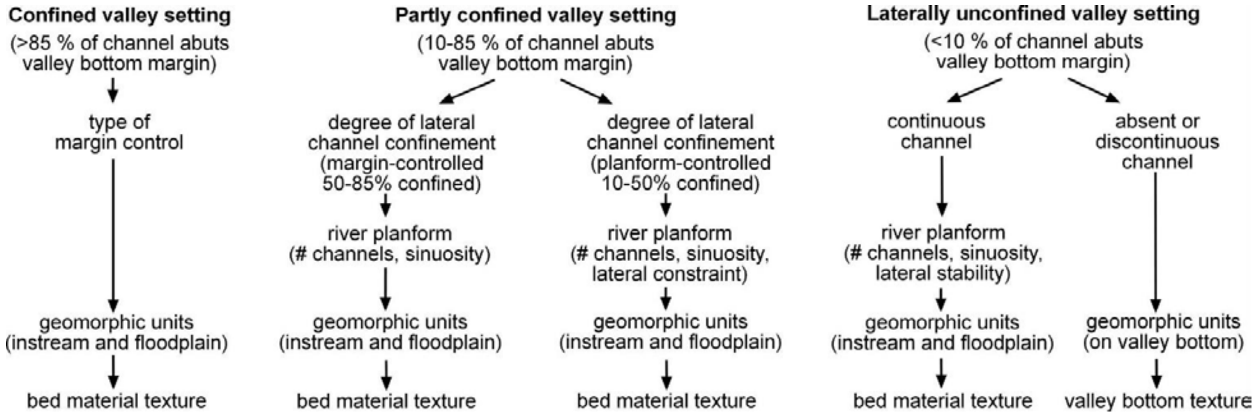


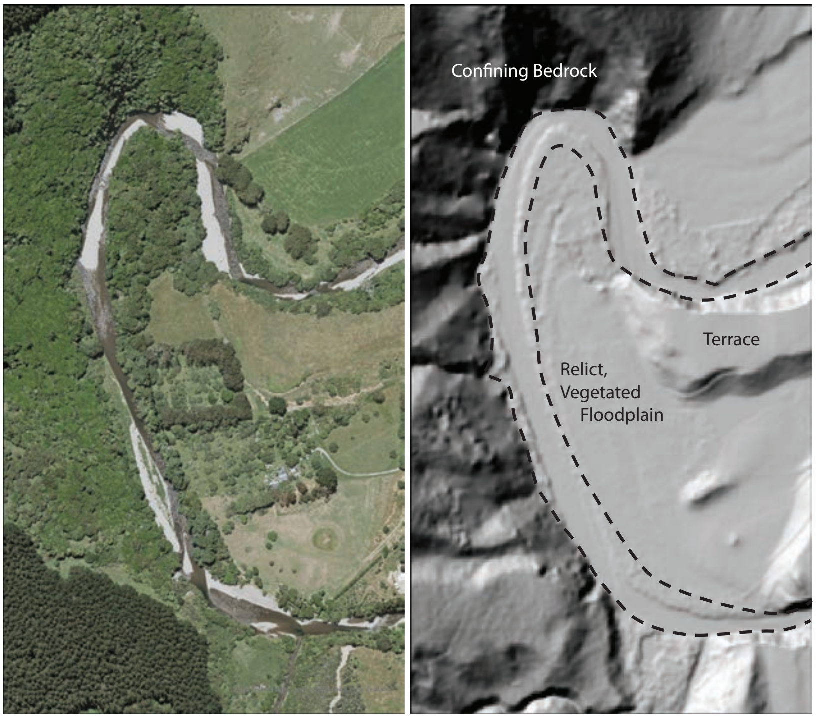
Figure 2-21 River Styles procedural tree for identifying different river types across the spectrum of river diversity. The approach identifies types of river based on a mix of measures including valley setting, channel planform, geomorphic units and bed material texture.

In the River Styles Framework, **confined rivers** have a channel that abuts the valley bottom margin along either bank along >85% of its length (previously >90%). **Partly confined rivers** have a channel that abuts the valley bottom margin along either bank along 10–85% of its length (previously 10–90%). Finally, **laterally unconfined rivers** have a channel that abuts the valley bottom margin along either bank along <10% of its length.

The next step in the procedural tree entails identification of geomorphic units. This is the key diagnostic indicator used for differentiating River Styles. Importantly, designation of River Styles names using procedures outlined here does not contain descriptors of position (e.g. headwaters, lowland plain etc.), nor descriptors of landscape units (e.g. plateau, rounded foothills, delta, etc.), nor place names. These positional or geographical attributes are not considered diagnostic indicators of river type, as some types of river can occur in different landscape positions or settings. Forcing river types into a particular landscape setting (and naming them as such) restricts generic application of the approach to naming conventions for rivers in different places.

Measures are only used in a particular valley setting if they provide useful information to help identify a river type. For example, measuring river planform in terms of the number of channels, sinuosity and form/ease of lateral channel adjustment does not provide a diagnostic indicator of river types located in confined valleys, nor for laterally unconfined discontinuous channel systems.

The naming process is the first of four steps in the River Styles Framework. In the current study, we have not formally applied Steps 2-4, but we leverage some of the essential principles based on the findings of the established river character and behaviour and insights from other desktop analyses.



Aerial Image

LiDAR Hillshade Image

Figure 2-22 River Styles assessment using aerial photos and bare-earth LiDAR hillshade imagery to discern controls on river morphology.

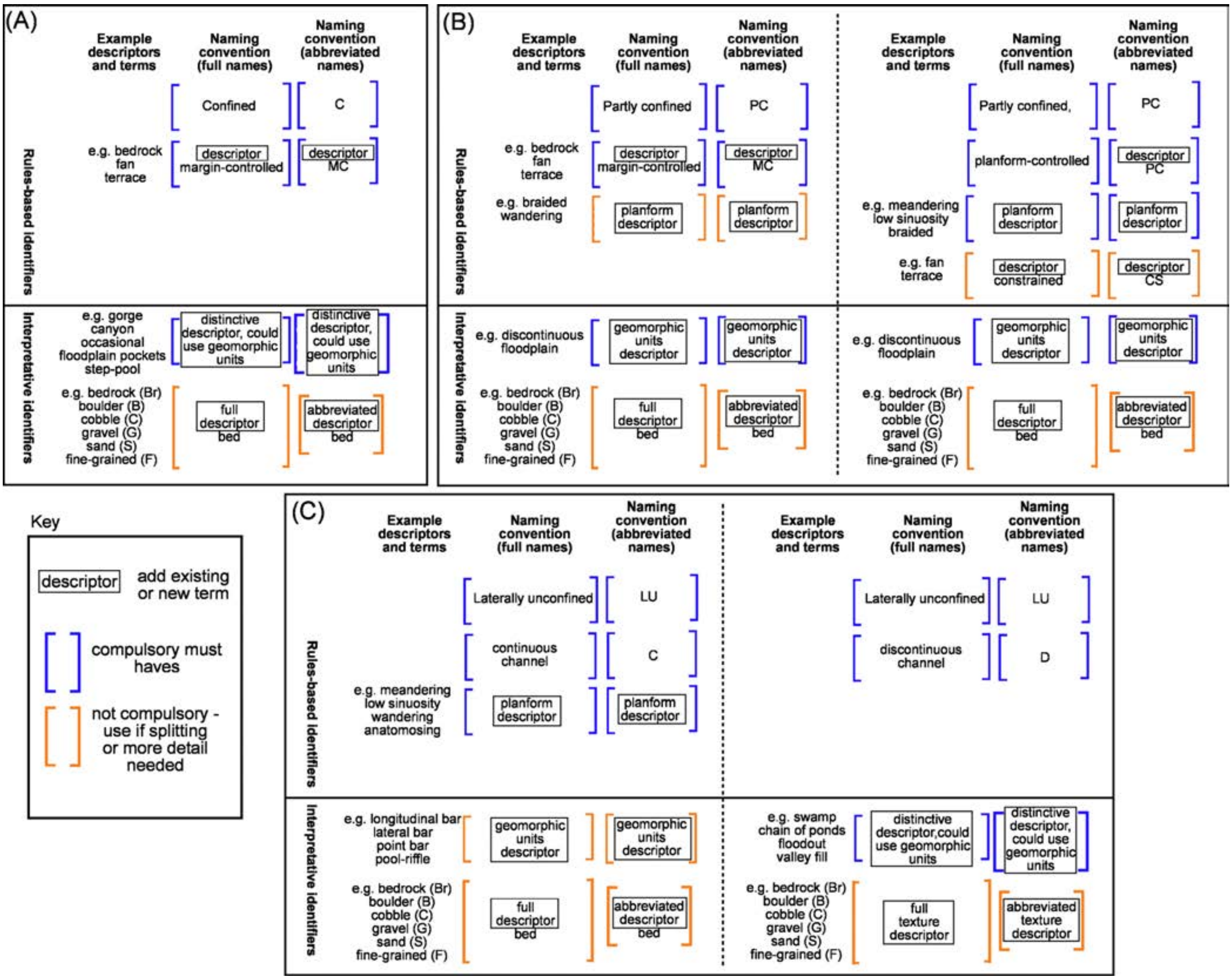


Figure 2-23 *The naming convention used for river types (Fryirs and Brierley, 2018). The approach is matched to the River Styles procedural tree (Figure 3.3) and produces full and abbreviated names; A) for confined valley setting, B) for partly confined valley setting and C) for laterally unconfined valley setting.*

2.6 Synthesis

The GIS tools outlined in the preceding sections can be used to develop a holistic picture of catchment-scale river function by layering essential information on network form, land use/land cover, catchment connectivity and river morphology. Dynamic simulations can offer further insights into potential hotspot behaviour and cumulative effects within the catchment.

Flow Direction and Connectivity Routing is firstly required to establish network pathways, and upstream accumulation area. This provides an important interface for querying river characteristics and applying numerical methods, from relatively simple assessments of discharge to more complex simulations of sediment dispersal pathways through a river network, for instance. TauDEM (Tarboton, 2016) is a robust and well-used application for this, that is available on a large number of platforms, including ESRI's ArcMap products.

River Long Profile Analysis is an essential first step in determining the energy gradient of the fluvial system and interpreting the influence of factors such as tributary junctions, geologic structure, tectonic forcing, glaciation, volcanism or base-level factors such as estuarine or coastal dynamics. TopoToolbox (Schwangart and Scherler, 2014) offers a large suite of tools for rapidly assessing both longitudinal and planform influences on river evolution.

Connectivity Maps help the analyst to understand and assess the effectiveness of the many drainage paths in the catchment, and the implications of changing land use or land cover. Our application of this tool in this work is specifically focused on recruitment of sediment from the landscape (following Borselli *et al.*, 2008), but the nature of the GIS analysis is general enough that it could be used for addressing the connectivity of any quantity: e.g., nutrients, contaminants, or organic material. It is simply a matter of tuning the land cover variables to some appropriate value, representing the likelihood of material recruitment.

Dynamic Simulation is used to determine the response characteristics of the river network, under the influence of some idealised disturbance over time. Network models such as Czuba's (2014) River Network Bed Material Sediment, Schmitt's (2016) CASCADE or Gilbert and Wilcox's (2020) SeRFE may offer important insights into cumulative network response.

Finally, ***River Styles Classification*** is a resource for systematically mapping channel morphology in a consistent manner, that can be compared across the network or across the region. Given the established information base on flow paths, energy gradient and connectivity, a coherent picture of river function emerges. The final stages of the River Styles technique involve an assessment of river trajectory: given the longitudinal sequencing of river forms, the various observed influences on the system, and historic trends of change, *what is the most likely evolutionary path of this river*?

This conversation is meant to be a collaborative work amongst stakeholders, managers and technical specialists. Once a common understanding of river evolution is reached, it is possible to develop a course of action that can support conservation efforts, optimise resources for rehabilitation work, target monitoring efforts, and set goals for desired change in the system. Ongoing discussions, visioning and modelling work can be used to manage ongoing efforts. The syntheses presented for the three Ngā Awa rivers presented below are largely starting points for what will be much larger, collaborative efforts.

3. Study Catchment Analysis

In the following examination of three study catchments, we use ArcGIS, TopoToolbox and the study area DEM to firstly trace the drainage network and then examine longitudinal trends of bed elevation, bed slope, the upstream accumulation area and the river stream power, which is the product of discharge, Q, and along-channel slope (S, m·m^{-1}): $\Omega=\rho \cdot g \cdot Q \cdot S$. Assuming that discharge scales approximately with catchment area ($Q \approx A^{0.8}$, e.g. Knighton, 1999), we use upstream catchment area as a proxy for the relative magnitude of discharge. Next, we use the *maplateral* function in TopoToolbox to visualise longitudinal changes in the maximum height of topography adjacent to the channel at a given offset. Collectively, these plots provide a picture of the river's energy gradient, and its capacity for dynamic adjustment. This helps us to refine the classification of the river system, while providing insight into the factors that sustain the river forms that we observe.

Next, we use Borselli *et al.*'s (2008) proposed workflow (via ArcGIS toolbox) to generate a map of catchment connectivity. We have employed the suggested parameters for the various landuse/land cover classes in the LUCAS dataset, but more sophisticated analysis could refine these values further, or generate more detailed mapping of the various landcover classes. These maps typically show a strong contrast between forested and unforested sites, given the high "impedance" weighting attributed to this category by the original authors. But if indeed forest cover reduces sediment production and transfer by an order of magnitude (or perhaps several), this is an important first-order control on connectivity, and we can expect to see strongly differing behaviours amongst these landcover classes.

The connectivity analysis is complemented by results from running Czuba and Foufoula-Georgiou's (2014) Network-Based Bed-Material Sediment code. By dynamically simulating the passage of discrete 'parcels' of sediment through the network, based on bed slope and flood discharge estimates, model results reveal 'hotspots' within the catchment, where the strong convergence of multiple parcels points to sites that may undergo dynamic adjustment over time.

Following the connectivity analysis, the components are assembled to generate a map of River Styles within the catchment, with a legend indicating the observed river types in the study river network.

3.1 Mahurangi Stream

Physiographic Setting

The Mahurangi River is a relatively small catchment (~76 km²) that is surrounded by hill country of subdued relief. The southeastern portion of the Mahurangi has experienced relative tectonic subsidence, leading to a 'drowned' river mouth, and substantial sedimentary filling of the deeply incised lower valley. The upper estuary is a 6.4 km-long tidal creek between Warkworth and Hamilton's Landing, bordered by dense stands of mangrove. Low-gradient intertidal flats lead out to the sheltered Mahurangi Harbour; these flats occupy roughly ~55% of its high tide area (Swales *et al.* 1997). A number of tidal creeks empty into this embayment as well. Given the sheltered setting of the outlet, there is relatively little sediment influx from longshore coastal processes. Sediment accumulation rates are estimated to be approximately 15-20 $mm \cdot y^{-1}$ in the upper estuary and 2-5 $mm \cdot y^{-1}$ in the rest of the harbour (see Trotter, 1990; Harris, 1993; Swales *et al.*, 1997).

The catchment has been heavily impacted by agriculture, forestry and urban development. Some remnant (~19 km²) native forest and about 12 km² of plantation forest cover the uppermost catchment areas. A little over half the catchment (40 km²) is cropland and grassland with various agricultural usages.

The hydrological and sedimentary connectivity of the system has been strongly altered, with roughly 50 culverts, 20 bridges and at least 2 km² of impervious surface (Auckland Council GIS data, 2017). The Puhoi to Warkworth expressway now cuts across five large streams, piping them through 100 m-long culverts as they pass under the highway embankment. Stormwater is highly managed, with nearly 10 km of pipes and drains to effectively route storm runoff to the river system. Regular wastewater-stormwater overflows occur in parts of the city (Auckland Council, Carapiet, 2011).

It is estimated that annual average sediment generation in the catchment may vary from 8,661 to 52,270 $t \cdot y^{-1}$ depending on where in the catchment sediment is being generated and which model is used to estimate these amounts. The corresponding specific sediment yield reported is 75 to 448 $t \cdot km^{-2} \cdot y^{-1}$ (Temple and Parsonson, 2014).

Restoration Aims

The Mahurangi Action Plan (MAP) is a collective effort amongst the community, tangata whenua, Auckland Council (AC) and the Rodney District Council (RDC). It has been underway since 2004. The MAP was introduced as a proactive response by AC and RDC to reduce sediment entering Mahurangi waterways, primarily through working with private landowners on best practice land management (e.g., fencing and riparian planting along waterways) as well as educational programmes. Focus has been centred primarily on Mahurangi Harbour as it is a significant asset for commercial activities such as aquaculture, fishing and tourism. It is also widely used for recreational activities by locals and visitors.

Ngati Whatua, Ngati Manuhiri and Ngati Paoa representatives have been involved with Auckland Council and its predecessors to help define their traditional and customary relationships with the catchment. These relationships help to sustain the mauri of the harbour and in turn the mauri of the people (Auckland Council, 2004).

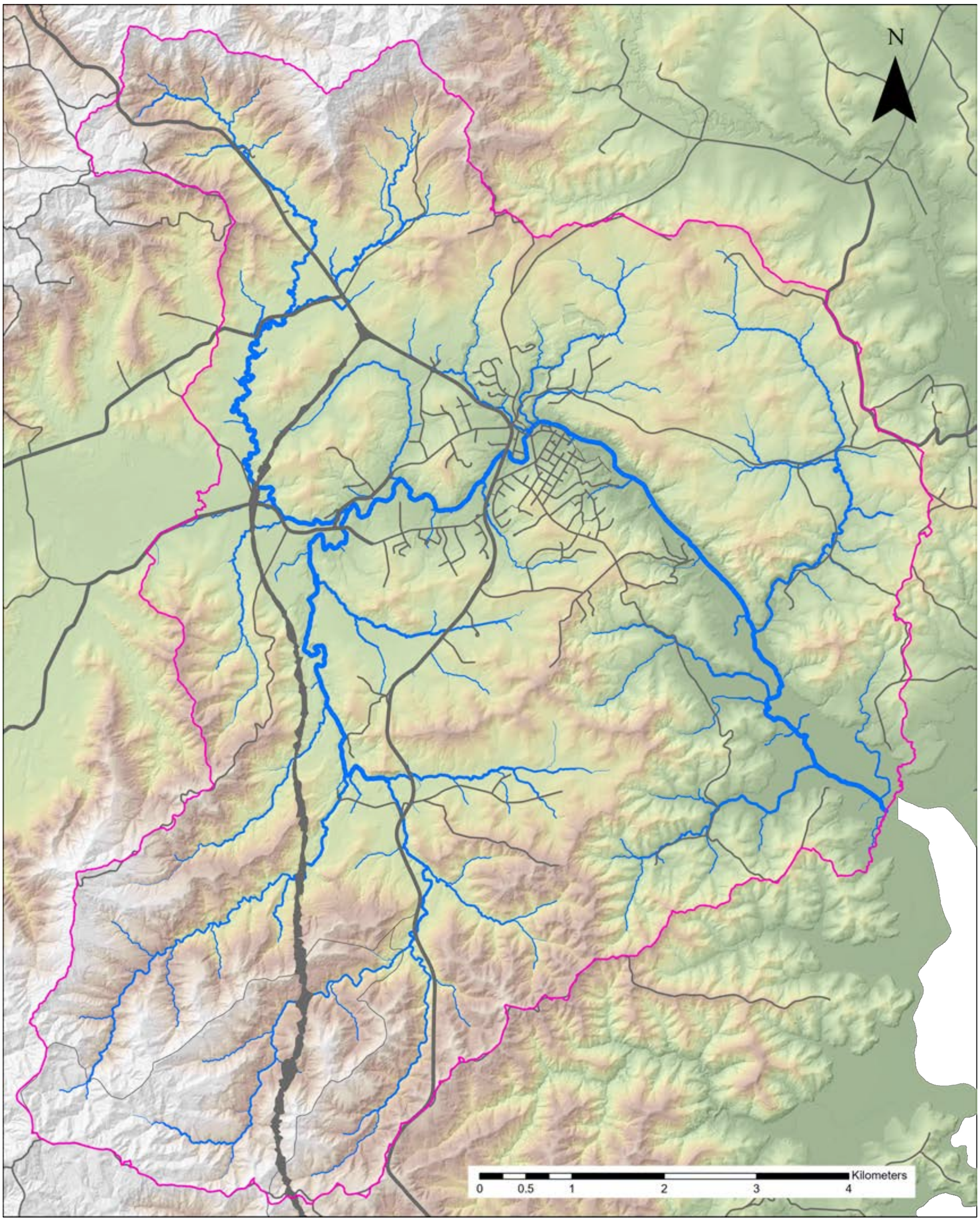


Figure 3-24 *Topographic map of the Mahurangi catchment, based on Auckland Council LiDAR survey (2013).*

Climate and Flooding

Most sedimentation in estuaries occurs during episodic floods that may last a few hours and happen perhaps only several times each year. In the Mahurangi catchment, a single flood in May 1985 delivered 75% of the estimated 20-year annual average sediment runoff to the estuary (Swales *et al.*, 2003).

The contemporary annual hydrograph time series (2009 onward) from gauging station 6863 (behind Mahurangi College) is relatively short at this point, but it provides a sense of the relative magnitude of more recent flows within the catchment. High flows occur fairly consistently in the late May-early September time frame. The wettest period on record was May 1985 and the driest was March 2013 (Figure 3-25; LAWA, 2021).

The highest annual peak flows, determined from measurements at 15-minute intervals, are ranked in Figure 3-26. The merging of two different monitoring epochs (1983-1999 and 2009-2020) does not reveal markedly different characteristics, with both showing a steepening of the relationship for higher flows - at least when plotted using the Gumbel distribution. The graph shows the record high flow was in 1985; there is no evident pattern of higher flows occurring in the latter monitoring period.

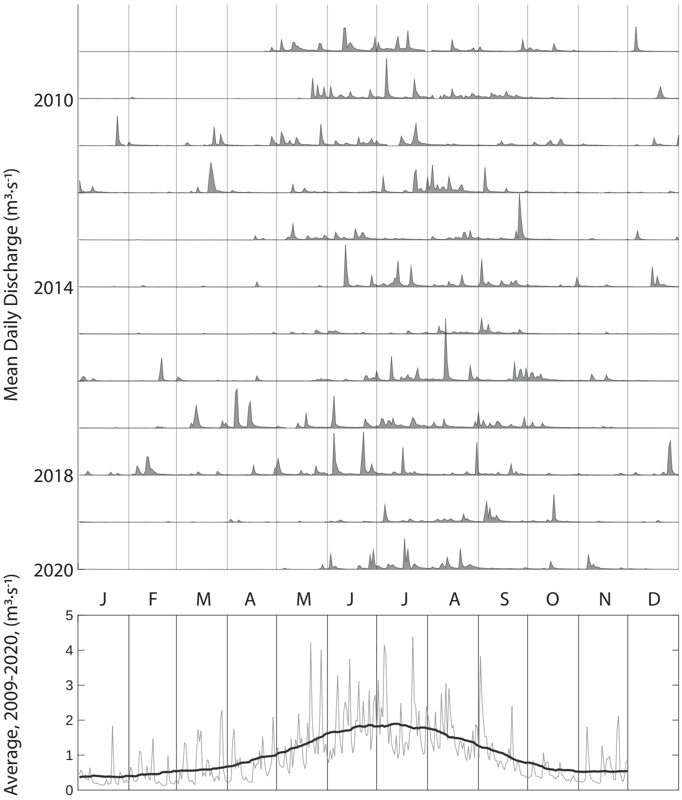


Figure 3-25 *Hydrograph time series for Mahurangi River at College@Argonaut, 2009-2020 shows the distribution of flows throughout the year over the more recent monitoring record.*

The MARVEX study (1997-2001; Woods *et al.*, 2001) used a network of 28 stream gauges and 13 rain gauges to provide a highly detailed pictured of river response to rainfall. It was found that soils in the catchment have water residence times of at least several months to a few years. The largest proportion of streamflow is thought to originate as baseflow from soil and regolith reservoirs that may be several metres to perhaps several tens of metres deep. During dry summer periods, it is more difficult to model and predict peak flows owing to a complex distribution of source areas (Bowden *et al.*, 2000). In winter, there is a greater proportion of direct runoff from rainfall events. The balance of groundwater contribution versus 'quickflow' - direct runoff via surface and uppermost soil layers - may account for the discernibly steeper relation evident among very high flows in Figure 3-26.

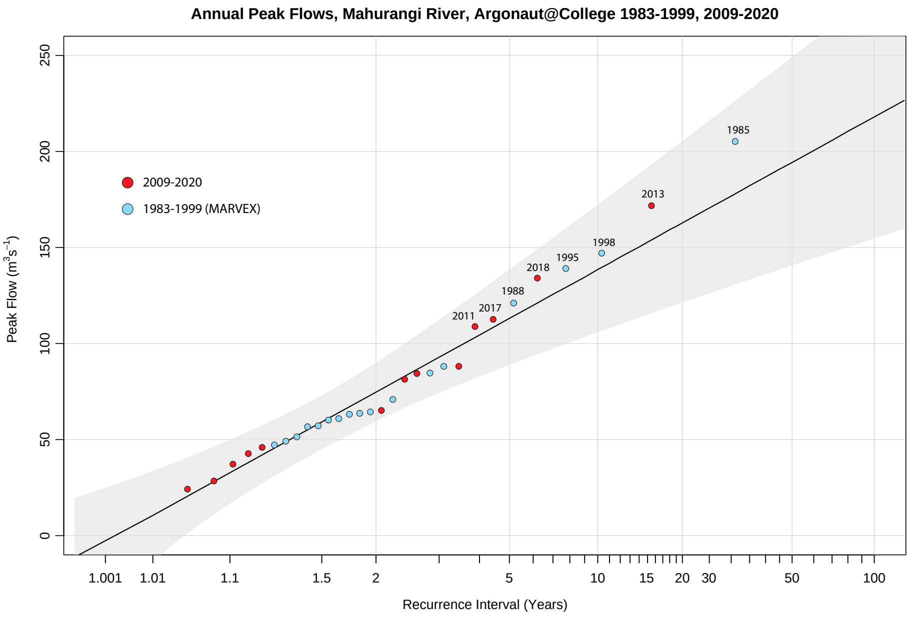


Figure 3-26 *Peak flows (15-min intervals) for the Mahurangi, plotted as recurrence intervals on a Gumbel distribution. Two different datasets from the lower river are combined, here: data from MARVEX monitoring (Woods et al., 2001) and more recent Auckland Council records.*

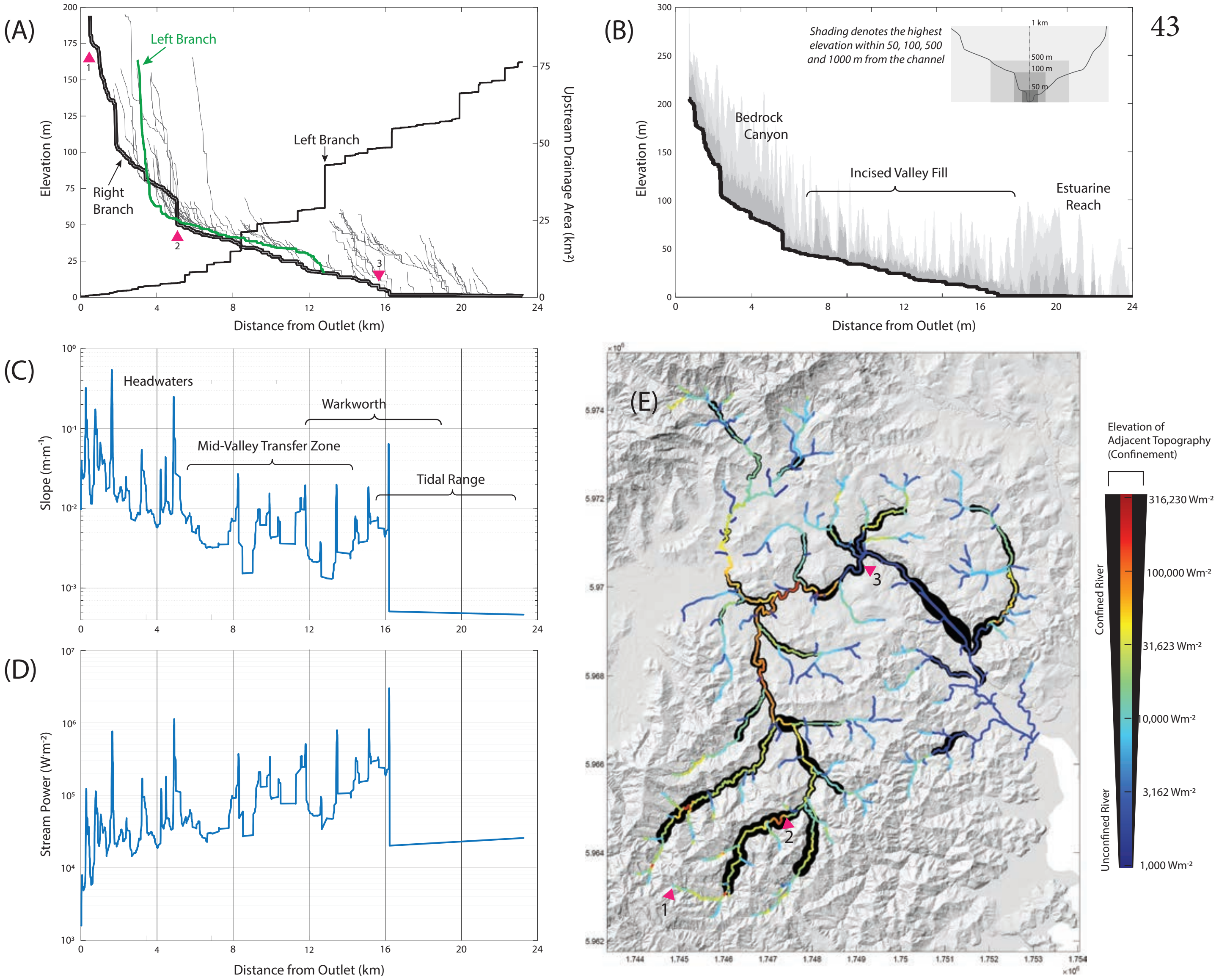


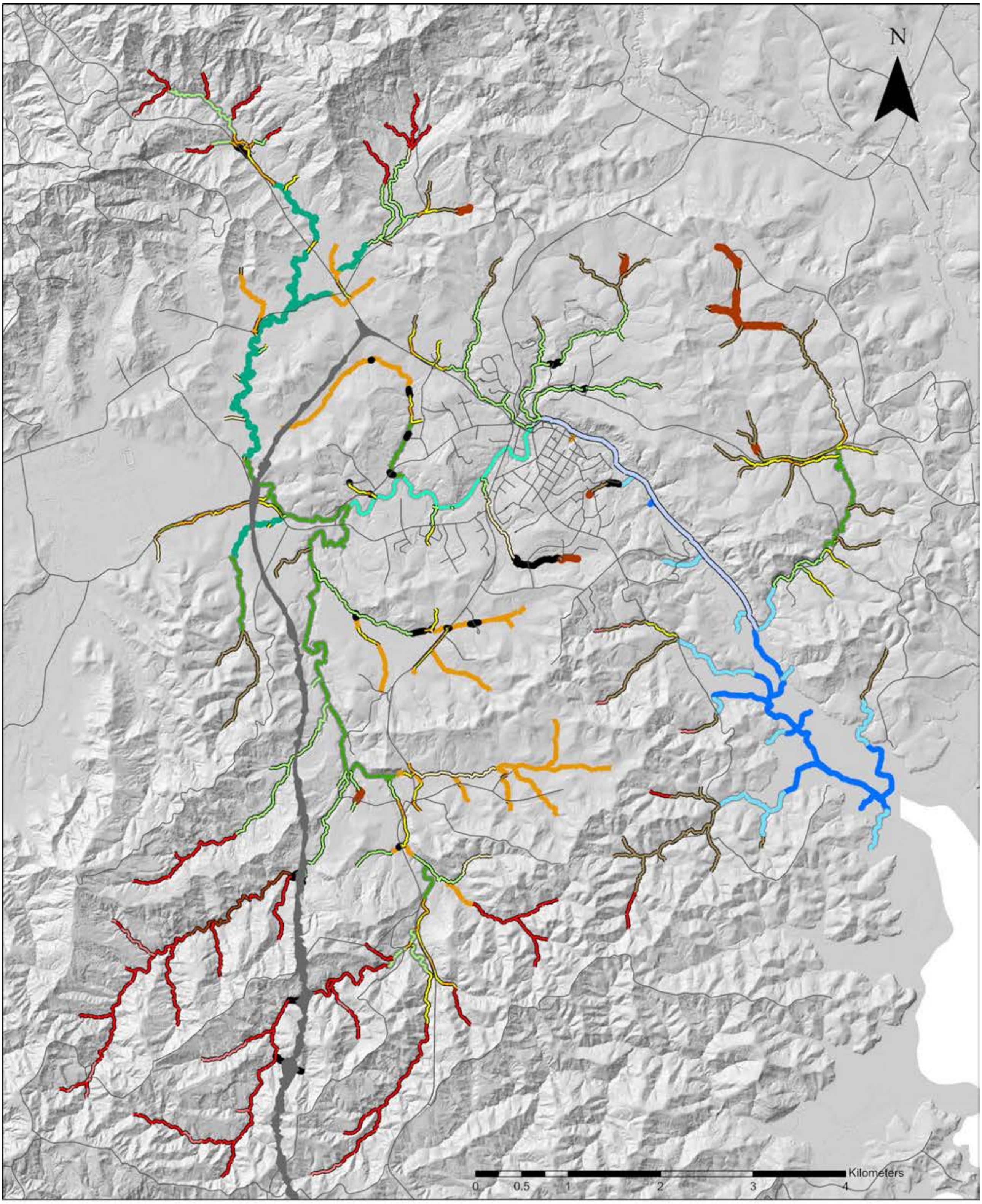
Figure 3-27 *The TopoToolbox analysis of the Mahurangi River. (A) Longitudinal profile of the bed elevation in the Mahurangi Right Branch and its major tributaries, as well as the cumulative upstream catchment area. (B) Valley confinement along the mainstem. (C) Longitudinal profile of bed slope along the river. (D) profile of stream power, the product of channel slope and upstream catchment area (a proxy for river discharge). (E) A combined picture of stream power and confinement: many reaches with relatively high stream power are confined by bedrock boundaries. High stream power combined with low confinement may signal sites that are predisposed to change, although closer analysis is necessary to properly assess this.*

Stream Power and Longitudinal Profiles

The long profile of the catchment (Figure 3-27A, B) reveals at least four major segments, from the flat tidal reach to the incised valley fill to steeper confined valleys, and finally the uppermost first-order drainages. A number of the steeper 2nd-3rd order streams have sharp breaks in the long profile, from cascades or waterfall sections. The stream power profile indicates a few sharp peaks at the cascade sections, but overall the stream power trends towards the highest values in the lowermost reaches, just above the transition to the estuary channel. The river is relatively confined throughout these lower reaches, emphasising the high transfer capacity of the system for fine grained loads, with relatively limited opportunity for channel evolution or deposition of the load.

River Styles

River Setting	Margin Control	Channel Gradient	Geomorphic Units	Bed Material (est.)	River Behaviour
Cascade, Step-Pool Channels.	Bedrock	High	Cascades, Step-Pool, Waterfalls	Coarse grained: boulder, cobble, gravel	Relatively little lateral adjustment, but in-channel components (boulders, clusters, riffles) can be dynamic.
Headwaters with vegetation, organic fill	Bedrock, terrace, colluvium, embankment	High	Ditches, swales, channelised fill	Mixed load	Low dynamism.
Unconfined, meandering river	Minor incision into the valley fill	Low-Med	Continuous channel; some sculpted bar forms	Mixed load	Incised, some meandering behaviour, but not very dynamic.
Terrace margin confined	Valley Fill	Med	Passive meandering channel.	Mixed load	Deeply incised; Moderate gradient and some potential for dynamic adjustment
Modified waterways	Embankment, Roads	Med	Ditches, canals, low-sinuosity meandering	Mainly fine materials, but a mix of transient washload	No dynamism.
Culverts	Concrete	Low-Med	None	Generally fine-grained	No dynamism
Impounded channels	Embankment	Low-Med	Ponds, stagnant pools.	Fine grained	No dynamism
Tidally-influenced lowland rivers	Bedrock; Confined to partly confined	Low	Low sinuosity, tidal.	Fine grained	Occasional reconfiguration, but strongly governed by mangrove and bedrock boundary



Mahurangi River
River Styles Categorisation

Notes:
- Based on LiDAR
- No Ground Checking
- Preliminary assessment
- See text for more details

FIGURE 3-28 *RIVER STYLES MAP*

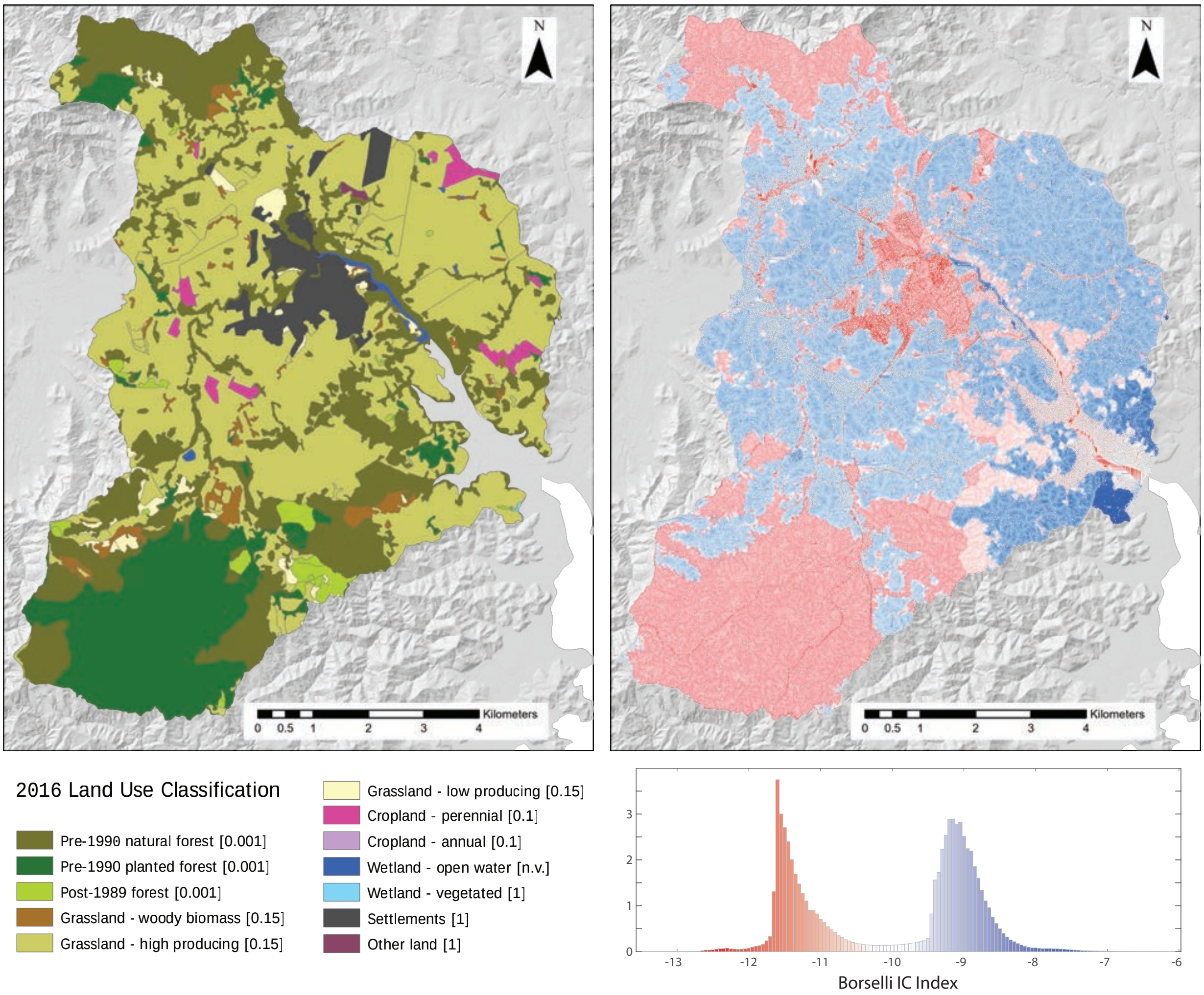


Figure 3-29 *Borselli et al's (2008) Connectivity Index, weighted by landuse/landcover class (LUCAS). The connectivity map highlights the different connectivity domains within the catchment, from the forested headwaters to the highly connected lowland, urban and tidal river reaches (see text). This mapping is indicative of how the IC index can be applied: more detailed parameterisation and modelling is required to use this tool for conservation purposes. The map does not include the new Puhoi-Warkworth Expressway, which has recently altered terrestrial and aquatic connective pathways in the southernmost headwaters of the catchment (Figure 3-32).*

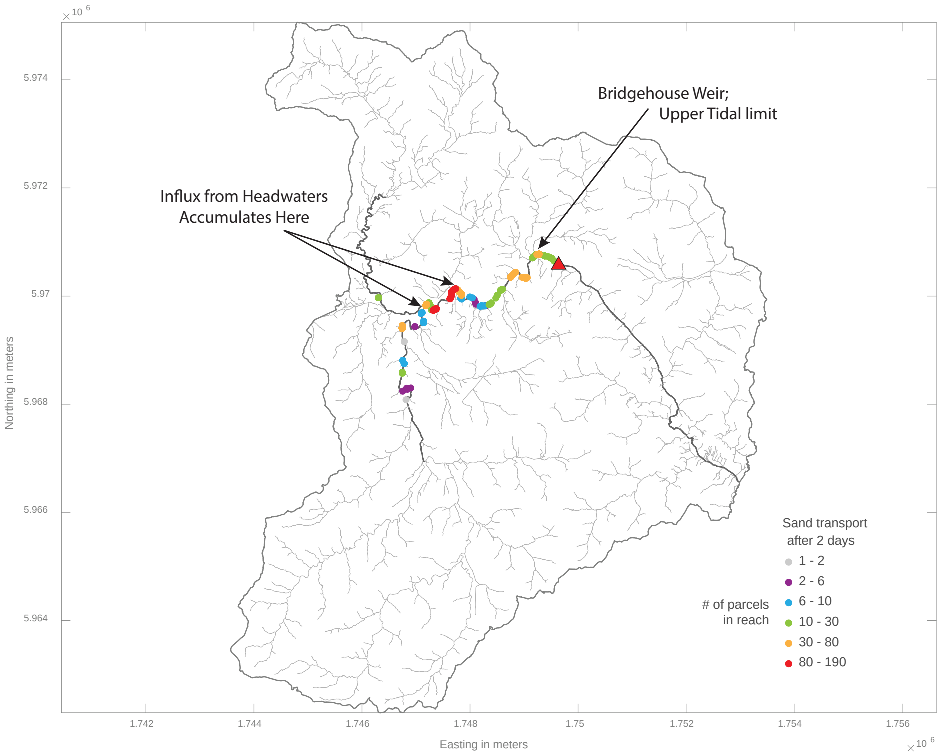


Figure 3-30 *Output from Czuba et al's (2014) model shows the clustering of sand 'parcels' near the confluence of the major upland catchments, the northern left branch and the southern right branch of the Mahurangi. Sediment moves through the incised mainstem channel to the limit of tidal influence at Bridgehouse Weir. This has a strong correspondence with the site of high stream power in Fig 2-15E. The model helps to highlight which sites may hold potential for dynamic river adjustment, and thus may respond to rehabilitation efforts.*

Sediment Connectivity

The connectivity map of the Mahurangi (Figure 3-29) reveals first-order contrast between the forested headwaters, stock/agricultural fields, and the urban centre. The forested headwaters show low connectivity, indicative of the remote setting and longer distances to the mainstem river. The urban centre indicates low connectivity as well, though for a different reason - paved surfaces are assumed to yield little sediment. There are at least four connectivity zones that emerge:

(1) Forested headwaters: the left branch rises within the Dome Valley forest to the north, and the Redwood forest covers the headwaters of the Right Branch. The Redwood Forest has approximately 16.3 km^2 of plantation forestry that may be due for harvest in the near future. Clearly this would alter the sediment connectivity characteristics of this zone.
(2) Peri-urban uplands: cleared stock and agricultural land. Drainage pathways are highly modified, straightened and dammed at numerous points. Many waterways have no riparian margin, and livestock is only partly excluded from access (FULSS, 2017).
(3) The lowland river corridor. River slope is ~0.004. The river has incised deeply (15-20 m) into the valley fill, and so follows the meandering course without significantly shaping the planform channel morphology.
(4) The urban centre occupies most of the lower catchment, surrounding and separating the river from lateral linkages. The river has no floodplain here.

The river network itself has a number of barriers to sediment and ecological connectivity. There are waterfalls and cascades within the catchment that may inhibit migration of some aquatic species. There are numerous river crossings, and two major sections of the Right Branch have been culverted, with major embankments now filling the valley.

Figure 3-31 ***Longitudinal connectivity entails connection along the river between upper and lower portions of the catchment. Waterfalls such as the Pohuehue Falls may inhibit upstream fish migration, but can effectively convey sediment and organic materials downstream. There is also good lateral connectivity from the riparian areas.***

Figure 3-32 ***At left, a major headwater reach (5.4 km^2 source zone upstream) of the Mahurangi is one of two tributaries that have been buried under the Puhoi-Warkworth Expressway. Instead of a bridge (viaduct) that would retain many of the natural features and much of waterway connectivity, this system comprises three 130 m long culverts. Barriers such as culverts strongly inhibit lateral and longitudinal connectivity, and any potential for local river evolution.***

The river trajectory

The Mahurangi River has been subjected to numerous cumulative impacts from the collective effects of urbanisation, farming and forestry. In order to carry out effective restoration work in the catchment, a coordinated plan is required. The nested nature of river ecosystems implies that patch- to segment-scale restoration attempts may be destined to fail in extensively developed catchments (Wohl *et al.*, 2015; Berhardt and Palmer, 2011; Holmes, 2019)

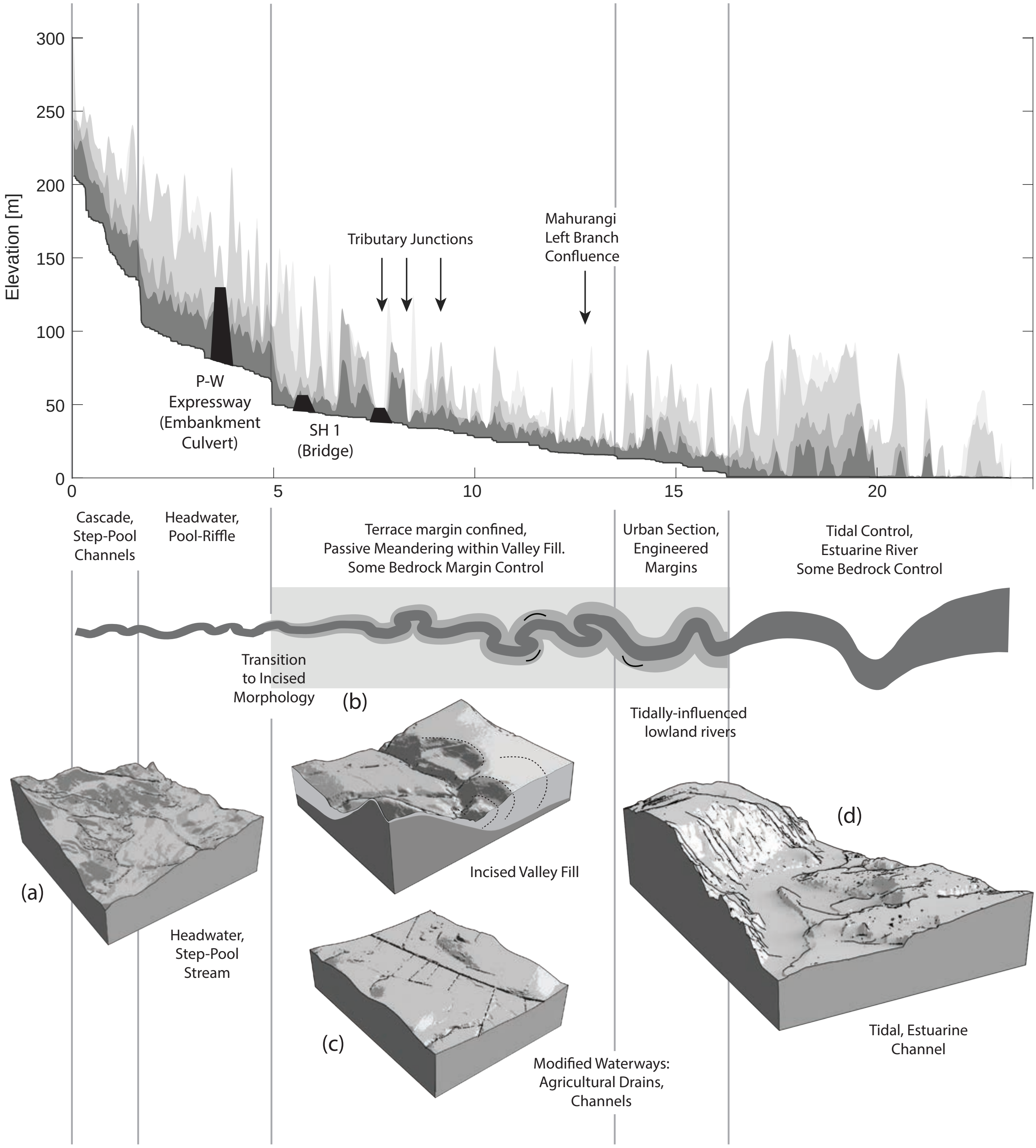


Figure 3-33 ***Longitudinal arrangement of channel types within the Mahurangi system. Based on the Right Branch, but also loosely applicable to the Left Branch. The river emerges from bedrock-confined headwater setting that includes a number of cascades and water falls, to flow through the incised channel that cuts through the fine-grained valley fill. Several tributaries join the mainstem, including some flows from modified waterways: canals draining stock and agricultural fields. After passing through the urban centre, the river emerges in a confined to partly-confined tidal channel.***

Many of the headwaters reaches are highly disturbed, either from modification for stock and agriculture, by forest clear-cutting, or through burial by recent expressway construction. Stroud (2003) pointed to sub catchments bordering the Mahurangi estuary, particularly Te Kapa Inlet, Pukapuka Inlet, and West Mahurangi as being important sediment sources due to extensive pastoral land use, strongly rolling to steep slopes, and soil types that have low infiltration capacity.

The collective effects from these impacts are difficult to mitigate, owing to vegetation clearance and the interruption of self-regulating channel processes, tipping of Lane's balance (Figure 1-2) in favour of greater runoff with no compensating accrual of bed material or hydraulic roughness. Where these rivers can be afforded a buffer of vegetative riparian growth, some ecological function may be restored. Continued modification and perturbation of headwater and upland rivers will thwart any attempts at recovery in the lower river and estuary.

The incised valley fill is relatively fine-grained, and the river here is potentially subject to bank failure by slumping and cantilevered failure after undercutting (Figure 3-33b). Distinctive arcuate (bow-shaped) erosional faces immediately adjacent to the channel are indicators of past sites of failure at the riverbank margins. These features may signal progressive long-term incision of the fill, and thus may be sites of significant sediment mobilisation. These reaches should be prioritised for protective planting and rehabilitation. The river here is lined with a fairly continuous margin of tree cover; this margin should be extended where possible to enhance bank stability and reduce the possibility of propagating knickpoints as the bed adjusts its gradient in response to bed incision. Knickpoints are distinct, local changes in stream bed gradient that tend to migrate upstream via erosion, releasing sediment in the process.

The river is highly charged with runoff during storm events owing to the greatly enhanced drainage across the catchment, and direct runoff conveyance from canals and drains to the river (Figure 3-33c). Erosion and further entrenchment of the fill may be eased by expanding wetland cover across the catchment to create buffer storage for high flow events (with multiple co-benefits from ecosystem services such as habitat diversity and carbon sequestration (Clarkson *et al.,* 2013). Any storage zones for surface water will help to moderate the intensity of peak storm runoff. These events are primarily responsible for sediment delivery to the estuary (*cf*. 1985 storm, above). Any measures to curb this process will pay important dividends towards restoring healthy estuarine conditions.

Current climate change predictions for the region are for decreased river flows (Collins *et al*., 2018, see Section 4) and therefore decreased water conveyance through the system may increase ecological resilience to climate change. With reduced flows, erosion mitigation through drought-resistant plantings may be quite effective at reducing sediment transport downstream.

Recovery of systems such as the Mahurangi are difficult, as the system has changed so markedly from its natural condition, and the forecasted growth for the area suggests that pressures on the available land and water will continue. Developing a clear vision for the restoration of the catchment (i.e., deciding what goals are prioritised) will be critical to strategically directing effort into effective solutions (Wohl *et al*., 2015).

3.2 Pelorus/Te Hoiere River

Physiographic Setting

The Pelorus/Te Hoiere catchment lies between Blenheim and Nelson, in the northern part of Marlborough (Figure 3-34). The catchment extends over approximately 890 km², with the inclusion of the Rai (to the northeast) and Whakamarino (to the southeast; previously Wakamarina) catchments. The Pelorus/Te Hoiere discharges into the Havelock estuary and Pelorus Sound. The Te Hoiere mainstem and the Whakamarino drain the northern side of the Richmond Ranges, while the Rai rises in the Bryant range to the northeast.

The Marlborough landscape evolved by drainage rearrangement from mountain uplift, strike-slip faulting and the headward erosion of mainstem rivers during the Kaikoura Orogeny, some 25 million years ago. The bedrock is predominantly Mesozoic siliceous greywackes and schists, with bands of serpentinite greywacke (Walls & Laffan, 1986). Weathering of weaker mineral bands in the schist produces planes of weakness prone to deep and surficial slippage with sediment detritus of characteristically flat (platy) form. Overlying the schist is a layer of hardened sandstones and siltstones as greywacke and argillite atop the Pelorus Group (Lauder, 1987).

Much like the Mahurangi catchment, the river's drainage has been dramatically influenced by differential, subsiding tectonic movement. Prior to the Last Interglacial, it is thought the Pelorus River flowed south, into the Wairau River instead of east and north into Pelorus Sound as it does now. The change in drainage direction reflects northward regional tilting (Mortimer and Wopereis, 1997; Craw *et al.*, 2007). The build-up of a thick (~60 m) sedimentary sequence in the Kaituna and Are Are valleys (to the east) prompted the overtopping of a subsiding drainage divide farther north, in what is now Pelorus Sound. Subsequent erosion through this divide was probably facilitated by shoreline retreat and associated downcutting during sea level high-stands of the Last Interglacial.

In post-glacial time the lower reaches of the modern Te Hoiere developed a substantial valley fill, owing to this relative rise in base level. This fill now provides valuable flat terrain for stock and grazing. Though there is evidence of Holocene meander activity across the fill (scroll plains and abandoned meander loops), the river course has been largely stabilised to accommodate settlements in the valley. Upstream of this (notably at Pelorus Bridge) the channel is confined by prominent bedrock exposures, as well as deep colluvial fills and fans. The river is coarse-grained in the headwaters, transitioning to gravel material for most of its course, and then to sand and fine-grained sediments near the estuary. Indigenous forests, dominated by beech, extend over much of the steeplands and montane areas of Pelorus/Te Hoiere. Exotic forest mostly comprised of radiata pine is the next largest single land use, followed by pasture.

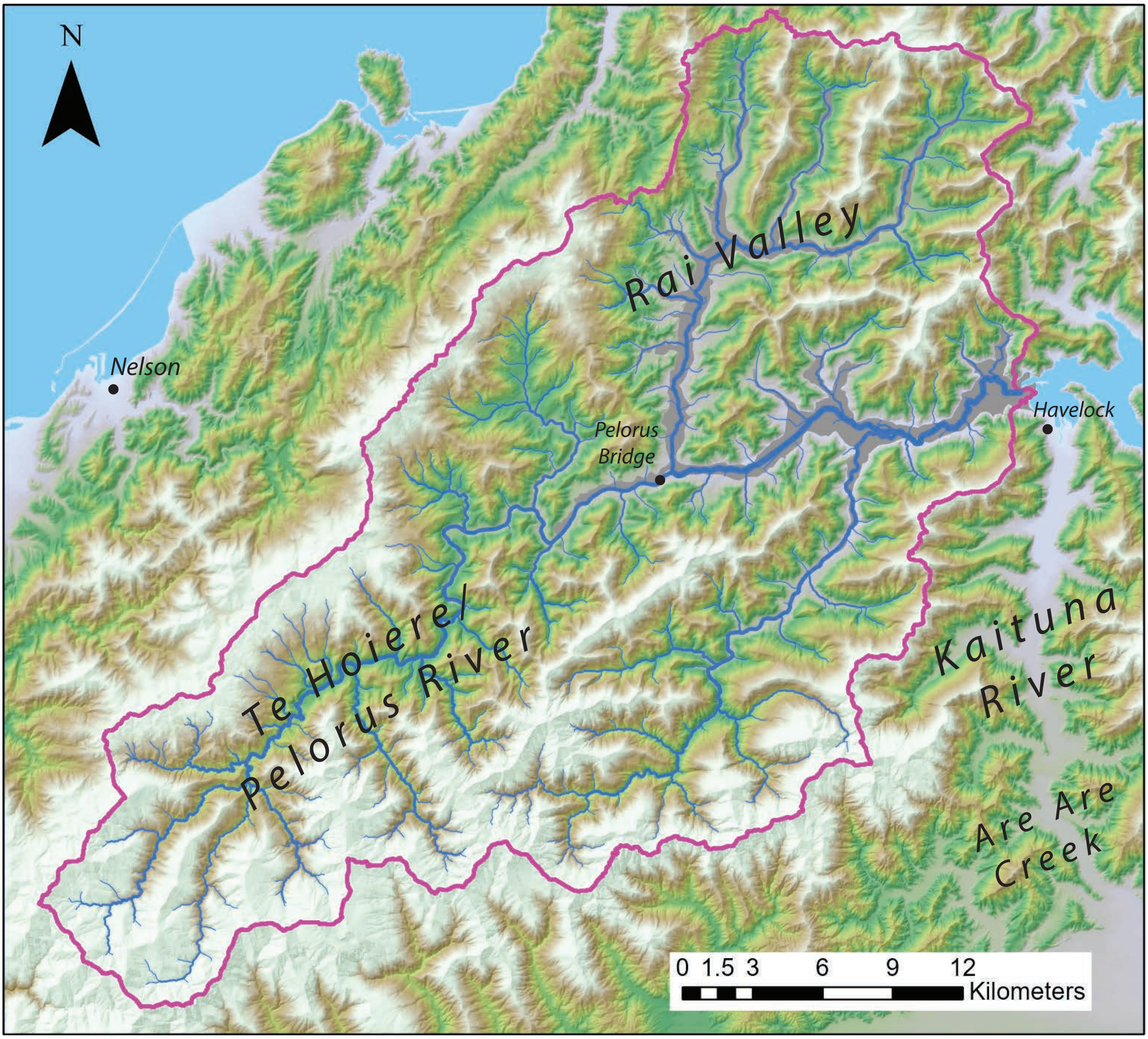


Figure 3-34 *The Te Hoiere/Pelorus River Catchment. Valley slope within the lower Rai and Te Hoiere/Pelorus is graded to a shallow tidal delta at Pelorus Sound; the valley fill is highlighted. Data from the NZ 8m Digital Elevation Model (2012) is used in this analysis; the catchment has yet to be surveyed by LiDAR.*

Restoration Aims

Fine-grained sedimentation from forestry activities have been identified as a primary stressor of estuarine and marine environments in the Marlborough Sounds (Urlich, 2015; Coutts and Urlich, 2020; Bright, 2021). Active, or recently active forestry blocks in the Rai, Wakamarina, and Pelorus are likely to have some impact on sediment regime, even with stringent controls in place (Urlich, 2015) given the steep slopes and proximity to the river. Fine-grained sediments eroded from the land during storm events are washed downstream and deposited in the Motuweka/Havelock estuary, now one of the muddiest in the country (Marldorough District Council, 2020). While indicators for nitrogen, turbidity, and *E. coli* are generally good (LAWA, 2021), there are concerns regarding trends in water quality in the lower river, and remediative works are underway to address this problem (Marldorough District Council, 2020). Given the strong interest in paddling on the river - and tourism potential - there is also a strong economic impetus to maintain high environmental standards in this charismatic waterway.

Climate and Flooding

Annual precipitation in the northern parts of D'Urville Island and outer Pelorus Sound/ Te Hoiere ranges from 1000-1200 mm. Rainfall in excess of 2000 mm occurs in the Bryant Range northeast of Rai Valley, and on the Richmond Ranges to the south of Rai Valley and Canvastown (Tait, 2017). MDC have records of high intensity rainfall events since 1979 in the Pelorus catchment. Historical events include the washing out of the Pelorus Bridge during a major flood in 1904 (Marlborough Express, 1904; Ward, 1987).

The annual hydrograph time series from the gauging station at Bryants (Stn 58902), upstream of Pelorus Bridge (Figure 3-35) shows the distribution of flows over time. A summary of average daily flows across the 42 years of record shows elevated flows in winter, between June and October. The flood of record (2010), however, occurred in December.

A report on the 2010 storm (Gray and Spencer, 2011) emphasises that a defining feature was not the total amount of rainfall that fell over this area, but rather the intensity of the rainfall. Peak rainfall intensities reached 44 mm per hour at Tunakino (on a tributary of the Rai), with over 180 mm recorded in 6 hours, and a total of 254 mm for the event. The most prominent types of erosion reported across the catchment and on a range of land cover types were shallow soil slips, debris avalanches and debris flows.

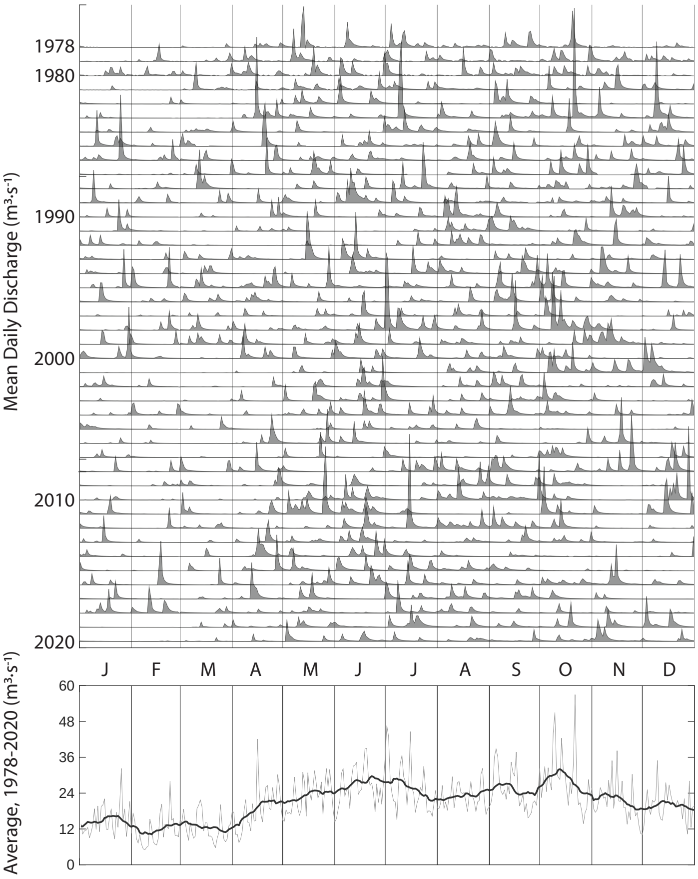


Figure 3-35 *Hydrograph time series for Te Hoiere/Pelrous River at Bryants (Stn 58902) from 1978-2020 shows the distribution of flows throughout the year over the full monitoring record.*

The highest annual peak flows, determined from measurements at 15-minute intervals, are ranked in Figure 3-36. There are three floods from the 2010s, versus two from the 1980s, which is not strongly indicative of intensification of flood peaks in the most recent decades. More in-depth analysis may reveal temporal trends in the intensity and duration of rainfall events, which may provide insight into shifting climate norms.

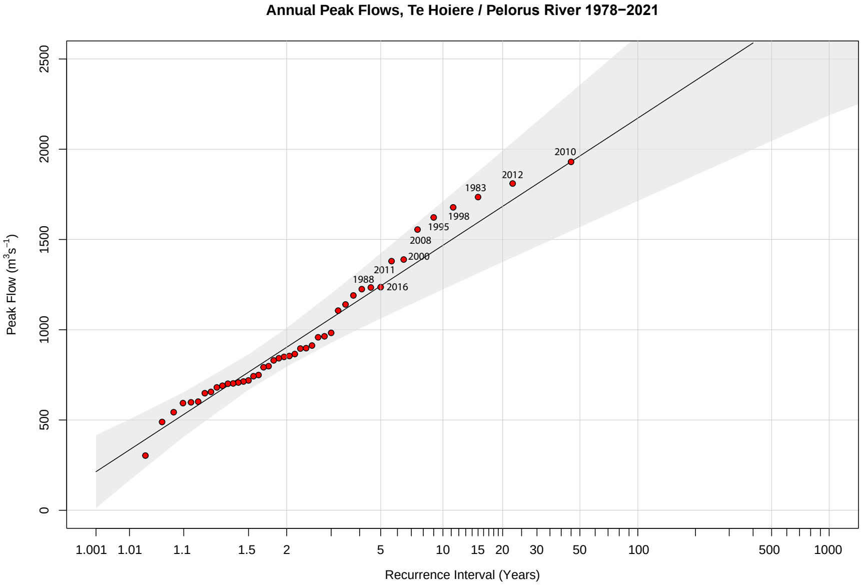


Figure 3-36 *Peak flows for the Te Hoiere/Pelorus River, plotted as recurrence intervals on a Gumbel distribution.*

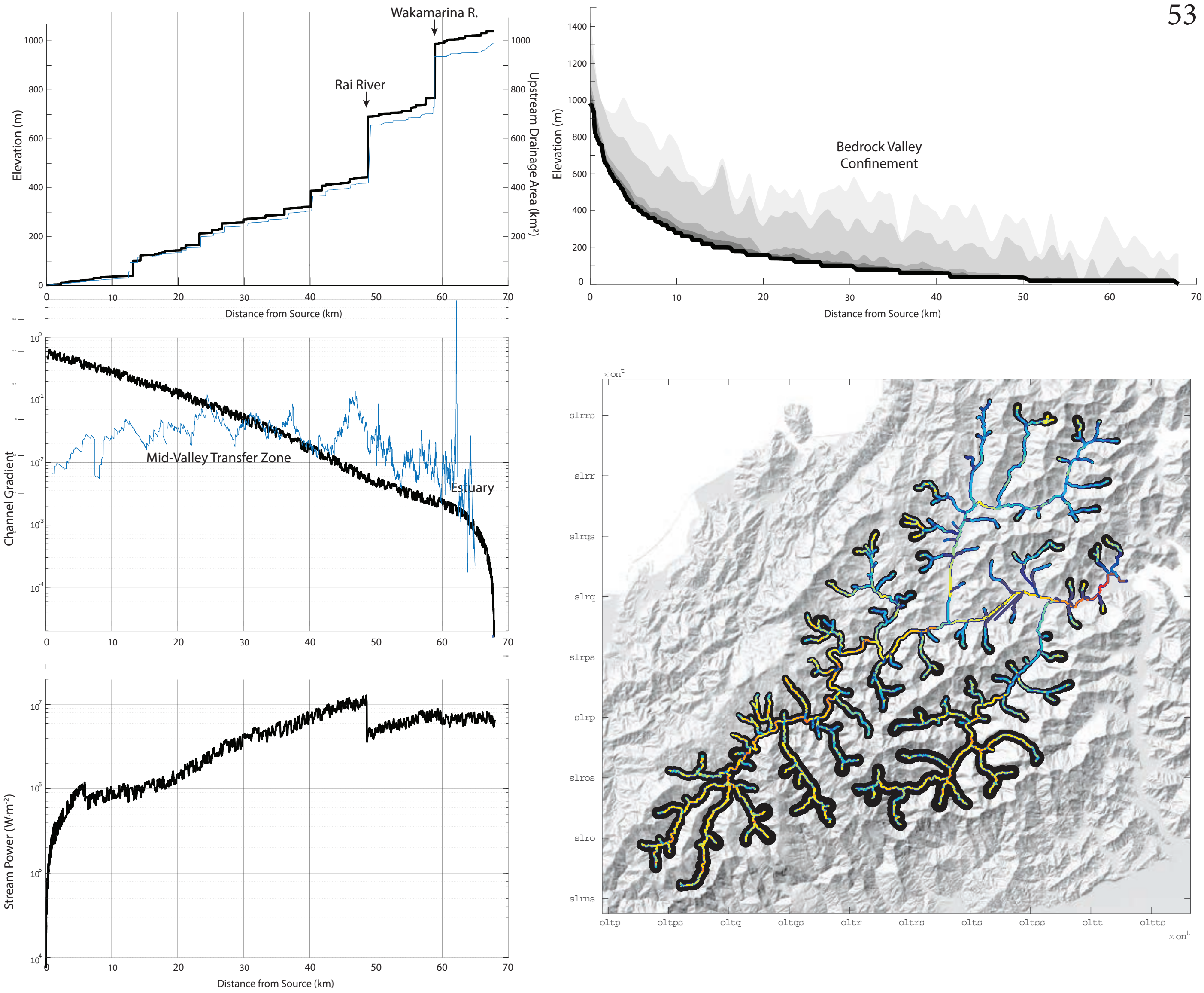


Figure 3-37 The TopoToolbox analysis of the Te Hoiere/Pelorus River. (A) Longitudinal profile of the bed elevation in the river and its major tributaries, as well as the cumulative upstream catchment area. (B) Valley confinement along the mainstem. (C) Longitudinal profile of bed slope along the river. (D) profile of stream power, the product of channel slope and upstream catchment area (a proxy for river discharge). (E) A combined picture of stream power and confinement: many reaches with relatively high stream power are confined by bedrock boundaries. High stream power combined with low confinement may signal sites that may be predisposed to change, although closer analysis is necessary to properly assess this.

Stream Power and Longitudinal Profiles

The first LiDAR dataset for Te Hoiere was flown in early/mid 2020. Analysis of the dataset shows the mainstem channel of the Te Hoiere/Pelorus river is quite evenly graded, suggesting a long-term equilibrium has evolved over post-glacial time, even with the outcropping of bedrock along the profile. While there is high stream power upstream of Pelorus Bridge, and within headwater areas, these sites are largely confined (quite deeply in many cases) by bedrock. This indicates high potential for sediment transfer and delivery from these reaches, but little capacity for morphological adjustment. The Rai valley has relatively low stream power, though there are a few sites, notably in the mid/lower reaches with higher power and evidence of past channel migration and switching. The lowermost, unconfined reaches of the Te Hoiere have relatively low stream power, and thus relatively subdued rates of planform adjustment. This is due to a very low channel gradient; as the river approaches the delta, it becomes somewhat more sinuous, and bifurcates into two channels.

River Styles

The upper catchment shows a full spectrum of mountain river types, from steep (>10% gradient) colluvial channels to step-pool systems and pool-riffle morphologies. There is an evident transition from steep mountain streams to confined rivers with intermittent bedrock bed exposed, to partly confined rivers with discontinuous floodplain.

River morphology within the lower valley reaches of the Rai and Te Hoiere/Pelorus river is predominantly confined to semi-confined, low-sinuosity channel. In the upper portions of the valley, the river is bounded by bedrock as well as deep colluvial fans and aprons. The lowermost trunk stream shows signs of incremental, active meandering in the past, but is currently set within a low sinuosity path along the middle of the valley. Further downstream, the river has a gradient of roughly 0.003 and follows a relatively straight course through the central valley. At a few tighter bends approaching the terminal delta the channel splits into two threads.

River Setting	Margin Control	Channel Gradient	Geomorphic Units	Bed Material (est.)	River Behaviour and Sensitivity
Headwater channels	Bedrock	High	Step-pool, canyon, cascades	Coarse grained	Relatively little lateral adjustment, but in-channel components (boulders, clusters, riffles) can be dynamic.
Confined upland valley	Bedrock confined throughout.	High: 0.01-0.03	Occasional floodplain	Coarse grained	Low planform dynamism, but high transfer potential.
Partly confined, bedrock lined river with colluvial terraces.	Terraces, Fans, Bedrock	Med:~0.001-0.01	Discontinuous Floodplain	Coarse grained	Low planform dynamism, but high transfer potential.
Agricultural drains and ditches	Floodplain alluvium, embankment, riprap.	Low	Low sinuosity anthropogenic channels	Fine grained (pebble to silt range)	Insensitive.
Main Valley	Unconfined, gently sloping colluvial and floodplain margins	Low	Low sinuosity meandering river	Gravel, sand	Generally low dynamism; signs of past meander activity.
Estuarine delta	Unconfined	Low	Sinuous meandering river; bifurcated	Sand, silt	The delta is gradually building out into Pelorus Sound. A network of sinuous channels has evolved within the mangroves.

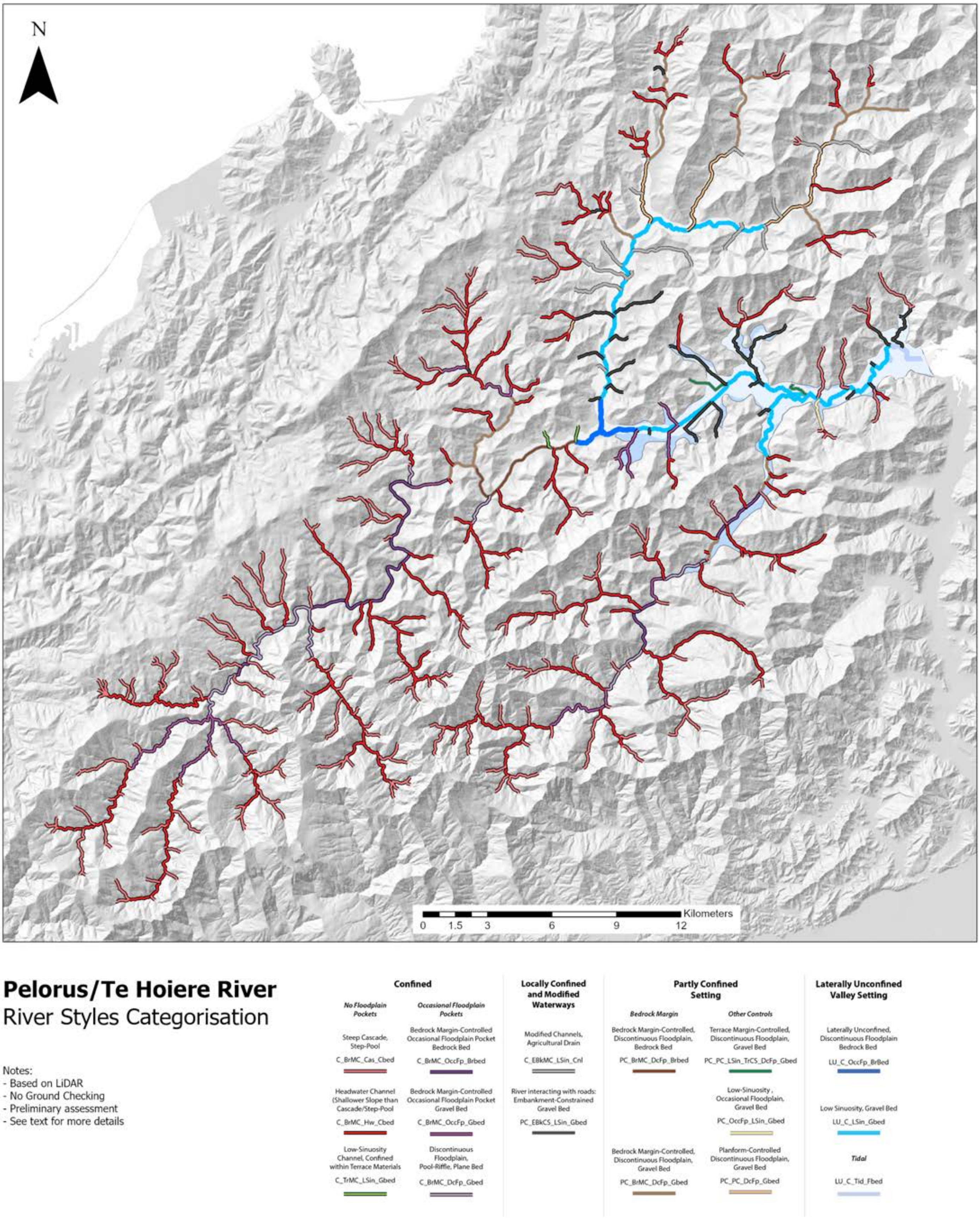


Figure 3-38 *River Styles Map; catchment boundary and valley fill are highlighted.*

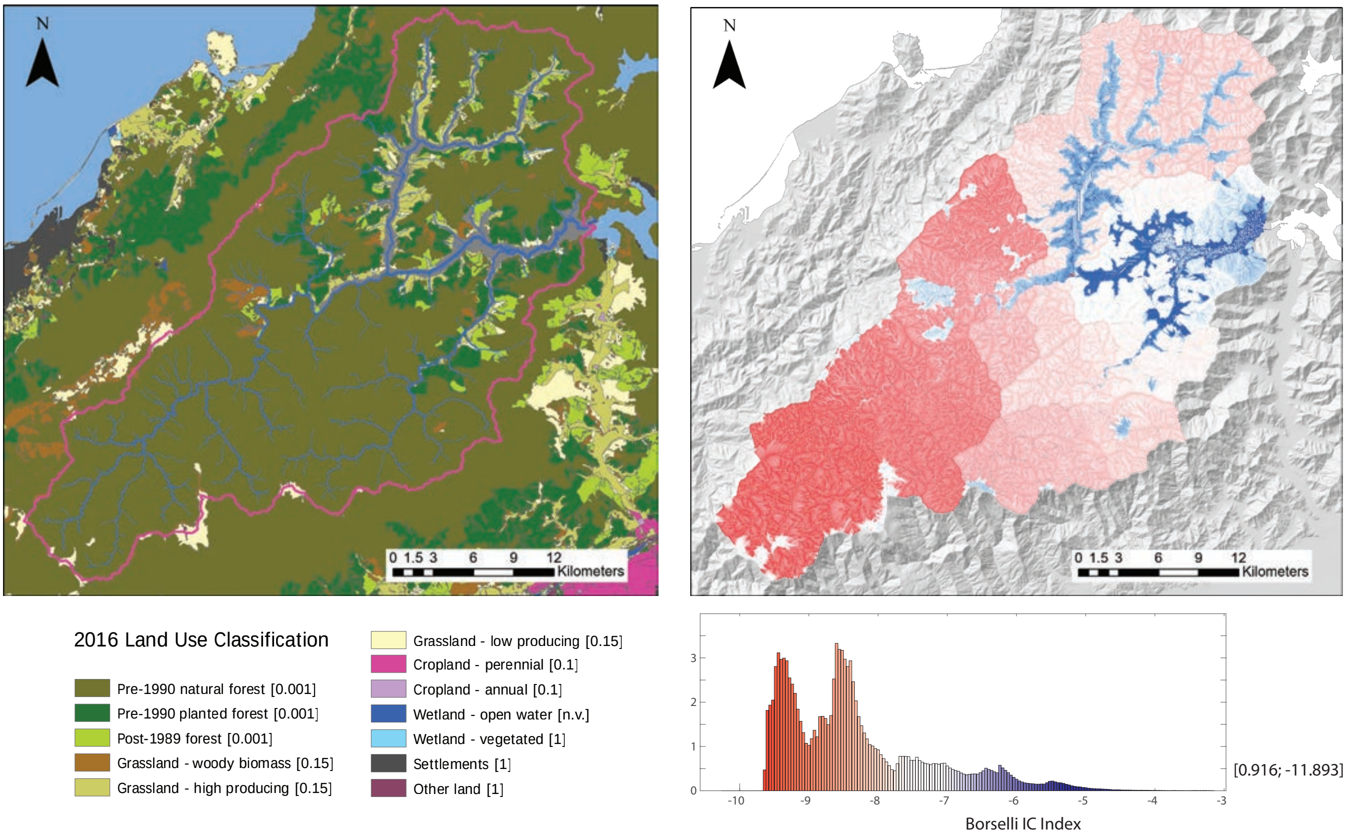


FIGURE 3-39 *BORSELLI ET AL'S (2008) CONNECTIVITY INDEX, WEIGHTED BY LANDUSE/LANDCOVER CLASS (LUCAS). RELATIVELY STEEP SLOPES ADJACENT TO THE RAI AND LOWER TE HOIERE/PELORUS MAINSTEM CHANNELS HAVE VERY HIGH CONNECTIVITY SCORES. THESE ARE ALSO THE SITES OF PROMINENT FORESTRY BLOCKS. THE FORESTED HEADWATERS SHOW LOW SEDIMENT CONNECTIVITY; THE WATER QUALITY SCORES IN THIS UPPER CATCHMENT (KAHIKATEA FLAT) RANK IN THE HIGHEST QUARTILE, NATIONALLY (LAWA, 2021). MORE DETAILED PARAMETERISATION AND MODELLING IS REQUIRED TO USE THE IC TOOL FOR CONSERVATION PURPOSES.*

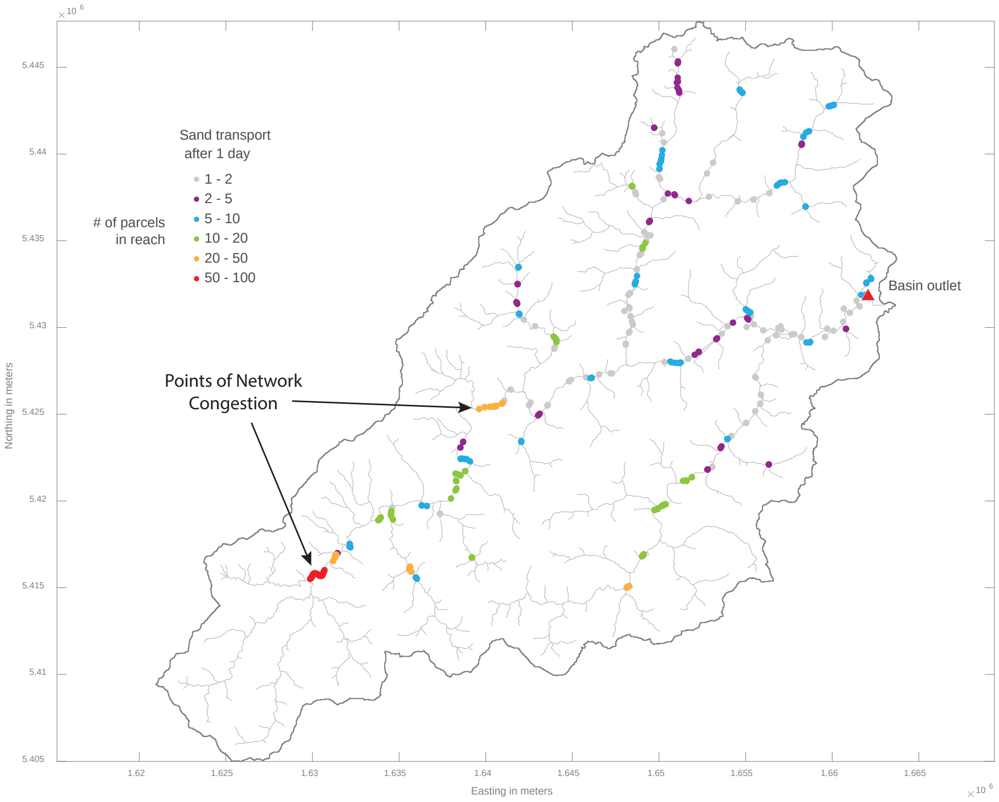


FIGURE 3-40 *OUTPUT FROM CZUBA ET AL'S (2014) MODEL SHOWS THE CLUSTERING OF MATERIAL IN TRANSIT AT TWO SITES IN THE UPPERMOST BASIN (BEDROCK CONFINED). THE ELONGATE, TRELLIS FORM OF THE DRAINAGE NETWORK HAS FEWER SITES OF MAJOR TRIBUTARY CONVERGENCE, HAVING RATHER MULTIPLE POINTS OF LESSER INFLUX DISTRIBUTED ALONG THE MAINSTEM OF THE RIVER. MODEL RESULTS ARE CONSISTENT WITH THE DEVELOPMENT OF SMALL FLOODPLAIN POCKETS AND TRANSIENT BUILDUP OF MOBILE SHEETS OF GRAVEL MOVING ALONG THE BEDROCK-LINED UPPER REACHES OF THE SYSTEM. A DISCONTINUOUS FLOODPLAIN EMERGES FURTHER DOWNSTREAM.*

Sediment Connectivity

The land cover of Te Hoiere/Pelorus catchment is roughly 74% natural forest (LUCAS, 2018). The forested headwaters of the catchment in Mount Richmond Forest Park show low connectivity (Figure 3-39); notably lower than swaths of natural forest in the Rai or Whakamarino catchments, owing to the remoteness from settled areas. As a protected conservation area, the upper catchment has experienced relatively little anthropogenic disturbance. Looking at the bare-earth LiDAR models, remnants of several very large landslides are evident (Figure 3-41) suggesting that the catchment may be subject to rare, high-magnitude landslide events.

The drainage network is relatively elongate, and the sediment routing model (Figure 3-40) shows only a few localised sites of strong tributary convergence, and thus potential sediment accumulation, mainly within the upper reaches of the catchment. This suggests that the mid to lower reaches of the system may be relatively resilient to disturbances originating from the headwaters. Many of the bedrock-lined channels in the mid-reaches show signs of shallow migrating gravel sheets, but no large accumulations of legacy sediments from past events.

In the populated lower portion of the catchment, many of the steeply sloping hillsides and colluvial aprons and fans have been cleared. Some steep valley walls, notably along the upper valleys of the Rai and Whakamarino rivers, have timber blocks. These slopes are closely coupled with the river system, and they emerge as sites of high connectivity in the map (Figure 3-39). Forest clearance and other disturbance on these slopes clearly poses a greater risk of introducing sediment and detritus to the river system.

Sediment connectivity is otherwise enhanced by a cleared valley floor with topography that slopes gently toward the river system. A narrow and intermittent vegetative cover buffers the river from adjacent stock fields. The lower floodplain reaches of the Te Hoiere/Pelorus, upstream of the delta, are highly connected. The adjacent floodplain shows signs of historical meandering across the valley floor, but only a few oxbows and channelled depressions remain.

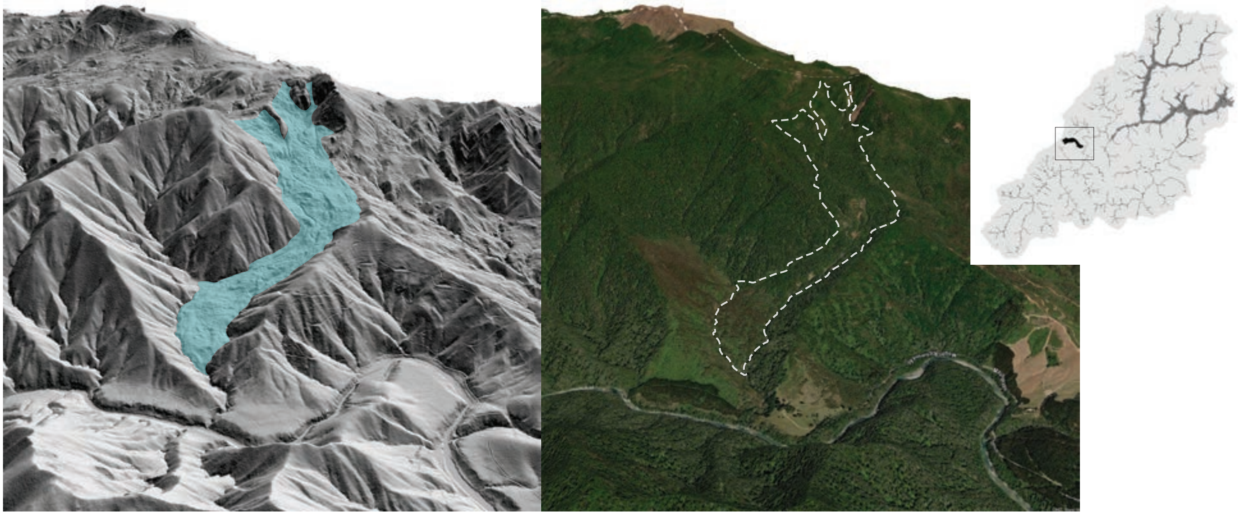


Figure 3-41 *A relict landslide deposit is one of several that are more highly resolved in recent LiDAR surveys of Scott Creek attests to the very large, but rare events that may impact the steepland terrain in the upper Te Hoiere/Pelorus river.*

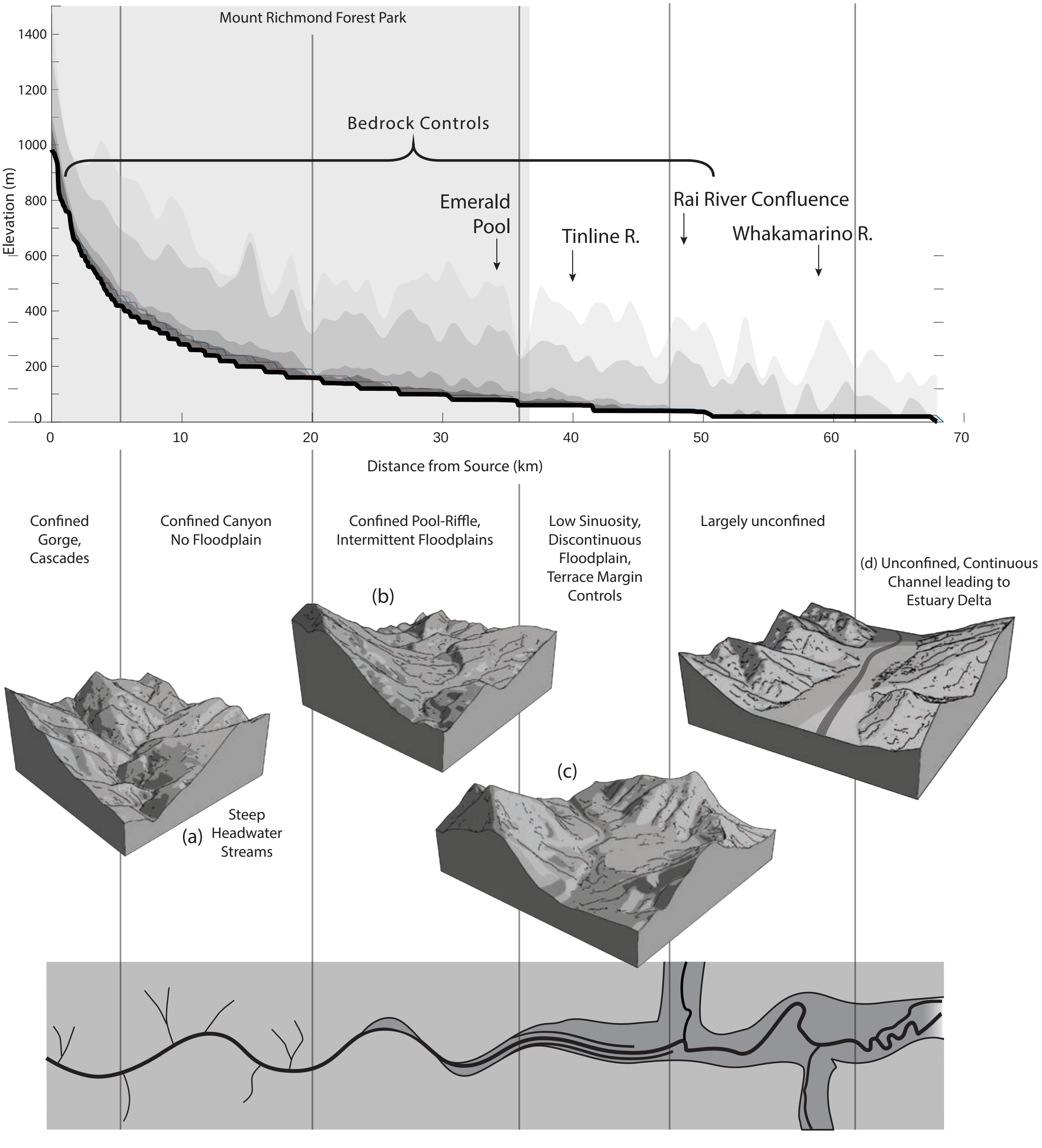


Figure 3-42 *Longitudinal arrangement of valley setting and channel types along the Te Hoiere/Pelorus system. The forested headwaters have a wide variety of steep and bedrock-confined river types, including alpine colluvial cascades and step pools channels. These transition to pool-riffle channels further downstream with discontinuous floodplains and pronounced bedrock margins. Aprons and terraces of colluvial material constrain the river against this bedrock in many places. Once past the Rai confluence the river transitions to a largely unconfined system, though still somewhat constrained by hillslope deposits and relict alluvial material. At the low-gradient terminus of the system, the river becomes more sinuous just upstream of the delta deposit.*

The river trajectory

The river morphologies of the Te Hoiere/Pelorus River are strongly controlled by the long-term active geological history of the catchment. Given the evidence of differential tilting and subsidence of the catchment, it is not surprising that the river channel interacts with bedrock in many places (Emerald Pool, Rai Falls, Pelorus Bridge), as it re-grades its profile on a millennial time scale.

The system headwaters exhibit a wide variety of steepland river forms, debris flow gullies, cascades and step-pool systems (Figure 3-42a). Many streams show large stable roughness elements, such as boulders and tree stems. Bedrock is exposed throughout the upper catchment channel system. As the river reaches gentler gradients, occasional floodplain pockets become evident, grading into a discontinuous floodplain with lateral and mid-channel bars forming.

Thick blankets of Quaternary colluvium and fan material have built out from the lower slopes of the valley walls, grading smoothly to the alluvial valley fill. Ancient landslide deposits influence the river course in places (Figure 3-42b). The modern river has incised into these coarse-grained deposits, (Figure 3-42c) becoming constrained between this terrace and the bedrock valley wall. There is a prominent outcropping of bedrock near Pelorus Bridge and the Rai River confluence, with transient sheets of gravelly material migrating among the rocky channel boundary elements.

The lower reaches of the river consist mainly of laterally unconfined reaches with discontinuous floodplain (Figure 3-42d) leading to the estuarine delta. While there are signs of past meander excursions, the river is on a low gradient and has not shown much lateral dynamism in the last 80 years, maintaining a relatively stable, low-sinuosity channel that flows down the middle of the valley. The river splits into two distributary channels, and shows a more sinuous course where it reaches the estuary delta terminus.

The river network in the upper catchment is largely undisturbed, making it an exceptional exemplar of headwater river conditions under largely native forest cover. By contrast, as the river winds among the flatter terraces and fills in the lower valleys, it is highly connected to the adjacent fields and rangelands. Riparian margins, livestock and farm fence boundaries, drainage from fields and access roads are a few of the critical pathways to be managed between the disturbed terrestrial domain and the river system. A detailed inventory of fencing status along nearly 500 km of river bank (GeoInsight, 2021) suggests that 25% of grazed parcels adjacent to the river have some form of livestock fencing.

Forestry activity in the Rai, the Whakamarino and the mainstem Pelorus remain a potential issue. More analysis is required to assess the cumulative effects of connectivity of slash, slopewash and mass-wasting resulting from forest clearance and roading in steep forest blocks adjacent to the river.

3.3 Waikanae River

Physiographic Setting

The Waikanae River drains the western slopes of the Tararua Ranges. The drainage area, including drainage from the coastal tract, is about 153 km^2. In contrast with the Mahurangi and Te Hoiere/ Pelorus rivers, the catchment has undergone gradual uplift, leaving remnant terrace surfaces 50-80 m above the modern channel in the middle reaches (Figure 3-43). Along the western margin of the Tararua Range, Hughes (2005) estimated uplift of approximately 0.3 mm/year. There is a distinct break in river setting at the rangefront, where the river emerges onto the coastal plain. This is a large alluvial fan, coalescing with sediments sourced from longshore coastal supply, as well as sand dunes migrating along the coast.

Until European settlement, the Waikanae's coastal floodplain was a series of wetlands, swamp forest and salt marsh constrained by coastal sand dunes, sustained by distributary channels from the Waikanae (Easther, 1991). The river bifurcated near the range front, with the Waimea River branch tracing a meandering path to the north of the current river and joining it again near the mouth. Many wetlands, salt marshes, lakelets and waterways were drained in the late 1800's and early 1900's as the river was consolidated and set within its current managed corridor. The lowland coastal forest and a portion of the Reikorangi hinterland forest was cleared between 1886 and 1930, a period that coincided with a number of notable floods (Easther, 1991).

Most of the modern management focus is naturally on the populated coastal portion of the river. Historically, bed degradation has been an issue, particularly downstream of the SH1 and NZR bridges. This problem first surfaced in 1958; the principal concern was for the stability of the bridge foundations. A series of weirs were built to compensate for inadequate foundation depth, initially on the NZR bridge and on the (old) State Highway One Bridge (Easther, 1991).

Cross-section surveys were initiated in 1991, and are carried out every 5 years, or following a major flood event (>20-year return period) as part of the Waikanae River Floodplain Management Plan. Surveys were carried out in 1995, 1999, 2004, 2010, 2014 and 2019. There has been a general trend of aggradation from the river mouth to Jim Cooke Park, and minor degradation above this point. Bank protection works and bed level controls were installed following the October 1998 floods, and are thought to have reduced the gravel supply from the reach (Campbell and Khanam, 2006).

Human interventions, such as the opening of the river mouth to the north and the construction of floodgates, have blocked off tidal action in the large historically estuarine arm, allowing the creation of Waimanu Lagoon as an artificial lake. Much of the riverbank falls into protected zones identified as “Key Native Ecosystem” (KNE) sites along the river. These are among the best-preserved examples of lowland riparian forest in the Wellington Region. The river supports a moderately diverse fish fauna including four species considered to be at risk (Goodman *et al.*, 2014). Brown trout are found throughout the river system and constitute a recreational trout fishery

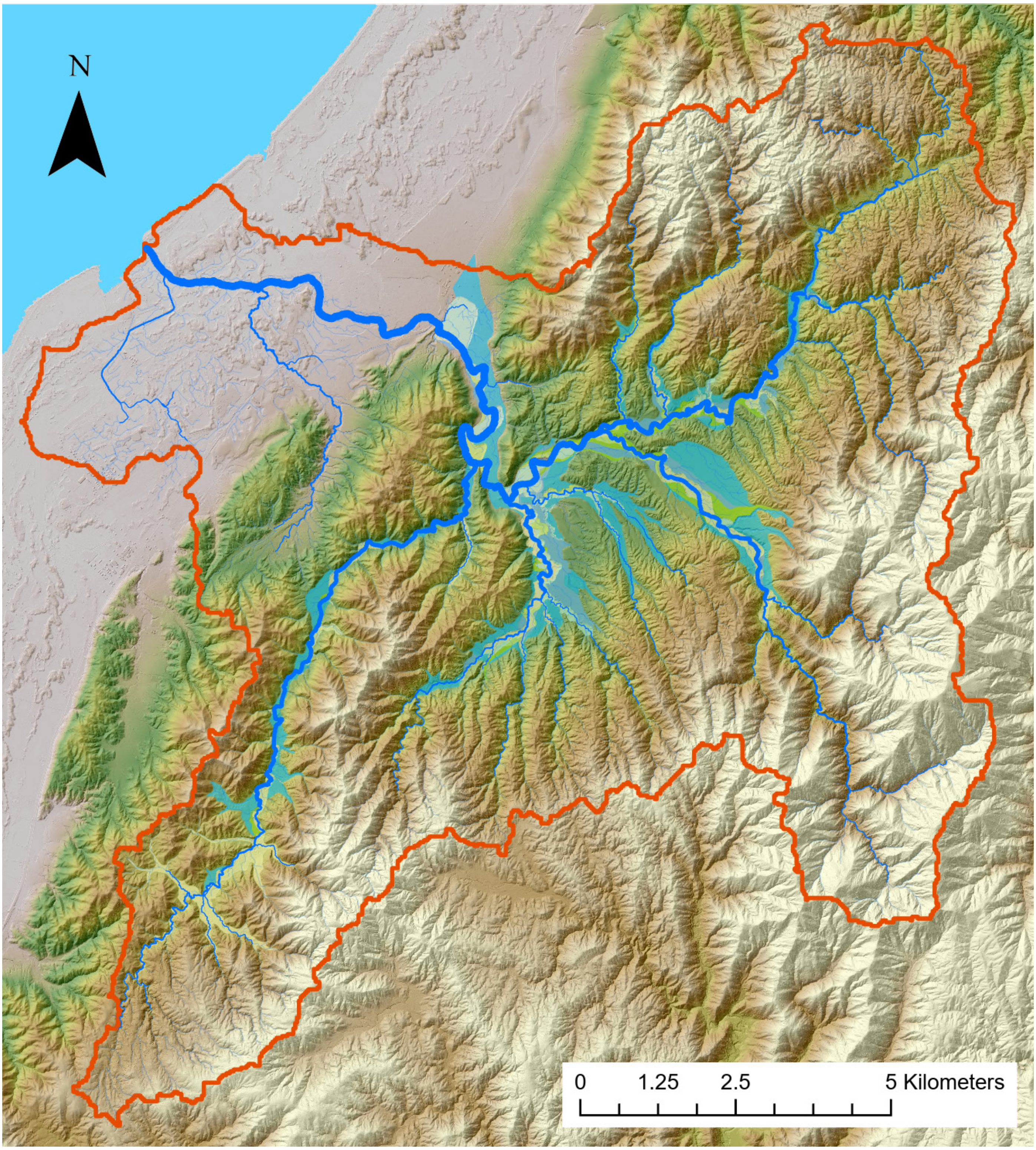


FIGURE 3-43 *THE WAIKANAE RIVER CATCHMENT. THE MID-REACHES OF THE VALLEY FEATURE DEEPLY INCISED TERRACE SURFACES, 60-100 M ABOVE THE MODERN CHANNEL.*

Restoration Aims

While there is strong interest in restoring the character of the river, there is also a strong imperative to manage flood risk on the populated coastal margin. Significant restoration work has taken place downstream of the SH1 Bridge; most of the available information on restoration work is focused on the lower river.

Climate and Flooding

The annual hydrograph time series from the gauging station at the Water Treatment Plant shows the distribution of flows over time (Figure 3-44). An elevated mean flow is evident in winter, between June and October. Given the steep topography and convergent network form, flooding can occur rapidly, although the relatively small catchment means that floodwaters tend to recede quickly as well. In 1955, a large flood extensively damaged houses on the coastal floodplain. Following this event an erosion and flood control scheme was established, which included stopbanks and erosion protection works. The flood control scheme covers the section of the river from the just below the Waikanae Water Treatment Plant to the river mouth.

The highest annual peak flows, determined from measurements at 15-minute intervals, are ranked in Figure 3-45. The peak flow from the 2005 flood was substantially higher than others on record. An earlier report by SKM (2006) concluded there was no clear evidence of climate change from 60+ years of regional rainfall records, however, floods from 2010, 2015, 2016 and 2017 chart in the top ten, a somewhat disproportionate representation from the most recent decade. This potentially suggests some tendency toward a more intense storm climate.

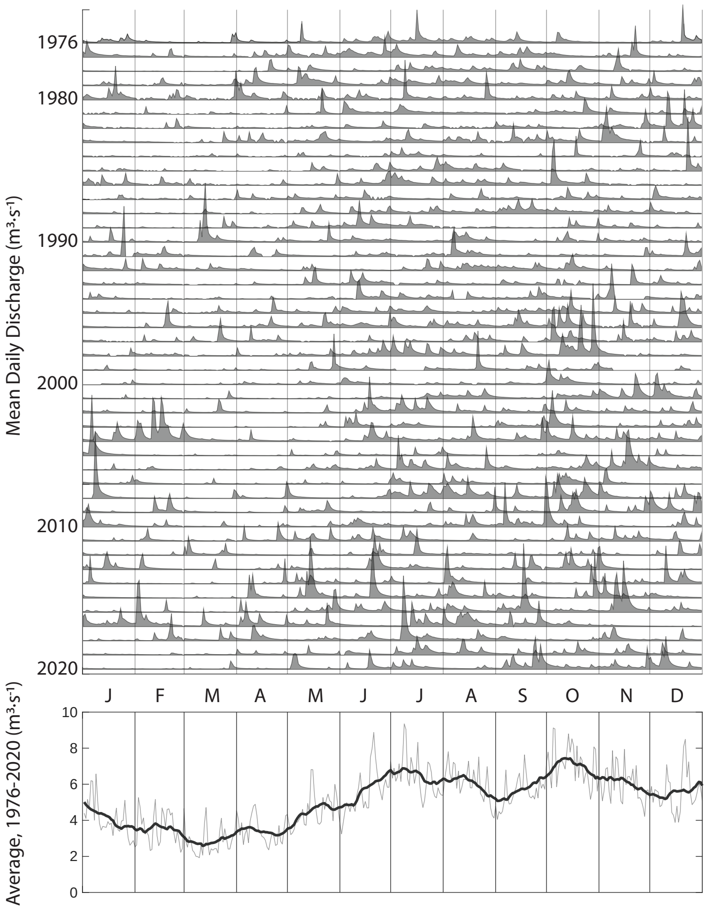


Figure 3-44 *Hydrograph time series for Waikanae River at Water Treatment Plant (Stn 58902) from 1976-2020 shows the distribution of flows throughout the year over the full monitoring record.*

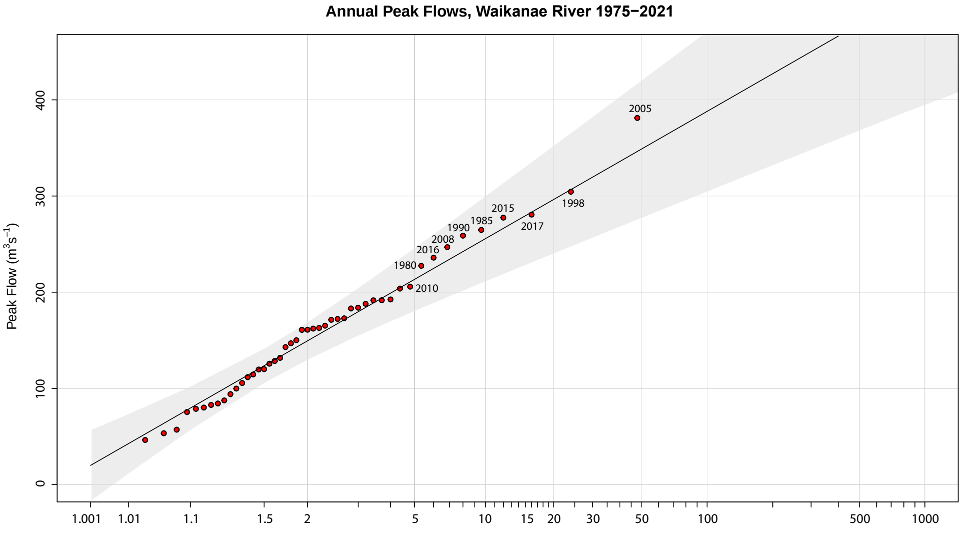


Figure 3-45 *Peak flows for the Waikanae River, plotted as recurrence intervals on a Gumbel distribution with 95% confidence bounds.*

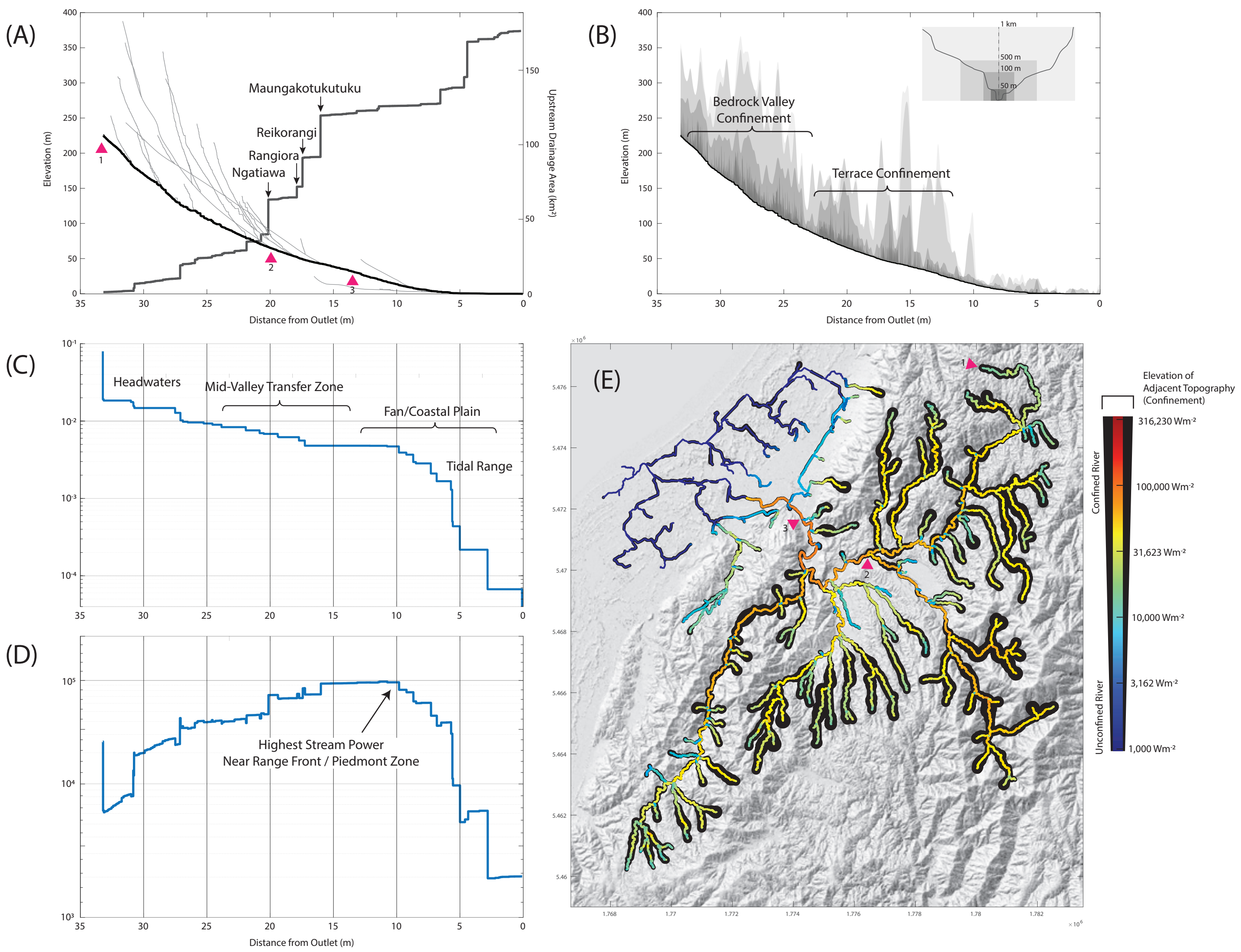


Figure 3-46 *The TopoToolbox analysis of the Waikanae River. (A) Longitudinal profile of the bed elevation in the river and its major tributaries, as well as the cumulative upstream catchment area. (B) Valley confinement along the mainstem. (C) Longitudinal profile of bed slope along the river. (D) profile of stream power, the product of channel slope and upstream catchment area (a proxy for river discharge). (E) A combined picture of stream power and confinement: many reaches with relatively high stream power are confined by bedrock boundaries. High stream power combined with low confinement may signal sites that may be predisposed to change, although closer analysis is necessary to properly assess this.*

Stream Power and Longitudinal Profiles

Much like the Te Hoiere/Pelorus, the mainstem channel of the Waikanae River is quite evenly graded, suggesting a long-term equilibrium has evolved over post-glacial time, even with the outcropping of bedrock exposures. There is a distinct peak in stream power as the river approaches the range front, downstream of the confluence points of the four major tributaries. The partly-confined gravel river in this section has considerable transporting power to deliver material to the coastal plain. Channel slope and stream power drop off notably downstream from this point, potentially promoting the deposition of coarser materials in the vicinity of the ancestral fan, and a transition to somewhat finer calibre gravels in the distal sections of the river.

River Styles

River Setting	Margin Control	Channel Gradient	Geomorphic Units	Bed Material (est.)	River Behaviour and Sensitivity
Headwater channels	Bedrock	High	Step-pool, canyon, cascades	Coarse grained	Relatively little lateral adjustment, but in-channel components (boulders, clusters, riffles) can be dynamic.
Terrace and bedrock margins	Med:~0.010-0.015	Meandering, discontinuous floodplain	Meandering to wandering gravel bed units, pool-riffle, lateral and point bars, medial bars.	Meander migration	Low dynamism; potentially activated in floods, but generally confined.
Same but steeper	Terrace and bedrock margins	High: ~0.035	Meandering, discontinuous floodplain	Coarse grained	Meander migration
Lower canyon to fan apex Terrace Constrained, Discontinuous Floodplain, Gravel Bed	Mainly terrace confined	Med: ~0.005	Pool-riffe units, lateral and point bars.	Gravel	Minor reworking of gravel bars; generally stable planform.
Mid-fan, stop-banked canal	Berm or embankment	Med-Low: ~0.002	Canal, discontinuous floodplain.	Gravel and sand	Potentially conveying high flows, but engineered to remain in place. Lower canyon to fan apex
Wetland channels (coastal tract)	Urban, some control from dunes and vegetation.	Low	Fragmented or disconnected ponds, wetlands, oxbows, channels	Fine grained	Low dynamism; potentially activated in floods, but generally confined.
Distal Fan, coastal interface	Dunes, beach, coastal vegetation	Low	Sinuous meandering river	Sand, fine gravel	Interacting with tides, dunes and coastal beach deposits. Short final reach of the river has a variable position over time (years-decades).

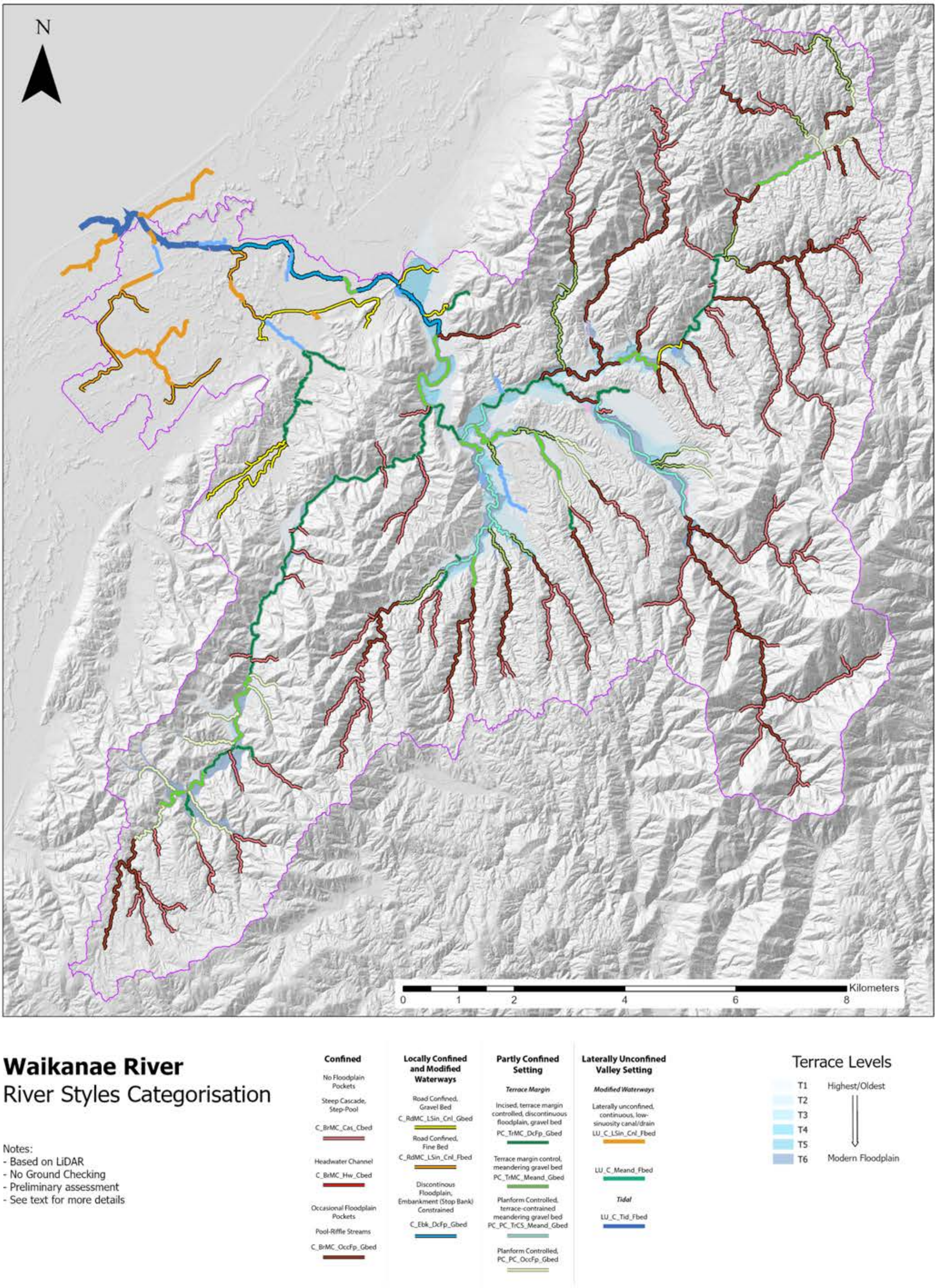


FIGURE 3-47 ***RIVER STYLES MAP***

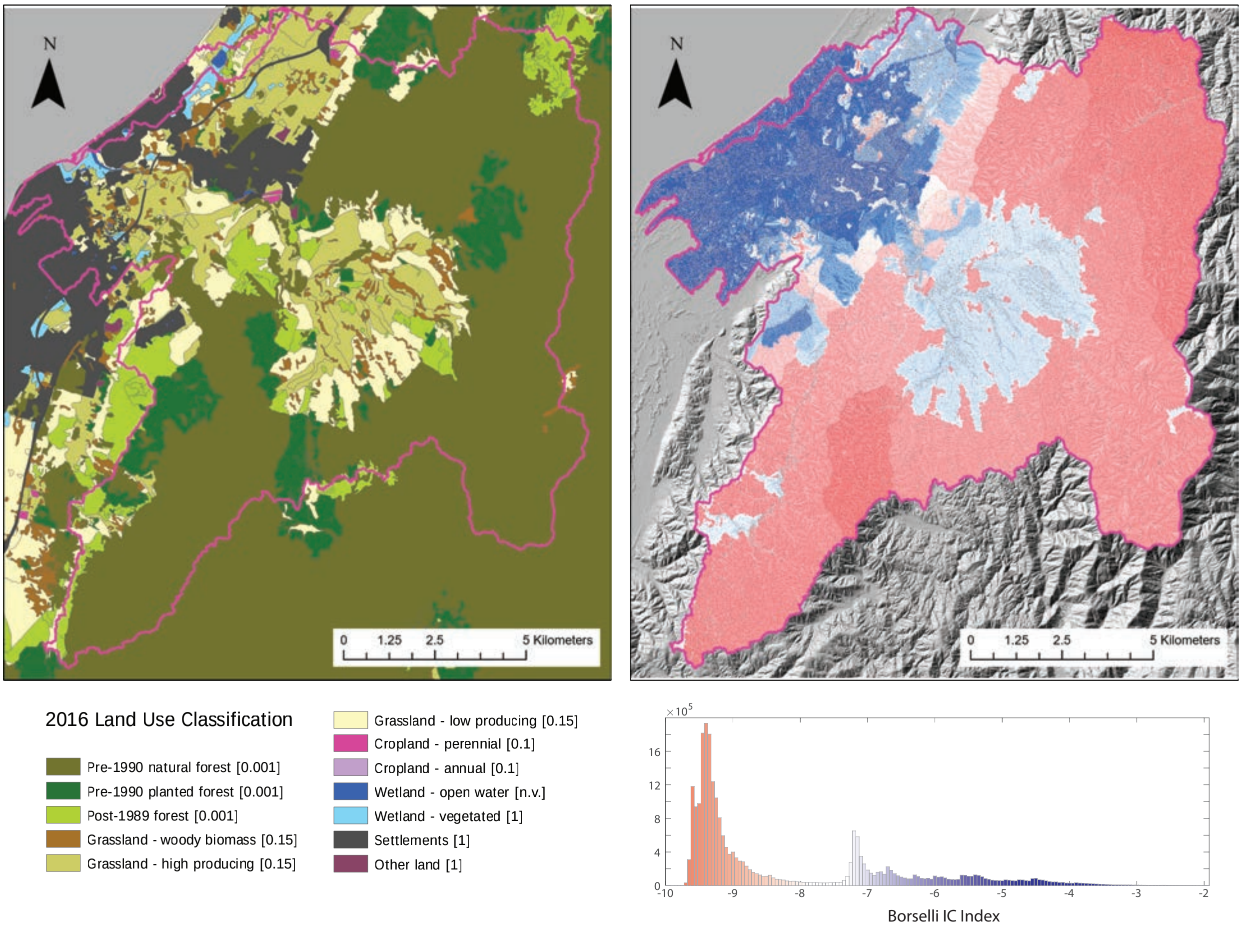


Figure 3-48 *Borselli et al's (2008) Connectivity Index, weighted by landuse/landcover class (LUCAS). The coastal tract and the lower reaches of the upper basin showing the highest connectivity, based mainly on the landuse characteristics there. The forested headwaters of the catchment show low connectivity, indicative of the intact forest and the longer transport distances to the mainstem channel. The border between high and low connectivity zones in the upper catchment is an important control on the cumulative sediment transfer to the river: reversion to forest cover at this interface could improve river conditions downstream.*

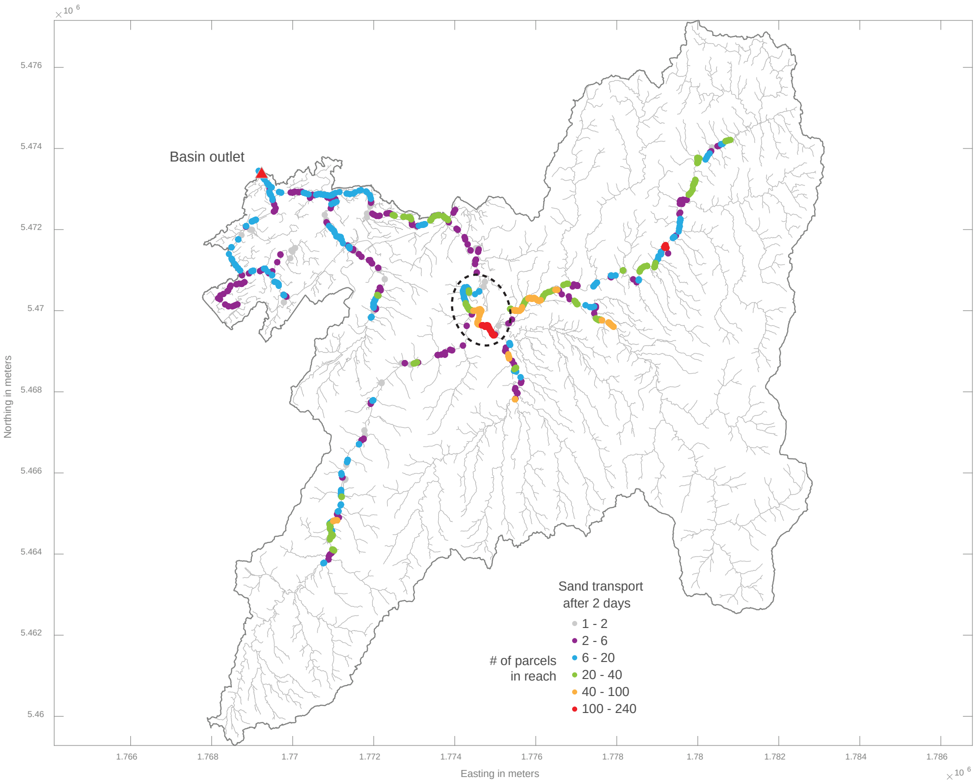


Figure 3-49 *Output from Czuba et al's (2014) model shows the clustering of sedimentary parcels at the confluence points of the Rangiora, Reikorangi and Maungakotukutuku streams.*

Sediment Connectivity

The network form of the Waikanae has evolved such that the four main tributaries (Rangiora, Reikorangi and Maungakotukutuku and Ngatiawa streams) converge on the mainstem within a roughly 4.5 km stretch of the mainstem, close to the outlet at the range front (Figure 3-46). The uppermost headwater reaches are approximately equidistant from their confluence points with the mainstem. The forested headwaters of the catchment show low sediment connectivity, indicative of the remote setting and longer transit distances to the mainstem river. The connectivity map shows a strong contrast between the forested headwaters, the cleared land in the middle valley and the high connectivity within the lower coastal tract. The forested headwaters are an important asset to the riverine ecosystem from the perspective of regulating stream temperatures and the delivery of water, sediment and organic material from the steep headwaters to the lower river.

The upper catchment shows relatively minor incidence of slope disturbance (landslides, shallow mass wasting). It is possible that an important sediment source is the lateral erosion of terraces and fans in the mid-valley reaches. The flux of coarse bed material in these reaches is quite important for regulating the regime of bedload supply to the managed river corridor on the coastal plain.

From an ecological connectivity perspective, the flow pathways on the coastal plain would benefit from a more detailed analysis. There is a complex network of ponds, marshes, wetlands, and canals that may vary seasonally or with groundwater conditions. The GIS flow routing from LiDAR does not capture this adequately. A mosaic of important habitat can be found in these environments, and there is notable risk of fragmentation, particularly with the placement of the new State Highway. By tracing out these pathways in greater detail, it will be possible to enhance ongoing efforts to protect and maintain these important ecological niches. The larger picture of connective pathways linking the ocean to the Tararua Ranges is a vital consideration as well. For species whose life-cycle depends on this connection, any broken linkages may compromise their continued vitality and their spatial distribution in the catchment.

The dynamic network routing model (Figure 3-49) shows the pronounced accumulation of sediment parcels at the confluence points of the four major tributaries. Since the model is initiated with sediment being delivered simultaneously to all first-order links, it is not surprising to see this coalescence of sediment parcels at this common, roughly equidistant, confluence zone. This offers the insight that catchment-wide disturbances (e.g. large storm events or seismically-induced landsliding) may induce accumulation and dynamic river behaviour within this central part of the network. A surplus of sediment in these reaches will in turn govern the aggradational status of the depositional reaches near the coast. The rate of transfer will depend on the sequence and intensity of subsequent storm events, and the calibre of the sediment delivered.

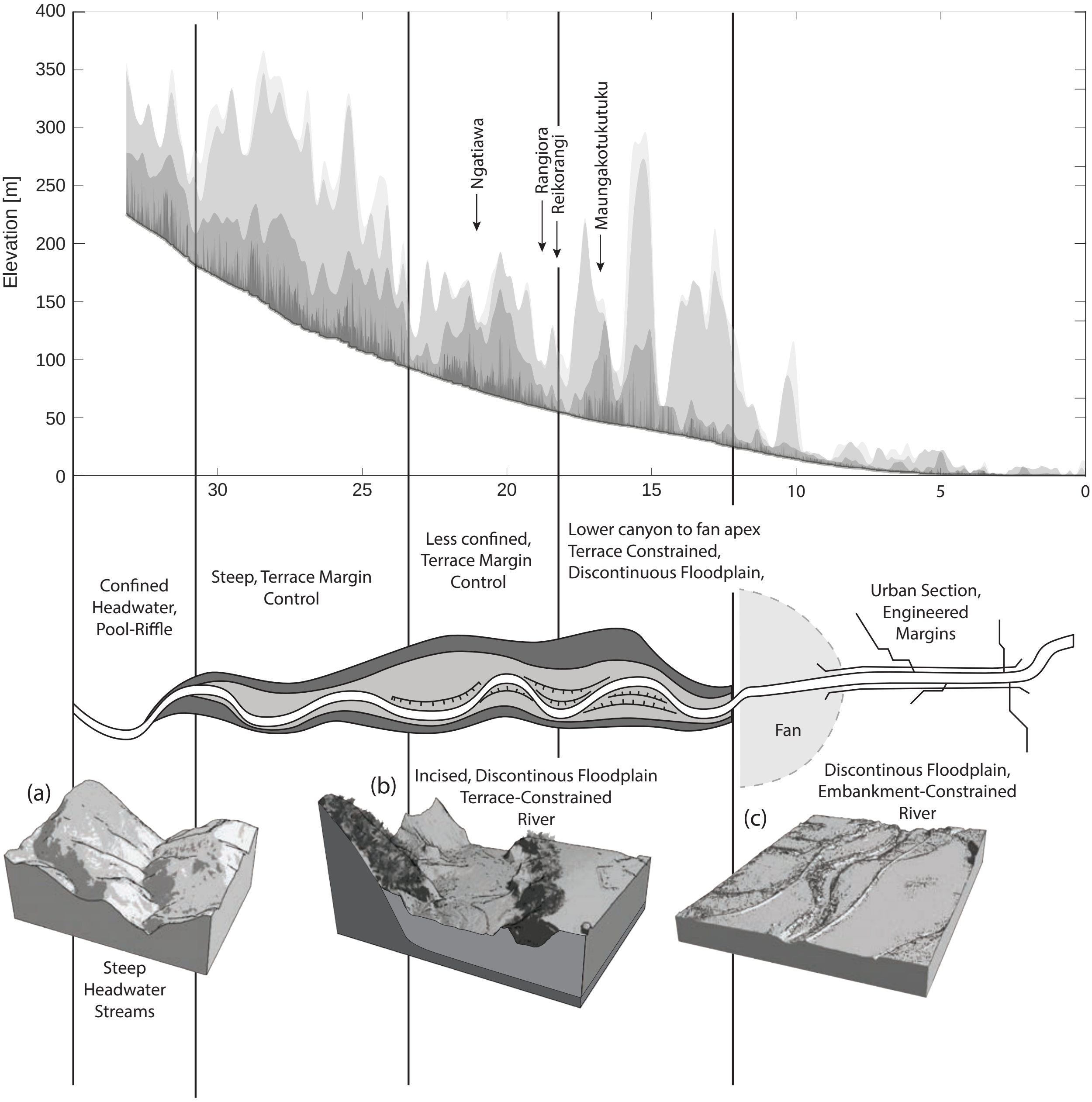


Figure 3-50 *Longitudinal transitions in the Waikanae River. Very steep bedrock-confined headwater tributaries wind through incised sections of Quaternary colluvium and alluvium: fills, drapes and fans that built up in prior glacial periods. Streams show varying degrees of incision into these relict surfaces, eventually joining with the mainstem river, which has incised 20-30 m below the highest adjacent terrace elevation. Human development in the valley has largely remained on the terraces, generally avoiding encroachment on the modern, active river belt. While the river is constrained by the terraces, it still has room to adjust. Downstream of the range front, the river follows a course through its ancestral fan deposit and dune/beach sediments to the coast. The lower river sits within a flood protection scheme, roughly 200 m wide and 7 km long, limiting overbank inundation of the surrounding areas.*

Figure 3-51 *(Facing page) Extents of the ancestral Waikanae Fan. Much as the river has incised through ancient alluvial surfaces upstream, the modern range-front river has cut down through Quaternary fan accumulations to reach its present position. The Waikanae once had a northern branch, the Waimea, that forked from the Waikanae, across the coastal reach, rejoining near the coastline. This river dried up around 1873 (Easther, 1991).*

The river trajectory

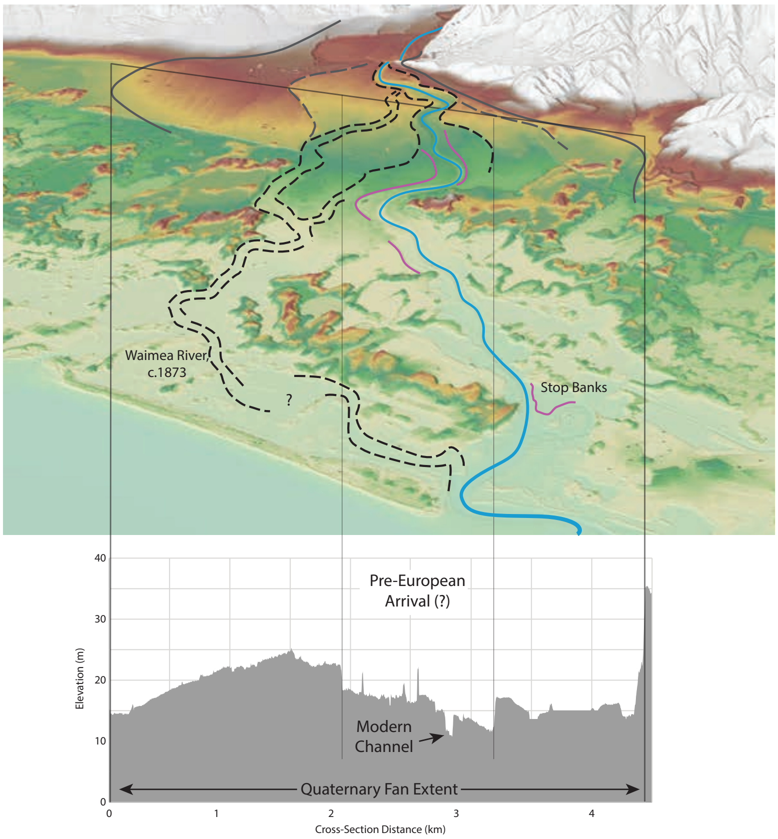
According to the LUCAS (MfE, 2018) inventory of land cover in the upper catchment (upstream of the range front), 66% of the terrain remains under natural forest cover. This appears to be ideal protection for the terrain adjacent to the steep and active headwater channels. The forest cover also plays an important role in regulating peak flows (Figure 3-45). This will become increasingly important under changing climate conditions. The water sampling site at Mangaone Walkway in the upper Waikanae showed the highest score in Wellington Region for Habitat Quality (GWRC 2017), excellent scores for all physico-chemical and microbiological water quality data indicators, and is noted as the 'best available' benchmark for low dissolved reactive phosphorus (Perrie *et al.*, 2012).

The remaining third of land cover in the upper catchment consists chiefly of pastoral rangeland on flatter terrain and forestry blocks on steeper slopes. The terrace-confined gravel bed of the river has variable but generally good riparian protection and stock exclusion, and there is limited river crossing infrastructure and encroachment on the upper river from development. The upper tributary rivers are unimpeded from natural erosion and transfer processes.

Much like the Mahurangi, pressures on available land and water will only continue to mount with the improved Kapiti transport corridor, and recovery of riverine processes and eological niches in the coastal tract will be more challenging. Reconnecting the remnant fragments of former wetland and forest ecosystems on the coastal plain should remain an important priority.

The balance of sediment supply in the Lower Waikanae may be expected to fluctuate according to sediment delivery dynamics in the upper catchment. Range-front fans (Figure 3-51) are well known for their pulsed inputs to the piedmont environment downstream (Coulthard *et al.*, 2002; Davies *et al.*, 2007; Clarke *et al.*, 2010). The managed river corridor has restricted the channel's ability to migrate laterally, reducing its capacity to store material and moderate downstream deliveries. Detailed surveys of bed and bar evolution in the lower 10 km of the managed system will help to develop a sediment budget that can be used to forecast the longer term supply.

Unless the lower reaches of the river are allowed more room to meander, storing and releasing a local supply of gravel, the river will be subject to supply surplus or shortages from further upstream. This will necessitate ongoing management interventions such as gravel extraction, which can significantly impact benthic environments at this critical coastal interface.



4. Discussion and Summary

The case studies in the preceding sections provide some compact examples of how catchments within the Ngā Awa programme may be assessed from the desktop, gathering a broad set of information at a range of scales, classifying river characteristics, and assessing structural and functional relationships to develop a coherent narrative for each river. Given the aims of protecting the *things that matter,* such as habitat diversity and productive ecosystems, this package of information provides a starting point for discussions with stakeholders, managers, funders and technical specialists. It also helps to set up targets for restoration, key sites to be monitored, and goals for success.

The three catchments highlight an important diversity of river types and different system equilibria under different disturbance regimes. The morphologic diversity particular to each catchment is vital to maintaining robust habitat conditions and crucial ecological linkages between terrestrial, aquatic and marine environments in the long term. The three rivers help to highlight the variable impacts and fragmentation that can occur within the drainage network. Forestry, agriculture, pasture, livestock rearing and urbanisation each have characteristic and sometimes compounding effects on stream systems.

4.1 Multi-scalar Evaluation of the River

Effective conservation management approaches must consider the nature and scale of potential impacts across a catchment. In assessing the opportunities for ecosystem restoration, it is helpful to consider a nested-hierarchical framework as a template for management (Figure 4-52; Beechie, 2010; Frissell *et al*., 1986; Gurnell *et al*., 2020; Naiman *et al*., 2002; Poff, 1997). River morphology moderates the linkages between geomorphic process zones and is thus an important determinant of river sensitivity to change. The biophysical setting of the river changes between source, transfer and accumulation zones, and this underpins the foundation premise of geomorphologically-informed river management practices: *Know your catchment* (Brierley and Fryirs, 2005). Typically, distinct catchment-scale patterns of reaches (or process zones) are found recurrently in a given

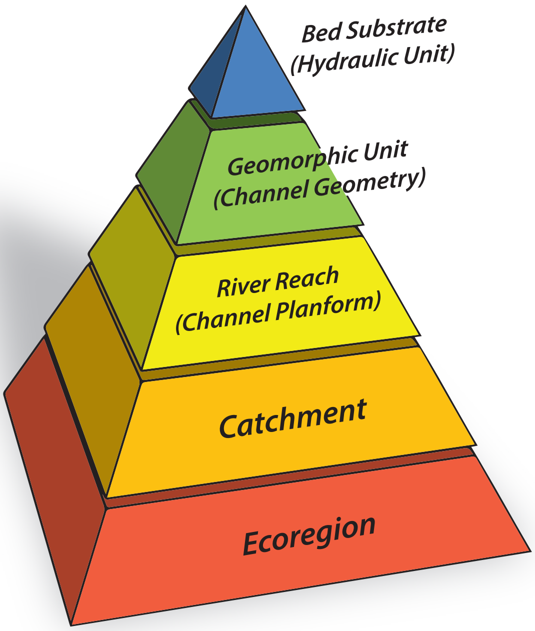


Figure 4-52 *A nested hierarchical (cross-scalar) approach to analysis of river systems. (Source. Brierley & Fryirs, 2021, Truths of the Riverscape. Fluvial geomorphology in practice. Geoscience Letters. Submitted). (after Frissell et al., 1986; Naiman et al., 1992; Poff, 1997)*

(eco)region, aiding meaningful transfer of geomorphic understandings and implications from one river system to another. Ecological relationships and patterns can be directly associated with these geomorphic (landscape) patterns (e.g., Benda *et al*., 2004; Poole, 2002).

At the reach scale, morphodynamic interactions (patterns and rates of erosional and depositional processes) produce characteristic assemblages of geomorphic units that recurrently adjust to sustain the physical template of a river (Kellerhals *et al*., 1976). The morphologic diversity particular to each catchment is vital to maintaining functional and robust habitat conditions. River types (or River Styles) may be identified, mapped and characterised/classified at broad scale (Fryirs *et al*., 2021) as an aid to interpreting biophysical conditions and thus habitat distribution.

At the finest level of detail, analyses of bed material size and associated flow hydraulics (biotopes, ecotopes, hydraulic units; Newson and Newson, 2000; Thomson *et al*., 2001) help us to characterise and understand geomorphic units (channel and floodplain features, patterns of which make up the dynamic physical habitat mosaic of river systems; *cf.* Brierley and Fryirs, 2005).

In the following we look at some of the key considerations at the intermediate scales (catchment, reach, geomorphic unit), drawing on some of the findings from the case studies in Section 3 to show how opportunities for advancing conservation initiatives may be assessed based on such analyses. The three rivers help to highlight a variety of impact types that occur within the drainage network.

Catchment-scale considerations

Rainfall runoff and routing drive the system. Any change in the infiltration and water retention characteristics of the land surface ultimately leads to some disequilibrium in the mutual adjustment of sediment supply and channel form. Catchment-scale conservation and restoration work should take some account of the capacity of forest cover and wetlands to buffer river systems from potential intensification of erosion by concentrated flows from subsurface drains, canal systems, culverts and floodwater management schemes. Rainfall-runoff modelling can help us to better understand the role of land cover in shaping the flood hydrograph, and to develop restoration strategies that optimise hydrologic interception and retention on the landscape.

Figure 4-53 *Te Hoiere/Pelorus river, looking downstream from the Pelorus bridge. An intact headwater ecosystem with native canopy cover is a tremendous asset for river restoration.*

Of the three study sites, the Mahurangi shows the most evident alteration of the drainage network, with roughly 15% of channel length classed as locally confined, modified or blocked. The population of Warkworth is expected to increase as much as five-fold by 2032, with 1 100 ha of future urban land earmarked for development (Auckland Council, 2018). This will undoubtedly lead to more profound changes in catchment hydrology via landcover change and flow diversion. Improved interception and storage of flow can help to reduce the erosional effects of storm runoff. Incorporation of water-sensitive urban design (Wong and Eadie, 2000; Wong, 2006) principles can contribute to this, with the strategic incorporation of constructed wetlands and swales. The upper Waikanae and Te Hoiere/Pelorus, by contrast, have relatively little capture, diversion and concentration of runoff. The upper Waikanae has 65% natural forest cover; the Te Hoiere/Pelorus catchment has 82% natural forest cover overall (LUCAS, 2016 classification; Figure 4-53).

Headwater Protections: buffering hillslopes, zero- and first-order channels. The flux of sediment, nutrients, biota and organic matter such as riparian litter and plant propagules from the upper source zones to the river network are vital to the sustenance of the larger ecosystem. Headwaters are important regulators of stream temperature and oxygen. Impacts of land use are proportionally most severely visited upon smaller, headwater channels, owing to their (collectively) very large surface area and steep and convergent (thus highly connected) form. What happens upstream impacts upon what happens downstream – it's just a matter of time. If geomorphic potential is compromised in these uppermost reaches, the likelihood of ecological recovery is lost. Again, the Mahurangi has had multiple impacts across headwater systems, limiting the capacity for rehabilitation of the system. The recent burial, culverting and paving of the upper valley tributaries of the Right Branch seem to be a particularly problematic precedent for transport corridor development. Both the Waikanae and Te Hoiere/Pelorus systems have generally intact headwaters. Forestry activities rarely afford a substantial vegetative buffer to steepland ephemeral streams or seasonal drainage pathways; cut blocks should be harvested in such a way that the headwater hydrologic system is buffered as broadly and effectively as possible. Runoff from forestry roads should be managed carefully, as well.

The river network. Network configuration is a key control upon sediment connectivity and the pattern of geomorphic hotspots (areas where river responses to disturbance are accentuated; Czuba *et al.*, 2014). The shape of the network and thus the nature of channel coupling with tributaries and sediment sources will influence the form of the yield response following disturbances, such as major storms or mass-wasting events. This network topology also governs the downstream trend stream power, and thus sediment transport capacity. Tributary junctions are commonly associated with a step decrease in bed slope, sometimes prompting deposition and dynamic behaviour. A significant rise in transporting power within convergent portions of the network can contribute to dynamic behaviour at these points if the bed and banks of the river are readily mobilised and modified (Figure 4-54).

The Waikanae has a strongly convergent network form, but this does not seem to have led to any profound changes, historically. This is likely owing to high and coarse-grained terrace boundaries. Segments of the network having both high stream power and high convergence are both steep and bedrock-confined, favouring onward transfer of material. The network arrangement of the Te Hoiere/Pelorus has a more elongate form and shows a lesser tendency for generating hotspots in Czuba's model. The Mahurangi has a major confluence point: the Left and Right branches meet within an incised setting, which could signal moderately higher erosive potential here, given the narrow confines and limited potential for bedload sediment recruitment within the lower reaches of the mainstem river.

Controls on River Gradient. A major priority for managing erosion is understanding the controls on longitudinal profile within alluvial and fine-grained fills. A drop in local stream bed elevation as a result of local scour or excavation works will lead to a local increase in bed gradient and thus erosive energy. This process can propagate upstream, dynamically re-grading the river's longitudinal elevation profile, and potentially triggering further instability within tributary streams, as well as river banks. Conversely, the buildup of excess bed material may introduce a discontinuity in channel gradient, changing the local sediment transport regime and substrate character.

In managing disturbed river systems, it is imperative to consider the bed before banks: interventions to stabilise bank erosion will not succeed if the river is in the process of actively re-grading its bed profile. Detailed longitudinal bed surveys may help to locate any discontinuities in the bed profile or sites of accumulation, and therefore potential zones of instability. There is much documentary evidence of instabilities arising from the extraction of bed substrate (Kondolf, 1994; Pont, 2009), emphasising the importance of monitoring the effects of such works.

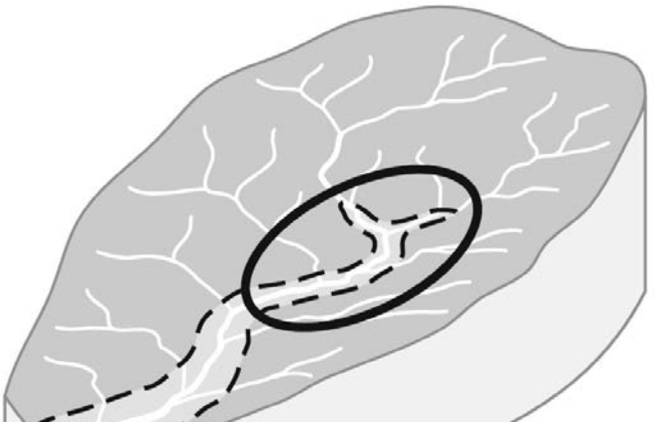


Figure 4-54 *The zone of greatest lateral activity in most river systems: reaches with high stream power in upper valleys receiving coarse sediment inputs from many upland tributaries (Church, 2015).*

The Mahurangi may be susceptible to local incision and bank erosion, and thus instability within the fine-grained valley fill. The Te Hoiere/Pelorus River by contrast, has extensive bedrock controls (Figure 4-53) that will limit the morphologic impact of high discharge events. The Waikanae also has bedrock controls, although the lower, depositional reaches may be moderately sensitive to changes in base level induced by significant gravel extraction, or potentially in the event of the arrival of aggrading pulses of material from upstream.

River reach-scale considerations

Which sites are likely to exhibit change? Maps of stream power and confinement (e.g., Figure 3-27) provide some sense of the relative energy available for erosion and entrainment of materials and the bounding topography that may keep this in check. The longitudinal trend in stream power will be variable, but there is typically a peak in transporting power in the mid-reaches of the river system, where we find an optimum between discharge (increasing downstream) and channel slope (decreasing). This also often coincides with a break in slope, where steep energetic headwater rivers converge on the valley floor (Figure 4-54). This zone has been identified as the point in the catchment where lateral shifting, channel avulsion or other changes may be likely to occur (Church, 2015).

Overlaying information layers (slope, stream power, confinement, sediment transport capacity) with maps of river typology (River Styles) and anthropogenic controls (stop banks, embankments) will also provide important insights into which reaches may be predisposed to geomorphic change. The less confined, alluvial (labile) river systems are likely to be the most dynamic, whereas deeply incised systems and bedrock-bounded channels will tend to be the most stable.

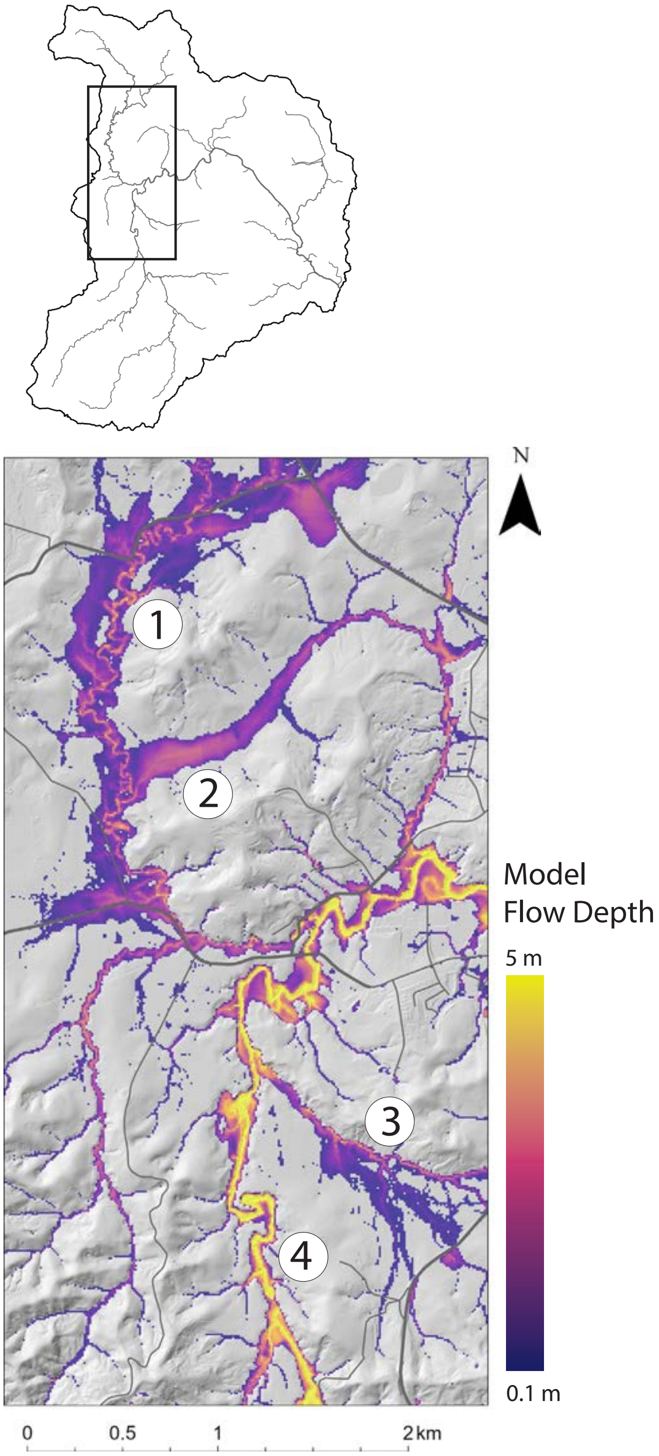


Figure 4-55 Auckland Council's (2017) Rapid 2D hydraulic flood model of the Mahurangi in a 100-year flood event. The model provides an approximation of high channel discharge, though the simulation does not include erosion and bed change that would occur at high flow (see reference for more modelling details). It is nevertheless instructive in showing how the unincised left branch (1) tends to have relatively shallow in-channel flows, and broad overbank extent (LU_C_Meand_Fbed), as do the shallow drains (2) and the modified channel (3). The right branch Mahurangi (4) contains flows up to 8m within the incised channel (PC_TrMC_Incis_Fbed).

The middle, terrace-confined reaches of the Waikanae River provide a good example of a steep and high-powered system, with the longitudinal trend in stream power peaking about 10 km before it reaches the coast (Figure 3-46D). There is a pronounced transition in slope once past the range front, as the river moves into to a regime of mainly deposition and reworking of bars within the stop-bank confined reaches there. The Te Hoiere/Pelorus River also shows high stream power in its middle reaches, tapering off considerably in the lowermost valley, indicative of a predominantly depositional regime.

Diversity of morphological units. Morphodynamic interactions between sediment and hydraulic forces (and vegetation) create and rework the dynamic physical habitat mosaic of a river. These various morphologies are vital for maintaining a diversity of riverine biota and may be important for different life stages of various fishes and insects. Modification of river forms for field drainage, roading and other infrastructure will change the conveyance characteristics of the river in flood. It is important to interpret river behaviour at different flow stages (e.g., within-channel processes that create channel geometry, relative to overbank processes that form and rework floodplains). Figure 4-55 shows the results of a 2D hydraulic simulation of flood flows within several different channel morphologies: flow velocities, connectivity with floodplains, and floodwater dispersal across the valley bottom vary considerably. Notably, the relatively shallow Left Branch shows substantial overbank flooding extent, while the Right Branch maintains in-channel flows, to depths of over 8 m.

Channelisation invariably entails straightening of the channel; this leads to increased channel gradient, in turn potentially leading to channel-bed scour and reduction of aquatic habitat diversity. Such manipulations may suppress morphodynamic processes and tend to simplify channel morphology and smooth channel flow boundaries. This has the result of systematically altering the form and function of the physical habitat mosaic and thus the integrity of fish communities (Frothingham *et al.* 2001; Rhoads *et al.* 2003; Rhoads and Massey 2012). Bank hardening interferes with normal staging downstream of bed material sediments since it prevents the lateral movement associated with bed material deposition and re-entrainment: it thereby suppresses the process of floodplain renewal.

River Style maps provide an overview of the many different types of river morphologies within the three catchments, the variables that govern morphology (Figure 4-56), and the distinctive pressures that may be acting to alter them. This mapping can be used to select suitable points for more detailed monitoring or inventories of factors such as bank state, fencing measures, or substrate condition. Application of the River Styles framework provides a rational basis by which lessons learned in one reach can be meaningfully applied elsewhere (i.e. for an equivalent type of river character and behaviour). Appropriately documented procedures for auditing and post-project appraisal are critical to achieve optimal environmental outcomes.

Lateral connectivity between the channel and terrestrial ecosystems is vital. Most threats to aquatic systems are of terrestrial origin (Linke, 2011). In addition to maps of stream power, confinement and River Styles, an inventory of bank condition and vegetation may help to target rehabilitation efforts. Systematic mapping of riparian conditions and livestock fencing have been carried out on the Mahurangi and Te Hoiere/Pelorus rivers, and these efforts provide a vital additional layer of information for interpreting river trajectory, and a planning tool for understanding erosion sources and planning restoration efforts at the catchment scale.

Considerations at the scale of geomorphic units

Forced channel morphologies. Alluvial channels are generated through natural, evolving feedbacks between formative flood discharge and the sediment supply from upstream (Lane's balance, Figure 1-2). 'Forced' channel morphologies arise when the river encounters an obstacle or boundary that changes the local hydraulic character of the river, in turn changing the local equilibrium of erosion and deposition and potentially the local grain-size composition. Channels may rendered more erosive by narrowing and immobilising the banks. In reaches where bank stability has been modified or disturbed by earthworks or stock trampling, the river may widen, resulting in shallower flow depths, and thus enhanced deposition. In the process of reach rehabilitation, it is important to assess the historic equilibrium suite of geomorphic units (and associated bank conditions) that had previously evolved at the site. The practise of designing 'natural' channel forms and habitats to offset losses elsewhere in the catchment can be particularly problematic: many natural conditions must converge (valley slope, sediment supply, nutrient flux, hydrologic regime) in order for high-quality habitat to emerge - it cannot be spontaneously manufactured.

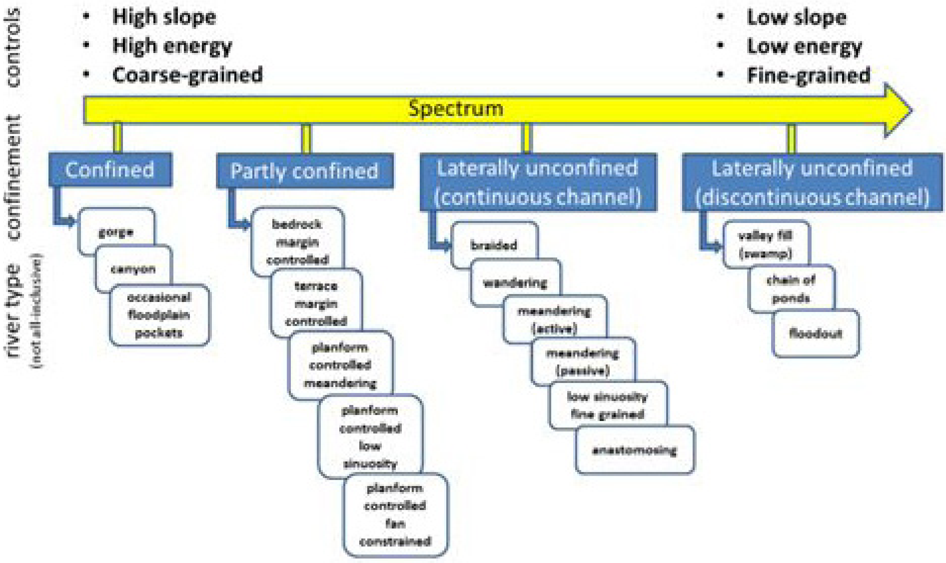


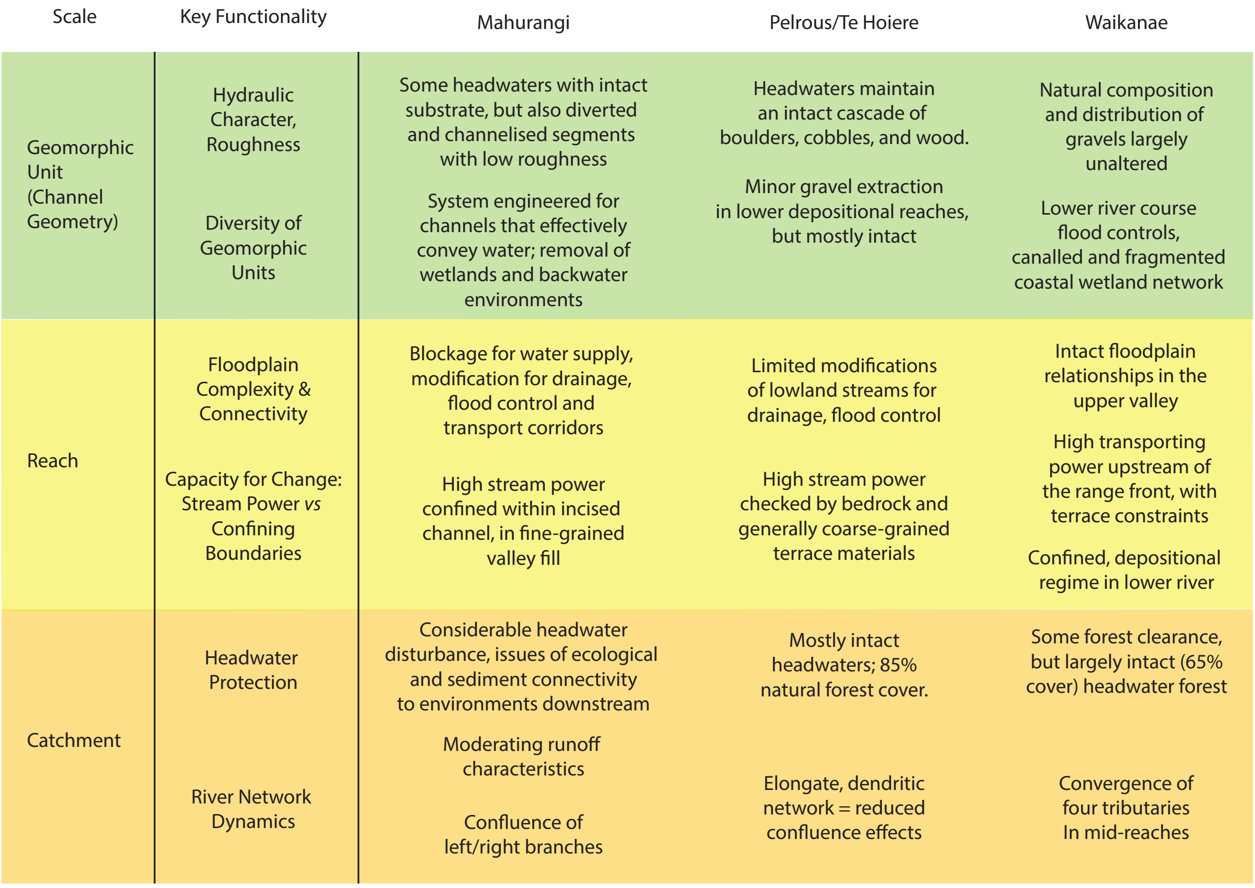
Figure 4-56 *The spectrum of river diversity along an energy gradient (Source. Brierley & Fryirs, 2021, Truths of the Riverscape. Fluvial geomorphology in practice. Geoscience Letters. Submitted).*

Natural hydraulic resistance within the reach. Channel and bank stability, and hydraulic resistance in coarse-grained river systems depend greatly on the roughness elements with the river system. The upper quartile size range (e.g. D_{75}-D_{99}) provide stable elements that dissipate flow energy, and influence the deposition of finer material. Structures such as clusters, stone lines, transverse ribs and networks of stone 'cells' (*cf.* Church & Ferguson, 2015; Harrison, 1950; Hassan *et al*., 2020; Mackenzie & Eaton, 2017; Parker, 1978; Wittenberg, 2002) are integral elements of a bed 'armour' that is only breached at the highest flows. This provides important habitat for invertebrate communities and higher-order stream dwellers. The feedbacks between river flow and the evolution of channel morphology are strongly mediated by these elements, for instance, in the development of coarse-grained head of bars and riffles (upstream end), and fine-grained deposition at bar tails and within pools. The coarser fraction is also the most valued component of gravel extraction operations. Selective removal of these fractions, and systematic return of the finer, discarded fractions will impoverish coarse-grained system, and diminish both channel stability and habitat potential of the river.

4.2 Summary of key issues

Figure 4-57 provides a summary of key functionality and some constraints observed in the rivers across multiple scales. This is from desktop work and is therefore only a preliminary assessment of elements to consider. It will require more extensive fieldwork to fully verify and document the issues that were identified, but the process highlights how the mapping of multiple layers of information and modelling can be used to sound out potential issues within each catchment.

The three case studies span a range of physiographic settings, confinement conditions, slope and stream power, substrate materials, disturbance histories, and therefore quite varied morphological types. High-value ecological assets (forest cover, intact riparian zones) should be protected, and opportunities for enhancing and restoring natural river functionality and morphodynamics should be pursued in the course of catchment restoration works.



Scale	Key Functionality	Mahurangi	Pelrous/Te Hoiere	Waikanae
Geomorphic Unit (Channel Geometry)	Hydraulic Character, Roughness	Some headwaters with intact substrate, but also diverted and channelised segments with low roughness	Headwaters maintain an intact cascade of boulders, cobbles, and wood.	Natural composition and distribution of gravels largely unaltered
	Diversity of Geomorphic Units	System engineered for channels that effectively convey water; removal of wetlands and backwater environments	Minor gravel extraction in lower depositional reaches, but mostly intact	Lower river course flood controls, canalled and fragmented coastal wetland network
Reach	Floodplain Complexity & Connectivity	Blockage for water supply, modification for drainage, flood control and transport corridors	Limited modifications of lowland streams for drainage, flood control	Intact floodplain relationships in the upper valley
	Capacity for Change: Stream Power *vs* Confining Boundaries	High stream power confined within incised channel, in fine-grained valley fill	High stream power checked by bedrock and generally coarse-grained terrace materials	High transporting power upstream of the range front, with terrace constraints Confined, depositional regime in lower river
Catchment	Headwater Protection	Considerable headwater disturbance, issues of ecological and sediment connectivity to environments downstream	Mostly intact headwaters; 85% natural forest cover.	Some forest clearance, but largely intact (65% cover) headwater forest
	River Network Dynamics	Moderating runoff characteristics Confluence of left/right branches	Elongate, dendritic network = reduced confluence effects	Convergence of four tributaries In mid-reaches

Figure 4-57 *Some of the key issues identified through application of desktop analyses in this study. Further field work is warranted to assess issues at the scale of hydraulic units (upper category).*

4.3 Changing Climate

Anything that alters the streamflow, sediment supply or river gradient may cause changes in river dynamics (*cf*. Lane's Balance, above). Catchment hydrology (including groundwater) is the key lever; secondary factors such as a changing mass wasting regime or riparian vegetation structure will contribute to further alteration of stream character. Changes to thermal regime will have important ecological consequences for stream biota.

The impacts of climate change upon New Zealand rivers will be quite varied, and depend greatly on terrain attributes, catchment scale, regional air circulation and the regime of weather types (e.g. Kidson, 2000; Williams and Renwick, 2021). Dominant flood-generating processes will vary with region. The timing, magnitude and frequency of rainfall or snowmelt in many catchments is predicted to change (more so by late-century), which may result in changes to riverine habitat conditions and river morphologies. The most pronounced effects that emerge from predictive modelling of change to river flows in rivers near the study catchments (Collins *et al*., 2018; Figure 4-58) are more intense mean annual flood flows (MAF) and lower mean annual 7-day low flow (MALF). The Te Hoiere/Pelorus catchment is expected to have notably higher winter discharge, and the Mahurangi may have a pronounced reduction in average flow levels in spring.

Comparatively small changes in annual precipitation may cause disproportionately large increase in the magnitude of flood discharge (Knox 1984; 1993; Arnell, 1996). Change in typical high flows, especially infrequent extreme flood events, is much more important to fluvial processes than change in the average flows (Ashmore and Church, 1999). Dynamic changes to morphology only occur at these high flows. The river bed's armour layer and key stabilising bed structures such as clusters and reticulate stone cells (see previous section) control sediment mobility. Once these are disrupted in flood conditions, channel morphology becomes highly susceptible to change. The frequency with which such events occur is expected to increase moderately in the coming century, such that channels with the capacity to evolve may become increasingly responsive to other environmental changes such as urbanisation or engineered river works.

Protracted low-flow conditions will put pressure on riverine water resources, as well as influencing river benthic conditions. Baseflows may be altered in periods of drought; the relatively deep storage of seasonal water surplus in the soils of the Mahurangi catchment, for instance, may not provide the same prominent contribution to baseflow as it does currently. Environmental envelopes or niches for river biota may shift as conditions in the local river environment exceed

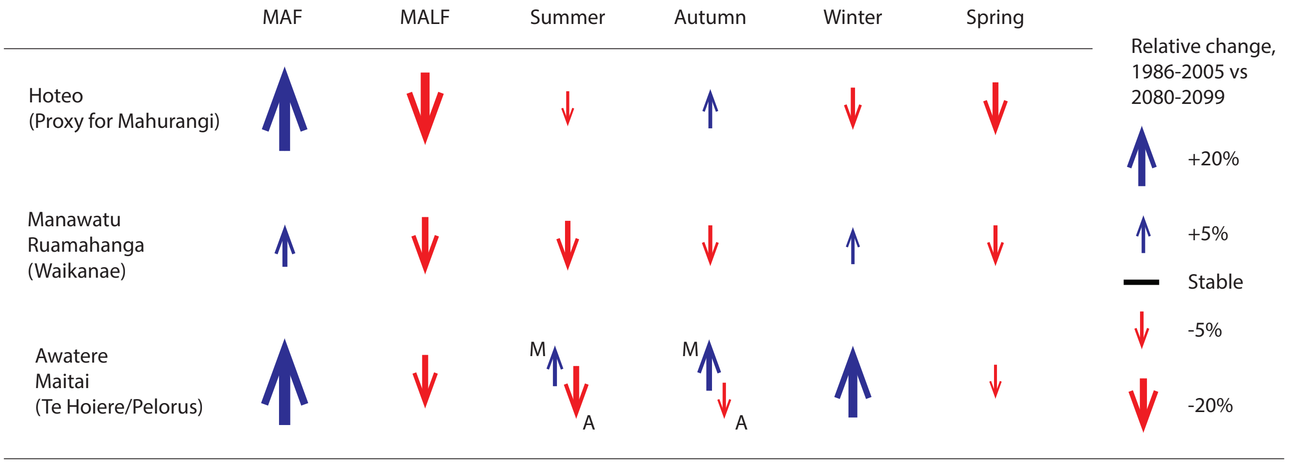


Figure 4-58 *Anticipated late-century changes in mean flows (MAF = Mean Annual Flood; MALF = Mean Annual Low Flow; Summer-Spring mean seasonal flows) for the high-end RCP8.5 climate projections in modelled catchments that are close to the study catchments (Collins et al., 2020). For catchments with two neighbouring sites, values are averaged; in the case of the Te Hoiere/Pelorus river, the Awatere (A) and Maitai (M) show weak opposing trends for summer and autumn flows, but are otherwise in fairly close agreement.*

tolerances of some aquatic biota. A changing groundwater regime will have important implications for thermal regulation and recharge of oxygen and nutrients in lowland rivers. Riverbed conditions may favour the growth and persistence of nuisance algae and periphyton; the Waikanae has had occasional issues with toxic cyanobacteria in periods of drought, for instance (Hamill, 2001; Stuff, 2019).

Headwaters and hillslope environments

Changing hydro-climatic conditions will impose different stresses on different portions of the drainage continuum. In the headwater regions of mountainous and hill country catchments, the extent of perennial streams may change, as water storage is reduced over long dry summers. In combination with warmer conditions, this will alter the species composition of headwater streams along altitudinal gradients. Such changes may be particularly pronounced in mountain rivers such as the upper Pelorus/Te Hoiere, owing to the reduced extent and duration of snow cover, reducing the magnitude of nival flood events.

The alteration of regional weather systems may lead to more intensive cyclonic activity, with disproportionately high impact on areas that are prone to major storm events. Crozier (2005) has pointed to the phenomenon of multiple-occurrence landslide events (MORLEs), that have impacted the Manawatu and East Coast regions. During these events, thousands to tens of thousands of landslides may be triggered by storm rainfall, with critical intensities governed by the prevailing antecedent moisture conditions or rainfall duration. The landscape may take decades to recover from the cascade of sediment released in such events (Tunnicliffe *et al.*, 2018).

Transfer Zone

Further downstream, rivers within the major valleys may be impacted by surplus or deficit of sediment yield from tributary systems. A regime of more intense storm events will result in proportionately higher sediment yield from various source areas in the landscape.

Extended periods of lower incidence and intensity of storm events leads to a changing aquifer conditions and soil-water balance: soils may dry out sooner, leading to a lower contribution to base flows, and regulation of stream temperature over the summer months. Reduced rainfall, especially paired with water extraction pressures, leads to reduced entrainment of bed material and turnover of the river bed, which may gradually alter the benthic environment. Extended low flows lead to enhanced conditions for the attachment and growth of nuisance periphyton. It may change the overall longitudinal assemblage of macroinvertebrate fauna in the riverbed substrate. Changes to the flow regime can also promote the invasion of introduced floodplain species that can tolerate the modified flow conditions (Bunn and Arthington 2002); gorse, broom and lupin are notable cases in Aotearoa New Zealand.

Lowland Rivers and the Coast

For large coastal rivers and wetlands, a changing hydrologic regime paired with sea-level rise is likely to affect low-lying coastal freshwater systems, as intruding seawater changes the saline balance. Obligate freshwater species will be replaced by more marine-tolerant biota as the sea invades these freshwater ecosystems (Kingsford *et al.* 2011).

More intense flooding in large river systems may shift the extent of floodplain inundation, which may have implications for riparian floral and faunal communities, as well as altering hazard zoning for humans. More frequent episodes of lateral adjustment of the river may occur, including the switching of channel course (avulsions), which may further alter biotic conditions along the riparian corridor.

The extent of aquifer zones, and the flow of groundwater through the river's parafluvial zone may change in protracted dry conditions. Gray and Harding (2009) have highlighted the great importance of upwelling springs as centres of invertebrate biodiversity within braided river floodplain environments. Flows in braided rivers flows are shallow and wide; reduced annual flows may disproportionately reduce the active width of these systems, relative to rivers with deeper and more defined channels.

4.3 Outcomes for River Conservation

The study catchments offer a range of insights into the diversity of New Zealand river settings, from steep bedrock gorges, to unconfined rivers in broad valleys or tidally-controlled estuaries. The desktop analyses outlined above can help to develop strategic (proactive) initiatives for Ngā Awa rivers, with a rational approach to prioritisation and an accompanying evidence base. By layering information on river typology and connectivity with conservation issues that have been identified within each catchment it becomes possible to collaboratively develop targeted interventions, avoiding any wasteful expenditure.

Restoration Strategy

Restoring interlinked catchment and river processes and nurturing the key morphological feedbacks required to sustain ecosystems is perhaps a more challenging process than literature on the topic might convey. Developing a solution that is appropriately tailored to the unique environmental and ecological conditions in each catchment requires a great deal of exploration and weighing of available options, trans-disciplinary technical input, and broad agreement on achievable outcomes. Priorities for protection should include refugia, key habitats and dispersal corridors for aquatic species (Turak *et al.*, 2011). The plan must extend to a full range of species in the area and should ensure the persistence of all the area's biodiversity attributes. Ideally the full range of biodiversity should be represented within the chosen area (Pressey, 1998; Linke *et al.*, 2011).

Historically, approaches to river restoration in New Zealand have largely been 'passive', involving measures such as livestock exclusion from riparian areas, fencing or diversion of sediment sources, or reforestation of pasture (Dodd et al. 2009; Greenwood et al. 2012; Holmes, 2019; Mckergow et al. 2016; Parkyn *et al.* 2003; Wahl et al. 2013). More active measures such as re-establishing river floodplains, bank contouring, instream addition of structural habitat such as large woody debris are much less common, but there is growing interest in such measures. By expanding fluvial 'process space', resilient ecosystems may be restored naturally, with minimal corrective intervention (Ciotti *et al.*, 2021). 'Working with the river', enhancing natural fluvial processes and feedbacks, holds important potential for restoring functionality in a cost-effective manner, particularly in the face of disturbance and climate change (Fuller *et al.*, 2019).

Coutts and Urlich (2020), in their investigation of local attitudes to river rehabilitation in the Te Hoiere/Pelorus river, point to the problem of "shifting baseline syndrome" (Pauly, 1995), where the next generation assumes the degraded environment is normal, and therefore its diminished state is accepted. Even for experts, it can be difficult to know what has been lost, and what the original state of the system was. Many profound changes occurred before the first systematic airphoto coverage of the country. In New Zealand, the remaining patches of analogue wetland and headwater systems, in particular, are important for re-establishing the diversity of riverine habitats and the web of connective links in these systems. The Ngā Awa programme provides an opportunity to better characterise some of these systems and can help to refine restoration targets.

Further Monitoring, Modelling and Emerging Priorities

Effective monitoring of river rehabilitation programmes is a prerequisite for appraisal of successes and failures. Unfortunately, the short-term nature of many restoration projects and associated funding, a lack of 'requirement' to undertake monitoring, and limited baseline information can limit the flow of information from restoration works. The Ngā Awa programme is positioned well to advocate and facilitate longer-term monitoring work that targets key indicators of river restoration. The three rivers in this report all have good historic datasets (Section 3), and good prospects for continued monitoring work. The rivers have datasets that include most of the following:

(1) The condition of river corridors, including stock fencing, bank conditions and riparian conditions. Indices of canopy density, light penetration and stream temperature provide a vital complementary dataset. The River Styles maps in this document can be field-checked, further refined, and linked to riverine species distribution and habitat conditions in the rivers (*e.g.*, Fryirs *et al.*, 2021).

(2) Surveys of bed substrate condition, grain-size composition and periphyton. Habitat potential is closely linked to the character and quality of substrate. The dataset is also of considerable value for modelling work, as it can be used in calculations of hydraulic resistance, sediment entrainment and transport capacity.

(3) Maps of historic channel change, derived from historic imagery. Work should be suitably focused on dynamic reaches (actively meandering or braided rivers). These can be used to assess long term trends of channel adjustment and rates of bank erosion. Recent work by Boothroyd *et al.* (2021) highlights the potential of Google Earth Engine and other remote-sensing platforms. LiDAR data provides an opportunity to delineate the extent of paleo-streams and relict floodplains obscured by past disturbances and modern landuse,

(4) A compilation of engineering river works carried out over the years; there appears to be a reasonably intact record from local councils in some cases (*e.g.* Waikanae River) but others have large gaps in the detail and chronology. Historical cross-section surveys are not always available, but even a sparse dataset can show the long-term trend of river adjustment.

Some additional works that could enhance the capacity for exploring scenarios of future river behaviour and informing river management include:

(5) An inventory of mass-wasting processes over time. The sediment budget for the system can be elaborated with a careful reconstruction of landslide and other mass-wasting occurrences in the catchment. A dataset spanning a few decades can provide insight into the spatial patterns and temporal persistence of these disturbances, and the transit time of materials through the landscape. This could be particularly useful for understanding the vulnerability of a system to rare high magnitude impacts (e.g., from MORLEs under climate change). Coupled with modern surveys of the lower river course, a balance of sediment flux can be deduced.

(6) Rainfall-runoff modelling, using widely available and open-source software such as SWAT, HEC-HMS or PRMS can be used to assess changes in runoff characteristics that might be achieved through changes in landuse. The relative benefits derived from various landuse scenarios can be explored by iteratively changing the modelled land cover characteristics of the catchment.

(7) More detailed hydraulic modelling of river flows (e.g. HEC-RAS, Delft3D, NAYS2D; *cf.* Figure 4-55) can be used to assess the flooding characteristics of rivers, connectivity with the adjacent floodplain, and the relative abundance of refugia in high- and low-flow (drought) conditions.

(8) Following from (7), slightly more sophisticated morphodynamic models can be used to assess sediment transport potential and morphological change in riverine and estuarine environments. These models are rarely able to accurately predict precise future morphologic changes, but they can provide good insights into the general trends of change based on different forcing conditions. This would be a good initial step in formulating 'process based' restoration initiatives. This would also provide good insight into the effects of gravel extraction.

With a balance of desktop techniques and more extensive field study, the priorities for river restoration can be established. Ensuring river network connectivity for nutrients, organic matter and for organisms at all life stages is a holistic basis for setting priorities: many project opportunities may flow from analyses related to this.

At the next level, linking river morphology processes with local governing conditions such as stream power or bank conditions on the river will help in assessments of which river reaches may be most susceptible to impacts, either by natural or human disturbance. Having an inventory of river morphology types will help to link this to biodiversity aims and overall habitat availability. It may also help to identify where resources can be directed to achieve the maximum results with minimum effort and expenditure - some measures may be relatively easy to achieve with stakeholder involvement.

Finally, the programme will help to identify thresholds and tipping points, where restoration efforts can yield substantial and sustained improvements in ecosystem function, and where more dedicated resources may be required to achieve results. Approaches to restoring and revitalising natural river systems continue to evolve, and Ngā Awa will be well-positioned to advance application of new techniques in a variety of river environments across Aotearoa New Zealand.

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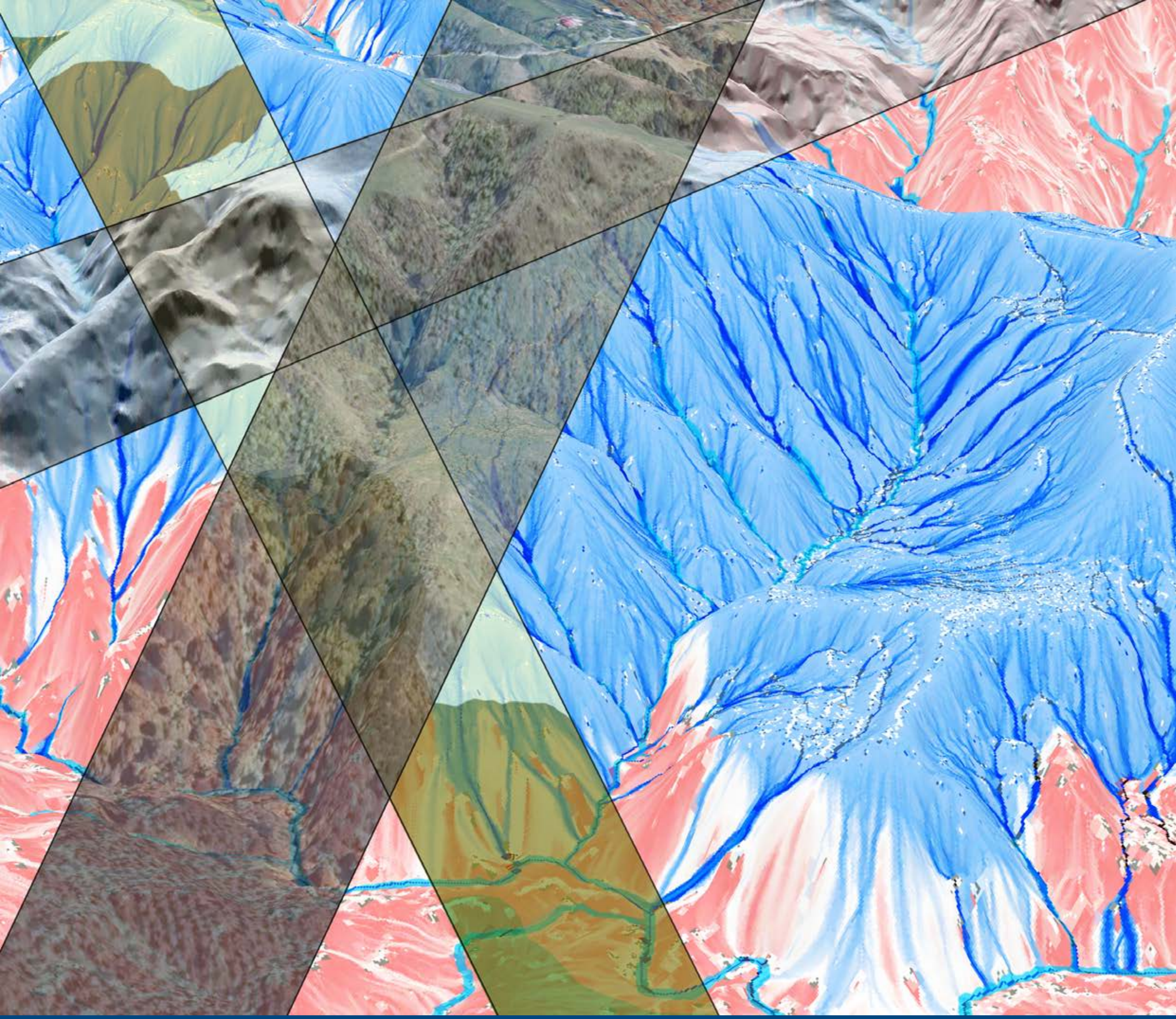

The report provides an overview of river geomorphology and the remote assessment of sediment connectivity, river network dynamics and reach classification. From a conservation perspective, it is important to ascertain the diversity of river forms within a catchment and the habitat potential within these river types. By overlaying multiple layers of landscape information, it is possible to assess which sites may be vulnerable to the effects of land use factors such as forestry, farming, urbanisation, as well as longer-term shifts arising from climate change. Through the use of remote sensing and desktop tools, a framework for planning and decision making can be developed in the context of the Department of Conservation's Ngā Awa Programme.

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