Integrating Process-Based Assessments of River Sensitivity through River Styles and Semi-Quantitative Sediment Connectivity Modelling to Inform Land Use Management in the Waimatā Catchment, Gisborne, New Zealand.

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Abstract

Identification of sediment sources, delivery pathways and storage sites can support the management of sediment issues in a catchment. The combination of high sediment yield in mudstone dominated tributaries and headwater reaches, and efficient delivery pathways have resulted in sedimentation issues in the lower reaches and beaches feeding from the Waimatā River at Gisborne. Analysis of patterns and processes was conducted using the River Styles Framework. Areas of high capacity for adjustment were differentiated as transfer and throughput reaches. Erosional and depositional features with a high capacity for adjustment were characterised in the transfer reaches. At the same time, throughput had a low capacity for adjustment and effectively flushed sediment through the system resulting in the Waimatā behaving like a sediment flume. Connectivity modelling highlighted the influence of land use on the potential for sediment generation and transport. High connectivity is exhibited in steep slope and low vegetated areas, whereas low connectivity is evident in low slope or densely forested reaches. These patterns were further illustrated using a sediment delivery model (CASCADE), which showed that highly connected reaches were often entrainment dominated, whereas low connectivity areas represented depositional areas. Lastly, the influence of changing land use was demonstrated for three land use scenarios. The forest removal scenario highlighted the influence of forest cover on sediment generation, as recently deforested areas had a dramatic shift from low to high connectivity. The two regeneration scenarios showed contrasting patterns, where reforestation promoted hillslope stabilisation, and the introduction of barriers, such as wetlands, resulted in sediment sinks. Ultimately, assessments of connectivity and River Styles demonstrate a multifaceted approach to assess catchment scale linkages of reach characteristics to support management applications.

The cover image depicts the Waimatā flats looking towards Mahia Peninsula

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Chapter One: Introduction

1.1 Context

As a result of its weak lithology, land use change, and frequent high rainfall, river systems on the East Cape of New Zealand have some of the highest sediment yields in the world (Hicks et al., 1996). Ongoing concerns for sedimentation issues in the Waimatā Catchment have prompted significant community interest in restoration initiatives, including the Waimatā Catchment Restoration Project and Waikereru Ecosanctuary. Since the early days of European settlement, land use practices in the Waimatā have included deforestation, afforestation, sheep and beef farming, and forestry (Cullum et al., 2016). The resulting biophysical changes have altered the sensitivity and resilience of the catchment, with accentuated erosion and significant landscape coupling (hillslope-valley floor and upstream-downstream sediment connectivity) have increased sediment delivery to the river mouth (Gundry, 2017; Marden, 2012). Periodic hillslope failures in response to logging activities from the late 1800s occasionally blocked off bridges and roads (Salmond, 2016). Reduced rainfall interception and decreased root stabilisation promoted increased soil runoff which led to widespread floodplain sedimentation and adjustments to channel planform (widening) and geometry (aggradation and scouring) (Marden, 2012). Dr Doug Hicks of Landcare Research commented: "In the Waimatā catchment right up in the headwaters, virtually nothing is stable" (Waimatā Catchment Erosion Management Project, 2015). Gullies, sheet wash, bank erosion, and landslides have sculpted the landscape. As the Waimatā River runs from forestry and farmland through suburbs to the beach, aggradation of the river floor and sediment and forestry deposits plagues the beaches of Gisborne to Tolaga Bay (Waimatā Catchment Erosion Management Project, 2015). In light of this situation, a catchment-wide approach to the analysis of sediment sources, sinks, and transfer pathways can help inform the management of the Waimatā.

Catchment responses to disturbance and the efficiency of sediment conveyance are influenced by landscape configuration (Brierley and Fryirs, 2009; Walley et al., 2018). Understanding hillslope-channel interactions are imperative to determine sediment delivery and flux patterns and rates through a system (Kasai et al., 2005). Depending upon river type, rivers adjust in different ways to change boundary conditions, including land use changes (Brierley and Fryirs, 2005). Coupling and decoupling processes within and between hillslope and channel compartments significantly influence these relationships (Fryirs et al., 2007a; Harvey, 2002; Hooke, 2003; Kasai et al., 2005). Analysis of within-catchment variability in geology, climate, and land use conditions is vital to explain the sensitivity and resilience of a river system (Harvey, 2002; Kasai et al., 2005).

Sediment flux in river systems can be described as a 'jerky conveyor belt,' shaped by variability in flow energy and capacity for a system to transport sediment through a network (Fryirs et al., 2007b; Kondolf, 1994; Schumm, 1977). The availability and delivery of sediment to the channel network directly influences these relationships, which behave markedly in different landscape settings, in relation to variability in landscape history, lithology, and topography (as outlined in Brierley et al., 2006; Fryirs et al., 2007b). Controls upon sediment flux and connectivity vary across different spatial and temporal scales (Borselli et al., 2008; Bracken et al., 2015; Cavalli et al., 2013). Hooke (2003) and Borselli et al. (2008) show that sediment transport and production are dependent on catchment physiography and the spatial organisation and internal connectivity of landforms.

Sediment connectivity helps determine the rates and quantity of sediment moving through a river system over time (sediment flux). The operation of sediment cascades reflects the catchment configuration and connectivity relationships (Fryirs et al., 2007b). Landscape connectivity is the efficiency of sediment conveyance from source to sink (Bracken et al., 2015; Fryirs et al., 2007b). Both structural (imposed) and process-based (flux boundary) controls underpin long term behaviour of sediment fluxes, shaping the formation of landforms (Bracken et al., 2013, 2015; Turnbull et al., 2008). Efficient sediment delivery and high sediment flux rates occur in landscapes with coupled hillslopes and valley floors (Kasai et al., 2005; Houben, 2008). Forest management affects hillslope-channel coupling, with clearance and subsequent scrub growth altering patterns and rates of sediment delivery to valley floors, mainly through landslides and gully complexes (Kasai et al., 2005). Similar responses may be observed in response to drainage of upland swamps (Fryirs & Brierley, 2001). In extreme instances, inputs of sediments can widen active channels and form sediment slugs (Madej, 2001; Nicholas et al., 1995).

Forestry management is a critical social and political issue in the Waimatā catchment. As a result of contaminant discharge, one of the forestry companies, Arutu Forestry Limited, was recently fined up to $379,500 by Gisborne Council under the Resource Management Act (Curtis, 2020). Current land use in the catchment is dominated by pasture and exotic pine plantations. Recent logging activity in the upper catchment induced profound off-site implications at the coast in the form of sedimentation and woody debris.

The landscape model proposed by Schumm (1977) differentiated sediment source, transfer, and accumulation zones as catchment compartments. Since the initial conceptualisation of the sediment delivery problem by Walling (1983), there has been significant progress in modelling soil erosion and sediment transport (Vente et al., 2008). Lexartza-Artza and Wainwright (2009, 2011) enhanced the understanding of sediment connectivity relations through an appraisal of rainfall-runoff relationships that acknowledge the generation and transmission of sediment in events of differing magnitude, frequency, and recurrence. A conceptual approach developed by Fryirs et al. (2007a) categorises different types of landscape disconnectivity. Fryirs (2013) argues that the strength of spatial linkages under various magnitude frequency events switches sediment connectivity on or off. Building on these principles, Schmitt et al. (2016) developed the CASCADE model to quantify the impacts of network configuration and spatial variability in sediment inputs upon sediment conveyance through a catchment. This application was enhanced by developing the CASCADE Toolbox (Tangi et al., 2019), allowing multiple scenarios to model sediment flux under different land use scenarios, sediment types/grain sizes, and roughness conditions.

The CASCADE Toolbox provides a means of quantifying and visualising sediment connectivity developed for sediment management and geomorphic studies in large river systems. CASCADE represents sediment transport from many individual sediment sources in a river network as a unique cascading process for each source. This allows for tracking sediment originating from a specific source and sediment provenance, i.e., sediment is delivered to a downstream reach. This study uses the CASCADE Toolbox to reconstruct past sediment flux behaviour and predict what may happen under different boundary conditions into the future. It relates these applications to the Connectivity Index (IC) developed by Borselli et al. (2008), which provides a means to move from qualitative to semi-quantitative evaluations of sediment transfer across a landscape. Due to the difficulty in directly measuring sediment delivery (Heckmann et al., 2018), connectivity indices have been developed to infer potential sediment movement in a catchment. The IC combines the influence of upstream contributing areas and the influence of sediment impediments to the delivery of sediment in a catchment. Figure 1.1 outlines relationships between laterally and vertical linkages across a landscape.

To date, data availability (quality) and the inability to include all relevant erosion and sediment transport processes impede accurate prediction of sediment transport at the catchment scale (Merritt et al., 2003; Vente et al., 2008). However, combining high-resolution LiDAR data and comprehensive grain size data for the entire catchment presents an opportunity to bridge this gap. Alongside this, the IC helps to visualise potential sediment movement in a system, supporting restoration initiatives. This analytical approach models the contribution of upstream and downstream impeding forces for a given cell in a Digital Elevation Model (DEM). These two separate ways of visualising sediment transport and connectivity will produce a more comprehensive picture of sediment flux in the Waimatā catchment.

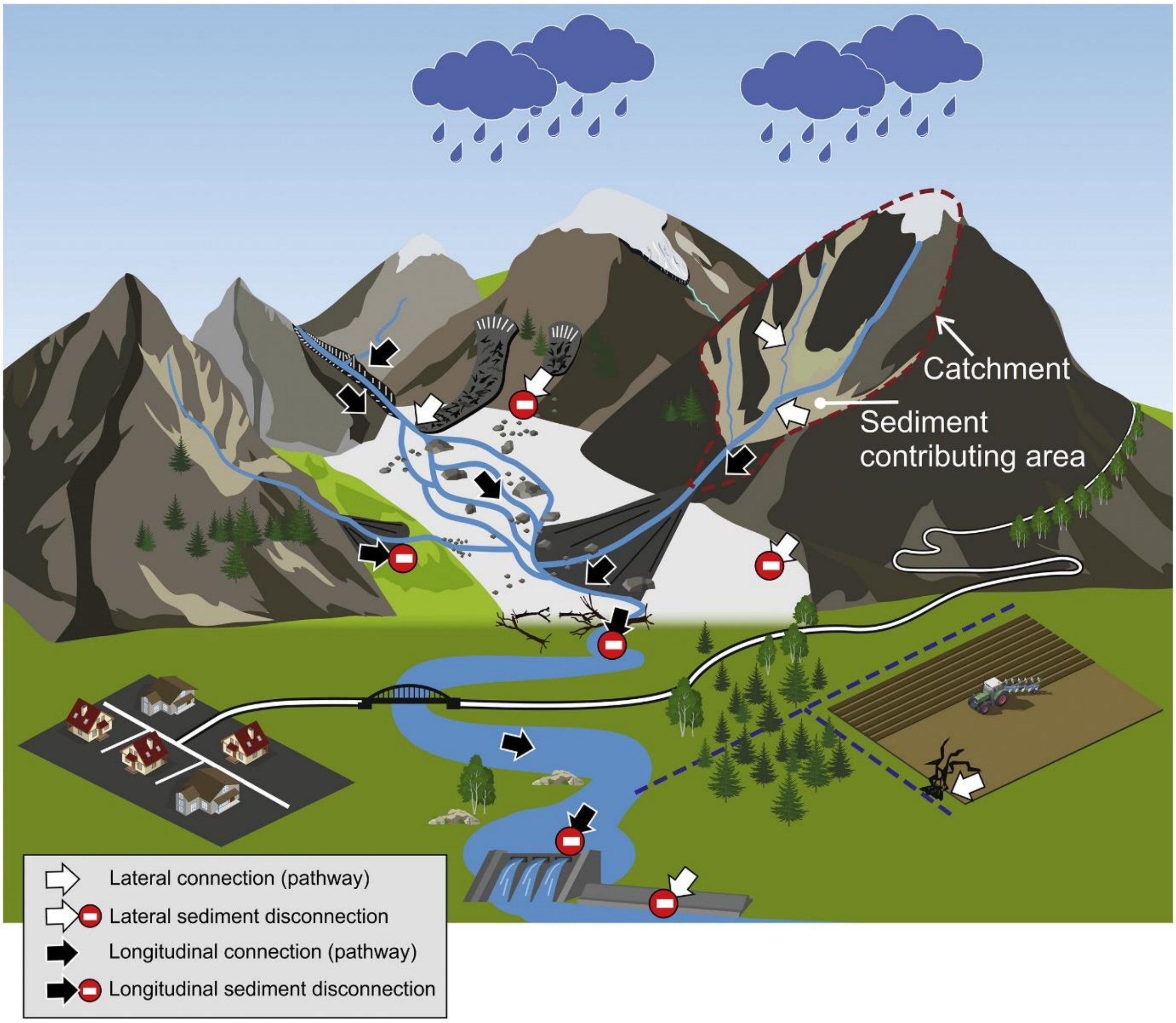


Figure 1.1 Schematic of sediment (dis)connectivity and intrinsic and geomorphic controls on sediment delivery relationships (From Heckmann et al., 2018).

Topography and slope are fundamental intrinsic structural properties that influence sediment connectivity in the catchment (Heckmann et al., 2018). These factors influence flow velocity, storage capacity and roughness (Heckmann et al., 2018), with impacts on microtopography exerting the most significant influence on sediment connectivity (Darboux et al., 2002; Heckmann et al., 2018). Soil surface characteristics such as soil texture, organic matter and soil cover by items such as stones partially determine the roughness of a system (Heckmann et al., 2018). The erosivity of a slope is determined by the type, texture and vegetation cover, with silty loams and fine sandy loams being notably erosive. In contrast, clay and silty clay loams are more resistant as cohesive bonds hold the soil together (Middleton, 1930). Therefore, local variability in soil type directly influences the sediment yield for a catchment or reach. Slope directly affects the processes that drive sediment connectivity, such as flow velocity and transport capacity (Heckmann et al., 2018), which can facilitate or eliminate the production of surface roughness and storage capacity—exploring how these different boundary controls that govern connectivity, and resulting sediment flux, is underdeveloped in literature (McMahon et al., 2020). This study uses a multiple scenario approach that assesses how the river responds to changing boundary conditions to address this gap.

Changing conditions are common themes in surrounding catchments, such as the Waipaoa catchment, specifically the Tarndale gully complex. Gully complexes have been estimated to contribute most of the sediment in East Coast catchments (Hicks et al., 2000; Marden et al., 2008, 2014; Taylor et al., 2018). As gullies enlarge, erosion processes combine such that surface erosion is enhanced by mass movement processes comprising debris flows, deep-seated and shallow land sliding. Work by Taylor et al. (2018) builds on previous work in the Tarndale gully to provide more accurate quantifications of annual sediment delivery characteristics. This study aimed to address the call by Fuller and Marden (2011) for further work to provide a more holistic appraisal of sediment connectivity and define processes responsible for sediment transfers in the active headwater reaches. This gully was of interest due to its changing conditions, including the reductions in slope stability and rapid gully expansion (Marden et al., 2012; Marden et al., 2014). Extension of the fan at the toe of the gully has provided an effective conveyor from the gully to stream (Fuller and Marden, 2011), subsequently aiding in increasing lateral sediment connectivity. Although gully complexes aren't as extreme as in the Waipaoa, similar sediment characteristics, climate, and land use provide insight into the potential situations if slope destabilisation were to increase.

The physical properties of individual reaches shape river responses to changing sediment inputs in the form of degradation and aggradation. The Waimatā exhibits extensive reach variability, with areas of degradation shortly followed by aggradation due to sharp changes in valley confinement, human alteration and geology. Catchment wide appraisals of river types have been completed using the River Styles technique to appraise changes in valley shape, confinement and planform control on reach sensitivity (Brierley et al., 2006). The emphasis in this study is placed upon differentiation of throughput and transfer reaches, showing how the sinuosity, valley confinement, and sediment availability influence the capacity for adjustment in a reach. An example of adjustment potential for different forms of geomorphic adjustment is highlighted in Figure 1. 2

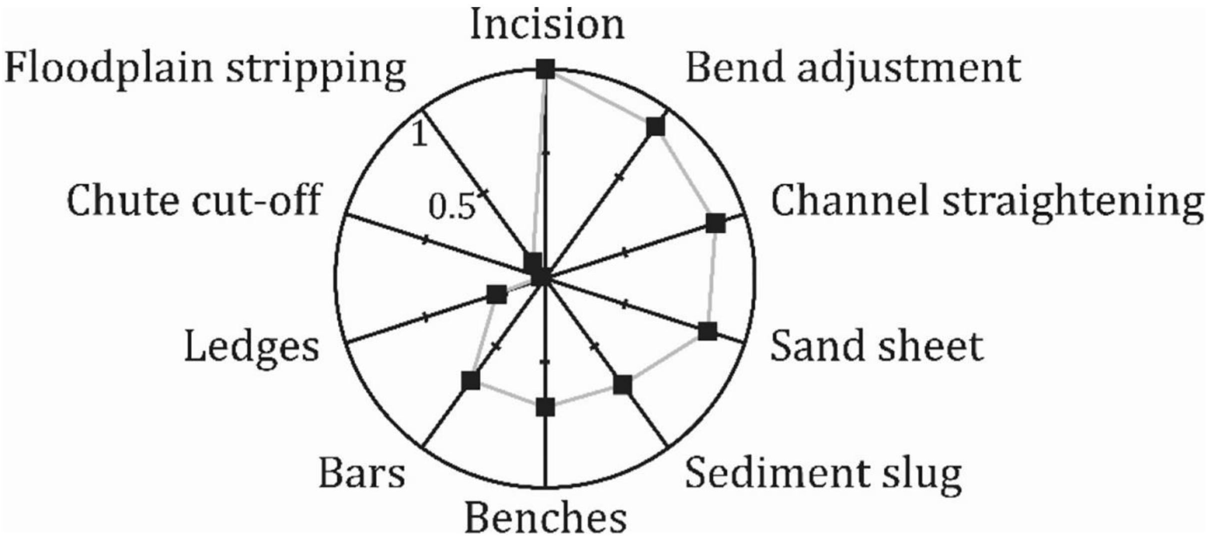


Figure 1.2. Normalised adjustment potential (P) was calculated for various geomorphic adjustments identified along rivers in the Richmond catchment (From Khan and Fryirs, 2020).

A systems approach at the catchment scale provides a tool to organise research in a hierarchical manner (Piegay, 2016). Reductionist approaches to these systems do not provide enough insight into the forms and processes underpinning geomorphic response (Piegay, 2016). Thus, a process-based approach to reading the landscape is required for in-depth analysis of temporal and spatial timescales of adjustment (Piegay, 2016; Lisenby et al., 2019). A significant issue in geomorphology is scaling up small scale erosion rates. Therefore, applying theories to an entire catchment is difficult as there is often no linear extrapolation of these processes (Bracken et al., 2015). Each compartment of a system is unique and has individual rates of landscape development (Bracken et al., 2015). Issues in the lower areas of a catchment are often a product of erosional processes occurring in the upper and transfer reaches of a catchment. Therefore, applying catchment approaches to reading and analysing the landscape are required to gain in-depth knowledge of sedimentation processes throughout the system. This study will use this approach by integrating a catchment scale model of sediment transport and reach scale analysis of these processes.

Land-use changes and erosion controls works may induce strong geomorphic responses in catchments. This can be reflected in the morphological evolution of river channels and responses within surrounding catchment areas, which must be understood in a historical and evolutionary context (Dollar, 2004). Otherwise, the ultimate controls on changes of river form and processes will not be fully appreciated (Boix-Fayos et al., 2007). Moreover, river management must be grounded in information on physical river characteristics specific to a catchment (Toriman et al., 2009). Remote sensing and GIS can aid in observing key geomorphic processes, such as avulsion, channel straightening/cut-offs (sinuosity), and modelling potential sediment transport rates and pathways.

This study will evaluate changes in geomorphology in response to land use changes, namely forestry and pastoral land use. This will be completed using remote sensing/GIS analysis and sediment modelling. Where GIS techniques will be used to visualise channel and land use changes, and modelling techniques will aid in reconstructing sediment flux dynamics in the past, present and future. Determining sediment flux dynamics from past land use scenarios can provide a potential set of boundary conditions in which the river adjusts and how sediment has behaved within those conditions. Therefore, having a basis for how a river has responded in the past can lead to potential predictions about how it may react in the future—subsequently providing catchment managers with a guideline of how their catchment sediment may respond to different land use changes in the future. Moreover, this thesis aims to contribute to the academic literature by building on existing frameworks, such as sediment connectivity and sediment flux, by incorporating different elements, such as land use change, sediment connectivity and future sediment flux trajectories based on these different scenarios.

This thesis aims to provide insight into how different methods of predicting and modelling sediment flux will contribute to management in rivers with sedimentation issues. Seeking information from past boundary conditions and how the river has responded compared to now will provide a basis for building upon and predicting future trajectories. Ultimately, the data and modelling should show that future land use scenarios which possess similar boundary conditions to those in the past should result in similar sediment flux behaviour. Past reconstructions of sediment flux are reflected in bank stratifications, showing similar levels of aggradation or degradation as shown in past sediment transport simulations. Changes to land use alter morphological properties of a catchment by either promoting degradation or stabilisation, both of which are exhibited throughout the Waimatā Catchment. Therefore, modelling how these changes have altered catchment dynamics in the past and present will help predict future trajectories the Waimatā may take.

1.2 Study Aims

This study aims to assess the effect land use has on sediment flux behaviour throughout the Waimatā Catchment. The Waimatā Catchment is the product of changing landscapes and cycles of erosion and deposition. Large terraces span considerable lengths of the river margin, resulting in unique patterns of connectivity and planform change. Beyond assessing the patterns and rates of sediment transport in the Waimatā, new data coverage for the East Cape region provides the opportunity to compare two model performances with different data resolutions. The MATLAB toolbox add in CASCADE Toolbox developed by Tangi et al. (2019) and the Connectivity Index developed by Borselli et al. (2008) are used. In addition to assessing model outputs, River Styles assessments of the catchment are revisited. Combining the quantitative results from the models with the infield and aerial assessments from the River Styles analysis provides a basis to appraise management techniques. By grounding potential management in scenario-based planning, targeted and prioritised management is likely to be more effective. The following key questions are addressed in this thesis.

1. How do River Styles change throughout the Waimatā catchment, and what does this mean for sediment behaviour?
2. How does data resolution affect modelling outputs that appraise sediment connectivity?
3. How do differing land use scenarios and impact sediment flux behaviour in the Waimatā Catchment?
4. How can the combination of modelling and grounded geomorphological assessments support prioritised management options based on viable modelling assumptions?

Two models of sediment connectivity are tested to address these questions, with differing data resolutions and land use scenarios.

Specific thesis aims include:

1. Identify the pattern of sediment movement in the Waimatā River and the significant controls upon it
2. Identify how particular River Styles operate as throughput and transfer zones that influence patterns and rates of sediment conveyance and resulting patterns of degradation and aggradation in the Waimatā Catchment?
3. Investigate the role of data resolution on model outcomes, analysing the importance of the study scale in relation to the data resolution.
4. Use two modelling applications to manipulate differing boundary conditions (land use, external sediment inputs) to interpret catchment-wide appraisal of sediment connectivity to support management applications.

The thesis is structured as follows. An overview of past and present morphology, climate, land use and vegetation composition will be completed in chapter two, regional setting. This chapter will also set up the context for site selection in the Waimatā, highlighting ongoing sedimentation issues and the influence of land use on sediment connectivity. This is followed by a critical review of the literature surrounding sediment connectivity, sediment connectivity modelling and their respective management applications in chapter three. Chapter four will outline the methods used to bridge the gaps in the literature and answer the questions proposed in section 1.2. The results chapter will then present key findings of these methods and highlight themes in the Waimatā regarding capacity for lateral adjustment, connectivity relationships, and land use influence from the three scenarios. Chapter six will then build on these critical findings and contextualise them in relevant contemporary literature. This will highlight the similarities the Waimatā has to other catchments, identify the complexities of the system on its own, and suggest future study opportunities. Finally, chapter seven will summarise the key findings, patterns and processes underpinning landscape development and sediment connectivity in the Waimatā.

Chapter Two: Regional Setting

The Waimatā river drains a sizeable hill-country catchment of approximately 370km2 north of Gisborne City. Before discharging into Poverty Bay, it joins the Taruherui River in the Gisborne CBD, forming the shortest river in the Southern Hemisphere, the Turanganui River (Forbes et al., 2018). With a length of 20km, the Waimatā flows through farmland, forestry and urban centres, resulting in diverse morphology throughout the catchment.

2.1. Geological Setting

The underlying geology of the Waimatā greatly influences rates of uplift, adjustment and sediment flux. New Zealand's east coast rivers experience some of the highest sediment discharge and uplift globally due to weak lithology and heavy rainfall (Orpin, 2004). This applies to the Waimatā, where the catchment consists of soft geology and lithology, aiding in its high sediment yields, commonly causing sedimentation issues throughout the catchment (Cullum et al., 2016). Figure 2.3 outlines the dominant geologies of the Waimatā catchment. Miocene to Pliocene interbedded sandstone/mudstone and mudstone with sandstone and limestone intrusions dominate the catchment (Marden et al., 2008). The steep slopes of the Waimatā characterise this with less susceptibility to mass movements. However, smectic clays allow for water absorption, meaning the rock will shear easily when water is presently facilitating the formation of earth flows (Cullum et al., 2016). Mudstone is the dominant lithology, with intrusions of well-bedded alternating sandstone and mudstone with shelly muddy sandstone (Mazengarb and Speden, 2000). Extreme gully erosion and earth flow extend towards the headwaters of the Waipoa and Waimatā. These correspond to strongly fractured and faulted rocks, including smectic clay stones. These rocks are juxtaposed, and the topography forms a hummocky appearance (Mazengarb and Speden, 2000).

The nature of discharge of suspended sediment reflects the quantity of material delivered from hillslopes and channel sources throughout the catchment (Bowie and Mutchler, 1986; Hicks et al., 2000). Understanding the sources and processes contributing to these sediments will help determine the delivery rate to the stream channels and formulate sediment budgets (Reid and Dunne, 1996; Hicks et al., 2000). Establishing links between these erosion processes and sediment sources can be identified through signatures of the dominant erosion processes in the relationship between sediment concentration and water discharge, the load distribution by flow interval, and the magnitude-frequency characteristics of event sediment loads (Hicks et al., 2000). Hicks et al. (2000) outline the features of river sediment in the adjacent Waipaoa River Basin. They identify the region showing higher storm rainfall required to activate landslips and gully erosion. Due to the catchment consisting of fine-grained sedimentary rocks or well-crushed greywackes and argillite that yield an abundance of fine, silt-clay grade material (Hicks et al., 2000), the suspended load will far exceed bed load.

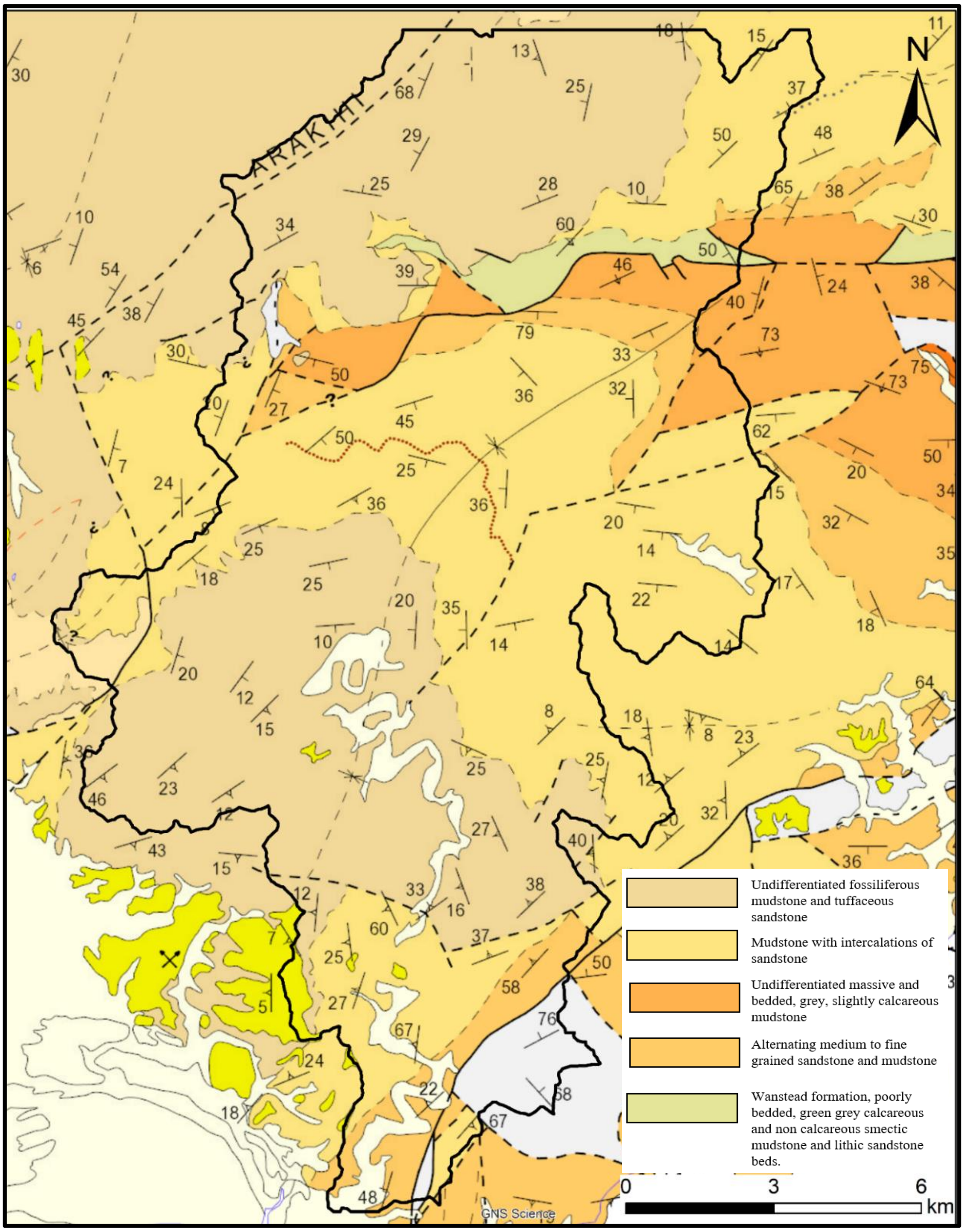


Figure 2.1 Regional underlying geology for the Waimatā Catchment. (adapted from Mazengarb and Speden, 2000)

2.2. Regional Climate and Climate Change

Gisborne is located on the East of New Zealand's North Island (Figure 2.2). Its position as the easternmost region of New Zealand results in differing weather conditions from those elsewhere. The climate is generally congenial, with high sunshine and low mean wind speeds (Chappell, 2016). Uneven rainfall distribution throughout the year, with high winter and low spring, often affects growth and limits agricultural activity. However, the Gisborne climate is suitable for beef cattle, sheep, forestry and viticulture (Chappell, 2016). Yearly averages have been recorded by Lawa (2019) as 1000mm.

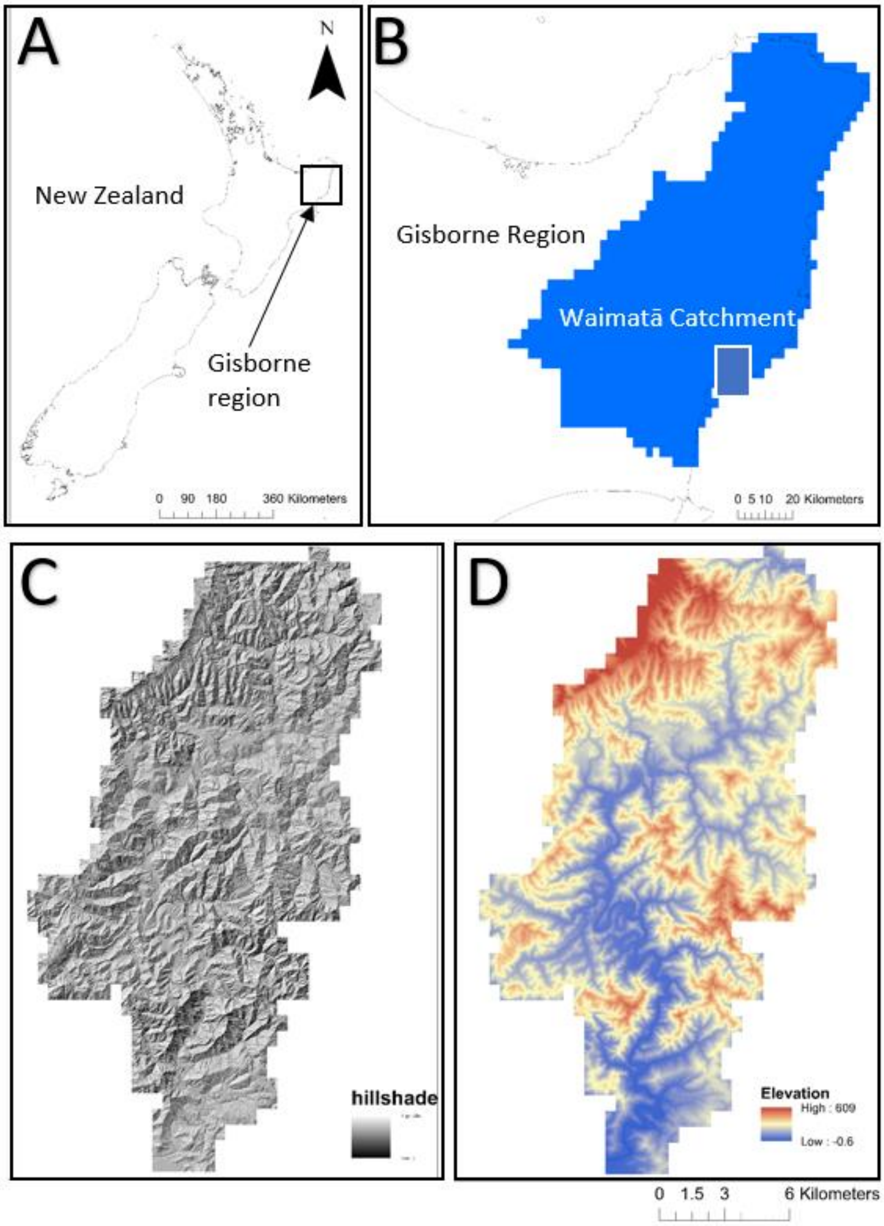


Figure 2.2. A) Location of Gisborne in relation to New Zealand. B) Gisborne region C) Hill shade showing topographic features D) Elevation.

The Waimatā catchment exhibits frequent landslides and flooding due to its susceptibility to cyclones from March to May (Cullum & Brierley, 2016). High rainfall underpins landscape evolution and sediment flux in the area. Throughout the Quaternary, climate fluctuation has sculpted contemporary landscapes (Newnham et al., 1999), for example, a reworking of fluvial terraces spanning much of the river (Berryman et al., 2000). The Pleistocene's climate and sea-level fluctuations have shaped relief, sediment dynamics, and terraces in the Waimatā. With Sea level being approximately 120m lower during the Last Glacial Maximum (14,700 ya), incision rates have fluctuated from high to low, where floodplains were able to form (Cullum & Brierley, 2016). High incisional periods exhibited high erosion, hillslope steepening, and valleys had large deposits of sediment. Imprints of these fluctuations can be seen today, with large terraces spanning the length of the river, with noticeable stratification and changes in facies (Cullum & Brierley, 2016).

The transition from natural landscapes to ones dominated by anthropogenic activities on the land surface has accelerated the sediment flux carried by rivers (Gomez et al., 2009). It is projected that changes in climate and land use have perturbed the sediment flux and set the background to change, which is proposed to occur during the 21st Century (Goudie, 2006; Walling, 2006; Gomez et al., 2009). Forecasting these changes' effects on sediment transport is critical as it provides a pathway for global geochemical cycles and ecological communities (Martin & Maybeck, 1979). It also provides the ability to predict the flux of sediment to drainage basins and offers informed approaches for evaluating land use policy options (Ashmore & Church, 2000). The influence of climate change on fluvial sediment transport is not well documented due to the difficulty to differentiate yield from climate change from concurrent changes in catchment conditions (Walling & Fang, 2003). Similar catchment scale indigenous forest clearance in the 19th and 20th centuries has occurred in the adjacent Waipoa River, Gisborne. Gomez et al. (2009) used this catchment to model the rivers sediment transport characteristics response to climate change in the 21st Century. Their model projected a range of differences in mean annual temperature and precipitation for Gisborne from the 2030s to 2080s and showed the effect on water and suspended sediment discharge. Changes in sea-level rise, denudation and vegetation shifts from climate change in response to climate change were assessed and showed that between 78 and 96% mean flow would decline in the 2030s and between 64 and 100% in the 2080s (Gomez et al., 2009). This directly impacts the suspended sediment yield, potentially varying between 92 and 109% of its present simulated value in the 2030s and between 85 and 128% in the 2080s. The results found in Gomez et al. (2009) have direct implications for the Waimatā given its proximity and similar climatic and erosional patterns. Gomez et al. (2009) found that the results had a clear impact on management decisions. Under the 'Local Government Act 2002' and the 'RMA 1991', management decisions must avoid or mitigate adverse effects on the environment (Ministry for the

Environment, 2004), including the legacy of deforestation and the future impact of climate change. Therefore, it is imperative to consider the effects of climate change and deforestation when assessing sediment flux patterns in the Waimatā.

2.3. Topography and Geomorphology

Active subduction caused by New Zealand being situated in the middle of the Pacific and Indo-Australian crustal plates has resulted in New Zealand being a tectonically dynamic landscape (Marden et al., 2008). The Waimatā River drains the Raukamara Peninsula and is situated within the Margin of the Hikurangi subduction trench (Marden et al., 2008), where Miocene-present has proved widespread (Mazengarb et al., 1991). Uplift rates from the Hikurangi subduction margin are up to 6cm per year (Wallace et al., 2009). River terrace analysis in the region suggests regional uplift of 0.5 to 1.1 1 mm yr^{-1}, driven by subduction and active faults and folds throughout the valley (Berryman et al., 2000; Marden et al., 2008). These high uplift rates and rainfall have resulted in the East Cape having some of the highest sediment yields in the world. The Waimatā is expected to have transported 2.6km^3 since the Last Glacial Maximum, transported into the ocean (Cullum et al., 2017).

Large terraces spanning the length on the Waimatā have withstood cycles of erosion and deposition and now resist erosion, leading the river to be confined within terrace margins (Salmond, 2015). Large areas of confinement and 'choke points' result in little room for sediment storage and accommodation space. The Waimatā can be categorised into three main transfer zones and eight different land types. The three 'zones' can be defined by headwater, transfer and accumulation zones. The headwaters drain from the Raukamara mountain chain, and this area comprises steep relief and yellow and brown earths and narrow v-shaped valleys. The transfer zones include steep and low relief. These are the earth flow zones, with u-shaped valleys as well as continuous floodplains and yellow-brown earths. As the river moves from source to sink, the catchment exhibits lower relief, alluvial soil depositions, and the presence of levees and back swamps on the floodplains (Cullum et al., 2016). The longitudinal profile for the Waimatā is illustrated in Figure 2.3.

Different land types can also characterise the Waimatā: lowlands, lower earth flow, finely dissected steep terrain, medium finely dissected terrain, gently dissected terrain, upper earth flow, and steep headwaters. The Waimatā Lowlands consist of pallic soils, primarily immature pallic (PI). These soils are characterised by pale subsoils and low levels of iron oxides. Mostly derived from greywacke and schist, they have a weak structure and high density in subsurface horizons and are typically dry in the summer and wet in the winter. The Waimatā lowlands are unconfined plains with low relief and gentle slopes. They exhibit both high and low connectivity. With low connectivity between the hillslopes and channel. Whereas, there is high connectivity between floodplain and channel as well as longitudinal connectivity, where the channel sediments are interrupted by structural elements, such as knickpoints. Landslip susceptibility in this area is low. Although the area is associated with weaker soils, the low relief governs sediment flux potential.

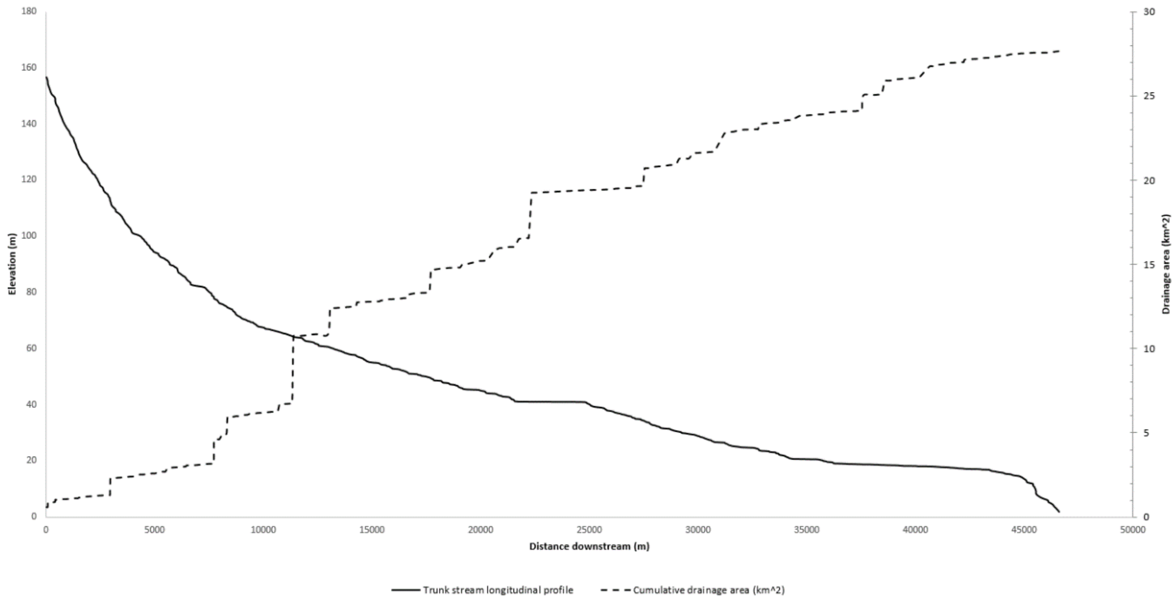


Figure 2.3 Longitudinal profile for the Waimatā with cumulative drainage.

The lower earth flow section of the Waimatā catchment comprises pumice soils, particularly orthic pumice; this results in the lower earth flow zone having low clay contents, generally less than 10%, meaning the soil strength is very low, with macroporosity and deep rooting depths. The soils are easily disturbed but generally resistant to livestock damage. The disturbance of these soils means that the lower earth flow zone has high sediment yield and greater erosions and transportation. Despite the high sediment yield and disturbance of the soils in this area, the connectivity is primarily low. The topographic configuration of the lower earth flow zone is a subdued relief, with gentle slopes and hummocking rolling hills contributing to the low landslip susceptibility. However, the nature of the soil composition contributes to some sediment movement in this region.

The finely dissected steep terrain in the Waimatā is characterised by recent soils (R). These soils are weakly developed, showing minor signs of soil-forming processes. This is typical of a steeply dissected terrain, and the earth is continuously being uplifted and reworked; this the soils don’t have time to form and age. These soils have variable textures, with common stratification of contrasting materials.

Spatial variability is usually high, and they show high potential for deep rooting plants, with high plant available water capacity. Steep U-shaped valleys dominate this section of the Waimatā catchment, highly dissected terrain, due to agriculture and weak stability can drive the sediment delivery in a region (Baartman et al., 2013). The U-shaped nature of the Waimatā displays high net erosion due to the steep valley walls. This area has high slope failure due to the steep slopes surrounding the river. Weak soils and steep slopes result in high net erosion and mass bank failure.

The medium finely dissected terrain consists of recent tephritic soils (RT) and Orthic recent soils (Ro). The RT soils originate from volcanic ash or other ejecta. These soils are weakly developed and show minor signs of soil-forming processes. There is a distinct topsoil layer. However, the horizon is either weakly expressed or absent. They are most common on unstable steep slopes, alluvial floodplains and slopes mantled by young volcanic ash. The other primary soils type is the recent orthic soils. These are mainly found in sites that have been eroded. The medium relief dissected terrain is subject to constant reworking, this the presence of Ro soils. These soils are weakly developed, showing minor signs of soil-forming processes. They exhibit distinct topsoil, but there is a weak or absent topsoil horizon similar to the RT. The physiographic characteristics of the medium relief dissected terrain are like the finely dissected steep terrain. It consists of medium width valleys and less steep slopes. However, relic terraces continue to confine the movement of the river, the landslide potential for this region is high/medium. Weak soils aren't able to bond and are thus susceptible to erosion and transportation. The medium slopes of this region limit the capacity for mass wasting, making it less common than in the finely dissected area. Connectivity between trunk and tributaries is high as there is a free flow of sediment and water throughout. Tributaries can freely connect to trunk streams as floodplains, and paleo features do not limit them. However, the hillslope channel connectivity is relatively low due to the presence of relic terraces. Sediment is trapped and stored here and requires high-intensity events to remobilise and transport the sediments to the main channel.

The gently dissected terrain exhibits similar soil types as the medium relief dissected terrain, including RO and RT. The gently dissected terrain shows similar patterns of slope stability and connectivity. Gentle slopes result in low slope failure as there is insufficient energy to entrain these sediments. Tributary trunk connectivity is high as there is a free and connected slow between the two streams. However, there is low hillslope/channel connectivity as there is impedance from relict terraces blocking sediments from being delivered to the trunk stream.

The upper earth flow zone is in the upper catchment, below the steep headwaters. The two primary soils for this region are brown soils (BOP) and gley soils (GOT). Brown soils are the most common New Zealand soils, covering 43%. They have brown or yellow-brown subsoil below dark grey-brown topsoil.

The brown soil consists of thin coatings of iron oxides weathered from the parent material. The brown soils have relatively stable topsoil with a well-developed polyhedral or spherical structure. In particular, the Orthic (BO) (common in the upper-earth flow) are weak or structured subsoils, common on slopes or young land surfaces. The second most common soil in the upper earth flow is the gley soils (G). These soils combined with organic soils represent a typical wetland soil composition. Gley soils are strongly affected by waterlogging and have been chemically reduced and have light grey subsoils. The grey colours usually extend to more than 100cm in depth. These soils have high groundwater tables, shallow potential rooting depth and high bulk density; in particular, the orthic gley soils (GO) are usually found on older land surfaced and stay wet all year round. The presence of these gley soils indicates relict and present wetlands across the upper earth flow region.

The upper earth flow zones are characterised by partial confinement, hummocky, rolling hills with low local relief and gentle slopes. Due to the geology and soil composition in the upper earth flow zone, landslip susceptibility is high. These landslides contrast those in the steep headwaters; the earth flows move more slowly, failing along the shear face, typically 1-2m below ground. Subsequently, these movements and erosion generate hummocky, low relief terrain with poorly defined stream channels (Cullum & Brierley, 2016). Frequent landslips result in low tributary trunk connectivity as tributaries are being infilled with slumps and downwards sediment movement. Hillslope/channel connectivity is also low. This results from the hillslopes being frequently disconnected by alluvial fans, floodplains and wetlands/swamps, impeding the flow of sediments to the trunk stream.

The steep headwaters are located at the sources of the catchment, including several streams feeding the Waimatā. RO soils and RT soils dominate the region. These soils are weakly developed, showing minor signs of soil-forming processes. These soils have varying soil textures, with common stratification of contrasting materials. They are generally deep rooting and have high plant available water capacity. These soils are typical of a headwater region as there are more uplift and weathering processes. Meaning the local geology has a greater impact on the texture of the soils created. The steep headwaters are characterised by narrow v-shaped valleys with high steep sides. This region’s steep, narrow nature, coupled with weak unconsolidated soils, makes for a very high susceptibility to landslips. The area lies atop a tectonic boundary and is subject to constant uplift and movement. Weathering rocks and destabilising slopes, thus, delivering large quantities of sediment to the streams. This area is comprised of narrow valleys with little space for accretion. Therefore, floodplain development is absent. Tributary trunk connectivity is very high, as there is a free flow of sediment and water through and between the channels. Hillslope/channel connectivity is also increased as there are little to no floodplains. Therefore, there is free movement between hillslopes and the streams.

As noted by Cullum et al. (2016), terraces border the banks of the river, pinning the river's course to a fixed position (Fryirs et al., 2016). Therefore, the Waimatā river acts as a chute, delivering sediment and woody debris out to sea. Marden et al. (2012) assert that forests slow down the rate of earth flow displacement; however, if the wet conditions prevail, forest cover cannot always prevent slope failure.

2.4. Ecology of the Waimatā

The Waimatā has undergone significant ecological shifts since the settlement of Europeans, mainly through forest removal. Leathwick et al. (1995) propose a pre-human terrestrial ecosystem of the Waimatā, showing that the catchment was comprised primarily of tawa (Beilshmiedia tawa), titoki (Alectryon excelus), kohekohe (Dysoxylum spectible) and podocarp forest, familiar in steep hillslopes in lowland and climatically warm areas. Altitude increases would have influenced species composition, with Kohekohe less dominant in the higher, northern headwaters of the catchment and a mix of species as it moved landward. Some kohekohe remained along with rewarewa (Knightia excelsa), pukatea (laurelia novaezelandiae) and scattered northern rata (Metrosideros robusta); these were all overtopped by emergent conifers kahikatea (Dacrycarpus decrydiodes), rimu (Dacryium cupressinum), matai (Prumnopitys taxifolia), totara (Podocarpus totara), tanekaha (Phyllocadus trichomanoides) and miro (Prumnopitys ferruginea) (Leathwick, 1995).

The alluvial river terraces of the upper catchment were dominated by tall forests of emergent kahikatea over the canopy of totara and matai. This ecosystem also features titoki, tawa, kowhai and black and white Maire. This is a common vegetation cover of alluvial terraces with recent brown, raw allophonic and pumice soils. This composition may have also been widespread on shallow hillslopes before human occupation (Salmond, 2016).

In the top half of the lower catchment, poorly drained, gley soils of the flat alluvial terraces and forest wetland margins of the valley floors, kahikatea forest was dominant (Salmond, 2016). A variety of vegetation would have occurred in disturbed areas throughout the catchment. Pioneer woody species, such as tutu and kowhai and small species like kohuhu, would have happened on the erosion-exposed soils.

European settlement in the 1700s was the beginning of the colonisation of the region. As land went through the Native Land Court from the 1880s, there was increased European settlement in Poverty Bay, leading to the clearance of native forest to make way for pastoral agriculture (Salmond, 2016). Gundry (2017) outlines the fertile alluvial soils in the Waimatā made agriculture an easy option for income. However, the location of sheep dips would contaminate the local waterways having adverse impacts on freshwater aquatic life. By the end of the 19th century, almost all the kahikatea swamp forests and wetlands had been cleared, and minor forests remained on the surrounding hills (Salmond, 2016). Wildlife was drastically affected due to large scale forest removal. Kereru and kaka were highly hunted throughout this period; E.F. Harris (Times Jubilee Handbook, 1927) recalled that in 1873, "20-30 pigeons were attainable to be shot". Extensive deforestation continued into the 1900s, with large areas cleared for logging and burning to convert land to pasture for cattle and sheep (Salmond, 2016). Over this period, an estimated 68% to 23% of the land area was reduced (Ewers et al., 2006). Government initiatives for forest clearance provided subsidies for land developed fertiliser grants, reduced loans and guaranteed minimum livestock prices (Ewers et al., 2006).

Today, native podocarp forests now account for only 2.5% of land cover in the region (Cullum et al., 2016). 40% currently consists of pasture, 19.3% exotic plantation forest or regenerating mānuka / kānuka scrub (9.1%). Significant changes to land use have left lasting effects on the geomorphology of the catchment. From 1892, denudation of the hills and slips left masses of loose soil on the hillside, where during flood events, a portion of them was being transported down the river (Gundry, 2017). Bush clearance was felt throughout the valley, with flooded land and homes, slumped riverbanks and extensive damage to bridges and beaches (Gundry, 2015). Rapid, widespread deforestation had devastating effects on more indigenous species through habitat destruction and the wider Waimatā Valley environment. Weak lithology, steep slopes, and heavy rainfall coupled with soil destabilisation from deforestation resulted in vast quantities of sediment being delivered to the river systems (Cullum et al., 2016; Salmond, 2016).

Today, the Waimatā consists of less than 17% native cover, with less than 50% of the catchment being forested (exotic or native). Present-day land use practices are shown in Figure 2.4. Cleared land for agriculture and pasture dominates the catchment. Cycles of erosion and sedimentation issues continue through the harvesting and replanting of exotic pines. Leading to widening and scouring of the river channel and sedimentation and woody debris deposits on farmland and the beaches; a significant issue throughout the catchment.

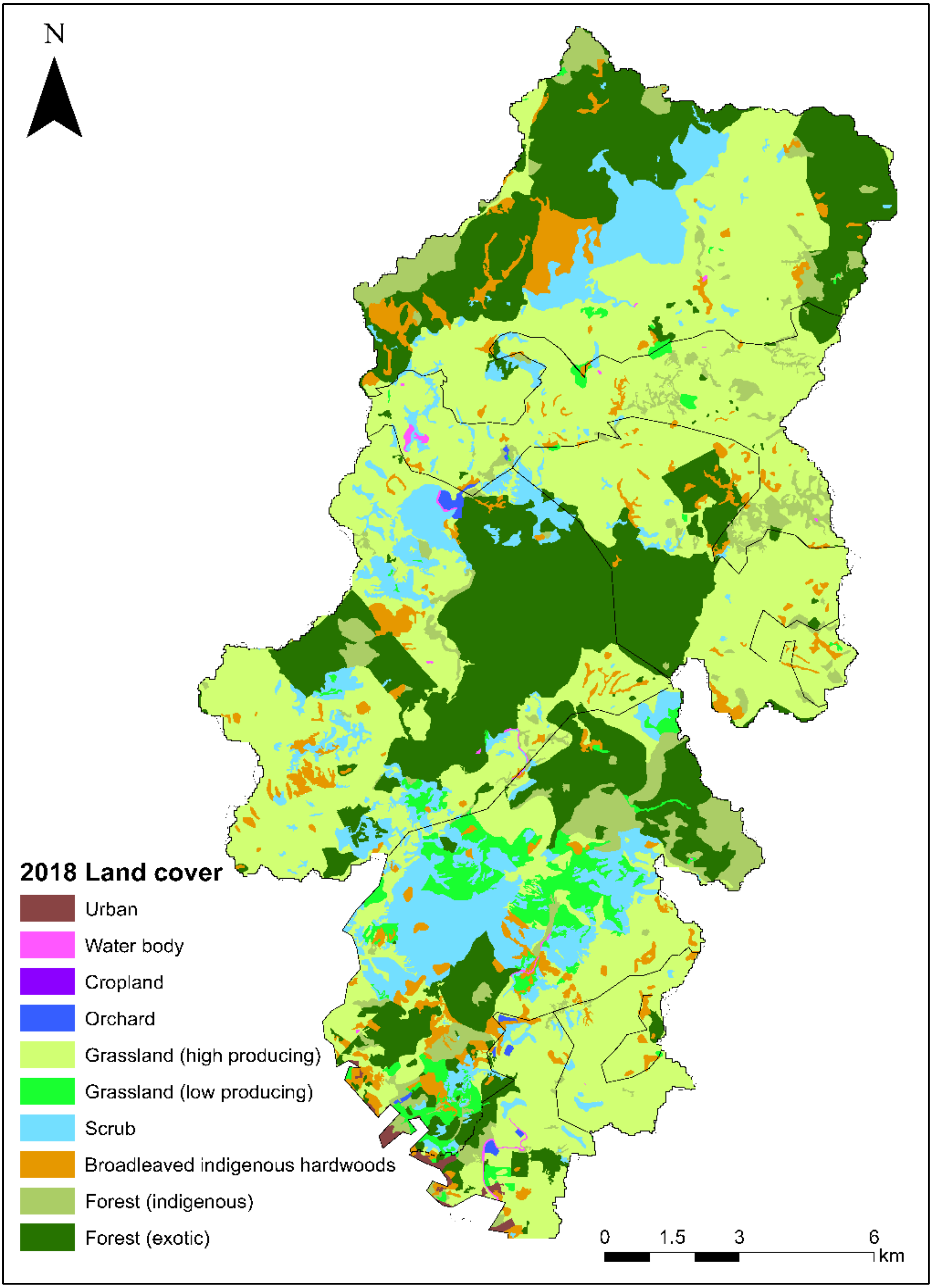


Figure 2.4 Land use in the Waimatā (LUCAS, 2018).

2.5. Contemporary Issues in the Waimatā

This theme leads into the processes acting within the Waimatā to deliver significant quantities of sediment and woody debris to the lowlands, Waikanae Beach and urban areas seen in (Figure 2.5).

Figure 2.5 Debris gathering of the Taruheru River under the Gladstone Road bridge, Gisborne. (Gisborne Council, 2015).

As noted in Cullum et al. (2016), the Waimatā is constricted and pinned against terraces, confining it to a semi-fixed position. This allows the river to act as a chute and flush sediments from source to sink. These confined areas delivering sediment and debris can be labelled as throughput zones, where there is a single straight channel, which is highly stable (Fryirs and Brierley, 2001). Throughput reaches in the Waimatā do not store significant volumes of material (Brierley and Fryirs, 2000; Fryirs and Brierley, 2001) and have the capacity to mobilise substantial portions of available sediment stores each year. Contrasting reaches in the Waimatā occur in the partially/unconfined reaches, where there is still a single channel thread; however, the channel is more sinuous. These reaches are characterised by discontinuous floodplains, point bars, benches and sand sheets (Fryirs and Brierley, 2001). Transfer reaches in the Waimatā have the potential to store and rework sediments. They are not constricted to a fixed position and can rework and transport sediments horizontally and vertically rather than just longitudinally. Stark differences in reach variability in the Waimatā can be seen in (Figure 2.6) where examples of transfer and throughput zones have been highlighted.

Figure 2.6 Examples of transfer and throughput reaches.

A combination of weak lithology, heavy rainfall and historical land use modifications coupled with confined valleys creates the unique Waimatā catchment environment. Valley constrictions and limited capacity for adjustment, through the prominence of throughput reaches, have resulted in high sediment yields (from weak lithology and climate) to flush through the system. Local efforts for restoration and ongoing forest harvesting has put the Waimatā in a unique position for restoration efforts. Determining rates and patterns of sediment connectivity generated through these morphological and geological characteristics can aid in these management efforts. It can help determine sources and transportation of sediment that ultimately washes out to the beaches.

Chapter Three: Literature Review

This chapter presents a critical review of the role of landscape connectivity as a driver of catchment-scale sediment flux. It highlights implications for modelling applications which are the primary focus of this thesis. Sediment connectivity is defined, and its influence on sediment flux dynamics are summarised, outlining the influence of land use as a critical control on sediment generation and transportation. The impact of data quality and study resolution on modelling-based approaches to sediment connectivity and transfer are outlined. Focus is placed upon publications that have directly applied related technological methods to assess the impacts of land use cover on sediment connectivity.

Key terminology used throughout this chapter is outlined below.

1) *Sediment connectivity* is the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape (Bracken et al., 2015).
2) *Sediment delivery ratio* is defined as the fraction of gross erosion transported from a given catchment in each time interval. It is a dimensionless scalar and conventionally expressed as

   SDR = Y/E,

   Where Y is the average annual sediment yield per unit area, and E is the average annual erosion over that same area (Walling, 1983; Lu et al., 2006).
3) *Sediment budget* is defined as the accounting of sources, sinks and redistribution pathways of sediment in a unit region over time (Slaymaker, 2003).
4) *Coupling* is an aspect of the structural resistance of the landscape and is defined as three coupling states: not coupled, coupled, decoupled. Not coupled landscapes show no linkage between two components; coupled landscape units have free transmission of energy and materials between components. Decoupled landscape units were previously coupled but are now decoupled due to deposition (Harvey, 2001). This term is predominantly used in terms of hillslope-channel coupling.
5) *Landscape sensitivity* is a function of the temporal and spatial distributions of the resisting and disturbing forces and may be described by the landscape change safety factor (Brunsden and Thornes, 1979).

   Sediment Cascade is the transport process conveying sediment from a specific source through the downstream network (Tangi et al., 2019).

3.1 Catchment Scale Approaches to Analysis of Sediment Flux

The catchment has long been recognised as the fundamental geomorphic unit (Chorley, 1969). Discussion around challenges faced in developing tools systematically appraises the complexity of catchment-specific process relationships (Horton, 1945). However, systematic approaches to model sediment flux at the catchment scale have been developed (Heckmann and Schwanghart, 2013; Schmitt et al., 2018; Czuba et al., 2014, 2015, 2017; Keestra et al., 2018). Generally, these applications adopt hierarchical principles in a systems approach, where landscape forms are viewed as compartments of a system (Piegay, 2016). Also, processed-based approaches to reading the landscape support in-depth analysis of spatial components, such as timescales and capacity for adjustment (Brierley et al., 2013; Lisenby et al., 2019; Piegay, 2016). Such applications recognise that reductionist approaches do not provide enough insight into the forms and processes underpinning geomorphic response (Phillips, 2004; Piegay, 2016). Phillips (2004) identifies 'scale linkage' as the primary issue, highlighting the variation in dominant and characteristic processes over shifting scales. Non-reductionist framings recognise the inherently hierarchical nature of landscapes in which the characteristics of higher levels impose boundary conditions on those below (Phillips, 2004; Poff, 1997). Through such a lens, catchment-scale appraisal of geology, tectonic setting and climate factors can help understand changes in intrinsic controls upon sediment connectivity relationships.

The concept of a nested/natural hierarchy suggests that a given system comprises multiple smaller systems that simultaneously exist as part of a larger whole (McMaster and Sheppard, 2004). Frameworks for analysing relationships between levels in multi-scale systems are referred to in the literature as 'Hierarchy Theory' (de Boer, 1992; Phillips, 2004). Fluvial networks are hierarchical systems that encompass a nested structure of sub-catchments. Typically, catchments with similar patterns of process relationships fit within larger (eco)regions, landscape units, or geomorphic provinces (Brierley et al., 2005; Dollar et al., 2007). Building on such understandings, hierarchical approaches to river management increasingly appraise organisational controls upon river evolution (Dollar et al., 2007).

Scaling up small (plot) scale erosion rates presents significant challenges in geomorphology, as a linear extrapolation of these processes to entire catchments does not work, as common characteristics in smaller reaches may not apply to the whole catchment. (Bracken et al., 2015). Hence it is essential to understand the continuum of sediment source, transfer processes and possibility for deposition through a system. Bracken et al. (2015) develop a nested hierarchical approach that shows small events contribute to the overall behaviour, wherein sediment connectivity provides a means to relate spatial variability in erosional processes to magnitude-frequency distributions. Sediment connectivity is dependent on both structural components (morphology) and process components (transport vectors, materials) which determine the long-term development of a landform (Bracken et al., 2013; Schmidt and Preston, 2003; Turnbull et al., 2008). Therefore, connectivity is not dependent on individual processes but rather the interplay of compartments of geomorphic development, including erosion, deposition, and sediment flux (Sandercock and Hooke, 2011; Bracken et al., 2015).

3.2 Landscape Connectivity

The operation of sediment cascades reflects catchment configuration and connectivity relationships (Fryirs et al., 2007b), with connectivity being defined as the efficiency of sediment conveyance from source to sink (Fryirs et al., 2007b; Bracken et al., 2015). The ability of a sediment pulse to move downstream is determined by network-scale patterns of storage (accommodation space). The relationships between storage and connectivity are well developed and reflect the patterns of connectivity which control them (Fryirs et al., 2007). Structural and process-based controls underpin long term behaviour of sediment fluxes, shaping the formation of landforms (Bracken et al., 2013; 2015; Turnbull et al., 2008). Lagged and offsite responses to geomorphic change often reflect the pattern and degree of disconnectivity within and between landscape compartments (Fryirs et al., 2007a). Longitudinal, vertical and lateral linkages reflect the operation of processes acting at different positions within a channel.

The concept of landscape connectivity was introduced by Brunsden and Thornes (1979). They conceptualised coupling as a geomorphic response to disturbance events that determine the propagation of effects from hillslopes to the channel (and vice versa). Harvey (2002) developed an approach to temporal and spatial connectivity theory, using the terms coupled and connected interchangeably. He differentiates three scales of analysis (Figure 3.1). The *local* scale includes hillslope connectivity, within channel relationships, hillslope-channel coupling and tributary junctions. The *zonal* scale incorporates the coupling of sub-catchment relationships. Lastly, *regional* coupling refers to catchment-scale sediment transport. Landscape connectivity and catchment-scale spatial relationships were related by Brierley et al. (2006), who differentiated connected or disconnected components of lateral, longitudinal and vertical connectivity (see sections 3.2.2 and 3.2.3)

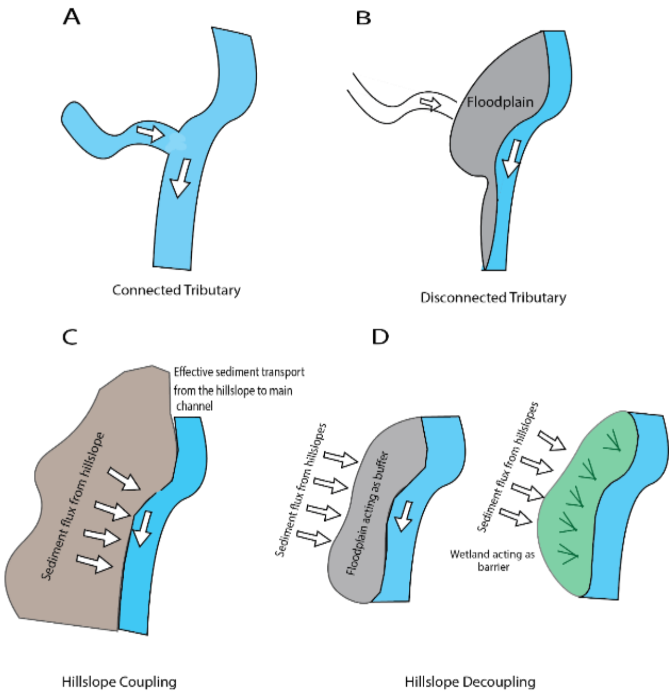


Figure 3.1. Schematic diagrams show the relationship between sediment delivery and the main channel. A) outlines a highly connected tributary, likely to have significant sediment input (depending on upstream controls). B) Is a disconnected tributary, a floodplain is impeding sediment transfer. C) Shows high connectivity with coupling between the hillslopes and main channel. D) Shows two scenarios of hillslope decoupling, with a floodplain acting as a sediment buffer and a wetland acting as a barrier.

3.2.1 Controls on sediment connectivity

Wainwright and Thornes (1990) and Ferguson et al. (1996) show how energy and sediment supply govern the magnitude and distance of sediment movement in river systems. Associated conceptual analysis of critical controls upon sediment connectivity are outlined in These controls govern landscape evolution and can help understand possible evolutionary trajectories systems may take.

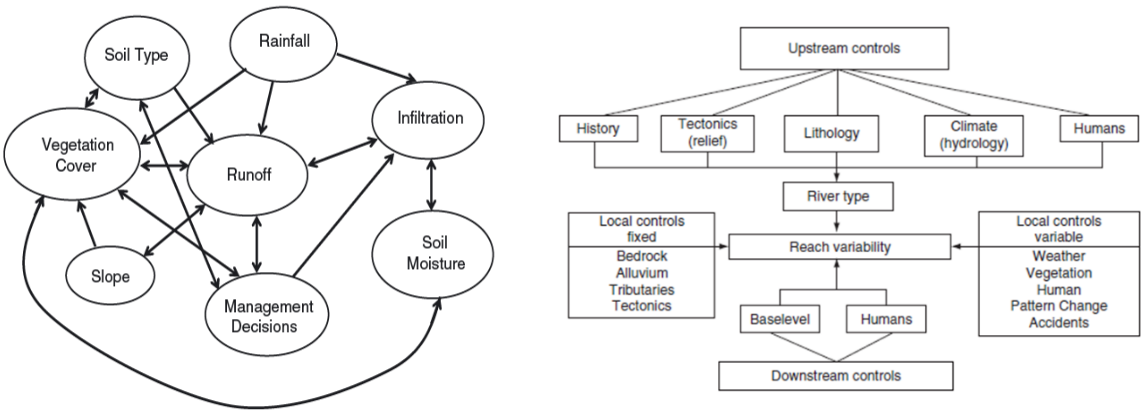


Figure 3.2 A) Conceptual model of critical controls driving sediment connectivity (Lexartza-Artza and Wainwright, 2009). B) Conceptual model from Piegay (2016) outlining catchment controls on river geomorphology.

The connectivity of a system is dictated by intrinsic structural properties such as topography and slope, which influence flow velocity, storage capacity and roughness (Heckmann et al., 2018). Slope directly affects processes driving sediment connectivity such as transport capacity and flow velocity (Poeppl et al., 2012; Heckmann et al., 2018). Transport capacity can increase with slope angle and flow accumulation, thus driving sediment generation and transportation (Borselli et al., 2008; Peoppl et al., 2012). The Sediment delivery ratio (SDR) is the popular term used to express the relationship between rates of soil loss and sediment yield (Walling, 1983; Walling and Zhang, 2004). SDR adjusts depending on changes in slope and topography as basins with low slopes tend to have more significant storage sites located between source and deposition (Boyce, 1975; Borselli et al., 2008). SDR reflects the ratio of sediment output from the catchment with gross erosion. Connectivity within the channel and hillslope is a crucial control of this, as high connectivity will increase the efficiency of sediment deliverance as it is no longer being impeded (Walling and Zhang, 2004). Only a fraction of sediment is delivered from source to sink in a catchment (Ferguson, 1981). Fryirs (2013) discusses this paradox regarding the concept of (dis)connectivity, where sediment stores are related to areas of low connectivity that impede and trap sediment from being delivered downstream.

Imposed boundary conditions determine a river's ability to adjust, such as geologic and climatic factors determining locations in a catchment where the channel can adapt (Brierley and Fryirs, 2005). Geology directly determines the relief, slope and morphology of a catchment and lithology influences erodibility, which impacts rates and patterns of weathering and subsequent erosion across a landscape (Fryirs and Brierley, 2012). Lithological structure determines network configuration, thereby influencing the sediment volume transferred to the stream (Walley et al., 2018). More resistant lithologies, such as igneous rocks, produce smaller sediment yields than softer rocks, such as sandstone and mudstone, which are easily weathered and lead to higher sediment volumes generated in the catchment. The region's geology ultimately determines the shape and configuration of the catchment, as uplift and tectonic processes drive hillslope formation and the pattern of valley width.

Valley shape and confinement act as larger-scale geomorphological drivers of sediment connectivity (Baartman et al., 2013; Heckmann and Schwanghart, 2013). For example, Baartman et al. (2013) link the influence of valley shape, such as v-shaped valleys, broad floodplains and terraces, to the amount of sediment being delivered and stored in different parts of a given catchment. Valleys with higher slopes, such as v-shaped, have higher SDR than V-shapes with floodplain followed by U-shaped valleys. Consequently, while V-shaped and U-shaped valleys tend to display high net erosion in some locations due to their steep valley walls, floodplains and lower-lying terraces in the latter have space to accommodate almost all the sediment generated on the hillslopes, while in the former instance, such materials are flushed through the system (Baartman et al., 2013).

Persichillo et al. (2018) argue that sediment connectivity within a catchment depends mainly on the morphological complexity of the catchment and is strictly related to the anthropogenic modification of a landscape. This is primarily seen through vegetation cover changes such as forest clearance. Vegetation and vegetation changes affect surface runoff and sediment dynamics on hillslopes which directly influence lateral sediment input rates to a channel system (Persichillo et al., 2018 Poeppl et al., 2017). However, this relationship to sediment connectivity varies temporally, often reflecting climate changes and land use/management practice modifications (Foerster et al., 2014; Lopez-Vincente et al., 2017). the relationship can be further changed in terms of magnitude and temporal evolution of sediment as connectivity relationships can vary in response to human activity (land use changes, drainage system modifications) (Cavalli et al., 2013; Poeppl et al., 2017; Persichillo et al., 2018) altering morphology through human disturbance (Ellis et al., 2006). For example, urbanisation may increase lateral connectivity as the increased paved surface area results in efficient overland flow pathways (Croke and Mockler, 2001). This can lead to changes in sediment retention and export along with the hillslope channel system (Tarolli et al., 2014).

Lastly, position within a catchment is a crucial control on sediment connectivity and differentiates the location of source, transfer and accumulation zones (Schumm, 1977). Headwater zones typically exhibit high lateral connectivity, where coupled hillslopes result in few floodplain pockets. This promotes high longitudinal transport and low storage/residence times (Figure 2.4) (Fryirs and Brierley, 2013). Small tributaries can contribute large volumes of sediment with long residence times; however, these are often episodic (Benda and Dunne, 1997b; Benda et al., 2005). Transfer zones are characterised by increased storage and occasional to consistent floodplain pockets, resulting in decreased lateral connectivity due to hillslope decoupling. Fryirs and Brierley (2013) assert that longitudinal connectivity remains high, with some impediments forming confluence zones and alluvial fans (Figure 3.3). Lastly, the accumulation zone is commonly found in downstream reaches, characterised by low slopes and continuous floodplains. These zones are highly decoupled as channel-floodplain connectivity results in higher sediment storage and longer residence times. (Figure 3.3) (Fryirs and Brierley, 2013). Network configuration, either as part of tributary-trunk stream relations or downstream changes in confinement and accommodation space, exerts critical influence upon rates of sediment conveyance (Walley et al., 2018; Poeppl et al., 2020). Variability in patterns and rates of reworking on fans and aggraded valley floor surfaces recurrently modify sediment connectivity relationships in high energy landscapes (Fuller and Marden, 2011; Marden et al., 2012; Poeppl et al., 2020).

3.2.2 Highly connected systems

Systems that exhibit high amounts of sediment transfer, laterally, longitudinally and vertically, can be described as highly connected (Fryirs et al., 2007b). Hillslopes and channels are closely coupled, transferring hillslope generated material to the drainage network (Harvey, 2001; Kasai et al., 2005). Incision, accentuated relief and dissected terrains driven by tectonic uplift generate highly connected landscapes (Baartman et al., 2013; Kuo and Brierley, 2013). Gorges and other confined valleys play a crucial role in aiding in delivering sediment (Kuo and Brierley., 2013) as the channel geometry of confined valleys results in small accommodation space, flushing sediment along an efficient conveyor belt (Fryirs, 2013; Goode and Wohl, 2010; Kuo and Brierley, 2013).

Highly connected systems are subject to profound responses to extreme events (Harvey, 2001; Kasai et al., 2005). Sensitivity and adjustment potential are high, but lag times are low, as these systems can rapidly evacuate sediment. Large magnitude events quickly rework sediment stores, efficiently transferring materials to lower reaches. However, in some instances, profound lateral inputs in highly connected systems can disrupt longitudinal connectivity and decrease the SDR as blockages occur (Nicholas et al., 1995). Hence, different parts of a system can exhibit high and low connectivity.

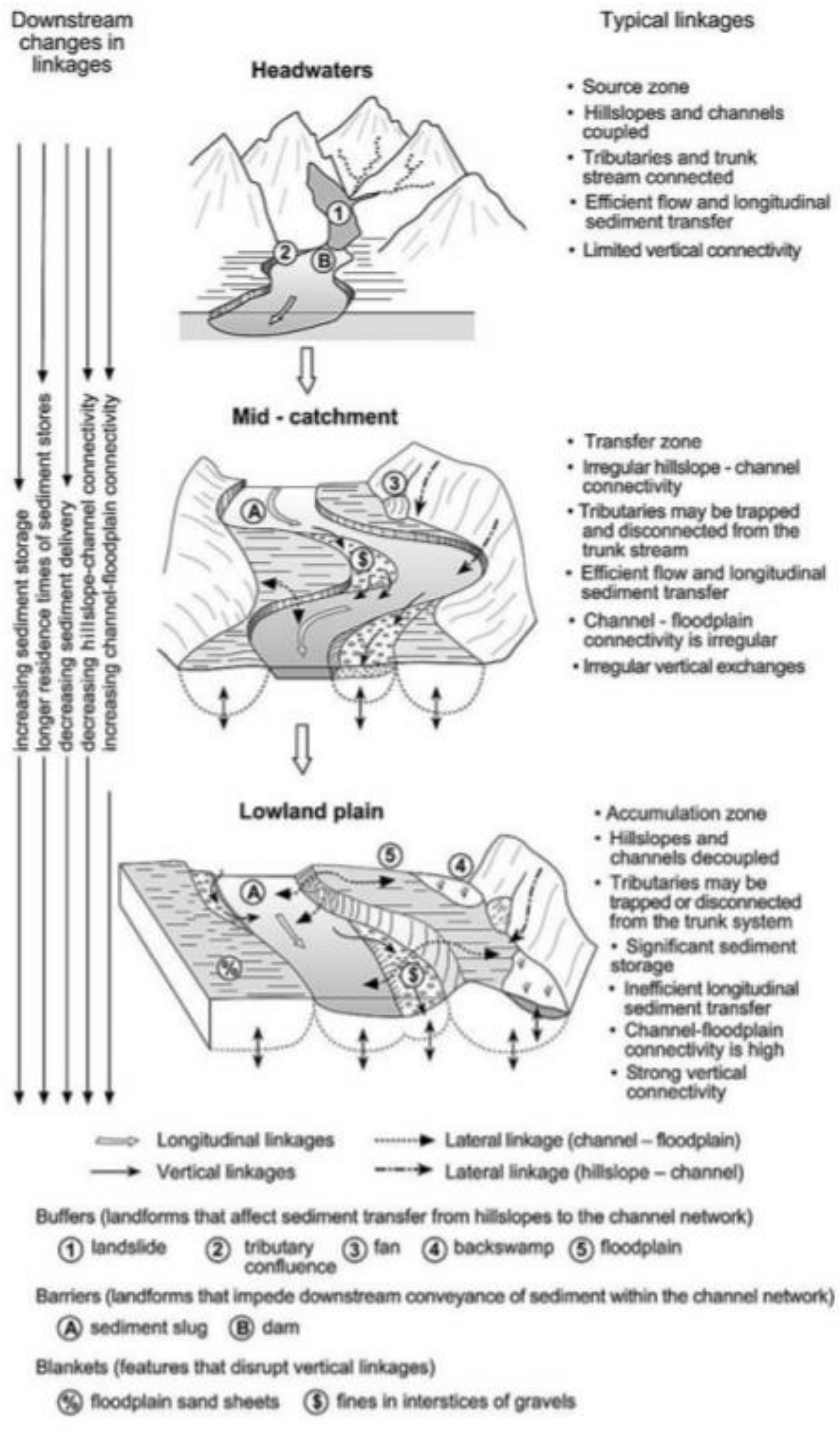


Figure 3.3 Conceptual model of downstream changes in linkages. From Fryirs and Brierley (2013).

3.2.3 Disconnected systems

In some instances, vertical, longitudinal and lateral process linkages in river systems may be disconnected (Fryirs and Brierley, 2012). This results in disrupted longitudinal linkages (Trimble, 1983;

Fryirs et al., 2012), inefficient sediment delivery (Walling, 1983) and lagged sediment conveyance (Benda and Dunne, 1997). Low slope often leads to sediments being stored on the hillslopes where they cannot be remobilised. Energy is insufficient to transport sediments to the mainstem (Harvey, 2001). Disconnectivity at tributary confluences occurs when the feeding tributary does not directly connect to the main trunk stream (Fryirs and Brierley, 1999; Fryirs et al., 2007a; Fryirs and Brierley, 2013; Rice, 1998;). Sediments can also become trapped behind floodplains or deposited in paleochannels, resulting in trapped tributary fills (Fryirs et al., 2007a). Disparities between carrying capacities between tributaries and the trunk can result in the deposition of coarser material as the channel is unable to transport it downstream, leading to longitudinal disconnection (Hooke, 2003).

Fryirs et al. (2007a) present three forms of landscape disconnectivity that trap and impede sediment conveyance in a catchment called buffers, blankets, and barriers. Buffers disrupt lateral and longitudinal linkages, preventing sediment from entering a channel network. Buffers consist of alluvial pockets within a floodplain or fan and occur on a lower slope area that decouples the channel's hillslope (Harvey, 2001; Fryirs et al., 2007a). These landforms span long time frames and cover large areas; they can be remarkably resilient as only significant magnitude events can breach them. Barriers alter and inhibit sediment movement within a channel, disrupting longitudinal linkages and altering channel geometry (base level and bed profiles) (Fryirs et al., 2007a). Barriers are smaller scale landforms than buffers and can include features such as bedrock steps and sediment pulses. Barriers have more variation in timescales, as hard barriers such as steps will span significantly more extended periods than a sediment pulse (Nicholas et al., 1995).

Anthropogenic influences on landscape connectivity include introducing hard engineering structures such as dams that inhibit longitudinal sediment movement in river systems (Brune, 1953). Blankets work differently to barriers and buffers by smothering landscapes, temporarily removing sediment stores, particularly on floodplains, thereby disrupting vertical connectivity as surface-substrate interactions are blocked (Fryirs et al., 2007a). Blankets can have markedly different influences on sediment movement depending on their position in the catchment. On a low-lying floodplain, the blanket will dictate the strength of landscape coupling by temporarily removing stores from the sediment cascade (Fryirs et al., 2007a). For example, bed armouring may inhibit the reworking of subsurface sediments (Church., 1998). These disconnectivities can span periods from years to hundreds of years. Unlike buffers, as blankets are often low lying, they are sometimes breached and reworked under low to moderate magnitude events.

3.3 Landscape sensitivity

The concept of geomorphic sensitivity introduced by Brunsden and Thornes (1979) seeks to understand how geomorphic systems respond to change. In some systems, the disturbance is dampened, whereas, in sensitive landscapes, the effects of disturbance may persist (Harvey, 2001). Sensitivity has been described as the ratio between the mean relaxation time of the system and the means recurrence time between events (Brunsden and Thornes, 1979; Harvey, 2001). Downs and Gregory (1993) appraised geomorphic sensitivity in relation to resistance to disturbing forces, threshold proximity and recovery potential. Harvey (2001) postulates that effective feedback links inhibit the capacity of large systems to exceed threshold conditions, thereby enhancing their ability to adjust (i.e. their resilience). In contrast, sensitive systems are vulnerable to disturbance, mainly where they operate near thresholds and exhibit internal instability. These differing scenarios determine whether recovery after a disturbance is slow or incomplete (Harvey, 2001). Fryirs (2017) describes landscape sensitivity as the livelihood that a given change in the controls of a system will produce a sensible, recognisable and persistent response (i.e. the capacity of the system to recover from any given disturbance).

3.3.1 Connectivity and sensitivity

Connectivity can influence the sensitivity of a system, moderating the propagation of geomorphic change within a catchment (Heckmann et al., 2008). Increased connectivity can result in a higher potential for channel adjustment (Harvey, 1991). Still, in instances where sediment is impeded by certain landforms acting as sediment stores, sediment is inhibited from travelling downstream. This forces the channel to adjust upstream rather than propagating downstream (e.g. Phillips, 1992). In contrast, if a channel is directly connected to surrounding hillslopes, a mass movement would be deposited in the stream rather than across a floodplain. Areas such as gorges and valley constrictions are highly connected provide limited deposition space within reach. Harvey (2001) asserts that the sensitivity of upland fluvial systems is dependent on the magnitude and frequency of sediment and flood events and is thus modified by the coupling characteristics of a system.

Sensitivity describes the ease with which fluvial landscapes can adjust their morphology over time and space (Brierley and Fryirs, 2005; Fryirs, 2017). Sensitivity and connectivity are intrinsically related as effective description and explanation of sediment movement's (dis)connectivity throughout a catchment provide a basis to identify sensitive parts of the landscape (Fryirs et al., 2007). The availability of sediment to transfer along with a river network to some extent controls system responses to disturbance, influencing the form and severity of future river adjustments (Hooke, 2003; Czuba and Foufoula-Georgiou, 2015). These relationships vary for different types of rivers, exemplified by the distinction between transfer and throughput zones.

3.3.2 Throughput and transfer zones

Like the marked variation in the distribution of sediment properties throughout a catchment, spatial and temporal clumping of sediment budgets can result in severe errors and misinterpretations (Walling, 1983; Wolman, 1977). Therefore, it is essential to explain variability by quantifying sediment routing at an appropriate scale, tying this to contextual understanding of the evolution of the river (Benda and Dunne, 1997). The rate and nature of lagged and offsite response and residence times also vary, based on slope-channel connectedness, river type and valley confinement (Madej and Ozaki, 1996; see also Grayson et al., 1998, Roy and Crawford, 1977). Storage in upper reaches and inefficient energy to transport sediment downstream results in longer residence times. Conversely, confined reaches characterised by high energy and low residence times and storage can be referred to as sediment transport 'boosters' (Fryirs et al., 2007a).

Forms of temporary sediment storage in such reaches may include vertical (bed) adjustment or reworking of lateral sediment stores. Brierley and Murn (1997) and Brierley and Fryirs (2000) refer to these situations as sediment throughput and transfer zones, respectively (Figure 3.4). Throughput zones are characterised by a single thread, low sinuosity and highly stable channels and are commonly located mid-catchment. Extensive bedrock outcrops, sand sheets, occasional pools and discontinuous floodplain pockets are typical geomorphic units for these reaches. The bedrock channel and associated pools may be exposed after floods, only to be re-covered by recurrent sediment pulse materials between floods. Transfer reaches are also found in the mid-catchment. These single thread channels are typically aligned as bends within a sinuous valley alignment, with point bars, point benches and sand sheets along the channel. Sediment stores on the inside of bends are recurrently reworked, meaning that over time, sediment inputs and outputs are balanced in these reaches (Fryirs and Brierley, 2001).

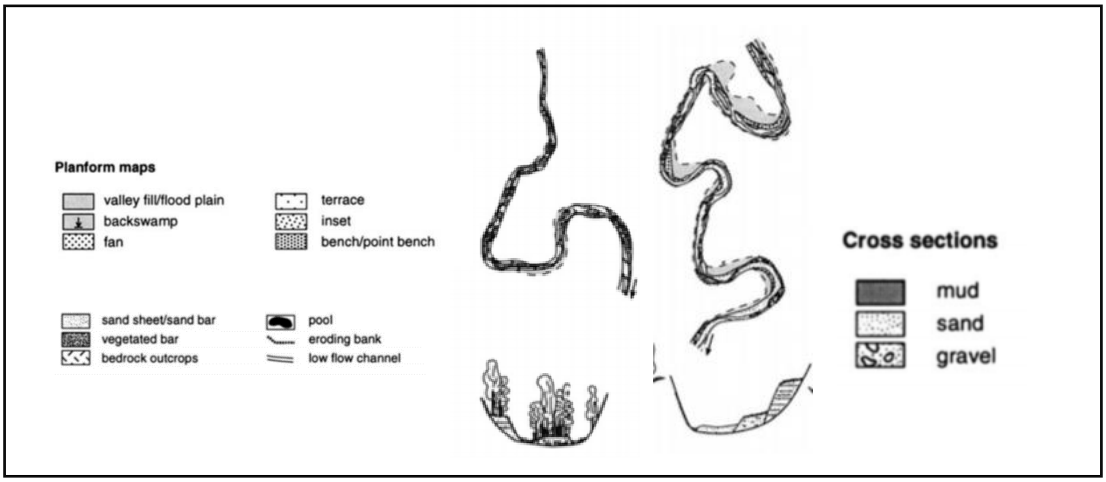


Figure 3.4 Examples of throughput (a) and transfer zones (b). Adapted from Brierley and Fryirs (2000).

3.4 Approaches to connectivity modelling

Sediment connectivity in river networks results from supply rates, grain sizes, distribution of sediment sources and the delivery of sediment through a river network (Bracken et al., 2015; Schmitt et al., 2018). Computational models can help characterise sediment sources, transport pathways and the magnitude and spatiotemporal distribution of responses of fluvial geomorphic processes to anthropogenic disturbances (Schmitt et al., 2018). Models predicting these fluvial processes can consist of quantitative (e.g. Borselli et al., 2008; Cavalli et al., 2013; Czuba et al., 2017, Gaspar et al., 2013; Heckmann and Schwanghart, 2013; Heckmann et al., 2015; Schmitt et al., 2018; Tangi et al., 2019), conceptual models (e.g. Brierley et al., 2006; Czuba and Foufoula-Georgiou, 2004; Fryirs et al., 2007a; Fryirs, 2013, 2017; Poeppl et al., 2017) and morphological approaches (e.g. Fryirs et al., 2007b; Harvey, 1997, 2001, 2002; Hooke, 2003, 2004; Lane et al., 2017; Nicoll and Brierley, 2017).

Numerical approaches to study network scale sediment transfers, channel adjustments, and connectivity have been introduced, advancing the study of sediment connectivity (Schmitt et al., 2016). Benda and Dunne (1997) proposed a distributed sediment mass-balance approach, where spatial distribution and stochastic activation of sediment sources have resulted in spatio-temporal patterns of sediment flux along a sediment cascade. Single river (Bizzi and Lerner, 2015) and network (Parker et al., 2015) stream power approaches predict deposition or erosion dominated reaches based on current hydro-morphologic forcing. However, they do not consider sediment transfers as an additional driver for channel adjustment. Like Benda and Dunne (1997), Wilkinson et al. (2006) identified depositional reaches at the network scale, with both approaches highlighting depositional reaches but being unable to quantify sediment source-sink relationships explicitly. Czuba and Foufoula-Georgiou (2014) implemented common sediment transport formulas in a graph-theoretic framework that accounted for individual sediment parcels' movement and resulting network scale dynamics. However, this approach did not quantify sediment source-sink relations, as sediment parcels were not subject to local transport capacity limitations and deposition (Schmitt et al., 2016).

Czuba and Fouloula-Georgiou (2015) address dynamic connectivity in fluvial networks by identifying hotspots of geomorphic change. This framework builds off previous work (Czuba and Foufoula-Georgiou, 2014) by assessing a system from its outlet. This approach allows understanding of how sediment is organised and where sediment can accumulate due to the combined effects of transport dynamics (slope, bed shear stress, grain size and geometry). This framework ultimately assesses the persistence of mass within different reaches of a network and identifies fluvial geomorphic change hotspots associated with high channel adjustment rates (Czuba and Foufoula-Georgiou, 2015). This framework can also pinpoint the sources of sediment contribution to large clusters, which can be used in management applications.

Appraisal of multiple sediment source-sink transfer in a network scale modelling approach to quantify sediment connectivity was proposed by Schmitt et al. (2016). The CASCADE approach (Catchment Sediment Connectivity And Delivery) modelling framework allows each sediment source to be assessed as the beginning of a new sediment cascade. This has allowed for analysis of connectivity from a source to sink approach. CASCADE quantifies how sediment supplied from a source is delivered downstream to sinks, allowing for sediment input tracing back to their source. It also provides for the total local sediment flux, the flux of each grain size, the spatial distribution of source and the connection times between sources and sinks to be determined. Subsequently, a MATLAB based model CASCADE Toolbox was produced by Tangi et al. (2019). The CASCADE Toolbox allows a multiple scenario approach to modelling sediment flux. Different land use scenarios, sediment types/grain sizes and roughness can be incorporated into the model to produce different outcomes. The CASCADE Toolbox provides a means of quantifying and visualising sediment connectivity developed for sediment management and geomorphic studies in large river systems. CASCADE represents sediment transport from many individual sediment sources in a river network as an individual cascading process for each source, tracking sediments from a specific source to determine where it is delivered downstream.

Connectivity has also been used to semi-quantitatively estimate the degree of water and sediment fluxes in catchments through the use of connectivity indexes (Heckmann et al., 2018). The main aim of these models is to quantify sediment flux dynamics through appraisals of sediment redistribution through a catchment (Baartman et al., 2020). Indices are usually a combination of land use and slope variables known to control the spatial organisation and intensity of sediment fluxes in a landscape (Baartman et al., 2018; Baartman et al., 2020). A widely used approach to connectivity index modelling is the Index of Connectivity (IC) proposed by Borselli et al. (2008) and since modified by other authors such as Cavalli et al. (2013), Gay et al. (2016) and Lopez-Vincente et al. (2017). Sediment connectivity indices provide simple semi-quantitative depictions of the potential sediment delivery between catchment compartments. Despite the widespread use of connectivity indices, these models have been focused on structural (physical) connectivity rather than integrating process-based connectivity (Najafi et al., 2021). Grauso et al. (2018) add that connectivity indices are generally dimensionless and need to be coupled with quantitative soil-loss data for land management and design purposes. Gauso et al. (2018) attempt to bridge this gap through the development of the simplified connectivity index (SCI) and the specific sediment potential (SSP), which are based on geomorphometric tools commonly found in open-source geographic information systems. This approach provides a straightforward assessment of SCI and SSP as functions of the estimated soil erosion per catchment unit area at the inverse distance of each unit area from the river outlet. Ultimately, this method expresses potential sediment transfer to refine theoretical models to assess the sediment yield in ungauged river basins.

Other indices of connectivity have been derived from graph theory, the study of graphed data (Cossart and Fressard, 2017; Heckmann and Schwanghart, 2013; Masselink et al., 2017; Cossart, 2019). Graph theory offers mathematical tools to statistically analyse the assemblage of all the components of sediment cascades (Cossart et al., 2017). This theory is a mathematical approach based on a graph representation of the hydrological network that has been used to describe the shape and organisation of watercourses (Strahler, 1957; Chorley and Kennedy, 1971). The framework focuses on structural connectivity, i.e., the influence of the spatial patterns formed by the linkages on sediment delivery (Cossart et al., 2017). Heckmann and Schwanghart (2013) integrate network analysis and graph theory using mathematical models of networks. Tools developed using graph theory have helped tackle several generic problems relating to complex systems, such as describing and assessing network structure, understanding exchange of matter, energy and information in networks and modelling propagation of system changes (Heckmann and Schwanghart, 2013).

Integrating connectivity theory and watershed modelling has been proposed as a solution to overcome model shortcomings associated with the spatial and temporal complexity of watershed properties, processes and pathways (Mahoney et al., 2018, 2020a, 2020b). Despite the increasing availability of high-resolution geospatial data, unified sediment connectivity frameworks applicable across spatiotemporal scales remain underdeveloped, especially concerning time-varying sediment processes (Bracken et al., 2013, 15; Wohl, 2017; Heckmann et al., 2018). Mahoney et al. (2018) further develop these principles by improving the spatial and temporal capabilities by coupling the physically-based connectivity formula with watershed modelling. This was achieved by formulating a probability equation that considers sediment connectivity magnitude, spatial extent, timing and continuity.

Many models focus on the concept of sediment connectivity to predict the sedimentary signal delivered at catchment outlets. For example, Grauso et al. (2018) use a sediment connectivity index model, which provides a method to assess the sediment yield in ungauged watersheds. However, this model is limited by its functional-based approach rather than integrating structural-based analysis. In terms of its inputs and outputs, the Grauso et al. (2018) model is a black-box approach and does not incorporate any knowledge of functional sediment connectivity processes. Cossart et al. (2018) propose a framework in which sedimentary signals are an emergent aggregation of local links and interactions. However, attempting to address the challenge of opening the black box of what happens within the sediment cascade requires accurate geomorphic investigations in the field and the development of tools dedicated to modelling cascades (Cossart et al., 2018). Assessments of graph theory, agent-based modelling and differential equations revealed that connectivity is an efficient conceptual framework to predict how a sediment cascade may transmit a perturbation throughout the system. This can include local perturbations and perturbations due to external-boundary forces.

Two methods of defining sediment sources are sediment fingerprinting and sediment tracing (Hardy et al., 2010; Fryirs and Gore, 2013; Koiter et al., 2013). Whilst sediment tracing helps establish a sediment source, tracing this way does not allow for historical analysis of sediment movement (Collins et al., 1997). Sediment fingerprinting, on the other hand, works from the sink upstream to determine a source, relying on the knowledge that often multiple natural properties of sediment will reflect its source location, such as; biogeochemical properties, nuclear properties and physical properties of the sediment. However, sediment fingerprinting is most effective where the critical concern is eroded materials and excessive fine sediments, where management of such material is crucial in restoring the watershed (Belmont et al., 2011; Gellis and Walling, 2011; Belmont et al., 2014).

3.5 Implications of connectivity and modelling on management

Depositional sequences deposited in downstream reaches often reflect long term records of external disturbance to river systems, resulting from tectonic, climatic or anthropogenic controls. The sediment delivery ratio (SDR), which is the ratio of total catchment erosion transported from the basin (Walling 1983; Fryirs et al., 2007b), provides a measure of catchment scale (dis)connectivity. Appreciation of landscape (dis)connectivity can help analyse sediment conveyance and depositional sequences in river systems (Fryirs et al., 2007b). The degree of sensitivity can be identified by the relative coupling (connectivity) of the system. Coupled basins are sensitive to upstream disturbance, and decoupled (disconnected) basins are minimally affected by upstream perturbations (Fryirs et al., 2007b). Therefore, historical depositional sequences can provide guides to the history of disturbance events in a catchment.

Managing for what is 'expected' in each system is critical in managing sediment (dis)connectivity at the catchment scale (Poeppl et al., 2020). Some systems are overloaded with sediments, while others are starved (Fryirs and Brierley, 2016; Poeppl et al., 2020). Sediment connectivity differs from river to river; the way rivers respond to ways and rates with which disturbance events are mediated throughout a catchment are highly variable (Fryirs et al., 2007a; Kuo and Brierley, 2013, 2014). Sediment types influence these patterns; for example, Poeppl et al. (2020) describe that some European examples are characterised by rapid response, whereas some New Zealand examples are characterised by slower response times due to coarser grains (Waiapu). Some cases in Australia are lagged even further due to the sediment starved nature of those rivers. Therefore, determining the types of sediment connectivity and their respective response times is vital when managing sediment.

Context and realistic goals for a river are vital, and determining what attributes and dimensions of the sediment regime are manageable is critical in this (Poeppl et al., 2020). Approaches to management should build upon understanding how humans have induced (dis)connectivity and how these relationships have altered a system's evolutionary trajectory (Fryirs et al., 2007a, 2007b; Poeppl et al., 2017 2020). Potential questions to ask in efforts to inform river recovery have been outlined in Gregory (2006), Fryirs and Brierley (2013), Brierley et al. (2013), Peoppl et al. (2017) and Wohl et al. (2019) and are summarised in table 3.1 below.

Table 3.1 Potential questions to ask when addressing river rehabilitation and management.

What is the current system state and how has the system changed in the past? How will/are disturbance responses and management treatments manifested in a system (e.g. sediment slugs, head cuts on the one hand, construction of sediment retention dams or revegetation activities on the other)?
What can/should be achieved by managing (dis)connectivity relationships in catchments (i.e. setting targets)? Where can efforts to manage sediment (dis)connectivity be prioritised?
What sediment issues can be realistically managed? Which tools can be used to manage (manipulate) sediment (dis)connectivity in catchments?
From where will the sediment be sourced and dispersed to enhance river recovery in the study reach? Is enhancing sediment connectivity required?
Where should sediment conveyance be suppressed to protect other reaches and minimise off-site impacts? Is enhancing sediment disconnectivity required?
Which geomorphic trajectories are likely and expected to occur over management timeframes?
How can the success of different management actions be evaluated?

Although sediment is a natural constituent of rivers, excess loading can impair sediment transfer and biodiversity loss. Identification of sources and mechanisms of sediment supply is needed for effective management (Belmont et al., 2011). As previously discussed, this can involve several approaches, such as sediment source tracing and sediment fingerprinting (Belmont et al., 2011; Walling, 2011; Belmont et al., 2014), indices of sediment connectivity (Borselli et al., 2008; Cavalli et al., 2013; Heckmann et al., 2018), mathematical approaches including graph theory (Heckmann and Schwanghart, 2013; Cossart, 2019) and network approaches (Bizzi and Lerner, 2016; Czuba and Foufoula-Georgiou, 2014) and lastly through tracking individual sediment cascades (Schmitt et al., 2016; Tangi et al., 2019). Attention needs to be paid to the types of sediment sources when producing these models. Many models aren't easily applicable to certain rivers because the model is developed in countries where a certain type of grain type prevails. For example, Hooke's (2003) approach to morphological connectivity modelling is only appropriate for coarse sediments as suspended sediments are ignored. Therefore, attention needs to be paid to the system in which the model was developed to determine if it can be successfully used on a different catchment.

Connectivity models allow for the visualisation of sediment routing in a catchment. Many studies reviewed by Najafi et al. (2021) are based on structural sediment connectivity, which is helpful for site prioritisation in management. However, there are still gaps in the understanding of functional sediment connectivity, which focuses more on the process-based interactions driving sediment movement (Najafi et al., 2021). Structural and functional connectivity should be addressed simultaneously (Najafi et al., 2021). Therefore, studies should integrate processed-based understandings with spatio-temporal consideration to close the uncertainty gap resulting in better interpretation of these systems (Najafi et al., 2021).

As a result of New Zealand's changing landscape, from indigenous forest to pastoral agriculture, soil erosion on hillslopes has increased (Dymond et al., 2016). As a result, SedNetNZ, a New Zealand version of the Australian SedNet model (Prosser et al., 2001; Wilkinson et al., 2009), has been developed to evaluate soil loss and sediment budgets. This version of the SedNet model reflects the nature of landslide, gully, earthflow erosion, surficial erosion, bank erosion and floodplain deposition, which are important forms of soil erosion relevant to New Zealand (Dymond et al., 2016). The SedNetNZ model divides large catchments into sub-catchments where each budget quantifies fine sediment sources associated with the important erosion processes. Soil loss risk assessments and SedNetNZ have become common when creating sustainable farm plans in New Zealand, implemented from 2007 onwards, based on detailed land-use capability assessments (Lynn et al., 2009; Dymond et al., 2016). Farm plans identify areas of high risk for erosion and suggest appropriate soil conservation measures (Dymond et al., 2016). These conservation methods often include planting trees, sediment traps, reforestation, and land retirement.

SedNetNZ has also been applied to scenario-based modellings, such as Dougall et al. (2005), who developed a set of scenarios with stakeholder input that recommended increasing grazing ground cover to reduce suspended sediment export from a catchment on Great Barrier Island, New Zealand. Alternative scenarios included spatial changes to hillslope erosion, gully erosion, and riparian vegetation, which substantially changed suspended sediment contributions. The resulting output from the scenario-based SedNetNZ modelling highlighted knowledge gaps which the local community could use to direct funding and improve data for future model applications. The SedNetNZ model has also been applied as a policy planning tool, especially in the Hawke's Bay region of New Zealand (Lynch et al., 2019). Lynch et al. (2019) identified sediment yield and erosion values for a set of riparian protection scenarios in rivers in the Hawkes Bay region. Allowing for the identification of high priority sub-catchments that could be communicated to the stakeholders. Ultimately, SedNetNZ allows for large scale sediment erosion risk modelling, which can be completed in shorter periods than other models and at a lower cost (Lynch et al., 2019). Moreover, SedNetNZ allows for easily communicable information for regional councils and can be completed at large scales, thus providing data for informed management approaches.

Despite the wide range of model inputs and considerations, SedNetNZ does not consider infiltration excess runoff, variable source areas, daily or sub-daily dynamics and morphodynamics of river systems (Elliot and Basher, 2011). This was addressed by later versions of the SedNetNZ model, which attempted to include long-term morphodynamics such as the dynamic adjustment of landforms and stream morphology in response to climate, geological, tectonic and anthropogenic factors. However, care must still be taken when applying this model to any catchment, as it may omit some of the complexities present for that specific system.

3.6 Conclusions

Sediment connectivity is an ever-evolving concept in fluvial geomorphology. It describes the transfer of sediment between and within landscape compartments and underpins the capacity for adjustment of a system. Identification of sediment sources and pathways can help highlight areas of high importance to a system, as upstream processes reflect sedimentation downstream. Sediment connectivity modelling approaches are ever-expanding, with a diverse range of applications being developed. Modelling approaches range from conceptual/morphodynamics modelling to differential equations and other mathematical approaches, reflected in the types of model outcomes in sediment volumes or patterns. Sediment connectivity modelling can provide meaningful information about catchment-scale sediment flux dynamics, communicated to policymakers and stakeholders. Quantitative model outcomes can aid in informed management, as the magnitude and trajectories of rivers can be predicted. This thesis provides a multifaceted approach to catchment sediment flux dynamics. Where sensitivity, landscape configuration and land use evaluations are coupled with two connectivity models to produce an overview of sediment connectivity, determine the potential for channel adjustment and possible trajectories of adjustment under different land use scenarios for the Waimatā River, Gisborne, New Zealand.

Chapter Four: Methodology

Determining sediment sources and sediment transport patterns are vital in determining the root causes of sedimentation issues in the Waimatā. Building off modelling work presented by Borselli et al. (2008) and Tangi et al. (2019), this thesis aims to create an overview of sediment connectivity patterns in the Waimatā. These patterns will be linked back to River Styles classifications throughout the catchment, which helps determine the types of adjustment present at a reach. Lastly, three land use scenarios for the Waimatā are presented presenting patterns of deforestation, afforestation and constructing barriers are assessed in relation to sediment connectivity. An overview of the methods chapter is shown in Figure 4.1.

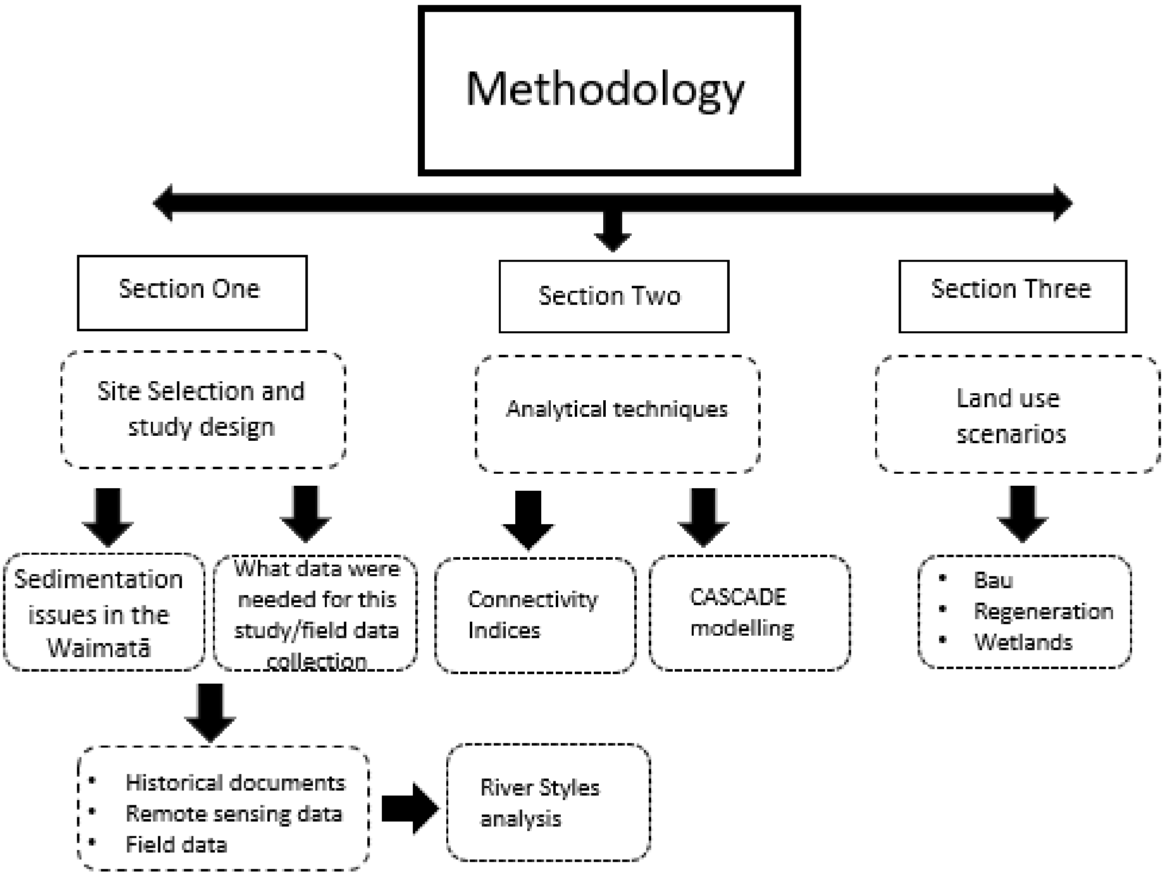


Figure 4.1 Overview of chapter four methodology.

4.1 Site selection

Changing landscape dynamics in the Waimatā Catchment and associated sedimentation issues throughout the system (e.g. Cullum et al., 2017) prompted the design and conduct of this research. The primary aim is to enhance geomorphic understanding of process relationships to inform management applications. Conducted effectively, process-based scientific insights can help prioritise management actions (Beechie et al., 2010; Brierley and Fryirs, 2000). In this thesis, analysis of the nature of sediment erosion and deposition is appraised for different River Styles (Fryirs and Brierley, 2005). Aspects of the Waimatā make this an excellent catchment to explore these themes, as terraces that span considerable lengths of the river create a flume type environment by flushing through sediments. Particular attention is given to the differentiation of transfer and throughput zones (Brierley and Fryirs, 2000; Brierley and Murn, 1997). These reaches are especially sensitive to geomorphic disturbance as sediment stores are reworked (Reid and Brierley, 2015). Figures 4.2 and 4.3 show key differences between transfer and throughput reaches in the Waimatā.

Figure 4.2 Example of transfer reach of the Waimatā. Note the patterns of sediment deposition where deposition is discontinuous, commonly located on the inside of the bend and a typical point bar (a product of contemporary depositional processes). Some areas also display point ledges, which are products of incision and lateral channel adjustment).

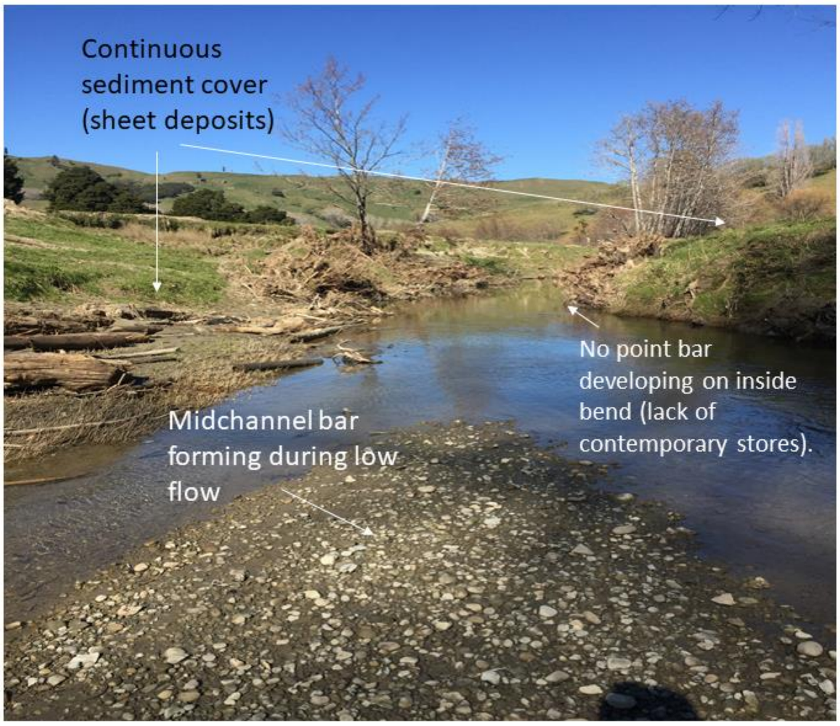


Figure 4.3 Examples of types of throughput reaches in the Waimatā. Note the limited contemporary sediment stores. The lower example has not developed point bars and has continuous sediment cover in the form of sheet wash. The upper example is constricted by bedrock resulting in forced pools.

4.2 Study design

The primary techniques used during this project were River styles analysis, connectivity index modelling and sediment transport modelling. The River Styles techniques were used to develop an overview of catchment dynamics and the capacity for adjustment by identifying throughput and transfer reaches.

4.2.1 River Styles Study Design

The River Styles Framework provides geomorphic templates in which spatial and temporal biophysical processes are assessed within the catchment context (Brierley et al., 2002). The degree to which the Waimatā can adjust varies for each style. Therefore management strategies must be adjusted to fit each style. Assessing the geomorphology of a catchment needs to be embraced as a core component of river management practices (Newson, 1992; Kondolf, 1995, Brierley et al., 2002). Understanding geomorphic processes and determining appropriate river structure and function at different positions in the catchment are vital for effective and targeted river management. Brierley and Fryirs (2000) noted that challenges arise facing resource management and the prioritisation of river management expenditure. Therefore, assessments of condition and recovery potential based on river types are vital in aiding such decisions. The River Styles assessment aims to describe the Waimatā catchment and recommend priorities for sediment management. This section will build on the work completed by Cullum et al. (2016) and assess the processes acting within the Waimatā, which result in high sediment generation, and the behaviour of the river as it moves downstream so effectively.

Data required for the River Styles assessment included a mixture of contemporary and historical field and aerial imagery. Contemporary field and aerial imagery were needed to determine the types of patterns and processes acting in each reach, helping to determine the River Style of each section of the river. The same data were used for the development of transfer and throughput reach maps and comparisons. Historical aerial imagery was used to assess planform change, for an example reach of each River Style. Representative reaches were selected based on imagery quality, cloud cover and the presence of an easily identifiable river margin. Reaches with considerable vegetation cover were not selected as an accurate delineation of the river position was not possible. Therefore, reaches with little vegetation cover, no cloud cover at imaging, and a clear channel edge were chosen. Contemporary aerial imagery was obtained using the New Zealand Imagery base map provided by Eagle Technology through ESRI ArcMap. This layer combines high-resolution imagery (0.075m-1.25m) and covers around 95% of New Zealand. Contemporary field imagery is the author's own obtained during field visits in August 2018, September 2019, July 2020 and November 2020. Lastly, historical imagery was obtained from various suppliers provided through Google Earth. Imagery from 2003, 2010, 2015, 2018 and 2020 was used, with these years being chosen based on data being available for all of the River Styles locations. For some of the examples, many years were missing, and therefore could not be equally compared as images were not taken during the same year.

Identification of changes in confinement was also needed to undertake a River Styles analysis. This was completed through a combination of hill shade-based valley width measurements and the extraction of the valley bottom using the Valley Bottom Extraction Tool (VBET). VBET 0.1, the custom ArcMap toolbox developed by Gilbert et al. (2016), was used to produce a single shapefile polygon that identified variations in valley bottom width. The input features used were an 8m DEM (Land Information New Zealand, 2012), a stream network clipped to the Waimatā Catchment (Ministry for the Environment, 2010), and a drainage area raster created using ArcMap.

4.2.2 Indices of Sediment Connectivity.

Sediment connectivity in river networks results from supply rates, grain sizes, distribution of sediment sources and the delivery of sediment through a river network (Bracken et al., 2015; Schmitt et al., 2018). Models can help characterise sediment sources, transport pathways and the magnitude and spatiotemporal distribution of the responses of fluvial geomorphic processes to anthropogenic disturbances (Schmitt et al., 2018). For this thesis, the Borselli et al. (2008) index of connectivity was chosen. Borselli et al.'s (2008) method is a widely adopted method of sediment connectivity modelling and results in spatial maps visualising areas of potential sediment movement. Due to the likeness of the Waimatā Catchment to the agricultural catchment, the model was created in the Borselli et al. (2008) model was fit for this purpose. Land use roughness values (C-values) provided by Borselli et al. (2008) corresponded with the recognised land use types found in the Waimatā, as well as the identification of prominent sediment sources, especially coming from hillslopes.

The Borselli et al. (2008) model is easily accessible and deployed with a raster math option in any GIS environment. This model also has simple data requirements, which comprise three main layers: a digital elevation model (DEM), a land use layer and a road network. Data resolution reflects the scale of the connectivity output. Thus two DEM's were used to create the connectivity index, one with a coarse 8m spatial resolution and the other with finer 1m resolution. The 8m DEM from 2012 was acquired from Land Information New Zealand (LINZ). The 1m resolution DEM was created by Gisborne Council, who interpolated 20m elevation contours obtained from airborne laser scanner (ALS), with post-processing and filtering to produce a region-wide LiDAR survey. The LUCAS NZ Land Use Map was obtained from the Ministry for the Environment (MfE) and is a vector multi-polygon that contains land use classifications from 1990 to 2016. The 2016 land use classification was used for this thesis. Lastly, the road network layer was clipped from the 'NZ Roads: Road Section Geometry' layer published by LINZ on the LINZ Data Service.

Sediment connectivity indices provide simple semi-quantitative depictions of the potential sediment delivery between catchment compartments. Despite the widespread use of connectivity indices, these models have previously focused on structural (physical) connectivity rather than integrating process-based connectivity (Najafi et al., 2021). Therefore, a process-based connectivity approach was required to bridge this gap, leading to the CASCADE Toolbox.

4.2.3 CASCADE Toolbox

As outlined in section 3.4, the CASCADE (Catchment Sediment Connectivity And Delivery) modelling framework allows each sediment source in a system to be assessed as the beginning of a new sediment cascade. CASCADE quantifies how sediment supplied from a source is delivered downstream to sinks, allowing sediment inputs to be traced back to their source. Other frameworks such as graph theory approaches do not cover sediment connectivity's most relevant process domains (Bracken et al., 2015). However, the CASCADE approach integrates previous approaches into novel network-scale modelling approaches to quantify functional sediment connectivity (Schmitt et al., 2016).

The CASCADE Toolbox provides a means of quantifying and visualising these patterns and processes in sediment connectivity and was developed for sediment management and geomorphic studies in large river systems. CASCADE represents sediment transport from many individual sediment sources in a river network as an individual cascading process for each source. The CASCADE Toolbox is an open-source MATLAB script that can be run in MATLAB 2017a. The MATLAB Toolbox requires external toolboxes such as 'Text Analytics Toolbox ™' and 'Bioinformatics Toolbox ™'. The toolbox also requires MATLAB functions for topographic analysis from 'TopoToolbox' developed by Schwanghart and Scherler (2013; 2014).

The CASCADE Toolbox requires a combination of data inputs from the field and remote sensing. Field-obtained data included grain size data and Manning's N roughness values. Grain size data were collected at 1km intervals throughout the accessible areas of the catchment (Figure 4.4). The sampling sites were selected to ensure even sampling distribution as far as practicable given accessibility constraints. Bed surface grain-size data were collected during the July trip throughout the catchment.

The conventional methods of Wolman (1954) were used by taking grain count every metre along 100m measuring tape transects. Sample clasts were picked at half-metre intervals using a ‘gravelometer’ template with half phi (–ϕ) size intervals to determine the grain-size distribution (Bunte & Abt, 2001). Following terminology definitions in Blott & Pye (2001), fines refer to any material below 8mm diameter while maintaining individual grains. Smaller materials are defined as silts, and grains larger than 128mm are referred to as boulders.

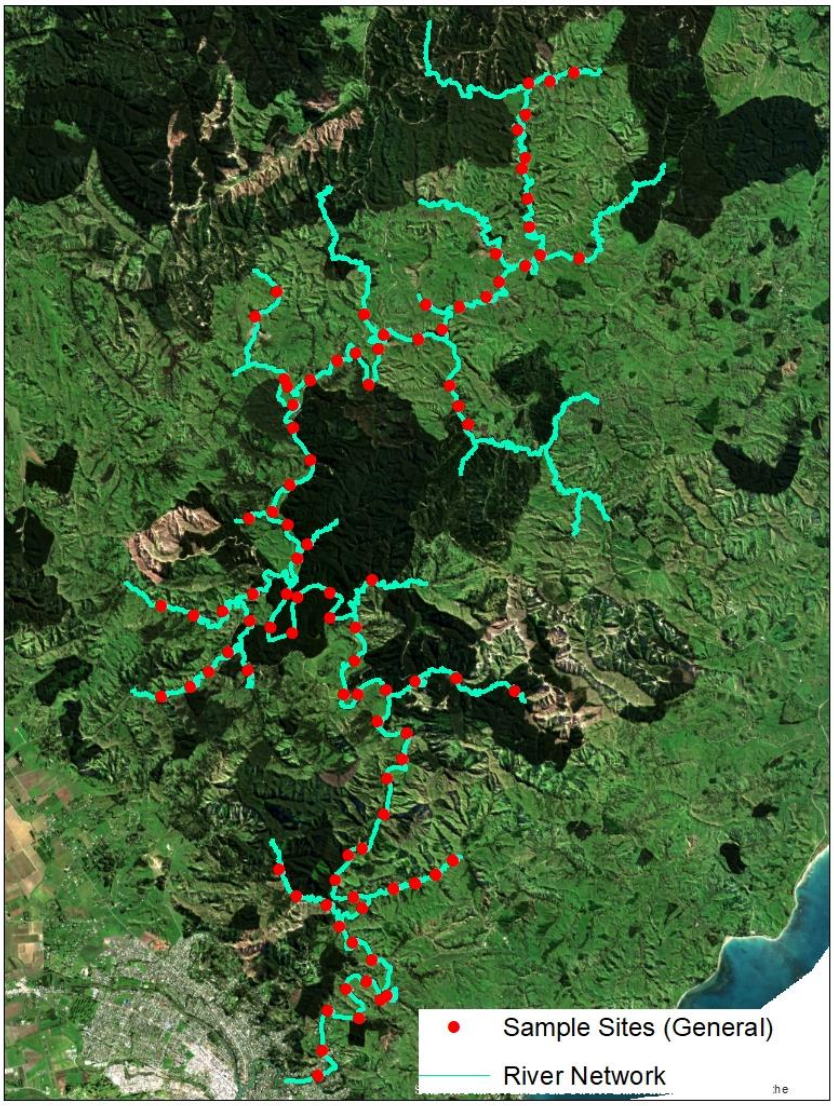


Figure 4.4 Proposed sample site location of Wolman Walks, with sites set at 1km intervals to ensure systematic data collection. Not all sites were completed due to site accessibility constraints.

Thirty-eight gravel-bed walks were taken during the July 2020 trip. The sampling aimed to capture the distribution of grain sizes throughout the catchment. Between 100-200 grains were counted along each transect. The size of visible bars played a significant factor in the sampling size as many sites did not have large enough bars to accurately count more than 100 clasts without disturbing the natural grain distribution. However, this count did follow the original minimum suggestion of Wolman (1954) to overcome operator errors. Clasts larger than the sieve size 128mm were manually measured. The ten largest clasts at each site were also measured to capture grain size variability between reaches further.

The three key metrics used to input into CASCADE were the D16, D50 and D84 diameter percentiles. Cumulative frequency results were input into the 'Grain Size Distribution Calculator' (Parker, 2004) and the web application 'BedLoadWeb' for simple percentile computations.

Manning's N estimations were completed in-field and remotely using the classification scheme presented in Table 4.1. The remaining data inputs required for the CASCADE Toolbox could be completed remotely using the 1m DEM (see section 4.4.2). These data inputs consisted of a mixture of automated inputs from the script and manual interpretation. Manual Using ArcMap's measure tool, channel width was obtained using the 1m DEM hill shade, allowing for a channel width measurement to be recorded at each node (reach delineations from CASCADE) using ArcMap's measure tool. Discharge was interpreted for each node using the catchment areas calculation outlined in equations 4.1 and 4.2 (McKe Q_A represents the total discharge value which was obtained from Land, Air, Water Aotearoa (LAWA, 2020). A_A is the total catchment area (370km^2). A_B is the contributing upstream area for a given node and Q_B is the discharge for each node.

$$\frac{Q_A}{A_A^{0\cdot 8}} = \frac{Q_B}{A_B^{0\cdot 8}}$$ Equation 4.1

$$Q_B = \frac{Q_A}{(370)^{0.8}} \cdot (x)^{0\cdot 8}$$ Equation 4.2

Table 4.1. Manning's n roughness values for river channels (From Chow, 1959)

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070

4.3 Analytical Techniques

4.3.1 River Styles Analysis

River Styles analysis was completed for the Waimatā Catchment using naming conventions set out by Cullum and Brierley (2016). The first two levels of the River Styles classification were used to reflect the confinement and controls of confinement throughout the catchment. The naming conventions used for this are outlined in Figure 4.5. A catchment River Styles map was produced in ArcMap using field and aerial imagery coupled with valley confinement classification using the hill shade layer and VBET to define River Styles.

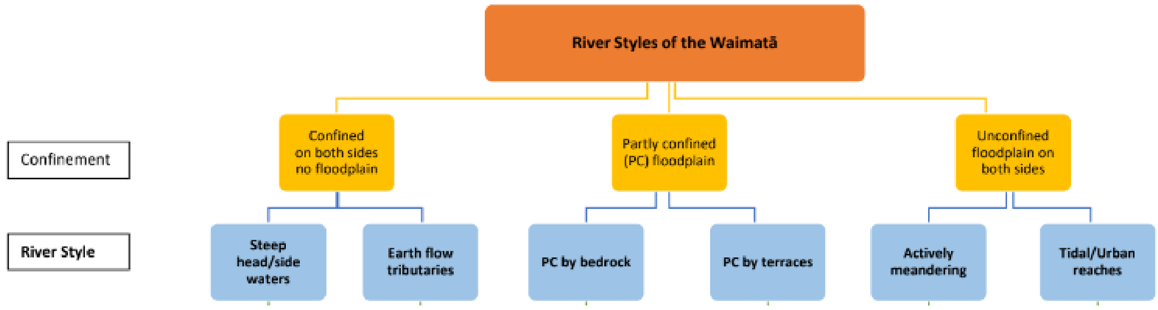


Figure 4.5. The first two levels of the River Styles naming conventions for the Waimatā (adapted from Cullum and Brierley, 2016).

Systematic analysis of River Types was then completed for the catchment with type examples chosen for each River Style to reflect common attributes. The Type examples also required in-field photography and available aerial imagery coverage.

Particular attention was paid to the capacity for adjustment for each River Styles example. Characterisation of capacity for adjustment was completed through a simplified adaption of that completed by Khan and Fryirs (2020), where importance was given to the control on valley confinement. Controls with 'soft' boundaries were considered less sensitive in terms of channel migration, where the channel displayed erosional and depositional features which coincided with lateral migration. These 'soft' controls included planform-controlled River Styles, margin controlled, earthflow tributaries and some instances of terrace controlled. 'Hard' controls of capacity for adjustment included River Styles with controls of valley confinement which resulted in the channel being fixed to one place with low potential for channel adjustment. These 'hard' River Styles included human modification, bedrock confinement and some instances of terrace confinement.

Historical analysis of channel migration was completed using aerial imagery taken at five-time slices between 2003 and 2020, using Google Earth and ArcMap. Example reaches of six River Styles (outlined in section 4. 2.1) were identified in Google Earth. A polyline was constructed to represent the river centreline for the five selected years, then imported into ArcMap for further analysis. Each river centreline represents the position of the river over 17 years. To produce an average channel migration, the difference between the 2003 and 2020 centre lines was determined, by creating 20m transects along the two lines and measuring the vertical distance between them. These values were then averaged out to create an average measure of channel migration for the six River Styles.

River Styles analysis was further extended through the identification of throughput and transfer reaches. Like the River Styles classification, aerial imagery and in-field photography were used to determine the presence of throughput and transfer reaches following a branch of the River Styles analysis outlined in Fryirs and Brierley (2001). The definitions used are summarised in section 3.3.3. Throughput and transfer zones were then plotted for the primary tributaries and trunk stream using ArcMap. The presence of throughput and transfer zones were related to the River Styles characterisation, grouping each River Style into transfer and throughput reaches, with defining attributes outlined through a series of examples.

4.3.2 Connectivity analysis

Visualising sediment connectivity in a catchment provides important insight when assessing the potential for the development of geomorphic features such as wetlands. This helps determine controls on the patterns of features which aid and/or impede sediment transfer within a system. Building on this, potential sediment sources can be determined, and sediment conveyance (routing) through the system can be tracked. Quantitative evaluation of this sediment transfer potential is vital in such work. Producing a sediment connectivity map using the approach developed by Borselli et al. (2008) provides helpful foundational work to interpret these systems.

The connectivity index (IC) was calculated using the following equation used by both Borselli et al. (2008) and Cavalli et al. (2013):

$$\mathrm{IC}_k = \log_{10}\left(\frac{D_{\mathrm{up},k}}{D_{\mathrm{dn},k}}\right) = \log_{10}\left(\frac{\overline{W}_k\ \overline{S}_k\ \sqrt{A_k}}{\sum_{i=k,n_k} \frac{d_i}{W_i S_i}}\right) \qquad \text{Equation 4.3}$$

Equation 4.3 represents a dimensionless measure within the [-∞; +∞] range. In this calculation, the upslope contributing area (D_{up},K) is divided by the downslope contributing area (D_{dn}, K) then multiplied by log10. The definitions of upslope and downslope contributing areas are highlighted in Figure 4.6. The upslope approach (Lu et al., 2006) considers the characteristics of the drainage area, including morphology and land use. The sediment delivery ratio decreases with increasing basin size as larger basins have a low average slope and more sediment storage sites between sediment source areas and outlets (Borselli et al., 2008). The downslope approach considers the flow path length that a particle must travel to arrive at the nearest sink. The distance between the source area and the sink is affected by surface roughness and slope. Therefore, the SDR is influenced by the length and surface characteristics of the shortest path to the nearest sink (Borselli et al., 2008).

$$D_{up} = \overline{W} \cdot \overline{S} \cdot \sqrt{A}$$ Equation 4.4

Equation 4.4 determines the potential for downward routing of the sediment produced upslope. The upslope contributing areas is defined by $\overline{W}$ which is the weighting factor (dimensionless). These can be determined by land use factors, such as runoff, infiltration, and erosion potential. $\bar{S}$ represents average slope. It is calculated in ArcGIS using the spatial analysis slope tool (m/m). Lastly, $\sqrt{A}$ refers to the upslope contributing area.

The downslope contributing area refers to the potential for sediment to flow through each reach of river/area of land, the *ith* cell, outlined in equation 4.5

$$D_{dn} = \sum_i \frac{d_i}{W_i \cdot S_i}$$ Equation 4.5

These cells are calculated by deriving the length of the flow path along the *ith* cell (d_i), then dividing these by W_i (weighting factor) by the $S_{i.}$ (slope of the *ith* cell). These are then summed and multiplied by log10. ArcGIS Spatial Analyst tools and the 'Raster calculator' were used to produce the final IC. The inclusion of the log10 parameter is to normalise the equation. Normalisation is not easy to achieve unless relativisation of probability to the catchment summing all the probabilities of the cells in which the catchment is divided is completed. Hence it is more convenient to introduce an index of the logarithm outlined in equation 4.3. This research utilised the Borselli et al. (2008) method of producing sediment connectivity indices. ArcGIS toolboxes can be difficult to operate due to limitations in software capabilities, whereas using a raster-based method allows for access on any computer with ArcGIS installed, proving the Borselli (2008) approach to be the most accessible. To ensure accurate results, the slope threshold needed to be determined and implemented. Slope and connectivity show a positive relationship whereby as slope increases, so does connectivity. Therefore, the slope was adjusted according to the Cavalli et al. (2013) modification within the range between 0.005 (m/m) and 1 (m/m). The lower limit is to avoid 0 and infinite values. The upper limit avoids bias due to high IC values on steep slopes.

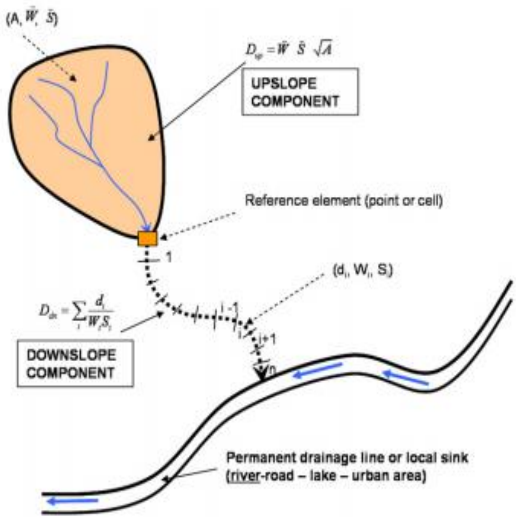


Figure 4.6 Connectivity Index representation of upslope and downslope contributing areas (From Borselli et al., 2008)

Table 4.2 C Factor values included in derivation of the Connectivity Index (From Borselli et al., 2008).

Level 1	Level 2	Level 3	C-factor
1. Artificial surfaces	1.1 Urban fabric		n.c.
	1.2 Industrial fabric		n.c.
	1.3 Mines, dumps and construction sites	1.3.1 Mineral extraction sites	1
		1.3.3 Construction sites	1
	1.4 Artificial non agricultural vegetated areas	1.4.1 Green urban areas	0.05
		1.4.2 Sport and leisure facilities	0.05
2. Agricultural areas	2.1 Arable land	2.1.1 Non irrigated arable land	0.1
		2.1.4.1 Vegetables cultivation[a]	0.1
		2.1.4.2 Nursery cultivation and cultivation under plastic[a]	0.001
	2.2 Permanent crops	2.2.1 Vineyards	0.451
		2.2.2 Fruit trees and berries plantations	0.296
		2.2.3 Olive groves	0.296
	2.3 Pastures	2.3.1 Pastures	0.15
		2.3.2 Pastures with shrubs[a]	0.13
	2.4 Heterogeneous agricultural areas	2.4.4 Agro-forestries	0.05
3. Forest and seminatural areas	3.1 Forest	3.1.3.1 Mixed forests[a]	0.001
		3.1.3.2 Discontinuous forests[a]	0.006
		3.1.4 Riparian vegetation[a]	0.006
	3.2 Shrub and/or herbaceous vegetation associations		0.04
	3.3 Open spaces with little or no vegetation	3.3.2 Bare rocks	0.9
4. Wetlands	4.2 Coastal wetlands	4.2.3 Intertidal flats	1
5. Water bodies	5.1 Continental waters	5.1.1 Stream courses	n.c.
		5.1.2 Water bodies	n.c.

4.3.3 CASCADE Toolbox

The CASCADE Toolbox was used to identify dominant sediment sources and recognise patterns in sediment entrainment and deposition. The toolbox structure outlined by Tangi et al. (2019) consists of extracting the network from a DEM. First, the river network reach must be identified, and key reach features defined and organised into a data structure named 'ReachData' (Table 4.3). The second step entails an evaluation of the sediment fluxes in the network with the CASCADE model. This includes graph pre-processing, hydraulic features extraction and reach transport capacity formulas. Data required to support the application of the model are summarised in Table 4.4.

Table 4.3 Key input parameters and the possible sources for deriving parameters values on network scales.

Data source	Parameter	Description
Extracted from DEM	Slope [m/m]	Derived from the upstream and downstream node elevation of a reach.
	Length [m]	Desired length of individual reaches. Set by the user, derived from the network topology (see Table 2), and/or according to user supplied break points.
	Ad [Km^2]	Drainage area at the downstream node of a reach derived from the DEM.
User defined	Q [m^3/s]	Discharge for a chosen discharge scenario. Obtained from interpolation of gauging station datasets (Schmitt et al., 2016) or spatially distributed hydrological models (Schmitt et al., 2018b).
	Active channel width [m]	Width of the channel section for a given discharge scenario. Obtained from satellite imagery (Schmitt et al., 2014, 2016; Schmitt et al., 2018b), field studies, or global data.
	D16, D50, D84 [m]	Grainsize distribution parameters of sediment on the surface of the river bed.Interpolated from available point sediment samples, expert-based assessments, or based on hypothesis regarding river sediment transport regimes.
	Manning's n	Manning's roughness coefficient for the bed material in the channel. Obtained from filed data or estimated from literature.

Table 4.4 Outline of reach data parameters and methods of obtaining them.

Parameter	Method of obtaining
Slope (m/m)	Extract from DEM
Length (m)	Extract from DEM
Drainage areas (km^2)	Extract from DEM
Discharge (m^3/s)	Gauging data (present), modelling (hypothetical)
Active channel width (m)	Interpretation from images and/or field measurements
Grain size data (D16, D50, D84) (m)	Field measurements – Wolman Walks, Bulk Sieves.
Manning's N	Estimation from field

Supplementary to the primary sediment routing automated through the CASCADE Toolbox, it is important to account for external sediment sources (Tangi et al., 2019). These user-defined sediment sources include inputs from hillslopes or riverbanks and the identification of barriers such as wetlands or dams that alter the rate of sediment delivered to and transferred through a system.

Once the river network has been extracted, reach attributes identified, and user-defined sediment inputs have been classified, the CASCADE Toolbox is able to simulate sediment connectivity. The model uses graph theory to determine areas of source and sink and the spatial relationship between each point (Heckmann et al., 2015; Tangi et al., 2019). Each section of sediment transport in the river is described as a "cascade" and originates from a source in the network. Ultimately, sediment is plotted spatially and graphically. These can include total sediment transport, patterns of deposition for a single sediment class as well as comparison between two or more sediment classes. Beyond this, changes in total sediment transport caused by the removal of an external sediment supply can be derived, for example, mass wasting in the upper reaches of the Waimatā due to logging activities. Lastly, within-reach analyses can be conducted so long as grain size distribution data are on-hand as well as sediment sources, deposition and entrainment in a specific reach. The overall workflow of the CASCADE Toolbox is shown in Figure 4.7.

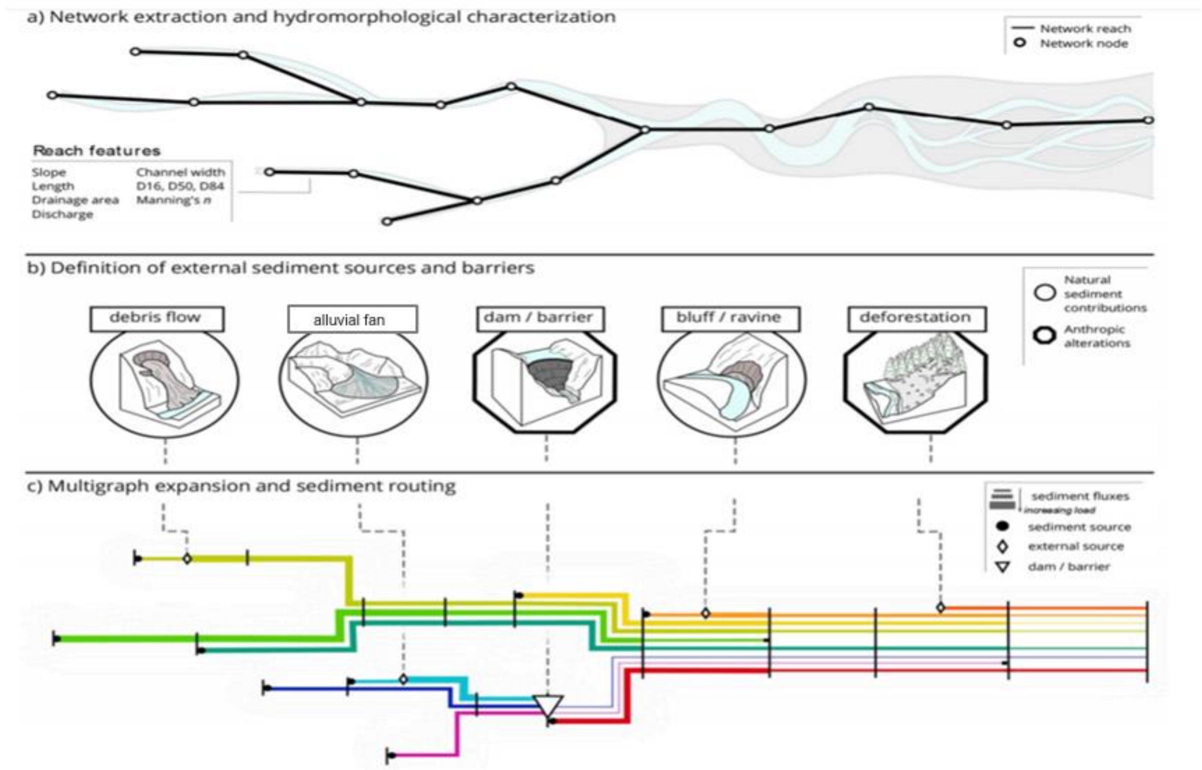


Figure 4.7 Schematic of the CASCADE Toolbox workflow. A) An outline of the network extraction and reach feature identification are either extracted from the DEM or user-defined. B) Examples of external sediment sources and barriers unique to each reach. C) An example of the sediment routing using the multigraph expansion including sediment barriers and external sources (from Tangi et al., 2019).

4.4 Land use Scenarios

Following the pre-processing of data, assessments of geomorphic change can be produced. Sediment transportation and deposition will be visualised and graphed in the CASCADE Toolbox and the Connectivity Index to understand the behaviour and patterns of sediment movement under a range of scenarios relevant to the Waimatā, including:

1. Forestry removal, land use changes and erosion control may induce a strong geomorphic response in the Waimatā. Loss of interception from vegetation can aid in the erosion of fine-grained sediment and result in greater sediment transport through the catchment (Marden et al., 2012).

2. Revegetation and rehabilitation of the Waimatā River scenario can help visualise the importance of planting and riparian strips. Retiring sections of forestry and agriculture and converting to native forest decreases sediment runoff and improves water quality and biodiversity.

3. Wetlands as barriers. Weak geology, lithology and uplift combined with high lateral and longitudinal connectivity contribute to sedimentation issues facing the Waimatā (Salmond, 2016). Wetlands and floodplains can act as buffers and barriers, disrupting sediment cascades and stopping sediment from entering a stream (Fryirs et al., 2007). Therefore, modelling the effectiveness of wetlands in mitigating sediment delivery to the trunk stream is vital as it could provide a method of limiting sedimentation throughout the catchment.

The scenarios outlined above were developed following an interview with a local catchment advisor and catchment experts (L. Easton, personal communication, 2020; A. Salmond, personal communication, 2020). Discussions surrounded what is realistic for the Waimatā as well as more aspirational approaches. These scenarios were implemented by creating new land use layers and assigning new roughness values relevant to each scenario. ArcMap 10.7 was used to manipulate the 2018 LUCAS land use cover layer (Ministry for the Environment, 2018).

4.4.1 Scenario One: Business as usual

The scenario entitled 'Business as usual' encapsulates what will potentially happen if land use in the Waimatā follows its current trajectory. This means that significant portions of the catchment with be clear-felled for forestry. 264 landslips representing 12.4ha or land are present in recently harvested areas in the catchment, whereas closed-canopy forest had 131 slips with an area of 13.8ha.

Conversely, farmland, open canopy pine with replant stems visible, had fewer slips than for closed canopy and recently harvested forest (Cave, 2019). Cave (2019) concluded that many landslides were generated by the failure of forestry landings (roads). Another common correlation was found between forestry roadways and poor water controls. Toe failures were also common, and there was a possible association of toe failures with locations downstream from landslides that originated from roadways and landings. Ultimately this indicated the influence that poor forest management has on the distribution of landslides in the Waimatā and the impact slips can have on downstream areas. This shows that analysis of forest clearance on sediment connectivity is vital as it provides an understanding of sediment behaviour due to poor stability and drainage. The areas highlighted in Figure 4.8 show the forested areas which will be removed in the coming years. This would lead to greater sediment transport and higher erosion. This layer was adapted from the MFE land use layer by grouping all areas categorised as forestry. The remaining features with similar roughness values were also grouped, with all the groups then being combined to create a new hypothetical land use layer.

The ‘Feature to Raster’ conversion tool then transformed the vector layer to a raster layer to be inputted into the Connectivity Index tool. New roughness values were then assigned to each of the categories based on the values outlined by Borselli et al. (2008) (Table 4.2). The ArcMap ‘Reclassify’ tool was used to reassign these values and convert them to integer values compatible with the IC, resulting in a new raster layer with new roughness values to input into the Connectivity Index. Implementing the new ‘business as usual’ scenario into the Connectivity Index involves running the Index with the new land use layer and roughness values.

Figure 4.8 Potential areas for forestry clearance.

4.4.2 Scenario Two: Regeneration of vegetation

The second land use scenario represents a 'best case scenario' restoration simulation for the Waimatā, aiming to mitigate future sedimentation issues (Marden et al., 2014). The creation of this layer followed a similar process as the 'business as usual' scenario, this time reverting forestry land use categories to indigenous forest and regrowth. Previous forestry layers were isolated and exported and renamed ‘forest regen’. The remaining land use layers, such as pasture, remained the same. However, the ‘woody biomass pasture’ roughness value was increased. This is because the absence of forest clearance would allow these areas to become denser and more resistant to erosion. The remaining land use classes were exported to a new land use file and merged with the ‘forest regen’. The ‘feature to raster’ tool was used to convert the land use layer to a raster layer, where the roughness values could be adjusted, in accordance with Borselli et al. (2008). Steps outlined in section 4.3.2 were then followed to create the regeneration scenario connectivity index.

4.4.3 Scenario Three: Wetlands as Barriers

The scenario ‘wetlands as barriers’ encapsulates using wetlands to impede sediment delivery to the main channel. This involves using wetlands as a ‘buffer zone’ as outlined in Fryirs et al. (2007a). To create this land use layer, areas suitable for wetlands were identified. The original sediment Connectivity Index layer created using the 1m DEM, and 2016 land use layer was loaded into ArcMap. Secondly, a conditional slope layer was created following the methods of Jain et al. (2008) to create a slope threshold at 5.78 degrees, indicative of floodplain forming conditions. This indicates areas where sediment would be deposited rather than being transported through a stream reach. Polygons were then drawn to represent areas of high connectivity impeded by low slope areas, indicating prospective areas for wetland construction that meet the slope threshold required for significant sediment deposition in reaches where hillslopes are decoupled (Harvey, 2001).

A clip operation was then completed using the geoprocessing toolbar. This created a layer which exclusively included the prospective wetland areas (decoupling) and low slope areas. The combined wetland layer was renamed “wetlands”. Forestry trends as indicated in the regeneration land use layer remained the same, as this scenario would encapsulate a cumulative ‘whole of system’ approach to restoration. Lastly, a riparian buffer zone was created. This entailed a 100m riparian buffer zone along the river network. The ‘wetlands’ existing land use layer from the ‘regeneration’ scenario and the riparian buffer layers were then merged to create the ‘wetlands as barriers’ land use layer. This was then converted to a raster format, and respective land use classes had their roughness values reclassified in accordance with Borselli et al. (2008) (Table 4.2). Steps outlined in 4.3.2 were subsequently followed to create the wetlands as a barriers connectivity index.

4.4.4 Cascade scenarios

The three scenarios were employed for CASCADE analysis; however, rather than manipulating roughness values, CASCADE can accept input sediment input values that could arise from changes to land use.

The 'business as usual' scenario entailed creating sediment inputs for a forestry removal regime. This was created using estimates from Larsen et al. (2010) and Cave (2019). The area of land sliding was calculated using the pixel size of the forestry category of the LUCAS (2018) land use layer. The entire forestry area which is expected to be removed in the next 20 years consisted of 85,551,378 pixels. To calculate area the following equation was used ($ps^2$is pixel size and psq is the pixel size quantity):

$$A = ps^2 \times psq$$

Equation 4.6

It is not likely that the entire forested area would result in landslides when vegetation was removed. Therefore, scaling existing patterns from Cave (2019) was used to derive a likely percentage. Cave (2019) discovered in a recently harvested forest bordering the Waimatā and Waipaoa catchments 1.67% of the area was occupied by landslips. Owing to the similarity of the nearby catchments, this factor was used to scale up the entire forested area of the Waimatā. This indicates a potential area of 1.336 km^2 being occupied by landslides under the business as usual scenario. Larsen et al. (2010) derived a landslide volume-area scaling relationship from a database of 1785 landslide events, many of which are in New Zealand. The scaling relationship can be defined as

Equation 4.7

$$V_L = 0.224 \times A_L^{1.26}$$

Where V_L is the volume of the landslide and A_L is the area of the landslide. This resulted in a combined V_L of 0.385km^2 of sediment contributing from all sources. For this thesis, each node located within the forestry removal zone was given an equal share of potential sediment volume. The interactive connectivity assessment was then run using the external sediment option input.

The regeneration approaches would not require manipulating external sediment sources as these scenarios aimed to reduce this. Rather, roughness values can be reduced along with discharge.

4.5 Conclusions

Sediment connectivity in the Waimatā has been assessed using two modelling techniques involving analysis of potential sediment movement, sediment sources and sediment transportation. Model outputs have been combined with the characterisation of River Styles present in the catchment, with attention paid to transfer and throughput zones and the capacity for adjustment in a river channel. Lastly, three informed management scenarios were produced, considering local and expert knowledge. These scenarios provide potential trajectories the Waimatā may follow in the future. The findings of these techniques are presented in the results section of this thesis (Chapter 5).

Chapter Five: Results

5.1 Overview of this chapter

The results chapter has three main sections: impacts of different River Styles on sediment transport, deposition and entrainment, an overall assessment of sediment connectivity and sediment flux behaviour in the Waimatā and the influence of changing landscape types (see Figure 5.1). The chapter begins with an appraisal of the impacts of river styles on the sediment behaviour and patterns in the Waimatā. By giving an overview of the diverse landscapes of the catchment, the different processes acting within these reaches in the past can provide a good picture of what may occur in the future, allowing for informed management. Assessment of sediment connectivity and flux behaviour will be made in Section 5.2, outlining the types of connectivity present in the Waimatā. This section will compare the CASCADE Toolbox and the ArcMap sediment connectivity index (IC) and an overview of the patterns occurring within the Waimatā, giving basis to where resilient and sensitive areas may occur. Lastly, section 5.3 presents the scenario-based work outcomes, providing insight into the potential paths the Waimatā may take under different boundary conditions.

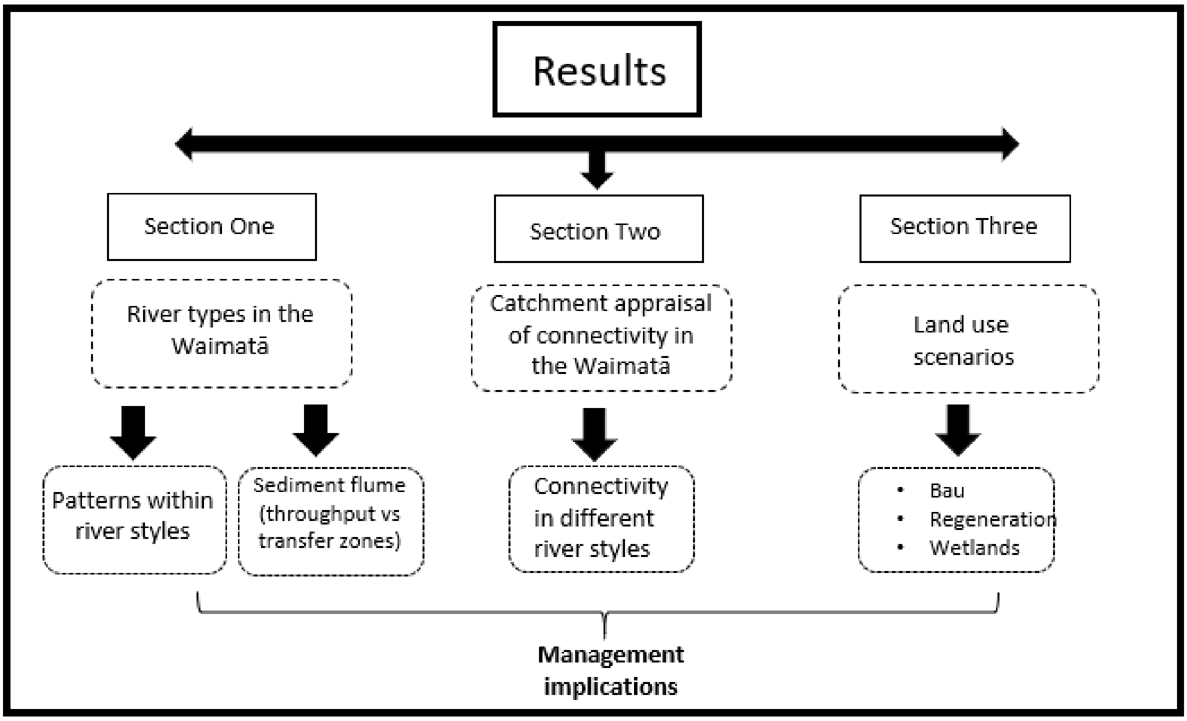


Figure 5.1 Overview of the results section.

5.2 River Styles of the Waimatā

Using methods outlined in Fryirs and Brierley (2018) and Cullum et al. (2016), eight River Style types were defined for the Waimatā Catchment. These River Styles types reflect the confinement and capacity for adjustment of a section of the river. River Styles naming conventions identified for the Waimatā are outlined in Table 5.1.

Table 5.1 River Styles naming conventions and controls for the Waimatā Catchment.

River Styles Naming	Confinement	Control
PC_PC	Partially Confined	Planform
UC_Urban	Unconfined	Urban
C_T	Confined	Terrace
PC_MC	Partially Confined	Margin
PC_BR	Partially Confined	Bedrock
PC_T	Partially Confined	Terrace
EF_trib	Earthflow	Tributary/margin
steep_headwaters	Confined	margin/hillslope

The River Styles map produced for the Waimatā Catchment is displayed in Figure 5.2. Two identified river styles are categorised as confined (C_T and steep_headwaters). These River Styles are categorised as narrow, V-shaped valleys with high steep sides and found in headwater and source streams throughout the Catchment. Confined sections of the Waimatā Catchment experience high landslip susceptibility due to steep slopes and have high hillslope-channel connectivity, with sediment free to enter the streams. Four of the eight River Styles have been identified as partly confined (PC_PC, PC_MC, PC_BR and PC_T). These reaches display evidence of discontinuous floodplain development and capacity for lateral adjustment. The position within the catchment determines the degree of adjustment of these River Styles types, as different types of confinement either allow or constrict any adjustment. The last two River Styles identified are unconfined and earth flow regions. The unconfined River Styles are found on the Waimatā Flats and are situated within cropland with a shallow slope. Unconfined sections of river have low tributary-trunk connectivity. Although sediment is free to migrate across the floodplain in these unconfined sections, hillslope-channel connectivity is low compared to other River Styles in the Waimatā Catchment. The final River Style in the Waimatā is the earth flow zones, commonly found in the tributary areas (EF_trib). These zones are characterised by rolling hummocky relief, low slopes, and a high risk of subsurface earth flows. Hillslope-channel connectivity in these zones is low as alluvial fans, and swamps frequently disconnect them. Examples of these River Styles are illustrated in Table 5.2.

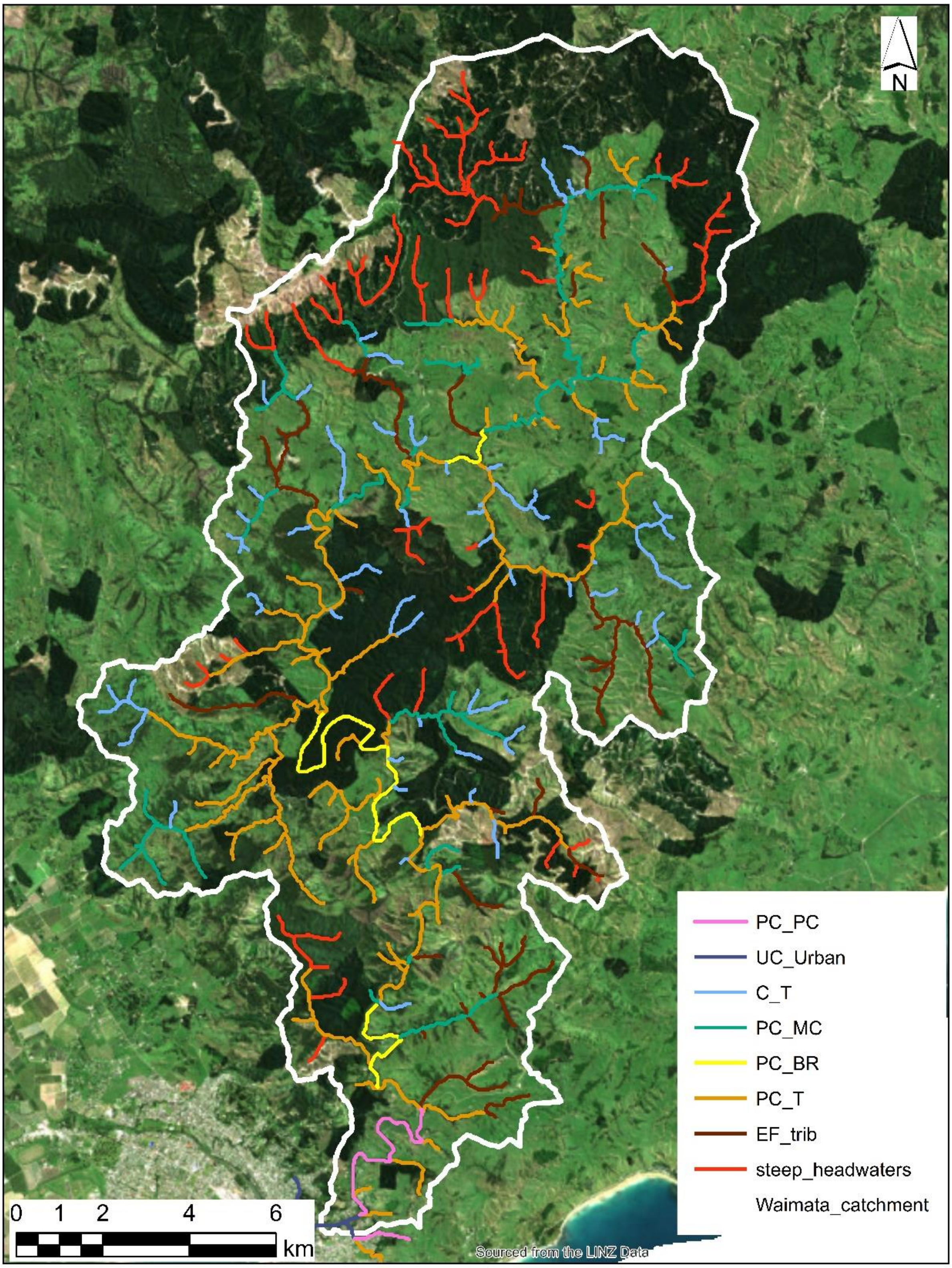


Figure 5.2 River Styles of the Waimatā Catchment, naming conventions are outlined in Table 5.1

Table 5.2 River Styles examples from the Waimatā Catchment.

River Style	Defining Attributes	Capacity for Adjustment	Comments	% total stream length	Transfer throughput
	Stream not immediately confined. Continuous floodplain development on both sides	High	Evidence of incising on outside bend and point bar development on convex. Channel free to laterally adjust on valley floor	0.29 %	Transfer
	Laterally unconfined area. Extensive floodplain development. Confined by human alterations.	Low	These reaches are artificially constrained to prevent adjustments. Under natural conditions these reaches would adjust freely, wandering across their floodplains through swamps and marshes.	3.41 %	Throughput
	Stream confined to the terraces. Little room for floodplain pockets. Lies within sinuous terrace.	Low	Constricted between terraces, not able to adjust laterally. Some adjustment may occur due to incision into the terraces/slumping	11.87 %	Throughput
	Confined within valley margins. Able to form floodplains on side , other constricted by valley wall.	Medium	Instream units, can adjust locally where space permits. However, banks can only adjust on side that is not constrained. Channel width can adjust only where floodplain pockets occur.	12.73 %	Transfer
	Confined by bedrock. Still enough space for floodplain pockets to develop	Low	Stream is not able to easily adjust laterally as it is constrained by bedrock on either side. Is able to move within space carved out within bedrock.	4.35 %	Can vary depending on space to move within bedrock constraints.

River Styles example table continued.

River Style	Defining Attributes	Capacity for Adjustment	Comments	% total stream length	Transfer throughput
	Stream confined on either side by terraces. Some room for discontinuous floodplains	Low	Evidence of incising on outside bend and point bar development on convex. Channel free to laterally adjust on valley floor	35.11 %	Throughput
	Partially confined by hillslopes. However, loose unconsolidated sediment allows for channel migration	High	Channel is able to incise and migrate laterally by cutting into hillslopes. Little floodplain development as sediments are stored on channel banks and reworked frequently.	14.06 %	Throughput/ transfer. Sediment is able to be stored, but large quantities being entrained and transferred.
	Stream confined within hillslopes. Steep topography allows for limited/no floodplain development.	Low	Constricted between hillslopes and dense vegetation. Not able to adjust laterally.	18.18%	Throughput

The second River Styles convention recognises the controls on confinement in each Style. In the Waimatā, identified controls include PC, MC, T, tributary, Br and urban (see naming convention Table 5.1). These controls directly influence the capacity for adjustment of a River Style. Although river conditions may change, for example, in response to changes in sediment inputs consequent to vegetation changes, these changes are constrained by the valley setting and controls on confinement. Therefore, each of the different settings of river styles means that each style has a different capacity for adjustment. 73% of streams in the Waimatā can be categorised as having low adjustment potential, reflected in Table 5.2.

Common themes within River Styles with low capacity for adjustment are partially confined/confined reaches constrained by bedrock, terraces and valley margins. There is enough space for floodplain development in some instances, such as PC_T and PC_BR. However, these are not depositional sites with long residence times (Figure 5.3). This is evident by the small accumulations of sediments on the bars, which are easily reworked. The remaining River Styles make up 27% of the catchment and range from medium to high capacity for adjustment. Common themes in the River Styles include large/continuous floodplain formation and external sediment sources feeding the stream. Examples of the types of geomorphic units present in River Styles with a high capacity for adjustment are illustrated in Figure 5.4.

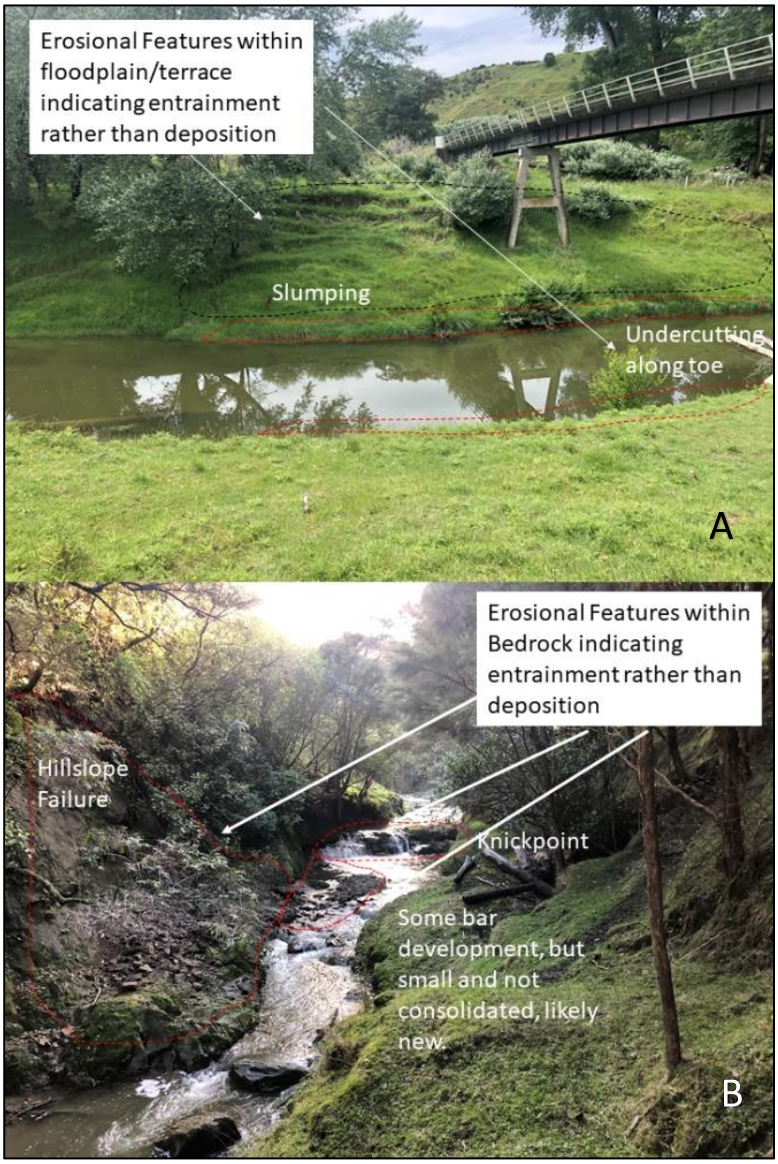


Figure 5.3 Example of River Styles with low capacity for adjustment and are partially confined/confined reaches, constrained by bedrock, terraces and valley margins. A) PC_T B) PC_Br

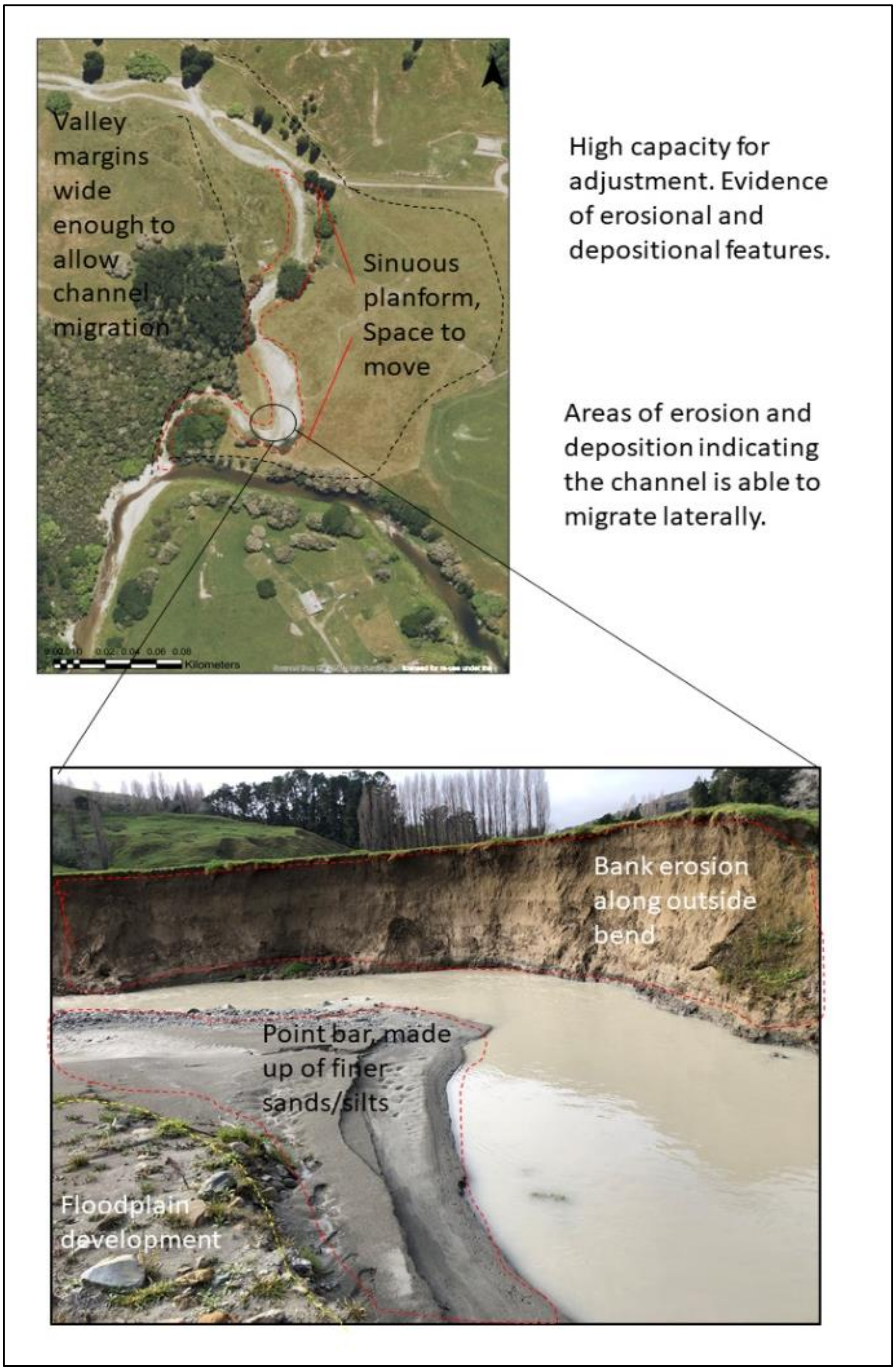


Figure 5.4 Example of a planform-controlled River Style. This reach exhibits depositional and erosional processes, and the river has enough space to adjust laterally.

The valley setting does not vary dramatically throughout the catchment. This is highlighted in the valley bottom extraction in Figure 5.5, which is consistent throughout the catchment, where tributaries commonly exhibit average valley widths <50m and trunk reaches up to <500m. Floodplain pockets are evident throughout the catchment, but there are not extensive floodplain reaches, causing adjustment to be limited. Due to this behaviour, the impact of disturbance responses associated with deforestation and land use change have been relatively limited in this system (in the upper/mid reaches). Similarities in valley width also highlight the importance of confinement and how confinement impacts a reach's capacity for adjustment.

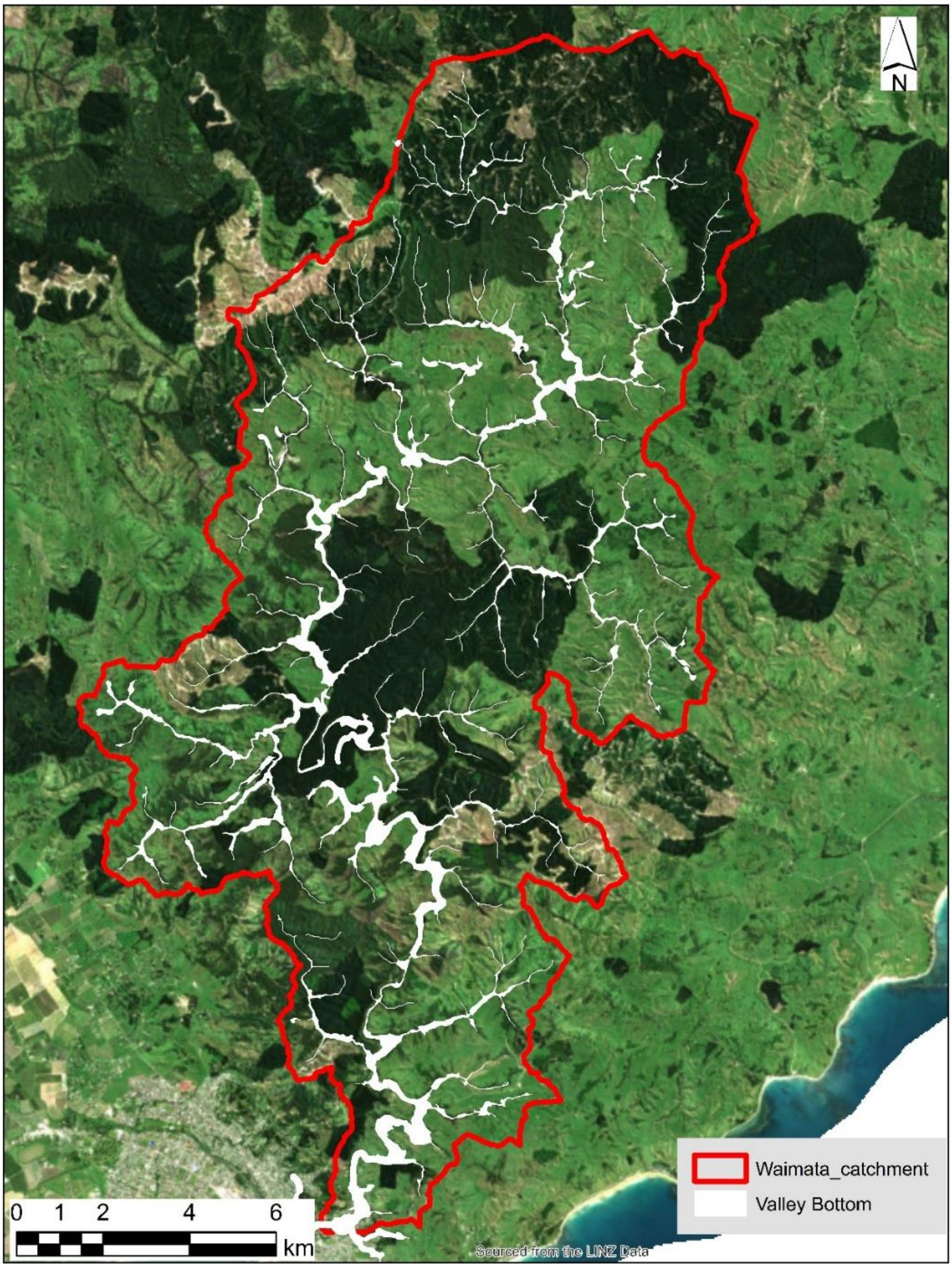


Figure 5.5 Valley bottom extraction, highlighting the similarities in valley confinement throughout the catchment.

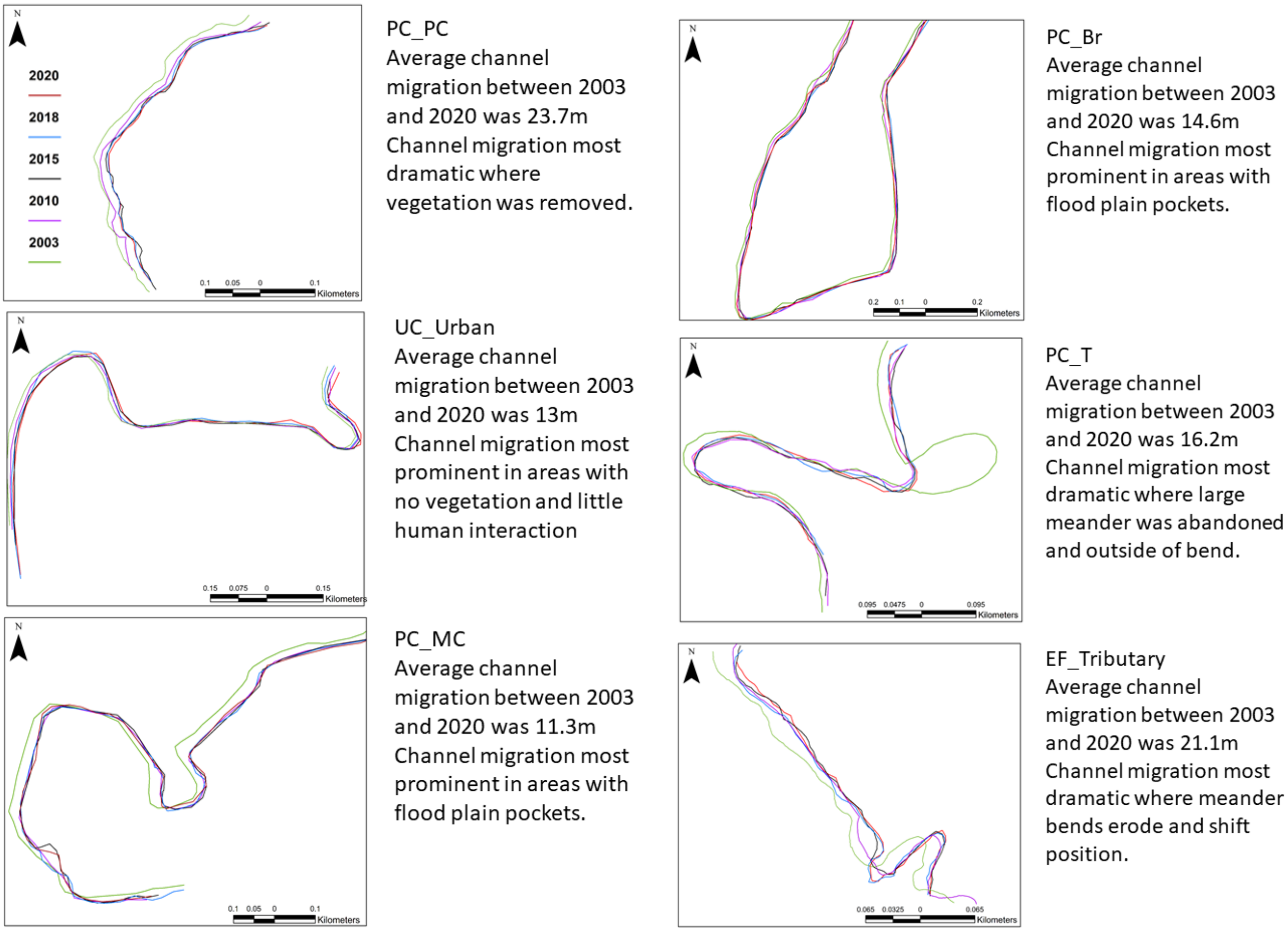


Figure 5.6 Evaluation of channel migration in six reaches representing the relevant River Styles between 2003 and 2020. C_T and Steep_headwaters were left out due to dense vegetation obscuring the view of the river.

Figure 5.6 also highlights the difference in capacity for adjustment amongst these six River Styles. As mentioned and highlighted in Figures 5.2 and 5.3, the confinement and controls influence the capacity for adjustment of a given reach. Partially confined River Styles with capacity for adjustment have displayed higher channel migration rates than River Styles with partial confinement and little capacity for adjustment. PC_PC and the EF_Tributary examples exhibited average channel migration of over 20m. Whereas PB_Br, UC_Urban, PC_MC and PC_T all show average channel migration rates of between 11.3m and 16.2m, reflecting the smaller accommodation space.

5.3 Capacity for adjustment: transfer vs throughput

Sediment conveyance and deposition patterns in the Waimatā can be further split into two categories; throughput and transfer, where throughput zones capture the River Styles with low capacity for lateral adjustment and transfer zones having a higher capacity for adjustment. Figure 5.7 identifies the throughput and transfer reaches for the Waimatā Catchment. Throughput zones occupy 82% of the catchment, while transfer zones occupy 18%, mainly in the trunk stream and significant tributaries. As outlined in Table 5.2, throughput zones are commonly found in confined and partially confined reaches controlled by terraces, bedrock, and hillslopes.

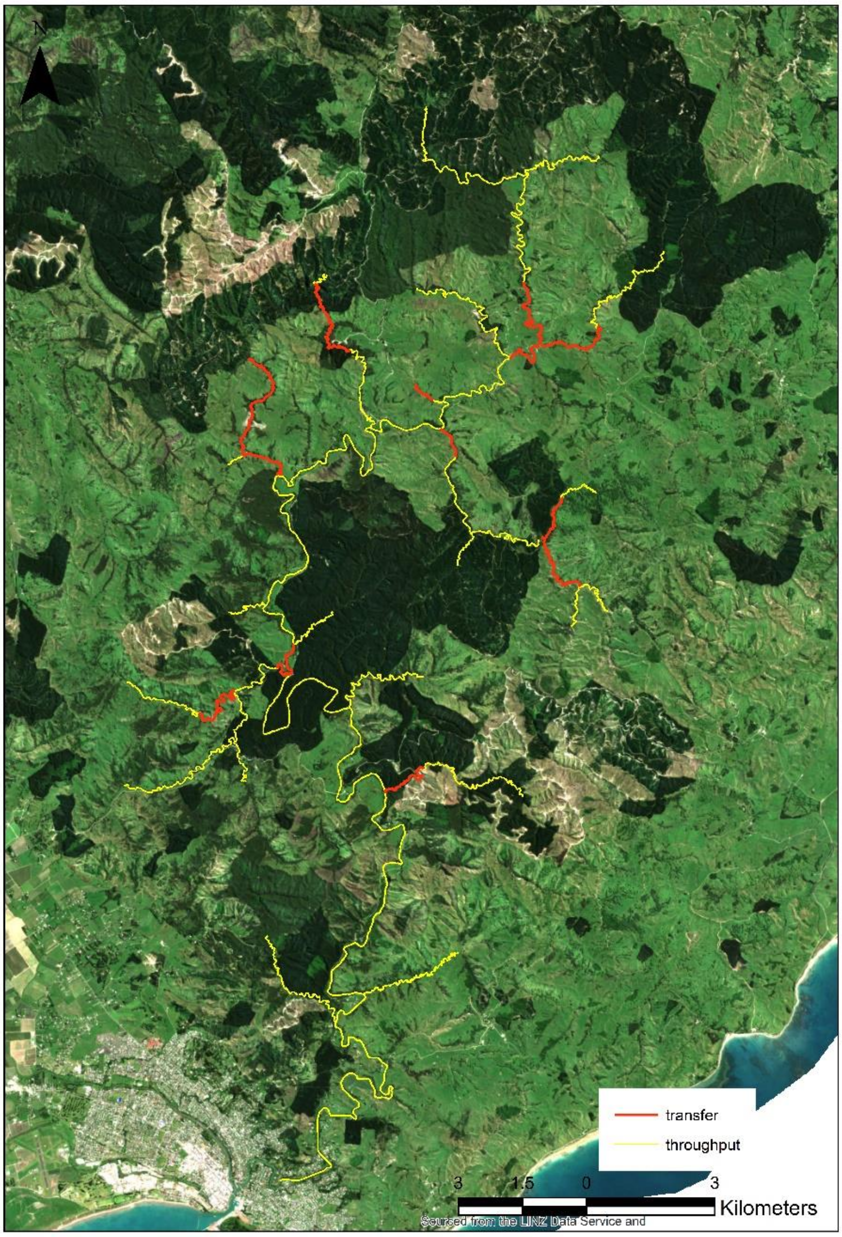


Figure 5.7 Transfer and throughput zones of the Waimatā Catchment.

Transfer reaches in the Waimatā are commonly found in partially confined areas controlled by planform or a dominant sediment source. Throughput zones in the Waimatā act to flush sediment through the system due to their low accommodation space. Figure 5.3 (PC_T) is a typical example of a throughput zone in the Waimatā, where evidence of depositional behaviour such as instream geomorphic units, sediment feeding from terraces and undercutting on outside bends is lacking. Other examples with similar throughput behaviour are illustrated in Table 5.3.

Table 5.3 Throughput reaches in the Waimatā Catchment found in partially confined and confined areas controlled by terraces and bedrock, exhibiting similar erosional characteristics.

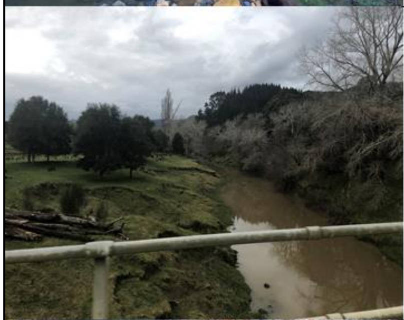
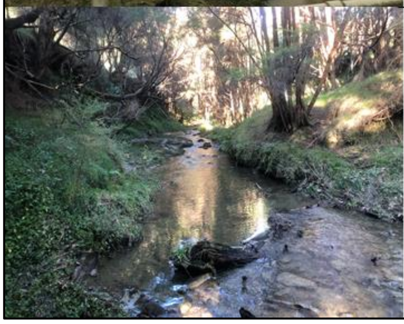
Throughput – Erosional Reaches	River Style	Attributes
	PC_T	• No Evidence of deposition • No visible in stream geomorphic units • Vegetation stabilising banks
	C_T	• Terraces beginning to slump • Small point bar deposits, unvegetated • Bank failure
	PC_T	• Mass wasting along left hand bank. • No visible instream geomorphic units
	PC_Br	• Undercutting • Flowing on bedrock • Banks slumping • Little/no floodplain formation.

Figure 5.4 shows a representative transfer reach of the Waimatā, which exhibits both erosional and depositional behaviour whilst displaying a high capacity for adjustment. Table 5.4 further exemplifies similarities in patterns of erosion and deposition found in transfer reaches.

Table 5.4 Transfer reaches of the Waimatā Catchment exhibiting similar erosional and depositional patterns. These reaches are commonly found in planform controlled and earth flow zones.

Transfer - Erosional and Depositional reaches	River Style	Attributes
	PC_PC	• Mid channel bar • Eroding outer banks • Point bar development • Scouring on inside bend
	PC_MC	• Prominent point bar • Inside bend scouring • Visible adjustment
	EF_Tributary	• Mid channel bar • Point bars • Bank attached bars • Identifiable sediment source • Bank slumping

Throughput reaches in the Waimatā exhibit straight channels, high terraces and narrow valley settings. This has resulted in sediment being flushed through the system. Some reaches show signs of sediment generation through bank failure and slumping. Often these sections of slumping span the length of the terraces and follow patterns in their sizes and shapes, resembling a 'scallop' shape. These sediments either get transferred downstream or remain at the toe of the failure and are then reworked back into the slope. An example of these scallop features is illustrated in Figure 5.8 and can occur from the upper reaches to the lower reaches of the Waimatā.

Figure 5.8 Upper reach example (left) of 'scalloping', the erosional feature is more localised than the lower reach (right) of continuous 'scalloping' along both channel sides.

Ultimately, types of controls on confinement reflect the capacity for adjustment of River Styles in the Waimatā. Reaches with immediate controls on adjustment, residence times, and erosion patterns reflect low channel migration and sediment storage, as seen in Figure 5.2 and Table 5.2. River Styles confined by planform development and immediate sediment storage see higher residence times and consistent erosion and depositional patterns, also reflected in the capacity for adjustment in these reaches. Furthermore, these patterns of confinement and sediment supply and transfer also reflect changes in sediment connectivity throughout the Waimatā Catchment. Relationships between sediment connectivity and sediment supply relationships will be developed in section 5.2.

Section 5.4 Patterns of Connectivity in the Waimatā Catchment.

Confinement in the Waimatā ranges from confined to partially confined, except for the short, laterally unconfined section flowing to join the Taruheru River. Confinement exerts a significant control on sediment behaviour throughout the system, as shown/demonstrated/outlined in section 5.2. Although significant sections of the river are categorised as partially/confined, different controls on confinement have been shown to influence patterns of adjustment directly. Sediment connectivity provides a method of evaluating the further potential for channel adjustment beyond the immediate influence of accommodation space, as discussed in section 5.2. Sediment connectivity considers the relative impact of slope, land use and hillslope coupling of a system.

Sediment connectivity in the Waimatā is high and can be split into five categories reflecting the potential for sediment transport between two landscape compartments. Table 5.5 illustrates the naming conventions for connectivity in the Waimatā based on model outputs from the Connectivity Index (IC). To provide consistency between the two model outputs of the different resolutions, types of connectivity will be related to the connectivity descriptor rather than the pixel values.

Table 5.5 Descriptions of connectivity for the 8m resolution IC and the 1m resolution IC.

Connectivity Descriptor	8m Pixel range	1m Pixel range
Very Low	-4.5 to -2	-7 to -1
Low	-2 to 0	-1 to 0
Medium	0 to 3	0 to 5
High	3 to 4.5	5 to 10
Very High	5.5 +	10 +

Figures 5.10a and 5.10b present catchment-wide assessments of sediment connectivity for the Waimatā. Figure 5.10b includes the connectivity index for the 8m resolution DEM and supervised land use cover. High/very high connectivity values occupy steep-sloped ridges and hillslopes. High/moderate connectivity values are more prominent in areas of partial confinement, whereas low/very low values are found almost exclusively on low slope floodplain areas. A logarithmic pattern between connectivity index value and the slope has been identified in which as slope increases, the connectivity index will become higher (Figure 5.9). Figure 5.10a presents the 1m resolution connectivity index for the Waimatā. Very low/low connectivity patterns have remained like the 8m connectivity index, with low sloped floodplain areas exhibiting the lowest connectivity within the catchment. Moderate/high connectivity dominates the catchment in this model output owing to the narrowly confined high slope areas that comprise the upper catchment recognised as medium/highly connected. The most significant change between the two outputs is the low connectivity identified in the densely forested area in the 1m index. In contrast, the 8m index reflects patterns of the slope.

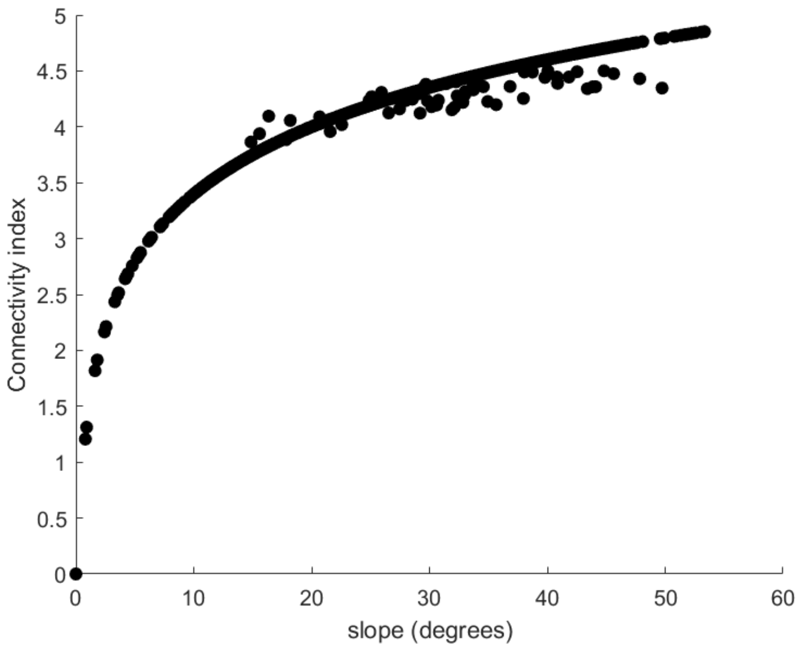


Figure 5.9 Scatter plots showing the relationship between slope and connectivity index.

Combining the two model outputs at different resolutions creates an overall picture of the patterns of connectivity in the Waimatā. It reflects the relative influence of vegetation and slope on sediment delivery. Different River Styles are also influenced by changing connectivity relationships, often determined by valley confinement, slope and vegetation. Representative reaches from each River Styles type and the types of connectivity located at each are outlined in Figure 5.11. Examples in Figure 5.11 show that the type of confinement does not directly influence the type of connectivity but rather the controls on confinement, especially slope and vegetation. Table 5.6 summarises the types of connectivity for each given River Style (in Figure 5.10), the capacity for adjustment and the controls on valley confinement/connectivity.

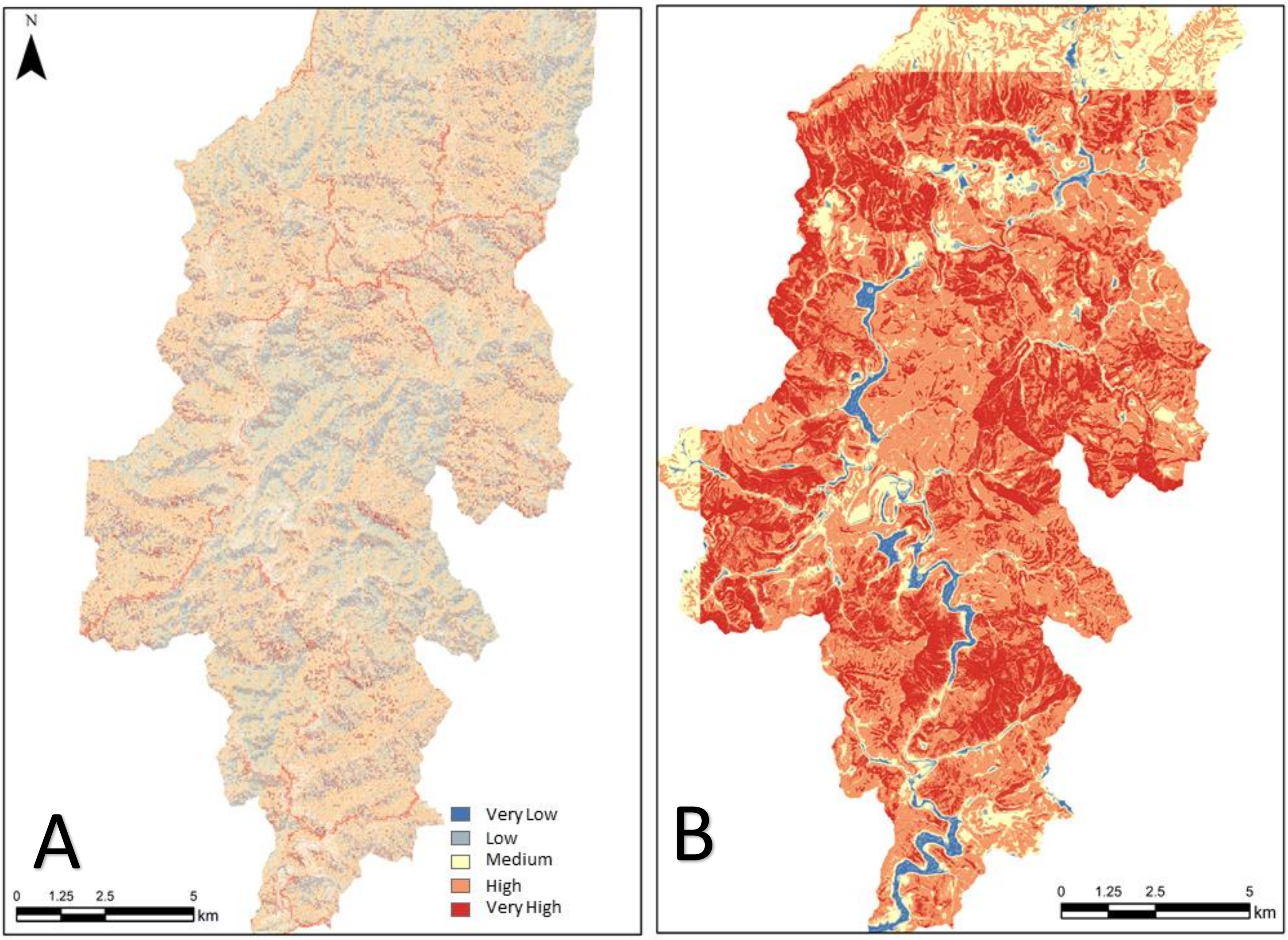
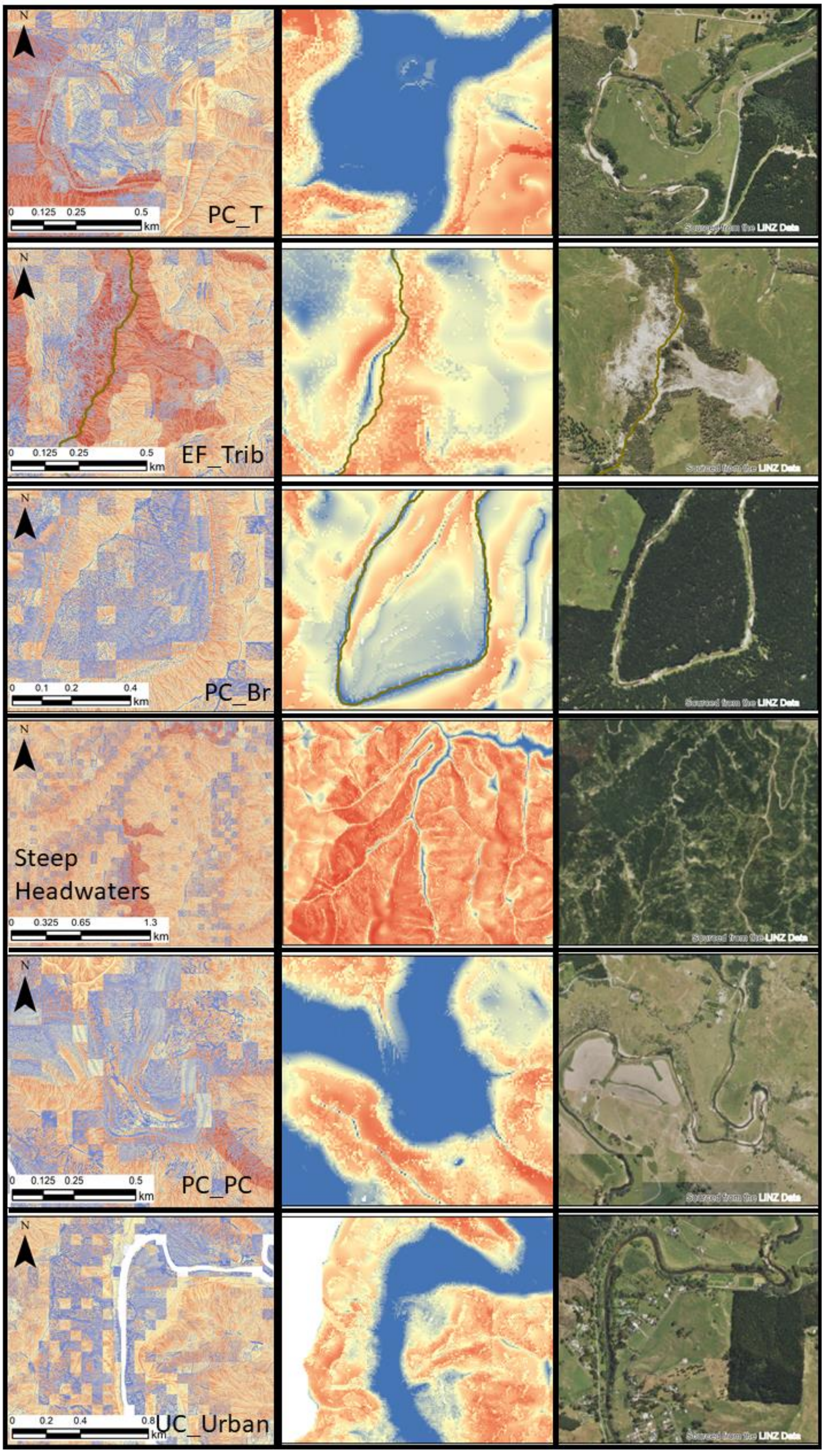


Figure 5.10 A) 1m resolution DEM connectivity index output. B) 8m resolution DEM connectivity index output. Legend reflects categories outlined in Table 5.1.

Analysis of sediment connectivity on the capacity of adjustment for each river style confirms that found in Table 5.2. The type of control on confinement, coupled with sediment input (can be influenced by slope, vegetation), will determine the capacity for adjustment. Patterns of high channel migration have reflected River Styles with no immediate impediments, external sediment supply and a relatively low slope. These patterns are primarily found in the PC_PC, EF_Trib and PC_MC river styles.



N
0 0.125 0.25 0.5 km
PC_T
Sourced from the LINZ Data
N
0 0.125 0.25 0.5 km
EF_Trib
Sourced from the LINZ Data
N
0 0.1 0.2 0.4 km
PC_Br
Sourced from the LINZ Data
N
Steep Headwaters
0 0.325 0.65 1.3 km
Sourced from the LINZ Data
N
0 0.125 0.25 0.5 km
PC_PC
Sourced from the LINZ Data
N
0 0.2 0.4 0.8 km
UC_Urban
Sourced from the LINZ Data

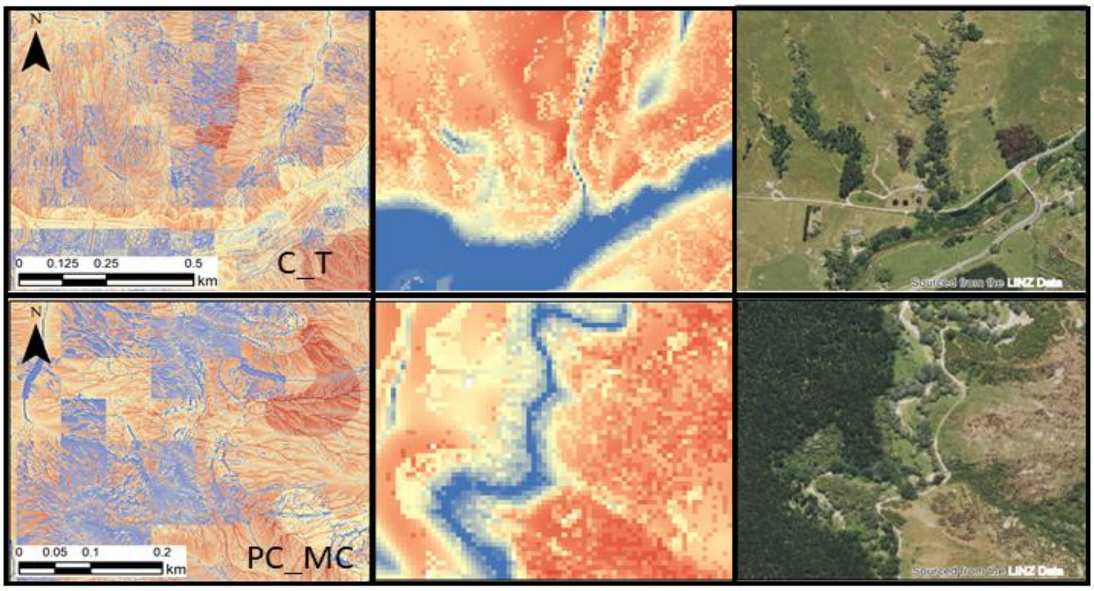


Figure 5.11 Analysis of differences between connectivity index using 1m resolution DEM and 8m resolution DEM for each river style. Sites used provide distinct meander bends or landscape features to enhance recognition of connectivity patterns.

Table 5.6 Assessment of the relationship between river styles, connectivity and capacity for adjustment for eight representative river styles reaches of the Waimatā (examples from Figure 5.11)

River Style	Type of Connectivity	Controls on Valley Confinement	Controls on Connectivity	Capacity for adjustment Internal (erosional/ space to move) or external (sediment supply/coupling)
PC_T	Low	Terrace on outside bend	Slope (floodplain), roughness, sediment supply from tributary	**High** in lower section due to sediment supply. **Low** in upper straight section due to terrace constriction. (internal/external)
EF_Trib	Very High	Sediment supply and terraces on either bank	Roughness, External sediment supply (mud-volcano), slope	**High** - high sediment supply and weak banks. High hillslope coupling. (external)
PC_Br	Low	Bedrock, hillslopes/vegetatio n	Intrinsic control (bedrock), slope, roughness	**Low** – bedrock inhibiting channel migration, low sediment supply, vegetation (internal)
Steep Headwaters	High/Very High	Hillslope/vegetation	Slope, roughness (forest removal)	**Low** – confined by hillslope, some sediment supply from coupled hillslope, but still erosional due to vegetation reducing supply. (external)
PC_PC	Very Low	Planform, crops, small terrace	Slope (floodplain)	**High** – accommodation space, limited sediment supply. (internal)
UC_Urban	Low	Housing	Anthropogenic sediment control, slope	**Low** – confined by human interaction, altering sediment conveyance. (neither)
C_T	Medium	Terraces/hillslopes	Slope, roughness	**Low** – accommodation space is limited. High slopes create potential for coupling and sediment transfer. (external)
PC_MC	Medium/High	Valley margin, vegetation	roughness	**High** – space to move, sediment supply from coupled hillslope. (internal/external).

The PC_T example in Figure 5.11 highlights the influence of sediment supply and space to move when assessing the capacity for adjustment. A sudden shift in confinement, where a terrace doesn't constrict one side of the channel, combined with sediment supply from a feeding tributary, allows deposition on the point bar and erosion from the hillslope.

Overall, the 1m resolution connectivity index produced a different map to the 8m connectivity index. Figures 5.10a and 5.10b highlight these differences, where forested areas have been recognised as having lower connectivity in the 1m than in the 8m. However, reach scale patterns of connectivity remained similar between the two resolution maps. Table 5.7 highlights the differences between the two map resolutions and describes the types of sediment (dis)connectivity present in each River Style building off the buffers, blankets and barriers approach presented by Fryirs et al. (2007) as well as hillslope coupling. Local-scale controls on valley confinement and slope have resulted in similar trends in connectivity between the two model outputs, highlighting the similarities in slope when switching from the 8m to 1m DEM. Both Figure 5.10a and 5.10b highlight that the Waimatā Catchment can be categorised as highly/very highly connected. This can be attributed to hillslope coupling, weak lithology and poor forestry practices. Areas of high connectivity are identified as earthflow zones and are in the mid/upper catchment. Cullum and Brierley (2017) noted that these zones are susceptible to landslides due to weak lithology, unstable soils, and steep hillslopes. Like in the 8m IC, the 1m IC exhibited similar trends in low sloped areas with floodplains and buffers showing low connectivity. This results from floodplains not providing enough energy to transport sediment from hillslopes to the mainstream.

Buffers are the most common form of disconnectivity in the Waimatā due to terraces and alluvial floodplain pockets. The river style PC_T commonly exhibits this behaviour due to large floodplains and decoupling the hillslope from the main channel. Figure 5.12 provides an example of this behaviour. This reach represents a high connectivity area being blocked by an area of low connectivity. This floodplain is covered by a blanket of sediment, which has been deposited during a large magnitude flood event. The sediments from the blanket are slowly being transported into the trunk stream. However, sediments from the hillslope are not due to slope and soil texture.

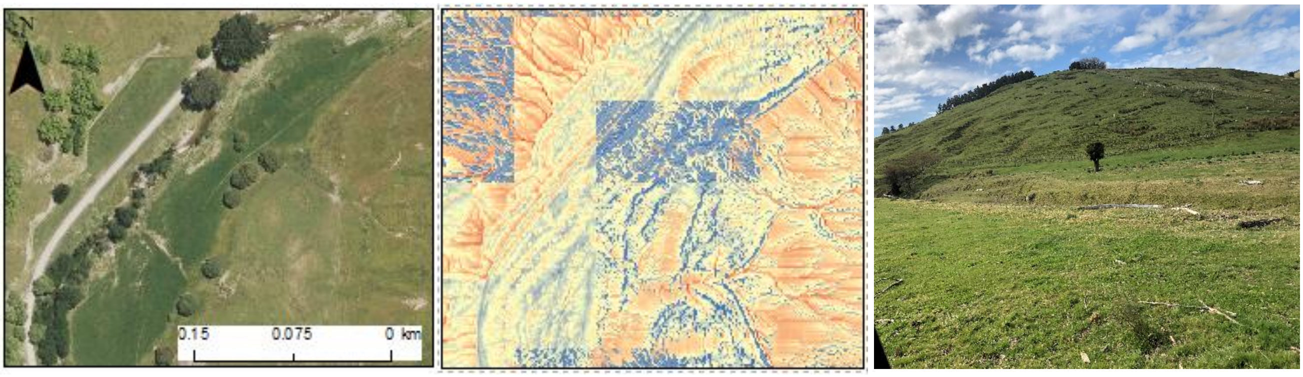


Figure 5.12 Example of low connectivity in the form of a blanket (PC_PC)

Highly connected areas in the Waimatā are the result of the high slope, sediment input (from forest removal or external sediment input) and hillslope-channel coupling. One of the main differences between the two model outputs was the smaller-scale changes in elevation. The example in Figure 5.11 (EF_Trib) highlights these discrepancies due to sediment feeding from the mud volcano to the Mangaehu tributary. This reach is dominated by silt sediment delivered from the sediment source and the hillslopes. The 1m DEM can pick up the elevation changes which aren't recognised in the 8m, thus identifying the sediment source as highly connected rather than low.

Table 5.7 Differences and similarities in connectivity types between the 1m and 8m connectivity indices. Types of disconnectivity and the processes underpinning development are also recognised.

River Style	1m IC	8m IC	Type of (dis)connectivity	Processes
PC_T	low	low	Buffer (floodplains), terraces.	Low slope and accommodation space has allowed the channel to migrate and form floodplains
EF_Trib	high	low	Hillslope coupling, external sediment supply	Mud volcano contributing sediment, week banks, high energy
PC_Br	low	low	Barriers (valley constriction)	Landscape scale geomorphic feature. Bottle neck to sediment transfer. Aid backfilling of valleys.
Steep headwaters	very high	very high	Hillslope coupling	Steep valley walls, little accommodation space
PC__PC	very low	very low	Buffers (continuous floodplains)	Low slope and accommodation space has allowed the channel to migrate and form floodplains impeding sediment from hillslopes.
UC_Urban	low	low	Barriers	Anthropogenic controls have fixed the channels and inhibits sediments from migrating across the valley floor.
C_T	medium	medium	Hillslope coupling	Steep valley walls, little accommodation space
PC_MC	medium/low	medium	Buffers (discontinuous floodplains) areas without	Valley margin allowing some channel migration forming floodplains. Areas without floodplains

5.4.1 Tributary trunk confluences

High connectivity from feeding tributaries can result in sediment transfer in a system as the effective catchment areas increase. Downstream patterns in tributary-trunk confluences result in different geomorphic units resulting from changing controls. The influence of tributary-trunk confluences can ultimately affect the overall connectivity, where the ability of a confluence to rework and distribute sediments can lead to longitudinal and lateral connectivity being increased. Geomorphic effectiveness of confluences allows for ease of transport between tributary and trunk, delivering sediments to the mainstream with no impediments, reflected by high connectivity. Highly connected systems can display clear joins between tributary and trunk streams, where a direct transfer of sediment is evident. Valley confinement and controls on valley confinement influence tributary-trunk connectivity by allowing accommodation space for the channel to widen to receive incoming sediments. The feeding tributary can also widen at the confluence, ensuring the sediment can be discharged into the trunk stream. Examples of changes in accommodation space within the same river style (PC_T) are illustrated in Figure 5.13.

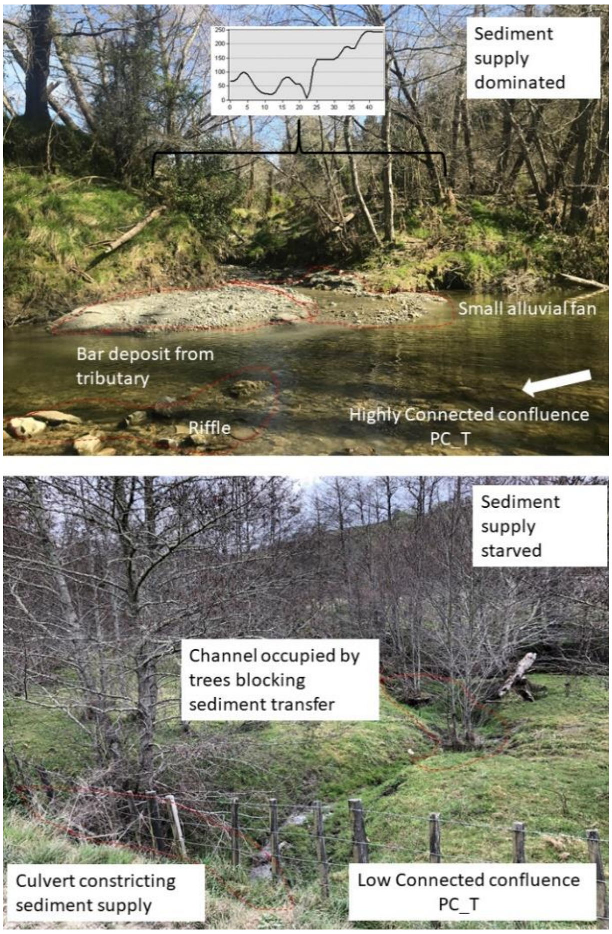


Figure 5.13 Differences in tributary confluence zones within the same river style, highlighting the influence of sediment supply and accommodation space.

Figure 5.13 contains two tributary trunk confluences located within the PC_T river style. Both confluences are located within partially confined sections of the river. However, their capacity for adjustment varies markedly. The highly connected confluence displays typical confluence geomorphic units, such as a fan and bank attached bars. Water and sediment can freely discharge into the trunk stream without impediments and enough energy (from the effective catchment area and slope). The second confluence located within the PC_T river style exhibits low connectivity. This is shown through the stream's vegetation, which blocks sediments from being transferred downstream by increasing roughness (Manning's N value) in the tributary. Potential energy to entrain and transport sediments appear to be extremely low due to low slope and a culvert impeding upstream flow, effectively choking the tributary.

5.5 Sediment flux behaviour: patterns of entrainment and deposition in different river styles.

Sediment flux behaviour is directly linked to sediment connectivity, where if sediment connectivity is increased, sediment transfer (erosion, deposition and transport) increases. Availability of sediments, slope and channel width all reflect types of river styles which can help determine the capacity for a reach to adjust. Predicting sediment transport, erosion, and deposition can help differentiate between transfer and throughput reaches and determine the sediment flux behaviour of a connected system. Examples of sediment flux behaviour generated in the CASCADE Toolbox model are visible in Appendix 8.1. Summaries of model output for River Styles types are illustrated in Table 5.8.

Table 5.8 Summary of river styles type and corresponding CASCADE output combined with river styles analysis and connectivity model outputs.

River Style	Reach ID	Entrainment/ Deposition ?	Connectivity (IC prediction)	Transfer/throughput	Dominant sediment supply (upstream, tributary, hillslope)
PC_PC	8	dep	low/medium	transfer	Hillslope, upstream
UC_URBAN	29	dep	low	throughput	upstream
C_T	59	entrain	high	throughput	hillslope
PC_MC	4	dep	medium/high	transfer/throughput	tributary
PC_BR	19	dep	high	throughput	tributary
PC_T	14	entrain	high	transfer/throughput	hillslope
EF_TRIB	52/53	entrain/dep	very high	transfer	hillslope
STEEP HEADWATERS	1	entrain	very high	throughput	hillslope

According to Table 5.8, there is no clear correlation between sediment entrainment/deposition patterns and connectivity/transfer/throughput. Each River Style possesses a unique set of model outcomes reflecting different environments. Partially confined River Styles consisted of both erosional and depositional sediment behaviour, which did not directly correlate with a respective connectivity value or transfer/throughput characterisation. But instead, each River Style is underpinned by its controls determining the sets of model outcomes. For example, reach ID 52, situated within the EF_Trib River Style, was located below the mud-volcano environment (Table 5.2 EF_Trib). This reach consists of highly erodible clays and silts, coupled hillslopes, high energy and steep slope (Figure 5.14). Combining these contributing controls has resulted in entrainment dominated River Styles.

Figure 5.14 Example from EF_trib river style, located within reach 52. The banks are collapsing into the stream resulting in a high sediment supply to be flushed through the system.

5.6 Interactive Connectivity Scenarios

Three land use scenarios have been produced to predict potential trajectories the Waimatā River may take. Sediment connectivity and sediment flux behaviour have been used to determine sediment pathways and sources from different management practices. Forest removal decreases roughness values and promotes sediment runoff. Figure 5.15 shows the changes to land use under different scenarios in the Waimatā. The main differences here are the conversion of forestry leads to destabilised hillslopes, reflected by expansive reaches on high c-values (Figure 5.15 BAU example). Common themes within the other two land use changes represent forest regeneration by planting native forest and riparian vegetation along riverbanks. The Wetland scenario also involved the construction of wetland barriers to impede sediment being transferred from hillslope-channel (decoupling). Figure 5.16 illustrates the connectivity index for each land use scenario. Each scenario reveals different patterns of sediment connectivity as a result of the newly altered landscape.

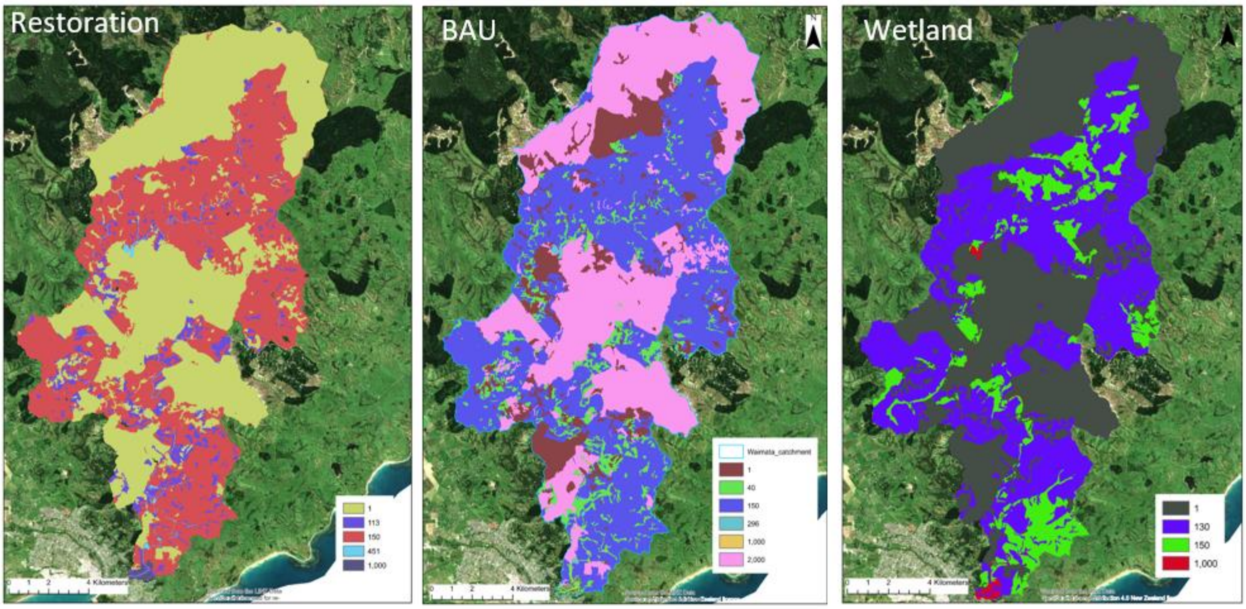


Figure 5.15 Land use scenarios with reclassed values according to Borselli et al. (2008). C-factors; Restoration (1) Forestry (113)Riparian buffer (150) Pasture (451) Crops (1000) Urban, BAU (1) Forest (40) Riparian buffer zones (150) Pasture (296) Crops (1000) Urban (2000) Forest removal, Wetland (1) Forest (130) Pasture (150) Pasture with woody biomass (1000) Wetlands.

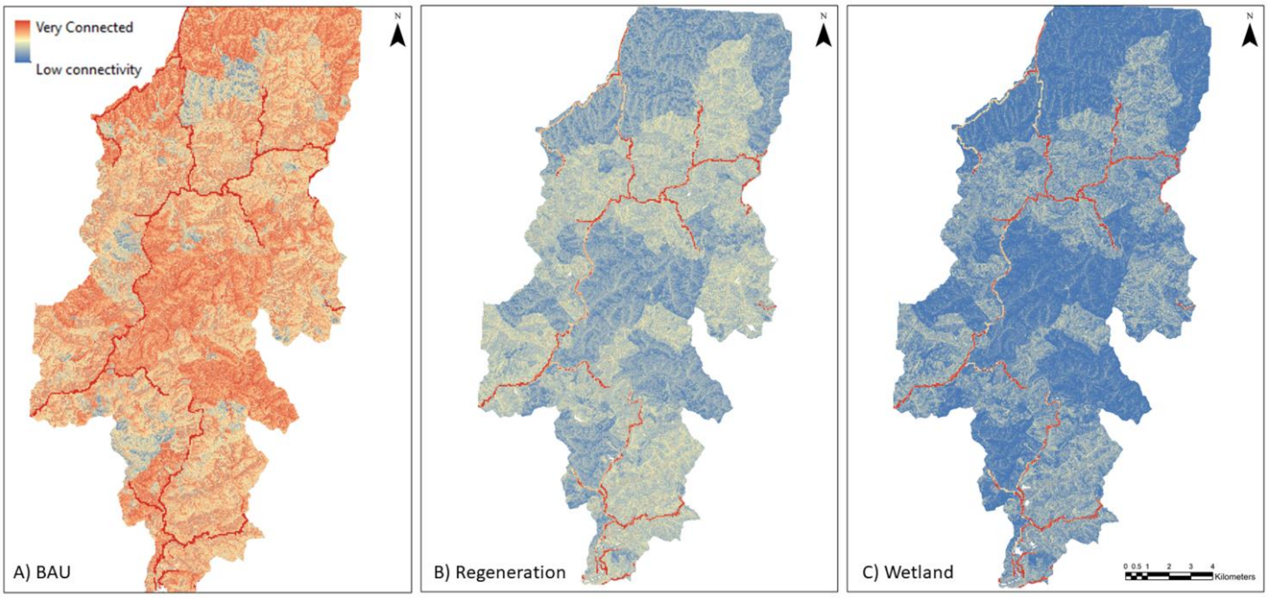


Figure 5.16 Sediment connectivity index for three scenarios, produced with the 1m resolution DEM. A) represents the 'business as usual' scenario B) represents the 'regeneration' scenario, and C) represents the 'wetland' scenario.

5.6.1 Scenario One Business as Usual

As outlined in Figure 5.16a under the 'business as usual' scenario, the Waimatā catchment becomes connected almost everywhere except for the remaining pockets of native forest**.** Forest clearance will significantly impact sediment flux for the Waimatā in the coming years due to the increases in sediment conveyance through the increased coupling of the system. Cave's 2019 analysis of forest clearance in two plantations in the wider catchment highlights clearance effects on landslide events. Assessments of the impact of land sliding resulting from the 2018 Queen's Birthday storms revealed that forest debris leads to significant blockages in the head of the Waimatā Catchment, particularly blockages on Waimatā Valley Road at the Utting's Bridge (Figure 5.17).

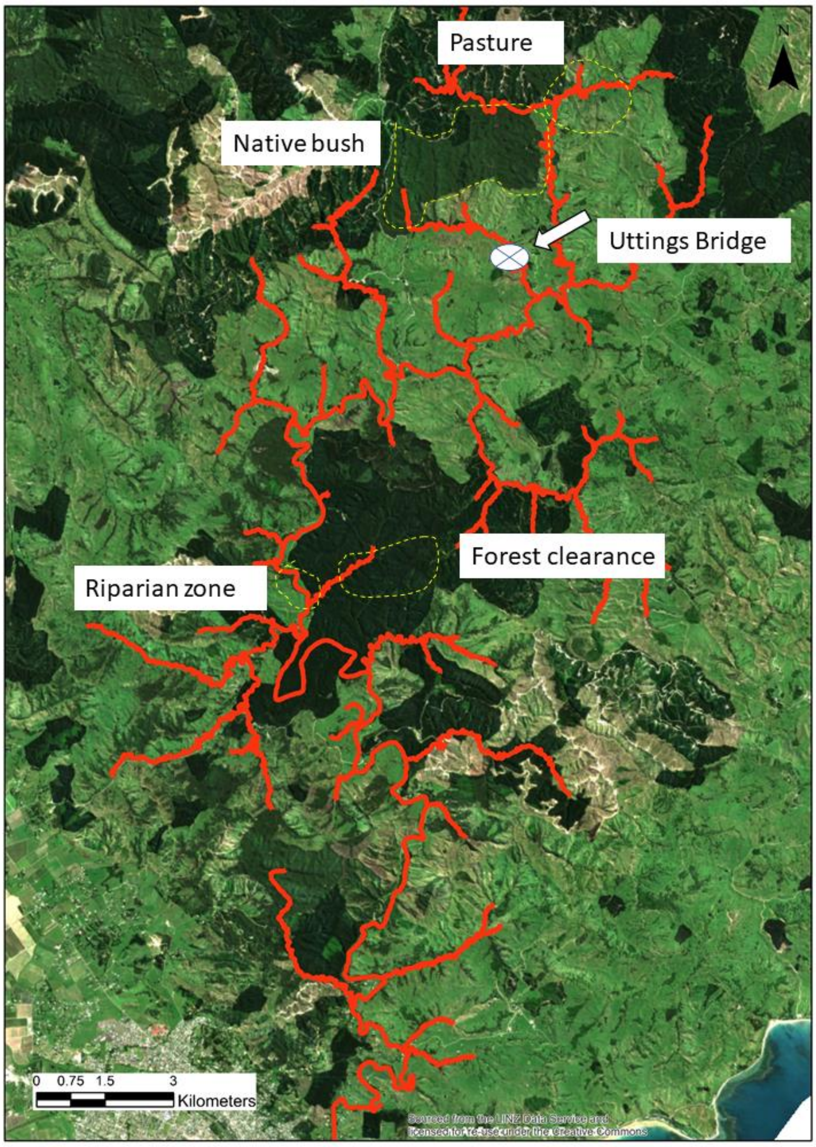


Figure 5.17 Locations of interest for representative reaches for assessment of sediment connectivity under the 'business as usual' scenario.

Figure 5.16a illustrates the connectivity index for the 'business as usual' land use scenario; connectivity ranges from very connected to medium/low connectivity. Most common areas of high connectivity form in gullies where hillslope derived sediments have been transported, indicating unstable soils and high sloped regions. Table 5.9 illustrates the impact of changing land use, sediment connectivity and sediment transport potential for representative reaches over the six land use roughness types. Table 5.9 also includes the sediment flux potential produced from the CASCADE Toolbox model. Areas that will have forest removed will show higher connectivity when compared to the original IC. High connectivity is present in deforested areas throughout the catchment and reflects the decrease in hillslope roughness. Areas that consist of regenerating forest, pasture and native bushes remain low because deep-rooted vegetation provides more slope stability (Table 5.8). Cave (2019) shows that forested areas exhibit slips, attributed more to individual slope failures resulting from weak geology and steeper slopes. Native forest areas display some areas of high connectivity within; this could be attributed to external sediment generation, or as mentioned before, weak lithology.

Agricultural pasture represents one of the lower connected reaches, attributed to buffers and barriers. Levees, relic terraces and riparian vegetation can help reduce the direct transfer of sediment to the mainstream. Some pasture reaches (Table 5.9) exhibit higher connectivity due to the high slope and external sediment generation from deforested areas. As well as changing the forestry behaviour, a riparian strip was added to the BAU land use layer (Table 5.9). This has resulted in lower connectivity in these reaches directly adjacent to hillslopes. Therefore, the sediment has the chance to be impeded before feeding the mainstream. These riparian strips act as buffers to sediment generated from the destabilised hillslopes.

The areas of removed forest outlined in Table 5.9 have seen some of the most dramatic changes under the 'business as usual' scenario. According to the CASCADE outputs, 19 and 94 are located within this forest area. Reach 94, located in the tributary flowing in the deforested area (Figure 5.18), switched from an entrainment dominated reach to a deposition dominated reach, going from 0 Kg/s of the deposited material to 140 Kg/s of sediment being deposited into this reach. Reach 94 joins to the trunk stream at reach 19. Sediments generated in the tributary (reach 94) propagate downstream and increase sediment deposition from 1.68 Kg/s to 140 Kg/s). There was also a change in grain size distribution, increasing the proportion of larger particle sizes transported during the "business as usual" scenario (Figure 5.19).

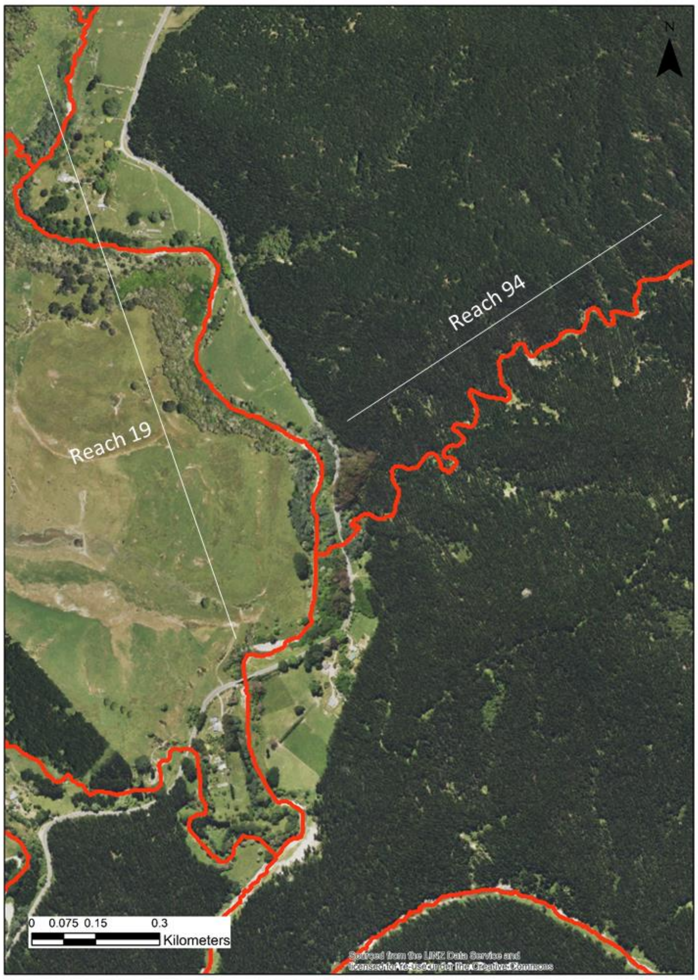


Figure 5.18 Locations of reach 94 and reach 19 in relation to each other.

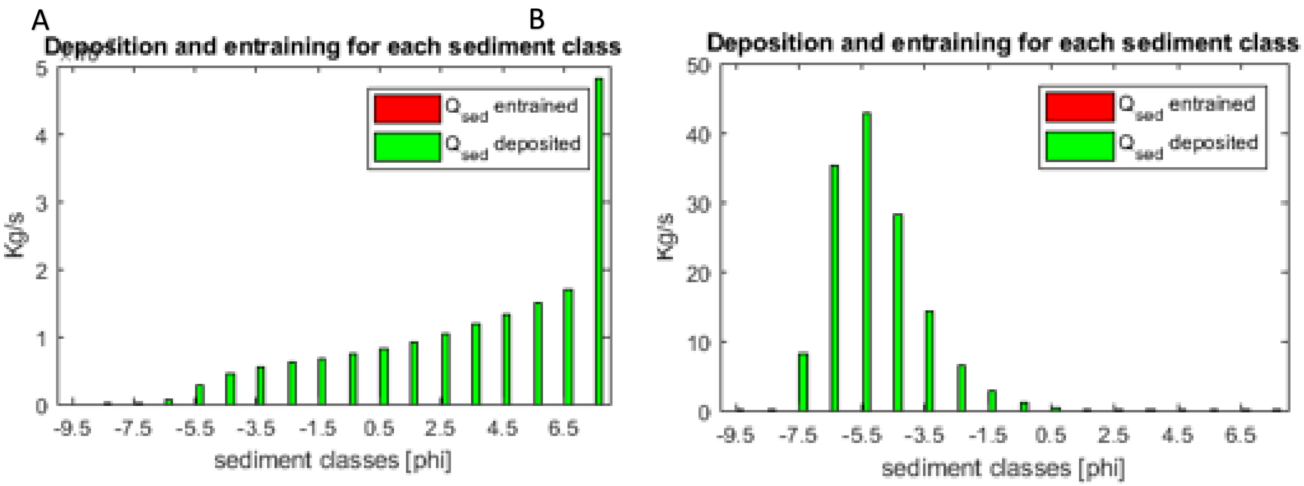
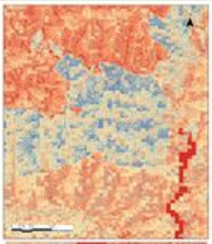
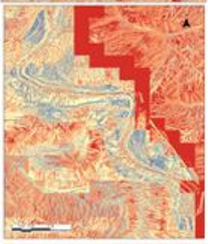
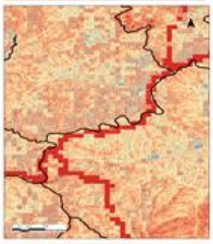
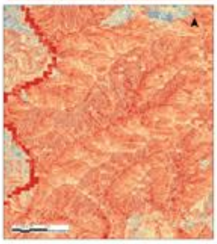


Figure 5.19 Sediment transportation distribution between regular land use (a) and ‘business as usual land use’ (b).

Table 5.9 Examples from representative roughness value land types.

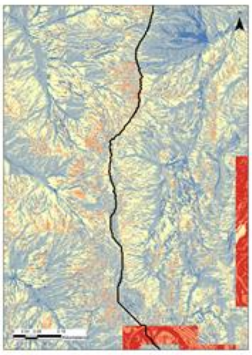
Land use roughness/type	**Example Reach**	**Connectivity behaviour**	**Entrainment/ deposition**	**Sediment sources**
Native forest C factor 1 Roughness very high.		Low connectivity within forested patch. External sediment contributions influencing this by supply sediment	Deposition dominated with 140Kg/s sediment deposition	Surroundin g hillslopes.
Riparian vegetation C factor 40 Roughness is high		Low in areas occupied by riparian buffer. Sediment incoming from hillslope being impeded by buffer and road landing.	Deposition dominated with 2.4kg/s being deposited and no erosion	Feeding hillslopes outside of buffer zone.
Pasture C factor 100 Roughness is moderately high		Relatively high over pastured area. Especially high on road landing. (black line denotes river course)	Deposition dominated however, levels are very low at 0.0012Kg/s . Most likely result of buffers.	Tributaries, surrounding hillslopes.
Forestry removal C factor 2000 Roughness extremely low		Extremely high due to forest removal . Very Connected Low connectivity	Entrainment dominant in hillslopes at 1.89 Kg/s	Hillslopes

Overall, sediment connectivity and generation/deposition have been altered due to vegetation removal under the 'business as usual' land use scenario. Areas that retained dense vegetation, such as native forest and riparian buffer zones, resulted in lower connectivity and less entrainment and erosion. At the same time, deforested areas and pasture zones lead to higher sediment generation, which results in sediment transportation into other zones due to high connectivity.

5.6.2 Scenario two: Regeneration

Connectivity in the restoration connectivity index (Figure 5.16b) range from low to medium except for the road landing. Revegetating the pasture areas and maintaining vegetation in forestry have resulted in low connectivity values throughout the catchment. Table 5.10 outlines key areas of interest for this scenario resulting from reforestation and management intervention. Dense vegetation has resulted in soil stability for erosive slopes, leading to lower sediment generation. Revegetation has also led to an overall decrease in connectivity, decoupling hill slopes from channels and creating buffers and blankets to trap sediments. Pasture with woody biomass (e.g. Table 5.10) has provided an extra layer of soil stability. Lizaga et al. (2018) mention that decreases in connectivity could reflect increases in trees and vegetation cover. Hence vegetation cover would likely improve soil quality by favouring infiltration and preventing runoff in the Waimatā. Areas of riparian buffer zones can also be seen to decrease connectivity values whilst being situated within pasture (Table 5.10), indicating riparian buffers can aid in impeding sediment generation from agricultural land.

Table 5.10 Examples from representative roughness value land types. Locations situated close to those found in Figure 5.17

Land use roughness/type	**Example Reach Situated near examples from 'BAU' scenario**	**Connectivity behaviour**	**Sediment sources**
Forest cover C factor 1 Roughness very high.		Very low , some gullies exhibiting medium connectivity due to hillslope-channel coupling	Low sediment contribution however, sediment being generated will be from upstream reaches or hillslope runoff
Riparian vegetation C factor 40 Roughness is high		Medium with some section becoming highly connected. Riparian buffer zone consistently low connectivity.	Surrounding pasture, high sloped areas.
Pasture C factor 100 Roughness is moderately high		Medium/low connectivity. Very Connected Low connectivity	Low sediment generation. Sediment which is generated will be from surrounding pasture soil runoff.

Overall, sediment connectivity has been reduced through revegetation in the 'regeneration' land use scenario. Sediment connectivity in forested areas is consistently low/very low despite changes in slope and valley confinement. Pastured areas in which woody biomass has been introduced have decreased connectivity. Lastly, a riparian buffer zone impedes potential sediment transport by decoupling hillslope-channel sediment transfer. Therefore, it is evident that reforestation in the Waimatā may be a viable option for decreasing sediment connectivity and, ultimately, sedimentation throughout the catchment.

5.6.3 Scenario three: Regeneration with wetlands.

Land use scenario three is like scenario two, with wetlands constructed between high connectivity zones and river sections. Figure 5.16c highlights the influence of revegetation of the system, with very low/medium connectivity throughout the catchment. Like in scenario two, patterns associated with vegetation density arise, with forested areas exhibiting very low connectivity and pasture with woody biomass displaying medium/low connectivity remaining similar in both scenarios, maintaining their medium/low connectivity appearance.

Table 5.11 Differences in connectivity indices between four proposed wetland sites for the wetland and regeneration scenarios.

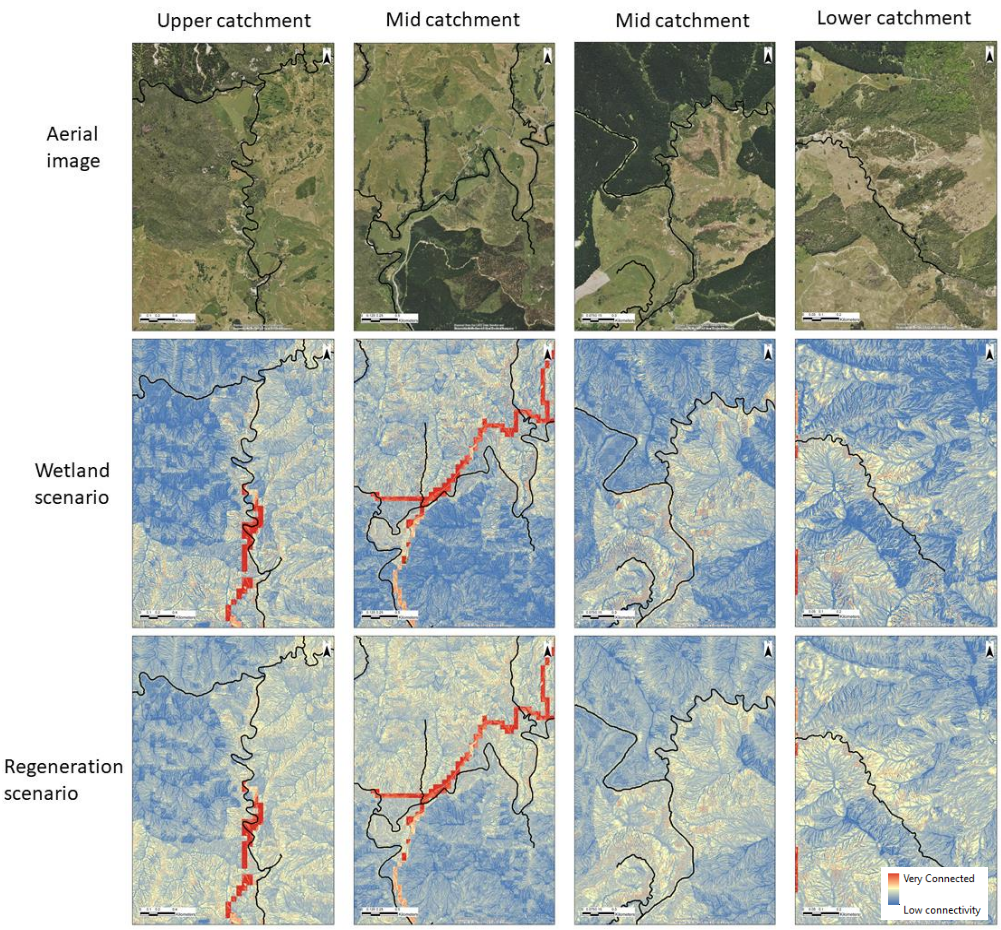


Table 5.11 highlights the influence of wetland construction sediment connectivity. Minimal changes can be observed between the wetland and regeneration scenarios. In flat areas, such as floodplains, the main patterns of difference are the change to the degree of connectivity in the adjacent hillslopes. The forested hillslope connectivity decreased from low to very low in all four cases. This could result from decoupling between hillslope and channel by introducing a barrier to act as a sediment sink.

Overall, the construction of wetlands has a similar impact on sediment connectivity compared to reforestation according to connectivity model outputs. The connectivity between hillslope and channel decreased, indicating wetlands' influence in decoupling lateral linkages.

5.6.4 Conclusions

Comparison between the four land use scenarios (original, BAU, regeneration and wetland/regeneration) show that increasing vegetation decreases the connectivity of a catchment. Therefore, if the Waimatā catchment continues or follows its trajectories now (BAU), it would likely adjust to accommodate high sediment connectivity, sediment erosion, and storage downstream. The two regenerative land use approaches displayed significant reductions in connectivity from very high/high to moderate/very low for both scenarios. Figures 5.10 and 5.15 show the catchment-wide IC and reflect the reduction in sediment connectivity throughout the catchment due to forest regeneration.

5.7 Summary of results

River Styles and the identification of differing sediment transfer and throughput zones allowed the capacity for adjustment in the Waimatā to be assessed. Transfer zones had a higher capacity for adjustment, as sediment could be deposited and reworked on the floodplains. The channel can also widen and become more sinuous as there is room to do so. The throughput zones exhibit a lower capacity for adjustment. There is insufficient room for sediment accumulation and therefore act as a flume for sediment. The River Styles type also reflects the reaches potential for adjustment. Reaches confined by terraces and bedrock have lower potential to adjust as they are fixed in place, reflecting significant portions of the Waimatā. Moreover, the confinement of a reach alone does not determine the capacity for adjustment. The controls on adjustment must also be considered when assessing the capacity for channel migration and river trajectories.

Overall, there are distinct traits of the highly connected and disconnected systems. Highly connected areas show visible sediment transport and supply, commonly seen through mass wasting and incision. An additional indicator is hillslope coupling which directly supplies the main channel with eroded materials. In the disconnected systems, there are extensive floodplains and disconnected channels. Distinguishing the difference between connected and disconnected systems is the first step in understanding the sedimentation behaviour in a system. The highly connected reaches have a higher potential for sediment transfer between and within landscape compartments. Therefore, they need to be tackled upstream where these sediment linkages occur before tackling sedimentation issues downstream. Highly connected reaches were most found in narrow valley settings, directly impacted by the controls on confinement. Areas with lower valley confinement may have higher channel migration and lateral adjustment capacity. However, narrower coupled River Styles with high lateral connectivity may experience adjustment through the inputs of external sediments.

The CASCADE Toolbox allowed an insight into the types and volumes of sediment moving throughout the system. Upper reaches in the main river and tributaries had high erosion and lower deposition, reflected in the high entrainment and lower deposition volumes. This is the result of higher energy systems being able to entrain and transport sediment downstream. Lower and mid reaches were reflected by lower entrainment and higher deposition due to lower energy flow being incapable of entraining sediments in these reaches. The sediment types being moved in the system also reflect this energy gradient as gravels and boulders are left in higher energy reaches as they cannot be transported downstream. In contrast, sand and silts are more commonly found in mid/lower reaches as they can be transported as suspended sediment.

The scenario-based connectivity analysis provided insights into how the system may respond under differing land use trajectories. Three land use scenarios were presented, reflecting different levels of management. The 'business as usual' scenario increased sediment connectivity. Hillslopes remained coupled to the river. The decrease in hillslope stability from removing vegetation through forestry would directly link mass wasting events and transfer into the streams. The two management approaches, 'regeneration' and 'wetland/regeneration', gave similar results. Sediment connectivity decreased significantly, and the roughness value of the slopes was increased as the land was converted to native bush and forest, which aids in stabilising the slopes and decreasing sediment transfer between landscape compartments by decoupling the hillslopes.

Chapter Six: Discussion

Geomorphologists have provided considerable guidance to support river management and river planning applications over the years (e.g. Brookes, 1995; Thorne et al., 2005; Brierley et al., 2002; Brierley and Fryirs, 2013; Fuller et al., 2019). Understanding landscape processes, forms, and evolution provide a critical template to frame a host of management applications (Brierley and Fryirs, 2013). If the geomorphic structure of a landscape changes, so does everything else (Fryirs and Brierley, 2013). Analysis of sediment connectivity relationships, defined by the ease of which sediment is delivered between and within landscape compartments, is a key part of such work, as they inform assessment of complex processes that drive landform development(Harvey, 2001; Harvey, 2002; Fryirs et al., 2007; Baartman et al., 2013; Heckmann et al., 2018).

The River Styles approach (Brierley et al., 2006; Fryirs and Brierley, 2018) provides a conceptual basis to analyse sets of processes underpinning landscape development and sediment connectivity. Building on the principles outlined in Brierley and Fryirs (2009), appreciation of river systems' inherent diversity, dynamics, behaviour, and trajectories have resulted in targeted rehabilitation and conservation. Allowing rivers to be viewed from multiple perspectives and scales, from reach scale interactions, such as geomorphic unit development to catchment scale geological and topographical influences underpinning landscape development. Process-based analysis of River Styles revealed patterns of lateral adjustment in the Waimatā. Most commonly, River Styles with space to move due to 'soft' controls on valley confinement have a higher capacity for adjustment, allowing 'hotspots' of adjustment to be identified.

Najafi et al. (2021) review of sediment connectivity modelling concludes that the sediment connectivity concept can be used to describe the structural and functional sediment transport processes occurring at the catchment scale. Ways in which to conceptualise and visualise sediment delivery can vary from the conceptual model from Schumm (1977), which depicts a catchment as three zones and Fryirs et al. (2007), who proposed the (dis)connectivity model and displayed different types of sediment disconnectivity. Sediment connectivity models have become increasingly analytical and begin to unravel the sets of processes underpinning sediment conveyance whilst providing tangible, quantitative outcomes (Borselli et al., 2008; Baartman et al., 2013; Cavalli et al., 2013; Heckmann and Schwanghart, 2013; Czuba and Foufoula-Georgiou, 2015; Tangi et al., 2018). Distinguishing the difference between connected and disconnected systems is the first step in understanding the sedimentation behaviour in a system. The highly connected reaches have a higher potential for sediment transfer between and within landscape compartments. Therefore, they need to be tackled upstream where these sediment linkages occur before tackling sedimentation issues downstream.

The indices of connectivity (IC) outlined in section 5.3 highlighted the influence of slope, land use and confinement on sediment connectivity. The 8m DEM revealed a logarithmic relationship between slopes, confinement and connectivity (see Figure 5.9), confirming the confinement and sediment transfer patterns shown in 5.1 and 5.2. However, the 1m DEM connectivity index exemplified the influence of land use on sediment connectivity. As mentioned in section 3.2, sediment connectivity within a catchment depends largely on the morphological complexity of the catchment, vegetation and vegetation changes affect surface runoff and sediment dynamics on hillslopes; these directly influence lateral sediment input rates to a channel system (Persichillo et al., 2018; Fuller and Marden, 2010; Poeppl et al., 2017). This is seen directly in the Waimatā, where dense vegetation cover, under current land use, exhibits lower connectivity than surrounding land types (e.g. Figure 5.10). CASCADE modelling revealed contrasting patterns compared to sediment connectivity using the IC. River Styles with capacity for adjustment exhibited both depositional and erosional behaviour (Table 5.8). Thus, care must be taken when associating reaches with a specific type of sediment transport behaviour. Targeted river management must be implemented in these cases, as each reach will display a unique set of erosional and depositional behaviours.

Brierley and Fryirs (2016) propose a moving targets approach to river management. This involves evolutionary trajectories and appraisals to system responses to changing conditions, allowing for proactive and tailored management action where targets can be set and adjusted to accommodate multiple scenarios. This was completed through the land use scenarios presented in section 5.6. Changing land use conditions indeed have significant impacts on potential sediment connectivity and sediment flux behaviour in the Waimatā (see Figure 5.15 and Figure 5.16). Land use scenarios with higher roughness values could stabilise slopes and impede sediments, essentially disconnecting the system as outlined in Fryirs (2007a). Whereas decreasing surface roughness promoted sediment transfer aiding in sediment coupling and increased soil runoff (Harvey, 2002).

Ultimately, the results outlined in sections 5.2-5.5 highlighted how effective the Waimatā is at transferring sediment from source to sink. Due to the trunk stream being dominated by throughput reaches, a consequence of valley confinement, sediment does not have space to accumulate and is essentially flushed through the system. Section 6.1 further discusses this, which will outline the importance of the Waimatā acting like a 'flume'.

6.1 Appraisal of patterns in sediment connectivity in the Waimatā

Appraisals of sediment connectivity revealed patterns of a highly connected system, highlighted in section 5.3, primarily through Figure 5.10. The Waimatā catchment exhibits steep terrains, which result in narrow valleys and steep hillslopes. This has led to the Waimatā River being closely coupled to its sediment sources. Patterns of connectivity reflect topographic signatures in the catchment. Figure 6.2 highlights the influence of valley confinement and slope on potential sediment transfer in the Waimatā. Throughput zones dominate the trunk stream (see Figure 5.7), which aids in transporting large quantities of sediment generated in the transfer dominated tributaries. Ultimately, these factors have resulted in the Waimatā behaving like a flume, with sediments flushing through the confined reaches into Poverty Bay.

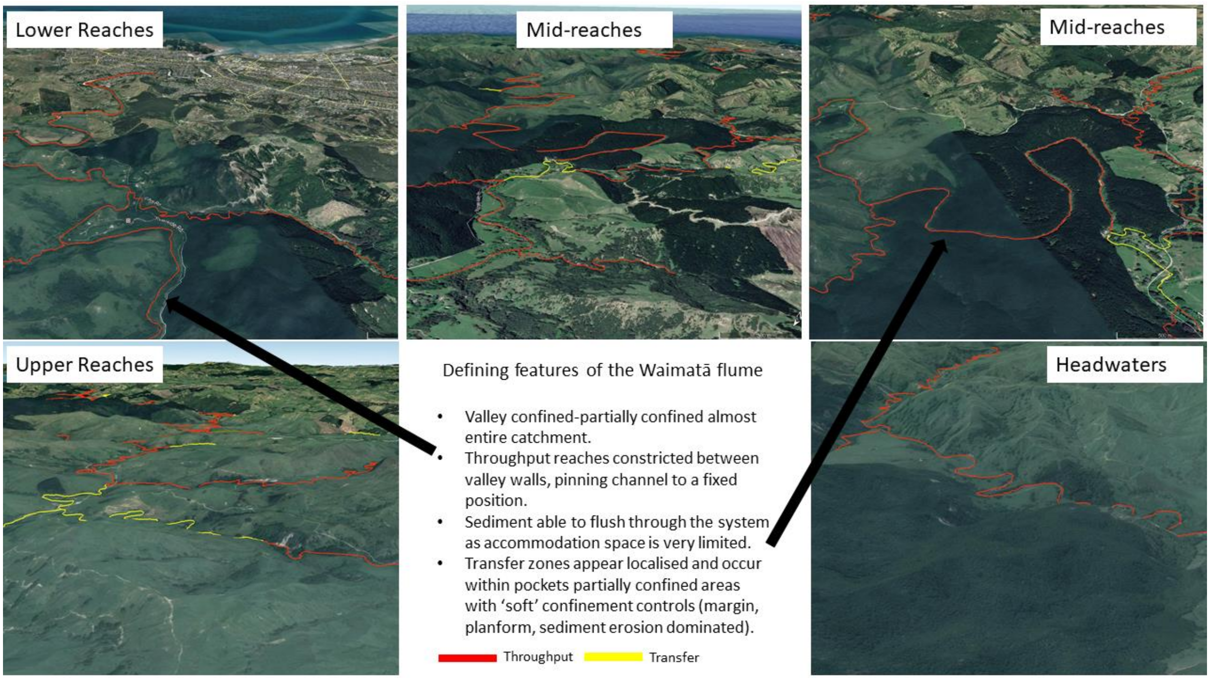


Figure 6.1 Relationship between throughput and transfer zones of the Waimatā with confinement and capacity for adjustment.

Highly connected areas are seen to be in the steepest parts of the catchment, resulting from the gravitational influence on potential sediment erosion (Lane et al., 1988). Surface runoff in upland areas, such as hillslopes, is often accompanied by soil erosion (Lane and Shirley, 1988). Low connectivity areas are more common in lower slopes, such as floodplains. Floodplains can act as buffers to sediment generated in the hillslopes (Harvey, 2001; Fryirs et al., 2007a). Sediment is impeded when deposited at the base of the hill slope. As outlined in Jain et al. (2008), slopes act as a threshold for sediment aggradation and floodplain formation, which may cause this sediment aggradation on lower sloped areas. These relationships are further shown in the sediment flux relationships. Higher sediment yields of up to 3.8 kg/s are recorded in reaches that exhibit high hillslope coupling, leading to effective sediment delivery in higher-yielding areas. The distribution of sediment stores and sinks reflect the influence of routes, travel distances and pathways of sediment transport within catchments (Brunsden and Thornes, 1979; Meade, 1982; Harvey, 2002). Transfer reaches typically exhibit more contemporary depositional stores, whereas throughput shows long term sediment stores and higher rates of sediment flushing through these reaches (see Tables 5.3, 5.4). Effective pathways (high connectivity) represent areas of sediment production (Schumm, 1977; 1984), areas with similar transportation and generation volumes can be considered the transfer zones of the Waimatā, and areas of high deposition and low generation are the deposition zones (Schumm, 1977) of the Waimatā.

Patterns of sediment connectivity are altered due to land use types of the Waimatā, where vegetation type and density influence sediment connectivity in channels (Sandercock and Hooke, 2011). Roughness is increased in some vegetation types, such as forest canopy, which consists of exotic and native in the Waimatā. Vegetation cover with lower roughness has the potential for high sediment erosion (Sandercock and Hooke, 2011) as factors, such as plant roots, incorporated plant residue and minerals increasing cohesion tend to protect the soil by reducing the rate of soil particle detachment by flowing water and raindrop impact (Lane et al., 1988). High roughness from forest cover has decreased sediment connectivity in some areas. Sediment generation in these areas is reduced, reflected in lower sediment flux values. Entrained values according to the CASCADE outputs are relatively low. However, the opposite is evident in the deposition outputs. Areas located in areas of higher roughness tend to deposit more sediment than they are supplying. At the same time, areas of higher connectivity with lower vegetation roughness display higher erosion than deposition. These patterns are found throughout the Waimatā for example, Table 5.4 EF_Tributary displays high sediment erosion with limited deposition. The interplay of erosional processes (detachment, transport and deposition) that are spatially and temporally variable reflects the sediment connectivity (Bracken et al., 2014). This is a common theme within sediment connectivity relationships. Land use changes within catchments can result in changes to sediment dynamics and landscape connectivity (Coulthard and Van De Wiel., 2017); in the case of the Waimatā, this includes deforestation leading to high connectivity (see Figure 5.14). Similar widespread recent time scale changes include deforestation (Marden et al., 2005; Ward et al., 2009) and reforestation (Liebault et al., 2005; Hooke, 2006; Keesstra et al., 2009). These have been shown to alter sediment movement and catchment sediment connectivity.

Ultimately patterns of sediment connectivity reflect the interplay of processes and catchment dynamics of the Waimatā. Building on Schumm (1977) sediment transfer model, the Waimatā can be seen as more of a continuum, where stores, pathways, and routes of sediment delivery depend on reach scale dynamics and can be conceptualised at smaller and larger spatial levels scales (Bracken et al., 2015). Patterns of sediment connectivity and sediment flux behaviour do not reflect three zones of sediment behaviour. Instead, the patterns depict the smaller-scale processes that create these zones of sediment erosion and deposition. Although these marked changes may still be evident in some catchments, appraisal of more local-scale influences on sediment connectivity is needed. Essentially, the Waimatā exhibits a band of steep slopes surrounding the margin, resulting in a narrow valley floor with little accommodation space and terraces which restrict channel adjustment, causing the catchment to act as a flume (Figure 6.1). The middle reaches exhibit distinctive behaviour, represented through transfer and throughput reaches. Transfer reaches are restricted due to valley confinement and accommodation space. Many tributary reaches in the earthflow zone, and margin-controlled River Styles can exhibit this behaviour. These reaches commonly exhibit incisional behaviour coupled with deposition on the point bars. Figure 4.2 highlights this, where point ledges represent lateral channel migration and point bars represent contemporary deposition (Fryirs and Brierley, 2013).

Throughput reaches are more dominant in the Waimatā, primarily due to valley confinement pinning the river to a fixed position. Throughput reaches typically exhibit continuous sediment deposits, resulting from larger magnitude events requiring higher remobilisation energy. Therefore, sediment transfer is more common in these reaches. This is combined with next to no contemporary accumulation areas in the lower course due to anthropogenic modification. As outlined in section 5.2, the influence of modification has resulted in low hillslope-trunk connectivity as sediment is not free to migrate across the valley floor. Therefore, removing the room for sediment deposition in the lower reaches propagated the sediment storage issues occurring in the upper reaches, leading to sediment and debris being pushed into the ocean.

6.1.1 What is Happening in the Waimatā?

The Waimatā is a highly connected system, with 95% of the catchment being classified as either moderately or highly connected, correlating with higher sediment flux transport. This is displayed as the hillslope-valley floor, channel-floodplain (lateral connectivity), upstream-downstream (longitudinal) and tributary trunk stream connectivity (Harvey, 2001, 2002; Brierley et al., 2006). Landscape compartments can interact laterally and longitudinally. As a result, sediment conveyance in the Waimatā is high, and connectivity relationships are stronger. Linkages between tributaries and main streams are reflected in sediment being transported from higher sediment generating tributaries to the main channel. Lateral connectivity is high connectivity due to hillslope coupling and transfer of sediments. In the case of the Waimatā, the main channel often runs at the base of terraces and hillslopes due to narrow valley confinement. This results in direct coupling (Harvey, 2001) with steep high banks, leading to large quantities of sediments being delivered to the channel.

Confluences are also key areas of connectivity in the Waimatā, driving the movement of sediment and water from tributaries to the trunk stream (Rice, 2017). The connectivity of these confluences influences the effective catchment area, as sediment transfer from these smaller sub-catchments contributes to the wider catchment's sediment flux (Fryirs et al., 2019). High tributary-trunk connectivity is evident in the Waimatā river. Two significant tributaries, the Mangahouku and Mangaehu, deliver large quantities of sediment directly to the Waimatā. Although, due to the nature of the sediment types coming from these tributaries (evident in sediment flux grain type assessments), they commonly discharge finer silts and sands rather than gravels. The Mangaehu tributary generates large volumes of sediments from the mud volcano and extremely erosive banks. (Figure 6.2). High connectivity is exhibited in these channel confluences (e.g. Figure 5.13 and Table 5.2 shown by the PC_MC River Style). These confluences can transfer sediment from tributary to trunk without impediments, such as floodplains, bedrock and valley constrictions. This has resulted in the Mangaehu and Mangahouku Streams being geomorphically effective sediment sources.

Figure 6.2 Major sediment source located in the Mangaehu Tributary. Sediments in this tributary consist of fine silts and muds.

Lateral inputs from hillslopes and tributaries exert variable impact upon longitudinal connectivity of sediment transfer (Walling et al., 2018). Network configuration and subsequent network topology influence channel slope and confinement at confluence zones, affecting sediment storage and conveyance patterns throughout a stream (Walling et al., 2018). Low order streams show contrasting patterns, with greater volumes of aggradation due to the presence of wood and log jams. Thus, sediment disconnectivity, aggradation, and disruption of hillslope sediment sources mask the tributary effects (Benda and Cundy, 1990; Rice, 2017). An example of this occurring in the Waimatā can be seen in Figure 6.3, when bedrock and log jams are longitudinally disconnecting the tributary, aggrading behind the impediment and constricting sediment transport downstream.

Figure 6.3 Tributary stream being blocked by woody debris. The stream cannot be diverted due to valley confinement, essentially disconnecting the stream longitudinally through the presence of a barrier.

Kuo and Brierley (2013) also note that it is not the catchment area or magnitude of landslides driving these relationships, but rather the type of confluence and the position of the confluence relative to the downstream sequence of river types. Connected tributary confluences, such as those illustrated in Figures 5.4 and 5.13, display effective delivery between tributary and confluence, resulting in downstream depositional geomorphic units, such as point bars and midchannel bars. Furthermore, the shape, order and valley confinement are critical determinants of tributary-trunk connectivity. The connectivity of these confluences can interrupt or promote sediment cascades and storage, thus driving longitudinal and lateral change (Rice, 2017).

6.1.2 Why is this happening?

Sediment connectivity and conveyance in the Waimatā is the product of its valley, geology and history. Valley confinement dictates accommodation space and sediment storage (Kuo and Brierley, 2013). Steep hill slopes and terraces spanning significant portions of the river have resulted in the catchment being predominantly partly confined to confined. Like that found in Jain et al. (2008), sediments are being deposited and stored in discontinuous floodplain pockets. Continuous floodplains rarely occur in the upper and mid-reaches of the Waimatā, resulting in little to no storage. Accommodation space is limited due to narrow valleys; therefore, deposition is limited; this is reflected in low deposition rates in the CASCADE outputs in the upper areas but high downstream. Typically, studies have found gently sloped catchments with wide valley margins prompt greater sediment storage (Kuo and Brierley, 2013; Nicoll and Brierley, 2016) which agrees with the opposite patterns observed in the Waimatā. A graded longitudinal profile is observed in the Waimatā (see Figure 2.3), with little evidence of major knickpoints and bedrock steps. Sediment can be flushed through the system due to the continuous topography and lack of accommodation space.

The Waimatā River is situated in a confined valley, where bedrock and terraces occur along both channel banks. Marden et al. (2008) claim that the Waimatā has generated $2.6 \pm 0.4 km^3$ sediments since the last glacial maximum, which is relatively high for its catchment size, especially when comparing the adjacent Waipaoa, which is predicted to have generated $14.08 \pm 2.1 km^3$ sediment (Marden et al., 2014). Sediment accumulation is evident in the lower floodplain areas, whereas there is limited deposition and accumulation in confined areas with greater slopes. Narrow valleys have resulted in channels flowing against bedrock and hillslopes. Prompting sediment transfer into the trunk stream, giving no opportunity for sediment accumulation and storage along the valley floor. Middle-upper reaches within the transfer zones have displayed some sediment deposition, which has been reworked and transported over time. Figure 6.4 depicts the same reach in the Mangahouku Tributary showing transfer behaviour, with evidence of adjustment, both vertical and lateral. This isolated transfer tributary can do this due to the absence of confining terraces. This is not the case in most of the Waimatā, as terraces and terraces span the length of the catchment. Not only do these terraces confine the river to a fixed position, but they also result in the rapid incision, contributing to sediment flux (Marden et al., 2014).

Figure 6.4 Lateral and vertical adjustment in the Mangahouku Tributary transfer reaches.

Network configuration exerts a first-order control upon sediment flux in river systems (Benda and Dunne, 1997), especially evident at confluence zones (Wohl et al., 2015). Czuba and Foufoula-Georgiou (2015) refer to highly connected tributaries, allowing for the transfer of material part of the landscapes 'hotspots', whereas geomorphically ineffective tributaries disruptions to processes along trunk streams (Rice, 1998). Some instances occur where confluences create bottlenecks, controlling sediment supply to the downstream link, where valley geometry constricts sediment transfer (Walley et al., 2018); these constrictions can be referred to as 'choke points'. This is common in the Waimatā, where the valley can change from partially confined to confined, especially moving into bedrock reaches.

A key example of this is the Mangahouku Tributary (Figure 6.5). Marked changes in valley confinement result in an abrupt shift in sediment storage and capacity for adjustment. The channel changes from flowing within a partly confined valley to the constriction where a mudstone bank leaves no room for storage or sediment generation. Wohl (2010) and Brierley and Fryirs (2013) noted that confined valleys promote sediment transfer; confined geometry and little accommodation space at the toe of a hillslope, the sediment is deposited directly into the stream. Areas of the river have been forced to incise and adjust its base level to accommodate the transfer and erosion of sediment, resulting in high banks and terraces flowing within highly confined valleys. In some cases, the bed material is less resistant than the bank material; therefore, as the channel reaches bank-full, energy from the thalweg is deflected from the banks to the bed. Constant energy exerted on the bed forces the channel to incise, adjusting the channel geometry (Pitlick and Cress, 2002).

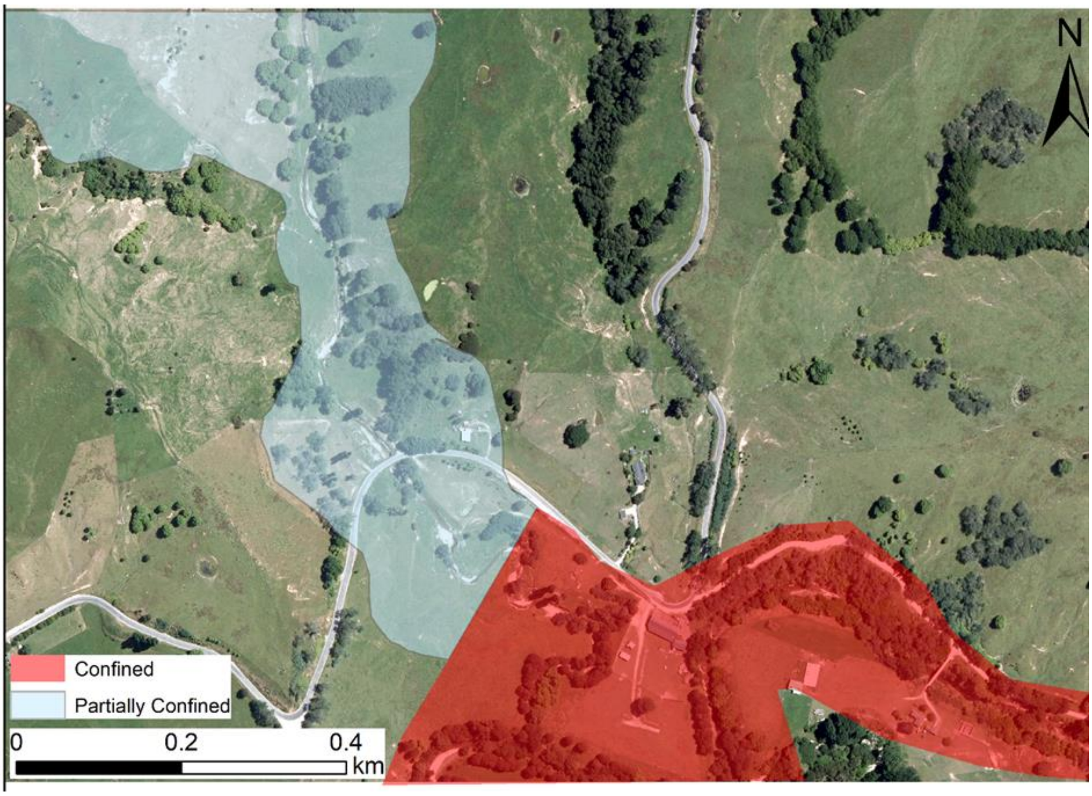


Figure 6.5 Changed in confinement in the Mangahouku Tributary due to changes to bedrock and the presence of a terrace.

6.1.3 The Waimatā in relation to other parts of the world

Connectivity trends in the Waimatā generally follow similar principles to those found in similar studies (Sandercock and Hooke, 2011; Heckmann et al., 2018; Llena et al., 2019; Heckmann et al., 2020; Najafi et al., 2021). With low sloped and densely vegetated areas exhibiting lower connectivity and sediment flux than high slopes, sparsely vegetated areas. Confined channels with little space to move have resulted in a highly coupled system in the Waimatā, with directly connected hillslope-channel interactions (e.g. Figure 6.6). Geological controls and landscape history constrain the patterns of sediment storage for any given catchment (Fryirs et al., 2007b). Progressive channel incision through the valley shapes the topographic signature seen today.

Figure 6.6 Hillslope coupling in the Waimatā between mainstream and actively eroding slope.

Often as rivers incise, their elevation changes, cutting through hillslopes, leading to the channel making its way to the underlying geology, resulting in floodplains to form (Kasai et al., 2001). However, in the case of the Waimatā, the river is incising through the terraces, with insufficient accommodation space to form floodplains and pockets of disconnectivity. The Waimatā is subject to legacy sediments that have been stored in the form of river and agricultural terraces. Agricultural terraces leave significant morphological imprints on the environment (Tarolli et al., 2014), resulting in floodplains and levees. The Waimatā is not subject to these characteristics due to the close coupling of the hillslope, terrace and channel network; little accommodation space leaves no room for sediment storage, a reworking of terrace sediments which supply the network with new sediments (Fuller and Marden, 2008). Constant energy exerted on terraces means they require large magnitude events to erode the sediments; therefore, even though the two landscape compartments are coupled, there aren't large quantities of sediment being sourced from the terraces. Instead, the terraces act as constrictions to the river by inhibiting the formation of floodplains and pockets of disconnectivity.

6.2 Controls on sediment behaviour

Proactive and adaptive approaches to river management are informed by understandings of past geomorphic adjustment but also recognise the future traits that may be different and not foreseeable (Brierley and Fryirs, 2016). Interaction between place-based knowledge of rivers and theoretical framed understandings are significant issues in river science management (Fryirs and Brierley, 2018). In recent years there has been greater recognition of ranges and the importance of geomorphic river diversity (Schumm, 1977; Wohl, 1988; Church, 2002; Fryirs and Brierley, 2018). Geomorphologists have developed language to help visualise and communicate understandings of landforms and landscapes (Tooth et al., 2016; Lewin, 2017; Fryirs and Brierley, 2018). The River Styles framework allows for characterisation of reaches displaying typical behaviour (form and function) (Brierley and Fryirs, 2005; Fryirs and Brierley, 2018). The Waimatā shows common themes throughout the catchment, which has allowed for in-depth analysis of these functions and processes acting to determine the sediment erosion, transportation and depositional behaviour throughout the catchment.

6.2.1 The Waimatā acting like a flume

The River Styles work in the Waimatā revealed patterns of sediment transportation through the constriction of the channels due to confined valley margins and terraces. Transfer reaches are more commonly found in the partly confined, planform-controlled reaches, exemplified by meandering sinuosity, stream geomorphic units, and floodplains allowing the channel to adjust (Brierley and Fryirs, 2000). Often, unconsolidated sediment is easily reworked, allowing the river path to adjust freely. Transfer reaches in the Waimatā have the potential to store and rework sediments. They are not constricted to a fixed position and can rework and transport sediments horizontally and vertically rather than just longitudinally. An example of this is illustrated in Figure 6.4, where lateral and vertical adjustment could be seen through the degradation of sandy sheet deposits.

Contrasting reaches in the Waimatā include the throughput zones, often located in the catchment's confined and partially confined sections. These reaches are characterised by confined valley margins and are usually margin controlled or terrace controlled. Throughput reaches are dominated by sediment generation and transport (Brierley and Fryirs, 2000) and do not have the potential to store significant volumes of sediment. The Waimatā is characterised by high terraces and confined valley margins resulting in extended throughput zones. Throughput reaches in the Waimatā exhibit straight channels, high terraces and narrow valley settings. This has resulted in sediment being flushed through the system. Often sections of slumping span the length of the terraces and follow patterns in their sizes and shapes. These sediments either get transferred downstream or remain at the toe of the failure and are then reworked back into the slope. However, they do not directly result in an adjustment to the geometry and planform of the channel; therefore, they could be creating a feedback loop. Due to stabilised banks, other sections of the throughput zones contribute little sediment to the system; instead, they act as flumes by transporting sediments through their reaches with little to no impedance.

Contemporary landscapes are imprinted by past events in a catchment, these manifest as geologic, climate and anthropogenic memory (Brierley, 2010). Geologic memory in the Waimatā arises through the fluctuation in sediment deposits, reflected by changes in Terraces. As Marden et al. (2014) outlined, the Waimatā and adjacent Waipaoa have experienced terrace incision resulting in sediment generation since the Last Glacial Maximum. This is seen through the stepped nature of these terraces (e.g. Table 5.2 C_T River Style), which reflect different stages of terrace incision; contemporary versions of this are now seen through point benches and ledges resulting from channel migration (e.g. Figure 6.7). Geologic memory can also be coupled with climatic imprint, seen through hillslope scars, reflecting large magnitude events required to induce hillslope failures. Other examples of climatic memory can include changes in the imprint of glacial/interglacial cycles (Brierley, 2010). Since the Last Glacial Maximum, Fluctuations in climate have carved out the valley due to changing sea level (see Section 2. 2).

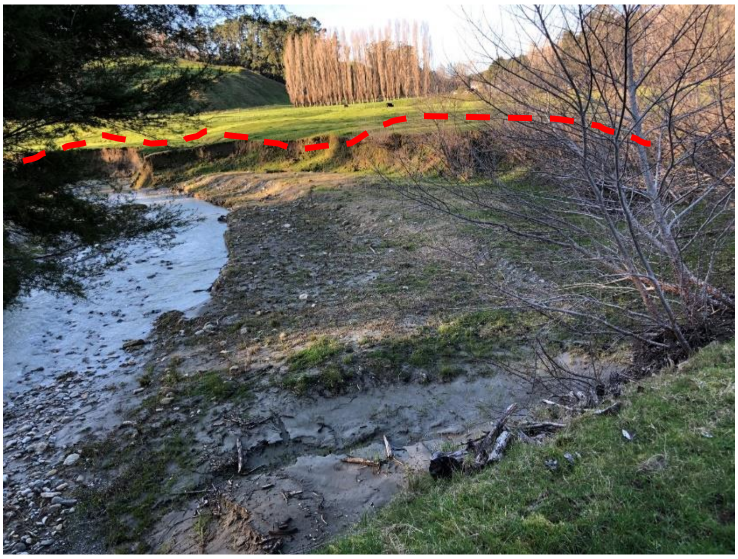


Figure 6.7 Example of point ledge indicating channel migration, location of point ledge shown by the red line.

Recognition of landscape connectivity when referring to these types of reaches can help understand a river's resilience and sensitivity, helping to infer rates and magnitudes of landscape adjustment (Wohl, 2017). High connectivity in the Waimatā has generally led to a sensitive river system in terms of longitudinal patterns and hillslope sediment generation (Bracken et al., 2015; Wohl, 2017). This results in the effective translation of sediment as relatively low lag times. High connectivity in the Waimatā has led to high sediment delivery and effective flow paths. Large quantities of sediment are being delivered to the main river, processes acting in upper reaches are being translated downstream, with surplus deposits resulting in aggradation occurring downstream (Lane, 1955). Connected systems often result in high sediment delivery ratios, whereby the sediment sources are coupled with the rivers. Usually fine-grained, these sediments are readily entrained and thus flushed through a system during low-moderate magnitude events. Following Reid and Brierley (2015), attributes of River Styles including; valley confinement and channel planform potential for adjustment were determined. Reaches with more accommodation space (e.g. PC_PC) had a higher potential for lateral adjustment, however, confined reaches with high hillslope-channel coupling (e.g. C_T) had a higher potential for longitudinal adjustment through sediment transfer. Sedimentation is a significant issue in the Waimatā. This demonstrates how sensitivity is fashioned by the behavioural regime of a reach and flow/sediment input from upstream. The approach to assess geomorphic river sensitivity outlined here could support 'room to move' or 'freedom space' approaches to river management by relating likely channel adjustments for the type of river (Reid and Brierley, 2015). Resilient systems are defined by the amount of change a system can undergo to retain the same function, structure and feedback (Fuller et al., 2019; Walker and Salt, 2012). Resilient systems in the Waimatā are more likely to be characterised by low capacity for lateral and longitudinal connectivity and must retain the same function under high sedimentation.

Logging, agriculture and naturally high sediment yields coupled with high longitudinal and lateral connectivity have led to a high sediment flux in the area. Sediments are constantly being reworked and transported from hill slopes and deposited on floodplains and banks. Tolaga Bay, located in the Gisborne region, has been subject to the impacts of several highly connected river systems. A storm in June of 2018 resulted in an estimated 1 million tonnes of debris being deposited onto private and public land (Sharpe, 2018). Forestry companies have been centred as the leading cause of this event due to the neglect of resource consents, such as forestry debris, skid sites, sediment control and erosion risk. The combination of poor management and high sediment connectivity led to a large extent of damage, and the debris was transported so efficiently.

Figure 6.8 Woody debris deposited in Tolaga Bay due to a large storm in June 2018 (From Sharpe, 2018).

6.3 Scale and resolution

Connectivity modelling has become increasingly popular in sediment research (Cantreul et al., 2018). Connectivity indices are a common method to quantify this, which work on the primary basis of topography (Cantreul et al., 2018); this is often represented by the digital elevation model (DEM). Varying resolutions of spatial data will influence the outcomes of a model as more or less detail is available to the model. The resolution of a DEM is characterised by its pixel size (Keesstra et al., 2014). Model outcomes from two DEM resolutions were tested in the Waimatā using the connectivity index (IC). Like Cantreul et al. (2018), IC outcomes varied with the DEM resolution; higher resolution input data resulted in more detail in the model results. For example, Figure 5.11 highlights the differences between using a 1m DEM and an 8m DEM. Generally, both DEM's revealed similar patterns of connectivity, defined by high slope, unvegetated areas exhibiting high connectivity and vegetated and low sloped areas exhibiting low connectivity. These patterns were most common in a larger scale view of model outcomes, e.g., Figures 5.10a and 5.10b show broad-scale connectivity trends.

At a smaller scale, differences in model outcomes were observed. For example, outlined in the EF_Trib River Styles in Figure 5.11, the two models characterised connectivity differently. The 1m DEM identified the sediment input from the mud-volcano, which contributed to sediment-hillslope coupling and ultimately high sediment connectivity. Slight elevation changes are essential in tracking sediment inputs, as often, the sediment input can be smaller than a pixel size (Cantreul et al., 2018). Cantreul et al. (2018) found a general difference of 20% when comparing DEM resolutions of 0.25m and 10m. Coarser resolutions showed more connectivity because of the simplification of flow paths. Ultimately, both resolution DEMs were able to identify similar patterns of connectivity. However, a finer resolution is needed when studying smaller scale reaches. Pixel size should be linked to the study objective; no single pixel size is suitable for every study, but a range of suitable pixel sizes, which Cantreul et al. (2018) suggested being around 1m, should be considered. Moreover, this is determined by data availability (Claessens et al., 2005), study site characteristics (Akbari et al., 2009) and the watershed type and size (Cantreul et al., 2018)

6.4 Management and future study

Fluvial geomorphology is experiencing an increased drive to become predictive as well as retrodictive (Wilcock and Iverson, 2003; Lisenby et al., 2020). Currently, fluvial scientists cannot simulate, model and detail the physical adjustments of rivers in response to environmental disturbance with great certainty (Wohl et al., 2015; Lisenby et al., 2020). The ability to forecast what changes may occur in the future is still a highly adopted concept and allows for "what ifs' to be incorporated (Lisenby et al., 2020). However, geomorphologists are bridging this gap by introducing landscape prediction methods through qualitative and quantitative landscape interpretation and analysis (Everard and Quinn, 2015; Lisenby et al., 2020). These skills can work together to inform and interpret landscape behaviour and development, in turn setting up and constraining landform analyses (Lisenby et al., 2020). This can be achieved through the relationship between landscape sensitivity and sediment connectivity. Appraisal of landscape connectivity, space to move relationships, and sediment dynamics can inform the interpretation of landscape sensitivity and the capacity a system must adjust. The sensitivity depends significantly on sediment connectivity. The available sediment and degree of transference within a landscape determine the capacity of the river to respond (Hooke, 2003; Fryirs et al., 2007b; Bracken et al., 2015; Lisenby et al., 2020). Correspondingly, sediment availability will control, to some extent, the form, number, extent and severity of future river channel adjustments (Hooke, 2003; Czuba and Foufoula-Georgiou, 2015).

6.4.1 How does modelling sediment connectivity contribute to management?

In recent years, connectivity has emerged in sediment management, describing the transfer of sediment between and within different landscape compartments (Najafi et al., 2021). IC and tracking sediment sources (CASCADE) allow visualisation and interpretation of sediment connectivity at multiple temporal and spatial scales. Allowing real-world data input into these models provides a tool for in-depth analysis of a given catchment. A range of spatial data available for the Waimatā allowed for coarse resolution and fine resolution visualisation of sediment connectivity patterns. Figure 5.6 exemplifies sediment connectivity at a range of scales and techniques. They allow for sediment connectivity to be analysed through multiple lenses. IC analysis provides a holistic look at sediment connectivity and the potential for sediment generation. The index allows for easy implementation and quantification of structural sediment connectivity at the catchment scales and accommodates catchments with limited data, especially in developing regions (Najafi et al., 2021).

Interpretation of river sensitivity and sediment connectivity can be applied to any catchment (Lisenby et al., 2020). These analyses can provide simple approaches to estimate the possibilities of river adjustment (Lisenby et al., 2020). River and catchment managers can be faced with extensive areas to cover; therefore, prioritisation of management and intervention efforts is needed (Lisenby et al., 2020). Here, a catchment-wide appraisal of connectivity using two different methods is offered. The Waimatā exhibits marked channel diversity, with valley confinement, geology and topography influencing the processes underpinnings landscape development. Sediment connectivity provides a means of visualising sediment transportation potential. These models have produced spatial maps, as seen in section 5.3, allowing managers to visualise their areas of concern. Often highly connected areas will be more sensitive, or in the case of the Waimatā, contribute larger volumes of sediment than the lower connectivity areas. This provides a good starting point for managers to begin their restoration efforts. Characterising sensitivity and sediment connectivity demonstrate that scenario-building exercises must be framed within a 'reach-in-catchment' perspective (Lisenby et al., 2020). This perspective encapsulates the recognition of a rivers potential to adjust its position in a catchment (Brierley and Fryirs, 2005; Wohl et al., 2005; Kondolf et al., 2006; Lisenby et al., 2020). River sensitivity, informed by connectivity modelling, can help determine the potential for future river recovery or restoration in different channel reaches (Fryirs and Brierley, 2000; Fryirs, 2015; Fryirs and Brierley, 2016; Lisenby et al., 2020). In some cases, rivers that have degraded suffer from a lack or overabundance of sediment, like the Waimatā (Fryirs et al., 2009; Lisenby et al., 2020). Therefore, understanding the sediment connectivity for a given reach is crucial to determine how or if a river is capable of recovery (Fryirs and Brierley, 2016).

6.4.2 Creating scenarios for informed management

Scenario-based analysis of connectivity in the Waimatā provided insight into how the system may respond moving into the future. Evolutionary trajectories and moving targets provide future states and associated behavioural regimes, assessing the likelihood of obtaining these states in each timeframe (Brierley and Fryirs, 2015). Large portions of the Waimatā are occupied by forestry, which will be harvested in the next 20-30 years. This poses significant implications to the management of the Waimatā. The IC and CASCADE outputs resulted in higher sediment generation and sediment connectivity under the 'BAU' scenario, which proposed forest clearance at its current trajectory. Higher sediment erosion in the upstream and mid reaches of the catchment would prove detrimental to the Waimatā. Understanding the dynamics of sediment transportation and aggradation provides further insight into how this system may respond. Like Lynch et al. (2019) and Dymond et al. (2016) use of the SedNetNZ model, outcomes using the IC and CASCADE to produce connectivity scenarios revealed patterns of 'hotspots' which enable prioritised management. Knowledge of valley confinement and terrace position along the Waimatā allows predicting how these sediments will be flushed through the system. Under the BAU scenario, volumes of sediment generated on the hillslopes will be flushed through the system like they have been seen to in the past (Cave, 2019) but on a much larger scale. Under this scenario, stakeholders, management personnel, and landowners need to be aware of these connectivity hotspots and consider different forest clearance approaches to avoid significant sedimentation, which could impact downstream and urban areas (A. Salmond, personal communication, 2020).

On the other hand, scenario modelling of the two regeneration options proved promising for the Waimatā. Revegetation of pine forest and replanting of the sparsely occupied hillslopes would increase the percentage of the forested catchment. Revegetation has been seen to stabilise root structures and reduce sediment runoff, thus increasing the roughness values (Borselli et al., 2008). Therefore, this scenario can decrease sediment generation and sediment connectivity. The addition of structural (dis)connectivity also adds to the decoupling of the systems. Wetlands can reduce the connectivity of the system. For example, Tables 5.8 and 5.9 show the influence of buffer zones and wetlands to trap sediment from hillslopes.

Moreover, visualising sediment flux volumes and potential connectivity scenarios can provide vital insights into management. When coupled with process base interpretations of landform sensitivity can bridge gaps in model production and integrate tangible estimates in your outcomes. Visualising sediment connectivity in the Waimatā using models without the process base understandings developed in the River Styles would leave gaps in the causes of sediment (dis)connectivity, typically displaying contrasting results.

6.4.3 Future directions for connectivity modelling

The concept of sediment connectivity has emerged into sediment management and describes sediment transfer from different sections of landscapes. Identifying areas susceptible to sediment loss is an essential component when designing strategies for management (Nosrati et al., 2014; Najafi et al., 2021). Indeed, connectivity itself is an emergent property – it changes, not always in predictable ways (Wohl et al., 2019). Sediment sources can be identified; however, this is not enough for effective management. Therefore, geomorphic coupling patterns must be identified (Harvey, 2001, 2002; Najafi et al., 2021). Implementing sediment connectivity management concepts is essential in areas where high erosion and sediment delivery rates threaten ecosystems and urban areas. Overloading sediment in the lower reaches results from high connectivity throughout the Waimatā catchment. Processes occurring in upper reaches (including erosion/landslides) propagate downstream due to the flume behaviour. Therefore, recognising these sources is critical in determining hotspots for prioritised management. Najafi et al. (2017) link this to the potential sediment connectivity indices have on developing countries, where erosion and deposition cause severe problems. Therefore, connectivity is one of the essential concepts in assessing the hydrological and erosional responses of watershed components having different natural and management characteristics (Najafi et al., 2021). Moreover, connectivity assessments may also be utilised for prioritised and targeted management techniques, as it is an effective screening tool for hydrological, erosional and sediment management (Poeppl et al., 2020).

Despite the need for more precise spatial data and estimates of sediment delivery, connectivity indices are not being utilised at the management scale (Heckmann et al., 2018). Sediment connectivity (including indices) provides a sediment transfer measure and can predict possible catchment trajectories. This thesis has attempted this; however, more quantitative outcomes will prove more effective for managers. Interviews from Smetanova et al. (2018) found that the perspective from stakeholders is that sediment connectivity is essential for management practices (85 samples) and meet requirements in terms of costs to require data. However, due to gaps in the technology not being utilised fully, further advancements could include a better explanation of the consequences of sediment connectivity to stakeholders for management purposes.

Furthermore, sediment connectivity has been created for small, relatively connected meandering river catchments (Borselli et al., 2008; Cavalli et al., 2013). Therefore, tailored methods of producing sediment connectivity indices should be recognised. Methods should be catchment specific and account for regional controls on geology, climate and topographic configuration as each catchment will respond differently, and these controls may impact each catchment uniquely.

These concepts have been circulating in fluvial geomorphology for a while. However, modelling hasn't been fully developed to capture the complete picture of sediment transport dynamics sediment connectivity. Models have not been able to fully quantitatively predict how different scenarios will play out. Czuba and Foufoula-Georgiou (2015) have been able to quantify sediment connectivity by developing a 'dynamic connectivity' model, which organises the network into parcels and defines clusters that display unique transportation information. Thus, allowing for tracking of sediment through a system. This is further built on by Tangi et al. (2018) in their modelling framework CASCADE (Catchment Sediment Connectivity And Delivery). CASCADE has integrated previous approaches into a network-scale modelling approach to quantify functional sediment connectivity (Schmitt et al., 2016). An important advance in CASCADE is that the sediment transported from each sediment source is conceptualised as an individual cascading process, and sediment sinks can be tracked to their source. This thesis has built upon the work developed in Tangi et al. (2019), Borselli et al. (2008) and Fryirs and Brierley (2019) and hopes to bridge the gaps presented when these works are used alone.

6.5 Data resolution and limitations

In light of the widespread use of remote sensing and River Styles, gaps in predicting sediment connectivity and the processes underpinning these patterns remain. The models of catchment scale connectivity presented in this study offer both analytical and conceptual methods to organise the complexity of river systems at the catchment scale. The CASCADE Toolbox allows for the visualisation of sediment sources and sediment transportation. At the same time, the IC and River Styles analysis provide more conceptual methods to look at river behaviour and processes. Although these methods provide ways to predict how systems may respond under different scenarios, they come with downfalls surrounding the quality of data, modelling techniques and interpretation of landscapes.
Increases in data resolution in the Waimatā has allowed for more in-depth analysis of sediment connectivity. The use of the 1m DEM has allowed for the delineation of a more complex geomorphic feature, such as terraces, small scale gullies and complex flow paths. Cantreul et al. (2018) identify that often, pixels sizes in coarser resolution data is greater than the width of a feature. Therefore, the

fewer smaller areas are less visible (Contreul et al., 2018). Increasing precision to a resolution of 1m allows field limits, linear features and complex flow paths to be observed. Pixel sizes of 8m also provide vital information about the nature of your system. Coarser DEMs still provide enough catchment appraisals of sediment connectivity. Major lowland areas and hillslope areas are still identifying, thus located areas susceptible to erosion and transportation. However, 8m DEM is not enough when evaluating smaller scale sediment connectivity. Finer details in sediment patterns and gullies are missed as they are often smaller than 8m. therefore, some areas could be misclassified as disconnected when they are truly connected. (Contreul et al., 2018). Moreover, there are no single suitable pixel sizes, but a range of pixel sizes best fit a study site (Akbari et al., 2009). Building off the principles suggested in Akbari et al. (2009) and Cantreul et al. (2018), the type of model used must also be determined the catchment characteristics and aims of a study (Fryirs et al., 2019).

Data input into models shapes the outputs received. Therefore, high-quality data needs to be input into models to receive good quality data out. Although inputs into CASCADE received data retrieved from the field for the grain sizes, other values had to be estimated from databases and imagery. In the future, it would be vital to retrieve values such as widths, depths and velocity to get better estimates of water discharge, rather than estimating from catchment rain gauges. Another vital data input to gather infield is the roughness values. Manning's N should be estimated in the field rather than field photography. This would capture the grain size and vegetation detail for reaches, especially canopy covered. Sensitivity analysis (e.g. Reid and Brierley, 2015) is also required to test the system's resilience in response to changing conditions. For example, both models could be run changing data inputs, such as grain size data and roughness values (Manning's N), to see how the river may respond to an event that dramatically alters the system.

Models are abstracts of reality and don't portray systems as they truly are (Oreskes, 1998; Oreskes et al., 1994). Therefore, model outputs must be evaluated critically. Often these models are solely structurally based and do not consider the sets of processes driving these interactions. The IC is topography based and isn't applicable for lowlands; therefore, the validity of the results between the up and lowland area should be questioned. Thus, field assessments of the sites are required to check the outputs from the models. More conceptual frameworks, such as River Styles, allow for the depiction of different types of structural sediment connectivity at various spatial scales and provide a geomorphological view of sediment connectivity. These approaches consider sediment storage and transportation patterns and attribute structural and functional connectivity. However, these approaches are often landform based. And do not provide tangible estimates of the potential for sediment movement. Moreover, approaches that combine field and geomorphological assessments with modelling-based techniques will prove the most effective into the future.

6.6 Thoughts for future research

Combining the connectivity index, CASCADE Toolbox and an appraisal of River Styles allowed for a broad overview of connectivity and capacity for adjustment to be made for the Waimatā catchment. However, many gaps were still present in this study, leaving room for future research. For example, more in-depth sediment sources using the CASCADE Toolbox could be made utilising the grain size functions present in the model; this could solve the sensitivity analysis of changing grain sizes to reflect different types of events and sediment sources. This should be coupled with a River Styles appraisal down to geomorphic units and bed material texture to truly encapsulate the processes acting in a reach. Moreover, multiple approaches to sediment flux analysis should be used when assessing potential management techniques. Models do not always capture the entire story (Najafi et al., 2019); therefore, demonstrating process-based understanding, such as River Styles, can help to bridge this gap.

6.7 Conclusions

Ultimately, this study offered insight into the forms and processes driving sediment connectivity in the Waimatā. River Styles analysis recognised the influence of confinement on sediment transport, highlighting the flume type behaviour due to the lack of accommodation space and capacity for adjustment. Lateral linkages were high throughout most of the Catchment; however, this did not result in all the catchment contributing sediment to the flume. This gave rise to the importance of throughput and transfer reaches. The Waimatā is dominated by throughput reaches, flushing sediments through the system with little room for adjustment due to the extensive presence of contemporary and relict terraces. On the other hand, transfer reaches and throughput reach, with high hillslope coupling to weak hillslopes, generated high volumes of sediment. However, sediment residence times were low, reflected in point bars and mid-channel bars. The connectivity analysis highlighted the influence of land use and slope on the potential for sediment movement. High connectivity was characteristic of high sloped areas and areas of low vegetation cover. In contrast, low connectivity reflected low sloped areas and highly vegetated regions. However, it was also characterised by areas of buffers, blankets and barriers. These trends were further enforced through land use scenarios, which highlighted ‘hotspots’ of adjustment under different river trajectories.

Chapter Seven: Conclusions

Ongoing concerns for sedimentation issues in the Waimatā Catchment have prompted significant community interest in restoration initiatives, including Hikuroa (2018), the Waimatā Catchment Restoration Project and Waikereru Ecosanctuary. Forestry management is a critical social and political issue in the Waimatā catchment. As a result of contaminant discharge, one of the forestry companies, Arutu Forestry Limited, was recently fined up to $379,500 by Gisborne Council under the Resource Management Act. Determining the sources of these sedimentation issues and the patterns of their dispersal was key in the development of this thesis. As a result, three methods of assessing sediment behaviour were used in the Waimatā, including the Connectivity Index and the CASCADE Toolbox. However, the models alone could not fully determine the processes and forms of sensitivity in the catchment, which led to the appraisal of River Styles.

River Styles and the identification of differing sediment transfer and throughput zones allowed the capacity for adjustment in the Waimatā to be assessed. Where transfer zones had a higher capacity for adjustment compared to throughput zones, which were commonly erosional reaches. Throughput zones dominate the Waimatā, caused by constrictions from contemporary and relict terraces and bedrock. The limited space for adjustment and accommodation for depositions have led to the throughput zones acting like a flume, flushing sediments generated in the transfer zones and erosional throughput zones out to sea. The River Styles type also reflects the reaches potential for adjustment. Reaches confined by terraces and bedrock have lower potential to adjust as they are fixed in place, reflecting significant portions of the Waimatā. Moreover, the confinement of a reach alone does not determine the capacity for adjustment. The controls on adjustment must also be considered when assessing the capacity for channel migration and river trajectories.

Overall, there are distinct traits of the highly connected and disconnected systems. Highly connected areas show visible sediment transport and supply, commonly seen through mass wasting and incision. An additional indicator is hillslope coupling which directly supplies the main channel with eroded materials. In the disconnected systems, there are extensive floodplains and disconnected channels. Distinguishing the difference between connected and disconnected systems is the first step in understanding the sedimentation behaviour in a system. The highly connected reaches have a higher potential for sediment transfer between and within landscape compartments. Therefore, they need to be tackled upstream where these sediment linkages occur before tackling sedimentation issues downstream. Highly connected reaches were most found in narrow valley settings, which are directly impacted by the controls on confinement. Areas with lower valley confinement may have higher channel migration and lateral adjustment capacity. However, narrower coupled River Styles with high lateral connectivity may experience adjustment through the inputs of external sediments. The CASCADE Toolbox allowed an insight into the types and volumes of sediment moving throughout the system. Upper reaches in the main river and tributaries had high erosion and lower deposition, which was reflected in the high entrainment and lower deposition volumes. This is the result of higher energy systems being able to entrain and transport sediment downstream. Lower and mid reaches were reflected by lower entrainment and higher deposition due to lower energy flow being incapable of entraining sediments in these reaches.

The scenario-based connectivity analysis provided insights into how the system may respond under differing land use trajectories. Three land use scenarios were presented, reflecting different levels of management. The 'business as usual' scenario increased sediment connectivity. Hillslopes remained coupled to the river. The decrease in hillslope stability from removing vegetation through forestry would result in a direct link of mass wasting events and transfer into the streams. The two management approaches, 'regeneration' and 'wetland/regeneration', gave similar results.

Ultimately, the results of this thesis have provided a multifaceted approach to the appraisal of sediment flux behaviour in the Waimatā. The three assessment methods have all highlighted the importance of valley confinement of sediment transfer. Valley confinement and sediment generation determine transfer and throughput reaches, whereas slope and land use are primary determinants of lateral sediment connectivity. However, how the sources of sediment link to the trunk stream determine the effective catchment area, mainly through tributary-trunk confluence and hillslope-channel connectivity. Coupling dictates this, where a decoupled system would result in sediments becoming stuck close to their source. This is the primary cause of the Waimatā's sedimentation issues. Tributaries and hillslopes, the two greatest sediments, are connected to the trunk stream, which is propagated downstream efficiently as a result of throughput reach acting as a flume.

Subsequently, future management must consider these lateral and longitudinal linkages to manage the Waimatā and other similar catchments effectively. This would include decoupling sections of the system with hotspots of sediment generation. As outlined in the Wetland scenario, wetlands can act as barriers to decouple the system by creating a sediment sink. This should be considered a potential management technique for the Waimatā as it is often a non-invasive method of protection. Ultimately, management should be targeted to reflect the system's processes and types of sediment generation. Assessments of connectivity and River Styles have attempted to provide a multifaceted approach of determining these reach characteristics and hope to provide methods future management can follow.

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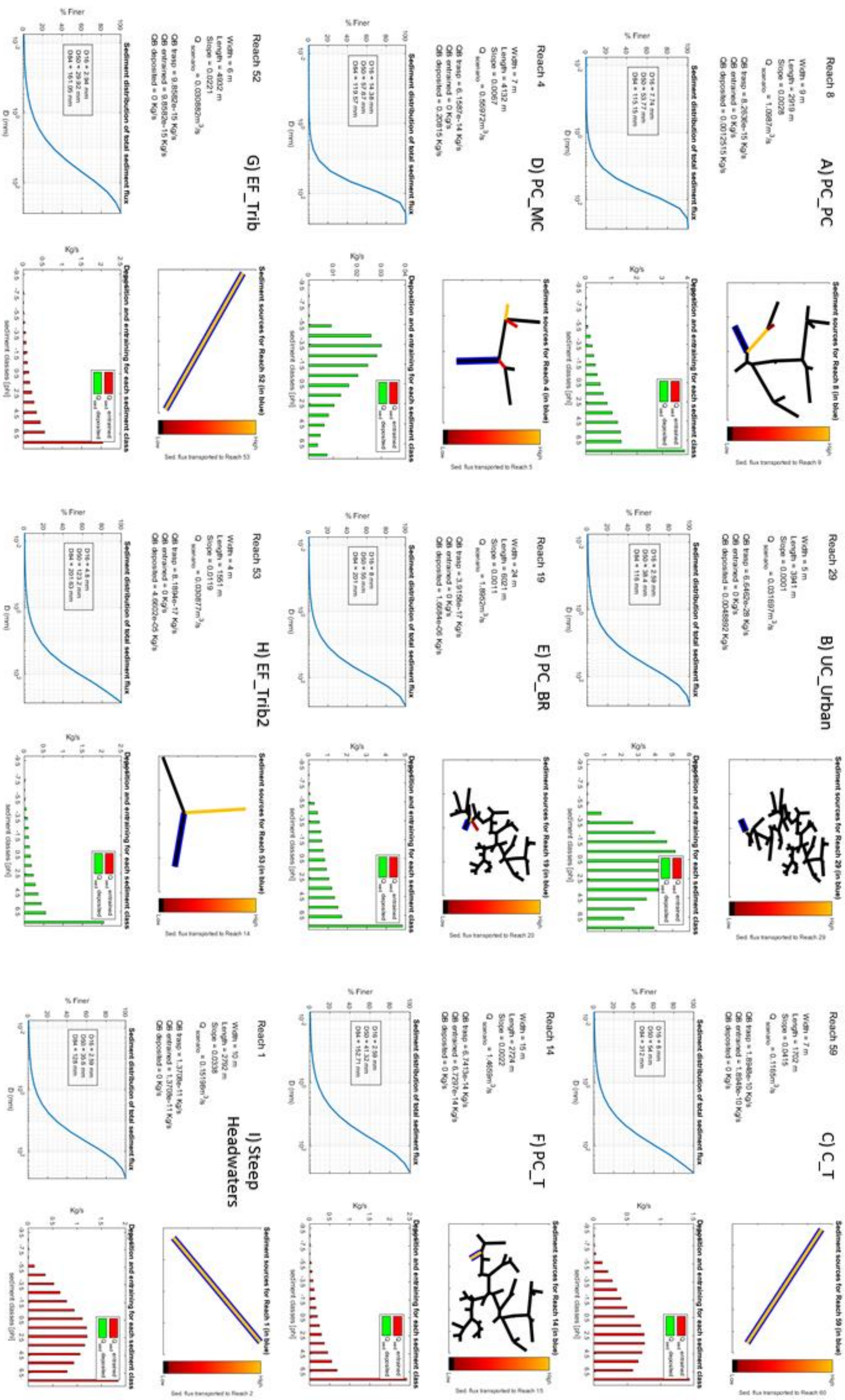
Appendix



Appendix 1. Cascade outputs with respective River Styles type. These outputs depict whether a reach is dominated by entrainment or deposition. Outputs also highlight the relative sediment generation sources.