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Measuring the Morphologic Response of Braided Rivers to Lateral Constriction

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Abstract

The aim of this thesis is to understand the morphologic changes to a set of historically braided rivers that have been narrowed. Braided rivers from the agriculturally developed Canterbury Plains, New Zealand, were studied from a period prior to much development (mid-1900s) to the present. Narrowing of channels, decreased braiding intensity, and loss of braided planforms were determined based on aerial imagery, changing the geography of braiding along all rivers. Channel width and count were statistically correlated and show the predictability of braiding change based on narrowing. Reaches with initially wide channels require more narrowing to induce a simplification of braiding, while narrower reaches may be closer to a threshold of change and require less narrowing to transition. The implications of the results can be used in river management to create wide enough river corridors that allow the rivers to maintain their naturally braided planforms while mitigating flood risk.

Keywords

Braided river, lateral confinement, channel pattern change, active channel width, braiding intensity, threshold predictors, Canterbury Plains NZ

Summary for Lay Audience

Rivers evolve due to natural changes in the environment, and in their more recent history, they evolve due to human induced pressures. Throughout the world, rare, braided river patterns are recording a loss in areas with human-caused lateral confinement. Lateral confinement restricts the natural mobility of rivers, decreasing river stability and increasing flood risk. This thesis aims to understand the changes to nine braided rivers in the Canterbury Plains, New Zealand, that have been laterally confined. The period of study captures the rivers prior to significant development (mid-1900s) to present. All rivers of interest were recorded to have narrowed over time with increased confinement along their channels. Some sections of the rivers also changed from more complex river patterns (e.g., braided) to less complex patterns (e.g., single channel). The amount of narrowing required to induce a change in river channel pattern was explored and showed that larger channels require more narrowing to see a change in pattern type compared to channels with narrower starting widths. This is useful for future river management plans that want to confine rivers, as a minimum width before braiding loss can be determined. The Canterbury rivers show changes similar to other rivers around the world that have been affected by human alterations. Parts of the rivers still maintain their braided patterns and there is time to effectively and sustainably manage the rivers to restore them back to their natural functions.

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Chapter 1

1 Introduction

Rivers are an important part of environments worldwide and have a vital role in the hydrological cycle as they transport water and sediment through a landscape. As river and surrounding environments change due to natural or human effects, rivers react and evolve. The scale and type of change within a river catchment influences the nature and magnitude of river response. For example, a driver of change such as human channelization directly and 'permanently' confines the lateral mobility of a river system, while a large rainfall event may cause high water levels or flood for a temporary period before the river naturally returns to its equilibrium state. The behaviour of a river system is determined by the characteristics of its surroundings therefore it is important to understand the patterns of change, diversity within the river, and influence of driving forces both natural and anthropogenic.

As humans shape rivers to accommodate population's ever-growing numbers, the issues arising from large-scale river changes become more and more prevalent. Populations tend to think of how a river system can be used and controlled and tend to ignore the needs of the river itself (Knight, 2019). Rivers are commonly confined to allow for transportation channels, constricted to increase land area, and secured into place to protect surrounding infrastructure; they are also irrigated, mined, dammed, and used to generate hydroelectricity. Indirect human effects on rivers also include land use change within river catchments and climate changes.

Controlling river systems has been a crucial part of human expansion. While providing the services listed above, the rivers also pose as a threat to the surrounding areas. Natural environments are unpredictable and therefore rivers are difficult to effectively control. A classic approach to control and protect developments from rivers is by constricting them by using stopbanks (or levees). The various pressures and influences imposed on river systems by humans can be very damaging to the rivers, modifying them from their natural state and causing decreased resilience. The response of rivers to these changes depends upon the degree of change as well as the type of river system. For example, wide multi-thread, braided rivers are particularly sensitive in comparison to single channel systems.

The complex dynamics of braided rivers can make them particularly difficult to control and their wide lateral expanse makes them prone to human-driven confinement, either by shrinking the channels or by direct encroachment. The influence of human alterations on braided river systems has been captured in literature (Gurnell et al., 2009; Stecca et al., 2019). Stecca et al. (2019) reports an increase of morphologic transitions away from braided patterns within the past few decades. Braided rivers require particular conditions and geomorphic qualities to form and are only found in a few places globally. One of the few places where braiding still exists is in New Zealand, but here braided rivers are being ‘strangled’ (Brierley et al., 2021) by engineered banks and gradual encroachment onto braidplains by surrounding landowners. In New Zealand there is concern for the conservation of these rivers as they represent an important natural and cultural landmark. Recognition of morphological diversity and understanding of river processes and change over time are essential for effective river management (Brierley and Fryirs, 2005).

The aim of this thesis is to identify the morphologic changes to a selection of New Zealand braided rivers that have been subjected to various confining factors. Through the analysis of these rivers, a dataset of morphologic characteristics will be developed that can be used to analyze morphologic relationships between lateral confinement (or change in channel width) and braiding occurrence. The dataset may be applicable to braided rivers worldwide and aid in more natural river management approaches by indicating the amount of room required to preserve braiding morphology or restore a river’s natural morphology. The overall thesis objectives will be explained in more detail at the end of Chapter 2.

Chapter 2

2 Braided River Characteristics and Loss: confinement, channel pattern transition, and the case of Canterbury rivers

Humans alter the natural environment of river systems in many ways. This includes land use change, gravel mining, irrigation, dam construction, invasive species, and lateral constriction (channelization). This thesis focuses on the influence of forced changes to channel width (i.e. lateral confinement/constriction) on braided river morphology and how changes in braiding can be predicted based on known channel characteristics. The goal of this Chapter is to provide the relevant background for the thesis and explain the overall research objectives.

2.1 Braided Rivers: morphology and response to change

Rivers have a continuum of pattern types from straight single thread to meandering to braided (Charlton, 2018). This thesis is focused on braided rivers (Figure 2.1). Braided rivers are natural and unique systems that are highly dynamic with multi-thread channels actively changing within wide braidplains. Channel threads diverge and converge around exposed channel bars in a repeating pattern along a river, a characteristic easily identifiable in plan view. Braided rivers develop through the balance of streamflow, slope, sediment availability, vegetation, bank resistance, and width-depth ratio (Ashmore, 2013).

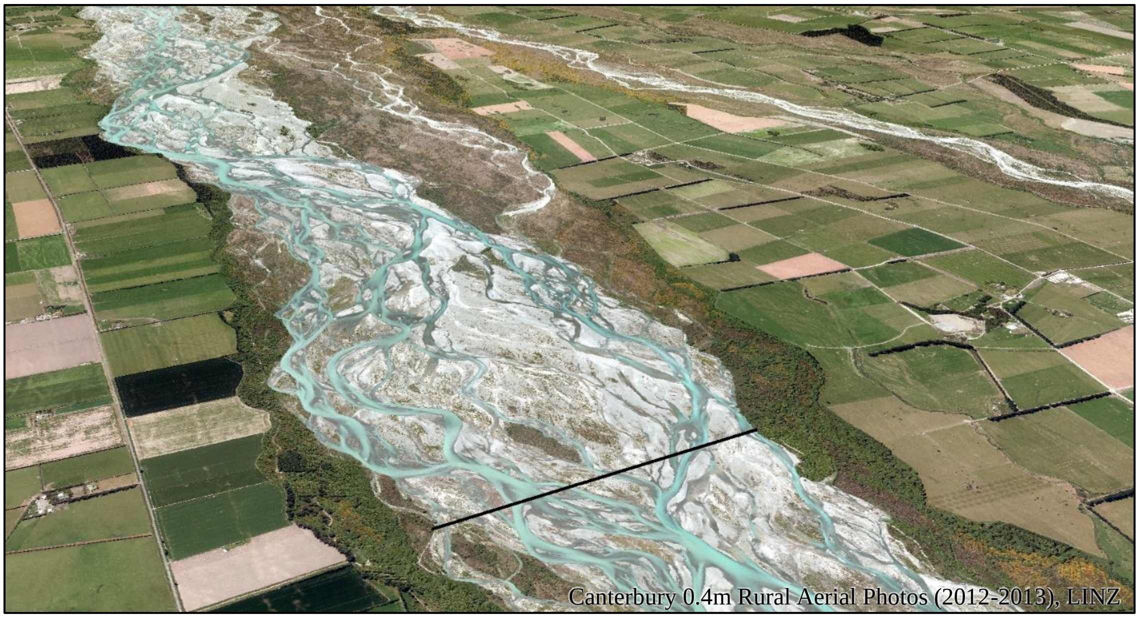

Figure 2.1: Braided river pattern of the Rakaia River, New Zealand. Looking upstream. Black line shows a channel width of ~1,200m. Data source for represented imagery is listed in References under 'Data Sources – Imagery'.

Braided rivers are found in a variety of geographic settings typically occurring in those with high energy (stream power), coarse bed material (in high supply), and less developed riparian vegetation (bed and banks have relatively low resistance; Ashmore, 2013). Braided rivers typically have erodible banks, and this lack of hard confinement allows the rivers to develop laterally, producing wide channels. The total area of a braided river channel may not always be occupied with flowing water. Most of the time, only a selection of the channel threads are flowing and modifying the river (Ashmore, 2022). This active width of the river is the portion of the channel doing geomorphic work and is expected to change in position over time.

The configuration and lateral position of braided rivers can change quickly when river flows increase. During periods of high stream flow, the active state of the river leads to instability as channels may develop, shift, and disappear quickly. Channel bars may become submerged during high flow events and as a result, changes in morphology occur. The high level of sediment and streamflow maintains the active state of braided rivers. The activity limits the formation of vegetation growth which may harden banks and bars (Williams et al., 2016). This lack of vegetation leads to the continuation of erodible banks which allow for the natural lateral migration that sustains the braided morphology (Ashmore, 2022). In relation to river engineering efforts, braided rivers tend to pose a problem regarding high flow events with their frequency of channel changes and high rates of sediment transport leading to high rates of erosion.

2.1.1 Worldwide Braided River Loss

As with the other river types, braided rivers can be found globally, however it has recently been noted that these river types are disappearing, most notably in human influenced settings. Stecca et al. (2019) reported the increase of changes to braided rivers due to anthropogenic factors from literature within the last few decades. The reason for the loss of braided river morphology has been traced back to numerous indirect (watershed conditions) and direct (in-channel interventions) causes including the increase of lateral confinement of river channels. While all river types are to some extent modified by lateral confinement, braided rivers are particularly sensitive as their dynamic systems react more quickly to such change (Stecca et al., 2019).

Braided rivers were commonly found in regions throughout Europe, however, increased human development and engineering interventions on the river systems, such as confinement, has led to most of the braided rivers being eliminated (Surian and Rinaldi, 2003; Surian, 2006; Gurnell et al., 2009; Surian et al., 2009; Belletti et al., 2015; Scorpio et al., 2018; Stecca et al., 2019; Hohensinner et al., 2021). There have been many studies observing the change in European river planform over multiple decades with most showing large channel changes. Over the past few centuries, as human developments have increased and expanded throughout Europe, many of the braided and near-braided rivers in the region have dramatically changed due to the impact of human activity (Gurnell et al., 2009; Stecca et al., 2019; Hohensinner, 2021). Most change is noted to have occurred in the 1900s where channels were narrowed and began to incise (Gurnell et al., 2009). Today, or in the recent past, stabilization and widening is becoming more common although narrowing still occurs (Gurnell et al., 2009).

A report of the loss of braiding morphologies by Stecca et al. (2019) also identifies similar changes in regions outside of Europe including North America and New Zealand (Brierley et al., 2021; Hicks et al., 2021). Published data for affected gravel-bed braided rivers in other continents including Asia and South America could not be found (Stecca et al., 2019).

2.1.2 'Room for rivers'

For human developments to thrive in fluvial landscapes, the manipulation of the landscape including river engineering is inevitable. Human implemented measures of confinement are often the leading control on the lateral movement of the river, and the effect of lateral confinement on braided river morphology and dynamics is relatively neglected (Fryirs, 2016). The confinement and straightening of rivers have increased erosion and flooding events putting more erosive pressure on riverbanks (Williams, 2017). It is stated by Williams (2017) that more cost-effective methods for river management will take the natural processes of rivers into account.

Emerging in the literature is a paradigm shift from engineering-based to more natural approaches to river management, going by a variety of terms such as 'freedom space' or 'room for rivers' (Biron et al., 2014; Reid and Brierley, 2015). These projects support the idea that enough space should be left around a river to let it adjust freely instead of 'straight jacketing' or 'strangling' the river into a single channel (Biron et al., 2014; Reid and Brierley, 2015; Brierley et al., 2021). For braided rivers especially, the engineering of channels is resulting in a loss of this type of morphology throughout the world. Room for rivers provides space for flooding and natural lateral migration of channels which can allow systems to self-heal, while also helping to protect ecosystems and reduce the risk of flooding and erosion (Scorpio et al., 2018; Fuller et al., 2020). This approach is considered more sustainable but at the cost of decreased land area for human activity (Biron et al., 2014). The value of certain land areas for human benefit makes this approach slow and unreasonable in some locations (Scorpio et al., 2018). A major problem with these endeavors is a consensus on a way to determine the amount of space required for a given river (Reid and Brierley, 2015). An understanding of the natural controls, dynamics, and morphology of full-scale braided rivers is key for assessing the effects of different levels of lateral confinement on river changes over time (Reid and Brierley, 2015; Fuller et al., 2020).

An outcome of this thesis is to help establish conditions for preserving braiding as part of a management approach that includes the room for the river and the conservation or restoration of elements of braiding.

2.2 Lateral Confinement of Braided Rivers

Lateral confinement which restricts the width of river floodplains is known to have major impacts on river morphology by affecting the extent to which rivers can freely adjust through a landscape (Fryirs et al., 2016). Lateral confinement can be both natural (e.g. hard canyon walls) and artificial (e.g. stopbanks). The artificial confinement of river channels is a common engineering practice which limits the lateral migration of a river, making it narrower and allowing for more land for human expansion as well as mitigating flood risk.

Recent studies have worked to provide consistent definitions and methods for the quantitative measurement of different levels of river confinement (Brierley and Fryirs, 2005; Wheaton et al., 2015; Fryirs et al., 2016; O'Brien et al., 2019). Three levels of confinement are named: 'confined', 'partly confined', and 'laterally unconfined'. Confined segments can be identified as having both sides of the channel controlled by hard confining margins continuously along the river (">90/% of channel abuts valley margin"; Brierley and Fryirs, 2005). Partly confined segments are those with confining margins frequently along the channel but not continuously ("10-90% of channel abuts valley margin"), and therefore have some room to adjust (Brierley and Fryirs, 2005). Laterally unconfined segments are those that have seldom or no contact with confining margins along the channels ("<10% of channel abuts valley margin") and therefore allows for natural lateral mobility and planform development (Brierley and Fryirs, 2005). Figure 2.2 illustrates the distinction between varying levels of confinement.

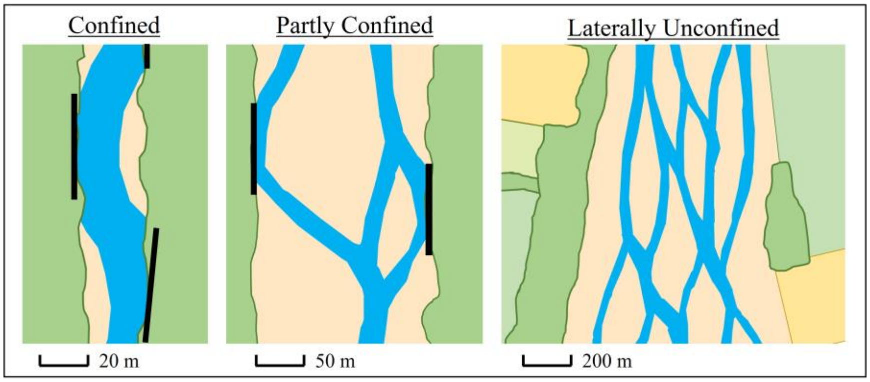

Figure 2.2: Levels of river confinement. Black lines represent actively confining margins. Note the variation of scales.

There is a notable distinction between the terms of confinement and constriction. Confinement is defined as restricting a channel by hard, laterally restricting margins, while constriction is confinement that limits the lateral channel planform and pattern development. Confinement definitions do not imply that both banks of a channel are restricted (Fryirs et al., 2016). Constriction makes a channel narrower, reducing river channel width-depth ratios which may lead to a simplification of channel morphology (e.g. braided to single channel). For example, a change in level of confinement from ‘laterally unconfined’ to ‘partly confined’ or ‘confined’ may be constricting to a braided river if the limited capacity to adjust causes a shift to a less complex morphology type (i.e. wandering or single channel). Figure 2.3 shows a real-world example of planted vegetation boundaries constricting a river channel and the observable simplification of morphology.

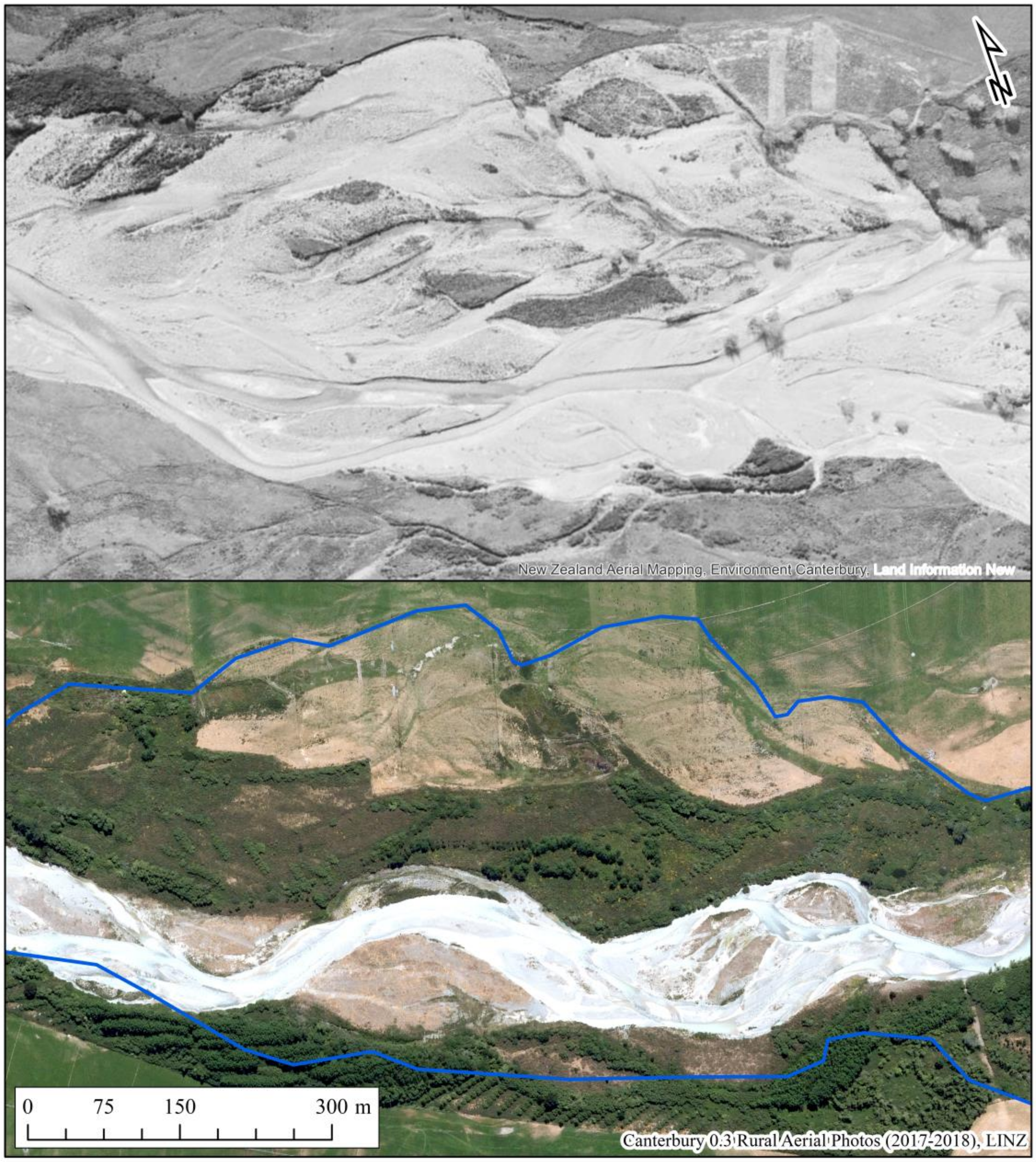

Figure 2.3: Lateral constriction of a braided river. Example from the South Ashburton River. The blue lines represent the extent of the historic active channel area.

The effects of confinement can be measured beyond transitions between one planform type to another. The reduction of braiding complexity can also be measured, even when the channel is still considered braided. Braided river complexity is associated with the number of channels present. Braiding intensity is a term used to describe the complexity of a braided river and is considered a fundamental aspect of the morphology type (Egozi and Ashmore, 2008).

Lateral confinement is known to reduce braiding intensity and braiding processes, and at high relative confinement may result in complete loss of braiding morphology, though an exact relationship is not well known (Garcia Lugo et al., 2015; Stecca et al., 2019). Experiments using physical models have shown that slight changes to the width of confinement can have substantial effects on bar dynamics and river channel pattern (Garcia Lugo et al., 2015; Carbonari et al., 2020). Analyses from these experiments quantitatively identified a smooth transition between single to multi-thread, braided, morphologies. It was concluded in these papers that increasing river width is required to maintain and improve the morphological complexity of river systems (Garcia Lugo et al., 2015). However, these methodologies were model based and only a simplified version of the real-world processes and full-scale rivers, therefore many features are neglected in the analysis (Hicks et al., 2021). The effect of confinement on braiding is also reviewed for full-scale braided rivers (Scorpio et al., 2018; Stecca et al., 2019). In these examples constriction is shown to result in complete braiding loss and transformation to alternate bar (or wandering) morphologies.

For defining the amount of lateral confinement on a braided river channel there is uncertainty regarding how wide a braided river is or needs to be, and the fundamental relationship between width and both the occurrence and intensity of braiding, and transitions to non-braided states. The delineation of the natural extent of braided riverbeds is difficult as they tend to be laterally unstable with poorly defined margins and complex braiding patterns that may flow through only a section of the total braidplain at a given time. In the current literature, a standardized method for defining the lateral extent of braided river channels has not been addressed (Hicks et al., 2021). The uncertainty and variability of the boundaries of these rivers puts them at risk of encroachment into the river by land-use activities such as agriculture as well as confinement to narrower widths. This can lead to increased risks of flooding and associated damage costs for surrounding areas, and long-term loss of braiding (Biron et al., 2014; Stecca et al., 2019). Knowledge of natural braided river extent is critical for analyzing the severity and effect of different levels of confinement on these systems and can aid in resolution of issues around providing room for the river and limiting land-use encroachment.

This thesis looks at the effects of varying levels of lateral constriction on braiding intensity and occurrence from a set of full-scale rivers. The objective is to gain understanding on the control of confinement (or width) on braided morphology which can help with the conservation strategy of room for rivers.

2.3 Defining Threshold Conditions for Braiding

It is accepted by fluvial geomorphologists that natural river patterns form a continuum that is controlled by a variety of complex factors (Ferguson, 1987). Thresholds for channel patterns are based on the ideas that distinct channel pattern types require a range of specific conditions. A large amount of research has been conducted to analyze the threshold conditions of braided river morphology. Stream power defines the capacity of a river to perform geomorphic work as it flows downstream (Charlton, 2008) and is a primary driver of channel pattern type. For rivers without lateral confinement, braiding occurs at higher stream power (total or specific) for a given bed material particle size (Carson, 1984b, c; Ferguson, 1987; van den Berg, 1995; Stecca et al., 2019). As research has progressed over time there has been a shift to an idea of transitional thresholds of morphologic change where change is blurry and more complex instead of a sharp threshold (Carson, 1984b, c; Ferguson, 1987; van den Berg, 1995; Bledsoe and Watson, 2001) partly because visual categorization of river types is imprecise. In some cases, a probabilistic approach, assigning likelihood of braiding is suggested to handle the scatter associated with datasets (Bledsoe and Watson, 2001; Stecca et al., 2019). In all cases, tests of these channel pattern thresholds have typically been done on a limited sample size because of the comparative rarity of braiding and uncertainty in channel pattern classification. Though there is great variation in channel patterns and the variables that control them, predictors such as those based on stream power can be viewed as a starting point for prediction of pattern type (van den Berg, 1995). Application of these predictors then allow anticipation of where braiding might be expected to occur and conditions and changes that might force transitions in channel pattern.

In cases in which channel pattern changes occur because of lateral constriction, rather than changes in, for example, stream power or sediment supply, alternative approaches to predicting pattern change are needed. A common approach is based on the role of channel width or width-depth ratio. This is tied to predictions of cross-section geometry and of ‘bar mode’ – the number of bars that develop across the channel for given cross-section dimensions (Fredsøe, 1978, Crosato and Mosselman, 2009; Millar, 2012; Scorpio et al., 2018; Stecca et al., 2019). Case studies of channel change (Scorpio et al., 2018; Stecca et al., 2019) and laboratory experiments (Garcia Lugo et al., 2015) provide examples of application of this type of threshold for braiding. Assessment of the applicability of these predictors more generally is lacking (Garcia Lugo et al., 2015) including tests on a sample of full-scale braided rivers of varying complexity incorporating natural variability in channel controls. The possibility that width alone (rather than width-depth ratio) might give a simple approximate threshold for braiding, or for different braiding intensity, can also be tested in a sample of full-scale rivers.

A goal of this thesis is to compile a dataset of braiding reaches that can be used to assess some of these braiding pattern predictors and to develop relationships between braiding and channel width as a simple, practical tool for assessment and restoration of channel pattern, and for understanding the geography of the occurrence of braiding for rivers within a region.

2.4 Braided Rivers in New Zealand

The main islands of New Zealand are located at a fault line on the Earth’s surface where the Pacific and Australian plates meet. Large mountain ranges stretch along this boundary. This landscape creates the conditions for high energy rivers, including braiding. Braided, gravel-bed rivers flowing from mountains and highland areas carry large amounts of gravel through the lowland plains and towards the coast. Braided rivers are iconic features of the New Zealand landscape, especially within the laterally unconfined valleys of the low land plains on the South Island. The rivers are highly dynamic, carry large sediment loads, provide suitable ecosystems for many species, and are naturally and culturally significant (Hicks et al., 2021).

There are a diverse set of ways of understanding river systems. In New Zealand and Māori culture, braided rivers are a part of their identity (Brierley et al., 2019). Māori view rivers as living systems and believe in their right to naturally self govern (Brierley et al., 2019). Scientific perspectives from fluvial geomorphologists coupled with Māori beliefs can develop a diverse understanding of river systems that can be upheld in legal circumstances (Brierley et al., 2019). River managers in New Zealand are beginning to adopt these joint ideas and the practice of 'room for rivers' is being explored as an element of this approach (Fuller et al., 2020). This idea requires more knowledge and context related to the historic characteristics of the river systems and controlling factors that influence how and why the systems may have changed over time as human development has expanded.

The impact of the natural and anthropogenic stressors that may affect the New Zealand rivers can alter river morphology through changes in stream flow, sediment supply, and bank resistance, naturally leading to significant environmental and engineering challenges (Hicks et al., 2021). Natural events such as earthquakes, heavy rainfall, and climate change can lead to problems with flooding, aggradation, and erosion (Hicks et al., 2021). These problems can be coupled with anthropogenic stressors such as land cover changes, lateral constriction, irrigation, hydroelectric power generation, gravel mining, and invasive vegetation.

The Canterbury Plains and inland basins on the South Island are flat lands that are suitable for agriculture and have a high concentration of braided rivers of different sizes. Intensification of agriculture and specifically dairy farming in the region threatens the rivers as the practices require large areas and volumes of water. The rise of intense farming developments surrounding these rivers has led to the demand for flat, irrigable land and the consequent artificial confinement and narrowing of river networks. Farmers are putting pressure on braided river systems by encroaching onto the riparian zones and alluvial plains where unknown or unset boundaries lie (Hicks et al., 2021). This removes the river from floodplains reducing the ability of the river to convey flood waters and destroys riparian habitats. Historically, some of the rivers also have been controlled with vegetation plantings and stopbank construction as well as being encroached upon by surrounding agriculture. In addition, irrigation to accommodate increasing water needs by farming activities within the plains greatly reduces the streamflow and amount of sediment transport available to river systems (Hicks et al., 2021). The amount of water available to a river is important to the river's natural cycles. Large flows turn over gravel from the riverbed and transport sediment downstream and may also be a controlling factor on vegetation growth within the riverbeds.

New Zealand, like most countries, has a history of deliberate modification of its river systems. The transformation of braided, gravel-bed rivers into single thread channels through lateral confinement (ex. stopbanks or erosion control riparian planting such as willow trees) has been an engineering practice in New Zealand for a long time, facilitated by the 1941 Soil Conservation and Rivers Control Act, and related engineering practices (Griffiths, 1989; Williams, 2017). Lateral confinement is the 'classic' engineering solution to flooding, the principle being that a confined river would carry water 'more efficiently' (Griffiths, 1989), while also claiming the surrounding land. This solution was based on the application of hydraulic theory where it is expected that confinement will increase shear stress leading to downward degradation therefore improving flood conveyance overall (Hicks et al., 2021). This tactic however has been unsuccessful in many New Zealand cases and has led to even more flood-prone rivers after the confinement was implemented (Hicks et al., 2021). The engineered confinement concentrates the aggradation effects which leads to raised bed levels that can cause increases in flood risk, and such problems may be lessened with their removal (Hicks et al., 2021). This combination of influencers on braided rivers and direct engineering works have led to costly flood damage of surrounding infrastructure, which then creates a feedback of more engineering required to mitigate flooding. As mentioned previously, throughout the world artificially confining rivers leads to a management strategy that requires the continuous and expensive maintenance of the engineered structures, designed to stop the rivers, and surrounding infrastructure (Brierley et al., 2021). Erosion control planting creates a vegetation barrier for erosion and can lock a river in place. In most cases the vegetation used is exotic (non-native) vegetation. This vegetation can become invasive and is seen with wide establishment along the river systems, changing the natural character and dynamics of the rivers (Williams, 2017). A more restorative approach could take the opportunity to reintroduce native species back to riverbanks as well as allowing braiding to re-establish.

Management plans that serve to provide a buffer zone around these rivers are contentious as these areas contain valuable land and, despite such plans being in effect, encroachment into these areas is still observed (Hicks et al., 2021). Due to the active states of braided rivers, the delineation of their natural spatial extent is not exact, and a standard definition of the river corridor is needed to lower potential risk and cost to landowners. The problem of the delineation of river extents is a contentious debate in New Zealand for these reasons and has brought into question the definable banks of the rivers (Hicks et al., 2021). A standard definition of the bed of a river was decided upon by the New Zealand Resource Management Act, however, the definition only works for single thread channels and is still too ambiguous for the ever shifting and dynamic braided rivers (Hicks et al., 2021). In their article, Hicks et al. (2021) identify key morpho-dynamic research challenges using cases from New Zealand. A main research challenge identified in this article is the need to produce a standardized approach to defining braided river extents that is clear, definite, and defendable from a legal standpoint (Hoyle and Bind, 2018; Hicks et al., 2021). The clarification of braided river boundaries may help to retain braided character, though questions remain about the amount of room required for a given amount of braiding. This thesis aims to study this relationship of braiding and braiding intensity with channel width as a fundamental question that may also provide input for braided river delineation deliberations.

Although the New Zealand rivers seem to be on a similar path to other historically braided rivers around the world, it is noted in a paper by a number of braided river researchers that New Zealand still has a chance to change its management practices and restore the rivers (Brierley et al., 2021). The Canterbury braided rivers are therefore internationally significant morphologically and ecologically, as the systems are rare and declining in prevalence. The New Zealand rivers have been well studied over time (e.g. Mosley (1983), Carson (1984a, b), Griffiths (1979), Hicks et al. (2021)) and much can be learned from them by coupling research reports from the past with present and future river changes, and by exploring new research methods and datasets. The specific objectives of this thesis that emerge from previous material in the chapter are detailed below. The results are aimed to address both the specific issues related to the Canterbury region, but also general conditions for braiding as a contribution to fluvial geomorphology more generally.

2.5 Research Objectives and Questions

The effect of lateral encroachment on braided river morphology is the main research interest for this thesis. The Canterbury region of New Zealand provides numerous examples of rivers experiencing and at risk of further encroachment onto their braidplains. The widths of the rivers are known to have reduced over time and, for whatever reason inflicting such change, it has caused a river response. This thesis examines the well-documented cases of Canterbury rivers to explore their changes over time as they responded to lateral confinement. The research studies the entire lengths of the rivers that flow through the Canterbury Plains, unlike previous literature where only select reaches of a river are used. In addition, while most papers discuss the shift of braided rivers to non-braided rather than the response of the river even if it remains braided, the research here also investigates the braided river response, in terms of braiding intensity, even if planform type was unchanged.

Research Objective 1 - Changes to the Canterbury Rivers

Increasing environmental pressures from anthropogenic forces throughout the world have put pressure on braided river systems. The standard management techniques for these systems have involved artificial lateral constriction. These practices lead to the decreased resilience and observable reduction of naturally braided river systems. To properly manage a river an understanding of its behaviour over space and time is key. Braided rivers identified in the Canterbury Plains region of South Island, New Zealand have been subject to drastically changing environmental conditions as the intensification of agriculture spread across the region. An observable change and ‘strangling’ of the rivers has been noted in literature (Brierley et al., 2021; Hicks et al., 2021). The first research objective for this thesis seeks to quantify the change experienced by selected rivers in the region. It is known that even in the more recent past, from the 1990s to present, the rivers have narrowed (Grove et al., 2015), but there is no inventory or quantification of how much the rivers have changed further back in history. Data was collected from a historic and recent period. The historic period dates back to the mid-1900s. This is the earliest period with georeferenced aerial imagery covering the rivers of interest. This historic period aligns closely, in time, with the 1941 Soil Conservation and River Controls Act which began the human intervention on the river channels after many large flooding events in the 1930s (Williams, 2017). Therefore, the study period begins with low levels of artificial confinement on the river systems and ends with the high, present-day confinement conditions. Measurements, such as channel width and braiding intensity, were collected to quantitatively compare changes in channel morphology continuously along the networks.

Research Objective 2 - Relationship of Channel Narrowing and Braiding Loss

The next objective after determining and quantifying how the rivers changed, is to look at how changes in width have affected river morphology, specifically braiding. Channel width is suggested to be a key parameter that controls braided river morphology (Garcia Lugo et al., 2015). When lateral confinement, which controls river width, is increased such that a river narrows it causes a simplification of river morphology. This has been explored in small-scale physical models and braided morphologies are observed to decrease and shift into more simplified states (e.g., braided to single-thread) with increasing constriction. The research proposed here determined if similar effects can be observed for full-scale braided rivers. It is expected that decreasing the lateral extent to which natural braided rivers may flow will lead to morphological simplification over time, similar to previous case study and physical model results (Garcia Lugo et al., 2015; Scorpio et al., 2018; Stecca et al., 2019; Carbonari et al., 2020). The methods aim to develop a better understanding of the natural dynamics and morphology of varying braided river systems as they respond to changes in their watershed, specifically focusing on the influence of artificial lateral constriction.

Measurements of change in channel width and count along with the planform type associated with each value can help to explain the conditions required for such planform types to form, and for braiding, the conditions required for a certain number of channels (or braiding intensity). It is predicted that the complexity of river systems would decrease in line with areas of channel width decrease, but the exact form of this relationship is unknown. The simplification of the rivers under study are expected to be observed at different variations depending upon the system. This may range from extreme responses such as an originally braided system becoming a single channel, or only slight variations in braiding intensity. Establishing these relationships may provide a predictive basis and guidelines for effects of further width reduction or strategies and outcomes for restoring braiding morphology.

Research Objective 3 - Predictability of Braiding Occurrence and Complexity

The dataset collected from the research also provided the opportunity to test braiding threshold theories. Based on the results and variables identified, a final research objective can be addressed which compares the dataset with proposed threshold conditions where morphological change from braided to more simplified morphology occurs. The selected Canterbury rivers provide a wide selection of river cases and were expected to provide enough information to identify any threshold instances where morphological change tended to occur. The data was sorted into three planform types: braiding, single channel and a transitional “wandering” category. Braiding intensity was also measured to quantify complexity changes within that category. This information may aid in the prediction of future channel trajectories. In particular, part of the objective is to establish critical widths that could be used as guidelines for anticipating changes in braiding from proposed confinement or restoration plans.

River channel width is often engineered in flood protection and river restoration projects, therefore threshold widths of constriction where morphological transformation occurs can be used in management solutions. A goal is to then help provide guidelines for conditions in which river systems may retain their natural morphology and set conditions to allow the systems to self-heal as part of more sustainable approaches to fluvial landscape and human interactions. This practice may also reduce the loss of natural braided morphologies being observed throughout the world. Although the study area for this project is New Zealand, this research may be applicable to other braided rivers experiencing the same effects of lateral confinement, ensuring the consideration of local variabilities.

Summary:

The overall goal of this thesis was to quantify the changes in braided river morphology within the Canterbury region related to lateral confinement and to develop a dataset from these rivers that can be applied to general conditions for braiding that will be applicable to other regions. This dataset can be used to analyze braided river response to changes in lateral confinement (or channel width) which can aid in restorative river management solutions by indicating the required width for a given river complexity.

Research Questions

1. How have braided rivers in the Canterbury Plains, South Island, New Zealand changed since the mid-1900s?

2. How does braided river morphology respond to channel narrowing over time?

3. Is there a predictability to braided river changes and does it fit with existing channel pattern theory, and can this be expanded to include variation within braiding rivers rather than simple thresholds between braiding and other pattern types?

In the following Chapter, the selected rivers of interest are introduced and research methods to complete the above research objectives are laid out. Chapter 4 presents, both visually and quantitatively, the changes to the rivers and river margins over the study period. Relationships between morphologic characteristics collected and the influence of channel narrowing on river complexity and planform type are studied in Chapter 5. Threshold theories in the literature are also reviewed and tested to see how well they predict river channel patterns based on the rivers of interest (Chapter 5). Chapter 6 provides a discussion of the results in a larger context and presents potential future risks to the Canterbury rivers.

Chapter 3

3 Methods

3.1 Study Area

The Canterbury Plains region of the South Island, New Zealand (Aotearoa) is one where braided river management and definition has become a significant environmental issue and where it is known that rivers have been ‘strangled’ to some extent (Brierley et al., 2021). Details of regional river changes dating back to the mid-1900s at high-resolution scales have never been documented or put into context of braided river sensitivity and ‘behaviour’. The region exhibits a range of channel patterns, making it possible to look at different responses to change. The history and significance of this region was discussed in more detail Section 2.4.

The Canterbury Plains contain the greatest number of braided rivers in the country. The rivers flow from high mountainous areas and foothills, generally eastward through alluvial, lowland plains, and towards the Pacific Ocean. The rivers are gravel-bed and have an abundant sediment supply from the mountains composed mainly of low metamorphic grade greywacke (Browne, 2004; Hicks et al., 2021; a geological map of region in Appendix A, Figure A.1). The lowland plains and inland basins were the areas of interest and a total of nine rivers that flow through these regions were studied (Figure 3.1, Table 3.1, individual topographic maps of each river in Appendix A, Figures A.2-10). Along the plains, there is little topographic variation and the rivers have relatively steep and constant gradients with no concavity at the downstream ends, atypical of most rivers (elevation profiles for each river in Appendix A, Figures A.11-19). The discharge and sediment size along most rivers are also relatively constant along the study segments, maintaining similar channel patterns all the way down the channels.

The Canterbury Plains has a concentration and intensification of agricultural practices putting pressure on braided river systems beyond the focused issue of lateral confinement for this thesis. Most irrigable land is located in the Canterbury region, and most is used for dairy farming (Irrigation New Zealand, n.d.). As a relatively dry region, the success of these practices relies on water extraction from rivers and groundwater (irrigated area map in Appendix A, Figure A.20). Agriculture surrounds the rivers on all sides and all rivers (excluding any evidence for the Eyre) have had their water abstracted to sustain these practices as well as some for hydroelectric power generation (Ministry of the Environment, 2004; Morgan et al., 2002). Water is allowed to be taken above the “minimum” flow (calculated by month based on streamflow records from gauging sites) for most rivers (Morgan et al., 2002). In addition, gravel is extracted from the rivers of interest for flood protection or for use as aggregate also leading to significant effects on the river morphology (CRC, n.d.b; Hudson, 2005a, b).

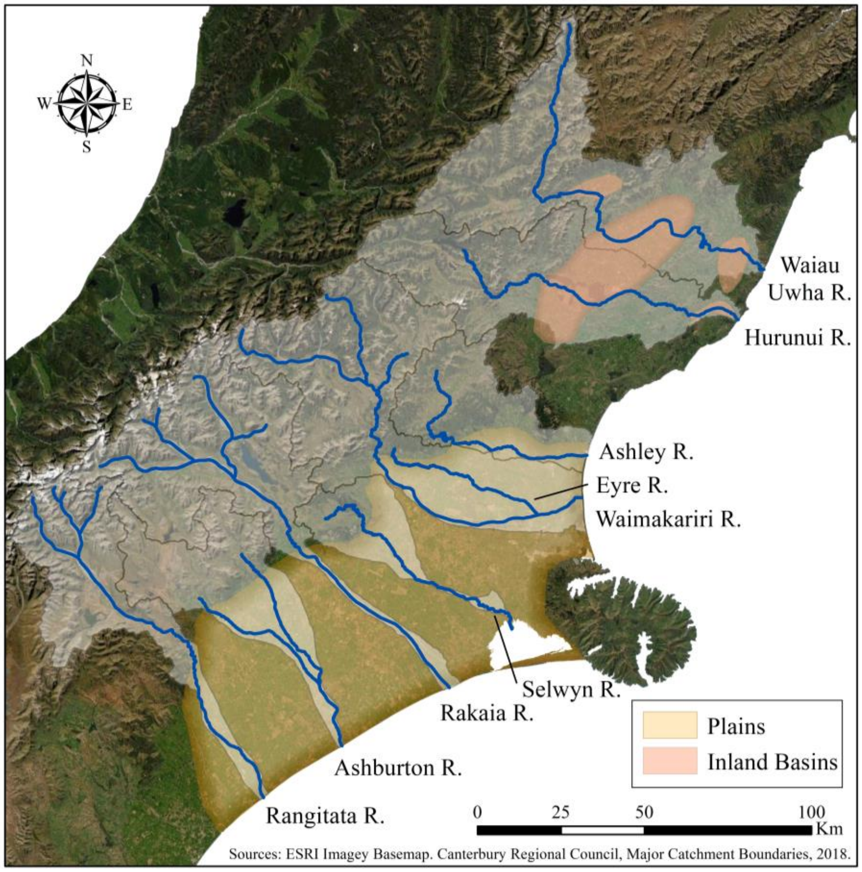

Figure 3.1: Study Area.

Three of the largest rivers of interest include the Waimakariri, Rakaia, and Rangitata. These rivers flow from partially glaciated mountains high in the Southern Alps, through narrow canyon sections, and then widen out through the Canterbury Plains towards the

Pacific Ocean. In the mountainous region, the rivers have wide, braided planforms, then through the hard confining canyon sections the rivers are confined to a single channel, and finally as the rivers emerge to the plains, the rivers widen, and revert to braided planforms. The Waiau Uwha and Hurunui rivers are also larger rivers that originate further north in the Southern Alps. This geographic difference has these rivers flowing through significantly different topographies, as instead of flowing from the mountains through the flat plains directly to the oceans, these rivers flow through wide inland basins spaced out between long narrow canyon sections. The large canyon or gorge sections confine the rivers into single channels between the rock walls and the large inland basins allow the rivers to expand to braided planforms. The rivers flowing from the Southern Alps are the largest of the rivers studied and tend to have higher flows (Tonkin and Taylor Ltd, 2022). The rivers are both rain-fed and snow-fed and peak flows occur late spring, early summer during snowmelt from upstream glaciers (Glova et al., 1985; Reinfelds and Nanson, 1993; Mosley, 2002; Booker and Snelder, 2022; Tonkin and Taylor Ltd, 2022). The rivers experience seasonal low flows, but heavy rainfall events throughout the year can trigger high flows and flooding (Griffiths, 1979; Glova et al., 1985; Booker and Snelder, 2022). The steep gradient of the rivers coupled with high flows can move significant sediment loads (Williams, 2017). For the Hurunui River, river flow is moderated by Lake Sumner (a headwater lake) which leads to less frequent flooding compared to the other rivers originating in Southern Alps, and low flow events are less common (Glova et al., 1985; Mosley, 1983).

The remaining rivers originate from the foothills of the Southern Alps. These include the Ashley (Rakahuri), Ashburton (Hakatere), Selwyn (Waikirikiri), and Eyre rivers. Historically, these rivers have been braided along most or some of their channels but the river management and change in landuse around these rivers have caused a significant portion of the braiding planforms to transition into simpler states. The Selwyn (Waikirikiri) and Eyre rivers are the smallest rivers of interest, ephemeral, and the only ones that do not empty directly into the Pacific Ocean. The mouth of the Selwyn is located at Lake Ellesmere (Te Waihora), a coastal lagoon, and the Eyre River is the main downstream tributary of the Waimakariri River which it joins approximately 15km from the coast. The flow regimes for these foothill origin rivers tend to be lower than the larger mountainous rivers. Flows are seasonal with peak flows during winter and spring and low flows over the summer (Mosley, 1983; Tonkin and Taylor Ltd, 2022). Rainfall events during the course of the year can also trigger high flows in these rivers (Booker and Snelder, 2022). The Selwyn River flows for short periods of the year typically after rainfall events along its network (McKerchar and Schmidt, 2007).

In summary, this area was selected as it contains a numerous range of braided rivers that have been subjected to direct encroachment and confinement of their channels. The area has also been well monitored over time through mapping and aerial imagery as well as stream gauging measurements. The rivers of interest have a range of character, morphology, and scale, providing a variety of aspects to study and compare including the effects of size on channel pattern and transitions, and sensitivity of different river patterns. This sample of rivers was used to address the research questions in a region where they are significant and contentious and require some background understanding.

Table 3.1: General Characteristics of the Rivers of Interest.

River	Catchment Area (km^2)	Approx. Total Length (km)	Study Segment Length (km)	Mean Annual Flood (m^3/s)
Waimakariri	3,592	155	85	At Old Highway Bridge: 1408
Waiau Uwha	3,322	166	92	At Marble Point: 1020 At Mouth: 1100
Rakaia	2,840	142	66	At Fighting Hill: 2520
Hurunui	2,674	111	77	At Esk Head: 226 At SH1: 780
Rangitata	1,779	129	45	At Klondyke: 1230
Ashburton	1,678	120	106.5	North Ashburton at Old Weir: 120 South Ashburton at Mount Somers: 95 At SH1: 350
Ashley	1,288	88	33	At Gorge: 280 At Rangiora Traffic Bridge: 550
Selwyn	769	90	71.75	At Coes Ford: 130
Eyre	409	58	54	At Trigpole Road: 15

*Refer to Appendix A - Figures A.2-10 for stream gauge locations listed in Mean Annual Flood column for each river. Mean annual flood data obtained from Canterbury Regional Council (2022).

3.2 Data Collection

A variety of datasets are required to study the river systems in terms of the research objectives (Table 3.2). To begin, the primary source of information comes from historical (mid-1900s) and recent (2012-2018) collections of aerial imagery. These were used to identify and digitize active channel polygons which provide width measurements at specified segments along the rivers of interest. In addition, visual assessments from the high-resolution aerial images of the channels and surrounding areas were done including categorization of confinement type and channel planforms and determination of the number of channels at specified segments along each river. The historic and recent measurements were compared to assess the changes in the river systems over time, specifically looking at width, confinement and planform type, and braiding intensity. Topographic information was used to determine characteristics along each of the rivers. Digital Elevation Models (DEMs) provided catchment area, channel gradient, and cross-section geometry information, although only available for recent periods. Streamflow estimations along the rivers for the recent period were also collected to compare the effects of this primary control on river channels. Various other shapefiles were collected to observe local characteristics of each river, these include vegetation types and flood protection boundaries.

Table 3.2: Data Summary and Purpose.

Variable	Purpose	Period of Availability	Data Type
Active Channel Width	Define the change in width along each river and relate to channel planform change.	Historic and Recent	Aerial Imagery
Confinement Type	Determine a categorical level of confinement to help understand change.	Historic and Recent	Aerial Imagery
Channel Planform Type	Determine the channel planform category to group other variables.	Historic and Recent	Aerial Imagery
Channel Count/ Braiding Intensity	Determine the complexity of rivers and relate to channel planform change.	Historic and Recent	Aerial Imagery
Channel Elevation/ Slope	Background information, stream power calculation.	Recent only	Digital Elevation Model
Depth	Hydraulic geometry analysis and comparison with published datasets.	Recent only	Digital Elevation Model
Catchment Area	Background information.	Recent only	Digital Elevation Model

Discharge	Background information, stream power calculation, and comparison with published datasets and thresholds.	Historic and Recent	Spreadsheet
REC Stream	To align discharge estimates to segments along new centreline shapefiles.	Recent only	Polyline Shapefile
Stream Gauge Sites	Background information.	Historic and Recent	Point Shapefile
Sediment Size	Comparison with published datasets and thresholds.	Recent only	Spreadsheet
Stopbank and Vegetation Boundaries	Background information.	Recent only	Polyline Shapefile
Vegetation Type	Background information.	Recent only	Polygon Shapefile
Irrigated Areas	Background information.	Recent only	Polygon Shapefile
Property and Topographic Maps	Reference for historic river widths.	Historic and Recent	Scanned and Georeferenced Digital Maps

3.2.1 Map and Imagery Data

Historical maps and aerial imagery are a useful tool frequently used by fluvial geomorphologists for visualizing the past extent of rivers and the development around them (Grabowski and Gurnell, 2016). MapsPast (http://www.mapspast.org.nz/) provides open-source historical topographic maps of New Zealand available at decadal intervals dating back to 1899. The historical map collection was scanned and georeferenced by Auckland University and MapsPast. The coverage is national with local areas of no-data availability that vary over the available time periods. The maps provide an idea of where the rivers may have flowed historically, however the accuracy of these maps vary depending upon the year, type of map, and sources available for mapping river extents.

For example, the oldest maps available are property maps where the natural river extents were not the purpose of the map and in this example the mapped river extents were smaller than measurements from the later aerial imagery. It is important to understand the nature of the source information and purpose of the map (Grabowski and Gurnell, 2016). In later topographic maps the actual extent of the river is likely to be more reliable and approaching the 1930s/1940s the maps can be directly compared with historical aerial imagery and the river extents line up well between the maps and aerial photographs. It is likely that the maps were drawn based on the imagery. Overall, there are limits to how far back the rivers can be analyzed. The historical maps may add to the story of these rivers by showing when major changes may have occurred, but the maps are not sufficiently reliable for quantitative measurements of river change intended for the thesis. Therefore, the main focus was on changes between the mid-1900s and present because that is the best that can be done reliably.

National historic aerial imagery of New Zealand is stored in the Crown Aerial Film Archive (LINZ, 2020). Canterbury Maps (https://canterburymaps.govt.nz/), an online open data source for the Canterbury region, provides collections of this historical data. The individual historical images are georeferenced and sorted into periods based on the dates of photo acquisition, the periods are separated at 5-year intervals beginning in 1925. The spatial coverage for each period varies, therefore a selection of imagery periods was used to study the historic region of interest (Figure 3.2a). The earliest imagery available for this area is from 1935-1939 and continues at 5-year intervals until 1959 (a total of five periods over 25 years). The imagery in each period tends to be clustered into large areas, and some rivers of interest are completely covered by one period while others require up to three (e.g., Rakaia). The photographs are panchromatic (i.e., black and white). They were taken by a variety of cameras (LINZ, 2020) and the scale of each photo varies depending on the individual image and date of acquisition but is within the range of approximately 1:10,000 to 1:20,000 which is equivalent to about 250 to 500m per inch (Retrolens, 2020). Image quality may vary between individual images. The resolution of the aerial imagery is stated as either 14 or 21 microns for each scanned photograph (LINZ, 2020). This translates to pixel sizes ranging from 0.15 to 0.25m on the ground.

The spatial accuracy of the georeferenced and mosaiced imagery from Canterbury Maps is unknown as the collections used are part of an early release that is still being updated and added to. An auditing process and accuracy assessment has not yet been completed by Canterbury Maps, and to provide error statistics on this dataset without knowledge of ground control points and images georeferenced within the study area is infeasible for a true assurance of geometric accuracy. Through manual comparison of major topographic features between the historic and orthorectified imagery, the accuracy is relatively good for the purposes of active channel estimation. The use of the historic photographs remain cautionary as the precision of georeferenced mosaics may differ from the measured high accuracy and resolution products available today.

Recent orthoimagery is available from LINZ Data Service (https://data.linz.govt.nz/) as open-source data. Single periods of orthoimagery cover total lengths of each river over a time range from 2012 to 2018 (Figure 3.2b). Table 3.3 displays the data specifications for each dataset.

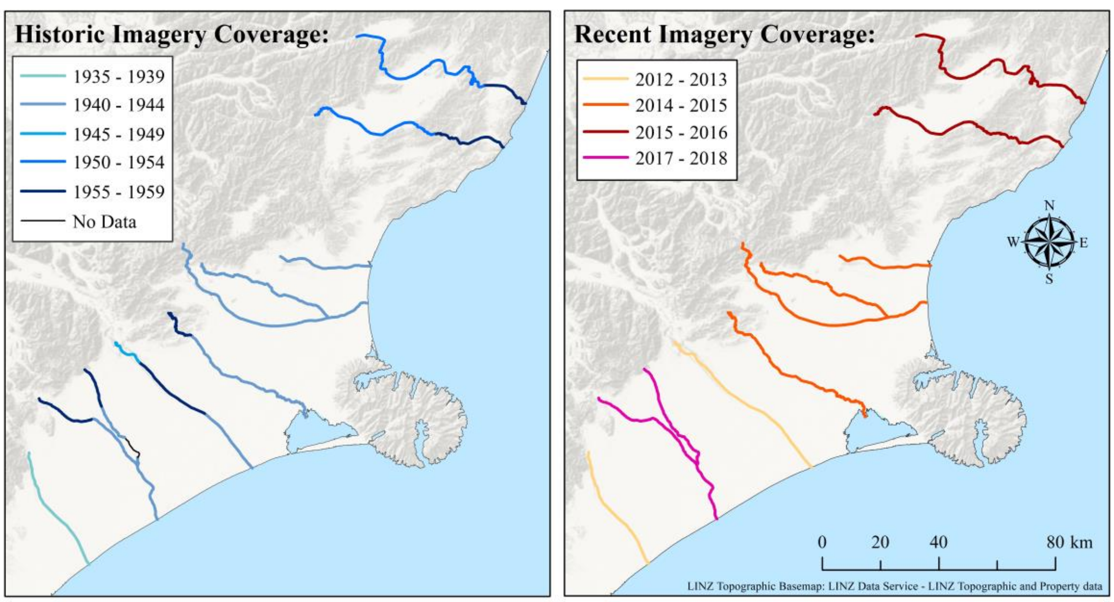

Figure 3.2: Historic and recent imagery coverage. Coverage is shown for the study segments only. The historic coverage varies along some rivers, while the recent coverage is constant along rivers. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

Table 3.3: Recent orthoimagery data specifications.

Survey Period	**2012-2013**	**2014-2015**	**2015-2016**	**2017-2018**
Spatial Resolution	0.4m	0.3m	0.3m	0.3m
Spatial Accuracy	+/-0.6m	+/-0.6m	+/-2m	+/-2m
Spectral Bands	3-band (RGB)	3-band (RGB)	3-band (RGB)	3-band (RGB)

3.2.2 Topographic Data

Digital Elevation Models:

Topographic data for the Canterbury region of New Zealand was collected from the LINZ Data Service (https://data.linz.govt.nz/). Multiple 1m spatial resolution DEMs created from LiDAR data are available throughout local areas in the region of interest at various time periods (Figure 3.3). All the data was prepared with the New Zealand Vertical Datum 2016 (NZVD2016) and had ±1m horizontally and ±0.2m vertically accuracies. Although, not continuous in coverage, the 1m LiDAR DEMs provide high resolution topographic information that transitioned smoothly between local areas of coverage. The data was used to determine elevation changes along the rivers and depict channels and channel depths at select cross-sections. A national 8m spatial resolution DEM was available to fill in the gaps of the LiDAR DEMs. This DEM was derived from the LINZ Topo50 20m contour data and had significantly lower accuracy than the LiDAR DEMs (LINZ, 2016). The horizontal and vertical accuracy of the national 8m DEM was ±22m and ±10m, respectively.

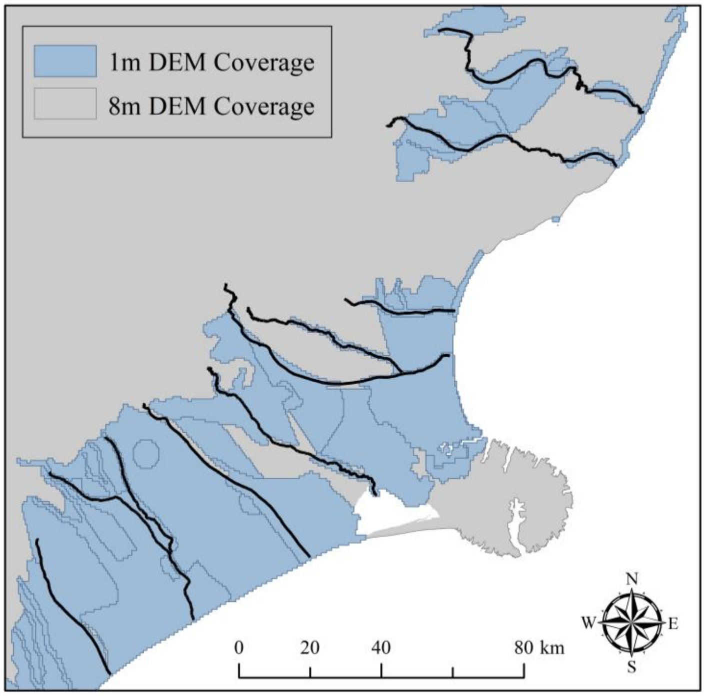

Figure 3.3: 1m and 8m DEM coverage. Data sources are listed in References under 'Data Sources – DEM'.

River Catchment Shapefile:

The Canterbury Regional Council (CRC), or Canterbury Maps (https://canterburymaps.govt.nz/), provides a shapefile of the major river catchment boundaries for the Canterbury region (CRC, 2018). All river catchment boundaries were available, except for the Eyre River catchment which was incorporated into the total Waimakariri River catchment. The Eyre River catchment and upstream catchment areas at equal intervals along the rivers were calculated separately (Chapter 3.8.3).

3.2.3 Flood Flow Data

Flow, and particularly peak flow, is a primary control of river dynamics and provides important information regarding the amount of energy required to trigger morphologic change. Historic measurements of peak flow data could not be found for the rivers of interest. Mean daily discharge measurements since the late 1960s to present however were available and provided by Environment Canterbury (or the Canterbury Regional

Council (CRC)) and the National Institute of Water and Atmospheric Research (NIWA). The NIWA New Zealand River Flood Statistics web app (https://niwa.maps.arcgis.com/home/index.html) provides estimates of flood flow values along each of the rivers of interest. The estimations are derived from a model created by Henderson and Collins (2016) that incorporates stream gauge measurements, upstream catchment area, and regional annual precipitation based on data exclusively from New Zealand, South Island (Henderson et al., 2018). The output results are estimations of mean annual flood flow values, and this model was furthered by the researchers to predict 5, 10, 20, 50, 100, and 1000-year return period flow values based on a regional growth curve (Henderson et al., 2018).

The standard error estimated for the mean annual flood values is projected at ±50%. A high level of error likely rooted in the lack of gauging station flow records and broad estimations across large areas. The estimates are calibrated to gauge flow records, so if there is only one or no gauging station, estimations are expected to have greater uncertainty. The Rakaia River is an example from the rivers of interest with only one gauging station located along the entire river network. Estimates at the Fighting Hill site differ from 2,520m^3s^{-1} mean annual flood from gauge data to 1,335m^3s^{-1} from the statistical model at the same location, and therefore may not be as reliable as one would like.

The data is presented in alignment with the River Environment Classification (REC) v.1 spatial model. The REC is a shapefile that contains all of New Zealand's river networks. The networks are segmented, and each segment contains physical characteristics (such as climate, geology, land cover, and catchment area) relative to each location (Snelder et al., 2010). The REC river network was derived from a DEM and manually corrected (Snelder et al., 2010), therefore the segments of the network had to be connected to the average centrelines created in this thesis for the rivers of interest due to differences in river line positions and segment lengths. This was completed by aligning the REC segments to the closest segment for each of the rivers of interest, then the segment lengths were manually adjusted to match the distances for both datasets. For example, the segment length from REC v.1 were irregular in terms of length and some may have been multiple kilometers long, which would be more than one of the segments for the constant segment study centrelines created in this project (discussed in Chapter 3.4). The final output is the discharge estimation datasets (including mean annual flood up to the 1,000-year return flood interval) along each segment of the rivers of interest based on the flow estimation data.

3.3 Active Channel Digitization

The aerial imagery acquired for the study area was used to delineate the active river channels for each river of interest. The active river channel is defined as an area with a wetted and/or recently mobile bed (bare gravel and under-developed vegetation) and is only a portion of the wider braidplain. Following the definition by Hoyle and Bind (2018) for braided rivers in this region, the active river channel was characterized by exposed gravel and connected wetted channels, however, due to the unknown and lack of consistent dates of data collection, a modification to this definition was made such that dry connected channels were included in the active channel area. The size and position of the active channel area, and wetted channel, varies over time and this modification aims to help compensate for differences related to variations in flow stage at time of image acquisition. ESRI ArcGIS software was used to outline the active channel areas. Initially, a method of supervised classification for the higher resolution, recent, imagery was proposed, however, due to the unknown period of image capture, seasonal variations affecting flows and vegetation growth could not be taken into account automatically. In addition, the tested results were too heterogeneous to produce reliable active channel outputs at a more efficient rate than manual interpretations and digitization of the channels. Therefore, a method of manual, visual interpretation of the active channel boundaries was used. Digitization was completed at imagery scales ranging between 1:4,000 to 1:10,000, and zooming in further when needed for unclear margins. Scale tended to rely upon size of the channel and visibility of channel banks. The larger rivers were the only ones digitized at the smallest scale. The areas were digitized at this scale for a compromise between both high accuracy and quicker completion, as digitizing at larger scales would take significantly longer. Figure 3.4 shows three samples of reaches with defined active channels from recent imagery (the historic boundary is also provided for reference). The completed digitization process resulted in active channel polygon shapefiles for both recent and historic time periods for each river.

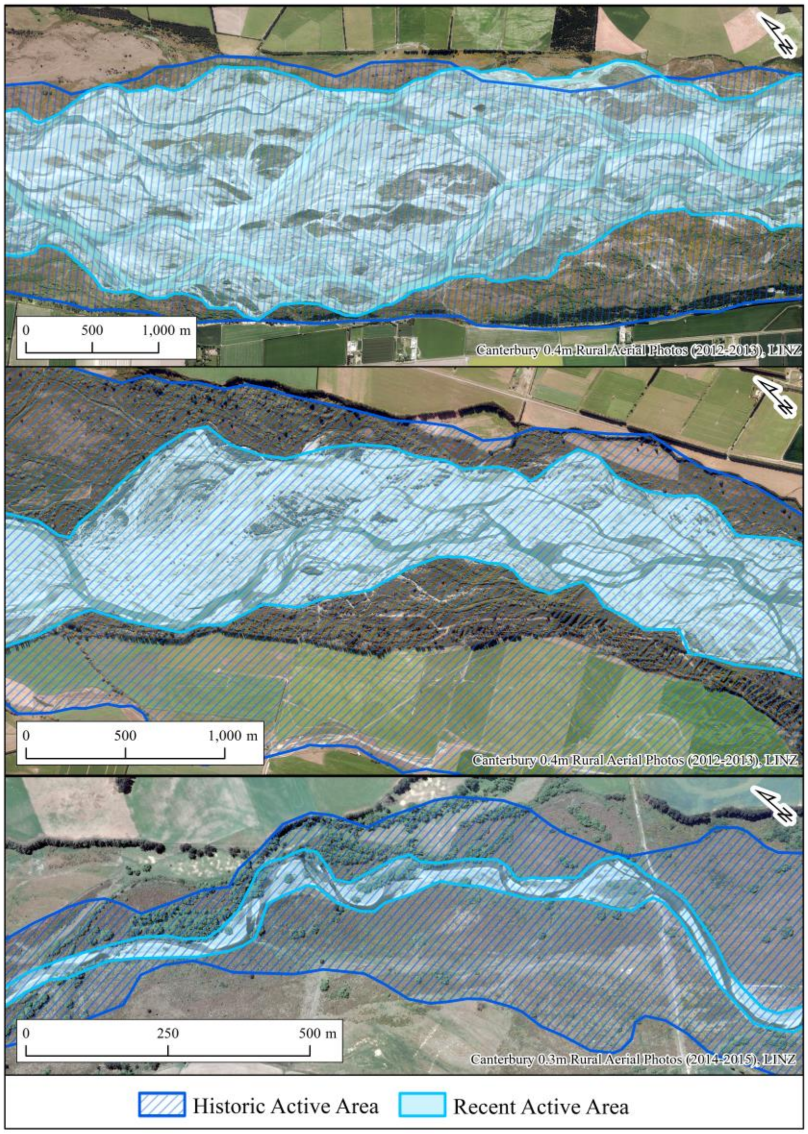

Figure 3.4: Sample active channel digitization. Top: Rakaia River, 1955-59 historic outline and 2012-13 outline and imagery (at 1:30,000 scale), Middle: Rangitata River, 1935-39 historic outline and 2012-13 outline and imagery (at 1:20,000 scale), Bottom: Selwyn River, 1940-44 historic outline and 2014-15 outline and imagery (at 1:7,000 scale). Historic outlines shown as reference for channel changes and evidence of accuracy of digitization along locations of constant topography. Data sources are listed in References under 'Data Sources – Imagery'.

An accuracy analysis was conducted for the active channel identification by comparing cross-section widths. As the methodology required a manual approach, error of consistency and identification of boundary digitization due to poorly defined banks are noted problems (Reinfelds and Nanson, 1993; Holye and Bind, 2018). The assessment was completed by randomly selecting 20 cross sections along each of the river networks, splitting the selections between the historic and recent imagery (total of 180 test sites). At cross-section sites, the active width was measured at a scale of 1:1,000 or larger, then compared with the cross-section width ending at the margins from the active channel polygon. Widths tended to be slightly overestimated in both periods and error was higher for the historic digitization (Table 3.4). Differences of cross-section measurements, averaged by percent difference from each cross-section, were about 2.7% (or 11m) in total, 3.8% (or 17m) historically, and 1.6% (or 7m) recently. Average errors for the historic period rivers range from 6 to 30m and 2 to 10m in the recent period. The historic measurements had slightly higher levels of error likely due to the inferior image quality. Larger rivers also had higher recorded errors, likely due to the tendency of digitization at smaller scales. The errors also reflect the unknown accuracy of the historic aerial imagery mosaics and may have been lowered with more cross-section samples. Overall, the accuracy results show acceptable ranges of error for the purposes of this project where changes are occurring at much greater levels (Surian et al., 2009; Grabowski and Gurnell, 2016).

Table 3.4: Root mean square error of active width measurements (in metres).

River	Historic	Recent
Waimakariri	29.6	10.4
Waiau Uwha	21.9	4.6
Rakaia	26.5	9.4
Rangitata	12.7	10.3
Hurunui	12.0	2.3
Ashley	11.8	4.7
Ashburton	6.2	4.6
Selwyn	8.8	3.0
Eyre	6.0	1.9
Total	**17.2**	**6.5**

3.4 Active Width Calculation

The active width of the rivers was determined using the active channel polygons and corresponding channel centrelines. To create the centreline of the active areas for each river, a polyline was created and drawn through the centre of the active channel area polygon of each river. This was completed for both the historic and recent polygons as in some reaches the river changed positions over time. In order to have channel characteristics recorded at constant segments along the rivers for both historic and recent time periods, an average centreline was created based on the average position of the two river centrelines. In most cases, the centrelines for both periods follow the same path due to minimal changes in planform or sinuosity. The river centrelines were then segmented into constant lengths based on the average estimated width for each river (either 250m, 500m, or 1,000m). For analyses, the rivers were separated based on general groupings of similar width ranges. The Waimakariri, Waiau Uwha, Rakaia, and Rangitata rivers have the largest ranges of width values with active widths reaching multiple kilometers wide. These rivers were therefore placed in the 'large' scale category (1,000m segments). Next, the Ashley and Hurunui rivers have active widths averaging well below one kilometer but maximum values exceeding that limit, and these rivers were given a 'medium' scale category (500m segments). Finally, the Ashburton, Selwyn, and Eyre rivers showed the smallest width values, with only the Ashburton containing peak values over 500m (and only in the historic period), and consequently these rivers were categorized as the 'small' scale rivers (250m segments). Once the average centreline for each river was segmented by defined lengths, the active channel polygons were clipped to match the distance between average centreline segments. Therefore, creating polygon areas at equal intervals along the river.

Width values were calculated by dividing channel segment area by centreline length. The historic and recent centreline lengths were used in the calculations (i.e., not the average centreline length) and therefore were greater or less than the average segment length in some cases.

3.5 Confinement Identification

The change in the amount of room for lateral mobility and development affects river morphology. Confining margins such as hard valley walls, dense vegetation, or stopbanks can dictate lateral mobility and direct where a river flows. Confining margins may constrict rivers, interfering with morphology and causing energy loss due to resistance. Confinement type also depends upon the channel planform and whether the channels reach a confining margin (Brierley and Fryirs, 2005). Three types of channel confinement were used to characterize the channels along each river and assess change over time. These categories include ‘confined’, ‘partly confined’, and ‘laterally unconfined’ (recall Section 2.2; Figure 3.5). The rivers were categorized by these three types of confinement visually along every segment of the river where the historic and recent imagery was available.

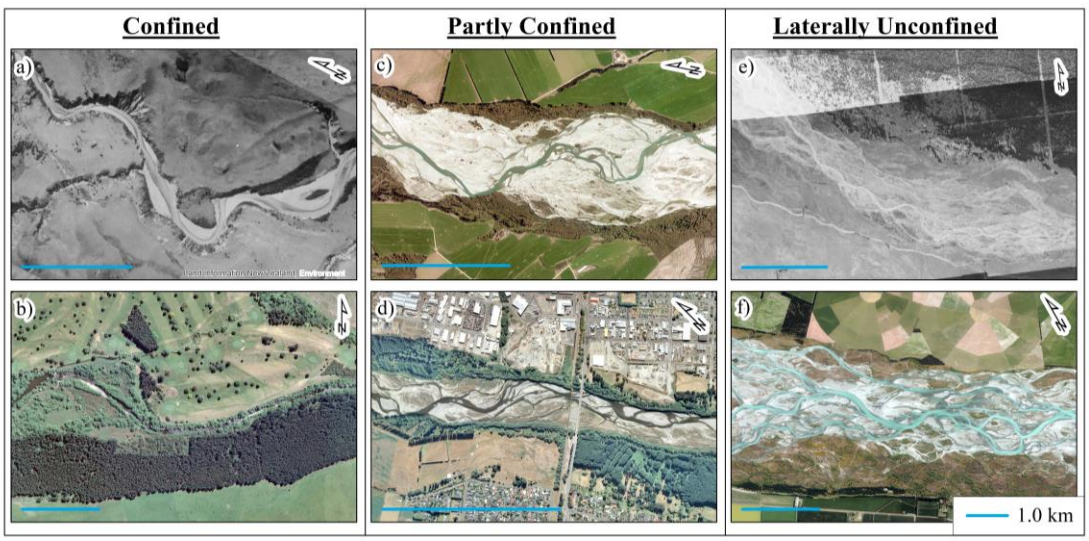

Figure 3.5: Confinement types. Example reaches of defined confinement types; confined, partly confined, and laterally unconfined. a) Confined – canyon example (Waimakariri River). b) Confined – vegetation example (Selwyn River). c) Partly Confined – vegetation example (Rangitata River). d) Partly Confined – stopbank and vegetation example (Ashburton River). e) Laterally Unconfined (Hurunui River). f) Laterally Unconfined (Rakaia River). The blue bar represents 1.0km. Data sources are listed in References under ‘Data Sources – Imagery’.

3.6 Channel Pattern Identification

River channel pattern can vary along river networks. Three general channel pattern categories (single channel, wandering, and braided) were used to characterize the river segments. The categories are sufficient to capture obvious transitions in channel pattern over time, and braiding intensity (or channel count, Section 3.7) will also monitor changes within the braided category. The single channel (Figure 3.6a) category includes dominantly confined, sinuous, or meandering channels that contain only one flowing channel. Next, New Zealand's rivers have been identified as having neither meandering nor braided patterns, but a transitional category, characterized in similar ways, referred to as pseudo-meandering or wandering (Carson, 1984a; Carson and Griffiths, 1987; Desloges and Church, 1989; Burge, 2005; Gurnell et al., 2009; Ashmore, 2022). This category, wandering (Figure 3.6b), is laterally active and has multiple channels that may split around in-channel islands and irregularly meander with some characteristics of braided morphology. Wandering channels were defined also by the number of channels and typically characterized by having 3 channels or less. The braided (Figure 3.6c) category includes channels with 3 or more channels. An overlap between wandering and braided channels based on channel count was possible and classification was dependent on the judgement of the site and its surrounding historic and recent characteristics. Both bar-braided (highly dynamic) and island-braided (more stable) planforms are included under the braided category; a general braided category was selected since the time of year and time since last large flood is unknown for the historical data (Belletti et al., 2015). The occurrence of transitions from braided to wandering (to single channel) and vice versa may lead to some uncertainty related to these classifications due to morphologic similarities during transitional stages.

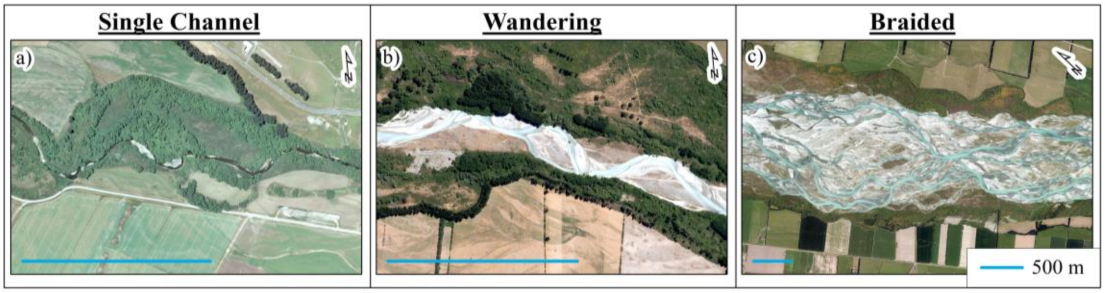

Figure 3.6: Channel planform types. Example reaches of defined channel patterns; single channel, wandering, and braided. a) Single Channel (Selwyn River). b) Wandering (Ashburton River). c) Braided (Rakaia River). The blue bar represents 500m. Data sources are listed in References under 'Data Sources – Imagery'.

3.7 Channel Count (Braiding Index)

The complexity of braided channels changes with factors that include flow regulation, stream power, bed material particle size and abundance, and lateral confinement. The complexity of a braided river pattern can be identified by a braiding index. There are various approaches used to determine a braiding index. In general, the methods fall into two categories: channel count and total sinuosity index (Ashmore, 2022). The channel count index is taken by averaging the number of channels within a certain reach of a river and the total sinuosity index is the measurement of the total length of channels within a given reach of a river (Egozi and Ashmore, 2008). For this project a channel count index was used. The channel count index is favored over the total sinuosity index as it can be easily measured from aerial imagery and was determined to be less sensitive to flow stage (Egozi and Ashmore, 2008). The spacing of cross-sections for collected channel count data is stated by Egozi and Ashmore (2008) to be best placed no more than the average width of the river apart and at constant intervals. Therefore, cross-sections for the rivers were placed at the beginning of each segment, as each segment is already defined and segmented equally at the approximate average width of the river. Channel counts were made at the beginning of the first channel segment and continued up the network. Braiding index included prominent dry channels (consistent with the definition of active width) in order to avoid the effects of, or dependence on, river stage (Surian, 2006). Channel count is linked to many factors including active channel width and flow, therefore variations in these parameters influence the measured channel counts. A level of error surrounding channel counts may be related to issues regarding flow variations or by how they were defined and other measurement issues. Once completed, a braiding index for both the historic and recent periods of each of the variables was calculated by averaging the cross-section results for every segment. The count value provided for a segment is the calculated average of the count from the downstream to the upstream end of the segment (visualization and sample calculations in Figure 3.7).

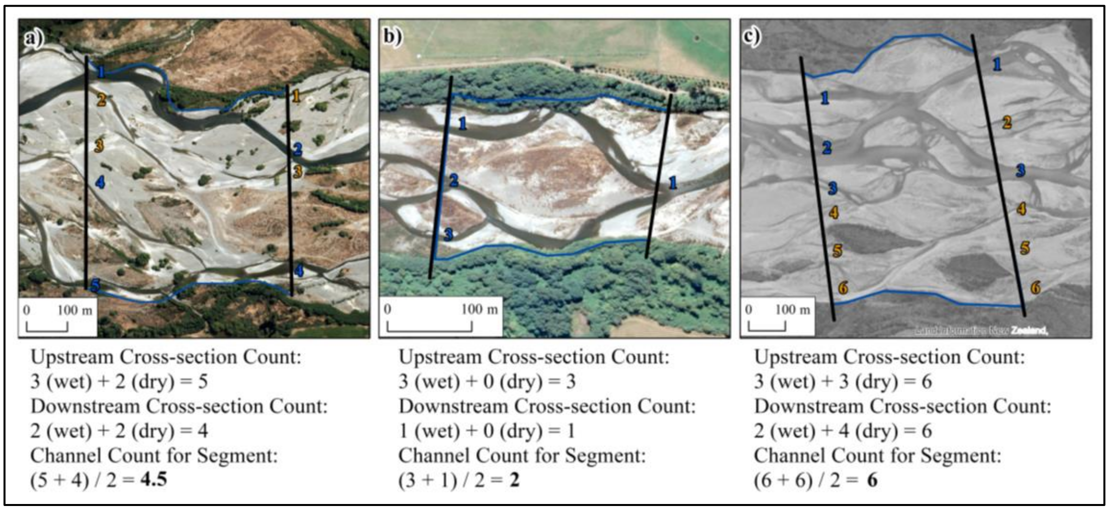

Figure 3.7: Channel count and calculation. Three channel segment examples from (a) Hurunui River (recent imagery), (b) Ashburton River (recent imagery), and (c) Ashley River (historic imagery). Channel counts include both wet (blue) and dry (orange) channels. Flow direction from left to right. Data sources are listed in References under 'Data Sources – Imagery'.

3.8 Topographic Measurements

3.8.1 Slope

Channel slope was calculated based on change in elevation across the digital elevation surface of each river centerline. Historical records of elevation along the total length of the river study segments do not exist. Only the most recent digital elevation models were used for the detailed analysis of the rivers as the models provided precise and high-resolution data. Elevation values were derived from the 1m LiDAR DEMs which only have partial coverage, therefore, some portions of river segments are omitted (recall Figure 3.3). Most of the missing data coverage is over the canyon reaches of the rivers, but some portions along the plains were not covered, most significantly affecting the Rakaia and Selwyn rivers. Although elevation data was only available in the most recent period, it was assumed that slope remains relatively constant over time for reaches with constant pattern types, and therefore was considered in both the recent and historic river analyses. This assumption is valid because the river segments are shown to remain with similar patterns over time with no major changes in sinuosity. To calculate slope along each river network, elevation values from the DEMs were extracted at the downstream end of each segment. The calculation for slope equals (elevation 2 – elevation 1) / segment length. Where elevation 1 is the downstream elevation value of a segment, elevation 2 is the elevation value at the upstream end of the segment, and segment length is the approximate average width (either 1,000m, 500m, or 250m depending on river scale, recall Section 3.4).

3.8.2 Depth

Digital elevation models were available to collect bankfull channel depth measurements along each river. The detailed 1m LiDAR derived DEMs allowed for accurate (±0.2m vertical error) determination of the channel bar tops and channel depths, although incomplete. The DEMs are hydroflattened for consistent water surface elevations (LINZ, 2021) and include some error regarding actual depth modelling for wetted channels. At the time of LiDAR data collection, low flow conditions are likely and therefore the error for measured bankfull channel depth is assumed to be a minimal underestimation (Mosley, 1983). As the availability of elevation data was not consistent for regular sampling, and due to the large number of possible cross-section measurements, a total of five cross-sections were collected for each planform type (braided, wandering, single channel) recorded along each river. The braided category was also split into three groups: narrow, representing widths less than 500m; wide, representing widths greater than 1km; and medium, representing widths in between. The selected segments were to be representative of the channel planform type for the river and rivers in general. Depth measurements were made in QGIS using the Profile Tool plug-in (Jurgiel et al., 2012).

The number of cross-sections per river was dependent upon the DEM coverage and planform types recorded along the rivers. For example, missing elevation coverage led to no data for certain planform types of a river and less than five cross-sections may have been collected when too few segments of a given planform type were available or present. A total of 97 cross-sections were completed (Table 3.5).

Table 3.5: Number of cross-sections with depth measurements recorded by river.

River	Number of Cross-Sections (B-W, B-M, B-N, W, S)
Waimakariri	B-W: 4, B-M: 5, W: 2
Waiau Uwha	B-W: 4, B-M: 3
Rakaia	B-W: 4, B-M: 1
Rangitata	B-M: 3, B-N: 3, W: 2
Hurunui	B-M: 5, B-N: 5, W: 5, S: 1
Ashley	B-M: 2, B-N: 5, W: 4
Ashburton	B-N: 5, W: 5, S: 5
Selwyn	B-N: 4, W: 5, S: 5
Eyre	W: 5, S: 5
Total	B-W: 12, B-M: 19, B-N: 22, W: 28, S: 16 (Total = 97)

* B-W = Braided-Wide (>1,000m width), B-M = Braided-Medium (500-1,000m width), B-N = Braided-Narrow (<500m width), W = Wandering, S = Single Channel.

At each of the selected cross-section sites, an elevation cross-section was measured and mean bankfull depth values were collected. For consistency at the braided and wandering channel sites, the maximum bar or island height (excluding vegetated islands) was used as the top of the channel, then depth was measured to the lowest elevation of each channel (Figure 3.8). The average depth of channels within a cross-section were determined to calculate the mean depth.

The purpose of the depth measurements was to determine the mean depth of channel planform types for each river covering the full range of river scales. The information was then used to determine width-depth ratios by dividing the cross-section width by the mean depth. Width-depth ratios are often used as a braiding criterion (Section 2.3) and were used to assess the threshold theories for braiding with the rivers of interest.

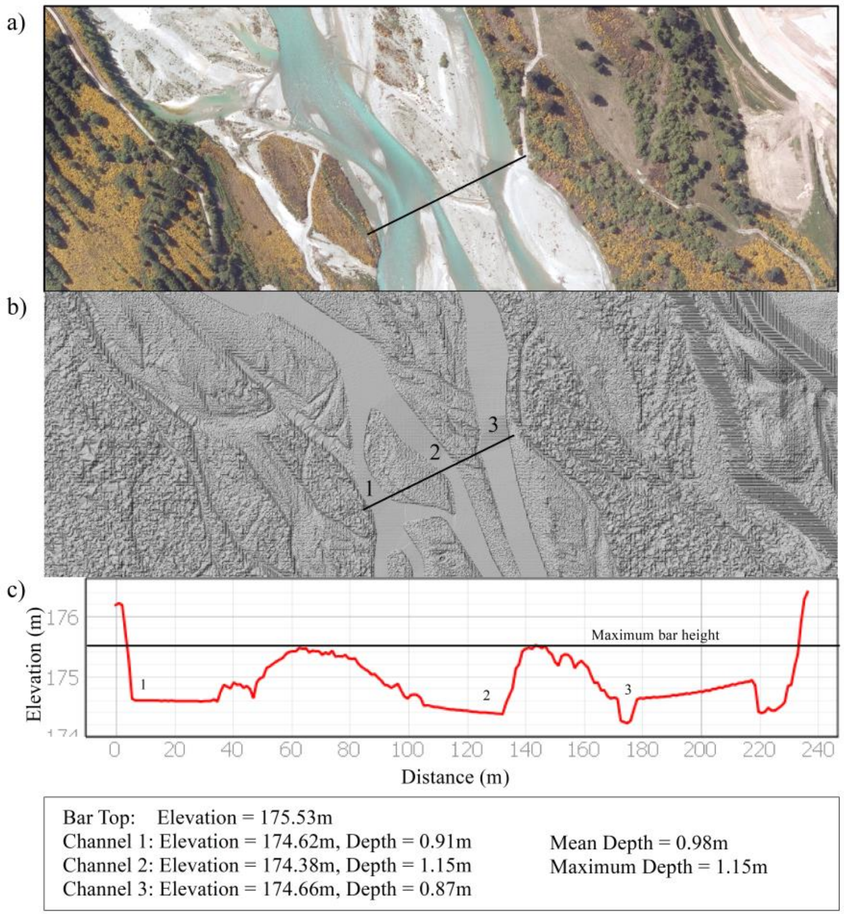

Figure 3.8: Depth measurement and calculations. This cross-section site comes from the Rangitata River. a) Imagery of cross-section site. Note the period of data acquisition for the imagery and DEM vary, hence the variation in channel positions. b) 1m DEM of cross-section site, with channels labelled. c) Elevation profile of cross-section derived from DEM. Measurements of channel depths and calculated mean depth below. Data sources are listed in References under 'Data Sources – Imagery' and 'Data Sources – DEM'.

3.8.3 Catchment Area

The upstream catchment area at each segment along the river networks was calculated for comparison with collected measurements above. Due to the large catchment areas of each river, the 8m national DEM was too large to complete the analysis (due to software crashes), therefore the watershed areas were created using the ArcGIS Online function

‘Create Watershed’. The inputs for this tool were the point files at the downstream end of each reach, and the tool uses an existing 90m worldwide DEM to calculate catchment areas (ESRI, n.d.). This resolution allowed for a fast and capable run time at the cost of a decreased data quality. The CRC catchment boundaries were used for reference to compare the same boundaries derived from the DEM (Section 3.2.2). The catchment areas calculated from the 90m DEM matched well for the upstream catchment areas, however, downstream, in the low-land plains, areas tended to be over-estimated compared to the boundaries defined by the CRC. In cases where boundaries differed, alterations were made to match the CRC boundaries.

3.9 Summary

Over 1,000 river segments were created along the rivers of interest creating a large dataset for the analysis of the effect of lateral confinement on river morphologies. Each segment contains historic and recent recordings of active width, channel count, confinement type, and planform type based on aerial imagery, though some segments were omitted due to gaps in data coverage or dry reaches. Discharge, elevation (recorded from the downstream end of each segment), slope, upstream catchment area, and depth also add to the dataset for the recent period along select segments of each river where the data was available. Overall, the methods described above were used to collect an extensive dataset on Canterbury’s gravel-bed braided rivers that cover a range of scales and braiding morphologies. The dataset was analyzed to show the changes in river morphologies over time, the relationships between collected variables, and the predictability of channel patterns.

Chapter 4

4 History of Channel Change

The measurements and interpretations from the historic and recent imagery described in Chapter 3 will be presented in this chapter. The chapter will focus on the overall changes in river morphology and the geography of changes, followed by an individual analysis of change for each river. The data is often grouped into three categories of scale (large, medium, and small) based on active channel widths and catchment size (recall Section 3.4). Some of the rivers also flow through sections of canyon; these reaches are not included in analyses and no change is assumed. Outcomes of this chapter will begin to answer the first research question: How have the rivers in the Canterbury Plains, New Zealand changed over time?

4.1 Active Channel Width

Active channel widths were measured for the selected historic (mid-1900s) and recent (2010s) periods based on available imagery (Section 3.2.1). The active channels were defined based on visual interpretations of the riverbed in the aerial images and are characterized as having exposed bed and connected channels. A major decrease of the average and range of active channel width between the historic and recent periods is common among all rivers (Figure 4.1 and Table 4.1).

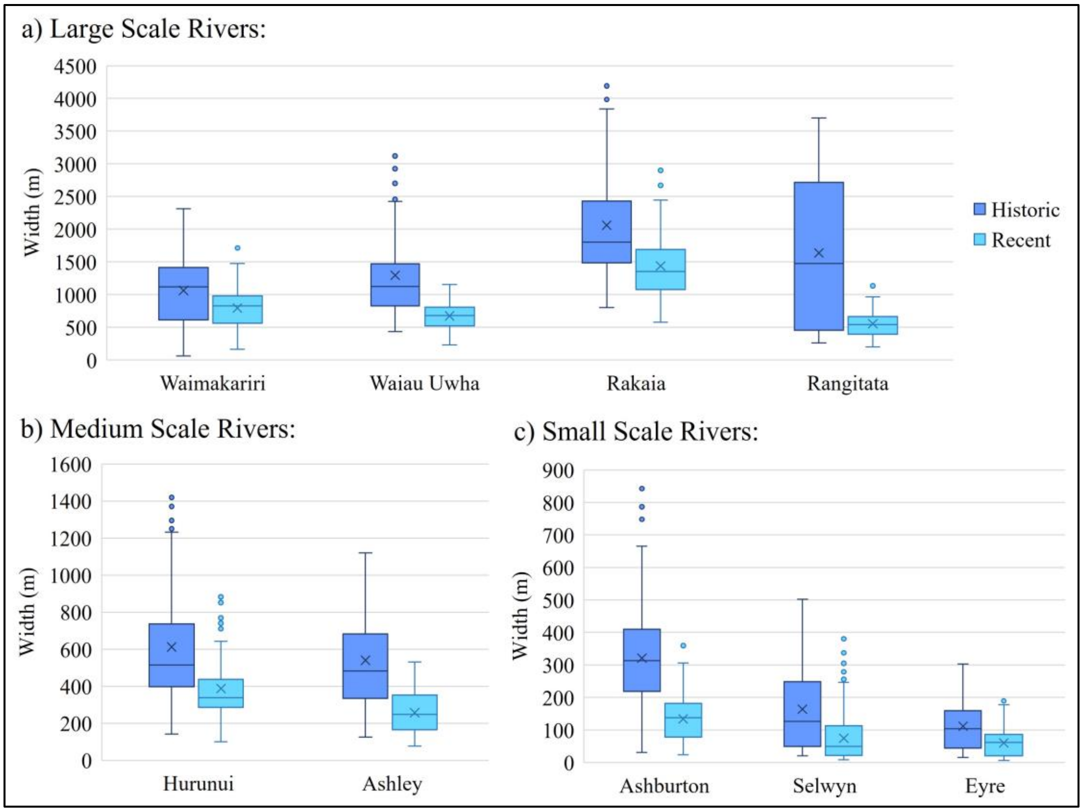

Figure 4.1: Active channel width ranges and change by river. The box represents the interquartile range and whiskers extend to the maximum and minimums (calculated without outliers). Mean widths represented with 'x' and median widths as a line across box (calculated without outliers). Outliers represented by points. Order within scales determined by catchment size, greatest to smallest.

Table 4.1: Mean active channel width change by river.

River	Period	Mean Width (m)	Mean Width Change (%)
Waimakariri	Historic	1063	-25
	Recent	794	
Waiau Uwha	Historic	1294	-48
	Recent	675	
Rakaia	Historic	2061	-30
	Recent	1438	
Rangitata	Historic	1637	-66
	Recent	554	
Hurunui	Historic	611	-37
	Recent	387	
Ashley	Historic	539	-52
	Recent	257	
Ashburton	Historic	321	-58
	Recent	134	
Selwyn	Historic	164	-55
	Recent	74	
Eyre	Historic	112	-46
	Recent	60	

Channel changes for each river vary significantly in terms of absolute and percentage change due to variations in historic sizes. The most significant change was recorded for the Rangitata River with active widths narrowing ~66% on average and the interquartile range dropping almost 90%. The lowest percent change in width values were recorded for the Waimakariri and Rakaia rivers at 25 and 30% narrowing, respectively. Although in these large scale rivers even small percentages of width decrease are large absolute changes in width. The medium and small scale rivers collectively have the greatest percent decrease in average channel width. Four of the five rivers narrowed close to or more than 50% on average.

The large scale rivers remain the widest over time, though the number of segments exceeding 2,000m and 1,000m greatly decreased. Historically, the Rangitata and Rakaia rivers shared the greatest number of segments with active width values over 2,000m. For the Rangitata River however, only 2km of the historic 25km of the total study segment remains with active widths over 1,000m in the recent period. Similar losses in maximum active width were observed in the other large scale rivers; in the recent period only 15km (historically 47km) along the Waimakariri River and 4km (historically 29km) along the Waiau Uwha River retain active widths greater than 1,000m. The amount of change recorded for the Rakaia River was much less, and the majority of reaches, 53km from the historic 59km of total study segment length, maintain a width over 1,000m, with a few segments still wider than 2,000m.

Along the total lengths of the rivers, most individual segments have narrowed over time (Figure 4.2). The largest absolute changes in width occur at segments with initially wide channels. These channels have larger riverbed areas marginal to actively braided channels that are more susceptible to encroachment and vegetation growth during periods of low flow. There are a few segments within all rivers that have widened over time. In most cases, these changes are observed to be relatively minimal, but there are cases of more significant widening. Figure 4.2 highlights the substantial decrease in the range of channel width between the two periods; it shows not just narrowing, but homogenization of width.

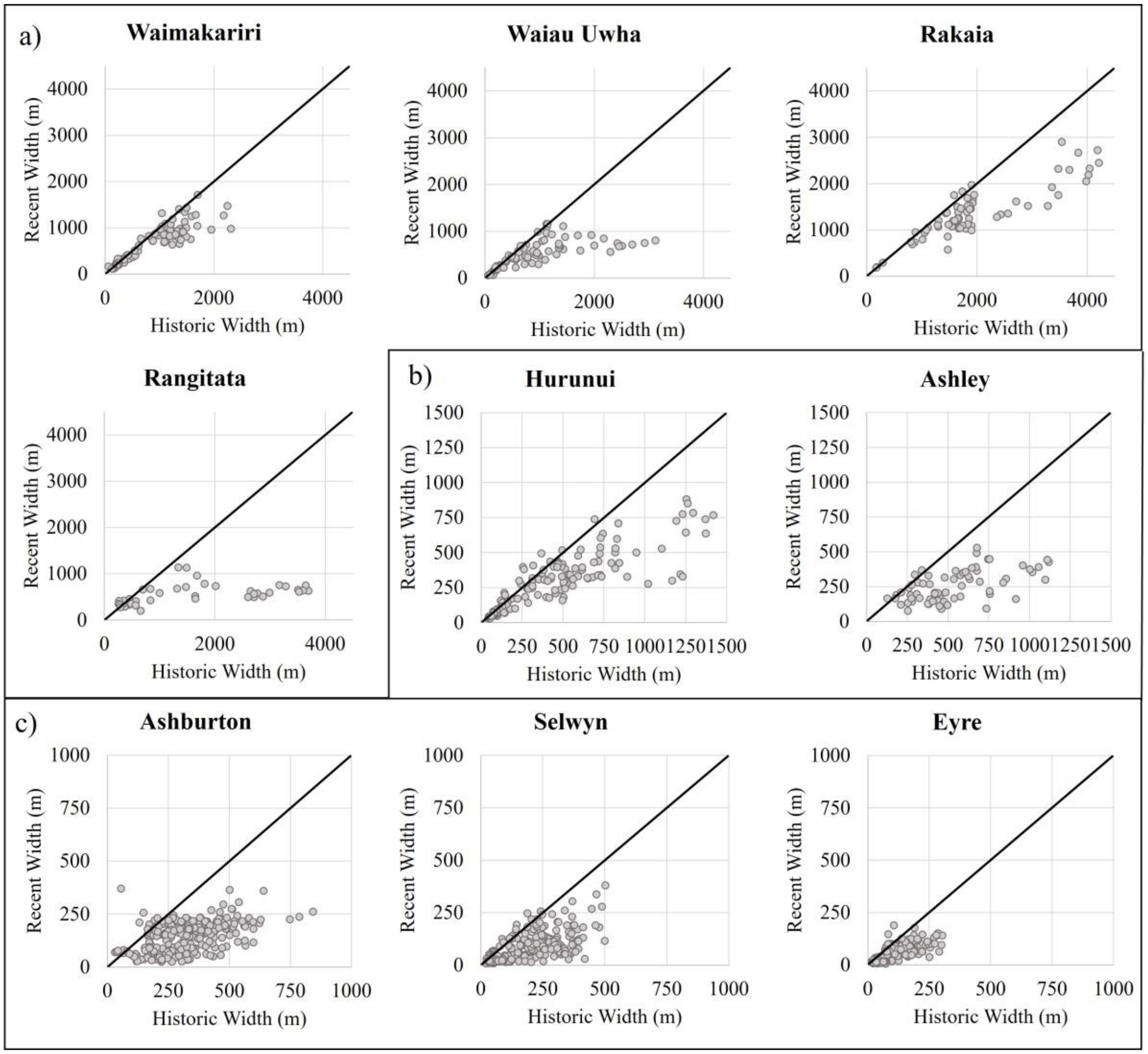

Figure 4.2: Change in active channel width by river. Points represent individual segments and the black line from origin to top right corner is the 1:1 line. Points that are on the 1:1 line have not changed in width between the historic and recent period. Most points lie below the line, indicating channel narrowing. Sorted by river scales (a) large, (b) medium, and (c) small.

The cumulative frequency curve of active width for each river varies, although common trends are apparent (Figure 4.3). In terms of shape, most rivers have a high frequency of low to mid-range width values as the curves tend to increase rapidly for a significant portion of the dataset. For the historic curves, a tail on the right occurs showing the data is positively skewed due to the few, but significant, wide segments along the rivers. The skew is less apparent on the Selwyn and Eyre rivers as these smaller rivers do not have such maximums. In all rivers the curve shifts to the left by the recent period, representing the general narrowing of channels and decreased frequency of larger width values. The skew becomes less apparent on the recent period curves for all rivers due to the narrowing of wider channels.

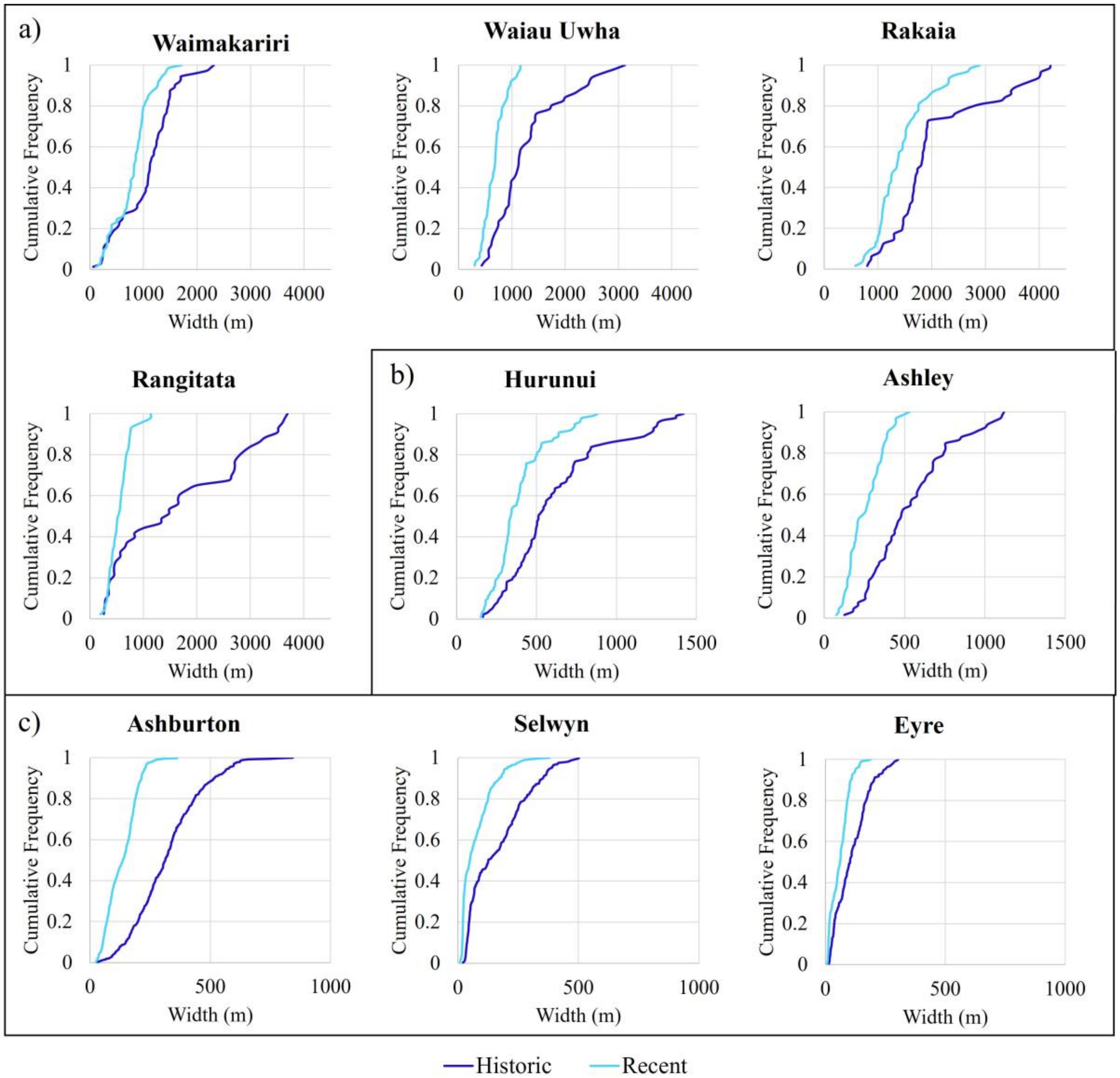

Figure 4.3: Active channel width cumulative frequency for historic and recent periods by river. Sorted by river scales (a) large, (b) medium, and (c) small.

By mapping the changes in active width over time, almost continuous narrowing can be easily visualized along all rivers studied (Figure 4.4a). Long segments of the large scale rivers had width decreases of over 500m with some decreasing well over 1,000m. The downstream ends of the Rakaia and Rangitata rivers as well as the inland basin areas of the Waiau Uwha River, exhibit segments of greatest absolute change, decreasing by multiple kilometers. The reasons for such active channel loss will be investigated in Section 4.4. In contrast, most reaches from the small scale rivers decrease in the 0 to 250m range. Appearing as much less significant change in Figure 4.4a, the changes to the small scale rivers in terms of percent change appear much greater when adjusted for their size (Figure 4.4b). Along almost 60% or more of each river a decrease over 25% of starting (historic) width is evident, and over 50% decreases are also common for many river segments.

The cause of narrowing in these rivers may be due to many factors within the river catchments such as agriculture encroachment, riparian planting, stop banks, decrease in streamflow due to irrigation or power generation, or gravel mining. Only a few segments within the entire range of study exhibited channel widening and may be attributed to natural lateral expansion or release of historically engineered channels. These sections make up a total of about 12km. Specific changes along rivers and the possible causes are explored further in Section 4.4.

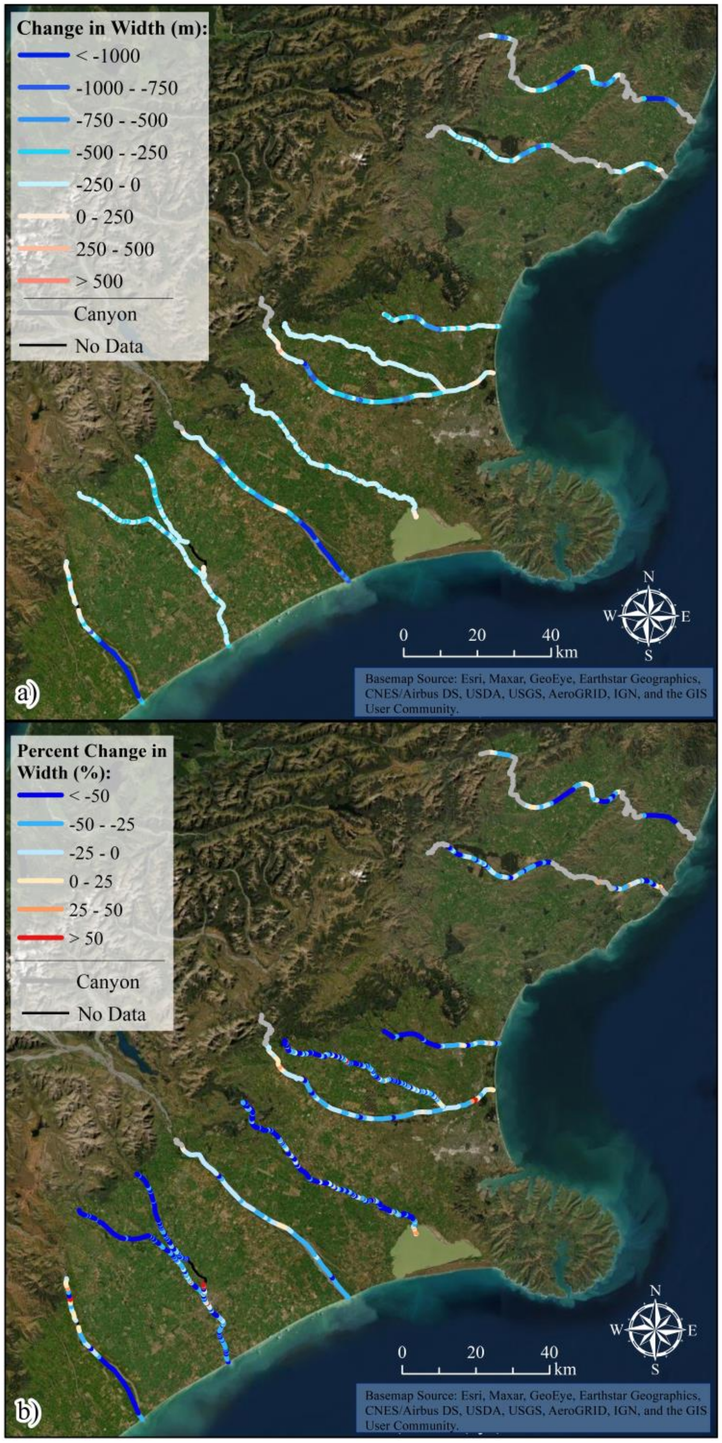

Figure 4.4: Change in active channel width maps. a) Absolute change in width. b) Percentage change in width from historic period. Negative values indicate a decrease in active width from the historic to recent period, and positive values indicate an increase.

4.2 Confinement

The definition of confinement controlling factors on river systems are important to understand river development and characteristics. Changes in the type of confinement as well as the change in the degree of confinement, that is whether it becomes narrower and constricted, is important to track over time to view its influence on river channel morphology. Based on interpretations of historic maps, the beginning of human caused channel confinement dates back to the late 1800s to early 1900s in some areas (Griffiths, 1979; MapsPast, n.d.), but only the changes during the study periods outlined will be described here.

Confinement is recorded as a categorical variable (‘confined’, ‘partly confined’, and ‘laterally unconfined’) that describes the length of channel affected by confining margins and does not directly reflect the amount of lateral confinement across the river, rather that could be to a certain degree what width change implies. Examples of each type of change between time periods are shown in Figure 4.5. Changes in level of confinement occur when the length of the river that abuts a margin restricting the channel’s lateral mobility increases. Causes of confinement include the planted vegetation belts (Figure 4.5a-f) or natural dense vegetation growth (Figure 4.5e-f), construction of stopbanks (Figure 4.5c), and agricultural encroachment (Figure 4.5a, b, f).

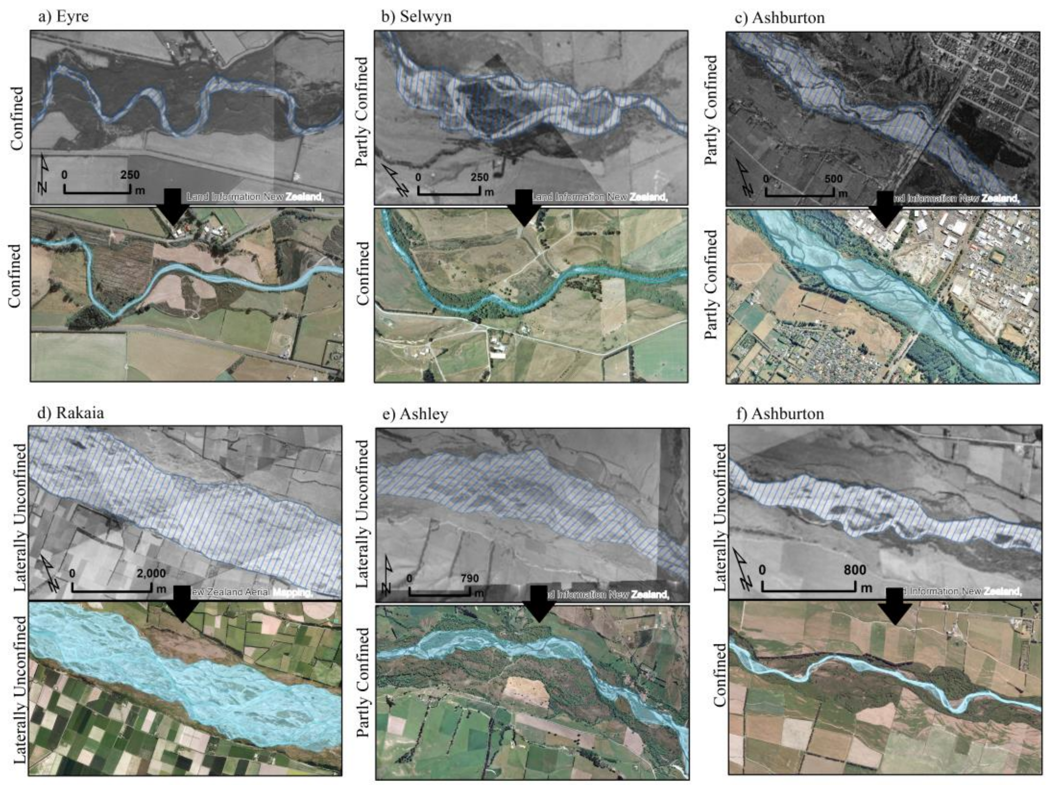

Figure 4.5: Sample images of confinement change. a) Confined - confined: Single channel Eyre River with further confinement from tree-belt. b) Partly-confined - confined: Wandering Selwyn River is constricted further by vegetation planting. c) Partly-confined – partly-confined: Wandering Ashburton River was historically partly-confined and confining margins have not changed/changed minimally. d) Laterally Unconfined – Laterally Unconfined: Braided Rakaia River has only had some vegetation growth and more intense agriculture surrounding the river, but developments have not constricted the river. e) Laterally Unconfined – Partly Confined: Channel and bars of historic Hurunui River have been replaced with vegetation. f) Laterally Unconfined – Confined: Braidplain of historic Ashburton River has had significant vegetation growth constricting the river down to single channel. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

All rivers experienced some changes in confinement type (Figure 4.6). Historically, laterally unconfined reaches were the most common along all river systems. This is especially true for the large and medium scale rivers. By the recent period however, partly confined and confined reaches replaced many of the historically less confined reaches. The most drastic changes are seen along the Waimakariri, Rangitata, Ashley, and Ashburton rivers which have lost 29, 23, 19 and 55.25km, respectively, of laterally unconfined segments to partly confined or confined conditions. Although many laterally unconfined reaches have been transformed into the partly confined type, a considerable portion of these unconfined reaches still exist. The Waiau Uwha, Rakaia, Hurunui, and Selwyn rivers remain with over 20km of laterally unconfined reaches. The Rakaia River, in particular, remains with 44km of laterally unconfined reaches. The Ashburton, Selwyn, Waimakariri, and Eyre rivers are the only rivers with confined reaches not attributed to canyons (both historically and recently). All show increase in length of confined segments over time, except for the Waimakariri River. In general, most changes are from a historically less confined state to a more restrictive confinement type, though some segments record a decrease.

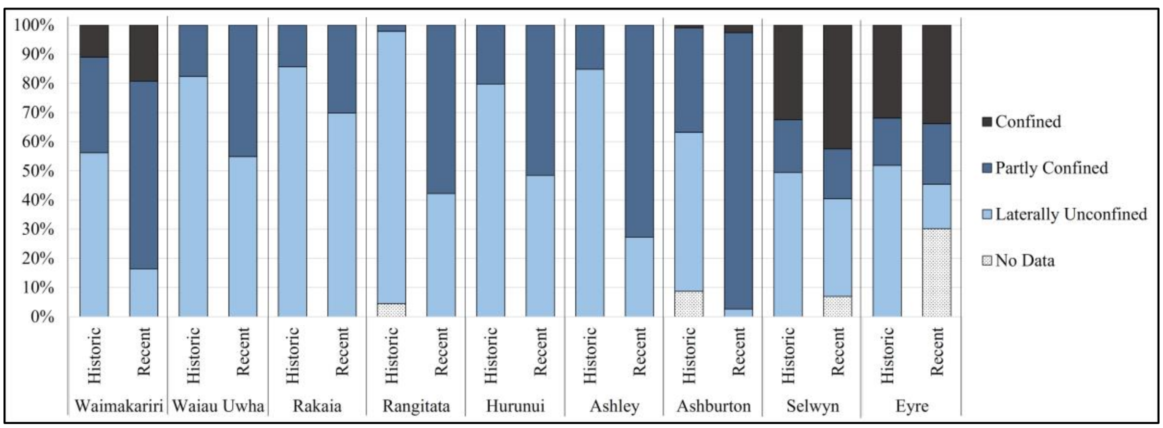

Figure 4.6: Percentage of confinement type in historic and recent period by river.

Historically, confined and partly confined segments centered around urban areas, upstream forested areas, and canyon sections (Figure 4.7a). As land cover change expanded over time, the confined and partly confined reaches have spread out along the channels (Figure 4.7b). Altogether, ~ 54% of segments recorded a constant confinement type over time, but even so many have narrowed. Of the segments studied, 35% have been confined further (i.e., have shifted to a more-confined category) and only 0.9% of segments have become less confined (i.e., a shift from a more-confined category to a less-confined category). In total, 9% of segments have no data on change in confinement as one period of study may have been missing data due to lack of imagery or dry channels. The implication of segments that have not changed in confinement type but have narrowed is that the active channel areas are closer to a threshold of change to more intense confinement type.

Confinement that is sufficient to change planform morphology is referred to as constriction and segments with such changes will be analyzed in Chapter 5. The change in confinement and potential causes (causes should be studied further) are discussed by individual river case in Section 4.4. The purpose of documenting the change is to look at the relationships between confinement and channel width and pattern.

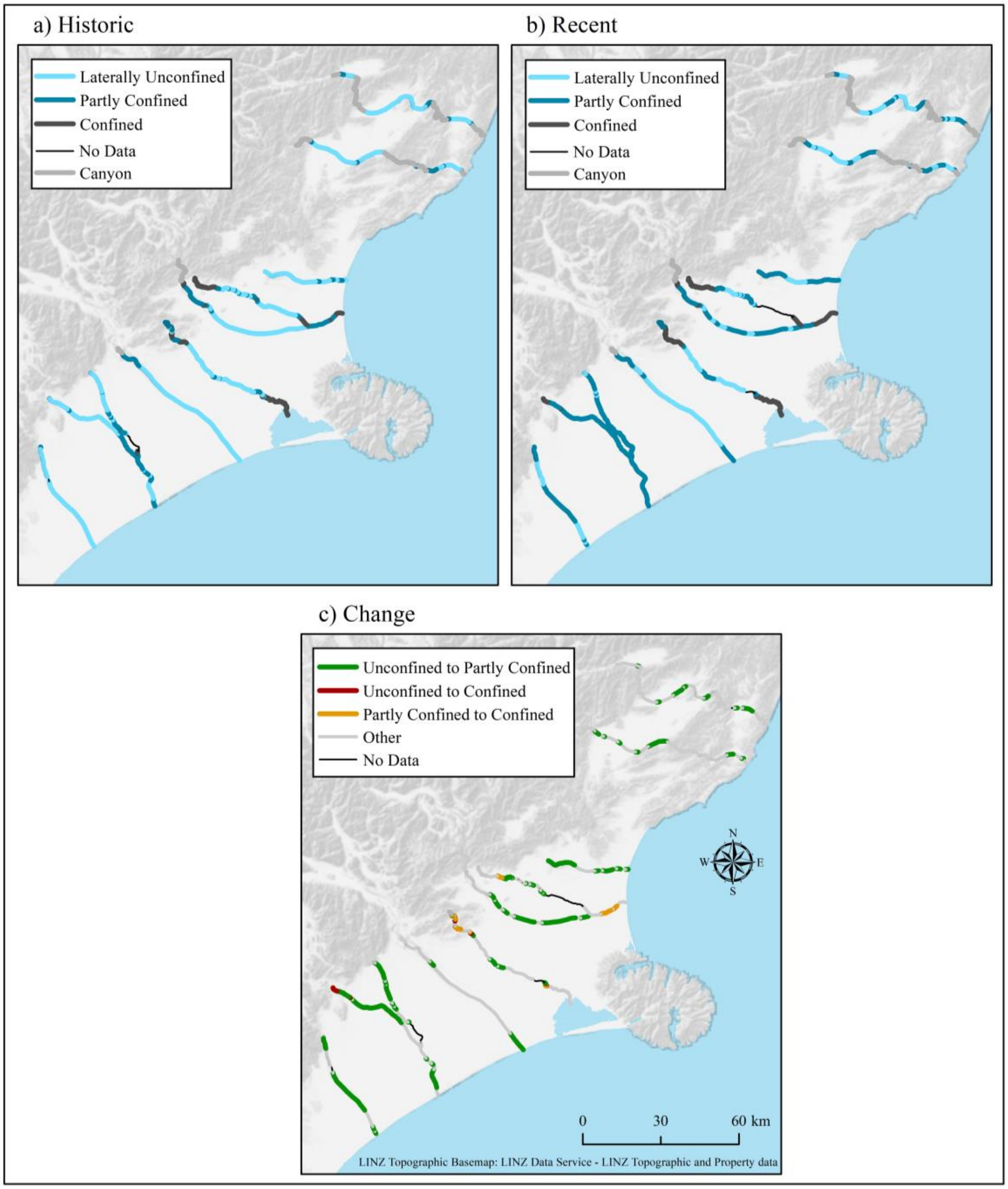

Figure 4.7: Change in confinement type maps. (a) Historic period confinement conditions, (b) recent period confinement conditions, and (c) change in confinement between historic and recent period ('Other' represents constant and rare cases of decreased confinement type).

4.3 Channel Pattern

The channel pattern of rivers can be influenced by a variety of factors including room for active lateral mobility (i.e. confinement). The planform morphology and channel count recordings were studied along each river for both historic and recent periods to observe the changes over time. The results presented here were also used to look at the relationship of channel width and other variables with channel planform type and braiding intensity (Chapter 5).

4.3.1 Channel Planform Type

Three general planform types were used to categorize each segment of the rivers. Figure 4.8a-c documents planform types in the three groups (braided, wandering, and single channel). There are a number of ways in which river planform can change over time, but based on the planforms selected, only broad categorical changes will be studied in this section (examples of each are shown in Figure 4.8). The cause of changes in channel planform may be concluded visually from the imagery, but more information is needed. Section 4.4 explores the channel planform changes more closely for each individual river.

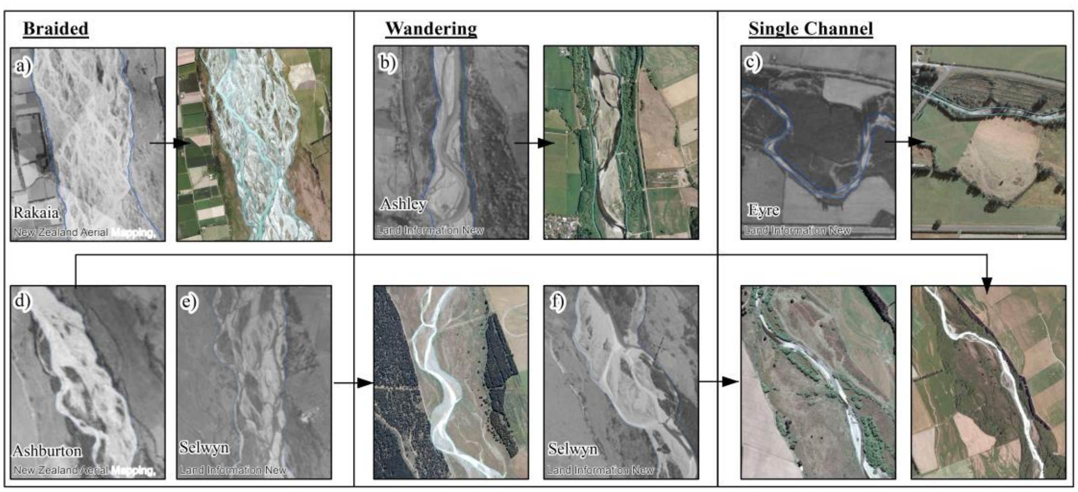

Figure 4.8: Sample images of planform change. a) Braided-Braided: Unchanged Rakaia River. b) Wandering-Wandering: Slight increase in vegetation plantings along Ashley River, but wandering pattern remains. c) Single Channel – Single Channel: Eyre remains a single channel over time, with significant planform

positional changes. d) Braided – Single Channel: Vegetation plantings constricting Ashburton River into single channel. e) Braided – Wandering: Scrub vegetation occupying historically braided area of Selwyn River. f) Wandering – Single Channel: Vegetation plantings constricting Selwyn River into single channel. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

All rivers recorded braided planforms historically, and all rivers (excluding the Selwyn and Eyre rivers) had it as the dominant planform type along their channels (Figure 4.9). In the smaller rivers, there were more wandering and single thread channels during the historic period, likely due to their small river character and ability to be controlled. Changes in river planform type tend to be observed more in the smaller rivers. The large scale rivers overall show the least amount of change as the majority of braided reaches still remain classified as braided despite significant narrowing of channels. The Rakaia River, for example, shows no change in river planform type over time. The Ashley River is notable for the large decrease from 70% braided to ~25% braided with channels shifting towards a wandering planform. The other small scale rivers show a similar decrease as well, the Ashburton River drops from approximately 66% braided to 26%, the Selwyn River from 27% to 4%, and the Eyre River from 24% of the network braided to 0% (although, the dry sections could have been classified braided, as they were historically). For the small scale rivers, most historically braided planforms shifted into wandering morphology, with a few transitioning into single channels. Most planform changes were a simplification from a level of high complexity (braided) to lower (single channel), but there were some cases of increasing complexity.

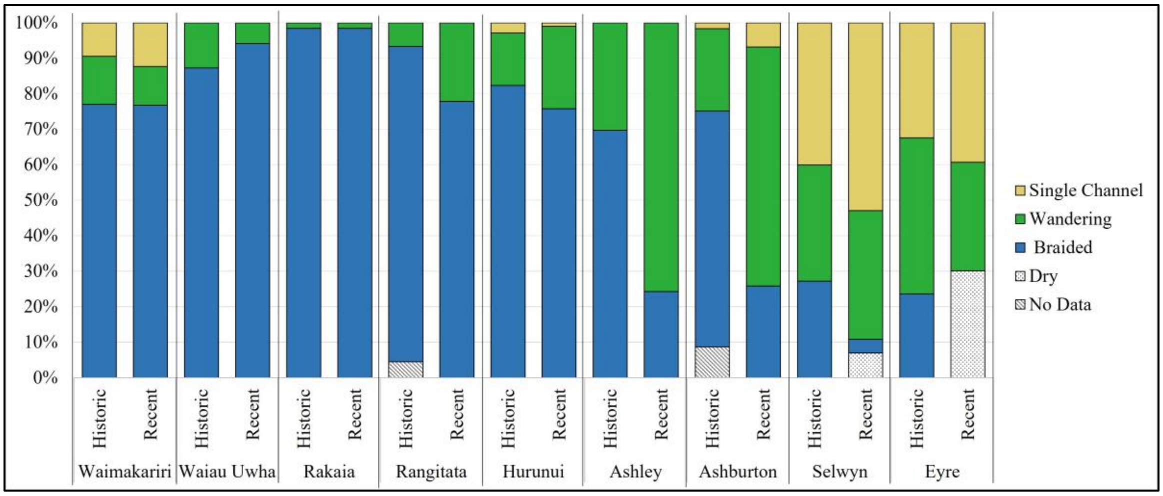

Figure 4.9: Percentage of planform type in historic and recent period by river.

A total of ~20% (or ~120km) length of the studied river networks recorded a simplification of planform type over time. The small scale rivers have the most of that change along their networks, accounting for ~14% (86km). The medium and large scale rivers therefore had very minimal changes along their reaches, ~4% (23km) and <1% (10m) respectively. The braided-to-wandering change segments were the most common changes recorded (96.25km of total study segments) and had an average width loss of ~55% or ~201m. Braided-to-single channel changes occur along 6km of the study rivers (small scale only) and channel widths narrowed 81% or by ~226m. Therefore, requiring more narrowing than braided-to-wandering. Wandering-to-single channel planform changes occurred along 16.5km of the total study segments and averaged with a low 90m narrowing or 67% decrease in starting width.

Spatial patterns of historic and recent river planform can be observed as well as the patterns of change (Figure 4.10). Long lengths of the rivers are characterized as braided. Braided planforms are the most common within the plains and inland basins, and single channel planforms are more common through canyon, developed, and small upstream reaches. Wandering planforms were typically found in the smaller rivers or transitionally between reaches of braided and single channels. The spatial distribution of planform types can be roughly related to the confinement spatial pattern where braided reaches tend to align with laterally unconfined reaches (and larger rivers). The lack of recorded change in the large scale rivers (and Hurunui River) are particularly evident in the change map (Figure 4.10c).

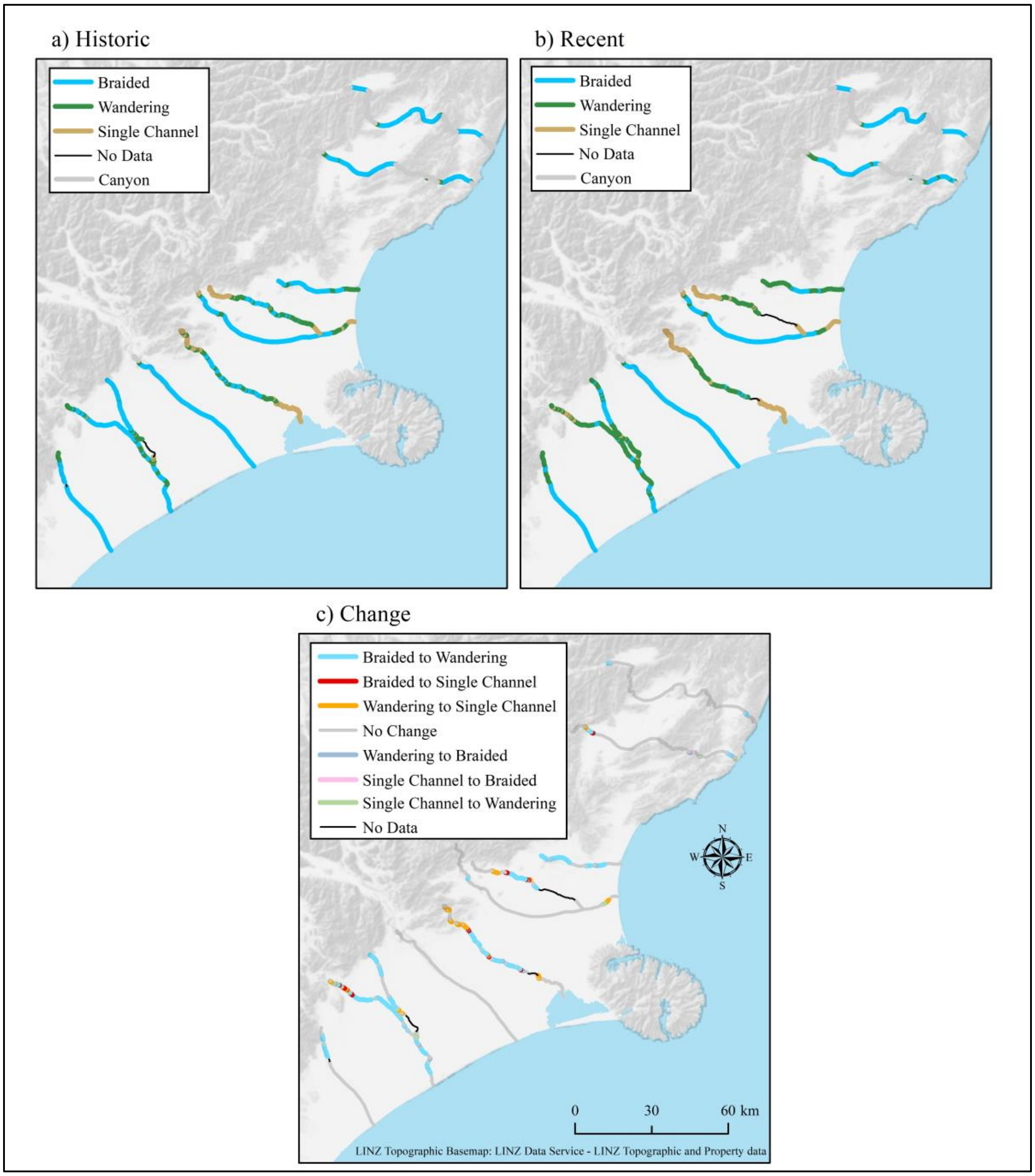

Figure 4.10: Change in planform type maps. (a) Historic period planform distribution, (b) recent period planform distribution, and (c) change in planform type between historic and recent period.

4.3.2 Channel Count (Braiding Intensity)

Channel count has decreased over time in all rivers regardless of whether they changed planform type. Channel counts from all rivers range from a maximum of 13 in braided reaches to a minimum of 1 (by definition) in single channel reaches. Similar to channel widths, a distinction between the larger and smaller scale rivers can be made based on the channel counts (Figure 4.11). As expected, the large scale rivers with dominantly braided morphologies have the highest recorded channel counts (historically) with a wide range of counts along their entire networks. By the recent period, the large scale rivers decrease in peak and average channel count, some becoming more similar to the medium scale channel counts. Historically, channel counts for the medium and large scale rivers reached maximum channel counts at or over 8. By the recent period however, only the Waimakariri and Rakaia rivers have channel counts that high. In the case of the Waiau Uwha and Rangitata rivers, average channel counts decreased by 1.5-2 and maximum channel counts decreased by 3-3.5. The small scale rivers have the lowest recorded channel counts historically and decrease further over time. From the small scale rivers, the Ashburton River had the highest channel counts, reaching a range of values similar to the Ashley River (medium scale).

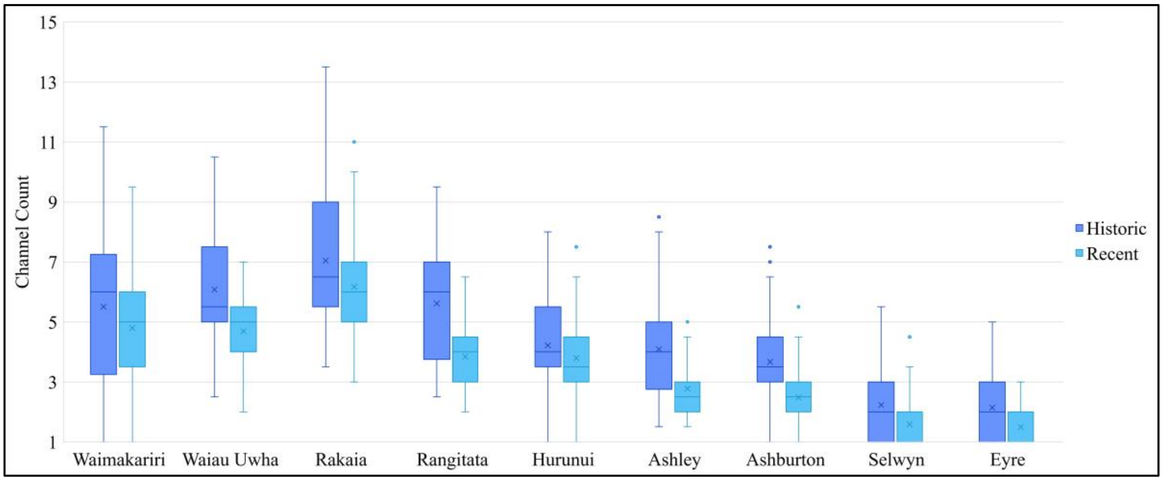

Figure 4.11: Channel count ranges and change by river. The box represents the interquartile range and whiskers extend to the maximum and minimums (calculated without outliers). Mean widths represented with ‘x’ and median widths as a line across box. Outliers represented by points.

A comparison of historic to recent channel counts reveals the greater proportion of reaches that have lost channels over time (Figure 4.12). In general, the larger the river scale, the greater the loss of channels as larger rivers were more likely to have wide, multi-channel, braided planforms to begin with and therefore the greatest number of channels to lose. Braiding intensity, recorded as the number of channels within a braided segment, has therefore decreased in each river over time.

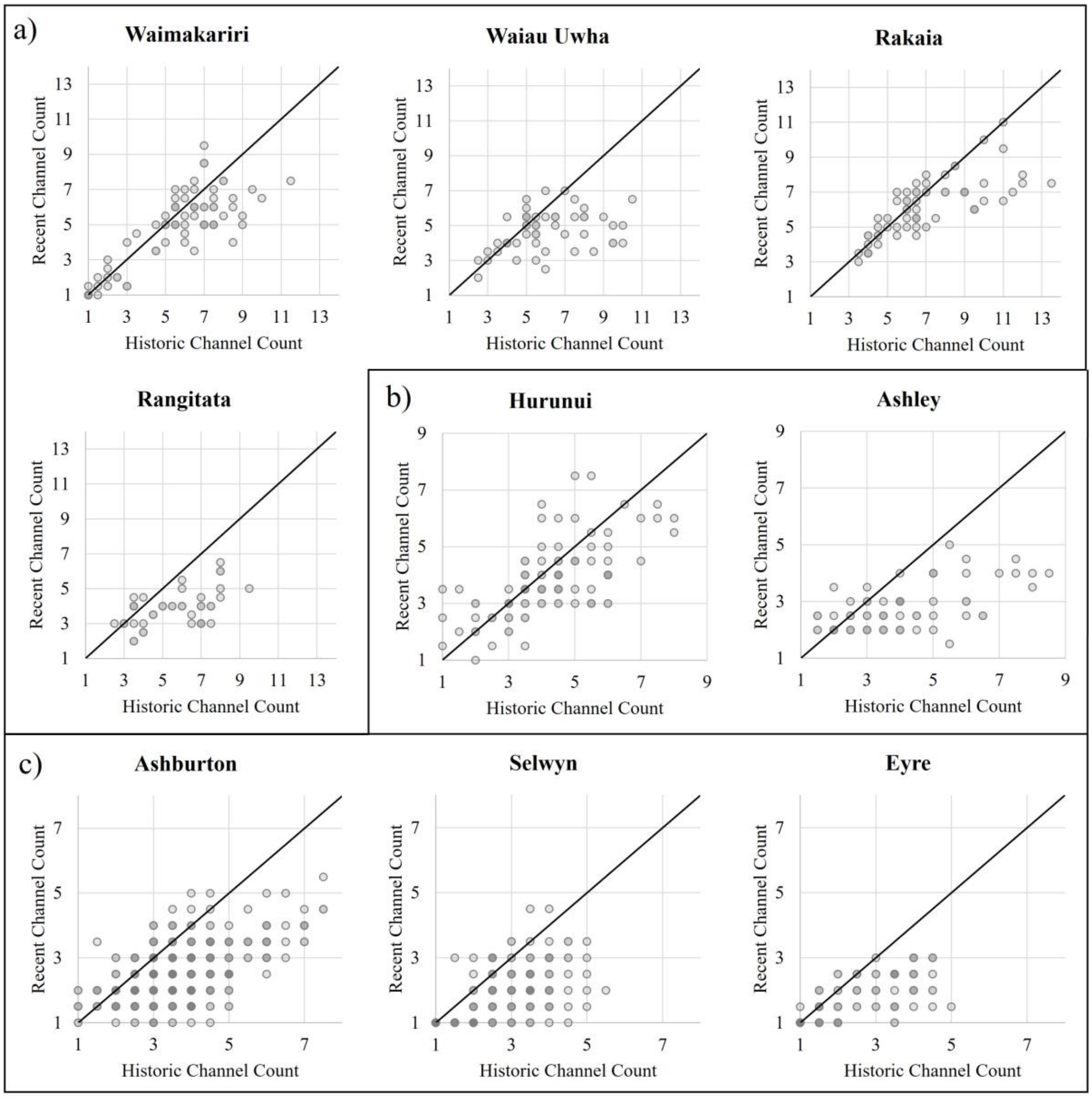

Figure 4.12: Change in channel count by river. Points represent individual segments and the black line from origin to top right corner is the 1:1 line. Darker shades

represent multiple segments with the same channel count loss. Points that are on the 1:1 line have not changed in channel count between the historic and recent period. Most points lie below the line, indicating channel loss. Sorted by river scales (a) large, (b) medium, and (c) small.

Comparing the braiding intensity of historically braided segments to the intensity in those locations today, there is general loss of channels (Figure 4.13). In addition to the loss of channels, some segments are also no longer braided. For example, the small scale rivers have minimum channel counts of 1 by the recent period, representing the shift of some segments from braided to single channel. Historically, the large scale rivers stand out with the highest braiding intensities, multiple channels higher than those from the smaller scales. Over time however, these braiding maximums begin to fall and the Waiau Uwha River and Rangitata River maximum channel counts fall below the medium scale Hurunui River.

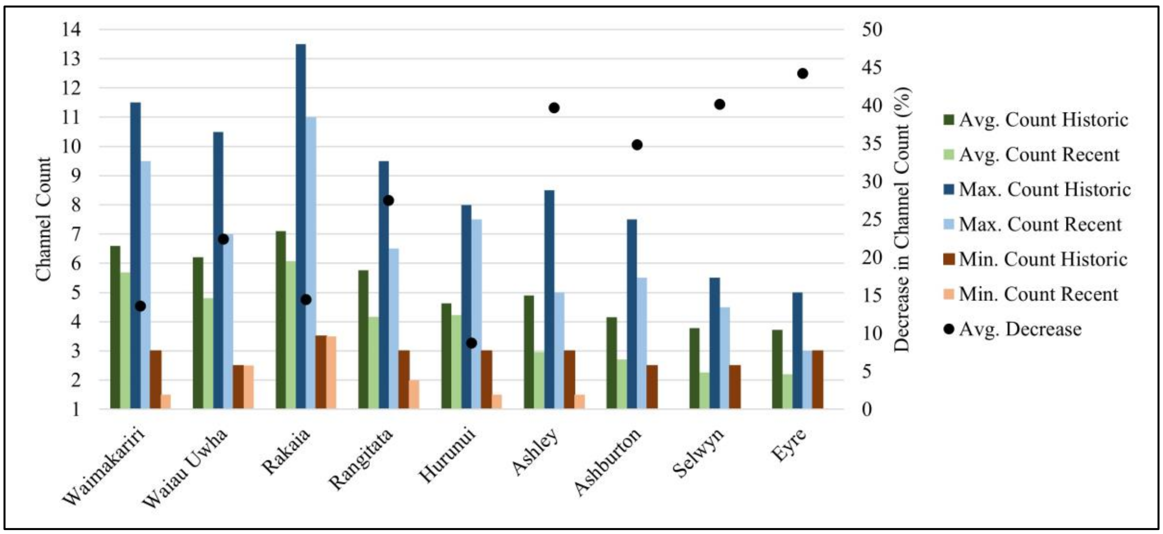

Figure 4.13: Change in channel count along historically braided reaches. Bars represent the average, maximum, and minimum channel counts for the historic and recent periods (primary y-axis). Points represent the average percent decrease in channel count (secondary y-axis).

In terms of the percent decrease in channel count, the small scale (and Ashley) rivers stand out with over 30% decreases in average channel count from historically braided reaches. Starting with fewer channels to begin with, these segments have also had the greatest recorded changes in planform types along their networks. The case of the Ashley River, for example, is interesting as the channel loss relates to the significant change in planform which included a reduction of about 45% of braided segments along the total study segment. The Waimakariri, Waiau Uwha, and Rakaia rivers have the lowest percent change in channel count around 10-15% decrease. These three rivers were also noted with the lowest percentage change in active channel width. From the large scale rivers, the Rangitata River has the greatest average decrease in historically braided segment channel counts. The Rangitata River lost both kilometers of active channel in the downstream end and many reaches of braided defined planforms, therefore the highest average reduction of braiding intensity in this river was anticipated. As rivers begin to have a reduction in braiding intensity, they may be getting closer to point of transitioning away from braided morphology.

There was an almost continuous loss of channels along the entire lengths of each river for the period studied similar to the spatial results of active width change (Figure 4.14). A distinction between the small scale and larger scale rivers can be made by observing the number of channels lost along the rivers. The small scale rivers have the lowest decrease in channel count, typically around 1-2 channel loss. This is expected as these rivers are the narrowest of the group and have less complex planform types compared to the larger scale rivers with wider, braided channels. The locations of greatest decrease in channel count also align with the areas of maximum absolute changes in width located at the downstream end of the Rakaia and Rangitata rivers and the inland basins of the Waiau Uwha River (recall Figure 4.4). When displayed by percent change (Figure 4.14b), channel loss stands out for smaller rivers because the loss of one channel can mean a loss of 50 or 33% if starting with 2 or 3 channels, respectively. The relationship of active channel width and channel count will be explored further in Chapter 5.

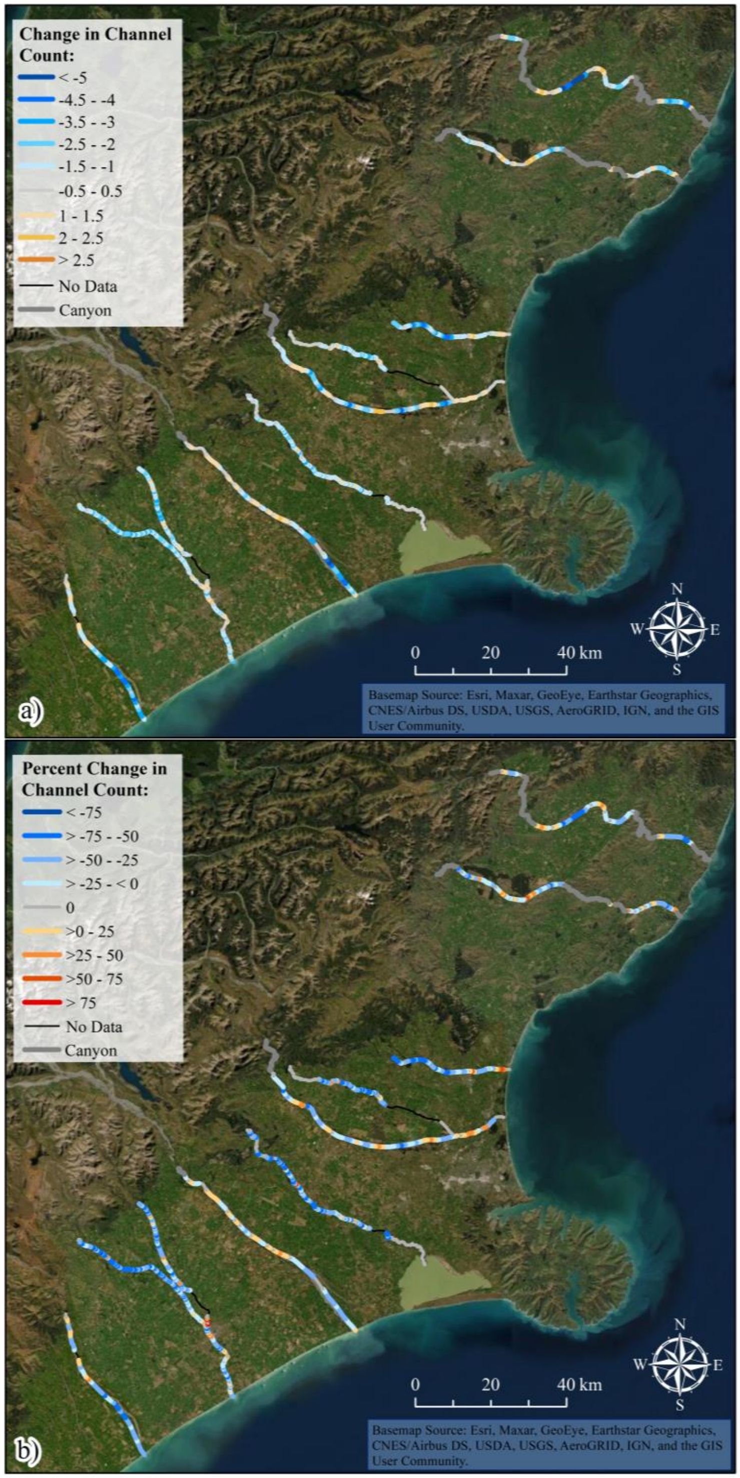

Figure 4.14: Change in channel count maps. Negative values indicate a decrease in channel count from the historic to recent period, and positive values indicate an increase.

4.3.3 Channel Width and Count by Planform Type

It is known that different channel planforms exhibit different characteristics. For example, braided channels are wide, relatively shallow, with high channel counts. The braided and single channel results are expected to be distinct and completely separable. Wandering channels, based on definition, are transitional and will likely lie in between and overlap with the ranges characteristic to braided and single channels. This is an outcome of the simplification of planforms into three categorical types.

Channel widths measured along each river were grouped by planform type and separated by scale. As expected, the braided planforms have the largest widths (~100 to >1,000m) and single channels the smallest (~10 to 50m), with wandering widths in between causing some overlap (Figure 4.15). The results clearly display the relation of width and planform type. The overlap may be due to the transition state of some segments or an effect of the combination of different scales. The width values for the wandering and single channel planforms in the large scale rivers are wider in some cases than small scale braided planforms. And in the large scale rivers, segments with active widths similar to the braided small scale rivers would more likely be classified under wandering (or even single channel). When all data is considered (Figure 4.15a), the outlier points for the single channel planform type are from the Waimakariri and Hurunui rivers only and these are the only large and medium scale rivers with single channel segments.

Braided planforms have the largest variation in active width values, as the rivers can be up to kilometers wide, while the other planform categories are limited by width and would likely transition to braided with enough power to become so wide. Between the historic and recent periods, the narrowing along all rivers is demonstrated by mean and maximum width decreases in all planform types. The braided widths, having the most active area to lose, had the greatest amount of narrowing.

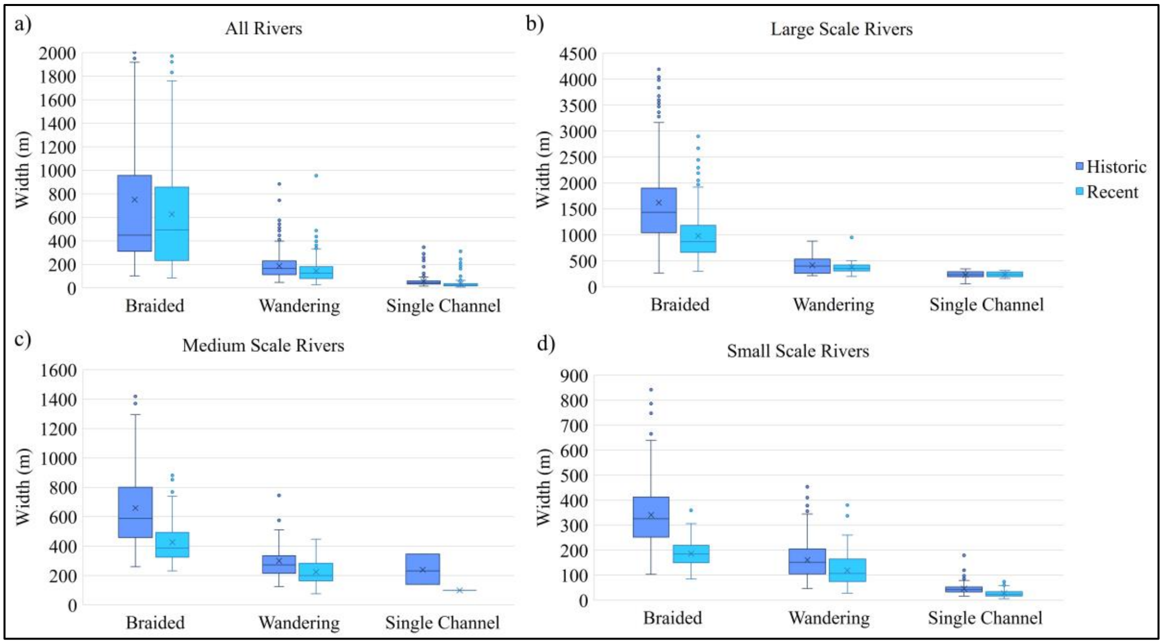

Figure 4.15: Channel width ranges and change sorted by planform types and scales. Braided outlier points extend beyond the width range of the y-axis for (a).

Planform types can partly be recognized by number of channels (Figure 4.16), with slight areas of overlap between braided and wandering segments. The braided segments are the only ones defined by more than three channels and have maximum channel counts over 10 in both periods. By definition of the wandering type, some segments overlap with the braided category where wandering channels have up to 3 or 3.5 channels. Cases of 3.5 channels are segments located at transition phases of planform types along the rivers where a wandering segment may be adjacent to a braided segment. The same may be true for braided reaches with 2.5 channels. The distinction between channel types was made by observing the planform of the total segment and recording the type that was most prevalent. Overlap between wandering and single channel reaches may also be due to these situations. Between scales, boundaries between planform types remain the same, as planform types are partly organized by number of channels. The large scale braided segments have the largest channel counts. In general, channel counts present in each planform type remain constant over time, with only a slight decrease in the braided segments due to the loss of maximum channel counts. The losses in the other types are not seen, as any significant changes would result in a change in planform type.

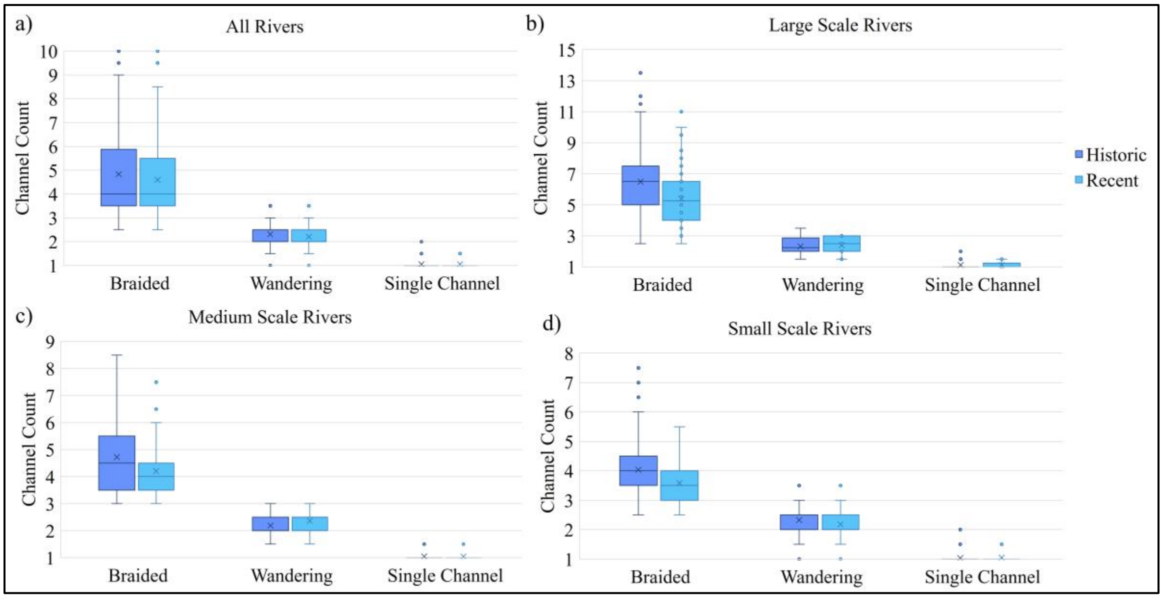

Figure 4.16: Channel count ranges and change sorted by planform types and scales. Braided outlier points extend beyond the channel count range of the y-axis for (a).

When sorted by planform type, the characteristics recorded along each segment of the rivers of interest show some trends. There are clear distinctions between planform types when sorted by active width and channel count. These relationships make classification easier and will be explored in Chapter 5. The results for braided rivers show this planform type has the largest active widths and channel counts (Table 4.2). The single channel results show the smallest of these characteristics and the wandering channels typically have results in-between. The overlap between segments could be due to error or segments on the cusp of channel change. Or these overlaps could come from the effect of scale. This is a potential influence of channel type classification as seen with the overlap between different classes from the different scales (Figure 4.15). Also, the lack of many single channel segments in the large scale rivers may make assumptions drawn from the large scale single channel segments uncertain and potentially inaccurate.

Table 4.2: All rivers total width and channel count ranges by planform type.

	Single Channel	Wandering	Braided
Active Width (m)	10 – 50	30 – 400	100 - >1,000
Channel Count	1	2 – 3	3 - >4

*Ranges include both historic and recent datasets (excluding outliers).

4.4 Channel Change by River

The previous sections introduced the overall changes and geography of channel characteristics, this section focuses on these characteristics for each river individually. Details for each river will be added by showing examples of changes and identifying effects that may have caused changes. Not every change in the rivers of interest could be included, such as all irrigation schemes, reasons and types of confinement, etc. Detailed exploration and explanation of the causes of change requires much more work and is beyond the scope of this thesis but an important focus for future work. The summaries provide examples and highlights of changes common along many rivers or unique and significant changes to particular rivers. Many analyses include the interpretation of Canterbury Regional Council shapefiles that provide insight into general vegetation growth and constructed flood protection measures not easily visible from imagery alone. Specific species of vegetation and dates of protection implementation are unknown. The timing of changes to the rivers are generally unknown, but partially explored in some rivers. In addition, the effects of flooding after the channel changes were explored where flooding imagery was available (Ashburton River). The rivers are presented in order of scale then catchment size (large scale rivers: 4.4.1 to 4.4.4; medium scale: 4.4.5 to 4.4.6; small scale, 4.4.7 to 4.4.9). The unique characteristics and differences between rivers, as well as the general influences on channel change, will become clearer as result of these descriptions. The results are also important in transferring knowledge to local interests and scientists.

4.4.1 Waimakariri River

The Waimakariri River is the largest river, in terms of catchment size, selected from the study area. The Waimakariri River has one of the longest segments of braided morphology, approximately 70% (or ~60km) of the total study segment, with active widths commonly surpassing 1km wide. Over time, the braided morphology of the river has been maintained although the narrowing of the active channel and the partial confinement of many laterally unconfined reaches led to changes in river planform that decreased the overall complexity of braiding.

Between the historic (1940-44) and recent (2015-16) period, both the active channel width and channel count along the Waimakariri River decreased (Figure 4.17). The narrow reaches in the upstream and downstream ends of the study segment are confined by canyons (upstream) and channel engineering (downstream). Continuous narrowing occurs along the middle reaches of the study segment where the river flows through the plains (approx. 10 to 60km upstream). This narrowing can be traced to constructed flood protection, including both stopbanks and vegetation buffers, and some accounts of agricultural encroachment (Figure 4.18).

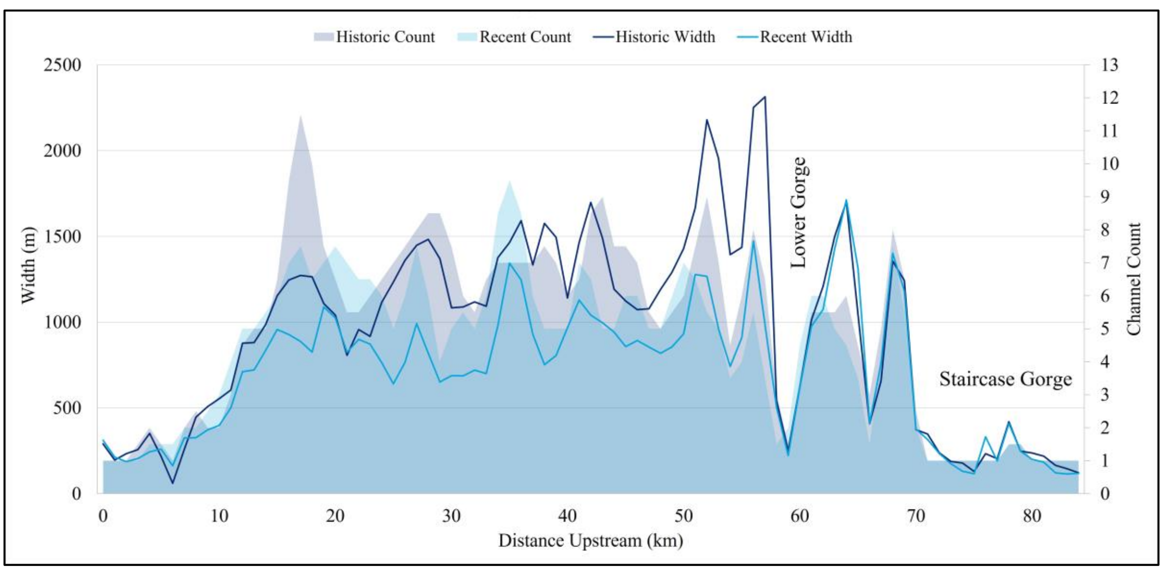

Figure 4.17: Historic and recent width and channel count measurements - Waimakariri River.

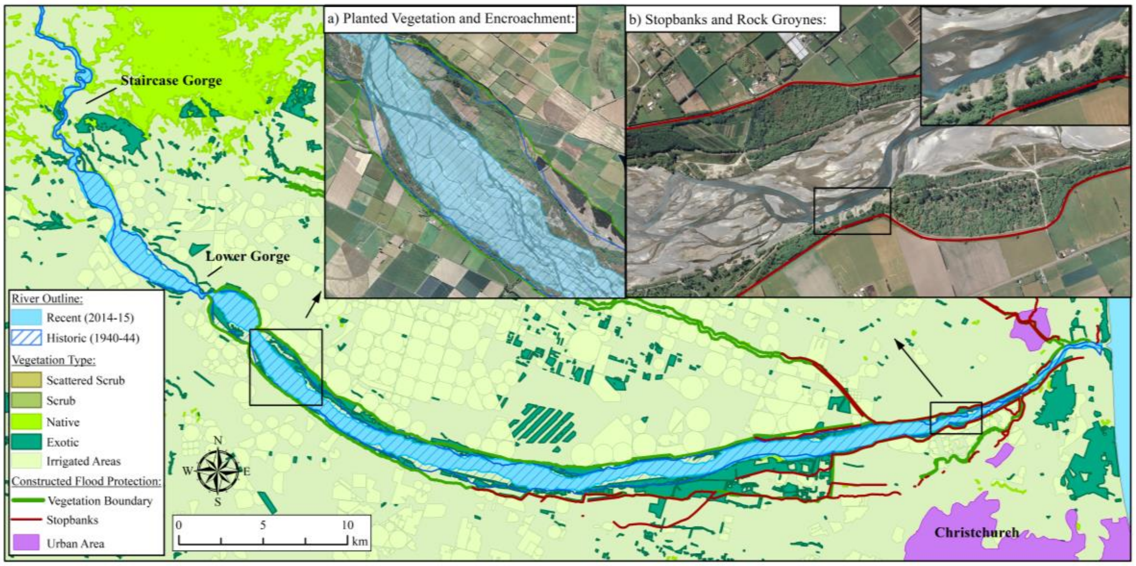

Figure 4.18: Flood protection along Waimakariri map. a) An example of vegetation planted within historic active channel area. b) Constructed stopbanks and groynes along the downstream banks of the river. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

Vegetated buffers extend along the majority of the river and were built to reduce erosion of terraces and stopbanks, protecting farmland (Williams, 2017). The vegetation is mainly exotic (namely willow trees) to New Zealand (Williams, 2017). Most of the vegetation has been planted within the historic active area of the river (Figure 4.18a). Stopbanks are present along both sides of the downstream end of the river. Most stopbanks are protected from the river by planted vegetation, but in some locations the river is observed to abut the large rock groynes (Figure 4.18b). Stopbank protection along the south bank of the river near Christchurch (to the South) is particularly important to direct the water away from the city and airport.

The locations of maximum widths along the river have shifted due to the vegetation and stopbanks. The flood protection measures are mapped up to the Lower Gorge. Historically, the area of maximum recorded narrowing was located directly downstream of this gorge, approx. 50-60km upstream. This site had widths well above 1,000 and

1,500m and the maximum recorded width (2,300m) of the whole study segment. By the recent period channel widths in this segment narrowed up to 1,000m due to growth of exotic vegetation within the historic active channel area (Figure 4.19). Currently, the widest reaches are located within the area upstream of the Lower Gorge where there are no flood protection measures, and the channels have been allowed to remain relatively constant over time within the flanking terraces. These relatively untouched areas, which were naturally confined by terraces, now have the largest widths along the river. Therefore, the changes to the river are not just causing overall narrowing, but a difference in the geography of widths along the river.

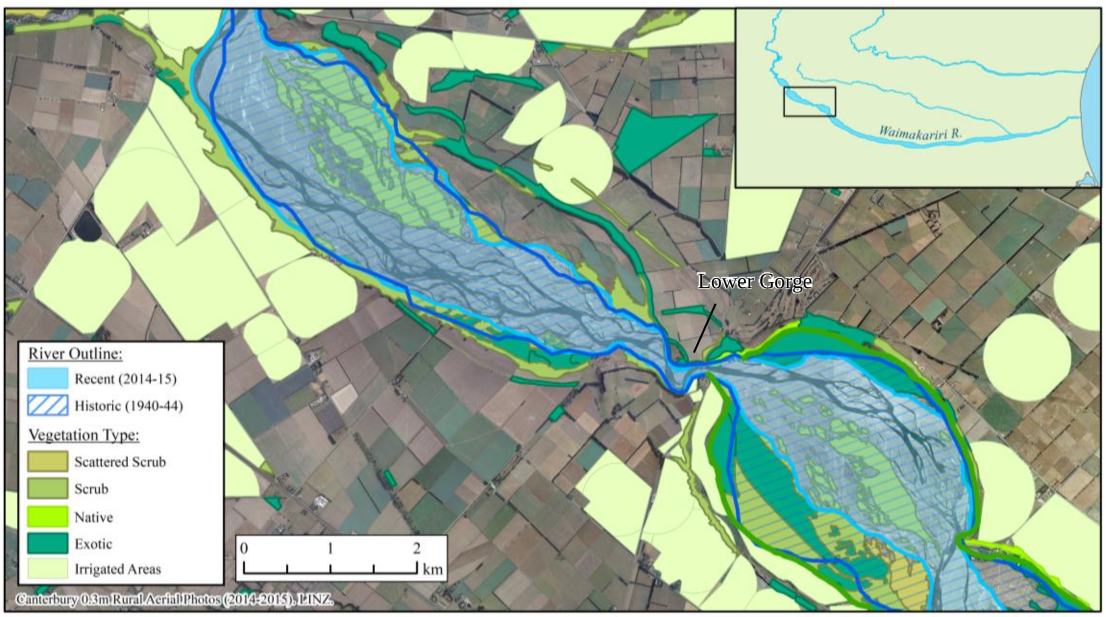

Figure 4.19: Location of maximum width change along Waimakariri River. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

Overall, the river has had minimal change in channel planform type, although the river appears to be locked in its course by vegetation growth and stopbanks to where it flowed historically (in 1940-44).

4.4.2 Waiau Uwha River

The Waiau Uwha River is the northernmost river of the study area and flows through a mountainous region with wide inland basins located between long narrow canyons (Figure 4.20). The main area of interest along this river flows through the inland basins where the river can laterally expand and create a braided morphology that has been maintained over time, though has become less complex. The river has changed in its ability to expand in these regions as the amount of lateral confinement restricting the river's movement has increased. The canyon reaches have had little to no change over the study period.

Historically (1955-1959 downstream and 1950-1954 upstream) the average active width of channels flowing through the inland basins was ~1,270m, but, by the recent period (2014-2015) this average dropped 43% to ~630m width. The Waiau Uwha River experienced some of the greatest changes in channel width observed throughout the entire study area with local reaches within the inland basins narrowing over 1,000m.

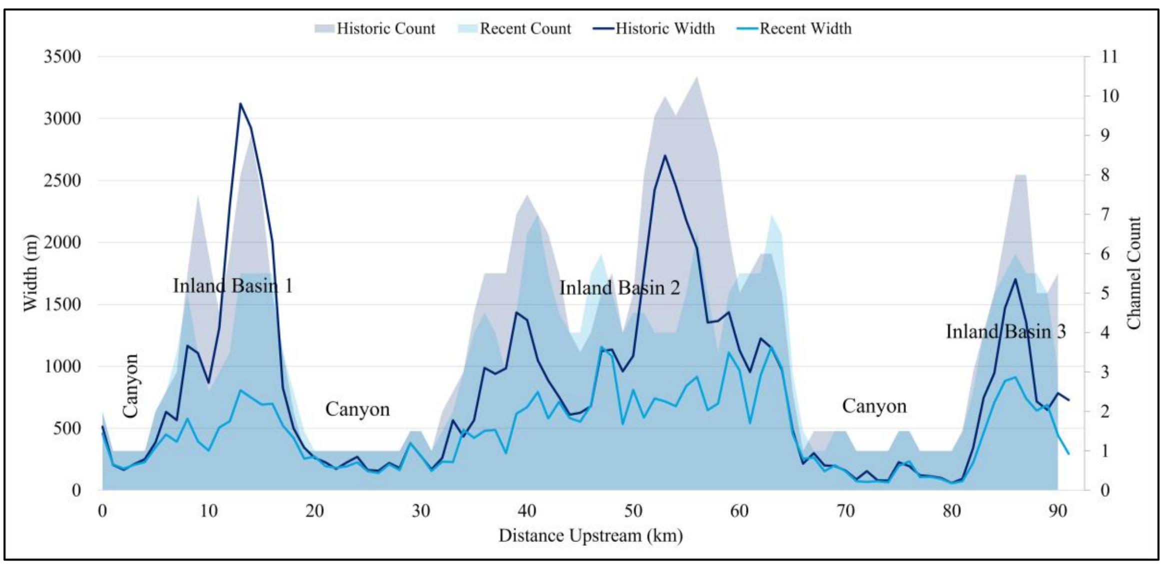

Figure 4.20: Historic and recent width and channel count measurements - Waiau Uwha River.

Of all rivers studied, the Waiau Uwha River has some of the most agricultural encroachment and least protection surrounding the river. Figure 4.21 highlights the present-day irrigated areas and constructed protection surrounding the river. From this scale, large portions of historic active area can be seen filled in with irrigated agriculture. Encroachment onto the braidplain occurred at multiple periods during the river's past. Imagery collections from Google Earth date back to the 1980s and capture the change in land cover at a few locations (Figure 4.21a, b). At the first inland basin (b) the major encroachment of agricultural area occurred at some point between 1985 and 2006, exact timing is unknown based on imagery available. At the second inland basin, a gradual change in land use is seen within the braidplain. From 2003 to 2012 there is minimal encroachment along the north downstream end identified and by 2013 almost all of the smaller branches on the north side of the channel are replaced with agricultural land cover.

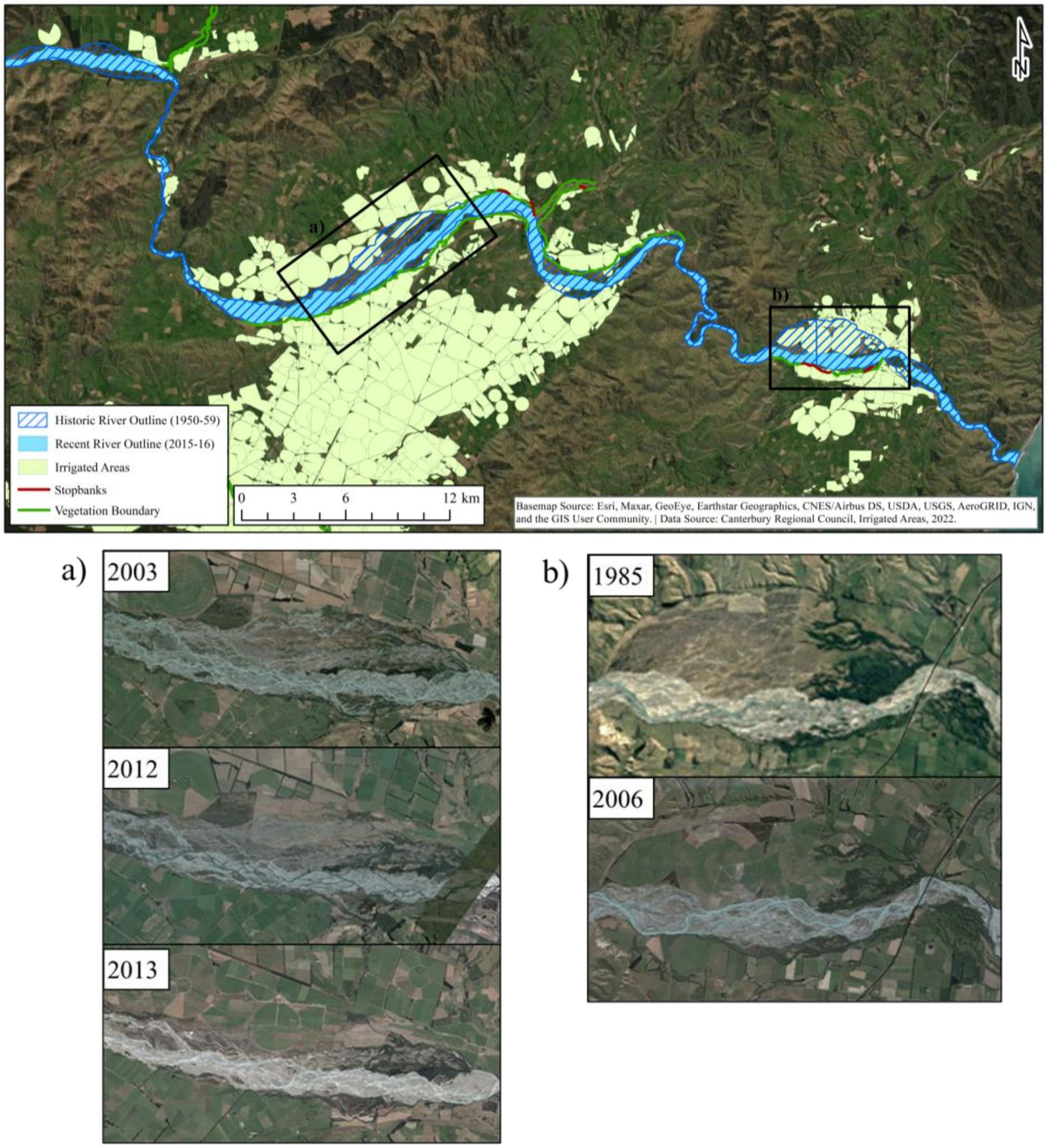

Figure 4.21: Timing of agricultural encroachment along Waiau Uwha River. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

The largest width changes occur within the two inland basins and both locations in Figure 4.21 correlate with the reaches. In these locations narrowing up to and surpassing 2,000m is recorded with huge channel losses. Historically, the maximum recorded active width was within the first inland basin (14km upstream) and measured 3,120m wide. This site narrowed by 2,300m (or about 75%) due to encroachment (Figure 4.22).

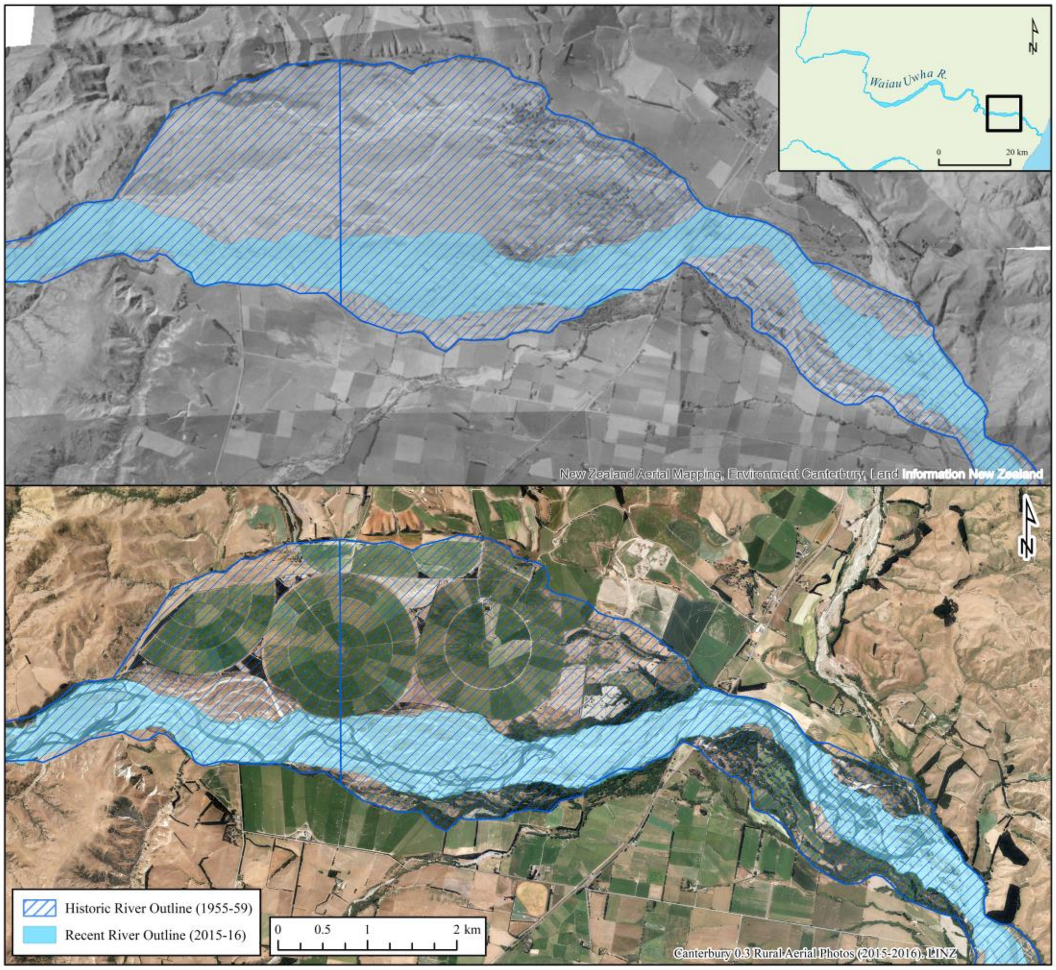

Figure 4.22: Major agricultural encroachment site along Waiau Uwha River. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

In many locations where encroachment has occurred directly onto the braidplain there do not appear to be many protective measures between the land and the river. This is unlike other rivers where vegetation is typically planted along the margins.

4.4.3 Rakaia River

The Rakaia River is currently the widest of the rivers studied and is the only river that remains with active widths exceeding 2,000m. The Rakaia River study segment covers mainly the network of the river through the Canterbury Plains, but also captures the downstream section of the canyon and transition (and return) of the river from a confined single channel to a wide braided river. The Rakaia River had no changes to the type of planform recorded along the study segment between the historic and recent period and is the only river to retain all braided segments, albeit with significant narrowing.

The Rakaia River historically (1940-44 downstream, 1955-59 middle, 1945-49 upstream) had the widest reaches of the rivers studied with widths exceeding 4,000m in the downstream end but have since (recent period: 2012-13) drastically changed (Figure 4.23). The downstream (~20km) end of the Rakaia River was the widest portion of the river where the channel splits in two around an island. This area had the largest decrease in active width and channel count over time as one of the channels drastically narrowed due to agriculture and vegetation developments within and around the island (Figure 4.24). Even after the massive loss of channel area due to surrounding development, parts of this section remain the widest (>2,000m) along the study segment and total study area.

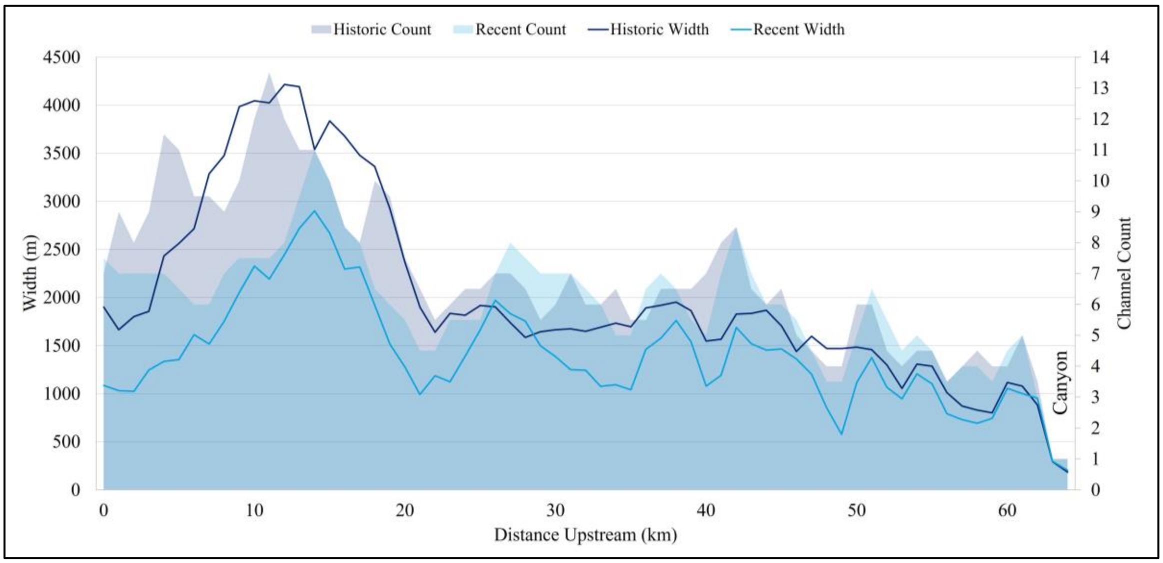

Figure 4.23: Historic and recent width and channel count measurements - Rakaia River.

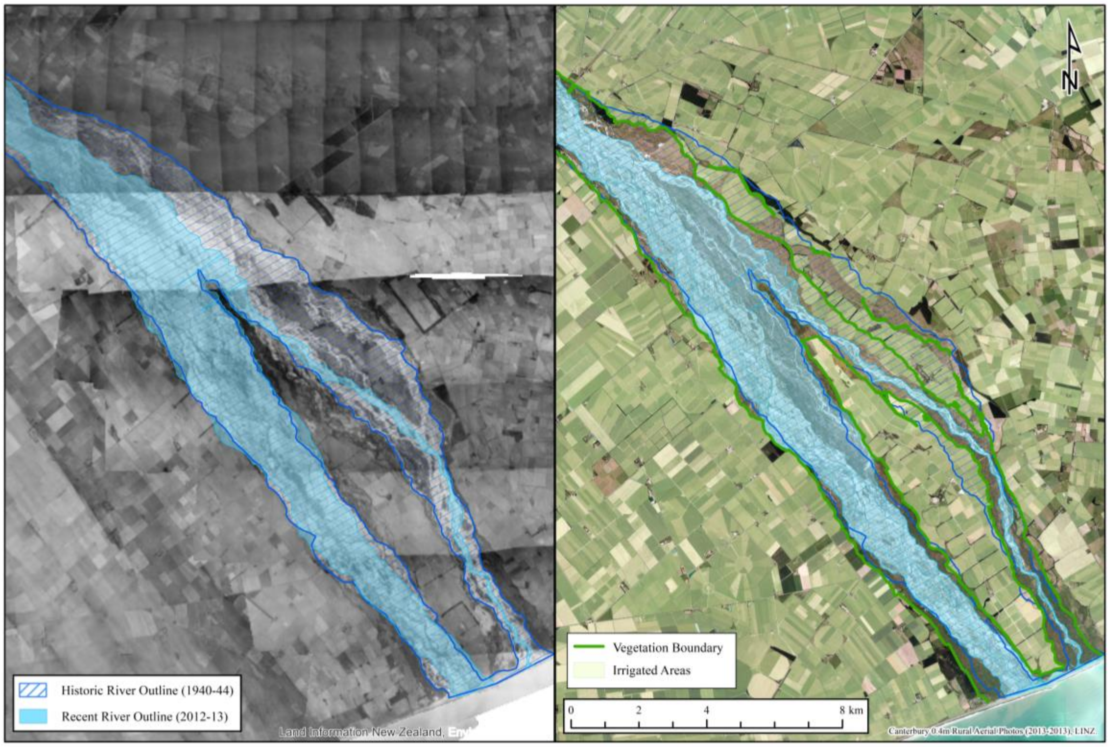

Figure 4.24: Downstream narrowing along Rakaia River. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

Upstream from where the river splits, there has been relatively minimal change in width and channel count. There is little dense vegetation surrounding the river channels. Only a thin line of vegetation exists along the vegetation boundaries and no stopbanks. Scrub growth within the extent of the historic active channel outline are the most widespread changes. Similar to Waimakariri River, vegetation tended to grow within the historic active area of the river, making the river narrow (Figure 4.25). As it is mainly low-density vegetation growth within the historic active channel, that may explain why the lateral mobility of the river has not been observed to substantially change (i.e. no change in confinement type) and why channel planform type has remained constant over time.

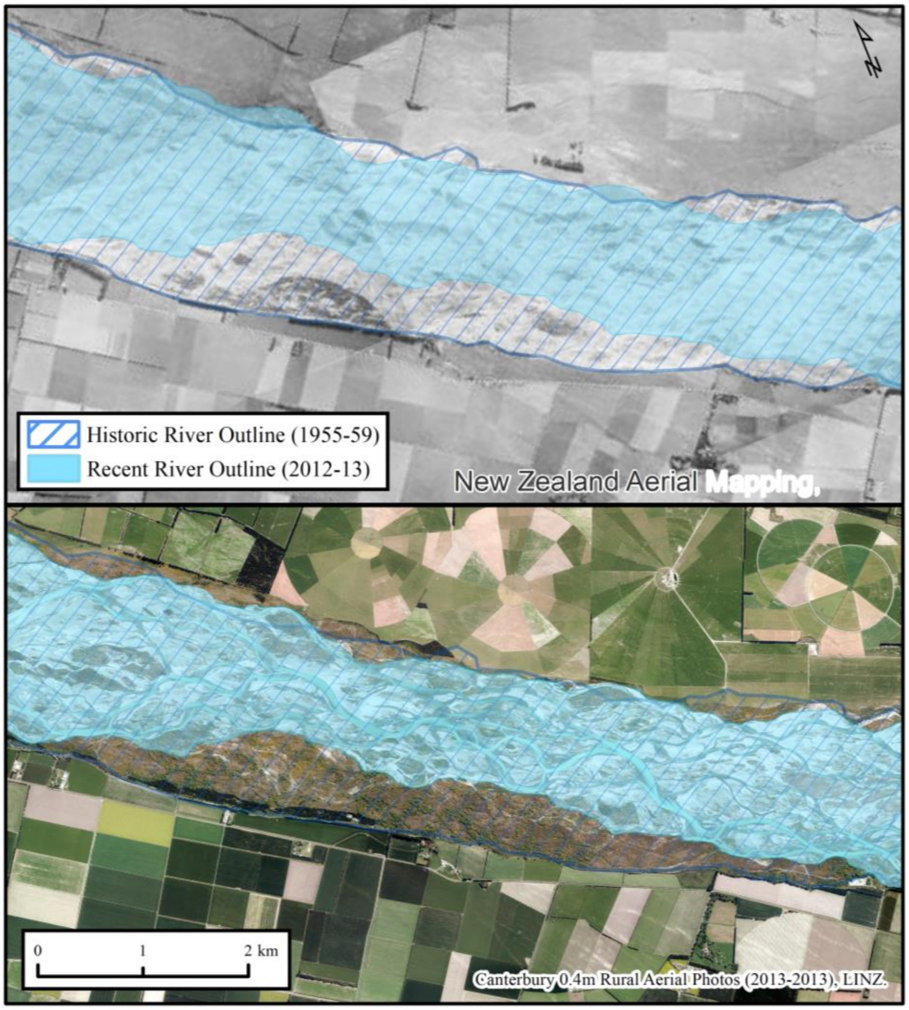

Figure 4.25: Vegetation growth within historic channels of Rakaia River. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

4.4.4 Rangitata River

The Rangitata River is the southernmost river in the total study area. This river has the smallest catchment size of the large scale rivers. Of the large scale rivers, it has had some of the biggest changes with large portions of the channel shifting from unconfined to partly confined and transitioning planform types from braided to wandering along the upstream segments.

The study period for this river is ~75 years (1935-39 to 2012-13). Over this time the downstream reaches (~20km) of the river have drastically changed, and the reaches upstream, while having less of a quantitative loss in width, have shifted from braided to more wandering channels, based on channel planform analysis (Figure 4.26). The major change in the downstream end is due to the loss of a branch that divided the river around a large agricultural island. By the recent period of imagery capture, this branch is completely dry and replaced by irrigated, agricultural area (similar to change in Rakaia; Figure 4.27). The large cut-off from the downstream branch led to an almost 80% decrease in width along the reach (identified in Figure 4.27), with a 2,200m average loss of width per segment and with the maximum width segment narrowing 3,300m. In addition to the land use change, the branch was further confined by dense vegetation growth along its channels.

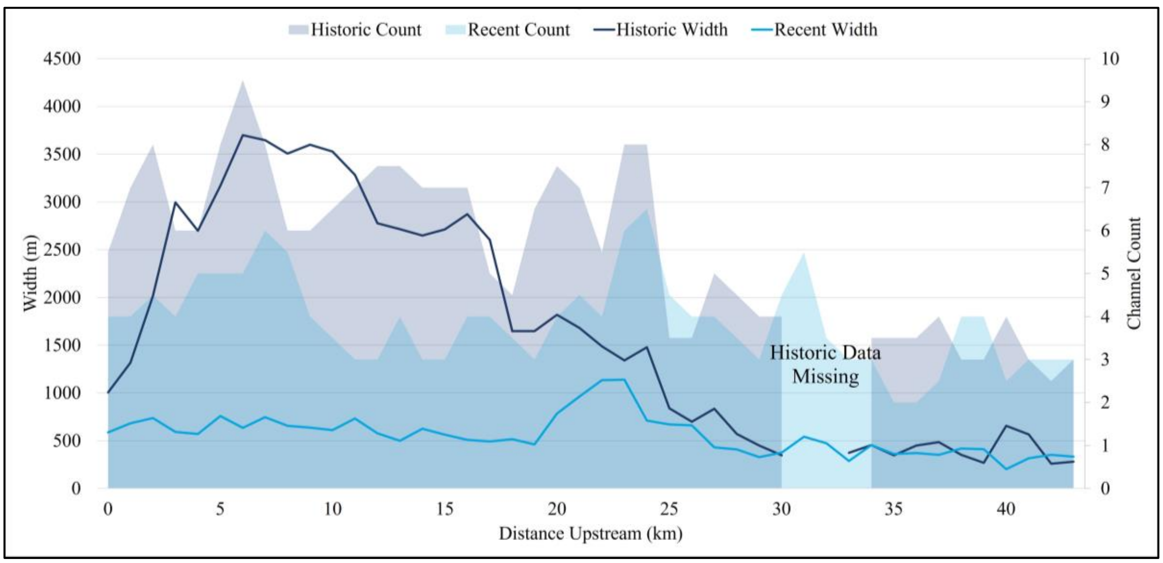

Figure 4.26: Historic and recent width and channel count measurements - Rangitata River.

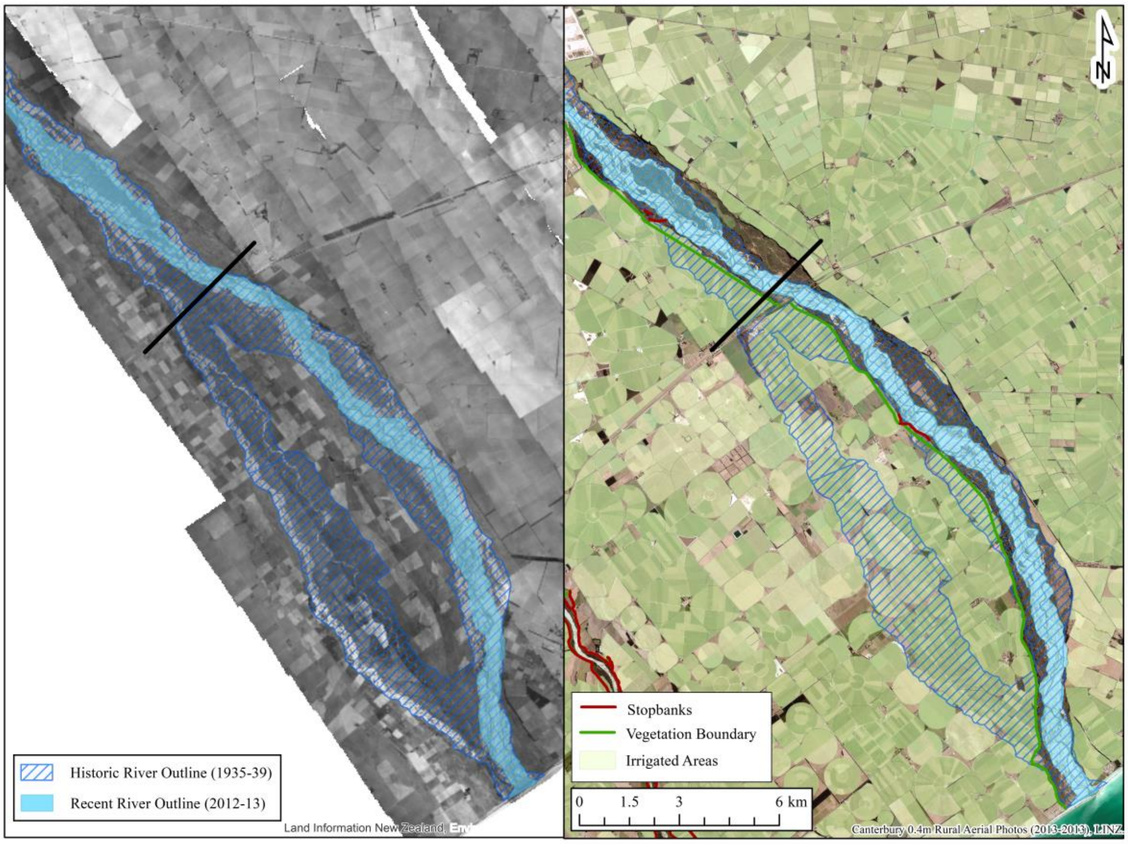

Figure 4.27: Downstream narrowing along Rangitata River. The most significant narrowing is located in the reach that extends from the mouth of the river to the black line (18km upstream). Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

A vegetation protection boundary is digitized along the south bank of the river and stretches from the mouth of the river 37km upstream. Although mapped on only one side, both sides of the river appear to have a vegetated buffer zone surrounding the river, with thick vegetation. Further upstream most segments had minimal change in confinement to their channels and minimal width change as stated above, though the pattern type of these sections have changed from braided to wandering (Figure 4.28).

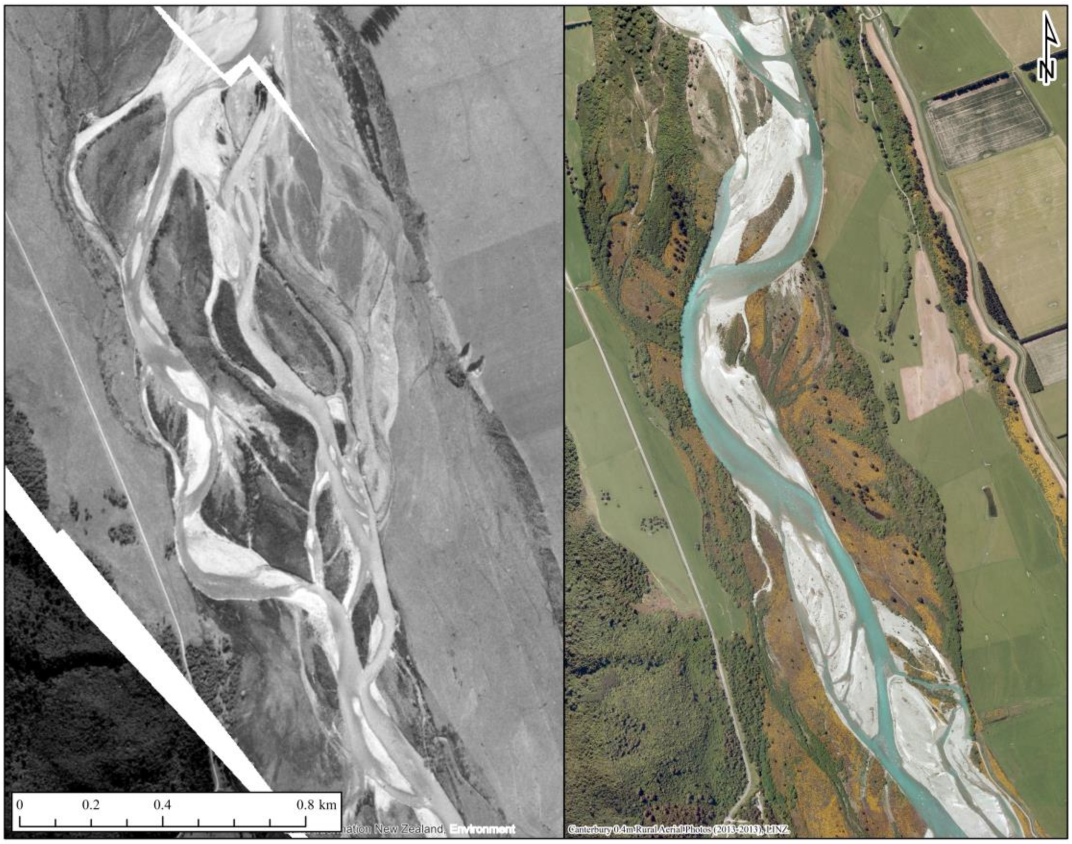

Figure 4.28: Braided to wandering planform change along Rangitata River. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

The Rangitata Diversion Race (RDR), which abstracts the most amount of water from the Rangitata River, began construction in 1937 and was not operational until 1944 (after the imagery collection for the historic period; Hopkinson, 1997). Water is abstracted downstream of the Rangitata Gorge before the river enters the plains, just upstream of study area, then directed across the plains, intaking more at the northern Ashburton River branches, and ending at the Rakaia River, irrigating the surrounding mid-Canterbury region along the way (Hopkinson, 1997). The intake of water along the Rangitata River during both low flows and the increase of intake during high flows has unknown morphologic effects on the Rangitata River, but changes in morphologic character have been noted by locals such as narrower and shallower braids in reaches downstream from the gorge (Hicks et al., 2021).

4.4.5 Hurunui River

The Hurunui River, located south of the Waiau Uhwa River, shares topographic features such as the wide, flat, basin sections divided by narrow canyon reaches. The river has a large catchment area, but generally smaller widths have it placed in the medium scale category. This river has had very minimal change over time compared to some of the other rivers, especially the Ashley River of same scale.

Figure 4.29 graphs the historic (1955-1959 downstream and 1950-1954 upstream) and recent (2014-2015) measurements of active channel width and channel count. The wide reaches within the inland basins and narrow canyon reaches are easily identified by their stark differences in width and channel counts. The largest area of change around 40-50km upstream is an example of a wide, braided reach that went from laterally unconfined to partly confined due to vegetation planted within the historic active areas.

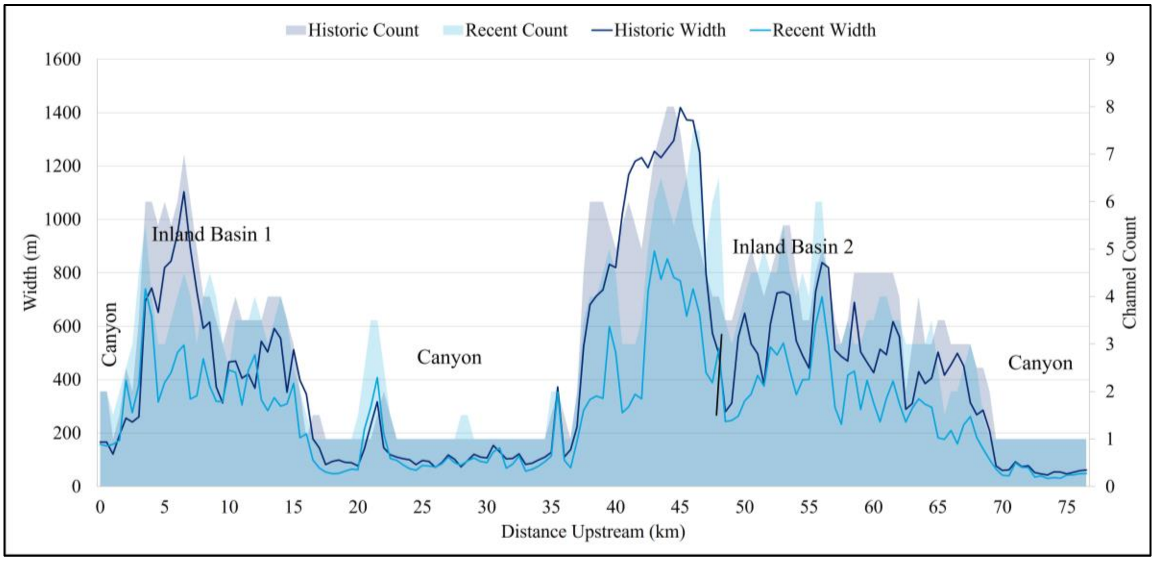

Figure 4.29: Historic and recent width and channel count measurements - Hurunui River.

There is only one site with digitized stop banking and vegetation boundaries along the river, it is located just upstream of the Highway 7 bridge (~50km upstream, marked by black line in Figure 4.29) and next to a large forest plantation. It has caused partial confinement of the river (Figure 4.30).

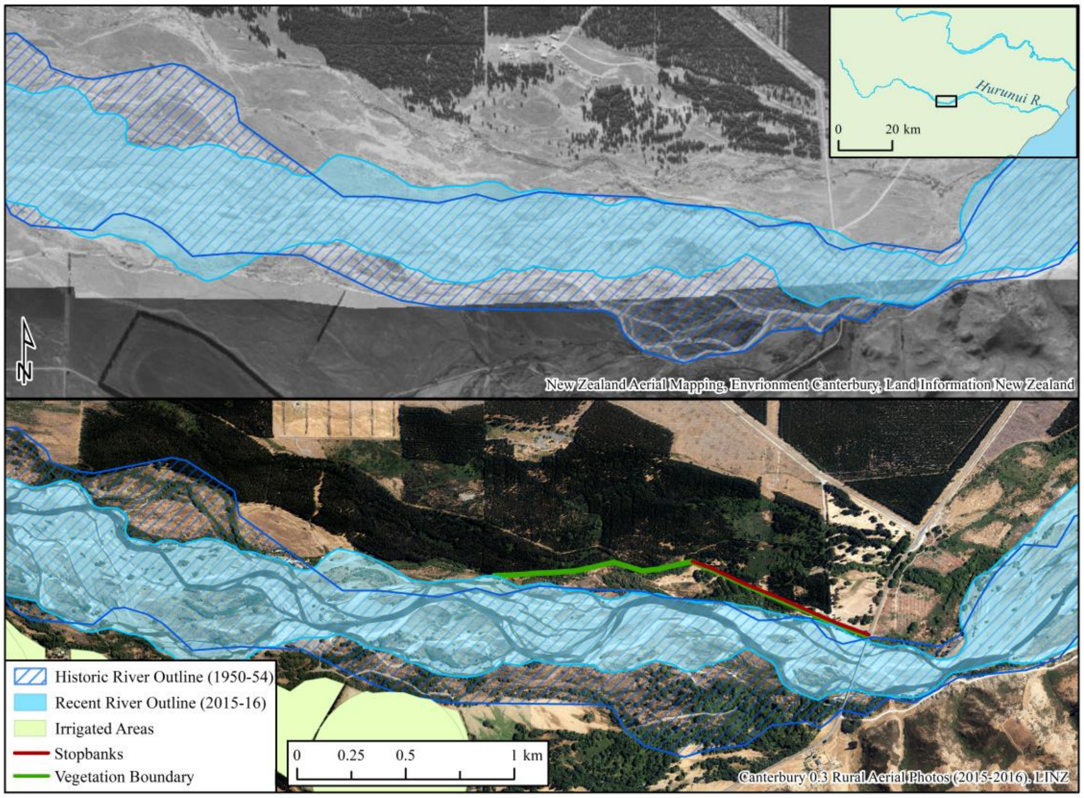

Figure 4.30: Partial confinement along Hurunui River. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

The forest plantation (partially shown in Figure 4.30) appears to extend along most of the upstream basin area, although does not come into much contact with the river. There are also irrigated areas surrounding the river, but these only encroach onto the historic active area in a few locations, unlike the encroachment on the Waiau Uwha River. Other scrub growth has occurred within the historic channels that has caused apparent narrowing similar to the vegetation growth in other rivers.

4.4.6 Ashley River

The Ashley River originates in the foothills and has a relatively small catchment size, but historically had wide channel widths. Being a smaller river, it has experienced a lot of morphologic changes. Significant decreases along the majority of the study segments are observed between the historic (1940-44) and recent (2015-16) periods, with one or two locations showing minimal increases in active width (Figure 4.31). From the mouth of the river at the Pacific Ocean to ~11km upstream, the river has reaches of both narrowing and minimal widening. Upstream of this section, there is continuous narrowing. On average the segments from the remaining 22km reach decrease in width by ~400m or over 60%. The maximum absolute narrowing was ~800m, while the maximum percent change in width from the historic period was almost 90% (~650m of narrowing). A notable drop in the historic widths at about 10km upstream reflects the location of a bridge crossing, present during both periods. The other drops, at ~22km and 30km upstream in the historic widths appear to be natural decreases.

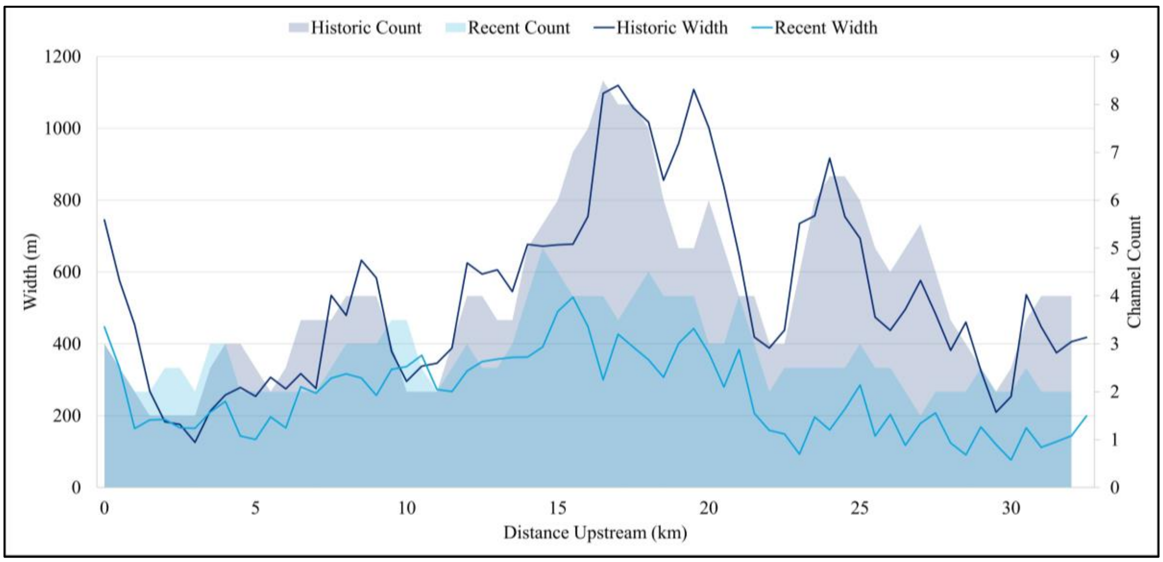

Figure 4.31: Historic and recent width and channel count measurements - Ashley River.

The Ashley River had the highest percent decrease in channel counts from historically braided reaches than any of the medium and large scale rivers. Channel loss occurred along many of the segments of the river, most significantly along the historically braided reaches. Most reaches along the river have channel counts below 3 by the recent period, reflecting the shifts in pattern type to wandering and the locations of channel confinement (Figures 4.7 and 4.10). The section of laterally unconfined, braided reaches remaining are located in the historically widest section (~11 to 21km upstream). This section, although significantly narrowed, remains the widest and has the highest channel counts of up to 4 or 5 in some segments, but those have dropped from the maximum of 8 channels recorded in the same area historically.

The Ashley River has a large amount of stop-banking and vegetation protection boundaries surrounding its channels and causing increases in confinement type. From the aerial imagery alone, stopbank structures cannot be seen as they are covered by vegetation. Using the 1m DEM, however, the stopbank locations can be visualized (Figure 4.32b). Generally, analysis along all rivers were dependent on the Canterbury Regional Council stopbank polyline shapefile. Figure 4.32b, shows how the stopbank positions are wider than the historic extent of the river, and that vegetation growth is occurring within the stopbank areas and in some places significantly encroaching. Therefore, it may be that the narrowing in this area is not always due to the stopbanks, but the vegetation plantings inside the stopbanks. The stopbanks extend upstream along the channel on the southern side of the river with a vegetation boundary along both sides. Where the protection ends, ~22km upstream, the recent channel is also significantly narrower than the historic channel, as the historic channel areas have been filled in by mostly scrub and potentially planted exotic vegetation (Figure 4.32) – an occurrence happening along all rivers it seems. The reach in Figure 4.32a shows the location of the highest percent change in active width and how it seems to be caused by vegetation growth and agricultural encroachment within the historic active channel area.

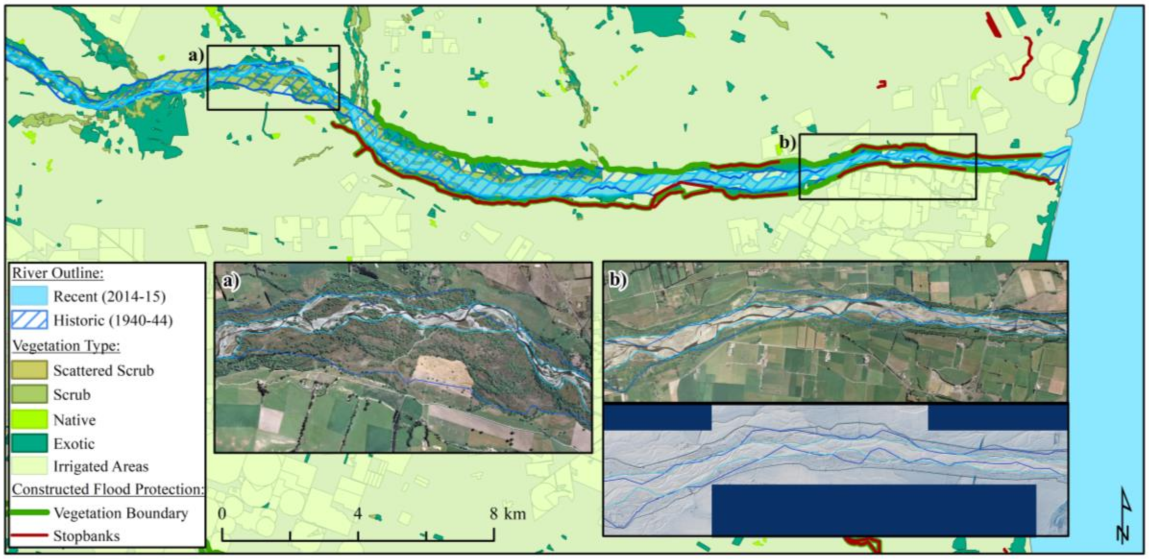

Figure 4.32: Flood protection along Ashley River map. a) Vegetation growth and encroachment within the historic active area of the river. b) Visualization of stopbanks and vegetation growth within stopbanks. Data sources for represented imagery, shapefiles, and DEM are listed in References under 'Data Sources – Imagery', 'Data Sources – Shapefiles', and 'Data Sources – DEM'.

4.4.7 Ashburton River

The Ashburton River originates from the foothills of the Canterbury region and is the widest and longest of the small scale rivers. The Ashburton River has two major branches: the North Ashburton and South Ashburton Rivers. The two branches converge about 20km upstream from the coast. The river had significant changes in confinement type, with almost the entire network partly confined by the recent period (Figure 4.7). The river also had the greatest length of pattern changes and the most variety of change (Figure 4.10).

Figure 4.33 graphs the active width and channel count for the river during the historic (1940-44 downstream, 1955-59 upstream) and recent (2017-18) periods. For the main and north and south branches there is an almost constant width compared to the historic variability. The south branch on average experienced the greatest amount of narrowing (an average 58% or 200m reduction from historic widths). The north branch also had similar reduction levels (on average 51% or 178m reduction from historic widths), although a large portion of this branch could not be considered as there was no historic imagery for a 9.25km long segment. The main branch has been narrowed as well, with an average of 38% or 153m reduction from historic widths.

The river was historically and recently partly confined due to terraces in the downstream end and dense vegetation surrounding the active channel area (Figure 4.34a-d). Currently, there is a continuous vegetation buffer varying in width and density along the network. This vegetation also lines up with stopbanks and acts to provide a buffer against floods and erosion. Stopbanks are located along the main and north branches of the river, and along some banks of the south branch.

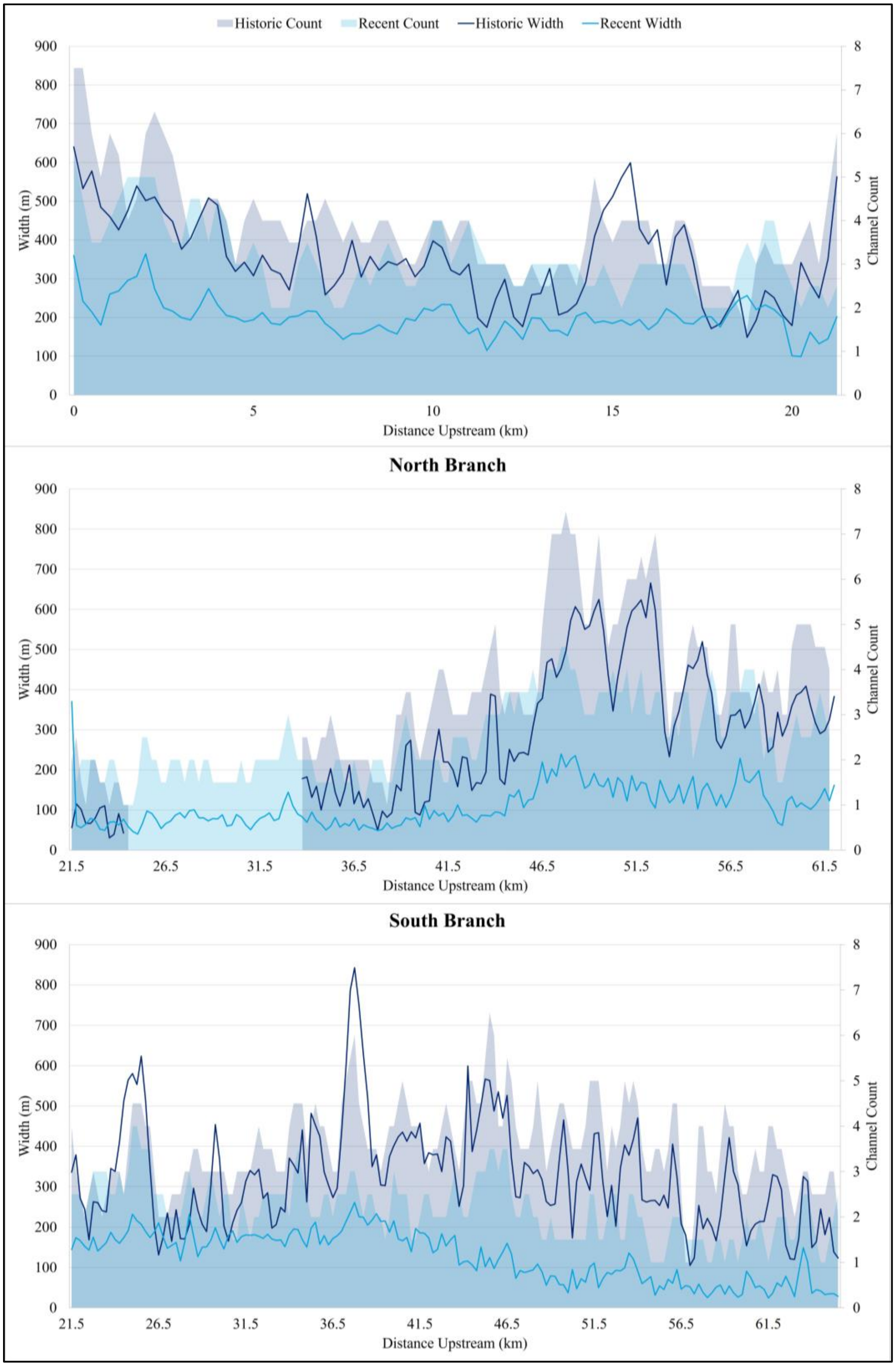

Figure 4.33: Historic and recent width and channel count measurements - Ashburton River. Top: main branch, middle: north branch, bottom: south branch.

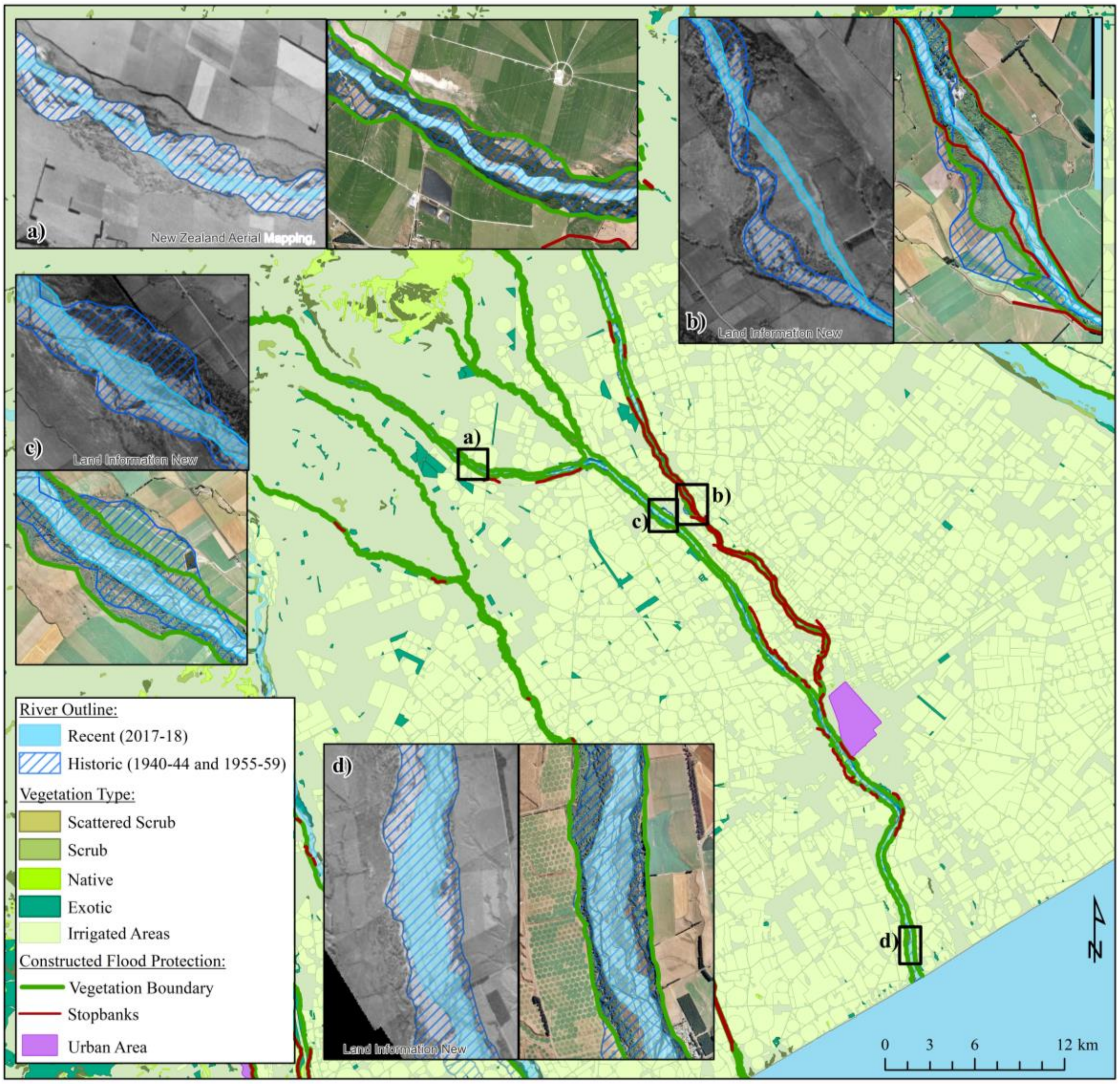

Figure 4.34: Flood protection along Ashburton River map. (a) Braided to wandering planform change. (b) Straightening of channel. (c) Confinement of channel by encroachment and vegetation planting. (d) Terrace and vegetation confinement. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

Starting with the main branch, vegetation growth is prominent within the historic active channel and parts of the channels are confined by stopbanks (Figure 4.34). Beginning at the confluence of the channels and heading upstream on the north branch, a 26.5km segment is partly confined by stopbanks on both sides. In most cases stop-banking contains the historic active channel area (recent area just reduced by vegetation buffer within the stopbank area), but there are some cases where the channel was re-routed (Figure 4.34b). Channel straightening was common along the Ashburton River as well as the other smaller rivers. Upstream of the stopbank section, the north branch is then confined by vegetation boundaries and in some segments the river maintains a lateral freedom and braided morphologies are retained, although with some transitions to wandering (Figure 4.34a). The south branch has some stop-banking on the north bank of the downstream section, but the branch has vegetation confinement along all banks. Typically, exotic vegetation can be found along the channels within the historic active area, but further upstream there is less exotic vegetation and more scrub within the historic area.

The Ashburton River, like all rivers in the region, is surrounded by agricultural area. Flood protection is therefore very important to shield these areas from high flows. In May 2021, an extreme rainfall event gave the upper branches of the river enough power to overtop its stopbanks and cut through the vegetation boundary normally containing it. The water and gravel carried by the river caused significant damage to surrounding agricultural areas, an impact that was still visible months later (Figure 4.35). Stopbanks along much of the river however prevented flooding, the upper branches were stated to have failed because the flow was much higher than what the protection measures were designed to withstand (CRC, n.d.a). Heavy rainfall events in the region are predicted to increase in intensity and frequency as the climate changes (Tonkin and Taylor Ltd., 2022). This is discussed further in Section 6.4.4.

Figure 4.35: May/June 2021 flooding along upstream branches of Ashburton River. Top images show affected sites prior to flooding, middle images show the immediate effects of the flood (June 1st, 2021), and bottom images show the long-term effects two months after the flood (August 9th, 2021). (a) Flooding site along north branch. (b) Flooding site along south branch. Arrows showing direction of flow and damage. Data sources for represented imagery are listed in References under 'Data Sources – Imagery'.

4.4.8 Selwyn River

The Selwyn River flows to Lake Ellesmere (coastal lagoon) unlike the other rivers that have mouths at the Pacific Ocean. The Selwyn River is hydrologically complex, due to its sections of both perennial and ephemeral reaches along the river, flows being dependent on seasonal rainfall and groundwater (Larned et al., 2008). The recent imagery was captured at a dry period and therefore a total change analysis of all segments along the river could not be completed as the flows were disconnected for about 5km.

Classified with many braided channels historically, in the recent period most reaches were categorized as wandering channels, an occurrence common to most of the smaller rivers. Unlike the Ashburton River however, the Selwyn River remains with large laterally unconfined reaches. Despite this, channel width and count decreased from the historic (1940-44) to recent (2015-16) period (Figure 4.36), leaving the river with mainly wandering and single channel planforms and channel counts averaging around 1.5 to 2. In terms of percent change in width, this river has the greatest, with some reaches experiencing over 90% decreases in active width (such as Figure 4.37b).

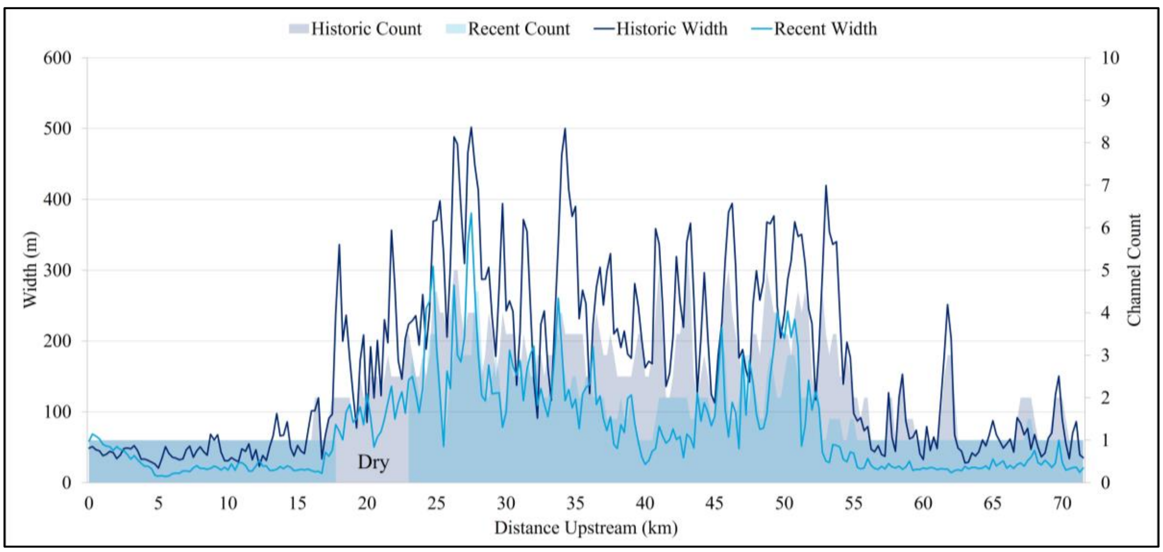

Figure 4.36: Historic and recent width and channel count measurements - Selwyn River.

The downstream 4km of the river is confined by stopbanks and vegetation in both historic and recent periods (Figure 4.37c). Upstream of this area, both stop-banking and vegetation boundaries continue, however the freedom space for the river generally increases and braided morphologies occurred historically. At 40km upstream the vegetation boundary ends. From this point to ~54km upstream the river flows laterally unconfined. Historically, this area was braided, but most recent planforms have a wandering planform. Upstream of this segment widths are confined and constricted into narrow channels and by the recent period any wandering classified planforms are transformed into small single channels that are surrounded and directed by a line of vegetation on both sides of the channel. In some cases, this confinement has changed the length of the river by straightening the channels (Figure 4.37a).

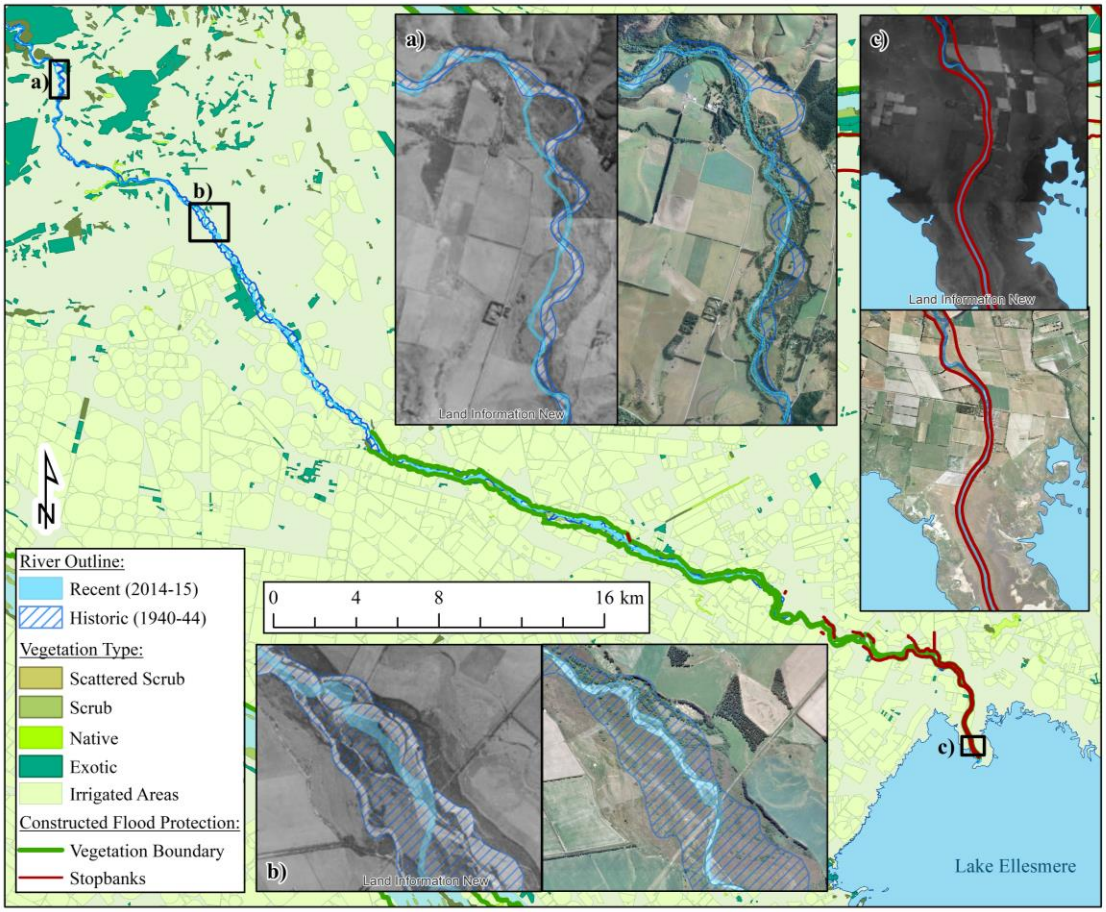

Figure 4.37: Flood protection along Selwyn River map. (a) Channel straightening. (b) Site of 90% decrease in channel width. (c) Downstream channel confinement by stopbanks. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

4.4.9 Eyre River

The Eyre River is a tributary to the Waimakariri River. Similar to the Selwyn River, it has periods with dry channels, again captured by the recent aerial imagery (for 16.25km length). Based on available coverage, by the recent period the total study segment is classified as wandering with upstream increases in single channel planforms as well. Some braided to wandering planform shifts occurred without change from a laterally unconfined confinement type, similar to reaches along the Selwyn River.

Figure 4.38 shows the difference in active channel width for the historic (1940-44) and recent (2015-16) periods on the Eyre River. The average widths were the lowest of all rivers studied. The total average width was approximately 110m during the historic study period and decreased to ~55m by the recent period. Although an active width could be distinguished from the recent orthoimagery, some reaches of the network were too dry for accurate channel counts (Figure 4.39c). The first 5km of the river are channelized by stopbanks and a vegetation boundary similar to the Selwyn River (Figure 4.39d). Upstream the vegetation boundaries continue on both sides of the river, with exotic vegetation and some scrub growth within the historic active channel area and along the river margins (Figure 4.39b). In the narrow upstream reaches a section of river straightening is highlighted in Figure 4.39a, though straightening continues along many surrounding reaches.

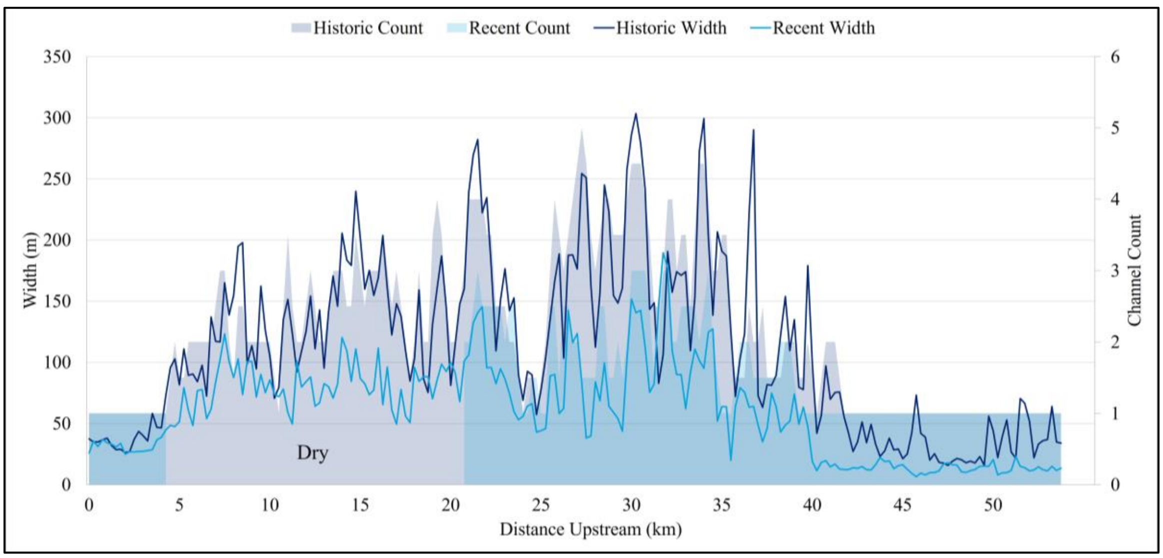

Figure 4.38: Historic and recent width and channel count measurements - Eyre River.

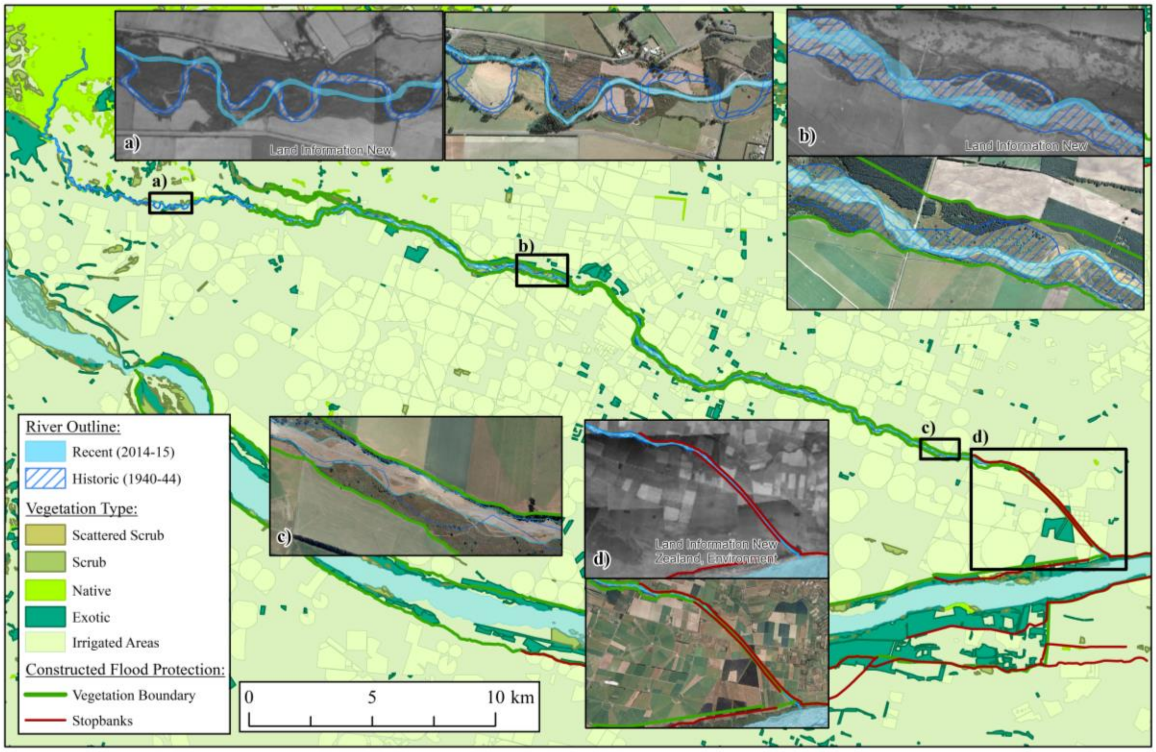

Figure 4.39: Flood protection along Eyre River map. (a) Channel straightening. (b) Vegetation growth within historic margins of the braidplain. (c) Sample site of dry channel (recent period). (d) Downstream channel confinement by stopbanks. Data sources for represented imagery and shapefiles are listed in References under 'Data Sources – Imagery' and 'Data Sources – Shapefiles'.

4.5 Summary

The selected rivers of Canterbury have undergone major changes between the mid 20th century and present. The characteristic braided river patterns of the region have changed, leaving a less braided and more 'controlled' fluvial landscape. The river margins have been subjected to artificial confinement in order to control the rivers and protect surrounding areas. Artificial confinement has involved vegetation planting of exotic plants, such as pine, willows, and poplar species, and engineering including stopbanks and groynes (Grove et al., 2015; Williams, 2017). The rivers have also been subject to encroachment to take advantage of the large areas that are not always actively occupied by the river. These actions have contributed to the general narrowing along all the rivers.

Each river has changed in unique ways, but there are multiple commonalities between the rivers and the types of changes observed. The most common change along all rivers is the narrowing of channels, on average rivers narrowed by ~43% (and ~48% for initially braided segments). Historic active areas were commonly observed to be replaced by artificial and confining flood protection margins and agricultural encroachment. Constructed confinement such as stopbanks and vegetation buffers along the rivers were built to protect surrounding areas from the river. In some cases, these margins are wider than the digitized historic active area of the rivers, although areas within the margins tend to be allowed to naturally fill with native or invasive vegetation making the river narrow. In many cases, rivers have been trained to have an almost constant width along their channels, compared to the historic variability. A consistent width reduces lateral pressures due to meandering channels (Williams, 2017).

Artificial confining margins built within the study period have constricted many reaches along the rivers causing simplification of channel patterns. Continuously along the rivers, channel count has decreased similar to channel width, therefore creating less complex systems. On average, braided channel counts decreased 27% (or by ~1.3 channels). In some reaches this has been significant enough to cause changes in planform type, most commonly, braided to wandering. In total over 100km length of the total rivers studied changed from a braided morphology to a less complex planform (either wandering or single channel). In particular, the smaller rivers have shown the most, in terms of both length and variety, planform changes over time. Vegetation belts planted and stopbanks constructed along the small scale rivers are very common and constricting, perhaps because these rivers could be controlled by such margins more effectively than the larger rivers. The large scale rivers remain the widest over time, despite considerable narrowing, and have the longest lengths of braided channel patterns still recorded, although with reduced intensity.

There are many factors controlling river channel morphology that were not addressed. A major example is discharge. It is unlikely that changes in discharge are a driving factor of river change. Although all rivers in the region have narrowed, the amount of narrowing varies between and along rivers. The amount of change in discharge over time could not have been enough to cause such drastic and selective narrowing. Given the spatial variability in changes and with some rivers having much more limited changes, there is no strong evidence in favour of a region-wide discharge change influence.

There appear to be many relationships between river characteristics collected. The next Chapter will explore these relationships and the influence of channel narrowing on planform simplification. The Chapter will explore whether channel pattern theory can help with understanding what is happening and if there are identifiable trends and thresholds that would allow anticipation of, for example, channel width at which braiding would be reduced or eliminated, or contribute to planning for enhancing braiding in the future.

Chapter 5

5 Analyzing Channel Pattern Relationships

The nine rivers of interest from the Canterbury Plains have significantly changed over the study period. Chapter 4 showed that there was widespread reduction in channel width, decrease in channel count (braiding intensity), and general loss of braiding to wandering or single channel planforms (as well as other channel planform changes). This chapter aims to study the overall association between the trends and explain the changes in channel pattern associated with width reduction. Lastly, braiding theory will be explored to see if it can explain the observed changes in channel pattern. The large dataset available allows for these ideas to be addressed and can go beyond conditions for braiding but also intensity of braiding which is above the threshold for its occurrence. The results will be useful to understand the changes in the Canterbury rivers and in understanding of braiding and channel pattern transitions more generally.

5.1 Channel Width and Complexity

5.1.1 Relationship

There is an overall relation between width and channel count. As rivers narrow, the number of channels within a segment decreases (and vice-versa; Figure 5.1a). At larger width values, ~2,000m, however, this trend flattens out and these wider channels are not necessarily providing higher channel counts. The relationship has a strong positive correlation coefficient of 0.91 (p-value <0.001). Between the historic and recent period, the relationships are very similar, the lower slope of the historic plot may be because of the larger range of widths exceeding 3,000m (Figure 5.1b).

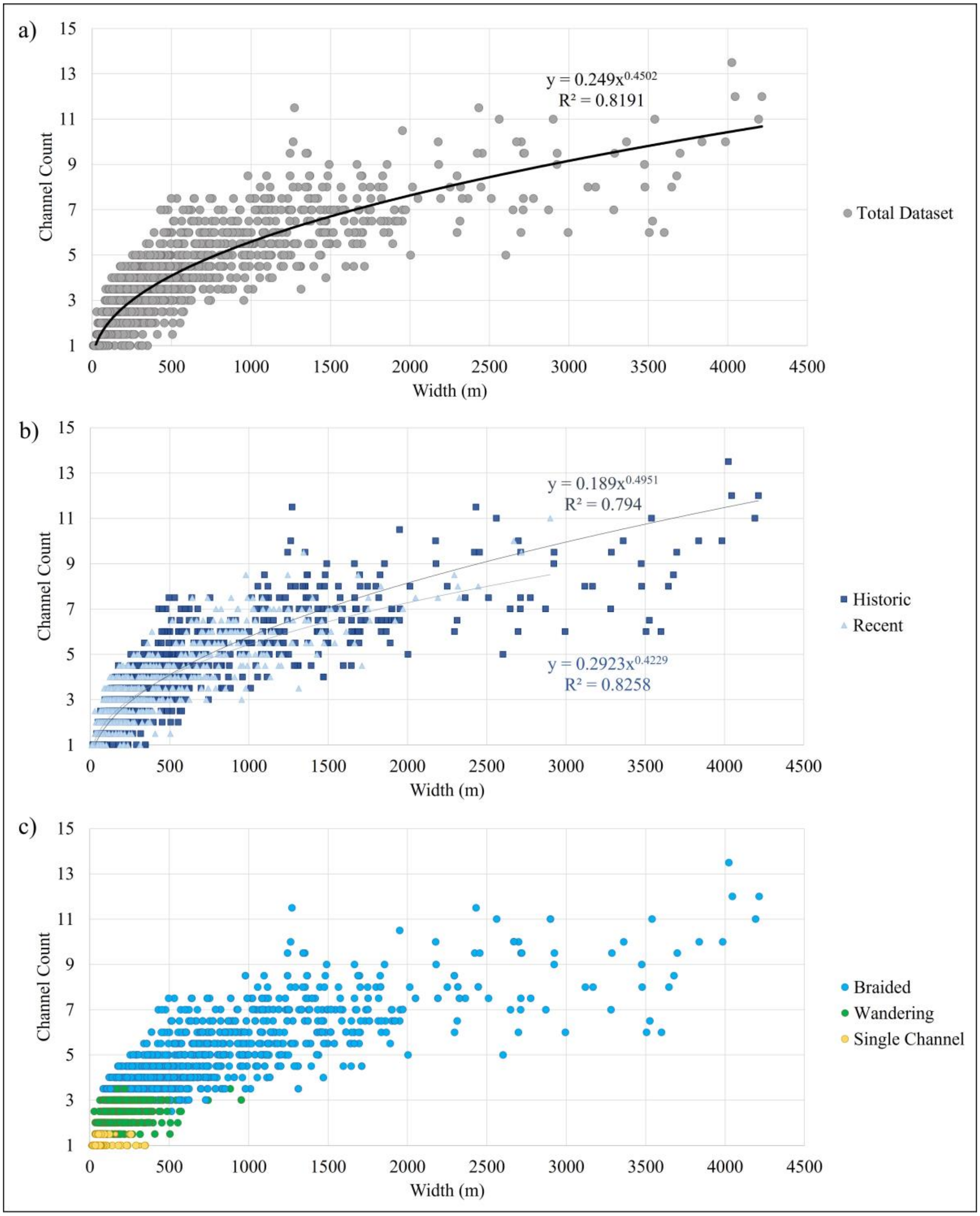

Figure 5.1: Width and channel count relationship. Individual segments coloured by (a) all rivers (both periods), (b) historic and recent periods, and (c) planform type (both periods).

Active channel width and channel count have distinct, yet overlapping, divisions between each planform type (Figure 5.1c). Single channels have the lowest recorded widths. As both channel count and width increase, wandering channels form followed by braided channels. Note, the channel planforms are initially defined in terms of channel count, and we know already that both width and channel count are correlated to channel planform types (Section 4.3.3). The widths at which change between planform types occur have significant overlap. For single channel and wandering planforms the transition range of widths is about 30-300m, and transitions between planforms begin when channel counts increase above a single channel. The transition range of widths from wandering to braided planforms (or vice-versa) is about 100-500m but only begins when channel counts are 3 or above. Above about 500m width, only braided segments occur.

Braiding is associated with larger widths and channel counts. Over time, the maximum recorded widths and channel counts were lost (Figure 5.2, note the shift of data towards the bottom left), and channels transitioned into less complex pattens. Trendlines of recorded data for each river were created, the recent trendline is slightly steeper than the historic trendline for each river. It implies that over time as the channels became narrower, they are more likely to have greater channel counts than historic trends for the same width. It is unknown if this is a transitionary remainder or vestige, or if other factors may affect this. The Waimakariri and Hurunui rivers had the least amount of change in width and channel count between periods and this is reflected in the minimal changes in segment values over time. The Rangitata and Ashley rivers on the other hand had significant changes over time, the Rangitata River responding to major confinement along its downstream end, and the Ashley River transitioning from mainly braided reaches to wandering along its network.

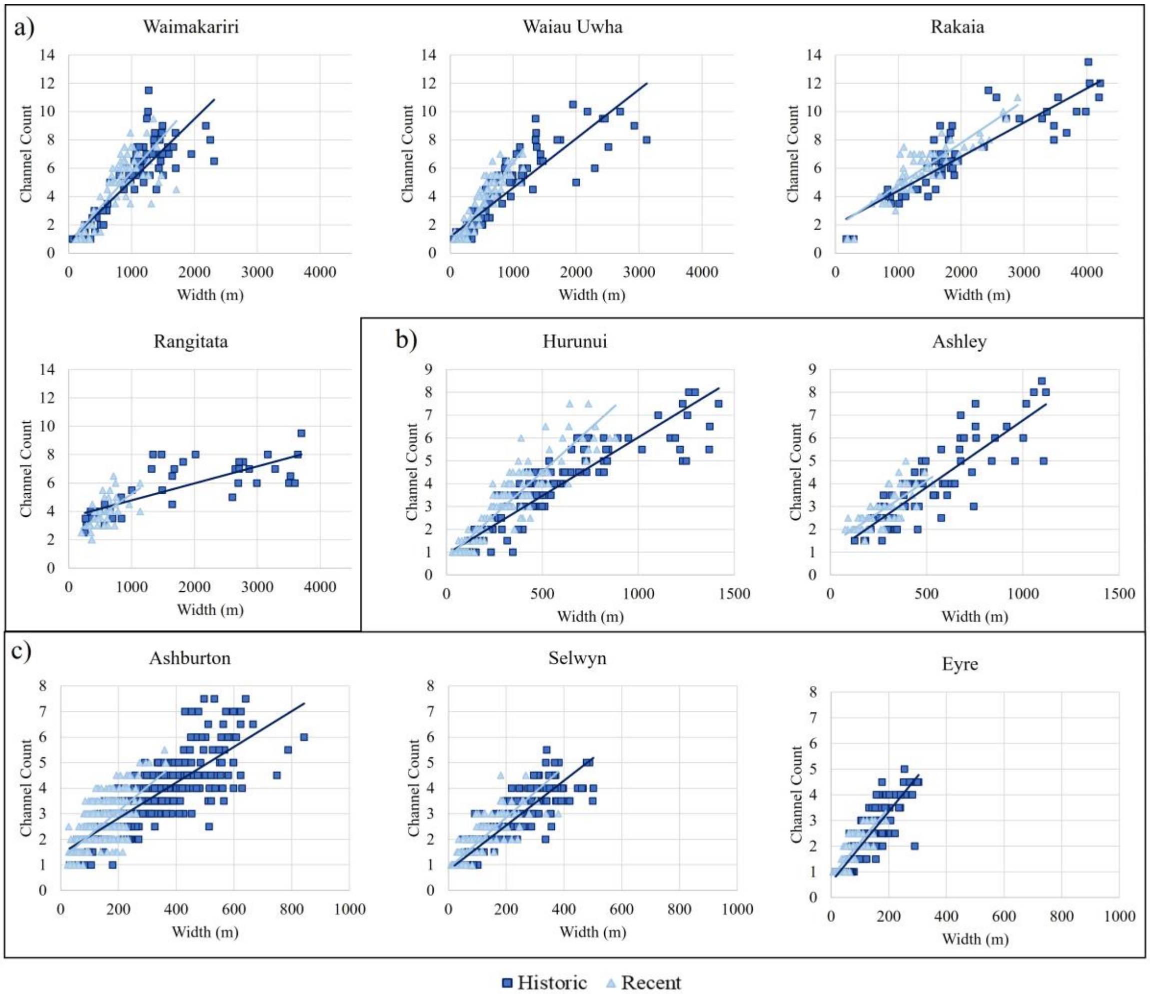

Figure 5.2: Historic and recent shift in width and channel count relationship by river. Sorted by river scales (a) large, (b) medium, and (c) small.

Overall, there is a strong association between width and channel count (braiding intensity) which tells us that width constraints will cause predictable (but scattered) loss of braided channels and possible transition to wandering or single channel planforms. The historic effect of width change has already captured this as both the intensity and presence of braiding planforms along the rivers has reduced.

5.1.2 Channel Count and Width Change

Channel counts tend to decrease as river segments narrow (Figure 5.3). Channel count changes ranging from +2.5 to -4 channels occur with width changes between +100m to -500m. Increases in active width are matched with increased or unchanged channel counts (with some exceptions). As more narrowing occurs, there is a slightly increased likelihood of additional channel loss. Segments with the most narrowing, tend to have the most channel count loss. Approaching -1,000m width change, the trend begins to become less well defined as the relationship disperses and no matter the decrease in active width, channel count change remains similar to that with lower width losses. This is part of the active width and channel count data trend as seen in Figure 5.1, where at about 2,000m widths the channel counts do not continue to increase with increases in width. There are a few reaches where channel counts increase. This tends to occur where there are increases or minimal changes to active width.

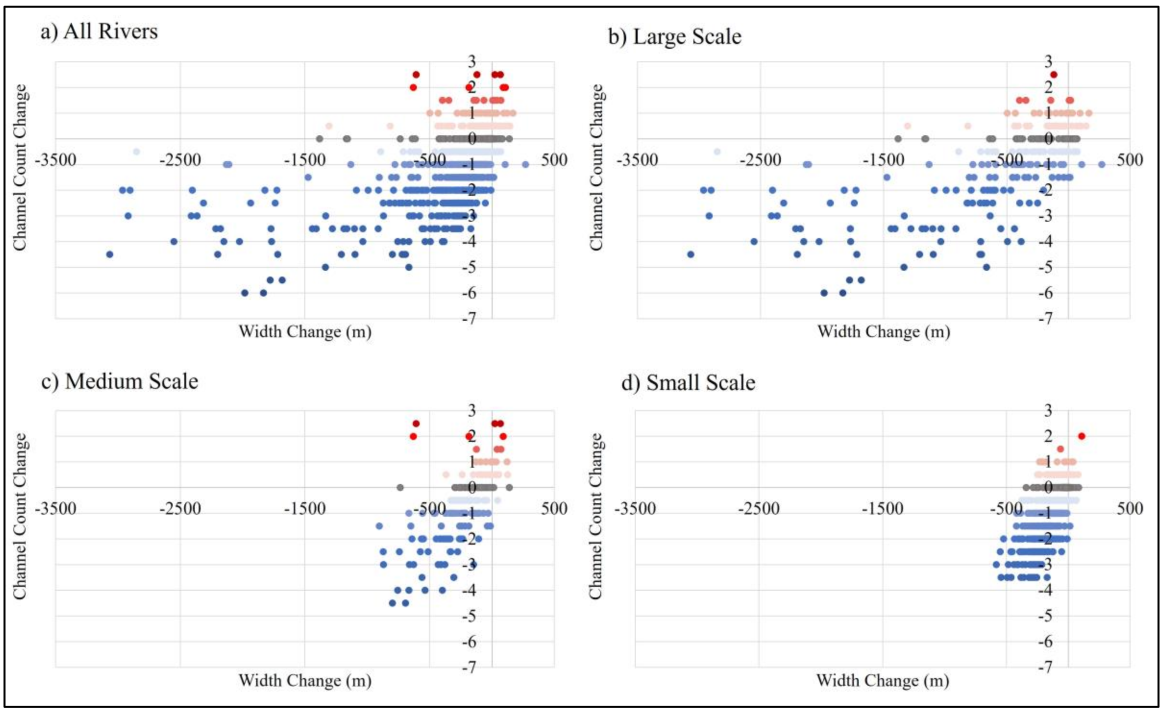

Figure 5.3: Change in width and channel count relationship. a) All Rivers, b) Large Scale Rivers, c) Medium Scale Rivers, and d) Small Scale Rivers. Points coloured by channel count.

When the data is separated by river scale, the same trends are seen. The large scale rivers (Figure 5.3b) contain the only segments wide enough to have greater than -1,000m narrowing and therefore show the most scatter. The medium and small scale rivers (Figures 5.3c-d) also have scatter, but at the smaller scales it appears to begin earlier than the large scale. The medium and small scale river changes have more closely related trends in width and channel count.

The overall trend and relation between percent changes in width and channel count shows a scattered but evident correlation (correlation coefficient of 0.60, p-value < 0.001) where channel counts decrease with decreases in channel widths (Figure 5.4). There is scatter but in general, segments that have more narrowing also have the most channels lost over time. Overall, there is a level of correlation between active width and channel count and this relationship may show the influence of channel narrowing on river pattern and pattern change. This will be explored in the following sections.

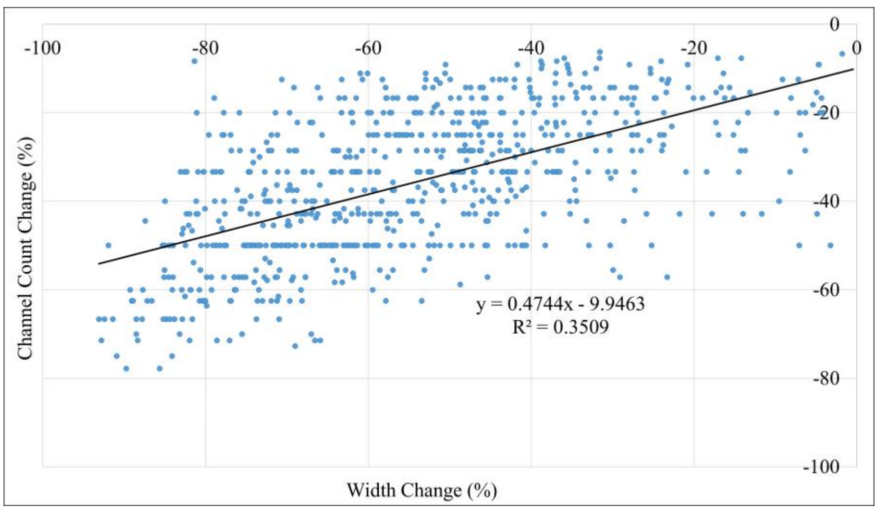

Figure 5.4: Relationship of channel narrowing and channel count. Excluding segments with increases or constant width or channel count changes.

5.1.3 Braiding Limits

Within braided channels there is a well-defined average and minimum width relationship with channel count (Figure 5.5). The average and minimum width for a given channel count increases when more channels are present. The width relationship shifts slightly between the historic and recent periods (possibly from measurement inaccuracy), but the results are consistent in general, and trends were measured with the total dataset (both historic and recent). The total trendline shows a strong relationship between the average and minimum channel widths for increasing channel counts. At the high channel counts however, the relationship changes. The historic dataset has active width data for segments with up to 13 channels. The number of segments with 12 and 13 channels however total two and one, respectively. These do not provide a reliable representation of reaches with such channel counts and were not included in trendline calculations (shown in average graph, removed in minimum graph). The recent data only reaches a maximum channel count of 11, but the similar problem of too few segments within that range led to those records also being excluded (shown in average graph, removed in minimum graph). The recent data only goes as high as 8 channels. Based on the historic dataset, the relationship of minimum width for braiding begins to change at about 10 channels. As channel counts increase above 9, the minimum width required (or recorded) does not need a significant increase contrary to what was seen with the change in lower channel counts.

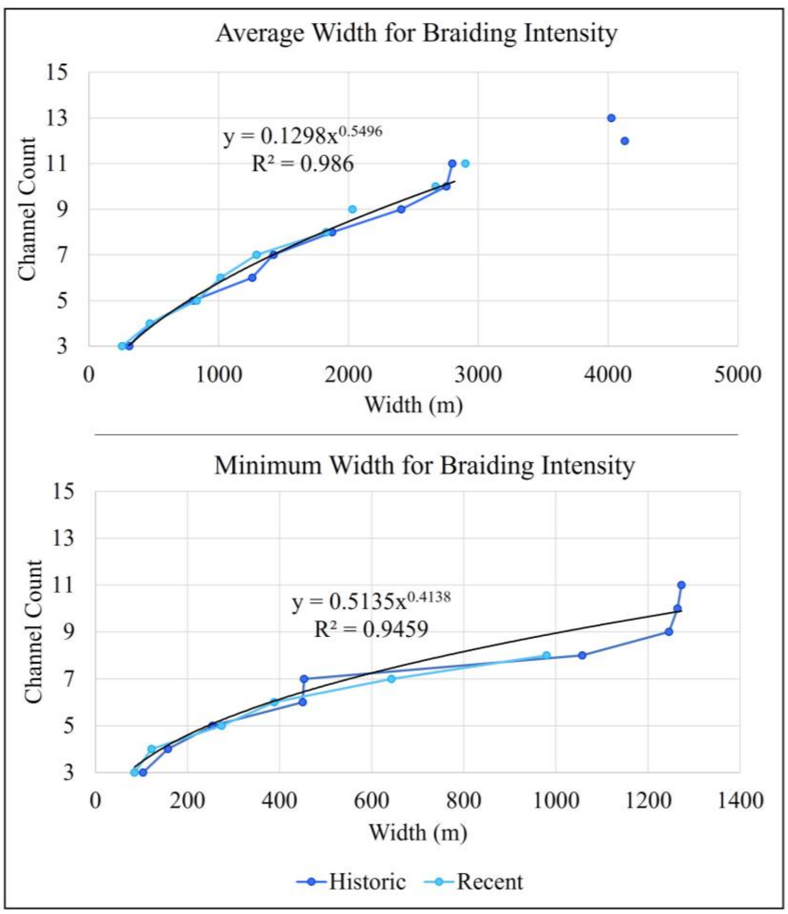

Figure 5.5: Average and minimum observed width for braiding. Trendline in black represents average or minimum width for the total (historic and recent) dataset.

The relationship trendlines show what braiding index to expect for a given active width and therefore what reduction to expect for a given narrowing. Along the total rivers studied, the minimum recorded width for a braided segment with 3 channels (the defined minimum number of channels required for braiding) was ~100m (historic, from Eyre) and 85m (recent, from Ashburton). The average width for braided segments with 3 channels was ~300m (historic) and ~250m (recent). When the braided results are analyzed by scale, the trends in width change with increasing channel counts remain, although the starting widths for each count are lowest for the small scale and highest for the large scale (Figure 5.6). Table 5.1 summarizes the minimum and average width requirements for a 3-channel braided reach, sorted by scales.

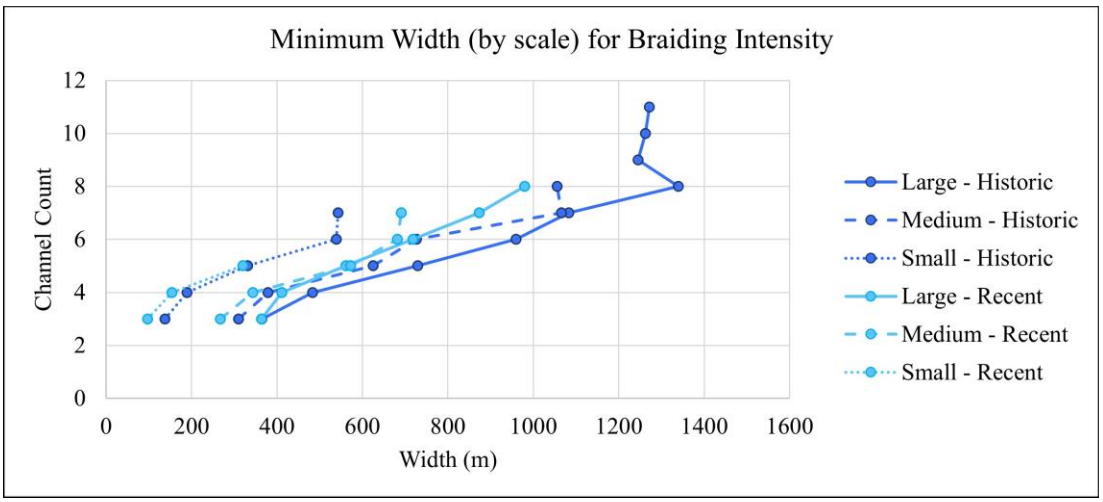

Figure 5.6: Minimum width for braiding, sorted by scale.

Table 5.1: Minimum and average width for braiding

Scale	Historic (minimum, average) width for braiding (>3 channels) in m	Recent (minimum, average) width for braiding (>3 channels) in m	Percent Change Historic to Recent (minimum, average) in %
Large	365, 566	364, 562	-0.1, -0.7
Medium	310, 419	267, 328	-14, -22
Small	138, 262	97, 172	-29, -34
All	138, 311	97, 256	-29, -18

The minimum average width for braided morphology based on all rivers is ~250m. Large scale rivers are typically much wider than this and therefore have a large buffer for reduction compared to the small scale rivers. This may be why most large scale rivers retained the most braided segments over time (though with lowered braiding intensity). The small scale rivers have no buffer for change, so if narrowed, they would lose channels and change planform type.

5.2 Width Change and Planform Change

5.2.1 Channel Planform Variation

This section will analyze the morphologic changes of historically braided reaches and begin to answer the second research question regarding how braided morphology responds to channel narrowing. Chapter 4 showed that some lengths of the rivers have undergone planform type change as well as channel count reduction along with, or because of, width change and confinement.

The range of recorded width values is large, however the bulk of the dataset shows channel pattern change is clustered below 500m historic width (Figure 5.7a). Most braided morphologies that remain unchanged with channel narrowing have widths greater than 500m, therefore the changes below are from braided-to-wandering, wandering-to-single channel, and braided-to-single channel (small scale rivers only) for already narrow braided reaches. The wandering range of widths remains relatively constant over time. The range is most significantly from about >50 to ~200m and most braided-to-wandering transition reaches fall within that range by the recent period. For single channel patterns this is also true with almost all single channels occurring in widths less an 100m. By the recent period, all historically single channels remain in that range, and all channels that have changed to single channel are also within that range. Overlap between historic and recent planform types is very common, but a clear distinction can be made between braided and single channels. Overlap by wandering segments may signify that some are at the cusp of changing morphologies, or an effect of grouping the results of all scales together.

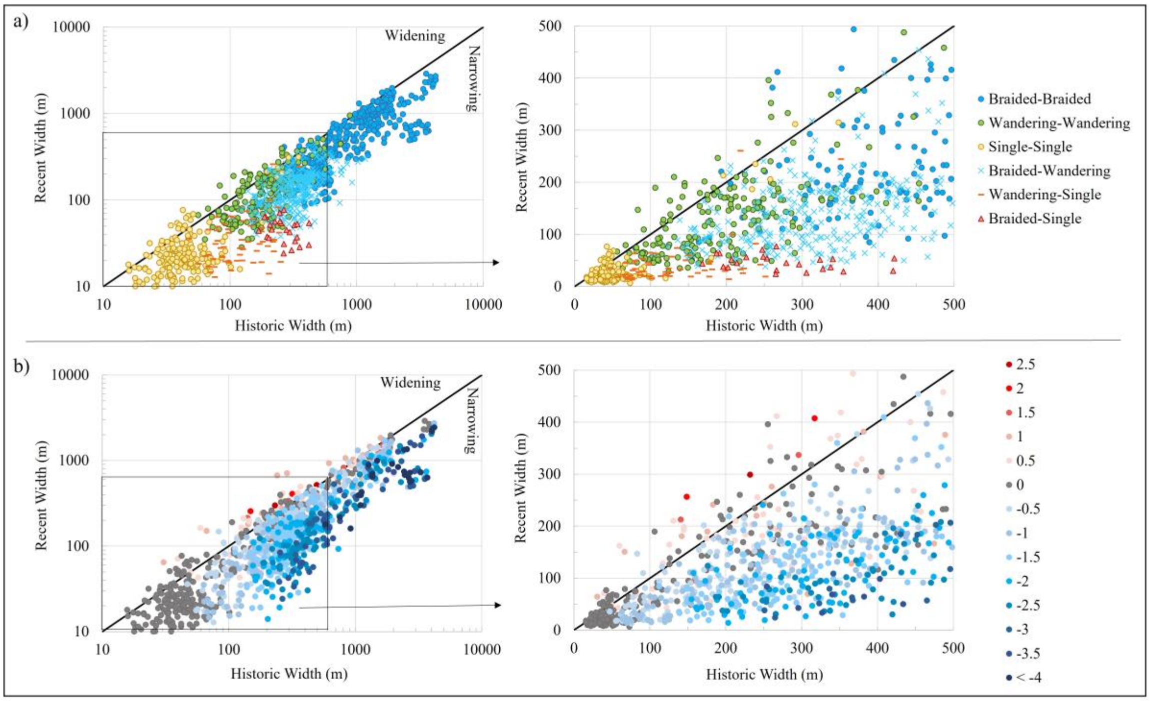

Figure 5.7: Relationship of channel width and pattern change. The black line from origin to top right corner is the 1:1 line. a) Points coloured by either constant or simplified planform change, b) points coloured by channel change (red signifying gaining channels, blue signifying losing channels).

Braided-to-single and wandering-to-single transitions plot in distinct areas of the graph with lower initial width and larger proportional width reduction. The further the shift beneath the 1:1 line for width change, the more common the pattern change is. The magnitude of change also influences the type of pattern shift, for example, braided-to-single changes need bigger width reductions than braided-to-wandering (of the same historic width). All types of pattern transitions occurred and were more prevalent in the smaller (initially less braided) channels. The larger braided rivers remained braided even with significant width reduction.

The relationship of width and channel count was already established. When historic vs recent widths are coloured by channel count in Figure 5.7b, a trend in channel count change is seen along the total dataset. The braided river region has the highest channel count loss of all the planform changes over time. Therefore, even rivers that maintained the braided category have lost significant numbers of channels, decreasing their complexity. A transition of greater channel count change away from the 1:1 line is also seen which lines up with the segments that also change in planform type. In general, the further below line the more channels lost, especially if starting from a larger historic width value. Focusing on the segments which had the most change in pattern type (500m historic by 500m recent widths), the relationship of more channel count change with distance from the 1:1 line is seen.

Channel planform transition and change in channel count depends on both initial width (and planform, and proximity to threshold for planform shift) and on the amount of width reduction.

5.2.2 Conditions for Channel Planform Change

There is a relation between pattern change, starting (historic) width, and amount of channel width change. This can be visualized when Figure 5.7 is replotted to directly show the trend in relation to amount of channel narrowing (Figure 5.8). As channels narrow, the likelihood of channel change also increases, conditional on how far from threshold it is at the start. The more narrowing, the higher the likelihood of channel change.

Figure 5.8a shows the relationship between historic width and change in width. The relationship goes in the direction of larger historic widths tending to have more narrowing than historically smaller widths, possibly because the larger widths were the ones most susceptible to encroachment or channel confinement. The categories of pattern change also follow a linear relationship. If the initial starting width is small, then the amount of narrowing required to induce a change in pattern is lower, but as starting widths increase, more narrowing is required to see a change.

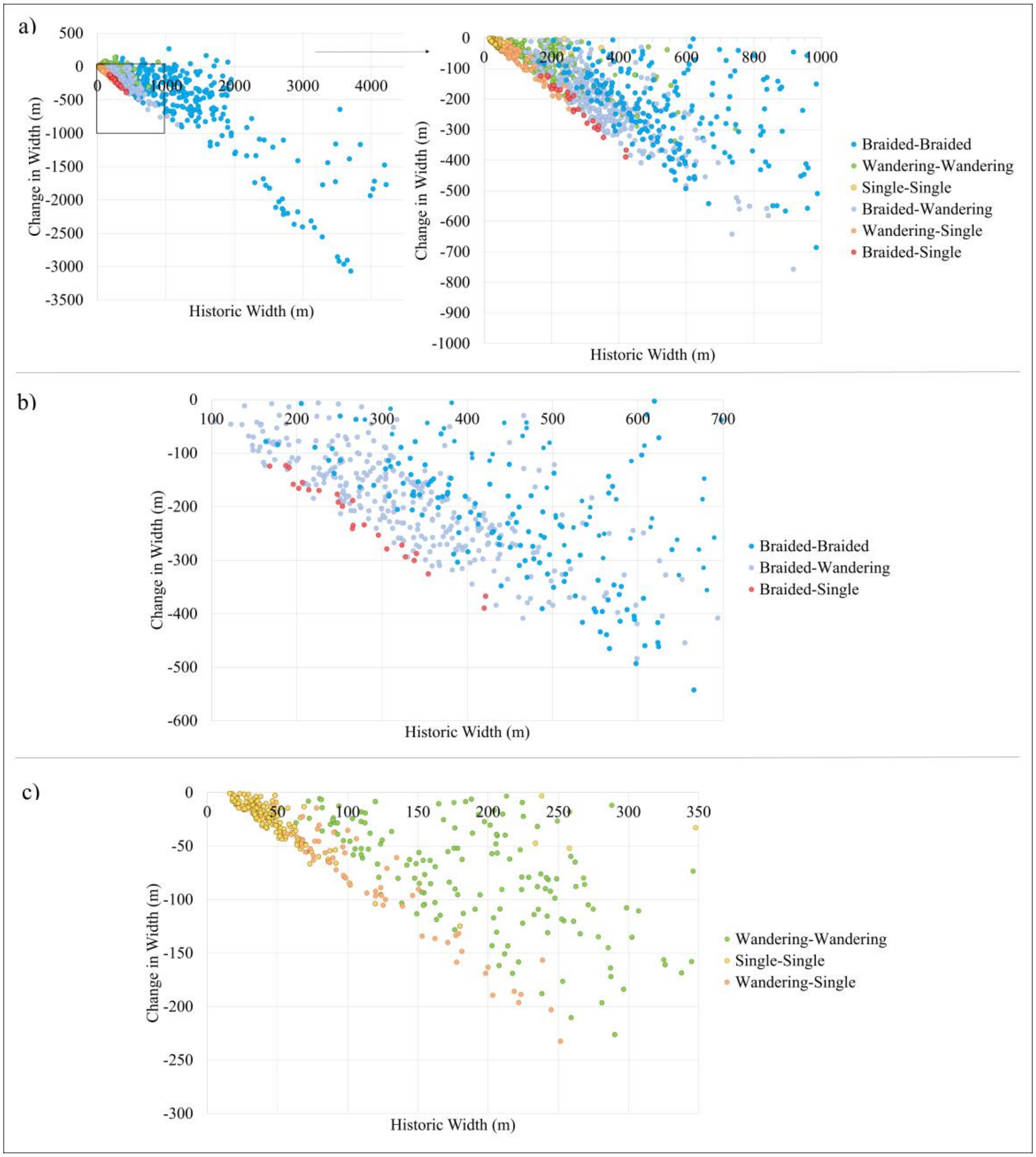

Figure 5.8: Change in width and planform type over historic width. (a) Points coloured by all constant and simplified planform changes, b) only showing segments that were initially braided, and c) only showing segments that were initially wandering or single channel.

The braided-to-braided category stands out with the greatest amount of channel narrowing. The difference between these segments and the ones changing planform type is likely the extremely wide starting widths. As historic braided channel widths get closer to around 500m, the chance of channel type change greatly increases with narrowing. This can be seen more clearly in Figure 5.8b where only segments that changed from an initial braided pattern are displayed. At the larger starting widths, braided-to-wandering is the only change recorded. The largest starting width for this change is seen just over 900m and the segment narrowed by about 750m to a 150m recent width. This value is no longer in the predicted range of braided planforms and consequently shifted planform types to wandering. As starting widths decrease and similar proportions of width changes occur, more braided-to-wandering transformations occur. Braided-to-single channel segments appear with starting widths as high as ~425m. For this example, the segment width decreased almost 400m, leaving only a 25m wide channel. This is well below the range determined for both braided and wandering pattern occurrence. The distinction between braided-braided and braided-to-single channel planform transitions is very clear. The braided-to-single channel points begin with lower starting widths (small scale rivers were the only ones exhibiting this type of channel change) and have the greatest narrowing of any segments beginning at those widths. The line of braided-to-single channel segments lies directly underneath the braided-to-wandering line, with some overlap and has no overlap with braided-braided points. For the wandering-to-single channel changes, the data points also follow a linear pattern (Figure 5.8c). Wandering-to-single channel changes occur at starting widths less than 300m and have a greater amount of channel narrowing than the wandering-to-wandering points, with some overlap. The single-to-single channel segments had the lowest starting width and least amount of change of all changes recorded. The transition from braided-to-single to wandering-to-single points is interesting as it occurs at almost the same trendline, but at a certain point near about 200m historic width, the points go from braided-to-single to wandering-to-single, as braided morphologies below or around 200m would have been too narrow for a braided planform to form historically.

The trends for each type of planform change are almost parallel but gradually converge (and cross) towards the top left of the data (towards a single channel pattern). This implies that there is a point of narrowing to a given starting width that results in a change in channel pattern type. If only slight narrowing, there is a higher probability of retaining the same pattern type, but if there is significant narrowing, the segment may fall near a channel pattern change line becoming more likely to change in pattern type.

Overall, these analyses show that change in planform type is contingent on both starting width (i.e. how close the segment is from pattern threshold to begin with) and amount of width change. Lower starting widths with more narrowing means a high probability of channel planform change. Braided-to-braided have larger initial widths and therefore even with significantly greater width reduction the threshold point of planform change may not be met. Recall Figure 5.3, braiding intensity also decreases with more narrowing, and the larger widths tend to have more channels to lose, becoming less braided despite no categorical change in pattern type.

5.2.3 Classifying Potential for Channel Planform Change

A linear discriminant analysis (LDA) discriminates between a given set of categories and was completed in R to determine if the data could be automatically classified by channel planform type based on starting width and width change (Finnstats, 2021). The analysis creates linear boundaries between given categories and maximizes separability by accounting for the variation between categories and maximizing the distance between category means (Doring, 2018). A quadratic discriminant analysis (QDA) was completed with the LDA to determine if the more flexible, non-linear boundaries may classify the data better than the linear boundaries (Doring, 2018). The statistical discrimination outputs accuracy measurements for each division of planform type change in a confusion matrix from which overall accuracy, precision, and recall of classifications can be determined. Overall accuracy represents the total number of segments classified into correct planform types based on the total dataset. While precision represents the accuracy of segments within a predicted planform type (or, out of all the times the analysis said a segment was braided-to-braided, for example, precision is the percentage that actually was) and recall represents the proportion of segments correctly classified as a given planform type out of the entire segments of that type in the dataset (or, of the total segments within a given category, the recall is the percentage of correctly identified segments by the analysis). The confusion matrices are provided in Appendix B.

An LDA was performed for the total dataset (where planforms simplified or did not change) and planform categories were classified with an overall accuracy of 60%. The QDA analysis provided slightly better results with an overall accuracy of 62%. Lower overall accuracies were expected considering the visual overlap and similarities between the groups. The most confusion occurred between the braided and wandering planforms and braided-to-wandering planform change categories and no confusion was recorded between braided-to-braided and single-to-single categories. The braided-to-braided and single-to-single categories had the highest precision values, while the braided-to-wandering and single-to-single categories had the highest recall. The braided-to-braided category was commonly classified as braided-to-wandering, lowering its recall.

The LDA and QDA analyses were run again but separated by river scales to remove any influence of scale-caused overlap between segments. Classifications when run separately by scale have increased accuracy results. For the large scale rivers, only the braided-to-wandering planform change was recorded. In the LDA results, all segments were classified as braided-to-braided and due to the larger proportion of braided segments in this scale the accuracy results were disproportionately high. The QDA analysis was able to correctly distinguish the wandering and single channel reaches in some cases with a higher overall accuracy of 91% compared to 88% from the LDA. The medium scale river overall accuracy results from the LDA and QDA analysis were 78 and 76%, respectively. These rivers also had only braided-to-wandering planform changes, and for the medium scale rivers, more segments were categorized as that type leading to more overlap between points and more confusion, compared to the large scale results. The small scale rivers show the most variety of changes within their segments. The overall accuracy for the small scale rivers was the lowest overall (LDA: 66%, QDA: 70%), this may be expected as these systems have the narrowest channels that generally require more subtle changes in width to cause planform change. Overall, higher accuracy results were found when the dataset was separated by river scales. The most confusion occurred between the braided-to-braided, braided-to-wandering, and wandering-to-wandering classes, which is expected as the reaches that changed may have been narrower to begin with and then decreased into the wandering width range. The braided-to-braided and single-to-single categories had the most separation as expected due to their distinct morphologies.

A final LDA and QDA were run to discriminate between braided-to-braided and the remaining categories to see how well only un-changed braided planforms could be discriminated. Both the LDA and QDA results were very similar with overall accuracies of ~83%. The overall accuracy is high due to the larger proportion of values now within the ‘other’ or non-braided category. Significantly more segments should have been classified as braided-to-braided based on the low recall around 50% in both analyses.

There is an initial challenge, separate from the discrimination analyses, of deciding, visually, whether a channel is braided, wandering, or single. The results of these analyses are, in a way, successful in showing this problem of categorization itself. Similarities causing overlap between planform categories was a known property of the categories, specifically between wandering and braided or single categories. In these transitional areas, uncertainty in defining type was expected. Unique and accurate ranges for each change was expected to be difficult and with only two parameters, starting width and change in width, not expected. The direct relationship of channel width change on planform type cannot be explained by active width and width change alone, there are other factors that influence river planform, though results suggest that they are a major factor. The purpose of the results was to present the ability to partially separate the data based on the effects of channel width changes. Therefore, the results are showing the expected outcomes that includes both the separability of planform types known to be distinct (braided and single channel) and more confusion with wandering related planforms due to the transitional nature of the category.

5.2.4 Channel Planform Change and Confinement Change

Confinement types are not distinct to a given width, though wide lateral mobility may reflect an unconfined channel and vice versa. If planform type is also related to width in this way, it is expected that there may be a relationship between channel planform and confinement type.

On average, widths tend to decrease 55% for laterally unconfined-to-partly confined segments, 72% for laterally unconfined-to-confined, and 61% for partly confined-to-confined. Therefore, more narrowing is required in order for a laterally unconfined segment to become confined over partly confined. There is a general trend of greater decrease in width when confinement type is intensified, as anticipated (Figure 5.9). Figure 5.9a and b graphs the same data from the Figure 5.8 above, but instead coloured by confinement change type. Laterally unconfined segments tend to be the widest, although, laterally unconfined segments from small scale and partly confined segments from large scale rivers are similar and cause overlap in the graph. Considering only segments that have changed in confinement type (Figure 5.9b), segments with the most narrowing are connected to increased confinement type, similar to the relationships of channel planform.

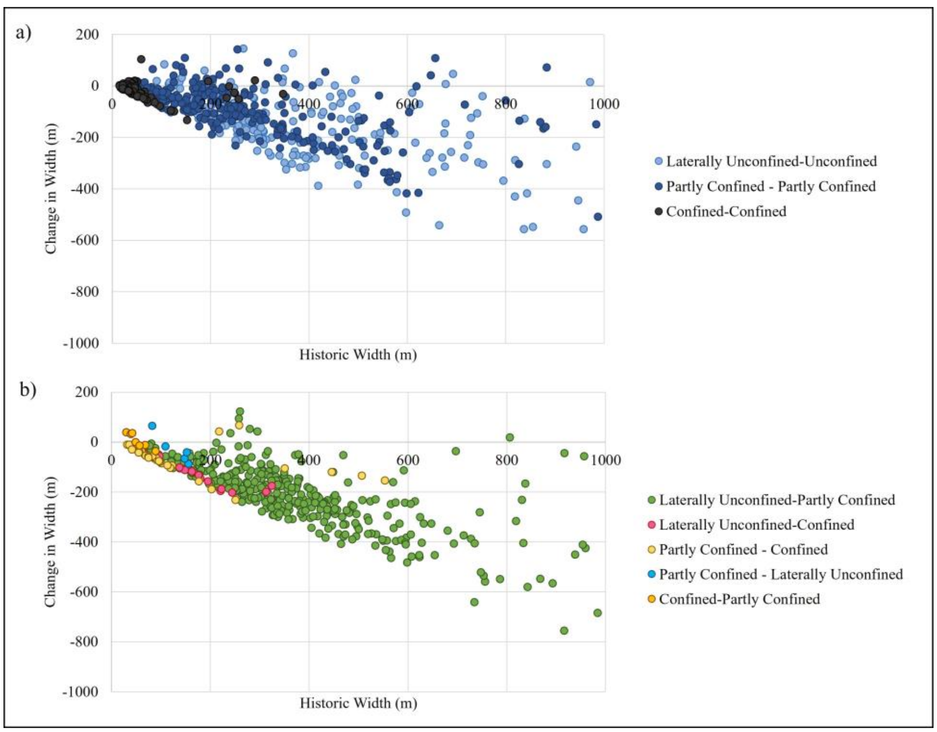

Figure 5.9: Change in width and confinement type over historic width. a) Only including segments with no change in confinement type, and b) only including segments with change in confinement type.

Comparing channel planform changes to confinement changes, transitions in one type can be matched with transitions in another, though only in a general, averaged sense (Figure 5.10). For example, laterally unconfined-to-partly confined segments have the greatest proportion of planform changes from braiding-to-wandering. Meaning that the increased confinement on the laterally unconfined, braided segment, constricted the segment enough to cause a change in planform type. This cause and effect is not absolute, and in other cases the same change in planform type occurs for a segment that has not changed in confinement type, but has narrowed. Another counter example can be seen in segments that have maintained a constant planform type but shifted into a more confined state.

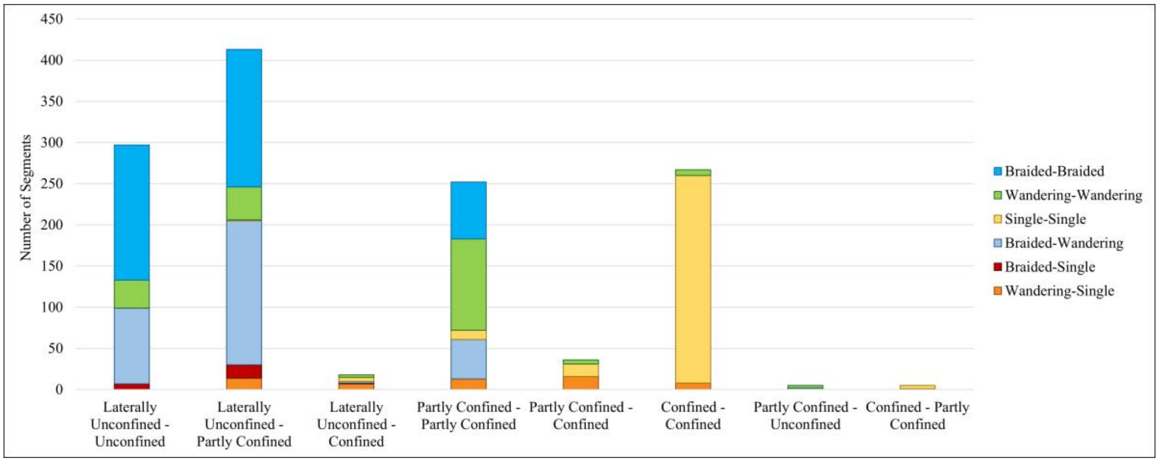

Figure 5.10: Proportion of segments by confinement and planform change.

Confinement type can be difficult to define. An association of confinement with width and planform type may exist but is hard to pin down. There is a problem in the limited categories and visual definition in defining confinement type, perhaps a different way of measuring it could be determined such as categorization in way that is not based on visual interpretation. Channel width alone does not work as a measure of confinement as natural or artificial changes to the river system, beyond that of confinement, may cause narrowing. Therefore, the focus remains on the quantitative analysis of channel narrowing with limited effects and interpretation related to lateral confinement types.

5.3 Additional Factors for Channel Change

5.3.1 Stream Power

Predictions of channel pattern are often based on stream power. Stream power is a primary driver of channel pattern types (for a given particle size). It is essentially a product of discharge and slope. Discharge and slope were obtained by methods outlined in Chapter 3. Although Canterbury rivers seem to have simplified because of width constriction and there is no evidence of major discharge change, the relationship between channel pattern and stream power historically and recently is an important aspect of the channel pattern characteristics and geography of braiding. Stream power can tell us which rivers have enough power to braid, and have higher braiding index, and can tell us if that changes or may change along the river.

Slope:

Channel slopes cover a fairly narrow range among the rivers (Figure 5.11). Slopes are typically less than 0.01m/m for each river and average around 0.006m/m. Slopes are consistent along many of the rivers (elevation profiles are almost straight, see Appendix A, Figures A.11-19) with the exception of the Ashburton and Selwyn rivers which have significantly steeper slopes in the upstream reaches compared to downstream slopes. Larger rivers tend to have slightly lower slopes, as expected, but the Rangitata River stands out with a generally steep gradient. Similarities between all rivers and planform types may reflect the fact that the rivers are flowing over the same regional slope of the Canterbury Plains and have similar bed material particle size.

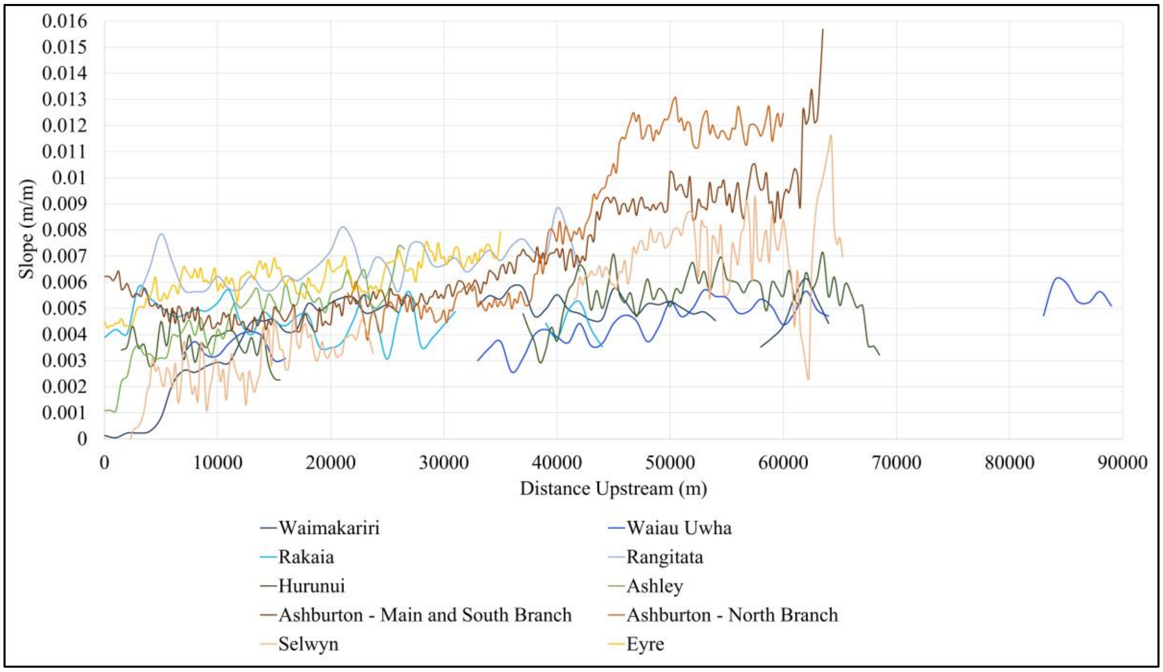

Figure 5.11: Change in slope along rivers. Note the breaks along some rivers are due to missing DEM coverage and canyon reach exclusion.

Discharge (Mean Annual Flood):

Historic Records

Records of historic flows in the early to mid-1900s either do not exist or could not be found for all rivers of interest. Stream gauging stations along the rivers vary in relative location along the networks such as upstream, downstream, or in the middle of the study segment (topographic maps with gauge sites in Appendix A, Figures A.2-10). Some rivers have multiple recording stations within the study segments while others only one or none (Eyre River). The year of first recording also varies by gauging stations with some constructed as early as the 1930s and other in the mid to late 1900s. The only historic mean daily discharge flow records that could be obtained from Environment Canterbury and NIWA date back to the late 1960s, or into the 1970s, for most rivers (CRC, pers. commun., July 11, 2022; NIWA, 2022). Mean daily discharge data may not provide much information regarding river morphology changes, as it is the peak flows that drive the changes, but the data can still provide an idea on the trends in discharge. If there are no obvious changes in discharge, it may start to discount declining flows as cause of narrowing. A general interpretation of discharge change over time was therefore dependent on the mean daily flow records from the late 1960s onward.

All rivers show minimal average changes in mean daily flow over time (data was analyzed by averaging daily flows per year, see Figure A.21 in Appendix A). The large scale rivers, and Hurunui River have the highest mean discharge values recorded. The large rivers show a slight decrease in mean daily flow with the Rakaia River flow having the highest recorded decrease which is interesting because this river had a relatively low amount of change (of the large scale rivers). The smaller rivers have much lower mean daily flows and show even less variation in flows over their period of coverage.

Estimations for present flow conditions

Estimates of flow (mean annual flood) along total river networks were obtained from the New Zealand River Flood Statistics tool (Section 3.2.3). Historical measurements of flow could be used to compare the changes over time and may be used to help explain the cause of channel narrowing and pattern change, however these measurements are not available and the unknown effects of irrigation on discharge change need to be noted, even if no major climate changes have occurred. If the analysis assumes that the historic flows are similar to the recent, there needs to be a level of caution regarding the unknown accuracy of the data for the period. The error associated with the New Zealand River Flood Statistics tool estimations was also discussed in Section 3.2.3 which related to the lack of gauging stations and general predictions of discharge values throughout the entire area.

The large scale rivers (and the Hurunui River) can be grouped as having the highest discharge values, while the small scale (and the Ashley River) have much lower discharge values (Figure 5.12). Distinctions are likely due to variations of mountain and foothill origins and upstream catchment areas (Figure 5.13). Each river has a relatively narrow range of discharge values along the length of river observed. The Rangitata River for example ranges only from maximum of 1,096m^3s^{-1} to a minimum of 1,088m^3s^{-1}. The study segments for each river flow mostly through the Canterbury Plains and have few or no tributaries in that region. Where abrupt and large changes in discharge occur, they reflect the locations where tributaries join the channel. The Rangitata and Rakaia rivers do not have any downstream tributaries and have relatively narrow catchment shape along the Plains (Figure 3.1), this may help explain why the rivers have opposite trends in discharge as they are recorded with a slight loss of discharge with distance downstream.

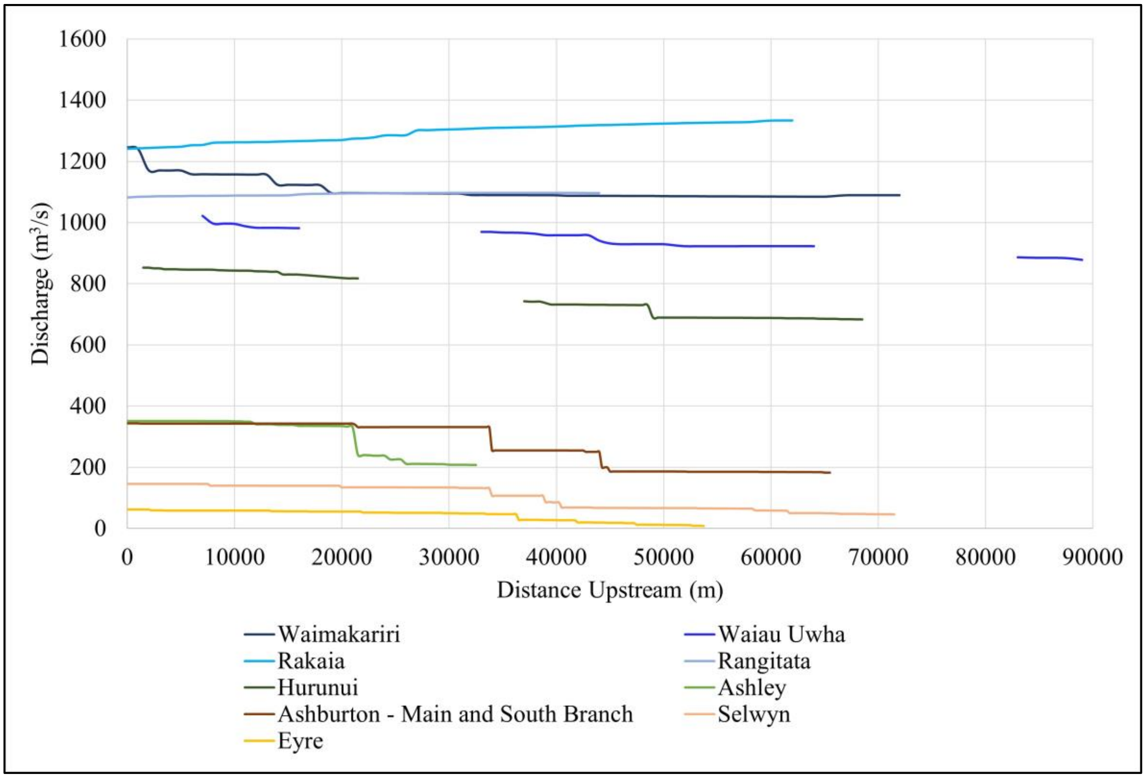

Figure 5.12: Change in discharge along rivers. Note that breaks are due to no discharge estimates or canyon reach exclusion.

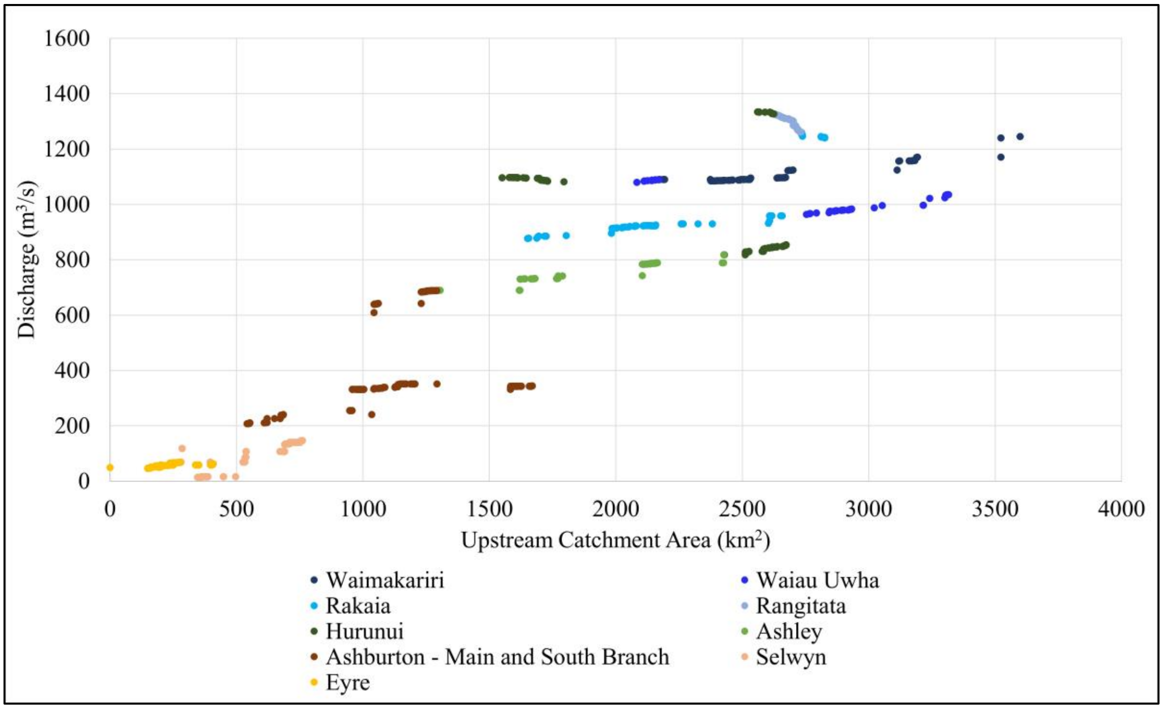

Figure 5.13: Relationship of discharge and upstream catchment area. Points coloured by river.

Overall, discharge (mean annual flood), similar to slope, changes little along many of the river lengths studied. There is only a small downstream trend in discharge. Between rivers however, discharge variations are clear and distinct in relation to river and catchment scale.

Stream Power:

The low variation in slope and discharge along the rivers means that stream power is consequently consistent downstream along many reaches of the same river. This may explain why pattern variation along the channels is small, except for confinement effects and canyons. Variations of stream power between rivers however is clear, reflecting the effect of catchment area on discharge.

The stream power values are mapped in Figure 5.14. The highest stream powers are on the Rangitata, Rakaia, and Waimakariri rivers, as expected based on the highest river discharges. Near the downstream end of the Waimakariri River the stream power values severely drop mirroring the slope reductions and the river transitions to single channel. The stream power values for the Waiau Uwha and Hurunui rivers are very similar, perhaps a result of their distinct topographies. The Ashley, Ashburton, Selwyn, and Eyre rivers have the lowest stream powers, due to their foothill origins and smaller catchment sizes.

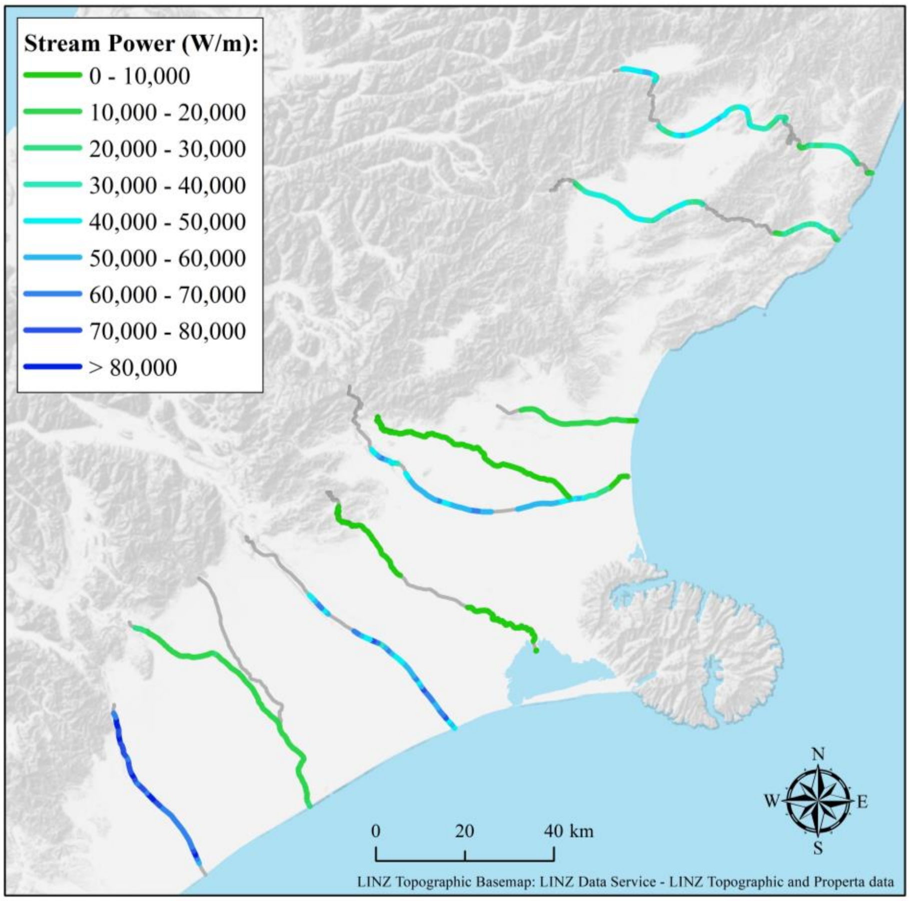

Figure 5.14: Map of stream power along rivers. Canyon reaches and missing slope and discharge data coloured in light grey.

Stream power clearly correlates with pattern type (Figure 5.15). Stream power is higher for braiding channels, in agreement with previous research. High stream power is required to maintain the morphology. Roughly speaking, >10,000 Wm^{-1} predicts braiding, but almost as high as 90,000 Wm^{-1} is recorded. The lower quartile for braiding is about 26,000 Wm^{-1}, distinct from the interquartile ranges of both single and wandering channels. Excluding outliers, braided and single channel stream powers are completely separate. Wandering and single channels occupy distinctly lower ranges than braided channels, with a bit of overlap. Organized by scale, similar trends between planform types are preserved. The large scale rivers have the greatest distinction between planform types. The medium scale braided and wandering planforms have some overlap but wandering stream powers are generally below braided. Braided and single channel stream powers are separate in the small scale rivers, although the wandering stream power ranges from above the braided maximum (~25,000 Wm^{-1}) to as low as the single channel average (~3,000 Wm^{-1}).

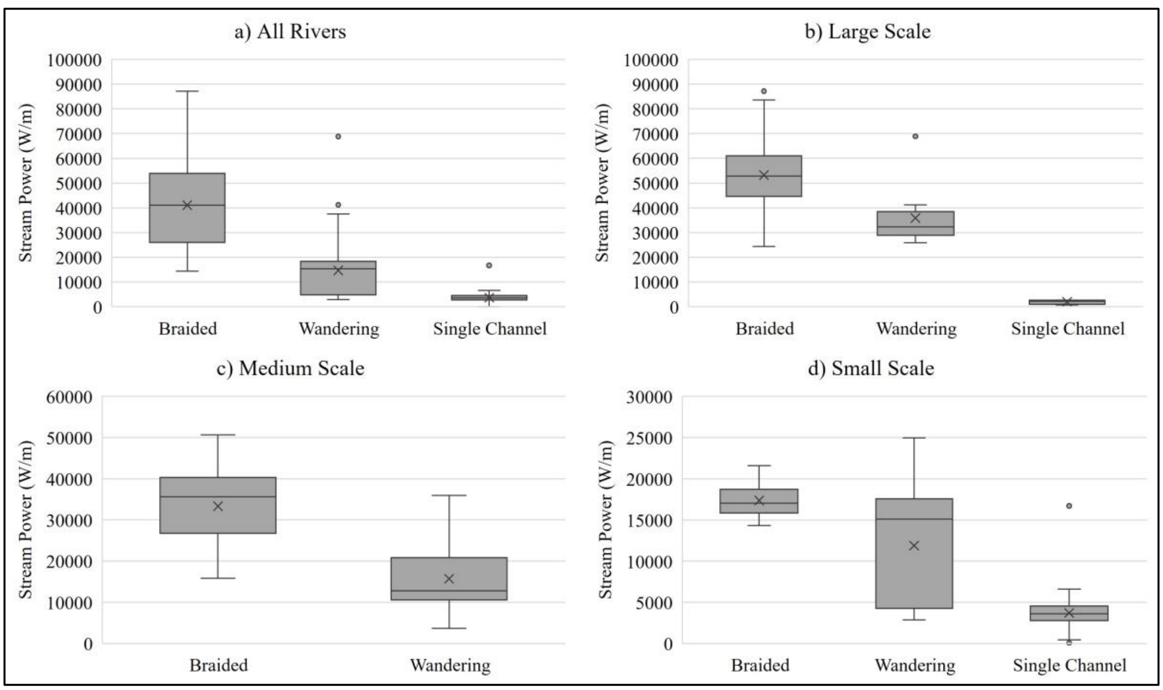

Figure 5.15: Stream power ranges sorted by planform types and scales.

5.3.2 Stream Power, Width, and Channel Pattern

The Canterbury dataset also shows the relationship of stream power with channel width, planform, and channel count (Figure 5.16). The historical data are plotted on the assumption that the stream powers calculated for recent data is the same in the historical case. Figure 5.16a illustrates the relationship between stream power and channel width, with points classified by channel planform. The correlation between width and stream power in both historic and recent width values is strong with coefficients of 0.88 and 0.89 (p-values <0.001), respectively. Figure 5.16b shows the same power-width relation adding the trend for higher channel count as stream power (and width) increase and also showing the changes in width and channel count between the two time periods. Figure 5.16c shows the stream power-channel count relationship more explicitly. The correlation defined for channel count and stream power is also strong. A coefficient of 0.83 for historic counts and 0.84 for recent counts (p-values <0.001). In all cases, stream power can be seen to be a major influence and explanatory variable for channel planform, width, and channel count and therefore in accounting for the differences in those characteristics among and along the rivers. It also points to the potential for future changes in stream power (e.g., because of climate change) to affect the fluvial morphology in the region in addition to any ongoing confinement and encroachment effects.

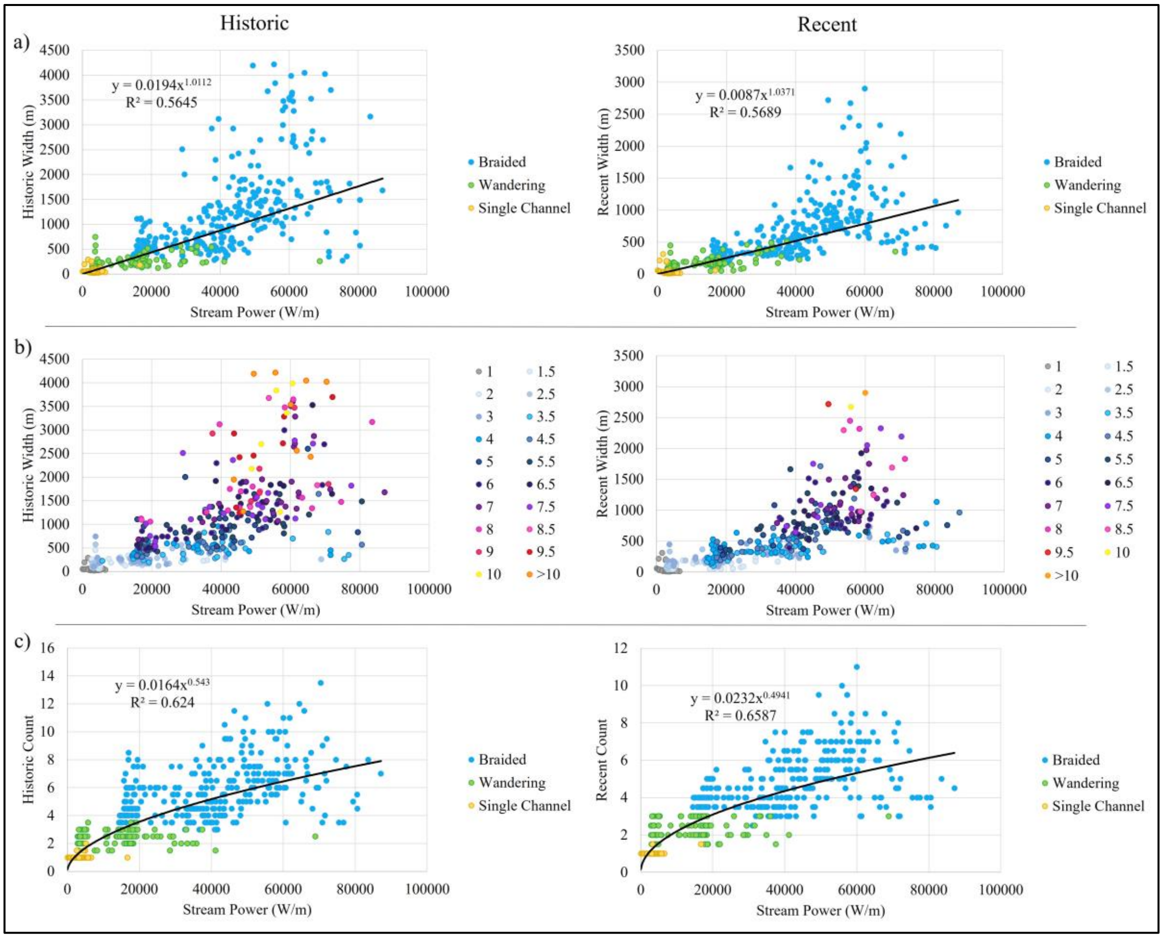

Figure 5.16: Stream power, width, and channel pattern relationship. Historic (left) and recent (right). (a) Stream power against width sorted by channel planform type and (b) the same data sorted by channel count. c) Stream power against channel count sorted by channel planform type. Black line shows trendlines.

5.3.3 Cross-Section Geometry

Van den Berg (1995) compiled river characteristics from segments along multiple rivers (135 gravel-bed in dataset used) including rivers from New Zealand (data provided by M.P. Mosley). From that dataset, reaches from the Waimakariri, Waiau Uwha, Rakaia, Hurunui, Ashburton, and Selwyn rivers are included. The paper defines the typical width, depths, and discharge values for braided, meandering (single channel), and straight (single channel) reaches showing the distinction between the channel patterns. It also compares the data based on median bed material particle size and specific stream power.

In this section the dataset described was used to compare with the data compiled along each segment from the nine rivers of interest.

The active width and depth versus discharge results (Figure 5.17) show similar results to the van den Berg (1995) data. Braided segments line up well and so do the single channel results, with the wandering segments located between the two. Although wandering pattern is not studied by van den Berg (1995), it is expected that this transitional pattern would appear there (Burge, 2005). The depth values for the braided rivers also line up well with the values from van den Berg (1995). The single channel results, however, tend to cross over to the braided points and do not show the same relationship with discharge. This may be attributed to error due to the few points collected for this planform type. Error in values may also be attributed to data collection. Overall hydraulic geometry of the dataset is consistent with previous published data. The data appears to show similar trends, and the New Zealand data (highlighted in Figure 5.19b) also lines up relatively well.

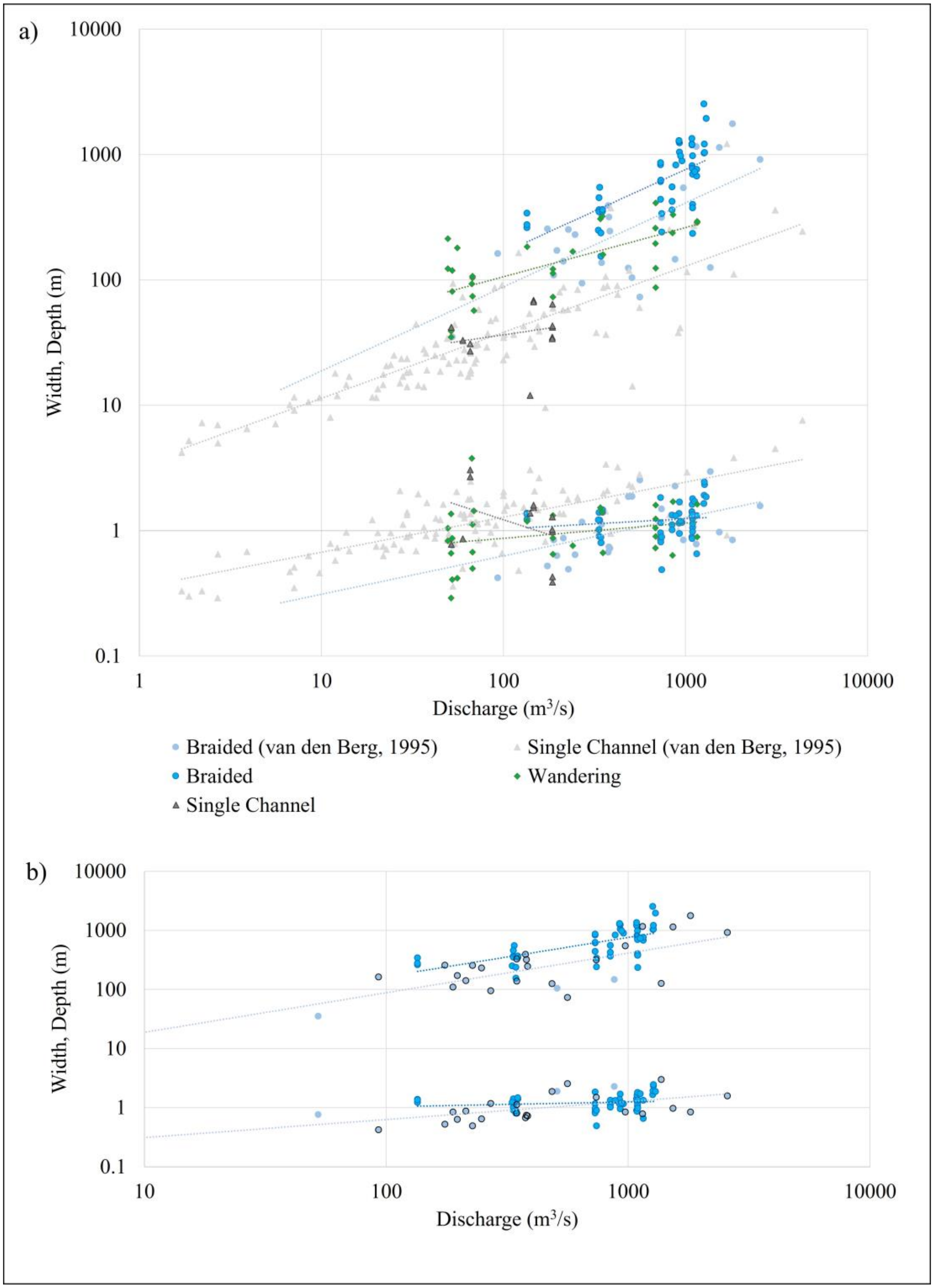

Figure 5.17: Comparison of Canterbury dataset with other gravel-bed rivers. Van den Berg (1995) gravel-bed rivers come from reaches worldwide. a) All gravel-bed rivers, braided, wandering, and single channel comparison. b) Braided rivers only, New Zealand data from van den Berg collection highlighted with black outline.

For braided rivers in particular (Figure 5.17b), width is much more sensitive to discharge than depth. The depths are similar among the rivers sampled and vary little (most within 0.5-1.5m) despite the large range of river size and type (Figure 5.18). The interpretation of depth measurements remains cautionary as the water surface levels captured in the DEMs cause underestimations of depths on wetted channels to an unknown degree (recall Section 3.8.2).

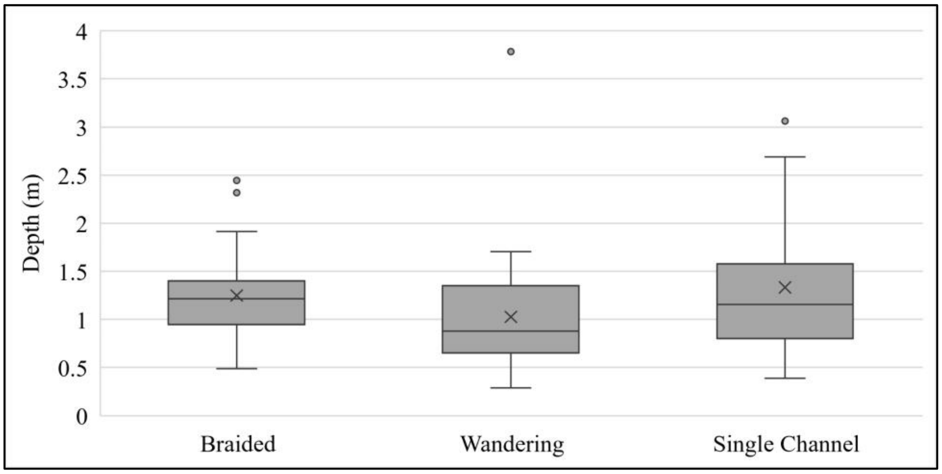

Figure 5.18: Mean depth by planform type.

5.3.4 Width-Depth Ratio

Width-depth is a scale variable, so bigger channels should have a larger width-depth ratio. When sorted by pattern type there is a trend of decreasing width-depth ratios with pattern simplification (Figure 5.19). The most overlap between categories is between braided (less than 500m) and wandering segments. Single channels occur at width-depth ratios less than 50 (with outliers around 100), wandering ratios fall between single and braided channels, and braided width-depth ratios are generally greater than 200, but have been recorded to occur as low as ~150 (overlapping with wandering ratios). It is important to reiterate the uncertainty regarding the depth measurements, underestimation of the depth may lead to an overestimation of the width-depth ratios.

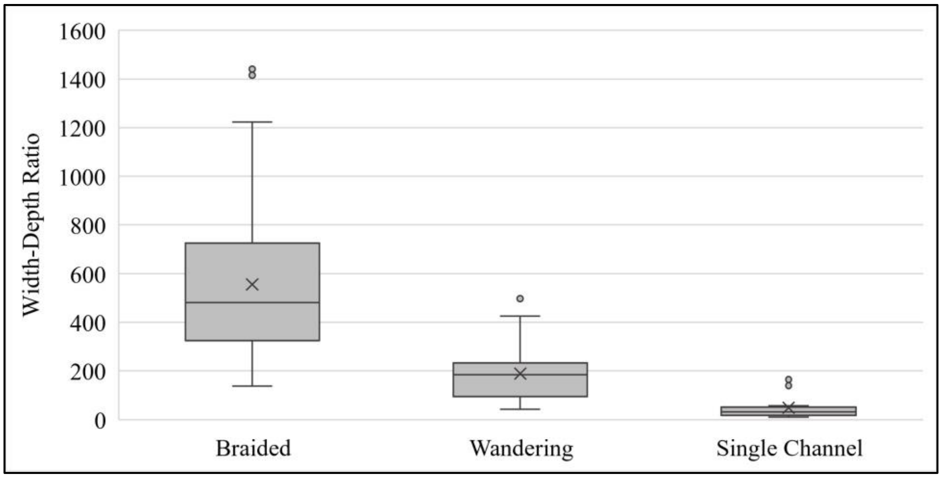

Figure 5.19: Width-depth ratio by planform type.

Braided rivers tend to get larger by widening much more than deepening. There is a weak or non-existent relationship between active width and depth, therefore the relationship for width and the width-depth ratio is very similar, up to about 1,500m (Figure 5.20). This means that almost all width-depth ratio increases can be linked to width change alone. Later, thresholds will be tested using the width-depth ratio, but according to the data collected, the same relations could be seen with width alone.

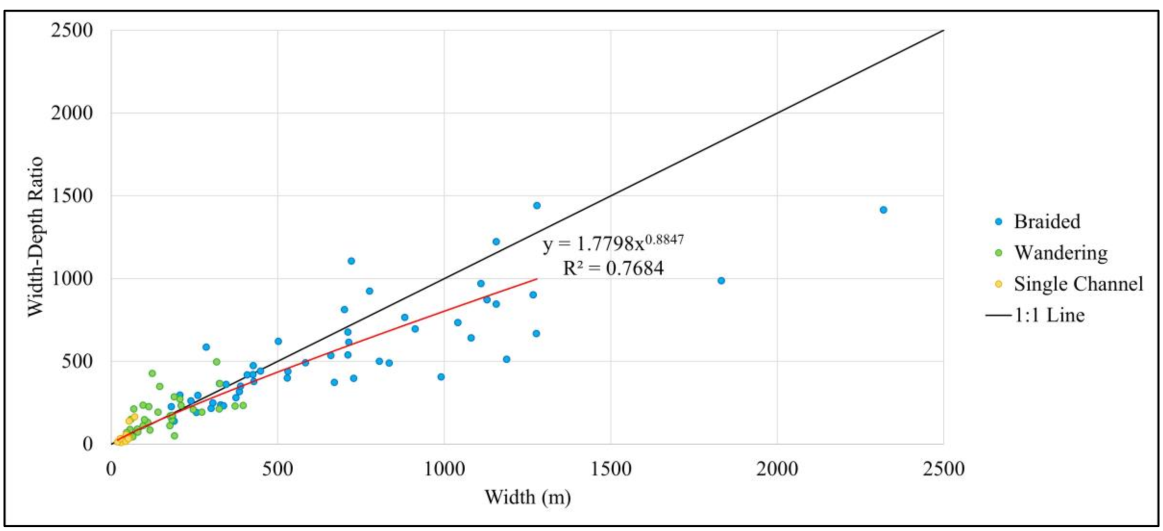

Figure 5.20: Width and width-depth ratio relationship. Black line extending from origin to top right is the 1:1 line and red line shows the relationship of width and width-depth.

As discharge increases, width-depth ratios also increase (Figure 5.21) so width-depth ratio depends on river scale also. The single channel segments are clearly separate from the larger braided segments. Almost all braided segments have higher discharge and width-depth ratios than single channels and some wandering. Within the braided segments however, the trend is relatively flat.

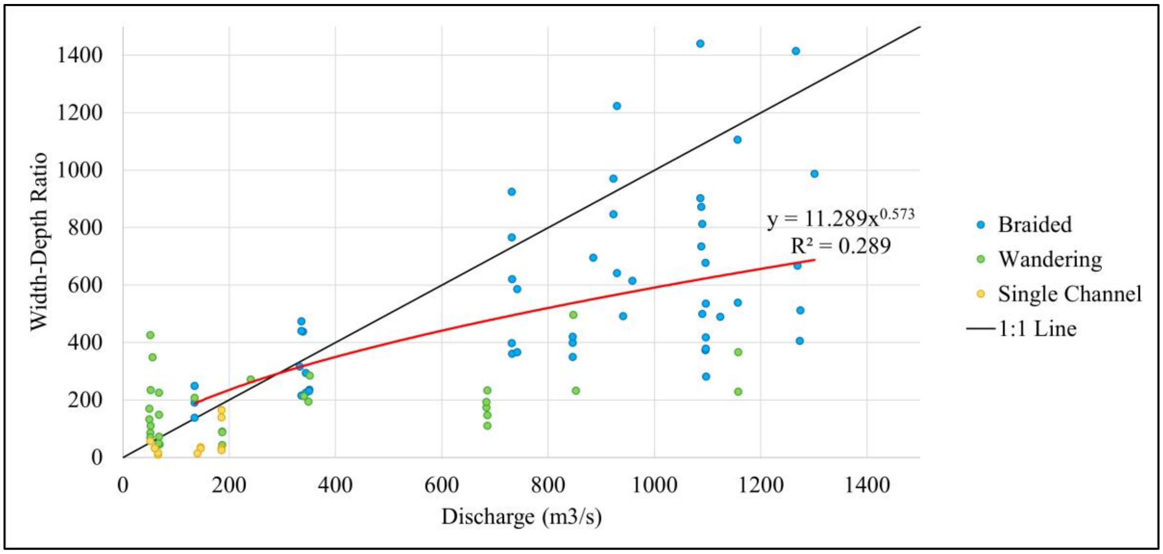

Figure 5.21: Discharge and width-depth ratio relationship. Black line extending from origin to top right is the 1:1 line and red line shows the relationship of discharge and width-depth.

The width-depth ratio strongly correlates to width and increases with discharge. Therefore, it is possible to think of the channel pattern effect as primarily related to width, rather than width-depth. Width is typically easier and more accessible to measure than channel depth. In the case of the data collected, if width alone could be used then the dataset to test theories would be much larger.

5.4 Empirical and Theoretical Predictors of Channel Pattern

Various predictors of channel pattern differences have been proposed by fluvial geomorphologists. Five threshold predictors were compared for the Canterbury rivers. The predictors are based on different controlling factors including width-depth ratio, slope, stream power, and specific stream power (stream power per unit width). Only a limited dataset could be used to analyze how well the Canterbury rivers are discriminated by the predictors as limited depth and particle size information was available. The depth data was available for select segments along each river to represent each planform type (Predictor 1). Grain size information was obtained from Browne (2004) for a more limited dataset that includes only the Rangitata, Ashburton, and Rakaia rivers (Figure 5.22). This data allows for comparison of the Canterbury rivers with channel pattern thresholds that require sediment size (Predictors 4 and 5).

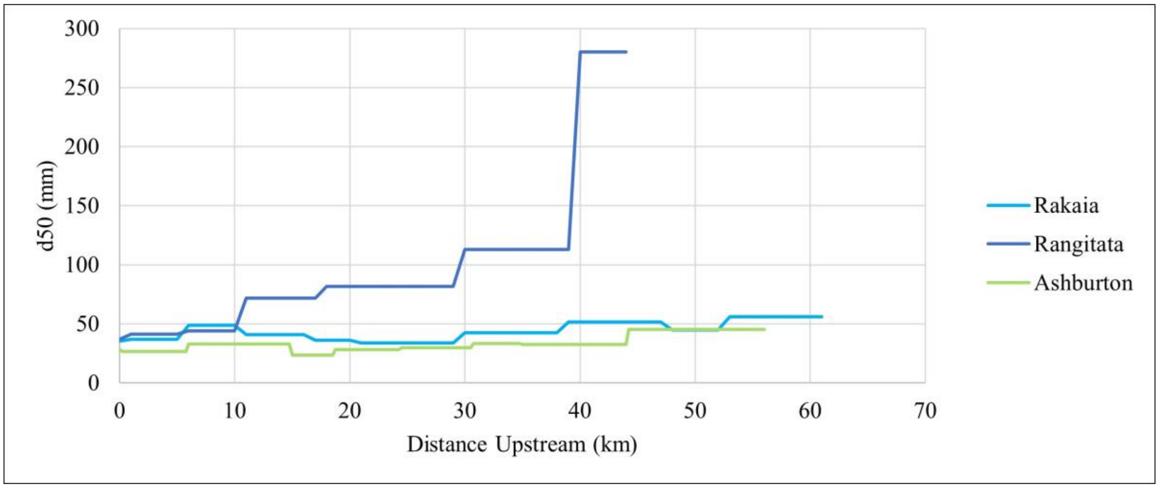

Figure 5.22: Bed material particle size along Rakaia, Rangitata, and Ashburton rivers. Data derived from Browne (2004), incomplete coverage for each river.

5.4.1 Predictor #1: Width-Depth Ratio

The first threshold analyzed comes from the 2012 paper by R.G. Millar where channel pattern is predicted with hydraulic geometry. The paper uses width-depth ratio as a predictor of channel pattern. The transitional width-depth ratio proposed by Fredsøe (1978) is presented where a width-depth ratio of about 50 represents the theoretical transitional point between meandering (single) channels and braiding channels. The predictor proposes that any reaches with width-depth lower than 50 (so narrower and deeper) will tend to be single (meandering) and any reaches higher than 50 (wider and shallower) would tend to be braided. Therefore, around a width-depth ratio of 50 it is expected to be wandering rivers – the transitional pattern. This predictor separates the gravel-bed rivers used in the Millar (2012) paper by pattern type well, proving the empirical accuracy of the predictor by Fredsøe (1978).

The Canterbury dataset looks at the predictor with a much larger empirically collected dataset. To display the data, the dimensionless discharge equation (Equation 1) used by Millar (2012) was applied to the dataset:

$$Q^{*} = \frac{\mathrm{Q}}{d_{50}^{2}\sqrt{\mathrm{g(s-1)}d_{50}}} \qquad \textbf{Equation 1}$$

Where Q* is dimensionless discharge, Q is discharge (m^3s^{-1}), d50 is median bed particle size, g is gravitational acceleration, and s is sediment specific gravity. Assuming default sediment specific gravity (2.65) and a constant median particle size (40mm). The results suggest that a threshold closer to the braided planforms may be near a width-depth ratio of 100-200 rather than 50 (Figure 5.23a). Most of the single channel segments lie to the left of this line, although there are a couple of segments reaching a width-depth ratio over 100. The wandering planform segments overlap with both single and braided segments, which is expected and seen in the Millar (2012) results. The majority of braided segments have width-depth ratios greater than 200. It is suggested that the line may be closer to this threshold point based on the Canterbury rivers dataset. This threshold can also be considered in terms of channel count (or braiding intensity) as these measurements were also recorded for the cross-section sites (Figure 5.23b). As width-depth ratio increases, the channel counts also show an increase. The highest braiding intensities are observed with the largest width-depth ratios. Therefore, the width-depth predictor can also show the transition point of number of channels. Using a ratio of 50, a threshold between a single channel and more than one channel is predicted. Shifting the predictor to a greater width-depth ratio such as 200, brings the threshold closer to the discrimination between counts less than 3 and greater than 3, therefore the braiding transition.

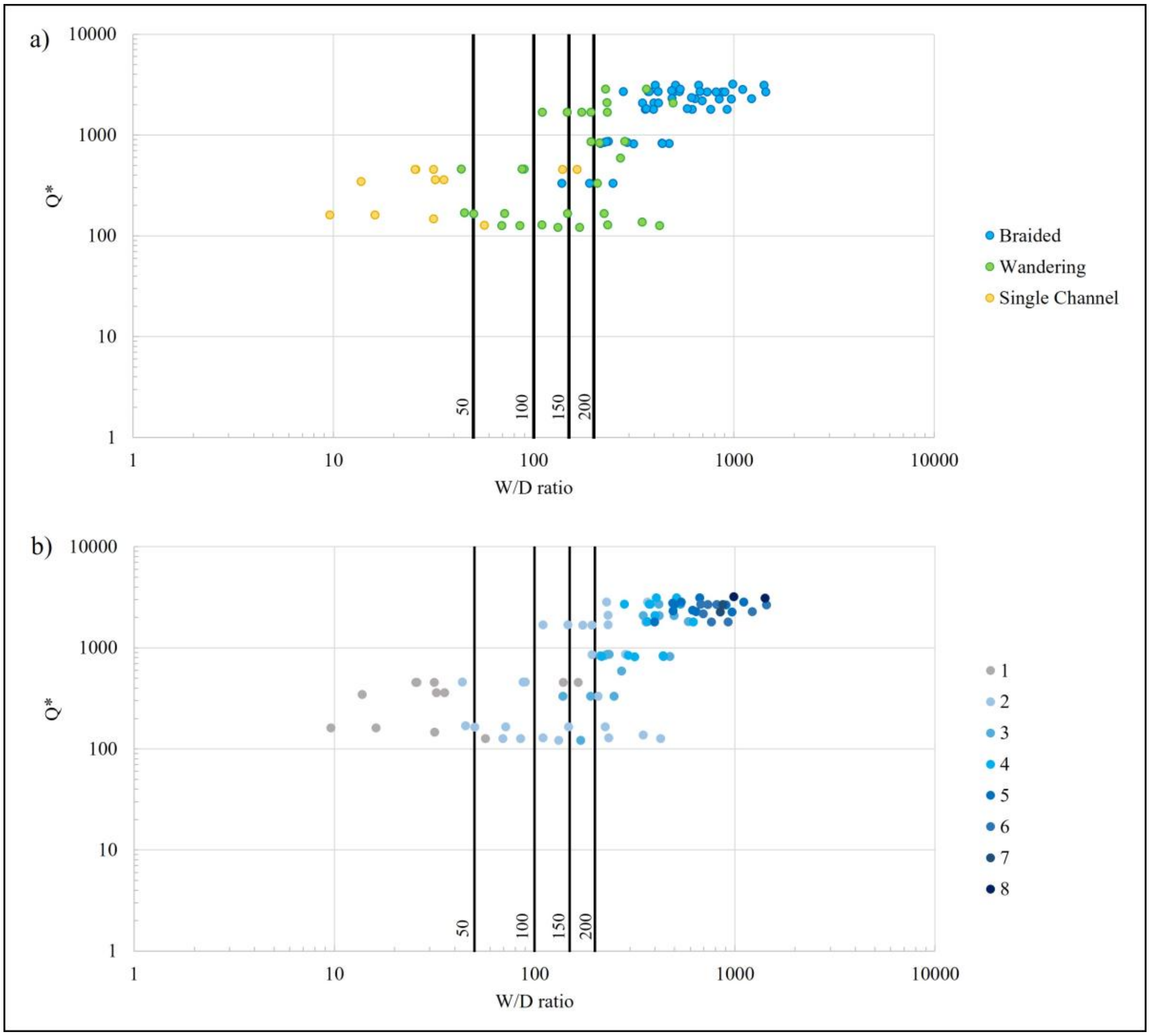

Figure 5.23: Width-depth ratio threshold predictor. a) Data sorted by planform type. b) Data sorted by channel count. Limited dataset to depth cross-section sites only.

This width-depth ratio predictor for channel pattern is relevant to the Canterbury case in which much of the observed changes have occurred because of channel width constriction and is therefore useful in setting criteria to limit de-braiding or allow re-braiding.

5.4.2 Predictor #2: Slope and Dimensionless Discharge

Eaton et al. (2010), as a way to predict channel pattern without knowing the width-depth ratio, coupled the width-depth ratio of 50 threshold with an association of slope and dimensionless discharge. By assuming the threshold width-depth ratio, a transitional slope between single and braided patterns can be calculated using only dimensionless discharge. Multiple equations were explored by Eaton et al. (2010), including both theoretical and empirical, though equations were relatively similar. In Millar's (2012) results, the theoretical equation by Eaton et al. (2010) showed a clear separation between meandering and braided channels, with wandering channels clustered and scattered along the line. Millar (2012) summarizes that this equation could be used as an alternative to the width-depth ratio predictor.

These threshold equations were tested with the Canterbury data to see if the same discrimination could be attained (Figure 5.24). The theoretical equation overpredicts the slope needed for occurrence of braiding along the rivers, while the empirical results both over and underestimate the threshold. For the Canterbury dataset, an equation between the provided equations would best separate the pattern types.

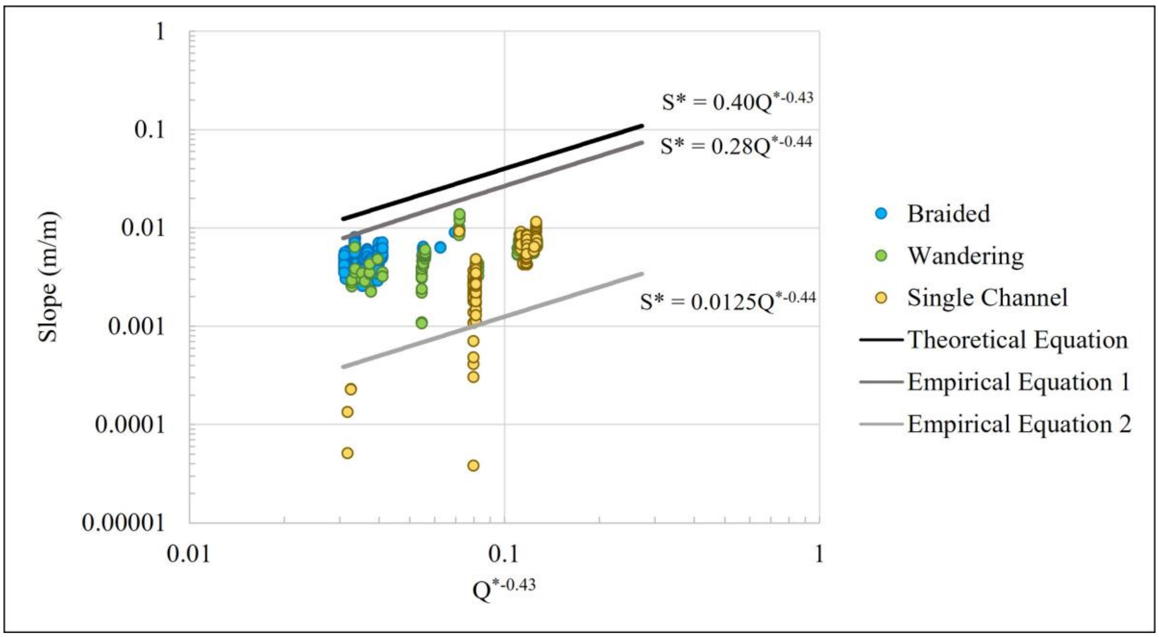

Figure 5.24: Slope and discharge channel pattern predictor. Based on equations by Eaton et al. (2010).

5.4.3 Predictor #3: Bar Mode

Millar (2012) suggests another theoretical slope criterion (based on the theoretical version of the threshold slope equation from the previous predictor) where the higher the ratio of measured slope to slope threshold for braiding, the more braided channels (or the more steady bars) the river will have. Therefore, the model predicts not just whether a channel braids, but how much it braids. This could be compared with the Canterbury records of channel count. Channel count should increase with the suggested bar mode results. Figure 5.25 shows that channel count increases with predicted bar mode so that bar mode theory is capturing the general trend in braiding complexity. The correlation coefficient is high, 0.79 (p-value < 0.001), though scatter is evident. Variations in results may be due to assumptions made in the theoretical bar mode predictions as they assume no bank resistance, while some levels of confinement are known for the Canterbury rivers.

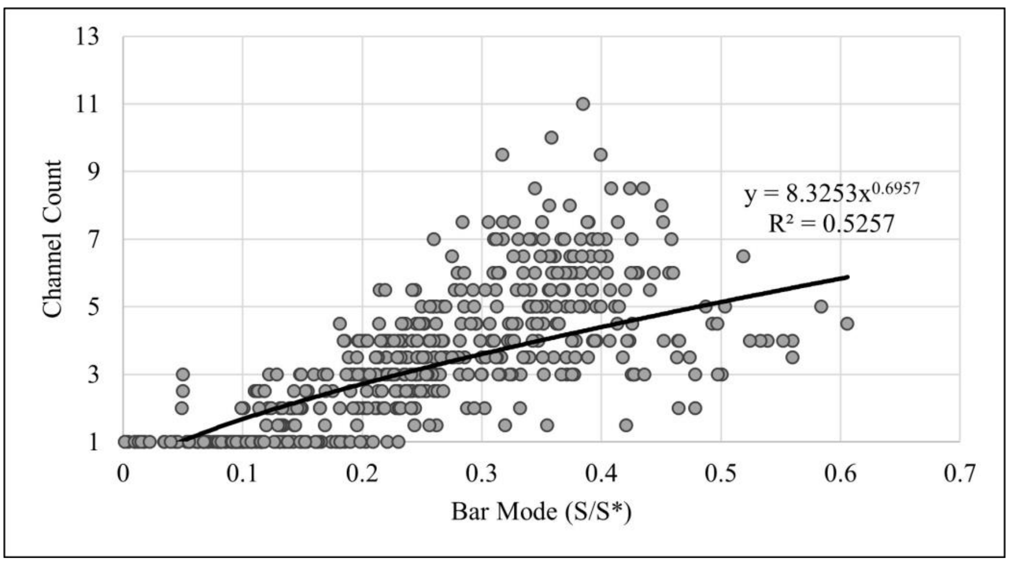

Figure 5.25: Measured channel count comparison to bar mode prediction. Bar mode is predicted by the model: S/S* (Millar, 2012) where S is measured slope and S* is threshold slope.

5.4.4 Predictor #4: Potential Specific Stream Power and Particle Size

Van den Berg (1995) also notes the problem of predictors of channel pattern type that require some knowledge of the channel geometry. Van den Berg (1995) created a method to discriminate between pattern types based on more channel independent characteristics: potential specific stream power (derived from slope and mean annual flood discharge) and bed particle size.

The equation created by van den Berg (1995) to predict potential specific stream power for gravel bed rivers was applied to the Canterbury dataset for rivers that have bed particle size information (limited reaches of the Rakaia, Rangitata, and Ashburton rivers). Figure 5.26 graphs specific stream power against particle size with the transition line between single channel to multi-channel by van den Berg (1995) displayed. All braided reaches are above the line where braided morphologies would be expected, although all wandering and single channel segments also lie above the line. For this dataset it appears as though the line needs to shift upwards in order to begin discriminating between pattern types.

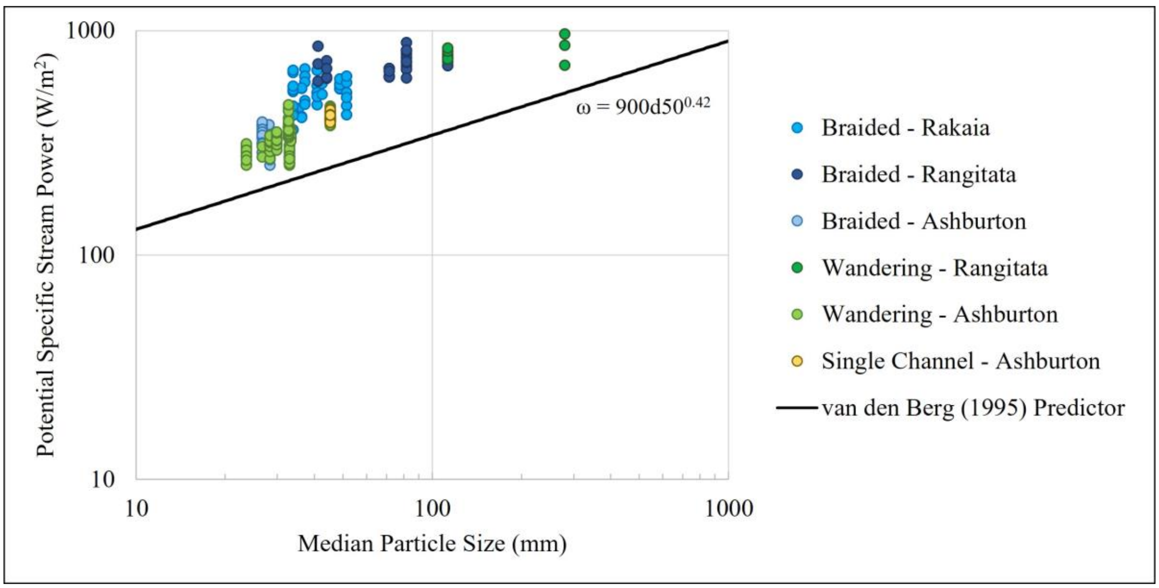

Figure 5.26: Potential specific stream power and particle size channel pattern predictor. The predictor equation from van den Berg (1995) was $\omega = 900d50^{0.42}$, where ω is potential specific stream power and d50 is median particle size.

5.4.5 Predictor #5: Stream Power and Particle Size

Bledsoe and Watson (2001) used a combination of meandering (or single channel) and braided reaches to predict channel pattern thresholds based on associated stream power and sediment characteristics. The idea being that excess stream power to the predictor may cause a transition from a single to braided channel (Bledsoe and Watson, 2001). Based on regression analyses of collected datasets, models for gravel bed rivers specifically were created that require slope, discharge, and median particle size.

Figure 5.27 compares particle size to a function of slope and discharge. Where mean annual flood recurrence interval is used for discharge and particle size values from Browne (2004) were used. The black line (Bledsoe and Watson (2001) equation 15) represents a 50% probability of braiding for gravel-bed rivers, with probability increasing above the line, and decreasing below. The limited data for the three Canterbury rivers plots just above the predictor. The line cannot discriminate between planform types at this point, but the 90% probability line correctly identifies some braided segments from the Rakaia and Rangitata rivers with the highest stream powers.

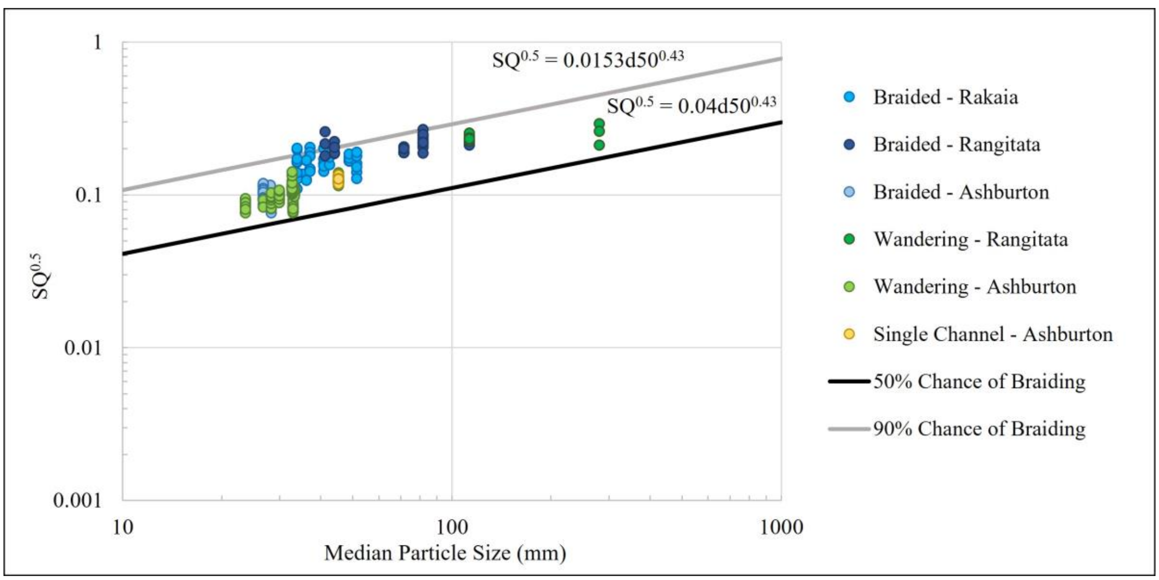

Figure 5.27: Stream power and particle size channel pattern predictor. The braiding predictors are from Bledsoe and Watson (2001), though the 90% chance of braiding predictor was estimated based on plotted results from the paper.

5.4.6 Proposed Predictor: Channel Width

Recall in Figure 5.22, width-depth ratio is mostly defined by variation in channel width, as depth varies little by comparison. So, if it is assumed that width-depth ratio variation can be defined by width alone, the ratio can be replaced with only width, and in this case, the total Canterbury dataset (instead of just the LiDAR cross-sections) can be used to find a threshold width similar to the Fredsøe (1978) width-depth ratio predictor. Figure 5.28a graphs channel width against dimensionless discharge (Equation 1) with threshold predictors located at 50, 100, 150, and 200m, assuming a 1:1 relationship of width-depth ratio to width (an over assumption, but close). Similar to the width-depth results, the predictor at 50m width does a relatively good job of discriminating between single and braided channels. Although there is some overlap of single channels to the right of the line and braided points are generally much wider, therefore the line could be shifted to the right towards a larger width threshold.

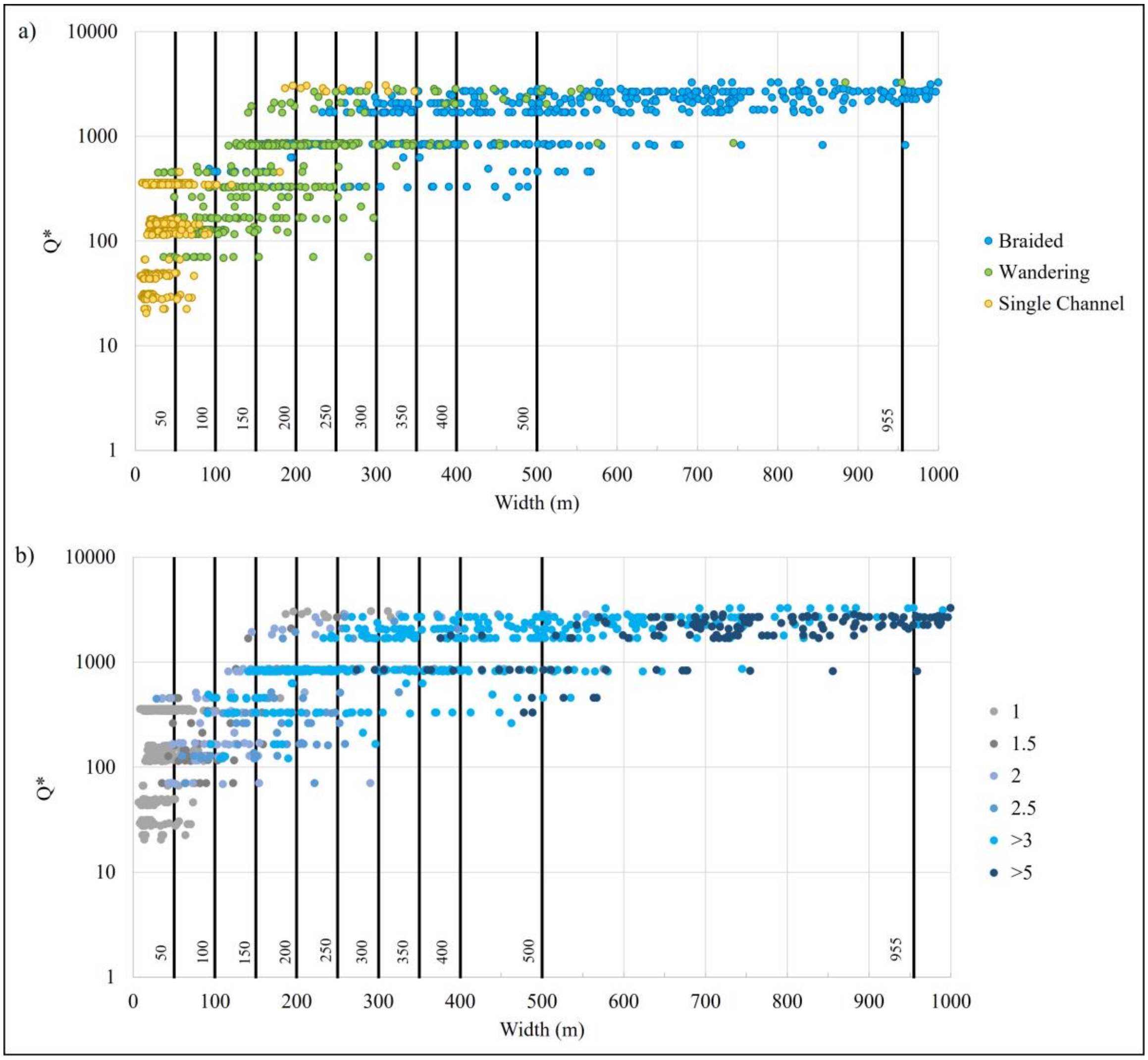

Figure 5.28: Width channel pattern predictor. a) Data segments sorted by channel planform type, b) data segments sorted by channel count. Note segment widths exceed the x-axis maximum reaching widths over 3,000m.

Multiple predictors for braiding were tested at various threshold intervals using a probabilistic method to handle the scatter of the dataset. To begin, the 50m predictor showed a 64% chance of braiding to the right of the threshold and 95% chance of single channel to the left. As this boundary is shifted further to the right, the percent chance of braiding increases and the separation between braiding and single channel becomes clearer (Table 5.2). It was not until 350m width that all of the single channel points fall to the left of the line and there is a 95% chance of braiding to the right (still some probability of wandering planforms). At 955m width the probability of braiding at wider values is 100%.

Table 5.2: Chance of braiding in excess to width threshold.

Width Threshold	Chance of Braiding (%)
50	64
100	72
150	77
200	84
250	90
300	93
350	95
400	97
500	98
955	100

The complementary plot (Figure 5.28b) showing channel counts, also shows that as width increases, there is a higher probability of more channels. At the 50m width threshold there is a 70% chance of a segment having more than three channels, 32% chance of a segment having more than five channels, and 95% chance of a single channel (Table 5.3). As the segments get wider, the likelihood of more than three (and five) channels increases. Segments with more than five channels begin at widths of ~275m, therefore the recording of the likelihood of more than five channels began at 250m. Widths exceeding 250m have a 94% chance of having three channels, while just over a 50% chance of having more than five channels. The probability of more than five channels for a given segment reaches over 90% nearing 1,000m widths. Generally, the results show how braiding intensity is expected to increase with wider channels and that a threshold of 50m may be a suitable width to distinguish between single and multi-channeled segments, though it could be argued that a wider value could be used.

Table 5.3: Chance of greater than 3 or 5 channels in excess to width threshold.

Threshold Width	Chance of >3 Channels (%)	Chance of >5 Channels (%)
50	70	-
100	79	-
150	84	-
200	90	-
250	94	53
300	96	57
350	98	62
400	98	67
500	99	74
955	100	91

*Note >3 channels may be picking up wandering defined channels.

There is potential for these predictors to anticipate changes in channel pattern and braiding intensity based on width and width change alone. It is important to note that the probability of planform or channel count occurrence is only based on what was observed with the Canterbury dataset.

5.5 Summary

Channel narrowing has been shown to influence channel pattern. As rivers narrow, it is more likely that they change into a simplified channel planform and decrease in braiding intensity. A strong correlation of width and channel count was established up to a certain maximum point (~2,000m), beyond which, the correlation diminishes. This relationship explains some of the historic effects of width change reducing both the intensity and presence of braiding patterns along the rivers.

The effect of a change in the amount of laterally active area for a river influences a channel in different ways. The starting, or historic, width seems to have an important effect on how much narrowing was required to see a change. A wide channel requires a lot of narrowing to convert it to a simplified pattern type. In most cases, it was seen that the widest channels that narrowed the most did not change in channel planform type, though narrowing did cause a decrease to braiding intensity. In contrast, if a channel was initially narrow, a smaller amount of narrowing was enough to cause a simplification of channel planform type.

The importance of the starting width for channel pattern response to narrowing leads into the effects of river scales. If actual pattern change depends on how close a reach is to the threshold for channel change, then narrower channels will be the most sensitive. Assuming a scale effect, the small scale rivers are the closest to these thresholds, while the larger rivers have more of a buffer to resist the changes. Though, if narrowed beyond this buffer, the larger river will change. Sorting the rivers by scales has shown this effect to be true. It was found that smaller rivers have shown the most change in channel planform type over time. Meanwhile, the larger rivers that have narrowed by greater absolute values have not shown the same level of channel planform changes, instead they have shown a decrease in braiding intensity not yet enough to cause a change in planform type. Larger rivers tend to be laterally unconfined with ample space for natural mobility, therefore they may only show small reductions in channel count because they have a larger buffer to resist being ‘de-braided’ by narrowing. Meanwhile, the medium or smaller rivers may show a more obvious channel planform response.

There is a continuum of river responses where reductions in channel counts will eventually cause a shift from braiding to wandering to single channel. The data can be separated by scale of widths, but the point at which change occurs along the continuum is similar between all scales. This means that the relationships established with the morphologic characteristics (including channel width and count) can be used to anticipate the effects of further narrowing for a river of a given width or channel pattern.

Additional predictors of channel change were also explored. Stream power was determined to have a relationship with channel width and pattern where increases in stream power cause increased likelihood of braiding and increased braiding intensity above the braiding threshold. In the Canterbury case, channel slopes do not differ greatly between and along rivers and therefore the differences in stream power reflect discharge differences related mainly to catchment size. A larger catchment size tended to correlate with a higher stream power, with some influence by slope. Overall, larger rivers have higher stream powers and more braided channels, while smaller rivers have lower power and channel patterns tend to be less complex and vary. The lower stream power for the smaller rivers may be the reasoning behind vegetation belts and stopbanks along the channels (as seen in the Ashburton River with total protection along all channel banks), the rivers are easier to control. This also leads to the outcome that braiding is strongly scale dependent.

The Canterbury rivers have been studied in terms of their hydraulic geometry and the results were compared with measurements and conclusions by previous studies. All seems to fit relatively consistently. The data was also seen to be supported by previously collected empirical results from braided rivers in New Zealand and around the world.

Proposed thresholds for channel pattern change have variable success in predicting the Canterbury river results, although with adjustment, and each provide a basis for interpreting the observed channel pattern. The uncertainly of the depth, discharge, and bed material particle size based predictors may be due to the uncertainties relating to the estimation and generalization of these variables. Although, the width-depth threshold predictor was shown to work the best. Width as a predictor of channel pattern type alone was shown to be a very effective approach to correctly identifying and anticipating channel planform and braiding intensity for the Canterbury rivers.

In the case of the Canterbury river historical changes, predictors based on stream power are unlikely to have anticipated the changes because there is no evidence of large changes to discharge or power, and certainly none large enough to have caused the observed narrowing and de-braiding. It can be assumed that the river changes are mostly due to confinement changing river width. Therefore, it is the width-related thresholds and predictors that matter more than the stream power thresholds, in this case.

The rivers studied exhibit a wide variety of channel patterns. Predicting changes in channel pattern is important in order to predict river responses to climate changes and river restoration projects. The influence of channel narrowing on a given channel width can be used to anticipate the effects of further encroachment and can show at what point braiding would disappear or be severely limited. The information might be used in restoration or anticipating effects of any further stopbank construction or encroachment. It is useful for decision making by knowing what future width changes might do and how rivers may become de-braided. If flow, power, and space for rivers increase, it is expected that braiding will increase.

In the next chapter the results will be connected to the loss of braiding worldwide and the possible future trajectories of the Canterbury rivers.

Chapter 6

6 Implications for Canterbury Rivers and Braided River Morphology and Conservation

Braided rivers are being lost throughout the world due to a variety of causes (Stecca et al., 2019). These include river confinement restricting lateral mobility which was the focus of this research. The research confirms the systematic narrowing of Canterbury's braided rivers over time. The rivers fit the trend for other braided rivers of the world that are being affected by anthropogenic changes. For the Canterbury rivers, there is still time before all reaches in the region transition away from their natural, iconic, braided channel pattern.

This Chapter will provide a discussion on the main findings and their implications for both braiding in general and the Canterbury rivers in particular. It will consider how the rivers may change in the future and explore current management plans. The Chapter concludes with a discussion of limitations of the thesis and how it can be improved and built upon in the future.

6.1 Geography and Predictors of Braiding Occurrence

Predictors of braiding occurrence, including stream power and width, were mapped along the Canterbury rivers. The predictors explain where braiding is likely to occur, and the high stream power and width segments identified align with observed braided morphologies. Stream power and width help to explain historic and current spatial patterns including the consistent braiding occurrence along entire lengths of the large and medium sized rivers. The variables reveal the predictability surrounding the geography of braiding and may be used to explain the changes in the geography of braiding observed.

Results from the Canterbury rivers have shown that total stream power is both a strong predictor of occurrence of braiding and braiding intensity. In the literature, general ideas of a threshold between total stream power and braiding occurrence exist (Bledsoe and Watson, 2001; Candel et al., 2021; Ashmore, 2022), though discriminations are rough and only made between braided or not braided. Research focusing on how braiding intensity relates to stream power above the threshold for braiding occurrence has been studied using a physical model (e.g. Egozi and Ashmore (2009)), but detailed cases from full-scale braided rivers are limited. Based on an empirical dataset for gravel-bed braided rivers sourced from van den Berg (1995), braiding has been suggested to occur at total stream power values exceeding 10,000 Wm^{-1} (Ashmore, 2022). The Canterbury dataset shows that discriminator works relatively well, though could be shifted to a higher threshold of ~15,000 or 20,000Wm^{-1} for the Canterbury rivers specifically. The dataset also shows the stream power threshold is larger for higher braiding indices providing an idea of the relationship of stream power and braiding index.

The changing geography of braiding is not attributable to power changes in the case of the Canterbury rivers, but clearly a consequence of channel width constriction (though this may change if climate change increases flood flows (Section 6.2.4)). A new width-based threshold, based in existing theory, was created based on the Canterbury rivers dataset and shows the probability of braided morphology based on channel width alone. This can be used to show the likelihood of braiding occurrence and intensity for a given width. The width threshold may be useful in future river management and restoration aimed at maintaining or restoring braiding morphologies along the Canterbury rivers. Further testing is required for applicability to other gravel-bed braided rivers.

There are various factors that limit braided morphology, but in this thesis the focus was on the influence of lateral confinement translated to effect of channel narrowing. In the future the effects of other limiting factors should be explored, and pattern prediction can be improved by adding relevant parameters such as bank strength (relating to confinement type) and bed material particle size (Candel et al., 2021).

6.2 How much ‘room for rivers’?

A main goal of this thesis was to contribute to the ‘room for rivers’ management strategy (recall Section 2.1.2) for braided rivers by providing an understanding of the relationship of channel width with braiding occurrence and complexity. This section will go over the morphologic relationships discovered in the Canterbury dataset and how they relate to river conservation by predicting a sufficiently wide channel that maintains or restores braided morphology.

To begin, it was identified that there is a strong relationship between channel width and count (or braiding intensity). The large dataset collected for the Canterbury rivers established this relationship and can be used practically to show what braiding index to expect for a given width or how many channels are expected to be lost based on channel narrowing. These results extend literature based only on defining braiding thresholds for a given width or width-depth ratio by adding a relationship for the braiding index component above the threshold.

The response of a river to changes in width is contingent on initial state (width and patten type) and the amount of width change. It is understood that the closer proximity to a threshold, the less change required to induce a pattern change. The Canterbury dataset looked at this effect quantitatively for both braiding threshold and braiding intensity. Braided rivers that are initially narrow (around 500m) have a higher probability of transitioning to a simpler planform type with narrowing. There is a clear scale effect where response in smaller rivers shows tendency for pattern transitions compared to larger braided rivers. Though trends in the data remained the same through the variety of scales, starting points for when certain morphologic characteristics or changes occurred differed. The starting width for a given braiding intensity is notably narrower for the smaller scale rivers and wider for the large scale rivers. This created overlap between the total analysis of the rivers, and separability between planform types were fuzzy. When the data was separated by scales, however, overlap was reduced and extreme outliers disappeared.

These results of river response to changes in channel width provide minimum width information that can be used for anticipating future change and for providing sufficient room for braiding. For the rivers studied, prior widths and channel patterns are known and can be restored back to their more natural states if room can be allocated. Solutions that maintain more land area may be more feasible however and, in these cases, width could be set based on the general trend of results to a desired braiding intensity. Based on the data trends an idea on the morphologic outcome of channel narrowing can be obtained for the Canterbury rivers and perhaps applied to cases more generally.

6.3 Canterbury Braided Rivers and the World

Stecca et al. (2019) concluded that the worldwide reduction of braided rivers due to anthropogenic pressures appeared to be true for rivers in Europe, but that trends in other regions were less clear. The paper concludes that the reduction of braiding depends on the region and its relationship with the river. This research looked at the changes to braided rivers in New Zealand, specifically in the Canterbury Plains where they are known to be affected by an intensifying agricultural industry. The research concluded that changes in these rivers can also be attributed to human modifications of the channels through constructed and planted flood protection boundaries and encroachment. Therefore, these rivers can be added to the collection of rivers outlined in the aforementioned paper that have been affected by anthropogenic pressures.

Stecca et al. (2019) report overall narrowing of braided rivers for a variety of reasons (including flow reduction (e.g., from hydropower effects), changes in land cover, gravel extraction, and direct engineering of channels). In contrast to many of the examples compiled by Stecca et al., (2019) that refer to limited reaches of individual rivers, the Canterbury rivers dataset covers the entire length of most of the rivers. In all rivers studied by Stecca et al. (2019), the reaches indicate an average narrowing of ~60% from the initial width with many of these reaches also transitioning from braided to more simplified patterns. In comparison, historically braided segments in Canterbury rivers narrowed by ~50%, on average, also with multiple cases of pattern simplification.

The results of the Stecca et al. (2019) dataset, others such as Gurnell et al. (2009) for European specific rivers, and now the Canterbury rivers, show a variety of different pressures that affected the rivers. Though the trajectories of change were similar, most notable is the commonality of narrowed braidplains and loss of braiding complexity. Brierley et al. (2021) note that many of the rivers in New Zealand are less modified than others in the world, therefore changing how the rivers are managed now may have an increasingly beneficial effect. Channel widening, providing sufficient room for natural lateral mobility and pattern formation, as a restoration method for rivers has been promoted for the New Zealand rivers and around the world, especially where changes in planform have occurred (Surian et al., 2009; Biron et al., 2014; Reid and Brierley, 2015; Fuller et al., 2020; Brierley et al., 2021). It is important to act soon because the predicted climate changes (discussed later) may cause more extreme flooding and drought in the Canterbury region and river management will become even more challenging.

6.4 Present and Future of Canterbury Rivers

Human activities have a large impact on river systems. Whether current river management is maintained or not, there are many future factors that could have effects on the river. The importance of maintaining the Canterbury rivers is indisputable. The rivers are drivers of the hydrologic cycle, they recharge groundwater and carry water across the plains, the water is used for drinking and most significantly irrigation to the region's intensifying agricultural practices (Tonkin and Taylor Ltd., 2022). The water is therefore vital, not only, for the region's population and economy, but also the culture and biodiversity (Tonkin and Taylor Ltd., 2022). The braided rivers also represent a culturally significant landscape, especially for Māori. Based on the results of this thesis, increasing channel narrowing will lead to further simplification of river morphologies and the eventual loss of braiding patterns. This would mean the loss of a nationally significant New Zealand landscape.

The threats to Canterbury rivers related to braiding morphology and processes also extend to related environmental conditions connected to overall river health. This section will go through the possible futures of the rivers of interest building from the outcomes of the analysis of braided river loss to include threats and issues such as continued irrigation, climate change, and ecologic impacts.

6.4.1 Braided River Conservation

Braided rivers are iconic national features of the New Zealand landscape and Canterbury has the greatest number of these systems. Understanding how rivers have changed over time and how they react to change is important for determining effective conservation plans, and establishment of new structures along the river margins. In the past, management of rivers concentrated on protecting infrastructure from flooding and erosion. In 2009, the Canterbury Regional Council (CRC) created the Canterbury Water Management Strategy (CWMS) where a set of goals were established involving the use and control of braided rivers while maintaining their natural character (progress is shared openly online; Canterbury Water, 2019; CRC, 2019). Projects to sustain braided river systems include weed control, legal protection of waterways, sustained flows, recreation management, education, and more (Canterbury Water, 2019). The main strategy to preserve the natural qualities of braided rivers is to maintain a clear path with a buffer around the margins (Hicks et al., 2021). This method seeks to decrease effects of erosion as well as to help control floods. The problem is in the use of the land area and farmers still tend to encroach on these margins (Mitchell, 2017; Hicks et al., 2021). The CWMS goal is to restore Canterbury's braided rivers to their natural dynamic by 2040 (Canterbury Water, 2019). The CRC is reported to be appealing to the High Court over the current riverbed definitions in the Resource Management Act where the current definition fails to provide a clear definition for braided rivers (CRC, 2019). In addition to regional councils, local citizen groups are also making an impact through research, education, and media (e.g. BRaid (https://braidedrivers.org/)).

Results from this thesis could support some of these efforts. In particular, knowing the historical changes is important context for current river states. The relationships between stream power, channel width, channel planform and braiding complexity provide a quantitative basis for anticipating the room that braiding rivers may need and the effects of particular restoration strategies such as vegetation removal and increased setbacks for agriculture. The width-based braiding criterion (Figure 5.28) is one obvious tool that could be implemented locally to plan restoration or demonstrate the corridor widths needed for a certain level of braiding for known discharge conditions.

6.4.2 Channel Narrowing and Groundwater

Channel narrowing also has an impact below the surface. Narrowing rivers has been noted to influence groundwater. With less surface area for infiltration, there is a reduced capacity to recharge the water storage below riverbeds. This information comes from a study of the Wairau River, located on the north end of the South Island, but is applicable to the Canterbury rivers. The study states that narrowing rivers could be leading to declining levels in groundwater (Hart, 2022). In the Canterbury region, aquifers are main sources for irrigation, drinking, and stock water (Vance, 2021). Groundwater is re-charged is through rainfall and the seepage of water from the rivers. But levels of groundwater have dropped over time (for Wairau aquifer specifically). There have been studies on how flood protection measures to contain the rivers and prevent flooding could be influencing groundwater recharge, along with natural changes in the bed elevation (Hart, 2022). Focusing on narrowing, constricting the river prevents the water infiltration across the landscape and prevents the occasional overflows when rivers flood, as the water is transmitted directly towards the ocean.

6.4.3 Irrigation

Beyond land demand and the confinement and encroachment onto the rivers, braided rivers are also at future risk due to the demand for irrigated water. Most irrigation comes from rivers, and the rest from groundwater (Srinivasan et al., 2011). Canterbury has a large water supply by the rivers and aquifers, but there are current concerns regarding reduced quantity and quality of water (Vance, 2021). Measurement of accurate water use in the area is "lacking" (Booker and Snelder, 2022). In 1991 the Resource Management Act was implemented which regulates water management (Booker and Snelder, 2022). Booker and Snelder (2022) report the increase of consented water abstraction since the late 1960s and rapid increase in the early 1990s. Regardless of a known amount of abstraction, demand will increase to maintain intensifying agriculture and growing populations. This will lead to a multitude of problems, including both environmental and socio-economic, that have already begun (Vance, 2021). In the Canterbury region abstraction for irrigation demands is the highest and expected to grow (Tonkin and Taylor Ltd., 2022).

Water abstracted from rivers reduces the flow and can lead to disconnection within the river and increased sedimentation (Vance, 2021). In addition to abstraction at low flows, flood water harvesting is also an issue. Most rivers have allocated amounts of surface and groundwater that may be abstracted, maintaining a minimum flow rule (Hoyle et al., 2019). The current system leaves flood flows there for the taking. This leads to what is called ‘flood-harvesting’, where water is ‘harvested’ and stored for later use (typically stored in the winter for use in the summer). This has many impacts on the river systems. Flood flows are important to maintain braided rivers, by turning over the sediment and transporting it downstream. Floods help the rivers move sediment, and if unable to do that then sediment may build up causing aggradation. Floods also control some of the natural vegetation growth within the bars of the river. Vegetation growth within the river can control the river morphology if left to grow. In addition to these effects, when floodwaters are stored, there are no flows to carry sediment through the system to the ocean. This leads to less gravel around the coast, thereby increasing risk of coastal erosion (NIWA, 2021). There is current research being done to look at the effects of flood harvesting on braided river geomorphology (Hoyle et al., 2019).

Regulations on water abstraction are proposed, but these will impact the livelihoods of those working around the rivers. The industries are relied upon by a population, but the consequences of unregulated abstraction are building up (Vance, 2021). Climate change coupled with continued irrigation will place more pressure on water resources from the rivers and groundwater. Predictions state that climate change will reduce irrigated water supply reliability due to decreased low flows, higher temperatures, and increased days with drought, leading to the inability to support current and future levels of supply to match demand (Tonkin and Taylor Ltd., 2022). While this demand for irrigation rises, so do environmental and socio-cultural issues (NIWA, 2021).

6.4.4 Climate Change

Predicted increases in temperatures, frequencies of drought, and changes to rainfall patterns have a large risk potential for the Canterbury rivers. Major risks, outlined in the ‘Climate Change Risk Assessment’ for the Canterbury Region produced by Tonkin and Taylor Ltd. (2022) include water availability on the surface and in the ground, water quality, supply for infrastructure, and flood protection. All of which have an influence on channel morphology.

Rainfall regimes are expected to change. It is predicted that, on average, rainfall in the Southern Alps will increase, but decreases will occur closer to the coast (Tonkin and Taylor Ltd., 2022). This will lead to different effects for the mountain and foothill origin rivers. For the smaller rivers that originate in the foothills, a decrease in rainfall occurrence means lower river flows. Though the mountainous regions are predicted to have increased rainfall, as air temperatures increase, the production and storage of water in snow and ice will reduce. This may result in many of the major rivers exhibiting more seasonal flows, as the early spring and summer month flows depend on snowmelt in the headwaters (Srinivasan et al., 2011; Tonkin and Taylor Ltd., 2022). Low flows are also linked to a rise in drought potential creating a major demand for and risk to the water supply. In all, the plains will have an increased demand for water.

Flooding is likely to become more of a problem with the projected increased frequency of high intensity storms (Srinivasan et al., 2011; Tonkin and Taylor Ltd., 2022). Flooding leads to increased erosion and scour in the rivers and may result in increased sediment, leading to significant effects on the morphology of the rivers, especially the smaller ones (Tonkin and Taylor Ltd., 2022). The increased floods can cause widespread damage to surrounding infrastructure including agricultural areas, bridges, and flood protection structures putting pressure on relied upon systems and generating expensive repairs and maintenance (NIWA, n.d.). It is expected that rivers with constricted floodplains will be especially sensitive to flooding due to the degradation and pressure on protective margins and also the rivers' limited ability to respond to increased flows (Tonkin and Taylor Ltd., 2022). Constraints on lateral mobility limit the adaptability of the rivers as they respond to changing conditions (Tonkin and Taylor Ltd., 2022). This is a very big problem when the floodplain is cut off from the river as the river will then be likely to cause even more damage. Rivers with fewer (natural or anthropogenic) constraints may be more adaptable to changes as they are able to naturally expand as needed.

6.4.5 Flood Protection

The Canterbury rivers have already been shown to have changed in character as braiding complexity and presence throughout the plains have decreased due to narrowing by flood protection measures. The narrowing reduces the rivers' natural ability to laterally respond to high flows and therefore can cause increased flood risks, especially when development is located directly within the natural floodplains. An example of recent flooding effects following braided river constriction has already been shown in Section 4.4.7 along the Ashburton River, though similar responses to high flows are noted along many other systems.

As rivers are subjected to increased high intensity flows it will lead to increased erosion and scour of the channels and risk of overtopping constructed flood protection structures. Current flood protection systems may not be enough to handle the increased pressures during such events (Tonkin and Taylor Ltd., 2022). In fact, according to Environment Canterbury flood engineers, cited by Tonkin and Taylor Ltd. (2022), many of the older stopbanks throughout Canterbury may only provide minimal protection as they were not designed to handle the changing flows. In addition, vegetation buffers are very important for protecting stopbanks, but if these regions are damaged by flooding, it may take a long time for them to re-establish at the same level of protection (Tonkin and Taylor Ltd., 2022). Stopbanks can be updated to provide for more protection based on future predicted changes in flow, but such upgrades require land and are costly (Tonkin and Taylor Ltd., 2022).

Changes to river flow regimes may change river characteristic and pattern types (Williams, 2017). Increased flooding can cause the rivers to widen and shift back to more braided states as stream power increases with high flows, as shown by results in this thesis (Figure 5.16). Stopbanks provide limited to no adaptive room for the river to respond to changes and past flood protections measures may not be able to contain the higher flows and morphology changes (recall Ashburton 2021 flooding example in Section 4.4.7). These flood protection measures would therefore require updates or more frequent maintenance. Another option would be to grant the rivers the room to adjust and maintain any re-braiding, though this would mean sizable land loss. The Canterbury rivers could look very different depending on how the climate changes and how the rivers are managed. All scenarios of climate change should be taken into account for future river management.

6.4.6 Ecologic Impacts

The application of this research can be linked to other disciplines, including ecology, as a way to help better understand the environment. Braided rivers are a rare landscape feature and on a national level braided rivers are classified as rare or uncommon ecosystems (Grove et al., 2015). The area of the river that provides a unique habitat includes the active riverbed and floodplain. While a braided river is a moving body of water, it provides connected habitats and an ecosystem around it. The rivers provide an important linkage between the mountains, inland habitats, and the ocean. Braided river habitats have very distinct characteristics and support a wide variety of biodiversity both aquatic and terrestrial (Grove et al., 2015). Under the current conditions, the biodiversity is threatened, and an increased risk is predicted.

Riverbeds, floodplains, and their margins support various species and are important aspects to consider for river management. Undeveloped braided margins tend to hold greater ecologic values and ecosystem services, while developed margins, with artificial flood protection for example, cause a loss of natural character and negative ecologic effects. Riparian plantings between rivers and land are useful in mitigating high flow effects, maintaining the stability of the river and its banks, and moderating river temperatures, while also providing habitats to various species (Grove et al., 2015). The riparian vegetation of the river margins is also important for providing a buffer between the intensified agriculture and river ecosystem that can filter out pollutants from farming activities (Grove et al., 2015). In locations where there are no buffers, perhaps due to land demand, pollutants have a more direct connectivity into the rivers. The buffer systems, however, are often plantings of exotic vegetation, instead of native plants, reducing the biodiversity. This creates new habitat characteristics, impacting the native species.

Planted vegetation may also become invasive affecting both the ecology and river morphology. This has already been observed as one of the causes of loss of braiding.

The natural low flows of the rivers are being intensified by human activities that involve the abstraction of water from the surface and groundwater. Abstraction decreases the flow of the rivers which leads to disconnection of river channels and higher pollutant concentrations (Vance, 2021). Slow moving waters and disconnection of the river will influence the morphology and ecology, specifically native fish species, of the river (Vance, 2021). Water quality is being affected and worsened as when the rivers dry up, algal blooms occur, oxygen levels decrease, and pools of disconnection harm and trap fish populations. Warmer air temperatures due to climate change will also lead to increased water temperatures which may affect the nutrient cycle, river productivity (promoting growth of algae and macrophytes), and may provide environments suitable for harmful invasive species (NIWA, n.d.; Tonkin and Taylor Ltd., 2022).

To maintain river habitat diversity, the river must remain natural. Natural conditions based on historical analyses show what the rivers could look like. This thesis has shown the modification and reduction of natural character along the Canterbury rivers studied. When restricted, such as by encroachment or engineering, the natural character is changed along with the habitat quality and diversity. Further development of the river margins and riparian environments and climate changes may have severe impacts on the habitat and species that can be sustained, and all of this connects and depends upon the river morphology. The ability to anticipate or predict river morphology is an important part of the basis for modelling river hydraulics and pollutant dispersion in rivers.

6.4.7 Summary

The future of the Canterbury rivers depends on understanding the systems and anticipating how they may respond to change. This understanding begins with a historic knowledge of the river morphology. The study period for this thesis began during a period prior to much development in the Canterbury region (mid-1900s) through to present day conditions. The rivers have significantly changed during this time period due to lateral confinement, irrigation, land use change, etc.; the most notable changes in channel morphology include the channel narrowing and loss of braiding. The management of these systems has many repercussions on the fluvial system. Ground water recharge, flood risk, effects of climate change, and biodiversity have all been shown to depend on river morphology. Understanding the response of rivers to change and interactions between systems is key for a sustainable fluvial landscape. The thesis results suggest methods for sustaining braided morphologies and provides predictions of conditions for braiding loss. If braiding cannot be maintained, the future impacts on the Canterbury region may worsen.

6.5 Limitations and Future Work

The large dataset collected provided the ability to conduct a regional analysis of river channel changes across the Canterbury Plains. Though the data included numerous accounts of river characteristics along the channels there are noted limitations and absences, which provide areas for future work. There are also numerous ways in which the thesis can be expanded upon.

To begin, only two periods in the rivers' history were used to study the changes over time. The time between periods is large and during that time significant changes to the rivers occurred that are generally unknown. It would be interesting to know when flood protection measures were installed and how long it took before the river responded to those changes. This would provide an idea of the response periods that this before-and-after study could not capture. The two periods of collection were also captured at an unknown flow stage. Variation in flow stage affects the morphology of a river and may influence the vegetation coverage within the channels, this influences the measurement of active width and channel counts. To build upon this research and mitigate these unknowns an interesting addition would be the inclusion of multiple periods of image capture within the study period. This could show the purpose or cause of the lateral constriction imposed on the river systems, the relative construction periods of bank protection, and the trajectory of channel pattern changes, while limiting any anomalies during image capture over time.

Another limitation previously mentioned was the generalization of morphology and confinement types into three categories. Discrete classification was difficult and fuzziness between categories was common. Improvements in the classification of confinement and morphology types could be made such that more quantitative parameters are used to categorize types or additional types are created to categorize to.

An automated method of active channel area would allow for more efficient analyses of regional mapping of fluvial systems. These tools have been developed though are limited by data availability and resolution. For example, an open-source Google Earth Engine program has been created that detects river channel change using multi-spectral Landsat satellite imagery (Boothroyd et al., 2020). This tool is able to detect active river channels based on the spectral signature of water and bare gravel, though spatial resolution of the imagery omits any detailed information such as number of threads in a braided channel and may not capture channels narrower than the pixel size. The high resolution orthophotos used in this thesis remove the issue of data availability and therefore with powerful enough computers and access to visible to infrared wavelength imagery (infrared imagery captured during similar period to recent period of this study (2012-2016) at 0.3-0.4 spatial resolution), similar automated analyses could be completed. Other tools have also been developed that include the use of digital elevation models and automatic classification of river confinement and morphology types (Demarchi et al., 2017). Advancements in the field of remote sensing have numerous possibilities for applications in river channel identification and classification.

The theoretical predictors in the literature could not be as extensively compared to this dataset due to many unknowns and therefore significant datasets were omitted or estimated. This includes unknown bed material particle size and some uncertainty about depth and discharge both historically and for present day. The effect of some variables (e.g. stream power) on channel morphology may depend on particle size. For all of the rivers of interest, there is limited information on this, and more data and analyses are required to see if there is a detectable particle size effect. Particle size information along river systems is an essential factor in fluvial geomorphology. Upgrades in technology have allowed for acquisition of extremely high-resolution imagery that can be used to detect bed material particle size both on the surface and below for granulometric analysis (Carbonneau et al., 2004; Langhammer et al., 2017; Ermilov et al., 2020; Marchetti et al., 2021). As research continues, techniques for large scale analysis of river channel particle size will become more common and work is already underway on this for some Canterbury rivers (James Brasington, pers. commun., 2021). In this thesis, depth measurements were based on LiDAR derived DEMs and values were underestimated due to the inability of LiDAR to penetrate water surfaces. It can be assumed that the water surfaces were near to the bottom of the channels causing minimal error, and the data did appear to align with depths from other datasets for rivers of similar size (Figure 5.17), though the true influence of this is unknown. Future work could include the remote determination of channel depth by different methods or through field measurements.

There is further potential for analyses with the Canterbury dataset in terms of channel pattern predictors that were not covered in this thesis. Numerous morphology related variables were collected, and many others could also be collected, such as bed material particle size, that could be combined to better predict conditions for braiding. The dataset can also be added to by collecting data with the proposed methods for other gravel-bed braided rivers from around the world. This would show the relationship of the Canterbury braided rivers with others and would show if the results can be applicable to braiding in general. If accurate predictions of braiding and braiding intensity occurrence could be made for the Canterbury rivers, and braided rivers in general, there is great potential for use in braided river conservation. The ability to understand and predict the response of a river to environmental changes can be used to define the requirements to maintain braiding or restore it to its natural function in many scenarios, beyond that of just narrowing.

This thesis has shown what can be done based solely on remote sensing imagery and shared (secondary) data. Although not observed from the ground, significant analysis of the total river systems across an entire region could be completed. In the future, this work could be improved by more local knowledge and ground measures to look at specific areas of interest.

The last period of imagery capture for this thesis was about 5-10 years ago. Within that time the rivers have not remained static. Rivers will continue to change, and it is expected that future river adjustments will occur and need to be measured and recorded.

Chapter 7

7 Conclusion

The purpose of this research was to contribute to the understanding of the effects of lateral mobility change on braided river morphology, looking at real world cases from the Canterbury Plains, New Zealand. The study region provided a variety of river scales and morphologies to compare the effects of continuous channel narrowing. A large dataset was created, covering hundreds of 250, 500, and 1,000m segments along nine rivers, and allowed for new ways to empirically look at braided river changes.

The first research objective was to show how the Canterbury rivers have changed over time and was investigated in Chapter 4. The results quantified the observable changes in river channel width from a period of low to high confinement along the rivers and showed that rivers have narrowed close to 50% on average and over 90% in some reaches. Channel narrowing was linked to varying levels and types of confinement. The most common confining margins were stopbanks and planted vegetation, typically occurring within the historically measured active channels of the rivers. The smaller rivers were most notably constricted by these confining margins, while the large scale rivers, though becoming confined, still maintain channel widths hundreds of meters wide. In addition to changes in channel width and confinement, channel pattern changes were measured including both planform type and channel count (or braiding intensity). These results show that, in line with channel narrowing, braiding complexity and occurrence has greatly decreased along all of the rivers of interest. While the larger scale rivers remain with long reaches of braided defined segments, the smaller rivers have almost completely lost the braided morphology along their entire length. Overall, to answer the first research objective the rivers have severely narrowed and decreased in braiding complexity and occurrence, thereby changing the geography of braiding throughout the region.

Measurements and predictions of river characteristics along each segment of the rivers of interest were used to create a dataset of braided river characteristics that were used to answer the second and third research questions (Chapter 5). A relationship between channel width and count was determined that showed how channel narrowing results in a decrease of braiding intensity, and with enough narrowing may cause a shift from braided morphology to wandering or single channel. An outcome of this analysis was an understanding that braiding is scale dependent. It was shown that narrower channels (common to the small scale rivers) are closer to a threshold condition for braiding and therefore require less narrowing than initially wide channels (common to the large scale rivers) to see a change. In general, it was shown that there is a predictability to braided channel simplification and loss, though results have some uncertainty due to overlap between pattern changes. Based on existing channel pattern theory and braided river datasets, the results line up relatively well, though some adjustments could be made to match the Canterbury rivers specifically. A width-based predictor of pattern change was created that can be applied to look at the effects of narrowing on both braiding complexity and planform change. This has potential application in aiding future river management plans for conserving braided river morphologies. Additional variables could be included to more accurately predict braiding changes and data from other gravel-bed braided rivers could also be added to the dataset to see if the results are applicable to braiding in general.

All the rivers face environmental pressures, including lateral confinement, land cover change (e.g. intensification of agriculture), water abstraction, major rainfall events, and climate change. Effective management of these rivers may reduce future management and restoration costs. One clear way to do this is provide the river with enough space to naturally adjust and adapt to change. Though under current land demand circumstances, complete freedom to braided rivers is unlikely and compromises will have to be made that can still maintain the braiding morphology. The results of this thesis show approximate minimum widths that rivers require to maintain a given morphology type or channel count. This information may guide future river management plans by anticipating the effects of restoration plans or any further encroachment, potentially lowering the risk of major flooding events. Essentially, enough space for the rivers to naturally migrate and respond to changes is one way in which flooding can be mitigated and braided rivers can be saved from extinction.

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Appendices

Appendix A: Supplementary Figures

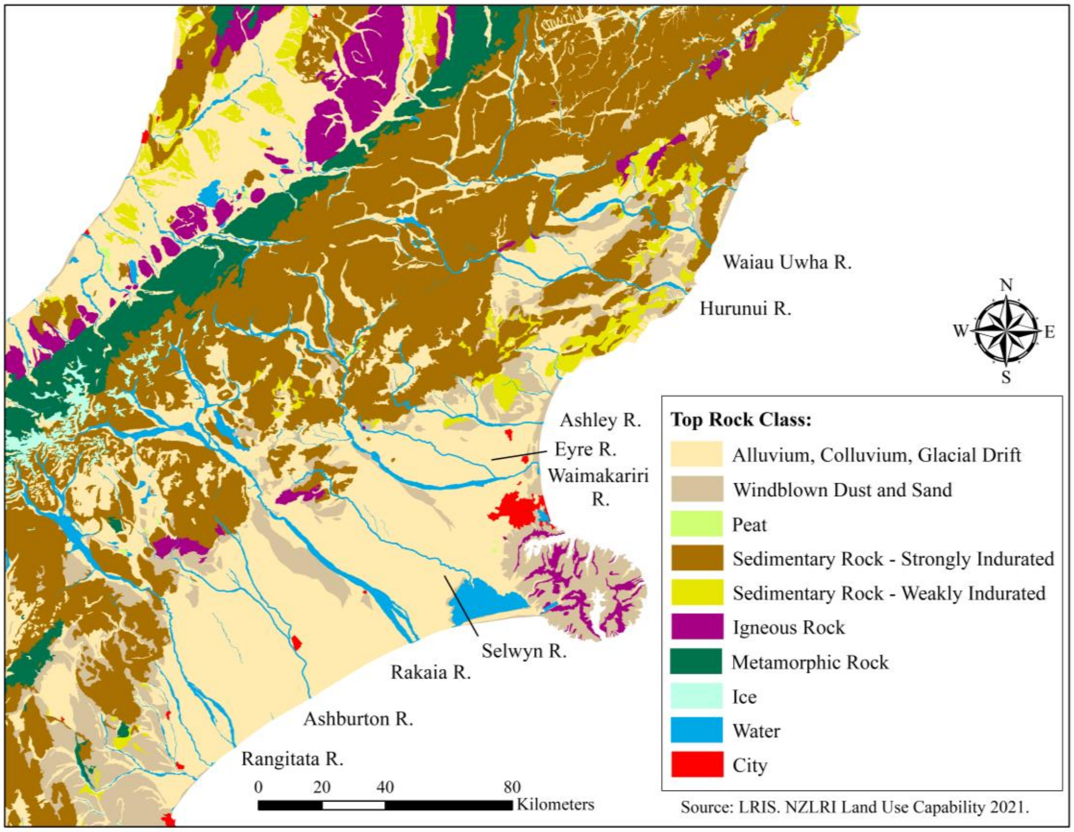

Figure A.1: Geologic map of study area. The map is only showing the top rock geology of the area, underlying geology varies. Data sources for represented shapefiles are listed in References under 'Data Sources – Shapefiles'.

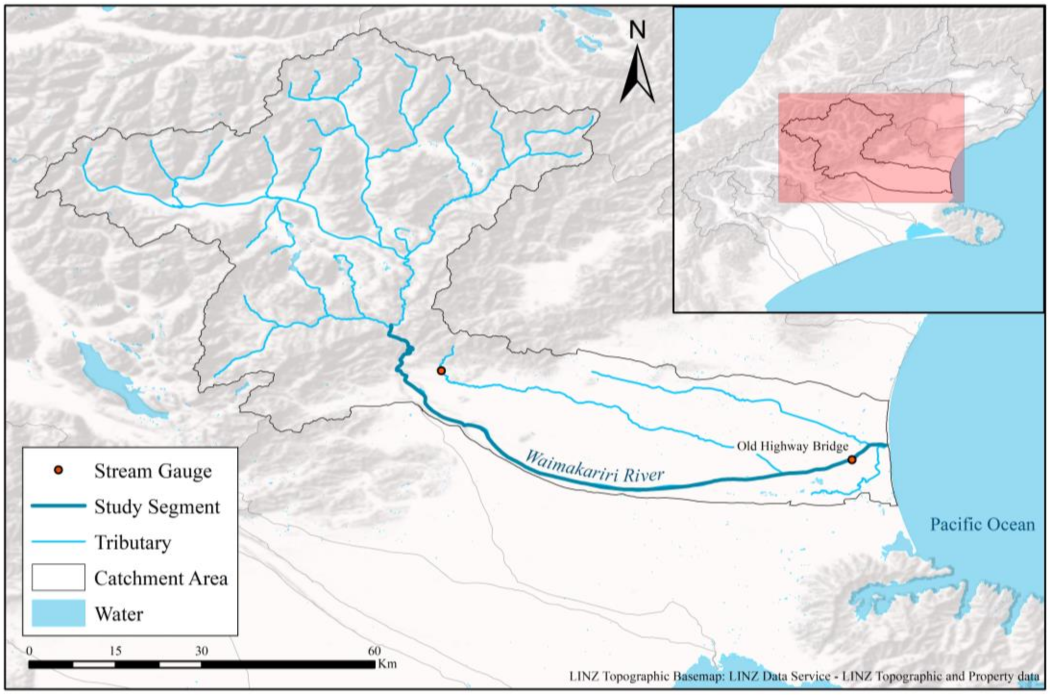

Figure A.2: Topographic map of Waimakariri River catchment area. Stream Gauge locations in orange with site names provided.

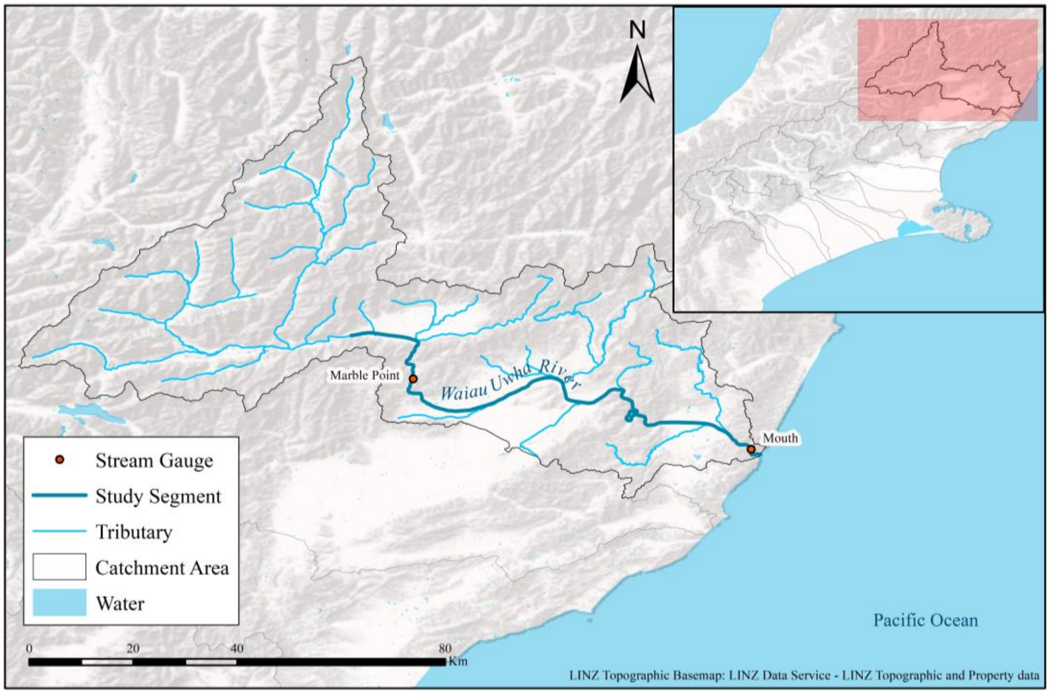

Figure A.3: Topographic map of Waiau Uwha River catchment area. Stream Gauge locations in orange with site names provided.

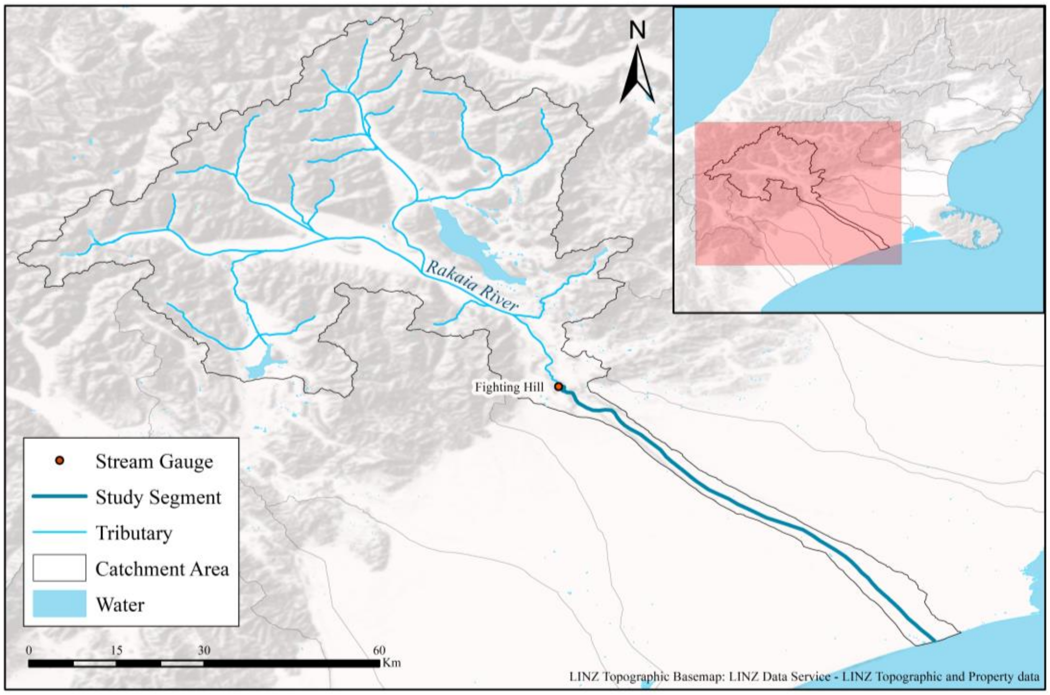

Figure A.4: Topographic map of Rakaia River catchment area. Stream Gauge location in orange with site name provided.

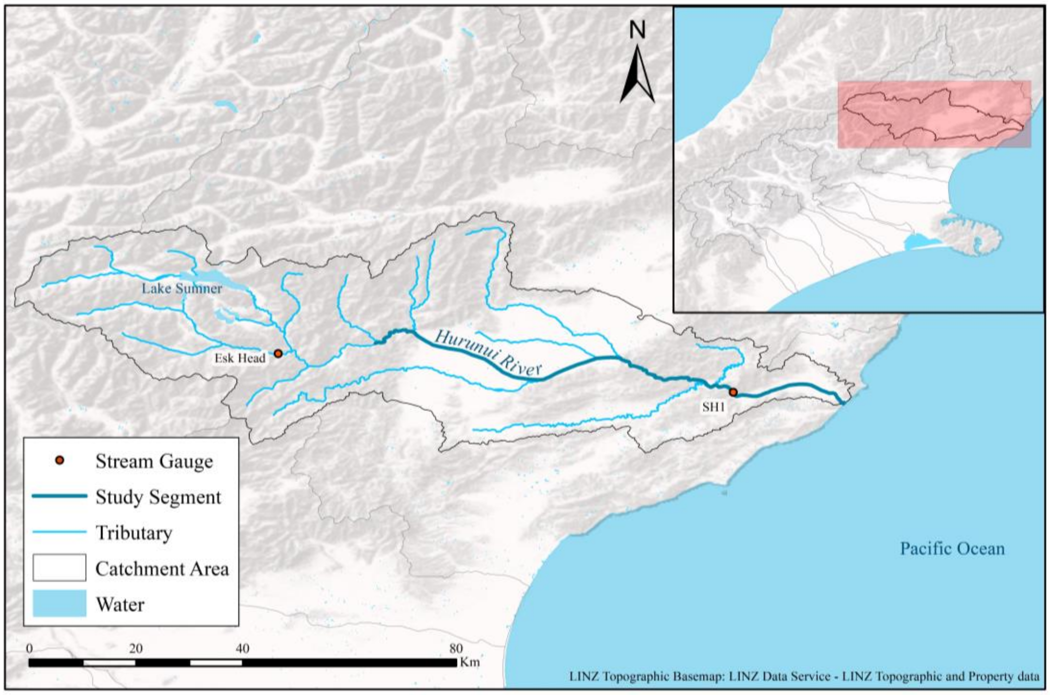

Figure A.5: Topographic map of Hurunui River catchment area. Stream Gauge locations in orange with site names provided (SH1 = State Highway 1).

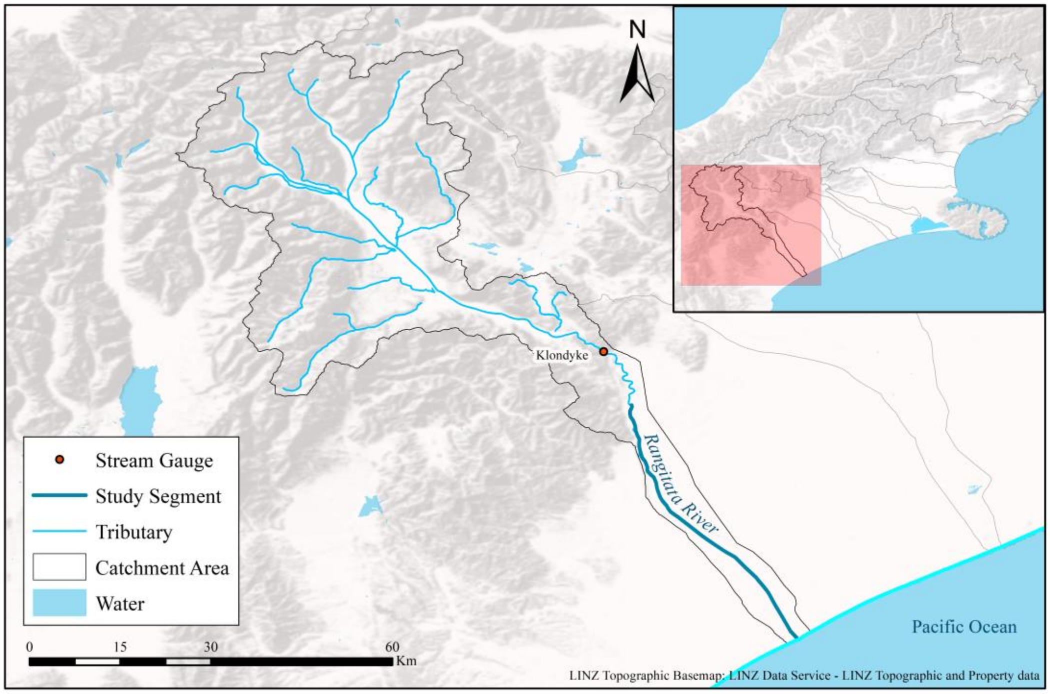

Figure A.6: Topographic map of Rangitata River catchment area. Stream Gauge location in orange with site name provided.

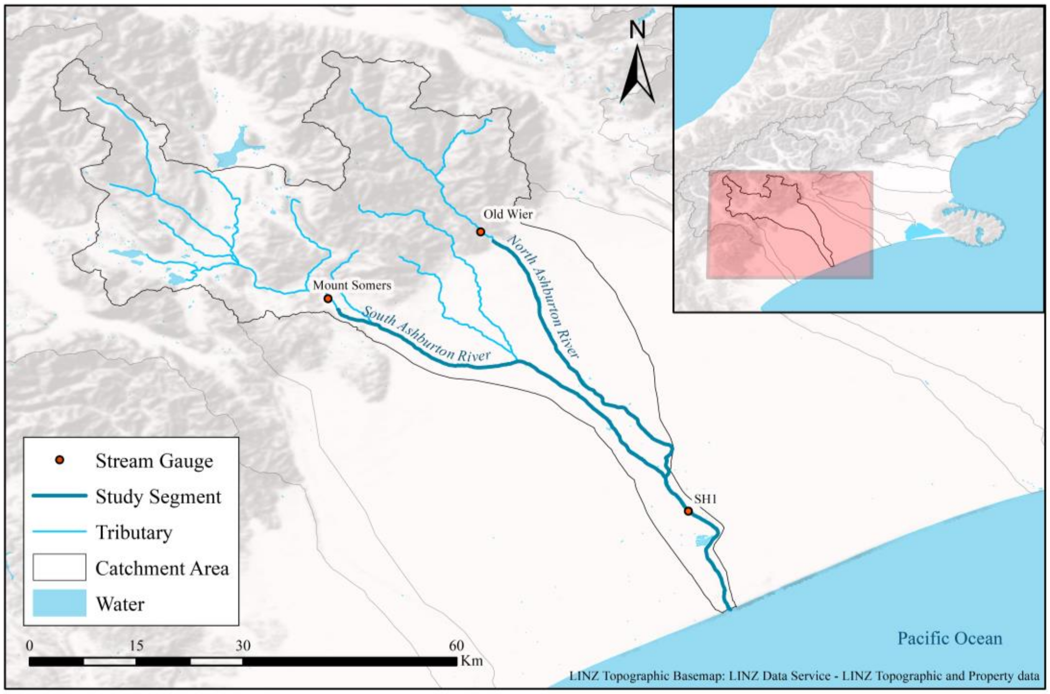

Figure A.7: Topographic map of Ashburton River catchment area. Stream Gauge locations in orange with site names provided (SH1 = State Highway 1).

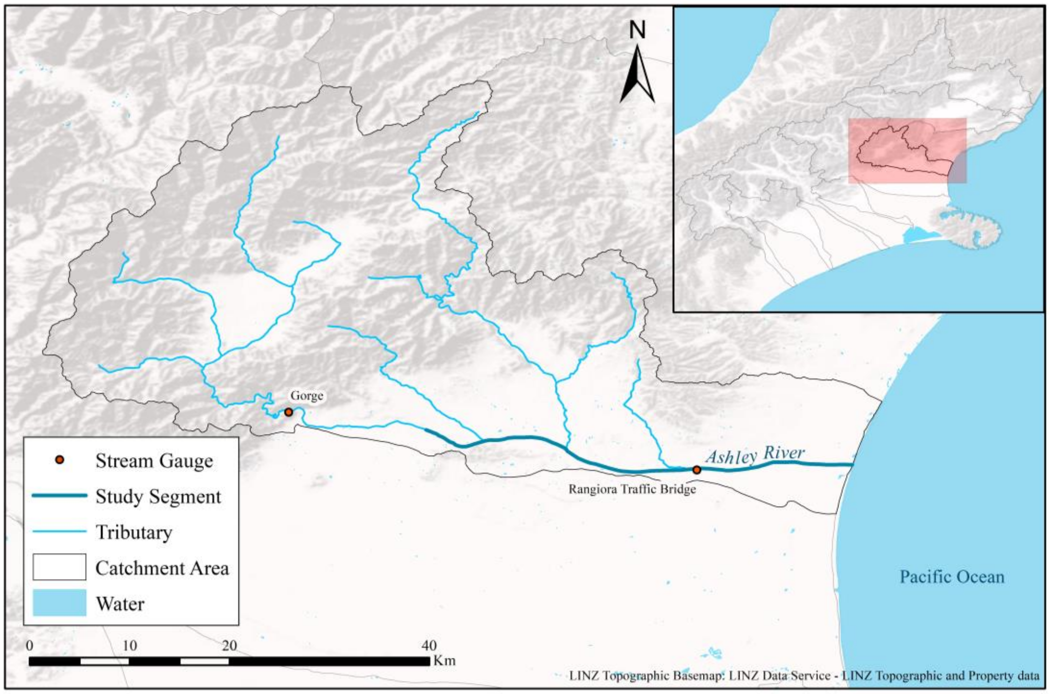

Figure A.8: Topographic map of Ashley River catchment area. Stream Gauge locations in orange with site names provided.

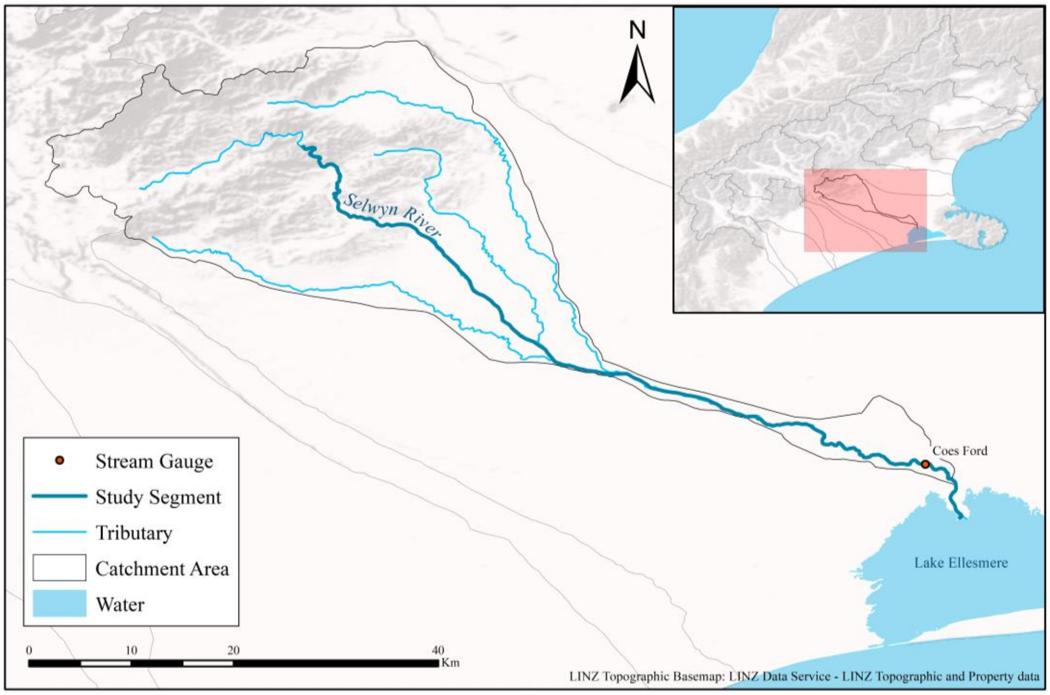

Figure A.9: Topographic map of Selwyn River catchment area. Stream Gauge location in orange with site name provided.

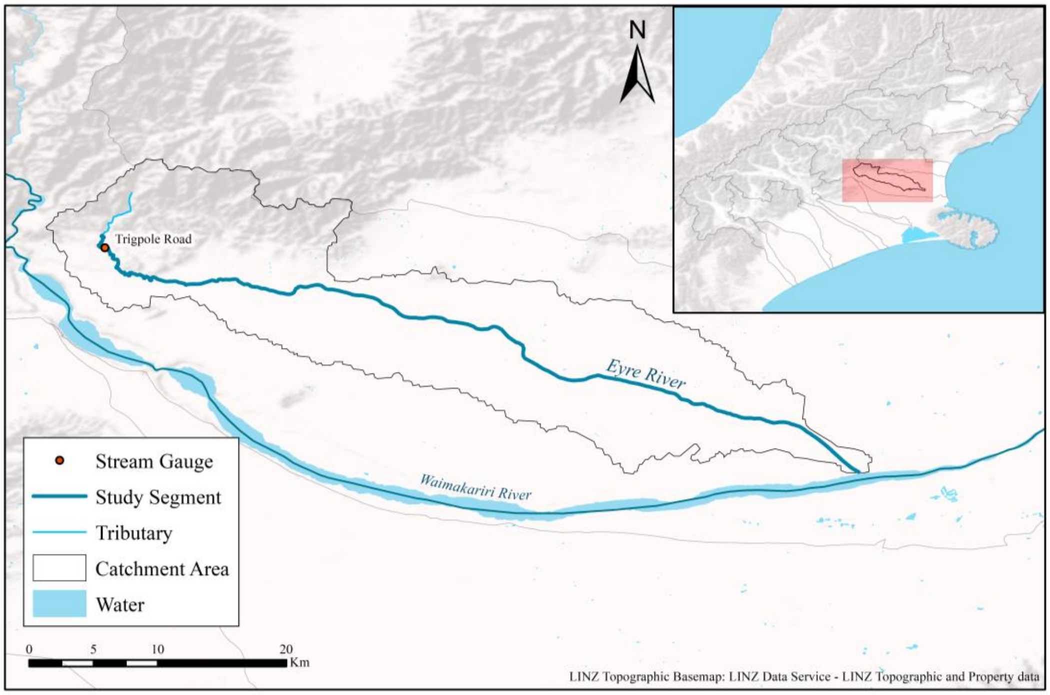

Figure A.10: Topographic map of Eyre River catchment area. Stream Gauge location in orange with site name provided.

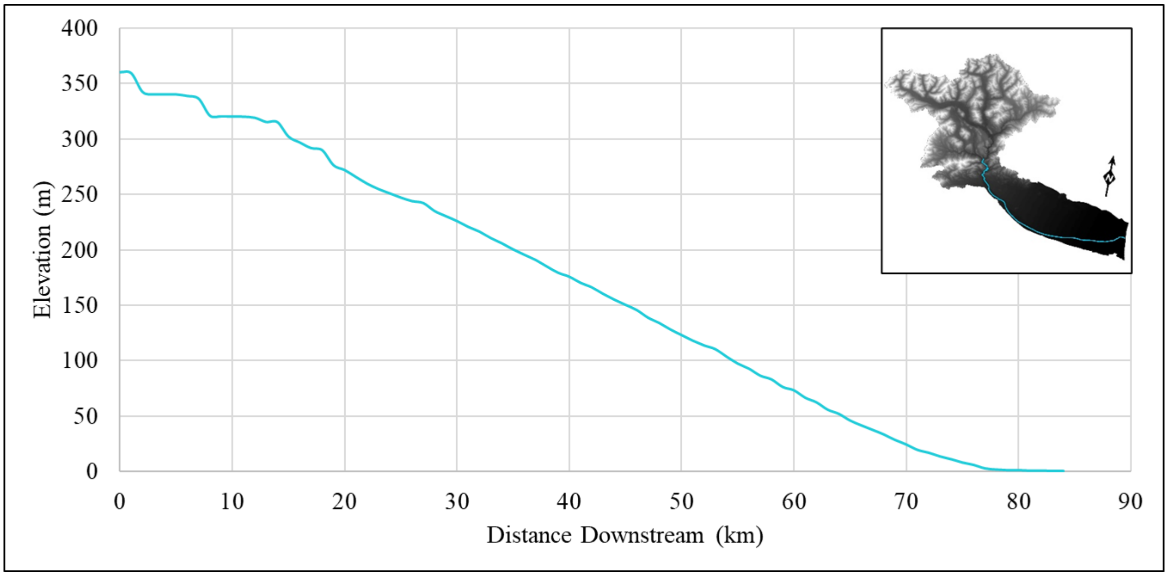

Figure A.11: Elevation profile - Waimakariri River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

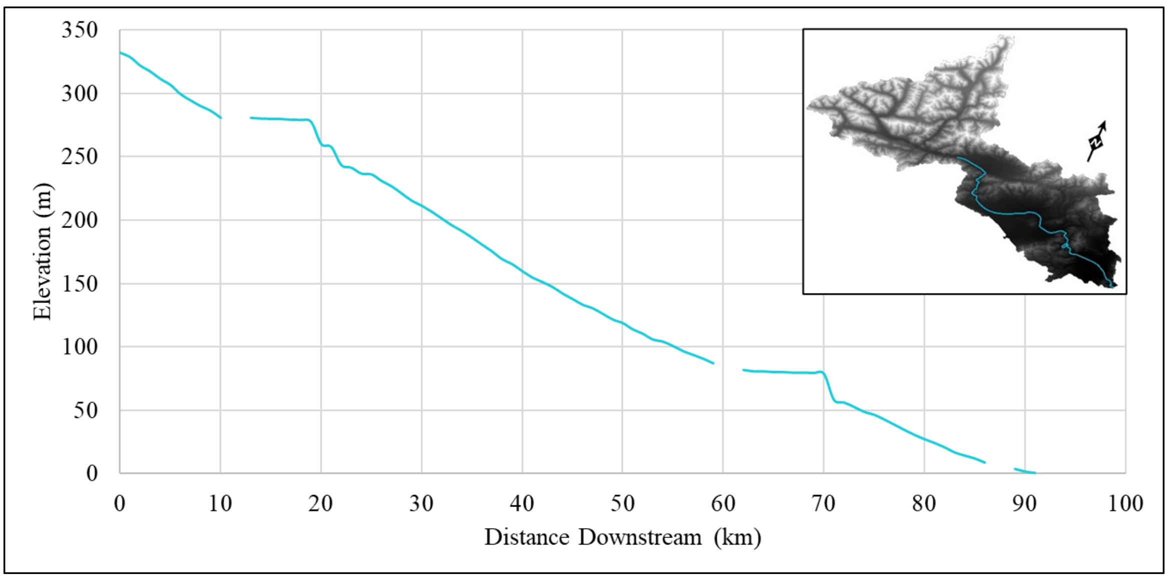

Figure A.12: Elevation profile - Waiau Uwha River. Derived from 1m and 8m DEM (preference to 1m DEM elevations). Missing reaches due to 8m elevation anomalies.

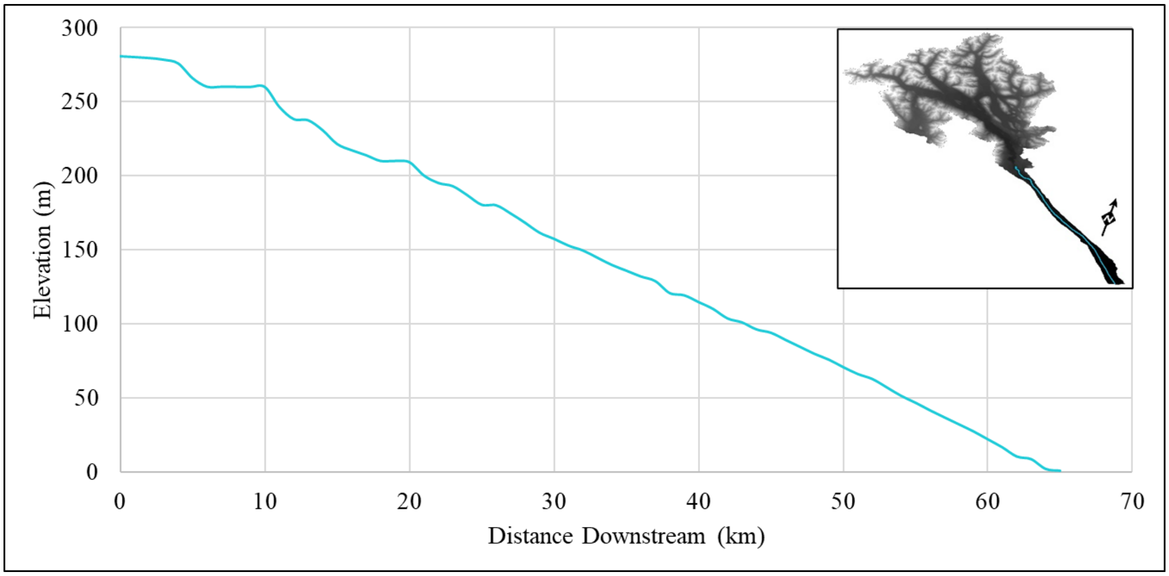

Figure A.13: Elevation profile - Rakaia River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

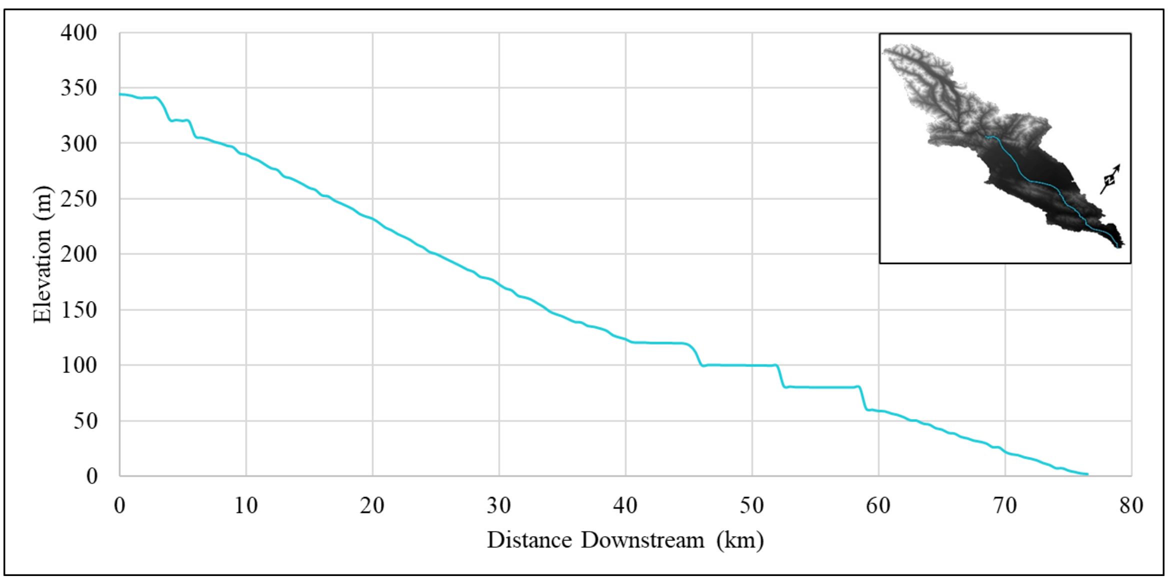

Figure A.14: Elevation profile - Hurunui River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

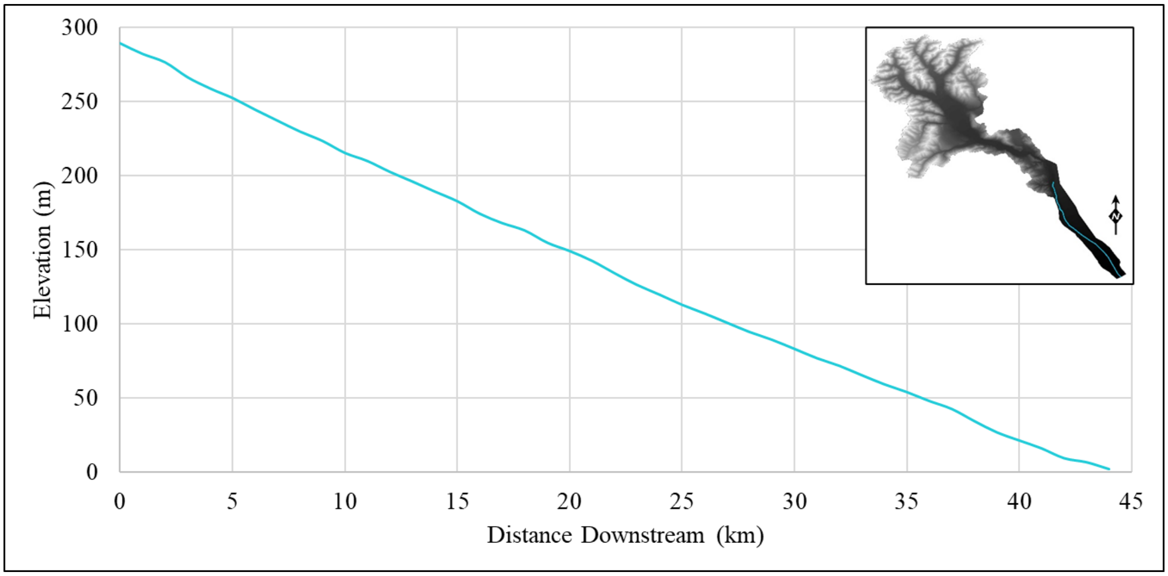

Figure A.15: Elevation profile - Rangitata River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

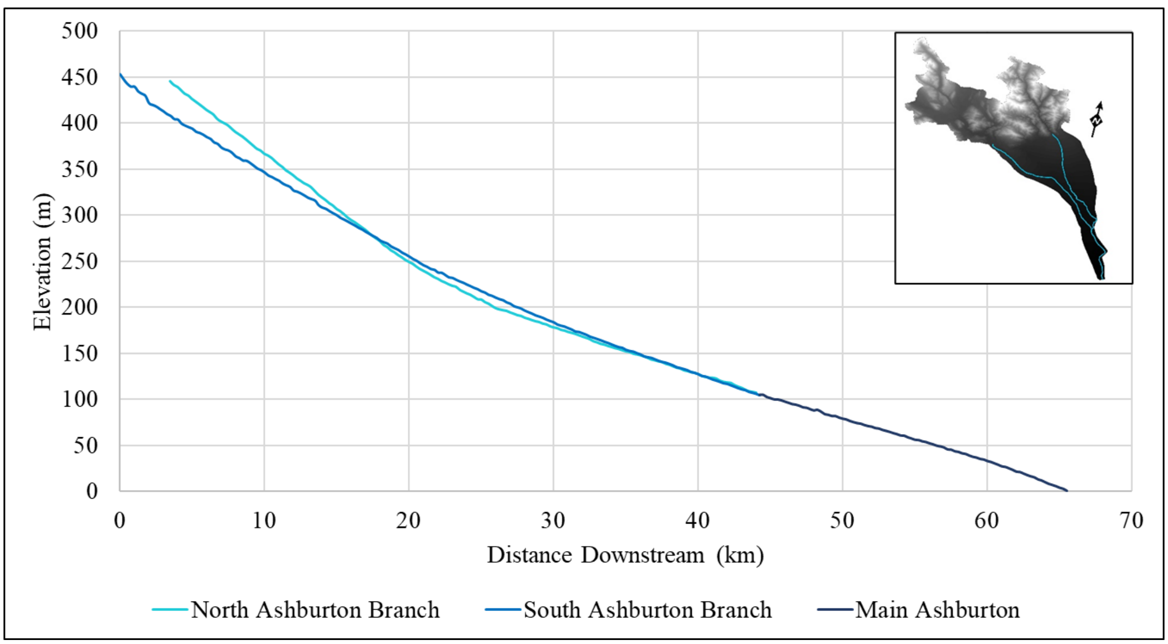

Figure A.16: Elevation profile - Ashburton River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

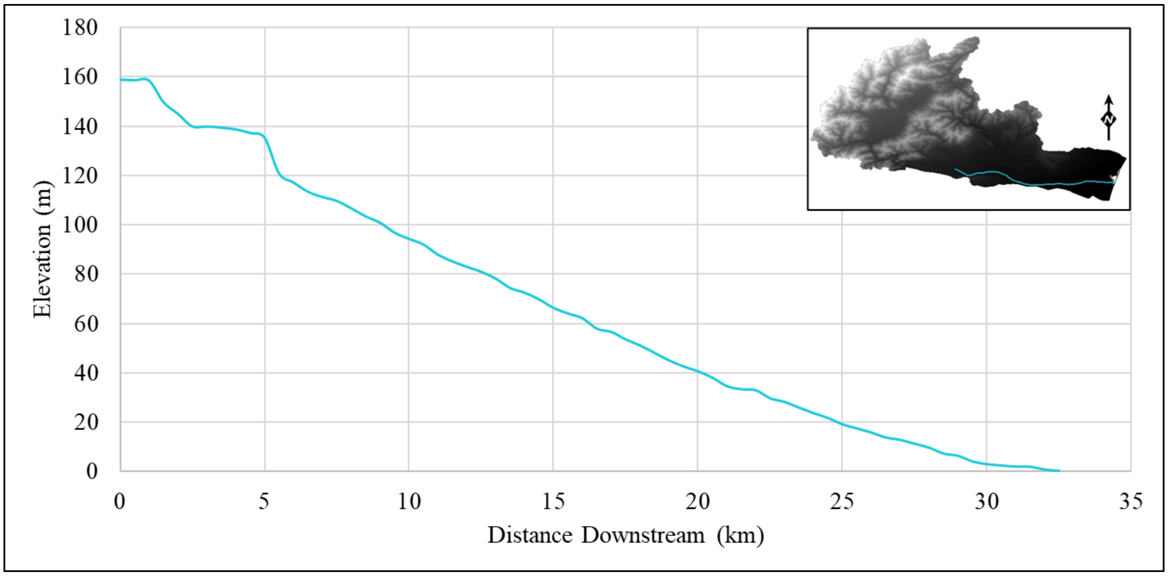

Figure A.17: Elevation profile - Ashley River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

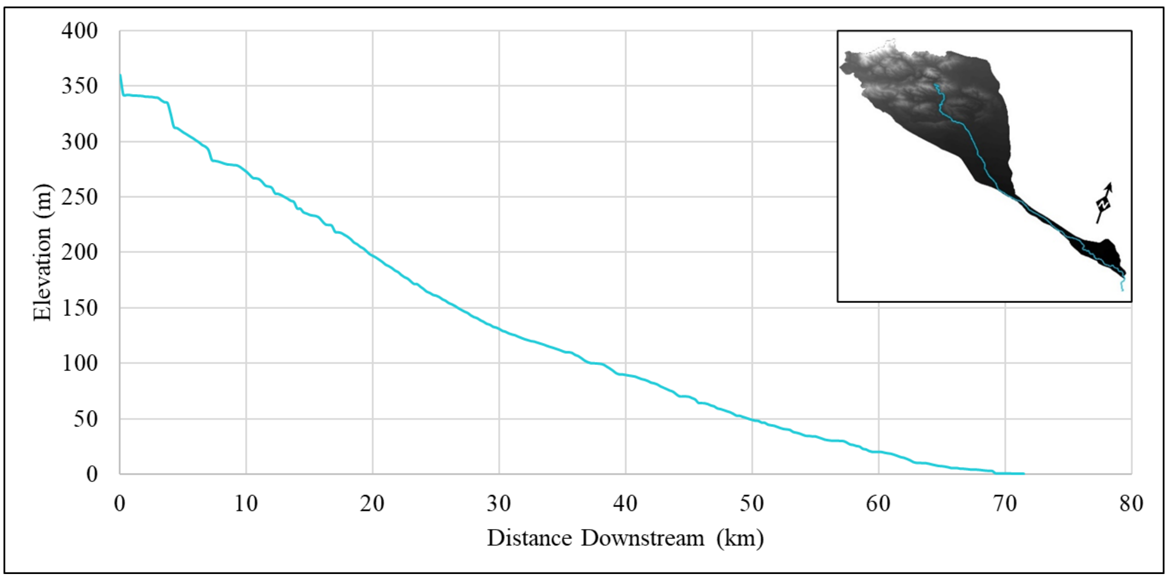

Figure A.18: Elevation profile - Selwyn River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

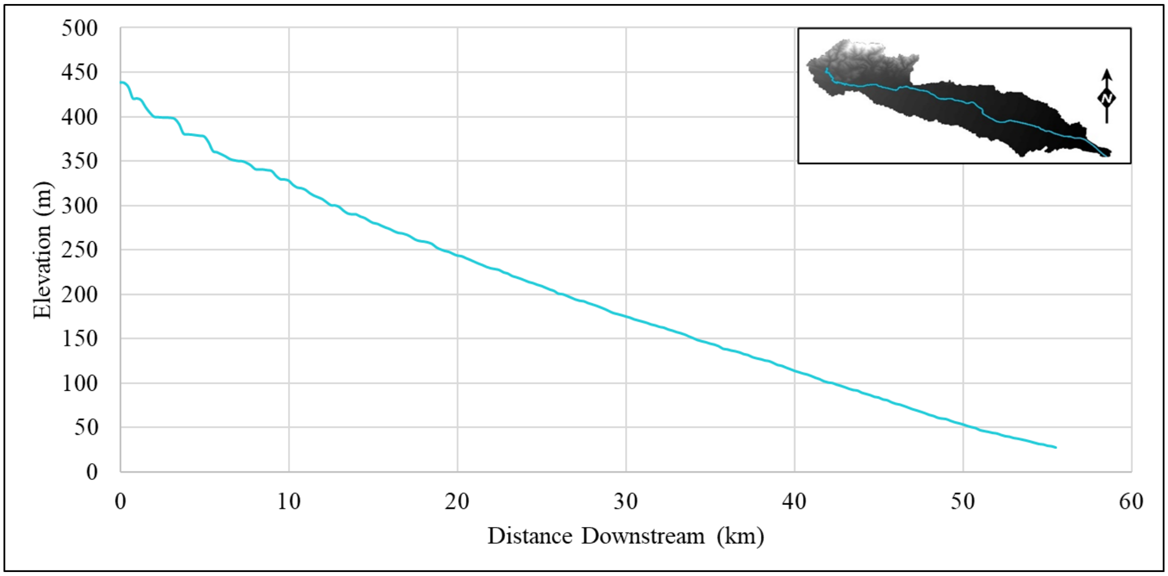

Figure A.19: Elevation profile - Eyre River. Derived from 1m and 8m DEM (preference to 1m DEM elevations).

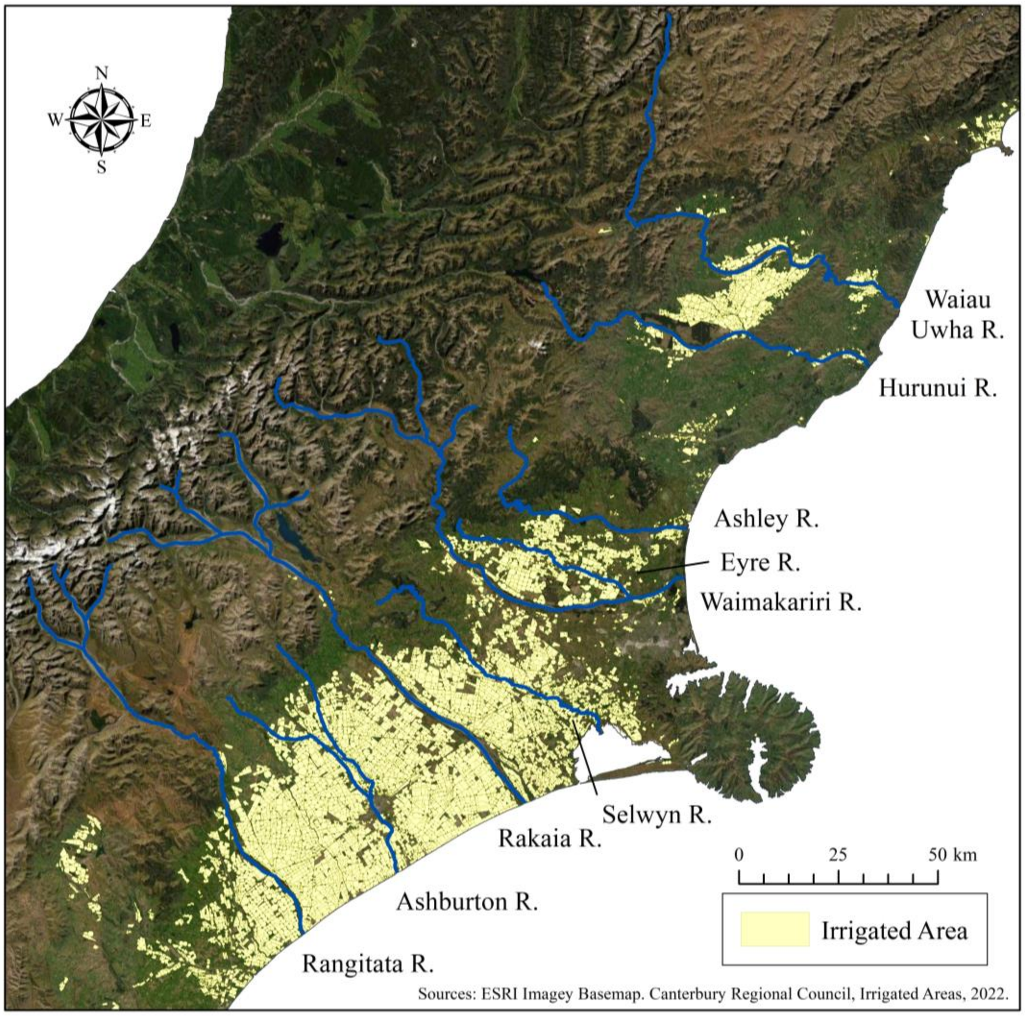

Figure A.20: Map of irrigated areas within study area. Data sources for represented shapefiles are listed in References under 'Data Sources – Shapefiles'.

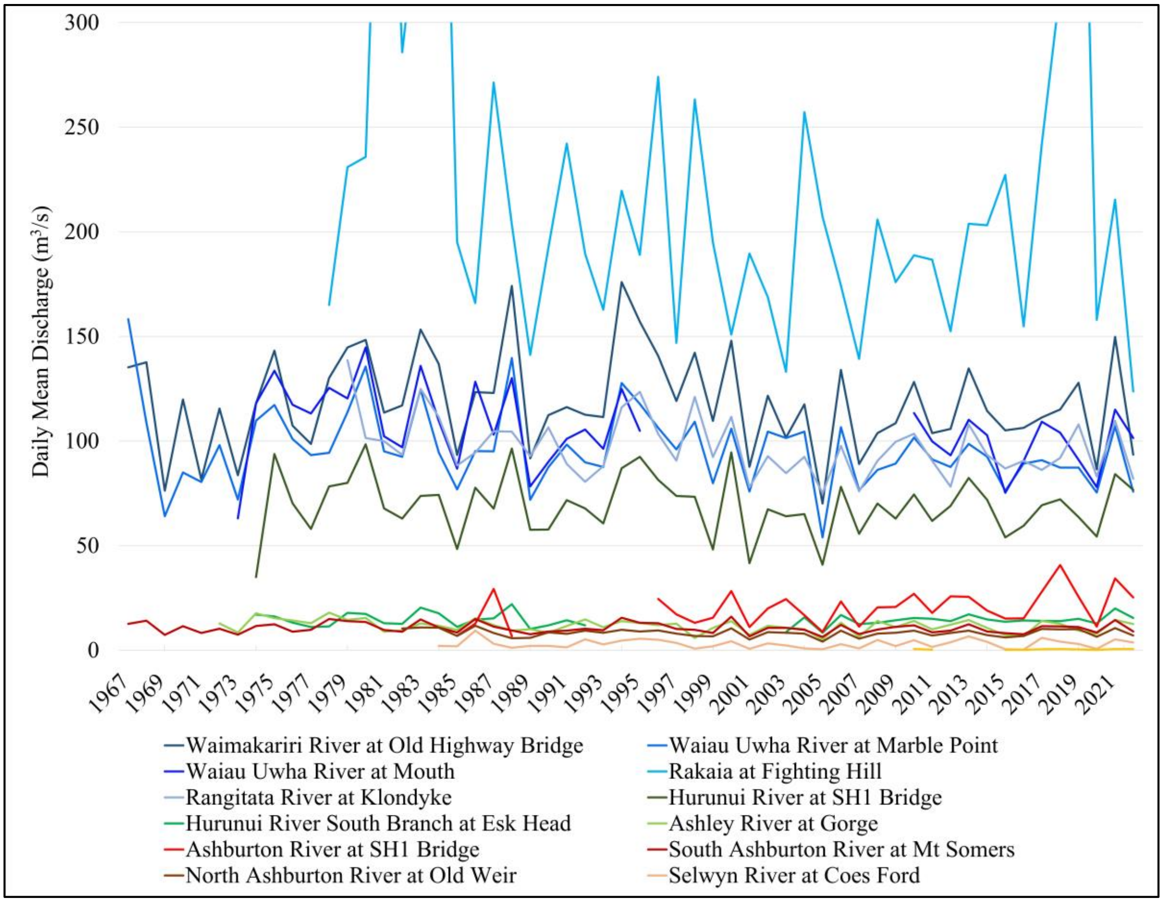

Figure A.21: Annual average daily mean discharge data from gauging stations along rivers of interest. Data provided by CRC and NIWA (CRC, pers. commun., July 11, 2022; NIWA, 2022). Rakaia annual flows in 1984, and 2019 recorded to exceed 500m^{3}s^{-1}.

Appendix B: Discriminant Analysis Confusion Matrices

Table B.1: Linear Discriminant Analysis (LDA) - All scales #1

	Braided-Braided	Braided-Wandering	Braided-Single	Wandering-Wandering	Wandering-Single	Single-Single	Precision (%)
Braided-Braided	**121**	31	0	11	0	0	74.2
Braided-Wandering	102	**237**	24	67	16	1	53.0
Braided- Single	0	0	**0**	0	0	0	0
Wandering-Wandering	16	43	0	**73**	0	6	52.9
Wandering-Single	0	0	0	0	**0**	0	0
Single-Single	0	6	0	44	40	**183**	67.0
Recall (%)	50.6	74.8	0	37.4	0	96.3	**Overall Accuracy: 60%**

Table B.2: Quadratic Discriminant Analysis (QDA) - All scales #1

	Braided-Braided	Braided-Wandering	Braided- Single	Wandering-Wandering	Wandering- Single	Single-Single	Precision (%)
Braided-Braided	**115**	28	0	14	0	0	73.2
Braided-Wandering	104	**213**	7	41	2	0	58.0
Braided- Single	0	11	**13**	3	1	0	46.4
Wandering-Wandering	20	57	1	**90**	2	7	50.8
Wandering-Single	0	5	3	13	**30**	7	51.7
Single-Single	0	3	0	34	21	**176**	75.2
Recall (%)	48.1	67.2	54.2	46.2	53.6	92.6	**Overall Accuracy: 62%**

Table B.3: LDA - All scales #2

	Braided-Braided	Braided-Wandering	Precision (%)
Braided-Braided	**110**	38	74.3
Braided-Wandering	129	**744**	85.2
Recall (%)	46.0	95.1	**Overall Accuracy: 83.6%**

Table B.4: QDA - All scales #2

	Braided-Braided	Braided-Wandering	Precision (%)
Braided-Braided	**122**	49	71.3
Braided-Wandering	117	**733**	86.2
Recall (%)	51.0	93.7	**Overall Accuracy: 83.7%**

Table B.5: LDA - Large scale rivers

	Braided-Braided	Braided-Wandering	Wandering-Wandering	Single-Single	Precision (%)
Braided-Braided	**199**	8	14	6	87.7
Braided-Wandering	0	**0**	0	0	0
Wandering-Wandering	0	0	**0**	0	0
Single-Single	0	0	0	**0**	0
Recall (%)	100	0	0	0	**Overall Accuracy: 88%**

Table B.6: QDA - Large scale rivers

	Braided-Braided	Braided-Wandering	Wandering-Wandering	Single-Single	Precision (%)
Braided-Braided	**188**	0	1	0	99.5
Braided-Wandering	3	**5**	4	0	41.7
Wandering-Wandering	8	3	**7**	0	38.9
Single-Single	0	0	2	**6**	75.0
Recall (%)	94.5	62.5	50.0	100	**Overall Accuracy: 91%**

Table B.7: LDA - Medium scale rivers

	Braided-Braided	Braided-Wandering	Wandering-Wandering	Precision (%)
Braided-Braided	**79**	12	6	81.4
Braided-Wandering	4	**29**	7	72.5
Wandering-Wandering	3	3	**15**	71.4
Recall (%)	91.9	65.9	53.6	**Overall Accuracy: 78%**

Table B.8: QDA - Medium scale rivers

	Braided-Braided	Braided-Wandering	Wandering-Wandering	Precision (%)
Braided-Braided	**69**	9	5	83.1
Braided-Wandering	8	**30**	2	75.0
Wandering-Wandering	9	5	**21**	60.0
Recall (%)	80.2	68.2	75	**Overall Accuracy: 76%**

Table B.9: LDA - Small scale rivers

	Braided-Braided	Braided-Wandering	Braided-Single	Wandering-Wandering	Wandering-Single	Single-Single	Precision (%)
Braided-Braided	**69**	32	0	1	0	0	67.6
Braided-Wandering	40	**187**	14	42	3	0	65.4
Braided- Single	0	0	**5**	0	1	0	83.3
Wandering-Wandering	5	41	2	**75**	1	1	60
Wandering-Single	0	1	2	0	**5**	0	62.5
Single-Single	0	4	1	35	46	**183**	68.0
Recall (%)	60.5	70.6	20.8	49.0	8.9	99.5	**Overall Accuracy: 66%**

Table B.10: QDA - Small scale rivers

	Braided-Braided	Braided-Wandering	Braided-Single	Wandering-Wandering	Wandering-Single	Single-Single	Precision (%)
Braided-Braided	**57**	21	0	2	0	0	71.3
Braided-Wandering	50	**187**	8	29	2	0	67.8
Braided- Single	0	7	**11**	3	1	0	50.0
Wandering-Wandering	7	46	2	**98**	6	5	59.8
Wandering-Single	0	4	3	18	**28**	4	49.1
Single-Single	0	0	0	3	19	**175**	88.8
Recall (%)	50.0	70.6	45.8	64.1	50.0	95.1	**Overall Accuracy: 70%**

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