Land use change in and around Aotearoa New Zealand's braided rivers

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By

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Abstract

This thesis examines the issue of land use change in and around Aotearoa New Zealand's braided rivers between 1990 and 2020. It develops and tests a method to ask: whether and how land use changed in and around New Zealand's braided rivers; and whether there are geographic patterns in the land use change?

The analysis of this research finds land use has changed across New Zealand's braided rivers and has changed the most in Canterbury of the South Island and in rivers with more gravel area. Land use has changed the least across the North Island's regions and Southland. The rivers in these latter areas have a reduced gravel content compared to Canterbury rivers.

This thesis concludes by looking into the future of legislative change to the definition of braided rivers in Aotearoa New Zealand.

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Chapter 1 – Introduction

Rivers are a crucial source of water, food, transportation, and other ecosystem services. A unique type of river that defines many New Zealand landscapes is the braided river. I use the Waimakariri River, Waiau Toa / Clarence River, and Ngaruroro River below to provide examples of different braided river characteristics and the associated land use change, alongside understanding the dynamics of braided river environments.

1.1 Waimakariri River

Canterbury's Waimakariri River (Figure 1), is one of the largest braided rivers in New Zealand (Figure 4). It is also marked by the complexities of land use intensification. Figure 1 shows the braidplain area that has been confined from 1942 to 2020 reducing the number of braided channels.

The lower part of Figure 1 shows the channel of the river has been controlled by stop banks and introduced plant species. Willows have been introduced to reduce the threat to the surrounding area of the river from natural processes such as flooding. Two quarries are pointed out in the image where gravel is extracted from the river sourced for aggregate, gravel is also extracted as a control for managing flood and erosion hazards (Environment Canterbury Regional Council, n.d.).

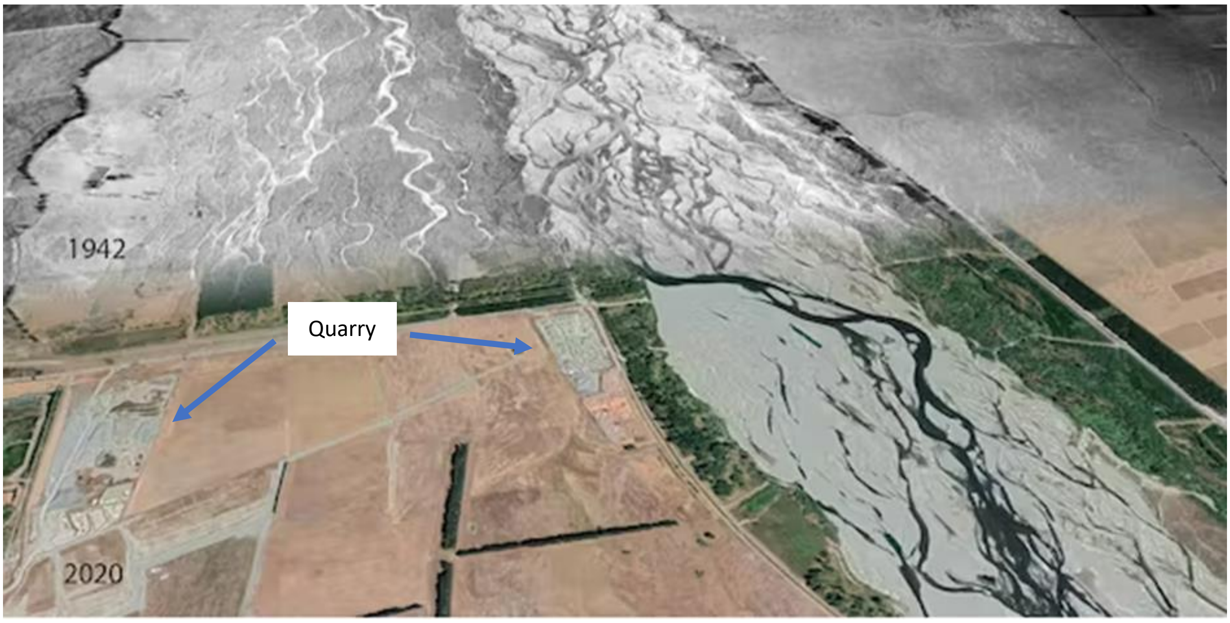


Figure 1: Image of the Waimakariri River showing the braidplain patterns and braidplain changing from 1942 (top) to 2020 (bottom). Note. From "Why we should release New Zealand's strangled rivers to lessen the impact of future floods" by Hikuroa et al. February 23, 2021, The Conversation (https://theconversation.com/why-we-should-release-new-zealands-strangled-rivers-to-lessen-the-impact-of-future-floods-153077).

1.2 Waiau Toa / Clarence River

Waiau Toa / Clarence River shown in Figure 2, is situated in Marlborough in the South Island of New Zealand (Figure 4) and extends over 230 kilometres (Cookson, 2019). The river features some braided sections, this river is different from the Waimakariri shown in Figure 2. It has a smaller braided area and shows historic braided sections. Many of the historical braided sections have been lost to land use intensification as shown in the image on the right. However, intensification on the Waiau Toa / Clarence River is not as extreme compared to the Waimakariri, perhaps due to the different river type or perhaps due to its remoteness. Figure 2 shows on a small scale, agricultural intensification in the braidplain where the plain extends from the irrigated paddocks on the left of the image to the valley wall on the right of the image. The effects of this on a larger scale include an increase in erosion and flooding events (Williams, 2017) as the natural ability for lateral migration is reduced (Scorpio et al., 2018). The specific stretch of the river illustrated in Figure 2 exemplifies a dynamic morphological system (Belletti et al., 2022) characterised by active channels and exposed river bars. The bare river bars are shown to be particularly vulnerable to the impacts of land use intensification due to the flat nature of the land with fertile soils. This fertile soil is however still a historical river bar within the braidplain.

Figure 2: Waiau Toa / Clarence River, left image shows active river channels and land use intensification on the riverbed in 2024. Right image shows historic image of existing braidplain and historic braided channels from 1978. Red circle references areas the same from each image. Note left image from: Retrolens - Historical Imagery Resource*, http://retrolens.nz and licensed by LINZ CC-BY 3.0.*

1.3 Ngaruroro River

The Ngaruroro is one of the largest braided rivers in the Hawkes Bay region of the North Island (Figure 4), (Hawkes Bay App, 2019). The river supports land uses including pastoral farming and horticulture. Its significance to the region lies in its crucial role in irrigation for agriculture (Forbes, 2011). Figure 3 illustrates river changes over time. Traditional flood protection measures are seen in the 1948 image in the form of stop banks that have been further engineered in 2022. Land use within the braidplain was already evident in 1948 and is further intensified in the 2022 image. By 2022, the Ngaruroro River looks more like the Waiau Toa / Clarence River, with a smaller braided area and less gravel, than the Waimakariri's complex braids.

*Figure 3: Ngaruroro River, 1948 (top) and 2022 (bottom). Located in Hawkes Bay in the North Island of New Zealand. Note. From "*Making Room for Rivers," *by J. Pocock, 14 April, 2023, New Zealand Herald (https://www.nzherald.co.nz/hawkes-bay-today/news/making-room-for-rivers-the-flooding-conversation-hawkes-bay-needs-to-have/ZJNBHNJPXZB2ZDZOSXOO5UQXUU/).*

Figure 4: Map showing New Zealand s braided rivers with reference to the Ngaruroro, Waiau Toa / Clarence River, and Waimakariri River.

1.4 Research Questions

This thesis explores land use change in and around New Zealand’s braided rivers on a national scale since 1990. To explore on a national scale, I developed and tested a method to explore land use change over time. I examine the entire population of New Zealand’s rivers with braided sections.

I ask these three questions in my research –

> *Question 1:* Has land use changed in and around New Zealand’s braided rivers, and how?
>
> *Question 2:* Are there geographic differences and patterns in the land use change?
>
> *Question 3:* Is the method I developed viable for measuring patterns of land use change?

1.5 Braided riverbeds and land use change

Land use change around braided rivers has been identified as a problem over the last 10 years (Grove et al., 2015) and, until recently, it was not clear that policy is moving toward fixing it (Vosloo et al., 2022).

Land use intensification affects braided river’s cultural, ecological, and economic systems as outlined in Brower et al. (2024). These effects include, but are not limited to; loss of habitat (Gray et al., 2018), reduced natural character (Brierley et al., 2023), decreased potential for groundwater recharge (Wöhling et al., 2018), decreased flood carrying capacity (Gluckman et al., 2017), heightened susceptibility to erosion (Piégay et al., 2006), and consequences for the connection between the Māori community and water environments (Hikuroa et al., 2021).

Land use change is critical to understand as its effects might threaten the physical abilities of a river to convey flood waters and control erosion (Hicks et al., 2021). The changes and reactions of rivers may be driven by the permanent confinement of a river system through channelisation by humans. This results in the confinement of the lateral mobility of a braided river. If a braided river is constricted and confined it decreases resilience to flood laterally and 'strangles' the river's systems (Brierley et al., 2023).

Goals of land use intensification include: protecting surrounding infrastructure, irrigating, gravel extracting, damming, and generating hydroelectricity (Knight, 2019). As the human population continues to grow and humans shape rivers to accommodate the increasing needs of the population, the challenges arising from extensive alterations to rivers are becoming more prevalent (Grove et al., 2015). As the natural environment of a river is unpredictable and therefore difficult to control, stop banks or levees are a common method for restricting rivers to protect those developments (Barlow, 2022).

1.6 What is a braided river and why is it different?

Braided river margins hold high recreational, indigenous, and ecosystem services along with high cultural values (Abell et al., 2023; O'Donnell et al., 2016; Westerhoff et al., 2022). In Canterbury, Ngāi Tahu considers land and water as taonga, integral to Ngāi Tahu's cultural and personal identity (Environment Canterbury Regional Council, n.d.).

The formation of braided rivers is the result of several factors, including the interplay of water flow, gradient, gravels, availability of sediment, presence of vegetation, resistance of banks, and the ratio of width to depth (Barlow, 2022; Church & Ferguson, 2015). Braided river systems are found globally including extensive systems found in New Zealand, Alaska, Canadian Rockies, European Alps, Russia, the Himalayas, and Japanese Alps. Braided rivers can also be found in Scotland, China, Poland, the US, Iceland, Belarus, Congo, Colombia, Brazil, Paraguay, Argentina, and the Touat Valley of Africa (Coluccio & Morgan, 2019).

Braided rivers are readily identifiable landscape features with a wide lateral expanse found predominantly in mountainous landscapes (Brierley et al., 2016). They cross range-front alluvial fans exporting high sediment loads to the coast and lowland plains from highland and mountainous areas (Bowman, 2019; Cook et al., 2014). Figure 5 shows the characteristics of braided rivers extending from almost always having gravel beds, a high spatial and temporal dynamism to sustaining productive ecosystems (Hicks et al., 2021).

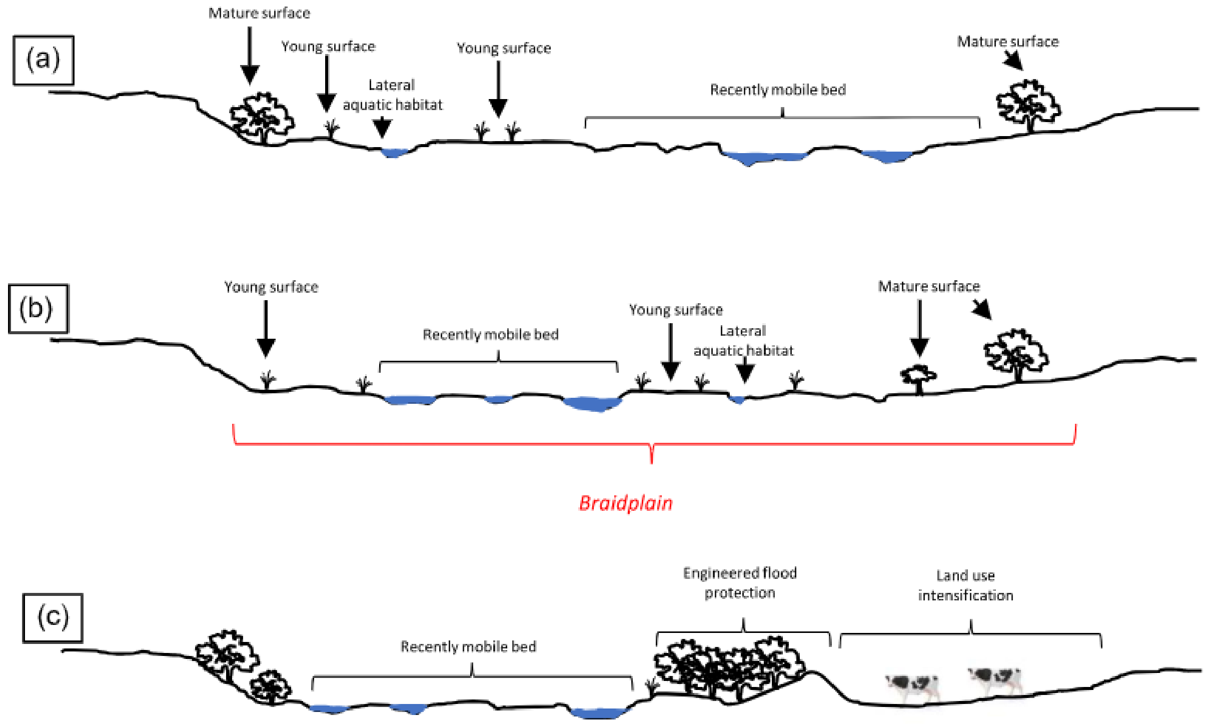


Figure 5: Figure showing braided river cross section with changes occurring over time. Section (a) shows multiple surfaces including a recently wetted mobile channel and mature to young surfaces. Section (b) shows different stages of flow where braidplain surfaces are reworked and shift in channels occurring. Section (c) shows changes in land use including intensification of the dry areas and engineered protection. Note. From "New Zealand's braided rivers: The land the law forgot" by Brower et al., 2024, *Journal of Earth Surface Processes and Landforms*, (https://doi.org/10.1002/esp.5728).

1.6.1 Stages of braid formation

Stages of formation include large variations of input, in areas with a seasonal climate, high amounts of sediment load, large coarse sediment, and steep slopes that generate at the upper course of a river (Brown et al., 2020). The high sediment and gravel load and with the low capacity to transport it eventually create a braided river (Bridge & Lunt, 2006). The formation and development of braided rivers are significantly influenced by the river's velocity and high-energy environment, the shape of the riverbed, and the existence of obstructions in the river channel (Surian, 2015). The formation of a braided river takes place over four stages (Marti & Bezzola, 2006). During the first stage, high-level discharge occurs due to periods of high rainfall generating high input and high discharge into the river channel. As a result, velocity increases and along with the increase in discharge, an increase in overall energy develops. With this increased energy comes channel bank erosion resulting in a greater supply of bedload (Schuurman et al., 2018).

During the second stage, a low level of discharge occurs during periods of low rainfall. This results in low inputs and a drop in the velocity and discharge of the river (Hoey & Sutherland, 1991). River energy falls and subsequently, there is not enough energy to carry the heavy load generated during the high input season (Schuurman et al., 2013). Sediment is then deposited with larger particles deposited first which serve as central points or cores. Finer sediment then deposits around the central points and cores leading to the formation of elongated shaped mid-channel bars over the course of time (Peirce et al., 2019). The main channel flow of the river is diverted to the smaller channels on either side of the newly created bar causing bank erosion to accelerate.

Stage three is again made up of high levels of discharge where high rainfall causes high input, discharge, and velocity. This time, some mid-channel bars are eroded away during the process of attrition. Attrition is the process by which rock and sediment are worn down as a river carries the particle down the system (Bravard, 2010; Simons & Şentürk, 1992). The particles collide with one another leading to the rounding of sediment as they are transported downstream (Attal & Lavé, 2009). This process is an important component of the formation of braided river morphology. If attrition does not occur, some sediment will be stabilised by vegetation trapping sediment in which the bars may become semi-permanent features (Henriques et al., 2022).

Stage four is a result of low-level discharge during a low input season. Processes occurring during this time include the formation of new mid-channel bars as well as existing mid-channel bars being exposed to the surface (Ashmore, 2013; Bridge & Lunt, 2006).

1.6.2 Braided river morphology

A braided river is: "A morphological feature developed by fluid flow across the surface of soft sediment, involving the entrainment or deposition of sediment" (Holden, 2005). The processes that cause braided rivers to continuously change include the development and migration of bars. The bars scour and fill, whilst intense bedload transportation occurs resulting in the development of braided river morphology (Ashmore, 2013).

As sediment is carried and the river is no longer able to carry the gravel, the formation of braids begins (Bridge, 1993). The braids branch out and re-join resulting in the evolution of islands along with shallow bars classified as distinct features (Lewin & Ashworth, 2014). During periods of low flow, bars exist as a less permanent feature to the more permanent islands which are often vegetated (Coluccio, 2018). Rainfall and snowmelt within a braided river catchment are significant drivers of a river's flow rate (Antoniazza et al., 2022). At times of low flow, gravel is dumped and the river braids into smaller channels around transient gravel islands. At times of high flow, when storms or snowmelt occur, rivers rising causes some or all the braids to combine to form a single, broad waterway that covers the gravel islands and occasionally washes them away (Stecca et al., 2022).

Human activity has contributed to changes in braided river channels, substantially affecting their morphology as shown in Figure 5. Braided rivers are often characterised as wandering rivers that move laterally as migration of the active channel occurs back and forth (Nanson & Knighton, 1996). When water levels rise, braided rivers tend to meander across the terrain unless there are geological structures like tall terraces and valley walls, or human-built flood defences to contain them (Wohl, 2010). The stretch of land where this occurs is referred to as the braidplain. The braidplain will flood only during periods of extremely high water levels (Dunne & Aalto, 2013). As the water levels recede, new channels and islands will emerge in various locations on the braidplain. This phenomenon is known as lateral migration and contributes to the deposition of substantial amounts of sediment and gravel and has given rise to the Canterbury Plains in New Zealand (Williams & Javernick, 2013).

1.7 Braidplain formation

The area in which the active channel moves is termed the braidplain including the area in which the river escapes during floods (Ashmore, 2013; Gray et al., 2018). In a braided channel and its surroundings, the land area is formed through the process of sediment transportation by water. As the water's speed decreases, sediment carried by the water is deposited on the adjacent land, raising the land area within and around the braided channel (Reinfelds & Nanson, 1993).

The discharge filling the braidplain is not constant but occurs intermittently, between yearly and every second year (Nanson & Gibling, 2003). As a result, braidplains become notably suitable for human activity including settlement and agriculture. Braidplains are deprived of their rich biodiversity due to centuries of development resulting in losses of forest, wetland, and coastal habitats (Meredith, 2023). Species that rely on the biologically rich braided river plains are declining fast as they form a vital ecological link from mountains to the sea (Gray & Harding, 2007). Not only are many species threatened by the loss of braidplains, but the coast is also affected (Harris et al., 2024). The coastline was once built outward by the spread of sediment (Caruso, 2006), now the confinement of rivers by stop banks and levees are stopping rivers from wandering over coastal land and building up sediment over coastal lands as they wander (Gray et al., 2018).

1.8 Riverbeds and land use change

New Zealand's environment is governed by the Resource Management Act 1991 (RMA). In the RMA there are clear boundaries set around development. Section 13 says development rules are quite different inside and outside a riverbed. Outside a riverbed, development is allowed with resource consent; and consent is generally granted on an 'innocent unless proven guilty' basis. In a riverbed, development is prohibited unless 'proven innocent'. Riverbed is defined as:

> *"The space of land which the waters of the river cover at its fullest flow without overtopping its banks"* (Resource Management Act, 1991, s. 2.1).

Vosloo et al. (2022) have said the law should better distinguish between braided rivers and other types of rivers. An example of this is the Dewhirst litigation. The definition of the riverbed – and hence where Mr Dewhirst could and could not develop - was central to the case. However the court relied solely on legal definitions dating as far back as the 19th century. Vosloo et al. (2022) explain:

> *"It is no wonder the law struggles to decide where the land stops and the river begins, because science describes braided rivers as complex flows of water and sediment — simultaneously land and water. Yet Canterbury Regional Council v Dewhirst Land Company all but excludes "various scientific explanations" from the decisions, stating the question is one of law".*

Vosloo et al. (2022) concluded that the current legal system fails to define and hence protect braided rivers and instead assumes all rivers are the same. They say the definition of a riverbed is inadequate for braided rivers, saying: *"Braided rivers require a legislative definition at the national level that embraces dynamism, complexity, and room to move. Above all, the legislative definition must recognise that braided rivers are land and water, both at once"*. I return to this in the discussion.

1.9 Others' research

There have been many studies centred around geomorphology (and a few of land use) of braided rivers; most have focussed on Canterbury's braided rivers. This study looks at land use change on a national scale.

Land use change in and around Canterbury's braided rivers has been researched (Barlow, 2022; Grove et al., 2015; Greenep & Parker, 2021). Barlow (2022) develops an understanding of Canterbury's River morphology and how it has changed due to lateral confinement from causes including irrigation and land use change. Her methods include developing a historical understanding of river morphology from the mid-1900s to the present day. She concluded that over time the channels of Canterbury's braided rivers are narrowing resulting in a loss of braiding. She uses methods for sustaining braided morphologies to keep a sustainable fluvial landscape and the need to understand rivers' responses to change. There are several ways my methods differ from Barlow's. These include using satellite imagery on a more recent timeframe, machine learning, and analysing change on a larger scale using New Zealand's entire braided river population. This is discussed in chapter 2.

A study by Grove et al. (2015) looks at land use changes when an undeveloped braidplain is being encroached on by agricultural development. The study aimed to identify agricultural development occurring on undeveloped and forested margins of braided rivers between 1990 and 2012. The authors assessed the rate of land use change and proposed strategies to improve biodiversity, ecological health, and the natural character of braided river systems.

Grove et al. (2015) found agricultural development and engineering activities have resulted in 11,630ha of land use change along the Canterbury region's braided rivers from 1990 to 2012.

Greenep & Parker (2021) repeated methods by Grove et al. (2015), but from 2012 to 2019. The study found a further 1,252ha of undeveloped land was intensified.

The studies by Grove et al. (2015) and Greenep & Parker (2021) point out that policies including the RMA and Canterbury Water Management Strategy (CWMS) tried to improve braided river management, but neither succeeded.

1.10 Structure of thesis

This thesis proceeds in the following order. Chapter 2 outlines the population of rivers studied and presents the methods. Chapter 3 presents results and answers my questions by discussing the changes in land use across New Zealand, between the North and South Island, and across the regions and individual rivers in Hawkes Bay and Canterbury. Chapter 4 discusses the implications of the results and considers a ‘where to from here’ for braided river management in New Zealand. Chapter 5 concludes.

Chapter 2 – Methods

To answer the question of how much land use has changed in and around New Zealand's rivers I started by outlining the 163 rivers containing braided and wandering sections from Wilson, (2001). To do this, I used QGIS and Google Earth Engine. I then developed, trialled, and redeveloped a series of methods to identify land use change. This relied on a multi-criteria analysis of trained classification and NDVI threshold methods to identify changes in land use between 1990 and 2020.

2.1 Study area and data

This is a national study of all braided rivers in New Zealand as outlined by Wilson (2001). Appendix A lists all 163 rivers that Wilson identified as having some braided sections.

I did a pilot study on three test rivers including the Ngaruroro, Waimakariri, and Mataura rivers and then scaled up to all 163 braided and wandering rivers in New Zealand. I selected these three test rivers because they have different land uses and climatic conditions surrounding the rivers. The Ngaruroro River is in Hawkes Bay in the North Island of New Zealand. Both the Waimakariri and Mataura Rivers are found in the South Island. The Waimakariri is in Canterbury and is one of New Zealand's largest braided rivers. The Mataura River is in Southland and despite having braided sections in the high country, the Mataura has much less gravel expanse and braiding than the Waimakariri similar to the Clarence River shown in Figure 2. I also used these rivers as there is sufficient data available through mapping and imagery to undergo land use change analysis that ensures my question is being tested.

2.2 Mapping New Zealand's braided rivers

I mapped New Zealand's 163 braided rivers using the Land Cover Database (LCDB) (Barnes, 2020), a digital map that identifies and categorises a series of land cover around New Zealand including surface water bodies using multispectral satellite imagery (Barnes, 2020). I collated a list of the 163 rivers from Wilson (2001), and then back in QGIS I defined a specific set of rules and conditions from the LCDB NZ River Name Lines Layer to filter only the names of the 163 braided rivers based on the list from Wilson, (2001). This process created a New Zealand Braided Rivers shapefile made up of river centrelines (Figure 6).

When developing the braided rivers shapefile, the LCDB river lines layer contained missing sections as shown in Figure 6 along many of the river areas. However, this was not an issue for the application of this study as I used river centrelines to create a buffer layer for the 163 rivers and the buffer tool did a good job of connecting the parts of the river I wanted to analyse. This is made up of the areas in which

I wanted to capture data and changes to the land use. If there were areas where this issue deterred me from capturing data, I manually joined the river centrelines to create a complete river centreline.

Figure 6: Braided rivers shapefile created in QGIS using the LCDB Rivers Centreline shapefile.

2.3 Generating braided river buffers

Using the New Zealand Braided Rivers shapefile I produced, I created a 2500m buffer around each of the 163 braided rivers which sufficiently captures the river environment we are interested in. This allowed me to clip my NDVI threshold method, detailed below, specifically within the area of the river buffer where I wanted to calculate land use change. This is because I am only interested in calculating the area of land use change within the set buffer area.

To create a buffer around each of the rivers, I took my New Zealand Braided Rivers shapefile and in QGIS used the Vector Geoprocessing buffer tool with a distance of 2500m on either side of the river centrelines which produced a newly created New Zealand Braided Rivers with buffer shapefile (Figure 6). After visually assessing the areas of possible land use change in and around the braided rivers on Google Earth I chose 2500m because from the centreline of larger rivers such as the Waimakariri River 2500m included enough of the gravel area and area outside of the gravel where I could easily identify areas of land use change.

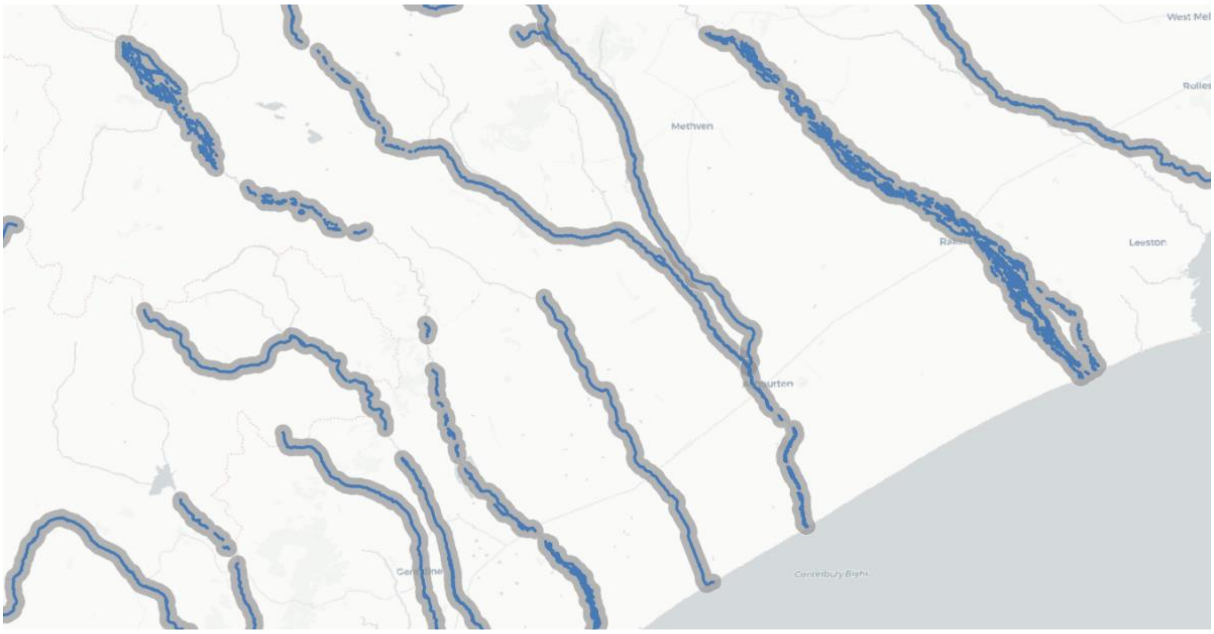


Figure 7: Braided rivers centreline with buffers developed from LCDB River Centrelines layer.

2.4 Satellite imagery

I obtained Landsat data through USGS Earth Explorer and Google Earth Engine Catalog which are both readily distributed and high-quality datasets (Hemati et al., 2021). Continuous observations have been available since mid-1972, though it can often be difficult to find data of moderate to high quality for New Zealand dating back that early. The data I have chosen can apply scientific applications using tools such as those found in QGIS and Google Earth Engine (GEE). Landsat data was used as it provides coverage of the Earth's land surfaces at a moderate spatial resolution (Gong et al., 2013). Landsat data provides repetitive coverage of the Earth's surface allowing human-induced changes to be identified over time including to differentiate, characterise, and monitor the Earth's surface (Wulder et al., 2022). To create a classification of land use change in and around braidplains I needed both 1) images with which I could differentiate between human-induced and natural changes and 2) a long enough data record to compare change in and around braided rivers over a series of time periods. For the year 1989, my visual assessment showed seasonal imagery including data from January, April, August, and November.

I did a visual assessment of Landsat data in USGS Earth Explorer starting with a filter of data dating from 1989 to 1992. I first assessed the data over my three test rivers, then the whole of the South Island followed by the whole of the North Island. The best data that had less than 20% cloud cover was from January. I chose January to assess all available imagery, for 1989 to 1992 and 2018 to 2023 for the North and South Island.

The Landsat data for 1989 to 1993 was taken from Landsat 4-5 Collection 2 Level 2. For 2018 to 2023 it was taken from Landsat 8 Collection 2 Level 2. In this study, I compare 1990 to 2020. However, some imagery for 1990 may have been taken between 1989 to 1993 and for 2020 imagery may have been taken between 2018 to 2023, for reasons of cloud cover but all images used were from January.

2.4 Methods Used in Others' Research

Several studies have developed methods to quantify the extent of human induced changes to unique natural environments. I am borrowing from their methods to create a series of integrated modelling factors relating to remote sensing including -

- Developing maps of national change in human pressure over several time periods
- Providing temporal changes in anthropogenic pressures using layers of spatial datasets using GIS and Google Earth Engine tools
- Utilising a combination of existing datasets, surveys, remote sensing, and NDVI threshold methods
- Analysing satellite imagery to create a dataset of human-modified landscapes
- Determining patterns and rates of change to landscapes

I used unique spatial methods to observe human intensification. Several studies discussed below highlight spatial patterns of change in human pressures that are not well understood. This thesis aims to better understand human pressures influencing our braided river environments. Other studies show the development of spatially and temporarily explicit maps of global change in human pressure over different time periods.

I used some similar methods to Hicks et al. (2021). They study changes in the environment using existing datasets along with data collected showing the level of human pressure in surrounding areas. Both the Hicks et al. (2021) study and mine aim to create a comprehensive and detailed map of human modification to New Zealand's braidplains. As an example, Hicks et al. (2021) created a series of datasets for 1990, 2000, 2010, and 2015 exposing temporal and spatial trends of human modification to land use. Datasets included the use of change stressors to determine the foundation of transformations caused by human activity.

Another study from Mahmoud et al., (2023) uses a classification method I have adapted to categorise land cover into forests, croplands, urban areas, and wetlands. Mahmoud et al. (2023) study trained a machine-learning algorithm on a subset of satellite imagery to classify land cover across the globe. My study focuses on just New Zealand but uses a similar methodology including the combination of datasets and machine-learning to quantify and map the extent and intensity of human modification.

A common theme of the above studies and mine includes the use of satellite imagery and remote sensing to determine land use change. Detailed mapping, processing large sets of satellite imagery, and developing novel methods allow authors, and this study, to quantify the extent and intensity of land use change in and around environments with the likes of braided rivers.

2.5 Testing methods

I trialled different methods to measure land use change in and around braided rivers. These included supervised classification and analysis using the normalised difference vegetation index (NDVI). I also developed methods to combine with supervised classification and NDVI analysis, including the creation of relative elevation models (REM) and contours, these are explained in detail in Appendix B. The methods that were trialled are outlined below, including the full methodology using NDVI that helped to make up the final analysis and results of land use changes.

2.6 Analysing land-use change using normalised difference vegetation index (NDVI)

A combination of processing tools including Google Earth Engine (GEE) and QGIS were used to trial land use change using NDVI. This method is a classification method used widely in land cover and land use change detection. NDVI indicates and detects vegetation coverage for different time periods and is easily applied in specified areas (GISGeography, 2023).

The objective of NDVI is primarily to detect changes in land cover because of human activity, in particular land use intensification and development. It can also examine the spatial and temporal fluctuations in vegetation coverage (Yi et al., 2022). The NDVI is defined as an indicator measuring the equilibrium between energy received and emitted by earth objects (Meneses-Tovar, 2011). NDVI is calculated by combining the red and near-infrared (NIR) bands of a sensor system and using reflective bands to estimate vegetation cover from satellite data (Ehsan & Kazem, 2013). The underlying principle of the NDVI technique is rooted in the idea that thriving vegetation exhibits low reflectance rates on the visible side of the electromagnetic spectrum due to the presence of chlorophyll (Aburas et al., 2015).

The methods mentioned below aim to create NDVI images that can be used to identify patterns of change that have occurred between 1990 and 2020. A previous study by Lyon et al. (1998) found that the NDVI differencing technique was the most effective method to detect vegetation change. They compared seven vegetation indices using three different dates of Landsat images to determine land cover change detection. Value ranges of NDVI are generally:

Table 1: Common NDVI value range. (Sinergise, n.d.)

NDVI	Characteristics
-1 to 0.1	Water, barren rock, sand, snow
0.2 to 0.4	Shrubs, meadows, grassland
Values approaching 1	Temperate and tropical rainforest

For the application of this study, NDVI thresholds have been defined and are outlined in Tables 2 and 3. The different thresholds for the North and South Islands are explained in detail below.

Table 2: NDVI threshold for 1990 and 2020 South Island NDVI analysis.

NDVI threshold	**Characteristic**
-1 to 0.2	Water, gravel
0.2 to 0.3	Shrub
0.3 to 0.4	Grassland
0.4 to 1	Intensified land use, live green vegetation, irrigated land

Table 3: NDVI thresholds for 1990 and 2020 North Island NDVI analysis.

NDVI threshold	**Characteristic**
-1 to 0.2	Water, gravel
0.2 to 0.4	Shrub
0.4 to 0.6	Grassland
0.6 to 1	Intensified land use, live green vegetation, irrigated land

Rises in NDVI values represent an increase in intensified land use for this study as it relates to more green vegetation; with reference to land use, this could be irrigated land and cropped paddocks or afforestation. Lower NDVI values represent water and gravel for this study.

The equation for NDVI is defined below as stated by Gessesse & Melesse, (2019):

$$NDVI = (NIR - R)/(NIR + R)$$

In Landsat 4-7 the equation is defined as –

$$NDVI = (Band\ 4 – Band\ 3)/(Band\ 4 + Band\ 3)$$

In Landsat 8-9 the equation is defined as –

$$NDVI = (Band\ 5 – Band\ 4)/(Band\ 5 + Band\ 4)$$

Ehsan & Kazem (2013) explain the methods of NDVI in which NIR represents spectral reflectance in the near-infrared band and R represents the red band. NDVI real values are represented between -1 and +1. Increasing green vegetation is indicated by increasing positive values and non-vegetated surface features are indicated by negative values. Examples of a surface feature with negative values include water, gravel, barren land, or clouds.

2.6.1 Calculating NDVI

The next steps were to calculate NDVI within the clipped contour and buffer layer using the 1990 and 2020 imagery.

To calculate NDVI using 1990 imagery, I first downloaded imagery for the extent of the North or South Island, a particular region, or the river I wanted to analyse. This involved searching Earth Explorer USGS (U.S. Geological Survey, 2023) for Landsat imagery in or near 1990. After determining the search criteria, the best image available was from the 8th of January 1989. The search criteria included for example: a full extent of the Waimakariri River braidplain and less than 20% cloud cover over the image extent.

I then downloaded the necessary bands required to calculate NDVI as outlined in the equations above. Using Raster Calculator in QGIS I calculated NDVI. I then imported my river buffer as a CSV into QGIS. Using the Clip Raster by Mask Layer tool, I clipped the NDVI image to the river buffer. I then used the Reclassify by Table tool to determine NDVI thresholds to calculate NDVI change over time.

The Reclassify by Table tool gave 4 thresholds from the manual input as outlined in Table 2. The maps and their corresponding areas were produced with colours representing each NDVI threshold as shown in Figure 9. To calculate the area of land use change, I used the r.report tool in QGIS that allowed inputs of the individual maps i.e., North Island, South Island, regions, and individual rivers reclassified NDVI with specific parameters set. The output was a text file as shown in Figure 10 containing the hectares calculated for each NDVI threshold. The outputs were tabulated in Excel and are shown in Appendix C.

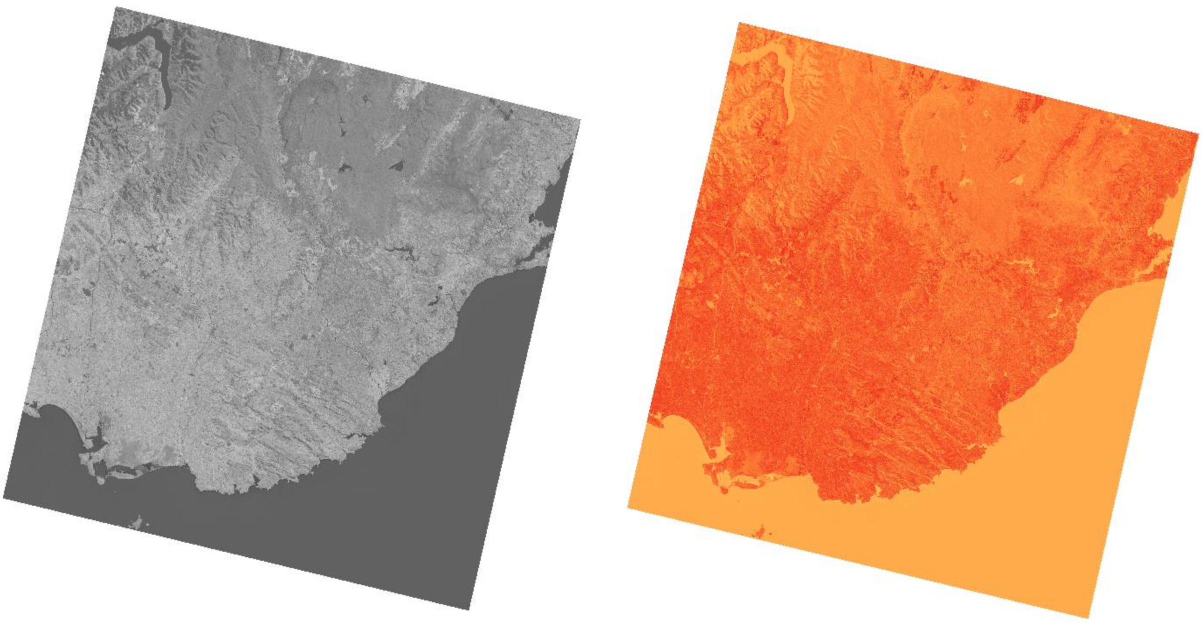


Figure 8: Example of Southland 2020 satellite imagery after NDVI calculations. Left image shows no symbology applied; right image shows symbology applied reflecting NDVI values, this is prior to reclassifying the image. Landsat-8 image courtesy of the U.S. Geological Survey.

Figure 9: Image showing 2020 un-classifed image (black and white) and reclassified image (red, orange, yellow image) and clipped to buffer image of the Mataura River. Landsat-8 image courtesy of the U.S. Geological Survey.

This method was repeated for each example area and the individual rivers as outlined in the results chapter, calculating variability of NDVI, by test river and by region and North and South Islands.

```
+-----------------------------------------------------------------------------+
|                         RASTER MAP CATEGORY REPORT                          |
|LOCATION: temp_location                               Fri Jan 26 13:15:35 2024|
|-----------------------------------------------------------------------------|
|          north: -4660755    east: 696675                                    |
|REGION    south: -4978275    west: 402135                                    |
|          res:         30    res:      30                                    |
|-----------------------------------------------------------------------------|
|MASK: none                                                                   |
|-----------------------------------------------------------------------------|
|MAP: (untitled) (rast_65b2f9a42162010 in PERMANENT)                          |
|-----------------------------------------------------------------------------|
|                      Category Information                     |            |
|#|description                                                  |   hectares|
|-----------------------------------------------------------------------------|
|4| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .|    195,942|
|3| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .|    298,005|
|2| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .|    355,150|
|1| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .|    404,460|
|-----------------------------------------------------------------------------|
|TOTAL                                                          |  1,253,557|
+-----------------------------------------------------------------------------+
```

Figure 10: r.report text file output from QGIS. The numbers 1 to 4 are the NDVI thresholds determined by the reclassify by table tool. This information was extracted and put into Excel to determine histograms and tables shown below.

2.6.2 Calculating 1990 North Island NDVI

I determined different NDVI thresholds for the North Island after trial and error and saw the previous thresholds used for the South Island failed to differentiate land use changes between NDVI 0.4 to 1. Instead, Table 2 and Table 3 show the NDVI thresholds used for each of the islands. The methods outlined above were repeated for the North Island, regions in the North Island, and Hawkes Bay rivers.

2.7 What is NDVI?

The higher NDVI values indicate high vegetation density while lower NDVI values indicate low vegetation density. I can also correlate low NDVI values to water and gravel. The change of vegetation patterns in this study is related to land use intensity, where higher NDVI values indicate there has been an increase in land use intensification over time if there are greater amounts of higher NDVI values in 2020 than shown in 1990. The study also shows that there has been a rise in some lower value NDVI indicating that there have been some instances of an increase in the presence of water and gravels during the studied time frame of 1990 to 2020. This has still been a land use change in the opposite direction.

Figure 11 below shows a stretch of the Ngaruroro River, both in satellite imagery and reclassified NDVI comparing 1990 and 2020 showing the land use change.

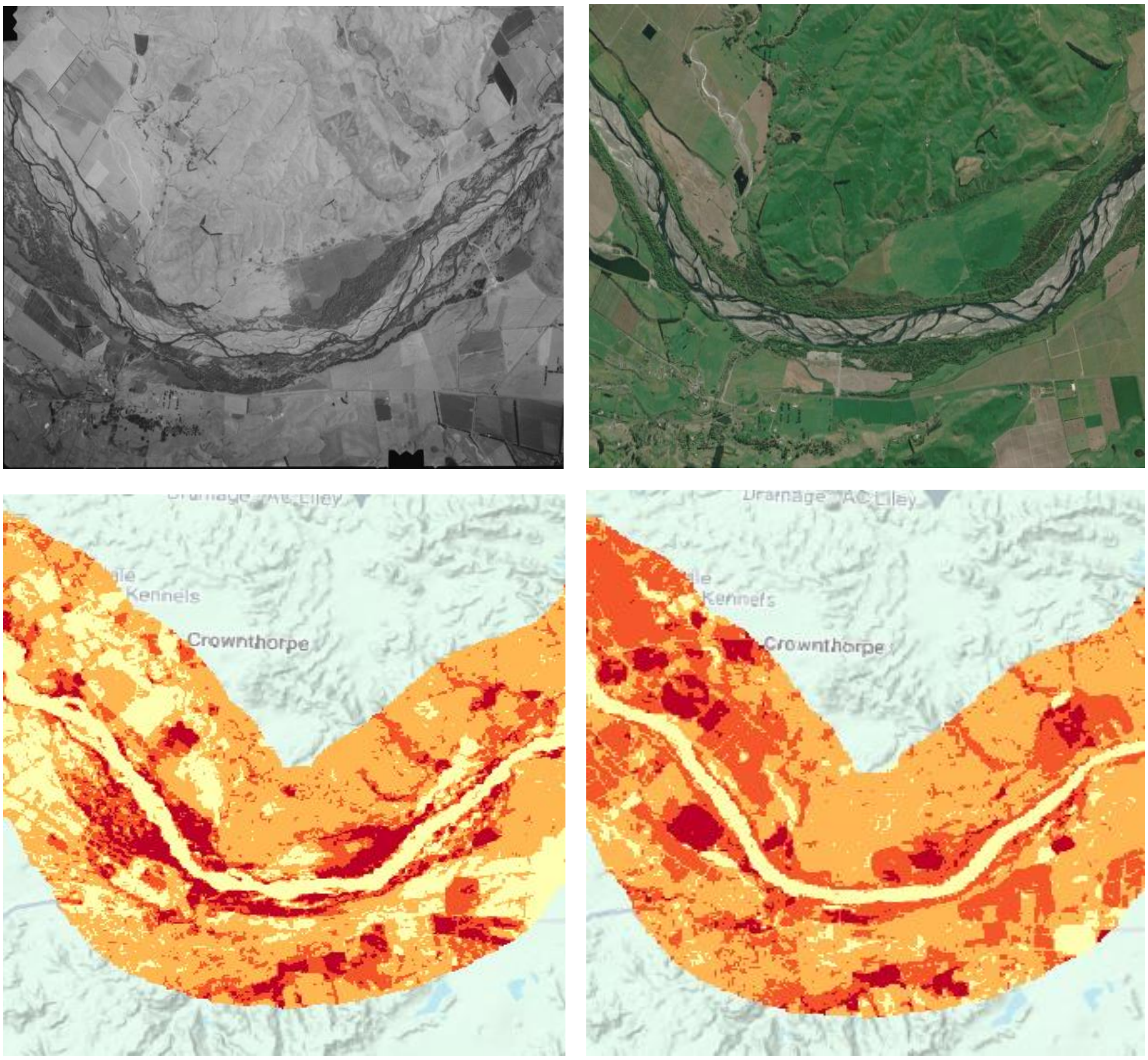


Figure 11: Ngaruroro River, top left image represents historic satellite imagery from 1996, bottom left represents 1990 NDVI, top right represents 2020 satellite imagery, bottom left represents 2020 NDVI. Note. 1996 image from Retrolens - Historical Imagery Resource*, http://retrolens.nz and licensed by LINZ CC-BY 3.0. 2020 image from Google Earth Pro 7.3.6.9750. (January 12, 2024). Hawkes Bay Region, New Zealand. -39.643211°, 176.641036°. https://www.google.com/earth/index.html (Accessed February 20, 2024).*

2.8 Methods trialled and deemed unsuitable - Classifying Braided River Environments using supervised classification

This method involved four phases I created to develop a code in Python to then classify the ‘wet’ areas of braidplains from the ‘dry’ margins in QGIS and integrate it into a user-friendly interface in Google Earth Engine (GEE) as shown in Figure 12. This involved supervised classification using four phases;

Phase 1: identifying classes of land use,

Phase 2: training GEE,

Phase 3: validation and retraining and

Phase 4: analysing variables.

The full method step by step is found in Appendix B.

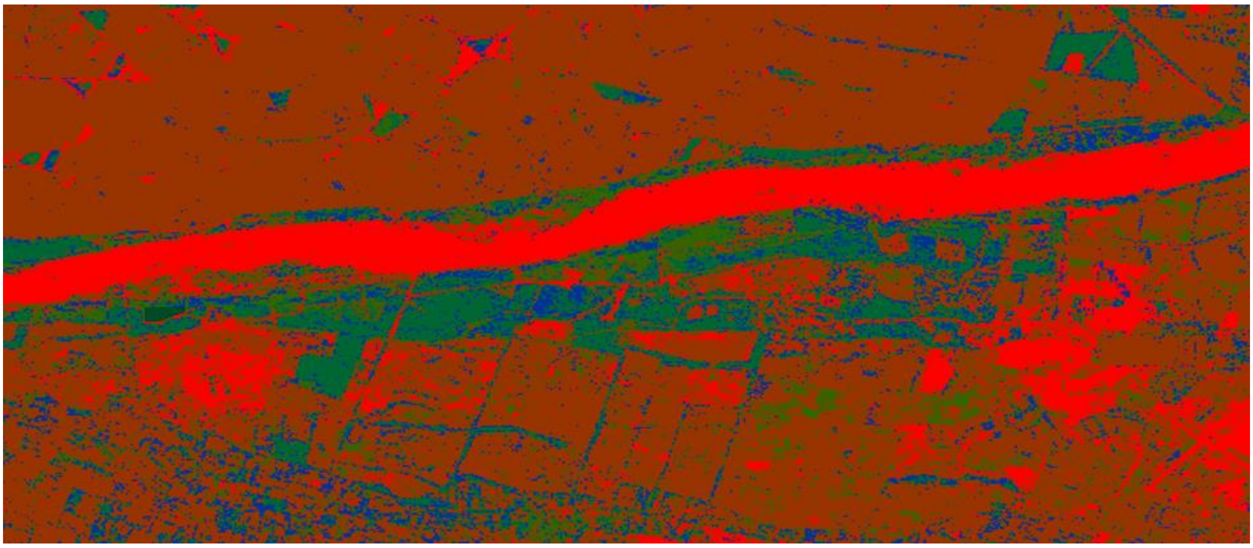


Figure 12: Supervised classification of Rakaia River delineated using five classes to determine encroachment intensification in 2020. Landsat-8 image courtesy of the U.S. Geological Survey.

This method was inconclusive about where land use had changed, as it required more training time to differentiate the areas of land use. This would have involved manual processing of polygon areas around most of the braided rivers. Having a large sample of 163 rivers meant the method was too time consuming with the time constraints I had.

2.8.1 Relative Elevation Model

I used the three test rivers to create relative elevation models to develop buffers based on elevation on the Ngaruroro River, Waimakariri River, and Mataura River. The relative elevation models provide information on elevation variations within the river's surroundings based on the elevation relative to the water surface (Jarihani et al., 2015). It also allows the visualisation of the historic migration of river corridors and floodplains including distinguished terraces and meander scars. Applying this information revealed more about land classification, particularly in areas where features of the river would have been otherwise difficult to discern using just aerial imagery.

2.8.2 Contours

I developed contours, a shapefile used to then clip to my buffer layer which created a new buffer output excluding the areas with an elevation of greater than 10m (Figure 13). This narrowed down the area of a river that would be classified when calculating land use changes. However, I proceeded to develop the braided rivers buffer shapefile layer inclusive of a 2500m buffer on either side of the river centreline for all 163 braided rivers of New Zealand. This is explained in depth below.

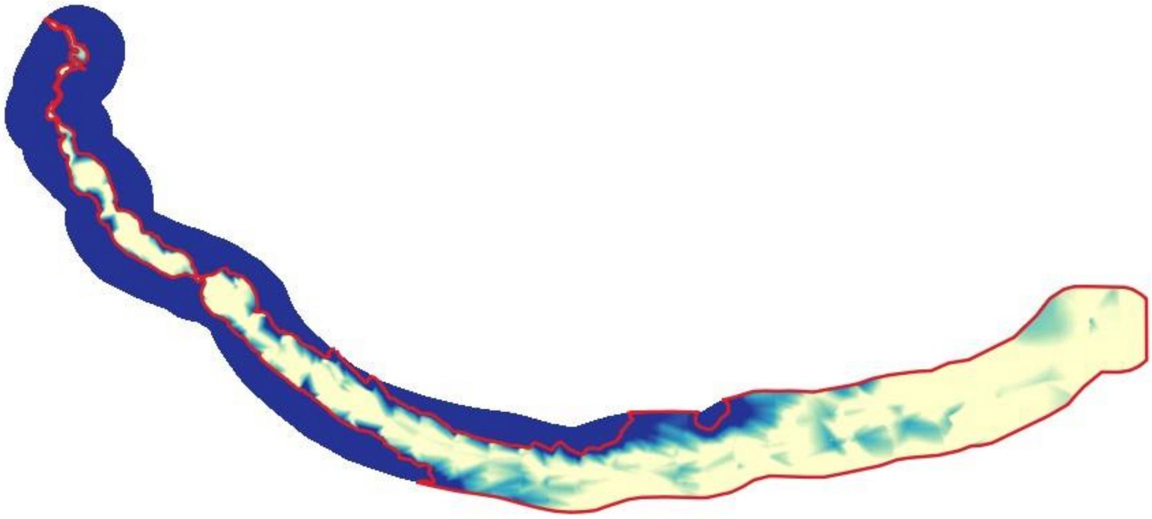


Figure 13: Waimakariri REM with <10m contour.

The REM and contour methods became irrelevant to my methods after developing the braided river shapefile as outlined below.

2.9 Methods Summary

A total area of approximately 3,400,000ha was analysed using the method as described above to determine land use change in and around New Zealand's braided rivers. The results are discussed below.

Chapter 3 - Results

This chapter answers my questions, as follows:

Q1: Has land use changed in and around New Zealand's braided rivers, and how?

Q2: Are there geographic differences and patterns in the land use change?

Q3: Is the method I developed viable for measuring patterns of land use change?

3.1 Q1: Land use has changed in and around braided rivers across New Zealand

This thesis asked a series of questions, the first being whether and how land use in braidplains across New Zealand has changed. Figure 14 shows an increase in land use change across New Zealand over time represented by an increase in intensified land use (NDVI 0.6 to 1) for 2020 shown in orange on the histogram. It also displays a decrease in water and gravel (NDVI -1 to 0.2) for 2020 shown in orange.

There are obvious patterns of land use change in and around braided rivers nationwide. This chapter will provide an overview of patterns of land use change using New Zealand's braided rivers from 1990 to 2020.

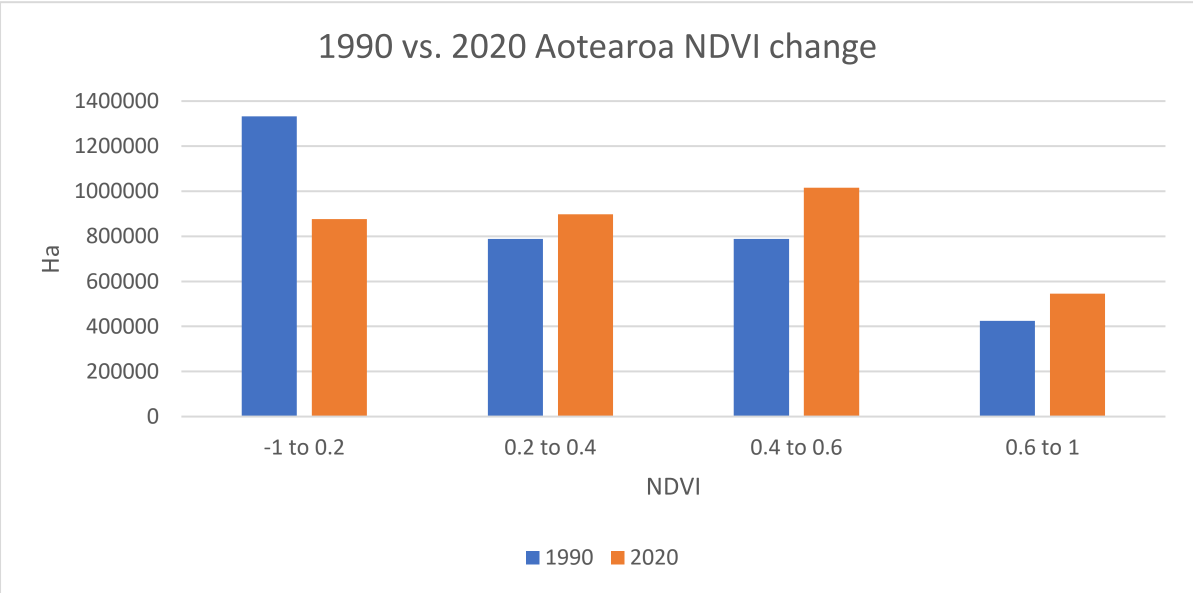


Figure 14: Histogram showing nationwide braided rivers land use change in 1990 versus 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS using a buffered shapefile of North Islands braided rivers extracted down to individual regions combined with Landsat imagery used to calculate NDVI.

3.2 Q2: Intensive land use decreased in the North Island and increased in the South Island

In the North Island, the overall trend shows a decrease in intensified land use (NDVI 0.6 to 1) and an increase in water and gravel areas (NDVI -1 to 0.2). The results suggest that in the South Island, intensified land use expanded (NDVI 0.4 to 1) and that there has been a decrease in water and gravel (NDVI -1 to 0.2). Moderate land use intensification (NDVI 0.4 to 1) was the dominant factor affecting NDVI changes on the braidplains of the South Island's braided rivers.

3.3 Q2: Land use had already intensified by 1990 in the North Island

Figure 15 shows that in the North Island, water, and gravel (NDVI -1 to 0.2) have expanded, and healthy vegetation representing more intensive land uses (NDVI 0.6 to 1) has decreased across the North Island's braided rivers. Water and gravel have increased by 47% from 53,500ha in 1990 to 75,000ha in 2020. Intensive land use has decreased by 270% from 224,800ha in 1990 to 149,500ha in 2020.

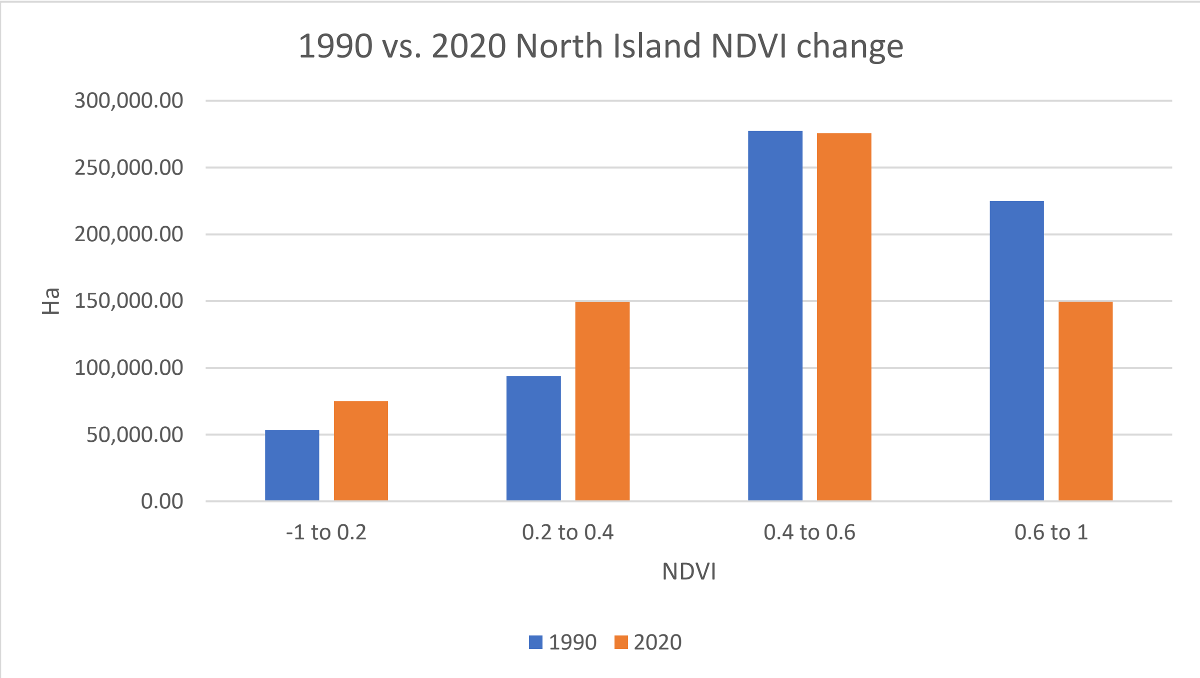


Figure 15: Histogram showing North Island rivers land use change 1990 versus 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS using a buffered shapefile of North Islands braided rivers extracted down to individual regions combined with Landsat imagery used to calculate NDVI.

3.4 Q2: Land use has intensified more in the South Island

Figure 16 shows water and gravel have decreased over time throughout South Islands' braided rivers and intensive land use has increased over time. The more intensive land uses (0.4 to 1) have increased more than the less intensive classes (0.2 to 0.3 and 0.3 to 0.4). Water and gravel have decreased by 37% and intensive land use has doubled between 1990 and 2020.

In the discussion, I will explore the North Island versus South Island comparison.

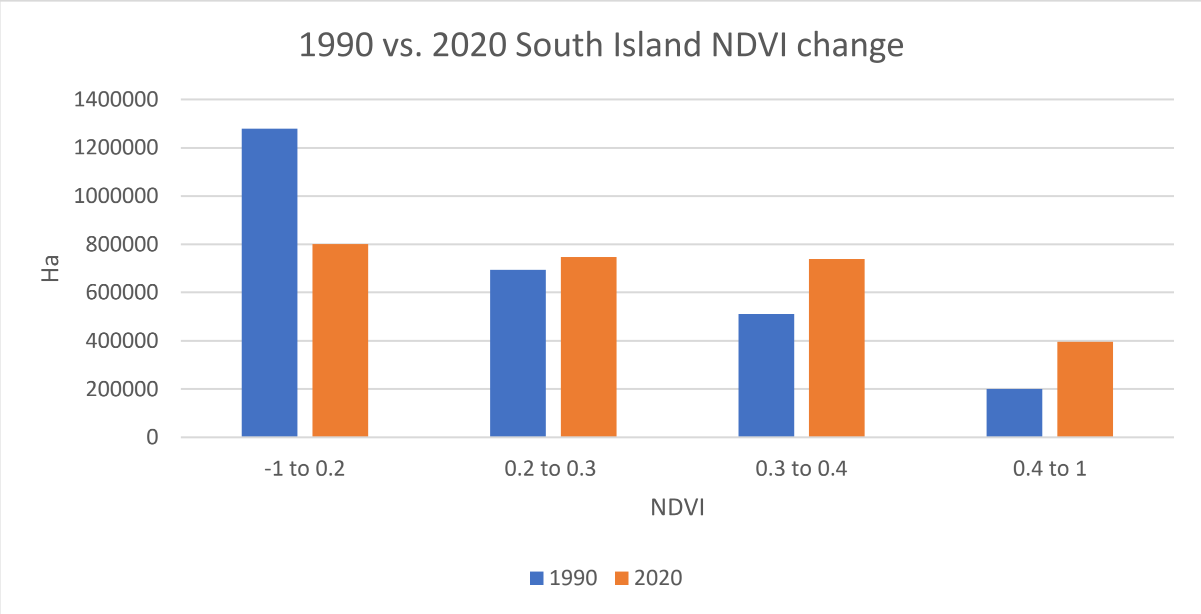


Figure 16: Histogram of South Island NDVI change between 1990 and 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS using a buffered shapefile of the South Islands braided rivers combined with Landsat imagery used to calculate NDVI.

3.5 Q2: Land use intensified differently in Hawkes Bay versus Canterbury

Rivers like the Mataura and Mohaka are less braided than rivers like the Waimakariri or Rakaia (Figure 17); we can see that in the smaller gravel expanses in the former. In this section, I narrow down the focus to rivers that are known to be prominent braided rivers, which are mostly found in Canterbury and Hawkes Bay.

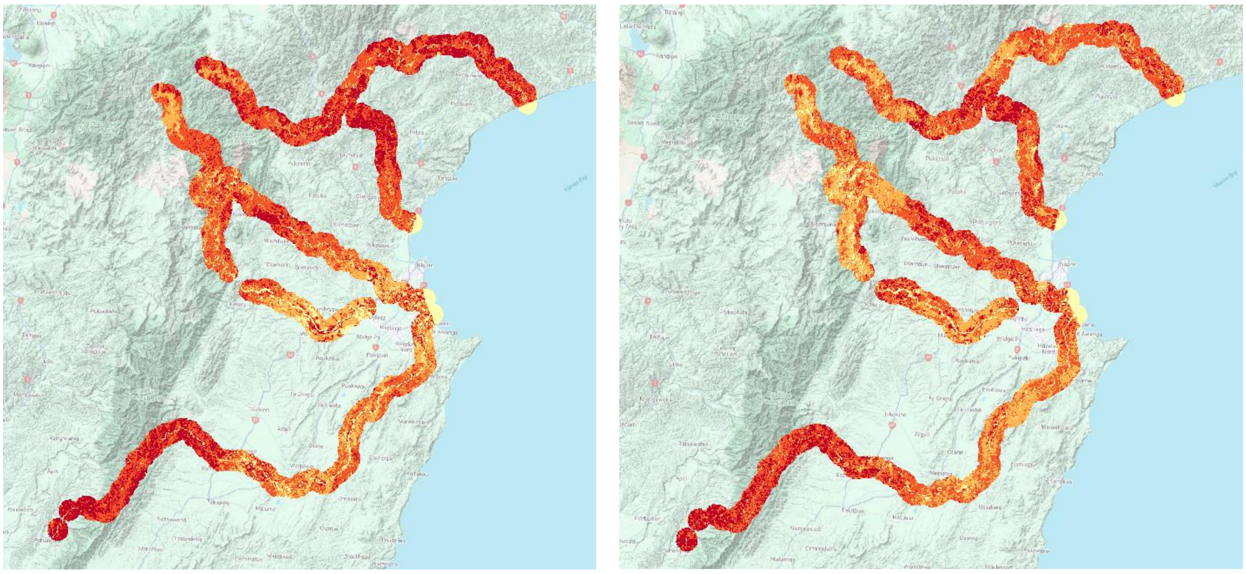


Figure 17: Hawkes Bay rivers from top to bottom, Mohaka, Esk, Tutaekuri, Ngaruroro, and Tukituiki. 1990 (left) and 2020 (right) comparison. This was created using QGIS, Landsat imagery was used to calculate NDVI, and a buffer shapefile of the Hakes Bay Rivers was used to extract the image to incorporate 2500m of braidplain either side of the centreline only. Yellow represents NDVI -1 to 0.2, orange represents NDVI 0.2 to 0.6 and red represents NDVI 0.6 to 1. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

3.6 Q2: Land use differs between Hawkes Bay rivers

Figure 18 shows Hawkes Bay braided rivers show two distinct patterns. Ngaruroro and Tutaekuri show a decrease in water and gravel (NDVI -1 to 0.2) and an increase in intensified land use (NDVI 0.6 to 1). Esk and Tukituki show a decrease in healthy vegetation (NDVI 0.6 to 1). However, the Esk shows an increase in water and gravel while Tukituki follows a pattern of decreasing water and gravel. All four Hawkes Bay rivers show shrub and grassland (NDVI 0.4 to 0.6) remains stable.

There are discernible differences in the patterns of change between the prominent braided rivers in the North and the South Island identified in Figure 15 and Figure 16 respectively. The dominant braided rivers in Canterbury show a prevailing pattern of increasing land use change compared to the dominant braided rivers in Hawkes Bay where there is a dominant pattern of increasing healthy vegetation. This is explored further in the discussion chapter.

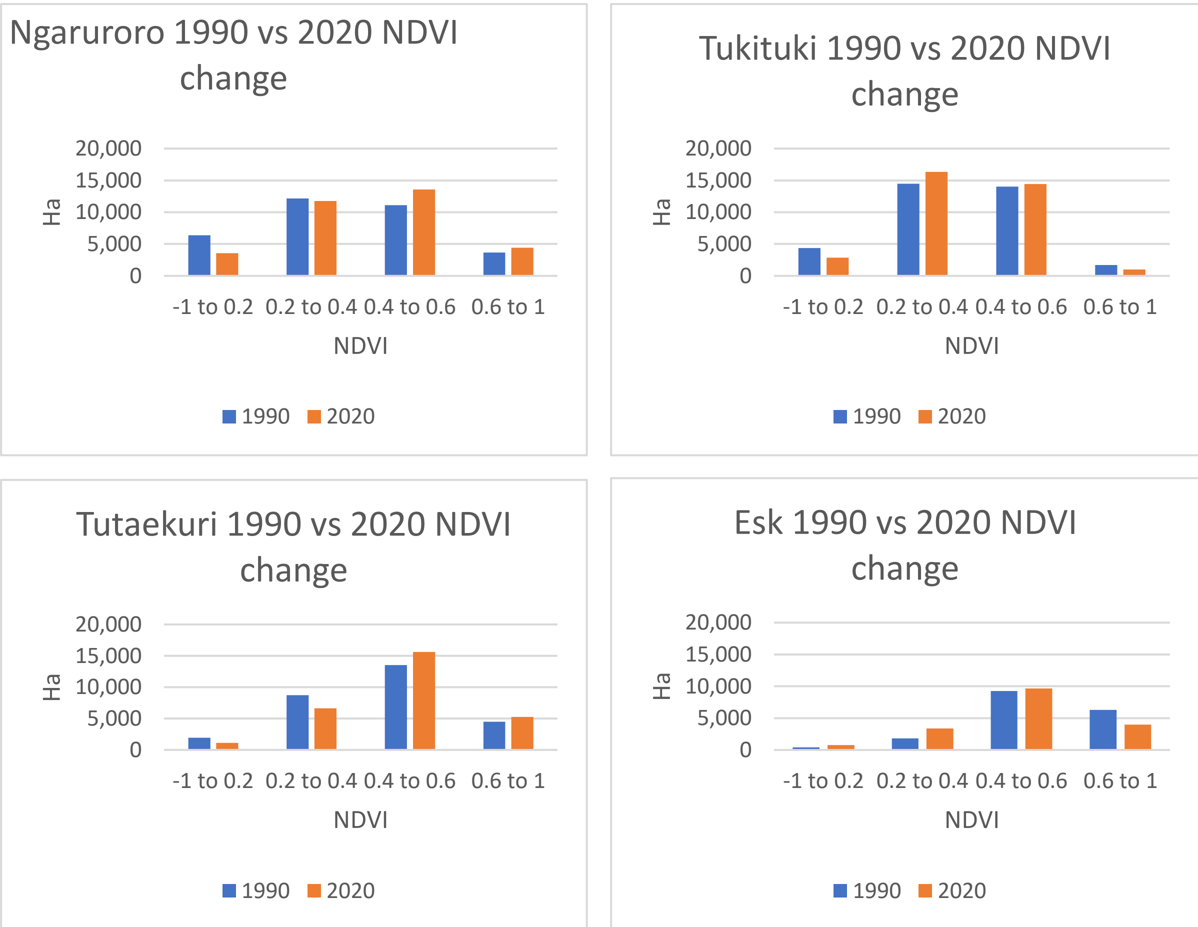


Figure 18: Histograms showing North Island regions river NDVI change 1990 versus 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS involving a buffered shapefile of the North Islands braided rivers extracted down to individual regions combined with Landsat imagery used to calculate NDVI. Note the change in hectares (Ha) changes on the Y-axis for each river.

3.7 Q2: Land use intensified across Canterbury Rivers

There is clear land use intensification occurring on Canterbury's dominant braided rivers which shows land use has changed over time.

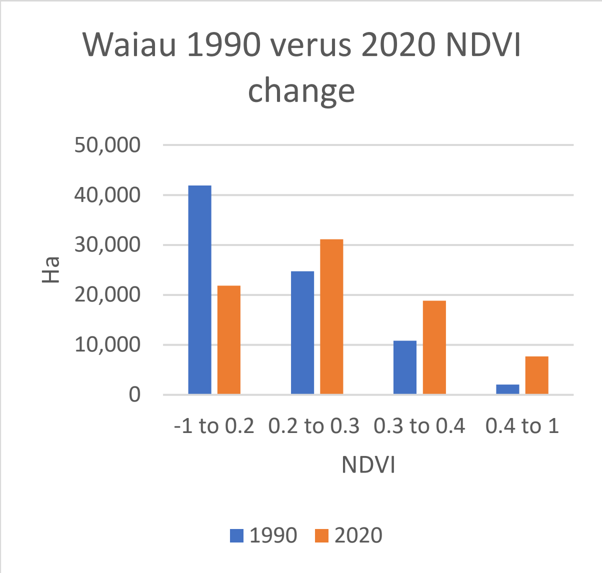
Figure 19 examines Canterbury's main braided rivers which show a similar but stronger pattern to that of the South Island analysis where we see a reduction in water and gravel (NDVI -1 to 0.2) and an increase in intensive land use (NDVI 0.4 to 1). Specifically, the Waiau River shows a 48% decrease in water and gravel alongside a 270% increase in intensive land use between 1990 and 2020.

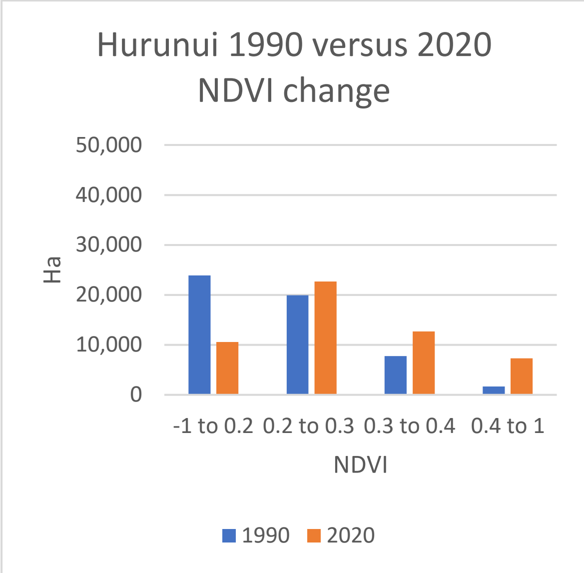
Overall, Canterbury rivers show an increase in intensified land use (NDVI 0.4 to 1). However, there are interesting sub-patterns. Ashburton and Rangitata Rivers show light intensification. Shrub (NDVI 0.2 to 0.3) and grassland (0.3 to 0.4) remain stable. Yet there is a significant loss in gravel and water (NDVI -1 to 0.2) and a large increase in intensification (NDVI 0.4 to 1).

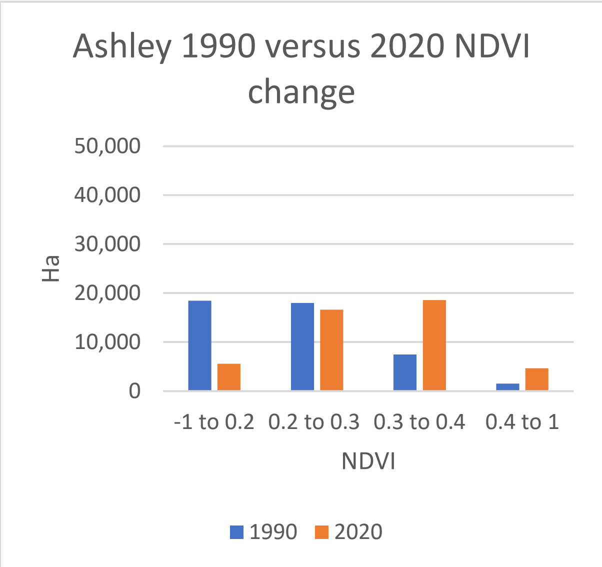
Selwyn and Ashley rivers show NDVI 0.2 to 0.3 remains stable, and gravel and water (NDVI -1 to 0.2) see a decrease while more intensive land uses (NDVI 0.3 to 0.4) increase. Waiau and Hurunui Rivers show a similar decrease in gravel and water (NDVI -1 to 0.2) and NDVI 0.2 to 0.3 remains relatively stable along with an increase in intensified land use (NDVI 0.4 to 1). Waimakariri and Rakaia Rivers show a similar decrease in water and gravel (NDVI -1 to 0.2) and a similar increase in intensified land use (NDVI 0.4 to 1). Waitaki River remains without a pattern but shows a slight decrease in water and gravel (NDVI -1 to 0.2) and an increase in intensified land use. It also shows an increase in grassland (NDVI 0.3 to 0.4) which is not seen in any of the other rivers.

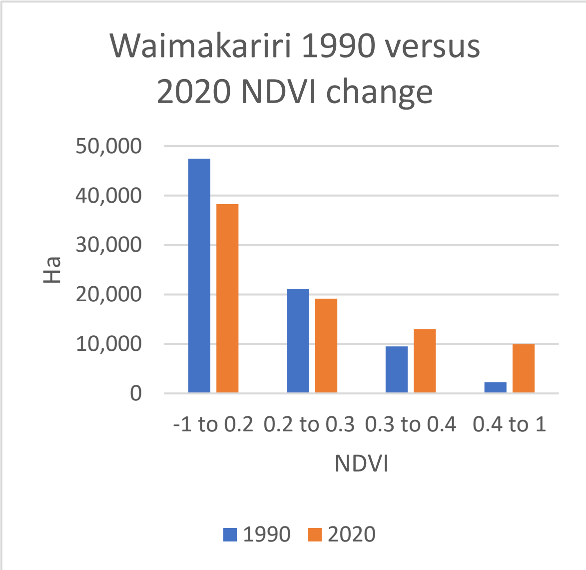
Figure 20 shows a section of the Rangitata River comparing 1990 to 2020. Yellow represents water and gravel or inactive vegetation and red represents intensified land use. The Rangitata River shows a 17% decrease in water and gravel and a 141% increase in intensive land use.

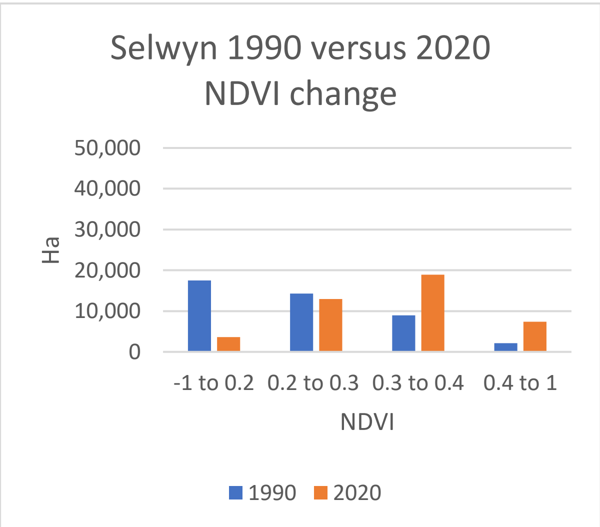
Among the examined rivers, the Selwyn River records the largest reduction in water and gravel at 79%, while the Waimakariri River shows the greatest increase in intensive land use, increasing by 340%.

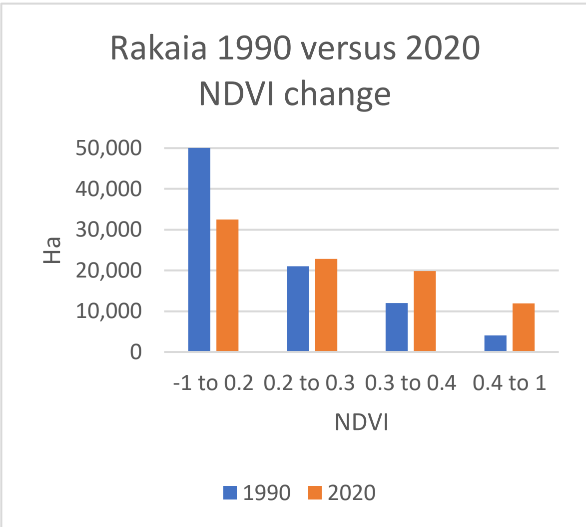

Waiau 1990 verus 2020 NDVI change
50,000
40,000
30,000
20,000
10,000
0
Ha
-1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 1
NDVI
1990
2020


Hurunui 1990 versus 2020 NDVI change
50,000
40,000
30,000
20,000
10,000
0
Ha
-1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 1
NDVI
1990
2020


Ashley 1990 versus 2020 NDVI change
50,000
40,000
30,000
20,000
10,000
0
Ha
-1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 1
NDVI
1990
2020


Waimakariri 1990 versus 2020 NDVI change
50,000
40,000
30,000
20,000
10,000
0
Ha
-1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 1
NDVI
1990
2020


Selwyn 1990 versus 2020 NDVI change
50,000
40,000
30,000
20,000
10,000
0
Ha
-1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 1
NDVI
1990
2020


Rakaia 1990 versus 2020 NDVI change
50,000
40,000
30,000
20,000
10,000
0
Ha
-1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 1
NDVI
1990
2020

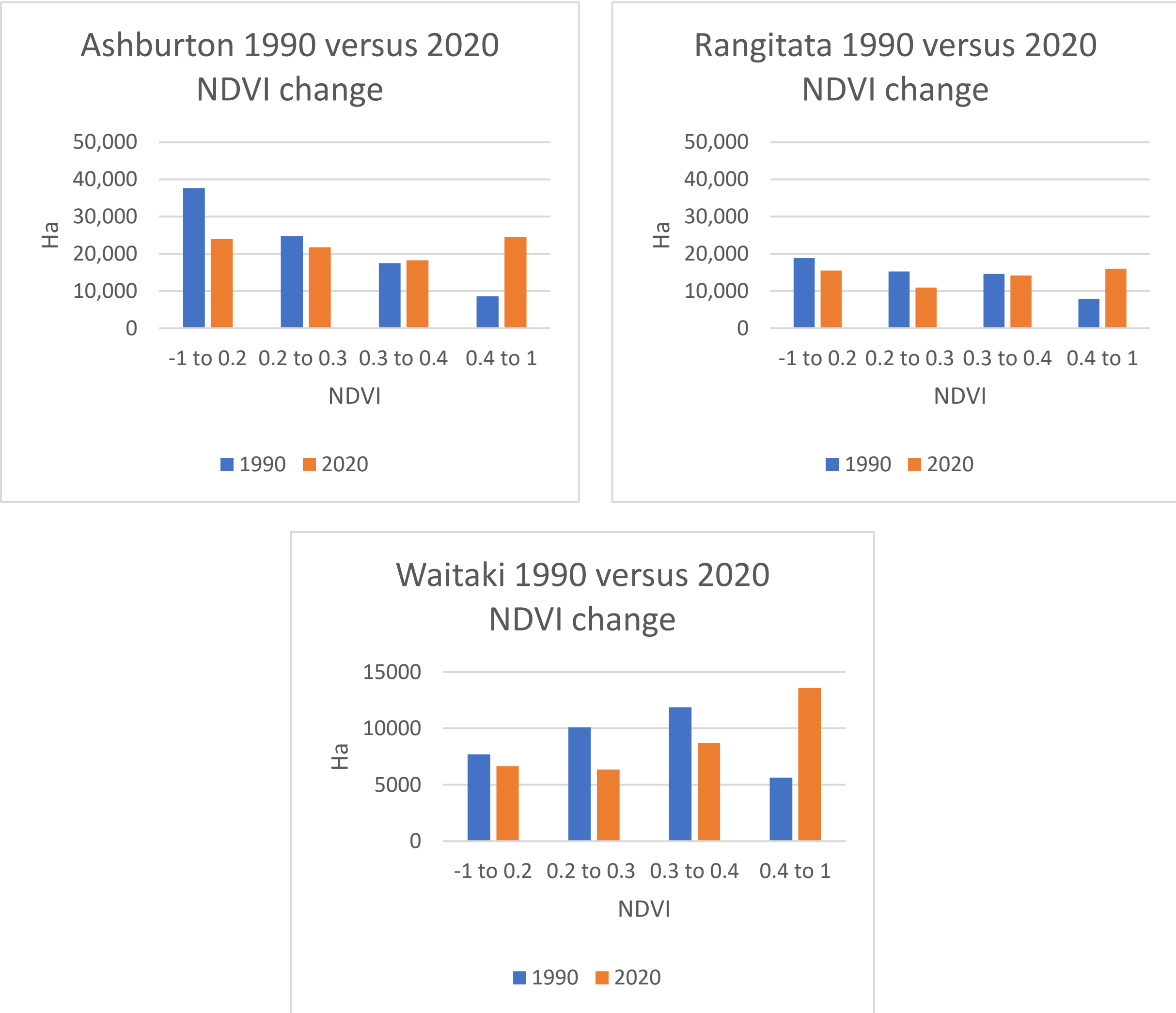


Figure 19: Histograms showing Canterbury rivers NDVI change 1990 versus 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS involving a buffered shapefile of South Islands braided rivers combined with Landsat imagery used to calculate NDVI. Note the change in hectares (Ha) changes on the Y-axis may differ for each river.

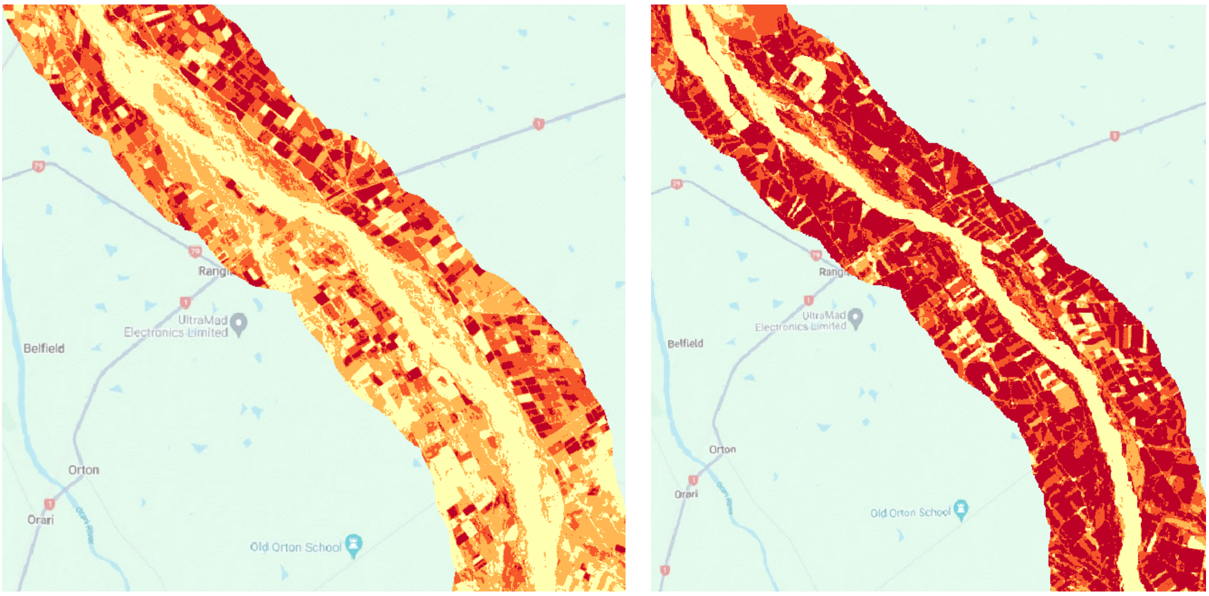


Figure 20: Image of the Rangitata River NDVI change, and subsequent land use intensification. 1990 (left) versus 2020 (right). This was created using QGIS, Landsat imagery was used to calculate NDVI and a buffer shapefile of the Rangitata River was used to extract the image to include 2500m of braidplain either side of the centreline only. Yellow represents NDVI -1 to 0.2, orange represents NDVI 0.2 to 0.4 and red represents NDVI 0.4 to 1. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

3.8 Q2: Land use patterns differ between the regions

3.8.1 North Island regions

The regions in the North Island (Figure 21) generally show the same pattern as the overall North Island analysis (Figure 15). All four regions show grassland (NDVI 0.4 to 0.6) remains stable with a decrease in intensive land use (NDVI 0.6 to 1). The Waikato and Gisborne regions show an increase in water and gravel (NDVI -1 to 0.2) and Hawkes Bay and Wellington show water and gravel remain stable. Shrub (NDVI 0.2 to 0.4) increases throughout all regions.

Figure 23 shows the Ngaruroro River comparing 1990 to 2020 where yellow represents water and gravel or inactive vegetation and red represents intensified land use. This shows more vegetation, and that land use has intensified between 1990 and 2020 by the increase in red and constricted riverbed. In 2020 the imagery shows that there is less opportunity for braiding to occur which is reflected by less yellow (indicative of water and gravel).

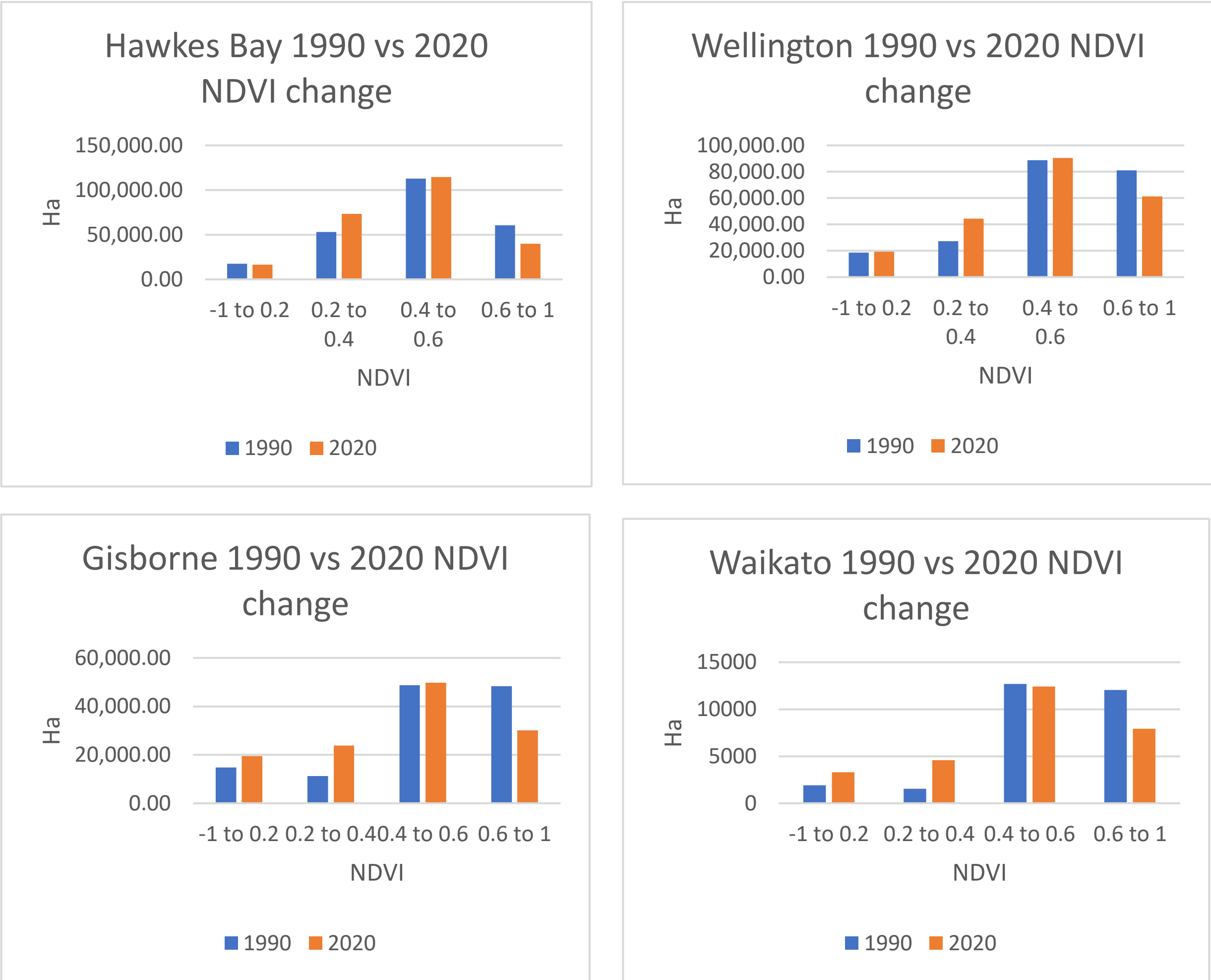


Figure 21: Histograms showing North Island regions river NDVI change 1990 versus 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS including a buffered shapefile of the North Islands braided rivers extracted down to individual regions combined with Landsat imagery used to calculate NDVI. Note the change in hectares (Ha) changes on the Y-axis for each region.

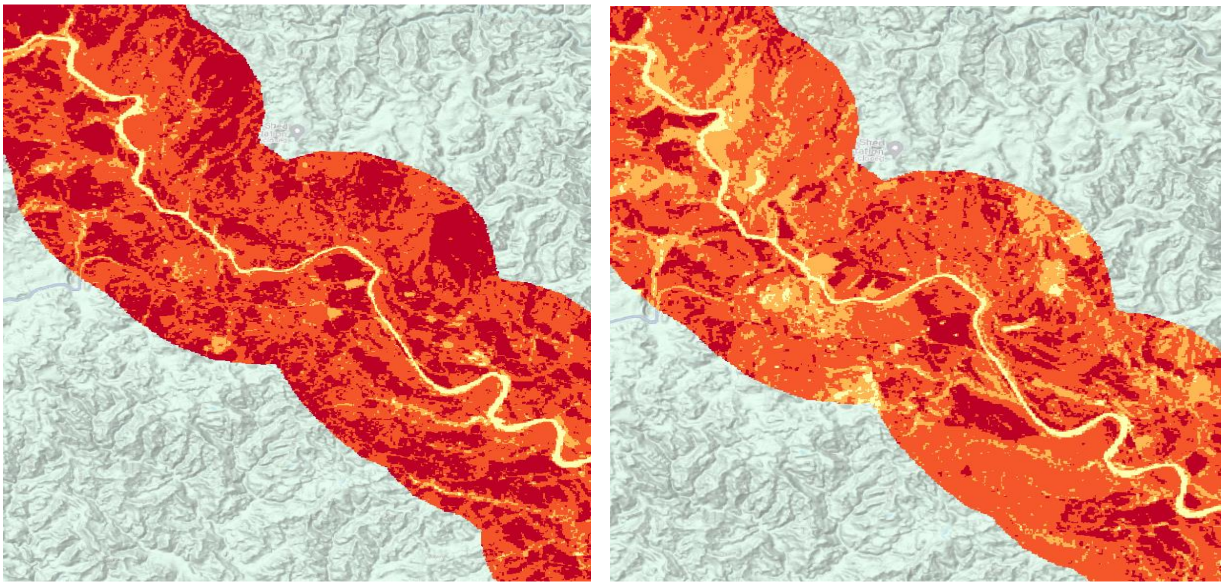


Figure 22: A stretch of the Mohaka River showing NDVI change. 1990 (left) versus 2020 (right). This was created using QGIS, Landsat imagery was used to calculate NDVI, and a buffer shapefile of the Mohaka River was used to extract the image to include 2500m of braidplain either side of the centreline only. Yellow represents NDVI -1 to 0.2, orange represents NDVI 0.2 to 0.6 and red represents NDVI 0.6 to 1. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

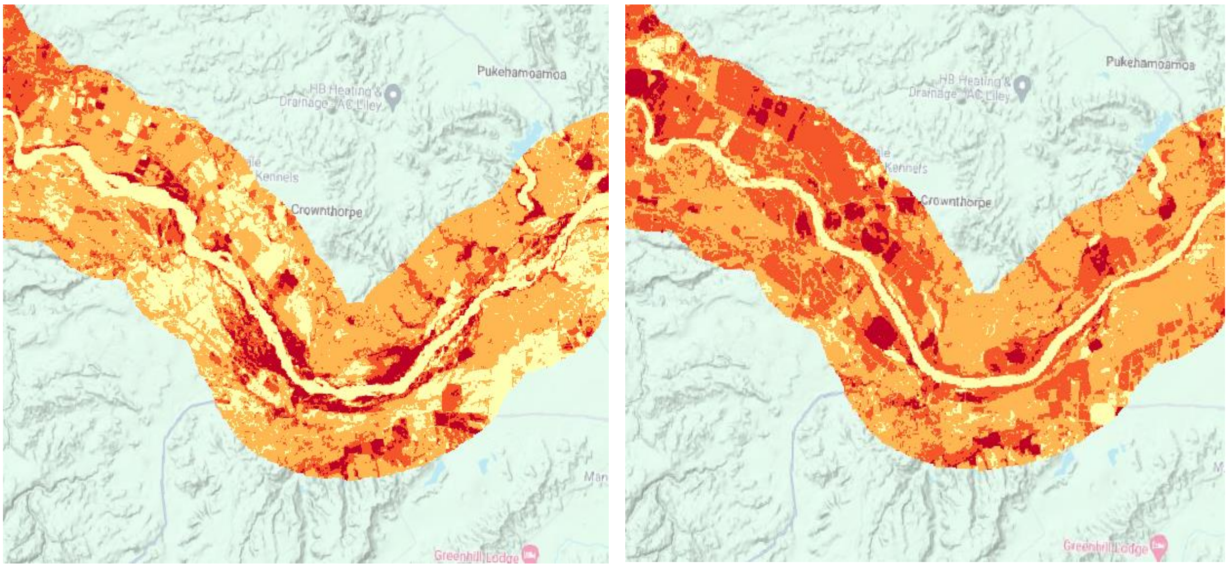


Figure 23: A stretch of the Ngaruroro River showing NDVI change. 1990 (left) versus 2020 (right). This was created using QGIS, Landsat imagery was used to calculate NDVI, and a buffer shapefile of the Ngaruroro River was used to extract the image to incorporate 2500m of braidplain either side of the centreline only. Yellow represents NDVI -1 to 0.2, orange represents NDVI 0.2 to 0.6 and red represents NDVI 0.6 to 1. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

3.8.2 Patterns show intensified land use across South Island regions

Figure 24 shows Canterbury's braided rivers comparing 1990 to 2020 where yellow represents water and gravel or inactive vegetation and red represents intensified land use or healthy vegetation. Figure 24 shows more vegetation, and that land use has intensified in 2020 which, in dry environments like Canterbury's braided rivers, regimes of land use include irrigation so is counted as intensified land use. It also shows a decrease in yellow between 1990 and 2020 representing a reduction in space occupied by water and gravel.

Figure 25 shows across the regions of the South Island the pattern of a reduction in gravel and water (NDVI -1 to 0.2) and expansion in grassland (NDVI 0.3 to 0.4) and intensified land use (NDVI 0.4 to 1). In Marlborough, there is more growth in grassland (NDVI 0.3 to 0.4). Southland shows an interesting pattern, a slight decrease in land use intensification (NDVI 0.4 to 1).

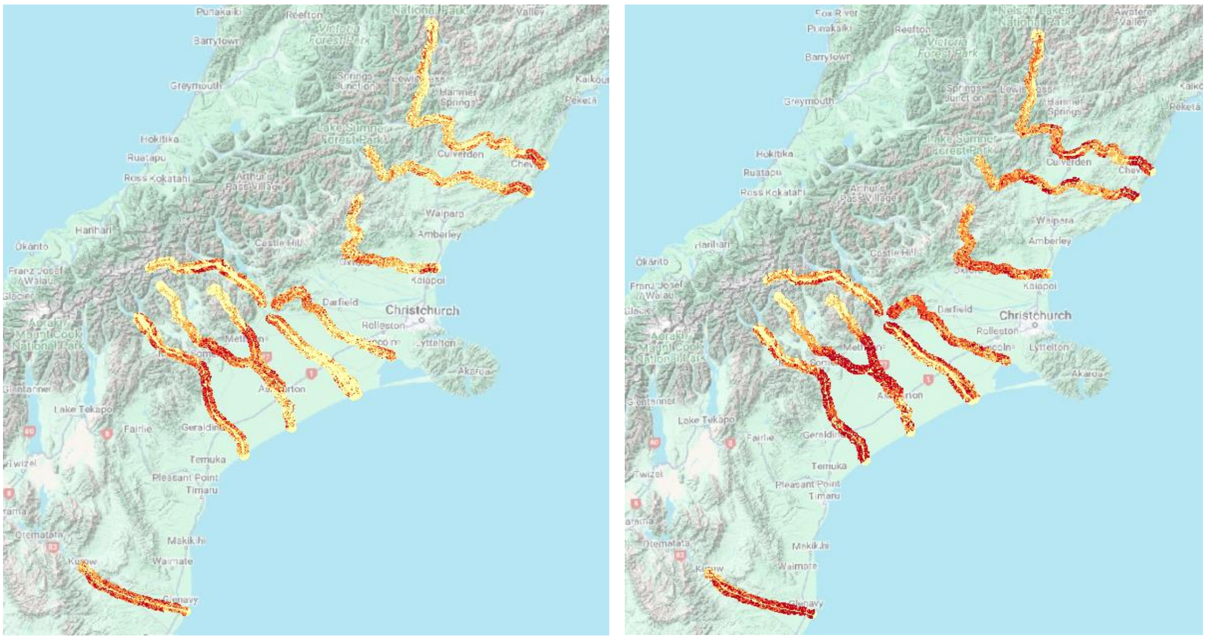


Figure 24: Canterbury braided rivers 1990 (left) versus 2020 (right). This was created using QGIS, Landsat imagery was used to calculate NDVI, and a buffer shapefile of the Canterbury Rivers was used to extract the image to incorporate 2500m of braidplain either side of the centreline only. Yellow represents NDVI -1 to 0.2, orange represents NDVI 0.2 to 0.4 and red represents NDVI 0.4 to 1. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

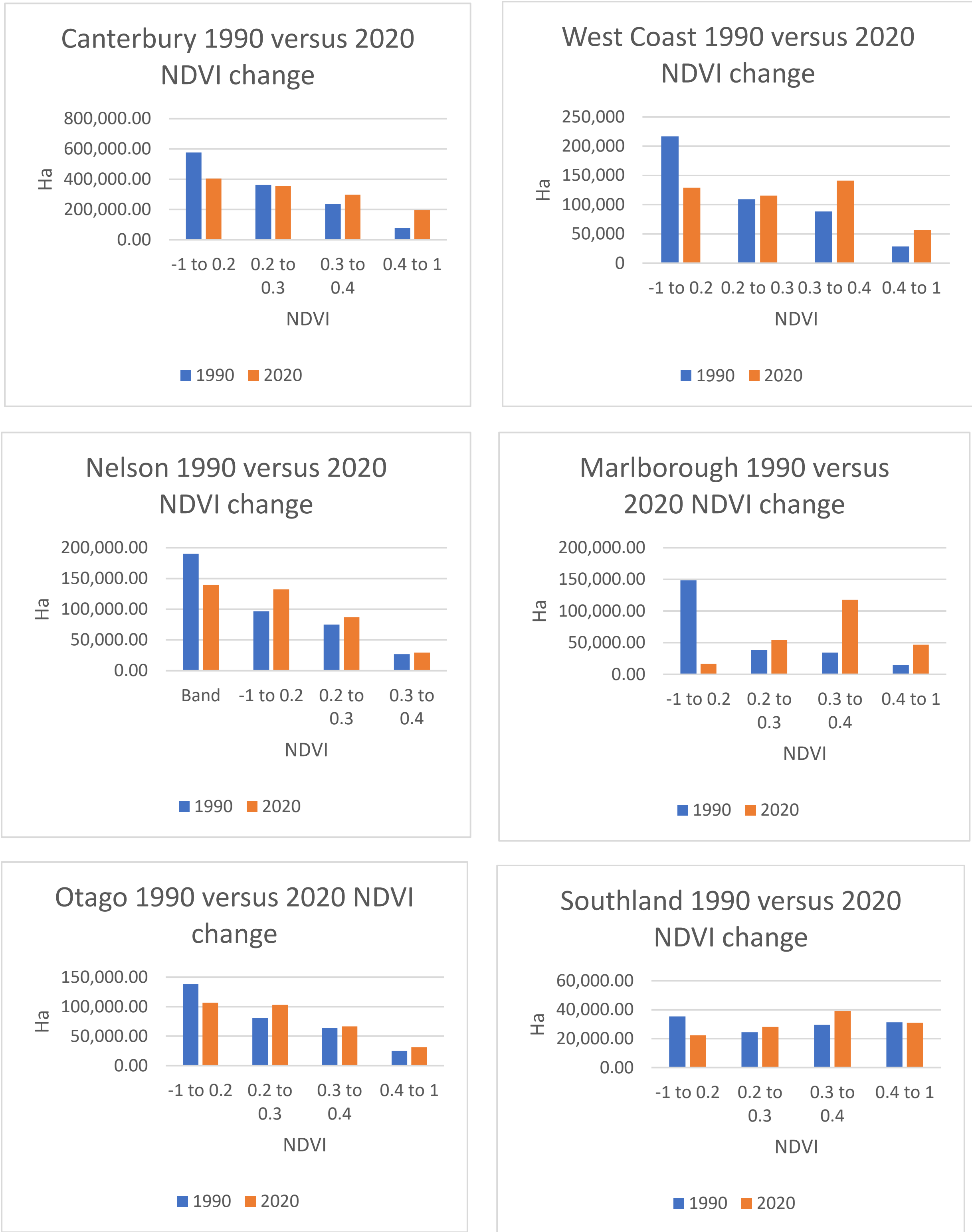


Figure 25: Histograms showing South Island regional rivers NDVI change 1990 versus 2020. The Y-axis displays the number of hectares (Ha) examined on the braidplain and the X-axis displays NDVI numbers. The histogram was created using results from NDVI calculations made in QGIS using a buffered shapefile of South Islands braided rivers extracted down to individual regions combined with Landsat imagery used to calculate NDVI. Note the change in hectares (Ha) changes on the Y-axis for each region.Figure 26

Chapter 4 – Did the method work? Why do some regions look so different?

4.1. Q3: My method works

The consistency of my results suggests that my method worked.

4.2. Q3: My method can detect seasonal changes when backed up by time-series

Results also show that several regions look very different. In short, I seem to be finding that the rivers of the North Island and Southland intensified less between 1990 and 2020 than the rivers of Canterbury and Marlborough. The differences in the regions might suggest some environmental factors.

In this section, I explore those differences to find out if the method may have failed in those areas, or if land use changed differently in those areas. Results suggest that environmental factors create different land use in different regions such as:

1. Farming practices and climatic conditions might also influence land use change; Figure 26 shows a time-series that explains why. To explore this seasonal/climatic possibility, I had to develop a new methodology using a monthly time-series. This is described in the paragraph below.

2. Rivers with less gravel area to begin with like the Mataura River, might exhibit different patterns of land use change than rivers with greater gravel area such as the Waimakariri. My results suggest land use intensification has already occurred in and around the less gravelly riverbeds and occurred later in time on the more gravelly rivers, but I cannot test this hypothesis. I have discussed this in detail below.

To create the time-series graphs shown in Figure 26 I developed a code in Google Earth Engine. The code consisted of using Landsat imagery from the Google Earth Engine Catalog and selecting a region of interest which was manually input by the user. For the application of this study, the region of interest was selected near the Ngaruroro, Waimakariri, and Mataura Rivers. The code then cloud-masked the image to remove false NDVI values from the calculations. A scaling factor was then added and applied to the appropriate bands to highlight the features within the satellite imagery, in this case, paddock, river, and pine plantation. A function was used to add NDVI, time, and constant variables to the imagery. The code then plotted the time-series of NDVI at the single location as selected on the map in the form of a chart in GEE. I then exported the time-series information from the chart as a CSV file and imported it into Excel.

The time-series graphs include a sinusoidal (sine) curve plotted in Excel using the time-series CSV file from Excel. It shows the period shift of a land use type over time by exhibiting a periodic oscillation

(*Sinusoidal*, n.d.). The sine curve has been plotted on each series of data shown in Figure 26 from my test rivers and has been calculated using the following sinusoidal function formula:

$$y = A \cdot \sin(B(x-C)) + D$$

The time-series results are discussed in detail below.

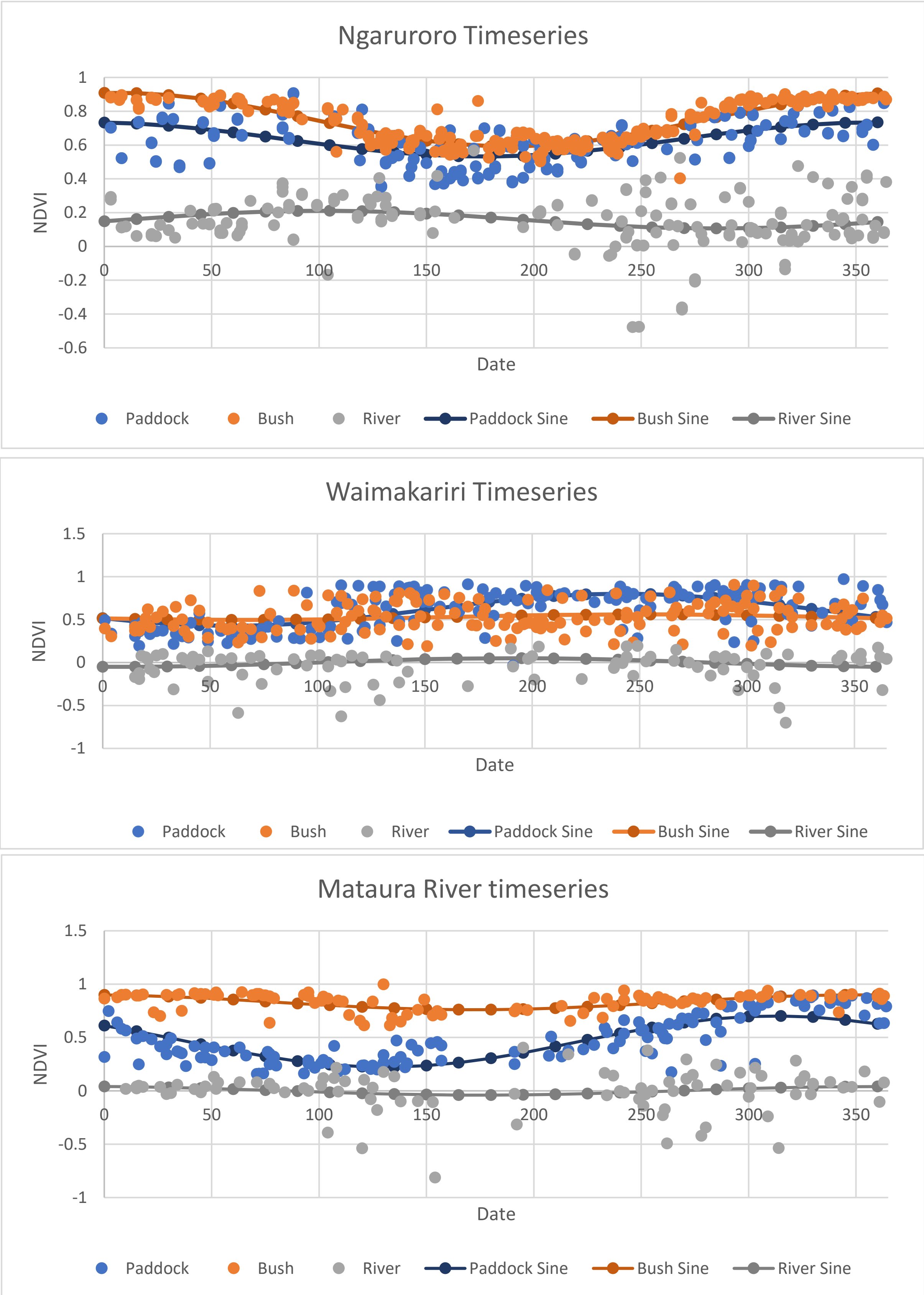


Figure 26: Ngaruroro, Waimakariri, and Mataura River time-series including sine waves to show periodic shift of the specific land use types over time. The X-axis shows the Julian Date (365 days) displaying seasonal changes of the land use type. The Y-axis represents the NDVI number corresponding to the land use type.

4.3. Time-series results

The time-series results reveal seasonal variability; they also suggest that the method worked fine but different regions have different land uses. Figure 26 suggests all three rivers show seasonal variability resembling cropping on a parcel of farmland. The Mataura River shows that in May, the paddock has been harvested and is bare dirt; in December, the crop is at its peak in terms of NDVI and grassland and is then harvested to bare dirt. this continues seasonally from 1990 to 2020.

The Waimakariri and Ngaruroro Rivers show seasonal variability on their paddocks. The pine plantations follow somewhat of a similar seasonal trend to that of the paddock between summer and winter and have high NDVI values due to their green characteristics and dense vegetation. They show random seasonality of the river in terms of NDVI. The time-series method also suggests my NDVI method worked fine.

4.4. Hypothesis on riverbed gravel area

Another hypothesis that is suggested by my findings is that land use changes depending on the nature of the river. This will be described by the area of bare riverbed or area of gravel. My results suggest when there is a greater area of gravel in the riverbed, there is greater intensification of land use. With my data set, this is an untestable hypothesis because I have only looked at known braided gravel bed rivers. To test this hypothesis, I would need a representative sample of all river types in New Zealand. I cannot be sure a greater area of gravel riverbed causes a difference as I have not looked at the whole population of non-gravel-bed rivers. My results suggest there is a relationship and imply that certain regions in the country experienced earlier intensification of their rivers compared to others.

If we take the example of the Mataura River, it shows a smaller area of gravel to start with and less land use intensification over time (Figure 27). Gravel in the Mataura is concentrated in the headwaters. The Mataura River is very different to the Waimakariri River, which has a large area of gravel through the course of the river and increases in land use intensification over time. This is displayed in Figure 27 and Figure 28 below where we see stretches of the rivers and obvious differences in gravel area between the two supporting the hypothesis. Another example is the Mohaka River (Figure 22) which also has less area of gravel and follows a land use pattern like that of the Mataura.

The difficulty of sampling bare land on rivers is when rivers have been constricted, the gravel volume is going to change vertically rather than laterally. A good test would be the expanse of the gravel rather than the volume of the gravel. Lateral expanse is all we can test using NDVI.

Figure 27 shows the Mataura River which demonstrates less braided reaches and as a result less gravel riverbed area. We see greater healthy vegetation in 1990 compared to 2020 because of less bare riverbed area.

The rivers included in my analysis are representative of medium to high gravel coverage and are inclusive of zero to low gravel coverage which would better represent the hypothesis outlined above. The gravel hypothesis looks as though it will have enough merit to test land use change.

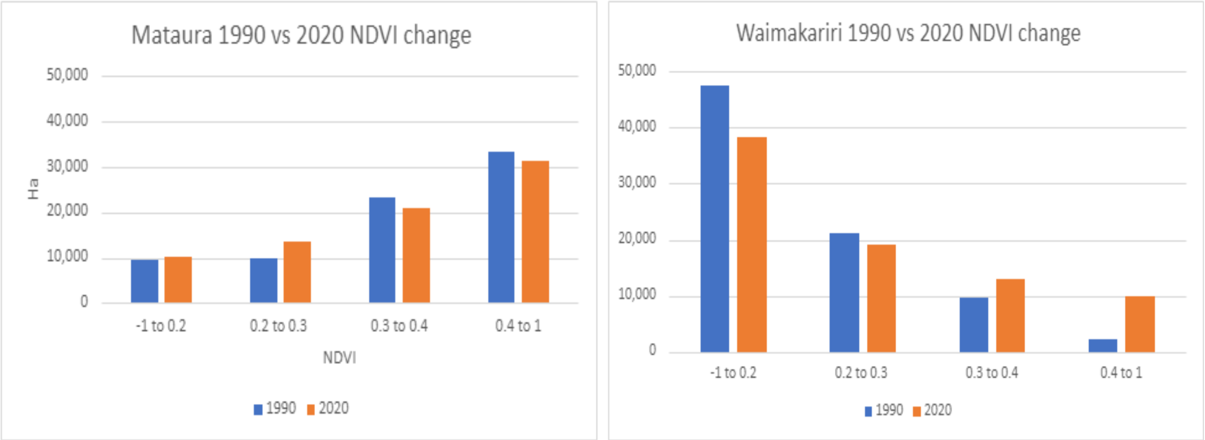


Figure 27: Histograms highlighting area of gravel and water (NDVI -1 to 0.2) and change in land use intensification over time (NDVI 0.4 to 1) for the Mataura and Waimakariri Rivers.

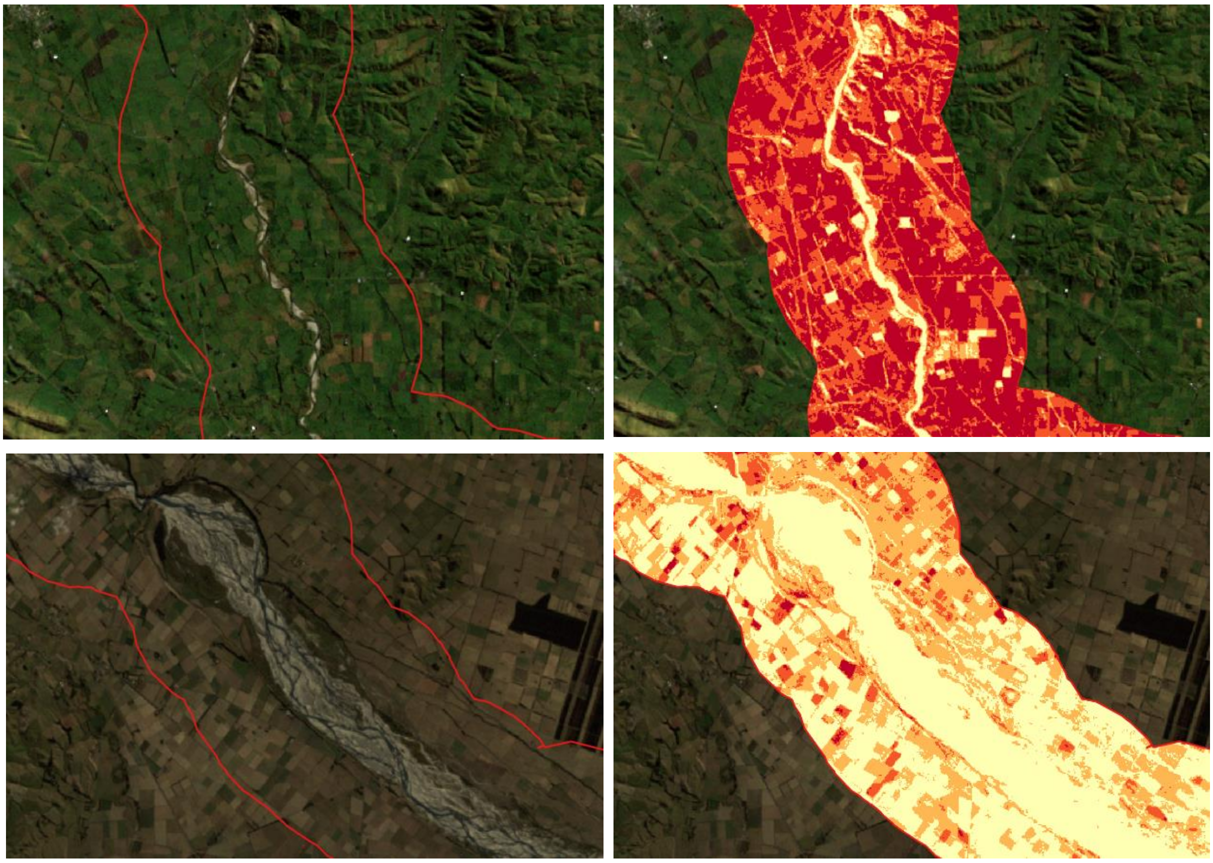


Figure 28: Sections of the Mataura River (top) and Waimakariri River (bottom) from 1990 showing concentrations of bare riverbed at both sites. The satellite images on the left show the example of river area and the NDVI image on the right shows the area of riverbed analysed for gravel and water area calculated. The NDVI buffer covers 2500m either side of the river centreline. The images are scaled at 1:50000. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

Chapter 5 – Discussion

This chapter presents an overall discussion of the study's results and evaluation of thesis objectives. As this study compares changes in New Zealand's braided rivers between 1990 and 2020, the results are discussed in detail from a North Island versus South Island comparison down to regional scale, finally down to the individual dominant braided rivers found in Canterbury and Hawkes Bay. The effectiveness and limitations of the methods are discussed.

5.1. Dominant patterns of land use change across New Zealand

Land use across the North Island and South Island braided rivers show dominant patterns of change including a reduction in land use intensification in 2020 in the North Island, and on the other hand, greater land use intensification in 2020 in the South Island. There are also changes to the amount of gravel and water across rivers in both islands including an increase in the North Island and a decrease in the South Island over the study time of 1990 to 2020.

5.1.1 Dominant patterns of land use change in Canterbury vs Hawkes Bay

When analysing the results on a smaller scale and looking at regional differences where braided rivers most commonly occur such as Hawkes Bay and Canterbury, there are two different patterns occurring. In Hawkes Bay patterns show intensive land use decreases across the Esk and Tukituki rivers, however, the Tutaekuri and Ngaruroro rivers show an increase in intensive land use in the braidplain. Along with a decrease in intensive land use, the Esk and Tukituki rivers show an increase in gravel and water. The Tutaekuri and Ngaruroro show a decrease in gravel and water. The patterns of the Tutaekuri and Ngaruroro are similar to that of Canterbury's braided rivers where we see an increase in intensive land use and a decrease in water and gravel.

5.1.2 Dominant patterns of land use change across New Zealand's regions

Figures 21 and 25 show patterns of land use change across the regions. The remaining regions of the North Island (Figure 18) follow a dominant pattern the same as the entire North Island analysis (Figure 15) where land use intensification decreases, and water and gravel generally increase. The regions of the South Island (Figure 25) follow a dominant pattern the same as the entire South Island analysis (Figure 16) in which land use intensification increases and water and gravel decrease. The South Island region that shows a variable difference is in Southland, where land use intensification remains stable, this is discussed in detail below.

5.1.3 Other causes for regional differences

We do see some regional differences occurring attributed to land use change across New Zealand's braided rivers. For example, regional differences may include but are not limited to farming practices changing between regions such as dairy farming in Waikato versus horticulture in Otago. There are also differences in climatic conditions including wetter regions such as the West Coast compared to Nelson or Marlborough.

It is difficult to attribute causality to region. And I cannot say with certainty that the regional boundaries cause differences in patterns. There could be several factors causing differences in patterns across the regions that are not testable using my dataset. It is a topic for further research.

5.2. Where do land use patterns look different?

Patterns of land use change vary across New Zealand, particularly between the North Island and South Island. The intention was to compare the NDVI changes using the same NDVI thresholds, however, due to climatic variability between the North and South Islands, I altered the NDVI thresholds to ensure NDVI was counted evenly for comparison for the whole of New Zealand. It was anticipated the land use change would follow a distinct change between the islands in which land use intensification would increase and water and gravel would decrease. However, the results were still conclusive of the method.

5.2.1 Why do land use patterns look different?

Land use patterns look different across New Zealand due to differing climatic conditions or land use practices. Land use has changed, just sometimes in the opposite direction to one another. Overall, the method provides adequate results to compare land use changes over time. If someone wanted to use the method on a smaller scale it would be a viable choice to delve further into the methodology and combine with the likes of time-series.

The method I have adopted is looking at land use, in which New Zealand is highly populated for agriculture, forestry, and horticulture with pastoral farming being the dominant land use. Comparing by month (January) as explained in my methods works for areas that are natural and haven't changed between 1990 and 2020. However, in areas associated with pastoral land use and the practices associated with it i.e., cropping and grazing, there is inconsistency in NDVI numbers month to month for the years examined.

5.3. What do patterns of land use change mean for observing New Zealand's braided rivers?

My results show it is possible to compare land use change over time using NDVI. For example, Figure 23 shows a stretch of the Ngaruroro River in 1990 versus 2020. There are patches of deep red circles indicating intensified land use converted to pivot irrigation. The change to intensive land use in the form of pivot irrigation is an example of farming practices changing from 1990 to 2020 at an individual river scale.

My results in the regions look different in areas where the area of gravel in a riverbed changed. By this I mean, that rivers with greater areas of gravel showed more intensification within the braidplain than in rivers with smaller areas of gravel. In Hawkes Bay and Southland, my results suggest land use had already intensified in Hawkes Bay and Southland. I think land use is different in different places best shown in areas such as the Waimakariri which has a large area of gravel compared to the Mataura which my method suggests was already intensified and had a lower area of gravel. The Clarence River shown in Figure 2 resembles a river with lower area of gravel, similar to the Mataura highlighting land use had already intensified.

My method does fail to account for seasonality, like in cropping. I suspect but do not know that this is seen more in wetter areas and less in drier areas like Canterbury and Marlborough. It also worked differently where harvesting practices were predominantly seasonal such as where cropping occurred on a seasonal scale. Farming practices differ between the regions and can reduce the practicability of NDVI analysis for one month of a year. Harvest times of any particular year could change month to month i.e., drought versus wet. In Southland, farming practices have changed from predominantly sheep farming to the conversion of dairy farming since 1990 (Forney & Stock, 2014).

When comparing individual rivers, there is a similarity between the Mataura River in Southland, the Waiau Toa / Clarence River in Marlborough, and the Esk River in the Hawkes Bay. This relates to the question of whether bare land surrounding the river such as the volume of gravel has to do with land use intensification over time and is discussed in chapter 4 above.

5.5. Limitations

In addition to what this study has mentioned above, there are limitations including the comparison of only one month of data from each year (January). It limits the consistency of NDVI numbers and shows strength for the gravelly rivers where there is obvious constriction of the bare land (gravel and water) in and around the rivers. It shows a weakness for the less gravelly rivers where the constriction of bare land is unable to be measured and rather changes in vegetation use is more common i.e., a change from native vegetation or shrub to paddock and cropland. Overall, it is a strength for identifying intensification, but a weakness for identifying seasonal changes. This also leads to the limitation of results in some areas being inconclusive of farming practices regionally and climatic conditions across New Zealand.

5.6. What does this mean for braided rivers and management going forward?

There has been ongoing pressure of land use intensification on the beds of braided rivers linked to the demand for flat land that is easily irrigable for agriculture and horticulture or highlighted for ease of urban development. Intensification in land use then can inspire the need for flood protection, particularly for urban development, as said in Brower et al. (2024):

"*Agricultural and peri-urban encroachment continues to operate across New Zealand like a ratchet because hard stop banks (artificial levees) or bioengineered vegetated river boundaries follow the migrating channels inwards from either flank but do not retreat".*

A river must then adapt to changes in the flow of water and altered sediment movements. Climate change forces further adaptation to changing river behaviour.

Vosloo et al. (2022) published a case note on the "difficulties in defining boundaries of braided rivers" using the example of Canterbury Regional Council versus Dewhirst Land Company. The publication outlined the need for legislative and regulatory change and concludes as follows:

"Braided rivers require a legislative definition at the national level that embraces dynamism, complexity, and room to move. Above all, to fulfil regional and national goals of protecting natural character of unique landscapes, the legislative definition must recognise that braided rivers are land and water both at once" (Vosloo et al., 2022).

This article said to create the room to move that rivers need; the definition of braided rivers must change. This gave rise to my thesis topic and to a programme of work to create legislative change which I now describe.

During my master's, I helped design and organise a workshop. The workshop created a group that presented a parliamentary submission and eventually changed the legal definition of the riverbed. The Land the Law Forgot is a group brought together by the 2023 workshop with funding from Te Punaha Matatini, which sought to discuss braided rivers and the management surrounding them. Our submission outlined the following:

"1) Problem: The continual and sustained constriction of braided rivers is making rivers less resilient, which causes problems – economically, agriculturally, culturally, and ecologically.

2) Cause: lack of a definition that works for braided rivers in the NBEA (and previous RMA). This is exacerbated by the Dewhirst decision in the Court of Appeal (2019).

3) Solution: change the definition in three ways:

a. Amend the Definitions of [proposed NBEA] clause 7, to include a nuanced definition of 'braidplain';

b. Amend clause 38(1) by adding a new (g): 'Braidplains of braided rivers'.

c. Make aligned changes to Spatial Planning Act clauses 8 and 17 (to be reviewed in a separate but aligned submission)"

Our group eventually succeeded in convincing parliament that braided rivers are different, and therefore need to be treated differently as my gravel hypothesis suggests. The change that we sought strongly resembles my findings. Not only has there been encroachment in braided riverbeds, but my findings suggest that the more gravel there is, the greater the encroachment. The changing definition also gives more direction for someone else to test the gravel hypothesis. Our group's contribution to the Natural and Built Environment Act (NBEA) saw two changes to the NBEA:

> 1) Section 7(1) excluded braided and wandering rivers from the existing bank to bank definition of the RMA.
>
> 2) Section 858(1) established a framework for the Minister of the Environment to provide guidance to the Cabinet regarding the regulations of the definition of riverbeds. The amended definition gives power to the Minister of the Environment to regulate and plan what development is or is not allowed within braidplains.

The act was passed into law in August 2023. A new government was sworn in on 27th November 2023. The NBEA was repealed on 24th December 2023. However, the regulatory route created by section 858(1) might still exist in regulation. The story of the year's work of submission, advocacy, legislative change and repeal is told in an article our group published in Earth Surface Processes and Landforms (Brower et al., 2024).

Conclusion

This thesis examines land use change across New Zealand's braided rivers from 1990 to 2020. It develops and tests a methodology to ask whether and how land use changed in and around New Zealand’s braided rivers, and whether there are geographic patterns in the change. The study reveals that land use has changed across New Zealand's braided rivers, with the most significant changes observed in Canterbury and rivers characterised by a higher proportion of gravel. The least amount of land use change occurred in the regions of the North Island and Southland, particularly in rivers with less gravel. For example, between 1990 and 2020, the Waimakariri River saw an increase in intensive land use by 340% and the Ngaruroro River saw a 20% increase in intensive land use between 1990 and 2020.

I developed a time-series method to question whether my method failed in Southland and the North Island, or if different regions had different land uses. The time-series results showed seasonal variability occurs on braidplains where the dominant land use is cropping.

My results also suggest a “gravel hypothesis” – that rivers with more exposed gravel intensified more between 1990 and 2020 than rivers with less exposed gravel. The hypothesis appears promising but cannot be tested with my dataset that includes only rivers with some braiding. It also appears that the rivers with less gravel intensified in their land use before 1990, hence experiencing less intensification during my study period. In other words, it is not that less gravelly rivers are less intensified; it is that the less gravelly rivers intensified earlier. This hypothesis is worth testing; a comprehensive dataset will firmly establish a conclusion about gravel area and land use change surrounding rivers.

The thesis concludes by exploring its contribution to legislative changes to the management of braided rivers.

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