Contrasting morphological responses to a singular flood event in neighbouring rivers and the implications for river management.

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Abstract

Geomorphic response to flood events is spatially and temporally variable and is influenced by many natural and anthropogenic processes. Research in recent times has shown the adverse geomorphic effects of rivers that have been managed by straightening, narrowing, and disconnecting them from their floodplain. This work attempts to evaluate the morphological response of small, rural gravel-bed rivers to discrete flood events and to put this response into the context of decadal-scale channel adjustments and river management practices. The Tauanui and Turanganui Rivers in South Wairarapa, New Zealand, were monitored and analysed to identify sediment dynamics within them and how they respond to discrete flood events and river management practices. This was achieved by analysing existing historic aerial and satellite imagery, cross-sectional survey data, and geomorphic change analyses using Structure from Motion (SFM) photogrammetry datasets collected in this project. Historical aerial imagery revealed that both rivers have significantly changed over time, with the area of active gravels reducing 38% in the Tauanui and 48% in the Turanganui River from the 1940s to 2013. A narrowing and straightening of both rivers and a proliferation of heavily vegetated banks was observed. It is suggested that these changes are linked to river management strategies, which have helped to develop floodplains for agriculture and occupation by people. Following a storm event on the 20th of June 2021, flooding caused significant geomorphic change. Geomorphic change analysis before and after suggested net aggradation of 1,564 m^3 in the Tauanui River and 3,430 m^3 in the Turanganui River. Although geomorphic change was significant in both study reaches, it contrasted. This contrast has been interpreted as a result of differences in river resilience and geomorphic thresholds. Similar to other studies, it is suggested that river management interventions have reduced resilience and brought both rivers closer to geomorphic thresholds. This has resulted in geomorphic change that is disproportionate to the flood magnitude. River management that homogenises river corridors is also detrimental to habitat diversity and increases the exposure of the surrounding land to flood risk.

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1.0 Introduction

It is estimated by the United Nations Office for Disaster Risk Reduction (UNISDR) that 1.47 billion people face at least moderate flood risk globally (UNISDR, 2015 in Mol et al., 2020). When considering the number of people evacuated and the economic damages, flood events are one of the world's most significant Environmental disasters. Flooding is considered one of New Zealand's most common and destructive natural disasters (Auliagisni, 2022). The geomorphic response to flood events is highly variable and destructive and causes significant changes in landscapes (Fuller, 2007; Fuller, 2008; Vincent et al., 2022). Floods and associated damage often occur quickly and unexpectedly, which can destroy homes and infrastructure. It is conservatively estimated that in the last ten years, floods have cost New Zealand $120 million in privately insured damages; this is on top of damage to public infrastructure (Frame et al., 2018). Flood damage costs are expected to increase due to the increasing magnitude and frequency of flood events expected under future climate scenarios (Manning et al., 2014).

Therefore, it is vital that river dynamics are understood to implement effective measures that mitigate future flood damage and its associated costs. Rivers near large populations are typically the focus of extensive investment in river management in New Zealand (GWRC, 2019; King, 2010). Rivers isolated from significant human populations, such as those in rural areas, are often a lower priority for flood risk mitigation. Nonetheless, rivers in rural landscapes can pose a significant economic threat to the agricultural sector and have the potential to damage infrastructure and isolate communities throughout New Zealand (Ryan et al., 2021). For example, the 2004 Manawatu-Wanganui floods isolated communities for several days and significantly disrupted agricultural businesses in rural communities (Smith et al., 2011).

River management practices such as channel straightening, stop bank building and planting are used to mitigate flood damage and convert floodplains to habitable and arable land. This is done to maintain a river's channel to a confined corridor that does not impact these human developments, particularly during flood events (Surian & Rinaldi, 2003). Such mitigation measures are usually implemented slowly over several decades, producing significant changes in the fluvial landscape (Fuller & Conley, 2022). These changes can prevent flooding to surrounding floodplains from moderate events but can be overcome in extreme floods by erosion, deposition, and avulsion (Rodríguez et al., 2012 in Garcia et al., 2021).

Significant portions of the globe's rivers, including New Zealand's, are modified and confined to corridors a fraction of their total floodplain to prevent erosion and flooding on developed land (Brierley & Fryirs, 2009; Garcia et al., 2021). This practice has been disputed in recent times, with several concepts such as "stream corridor" (FISRWG, 1998 in Piegay et al., 2005, p. 774), "riparian corridor" (Thorne et al., 1992 in Piegay et al., 2005, p.774), or "living with rivers" (Garcia et al., 2021, p. 2). The "stream corridor" (FISRWG, 1998 in Piegay et al., 2005, p. 774) and "riparian Corridor" (Thorne et al., 1992 in Piegay et al., 2005, p.774) river management practices involve defining boundaries within the riparian zone of a river that can freely erode to produce more diverse geomorphic systems. The "living with rivers" concept (Garcia et al., 2021, p. 2) is an integrated management framework that involves working across multiple disciplines to effectively plan development on floodplains and educate communities about fluvial processes and implications of management. These concepts promote river migration and sediment flux as a natural process that should not be prevented outright but allowed within a defined extent of a river's floodplain. This raises the question of the effectiveness of management practices in response to flood events with regard to New Zealand's rural gravel bed rivers. In-depth studies have been conducted in small, gravel-bed rivers in New Zealand, such as the Kiwitea and Motueka Rivers (Fuller, 2007; Fuller, 2008;

Fuller & Hutchinson, 2007; Fuller & Basher, 2012). However, little to no research has been conducted in the isolated gravel bed rivers flowing from the Aorangi Range, South Wairarapa. Therefore, the Tauanui and Turanganui Rivers were chosen to evaluate their morphological response to a discrete flood event over the winter of 2021. The first surveys were conducted in May 2021 while both rivers were in drought conditions in anticipation of a flood over the winter period. The flood on the 20th of June 2021 resulted from a southerly storm event that resulted in 143.6mm of rain falling in 24 hours in the upper catchment of both rivers and 40mm of rainfall falling in the lower catchment. The resulting flood had a maximum discharge of 40m^3/s in both rivers. It caused significant damage from geomorphic change in the Turanganui, yet relatively little change occurred in the neighbouring Tauanui River. Geomorphic flood response is often highly variable, with some floods resulting in catastrophic change (Milan, 2012), while some floods have comparatively little geomorphic response (Miller, 1995). Rivers with neighbouring catchments or within the same catchment have been observed to have vastly contrasting responses in some cases (Fuller, 2007; Fuller, 2008). It is established that contrasting responses to floods are due to flood magnitude, river characteristics and anthropogenic modification (Fuller, 2008). Due to these factors varying throughout a river system, a uniform river response is unlikely (Miller, 1995; Fuller, 2008).

Therefore, it is crucial to investigate whether the drivers of specific geomorphic responses in these two rivers are due to inherent characteristics of the river or human modification of the river and surrounding catchment. Using historical imagery and structure from motion (SFM) surveying, the morphological response to flooding in these two rivers is analysed and put into context in relation to decadal scale channel adjustments and river management practises implemented historically and today. Because flooding is New Zealand's most common natural disaster, with significant populations of the Greater Wellington region living in flood-prone areas (GWRC, 2021; Auliagisni, 2022), it is imperative that an understanding of New Zealand’s Hydrology and fluvial geomorphology are further refined, to manage these resources effectively and safely.

1.1 Research gap

- Historic geomorphic features of both rivers have not been assessed.
- Erosion patterns vary from site to site, and aside from cross-section surveys, no in-depth geomorphological study has been undertaken in these catchments.
- Channel response to Discrete flood events and at a decadal scale has not been determined in either river.
- The geomorphic impacts of river management have not been assessed in these two rivers.
- No research has been conducted in this area. Applying standard research methods to a new area.

1.2 Aim

This research aims to evaluate the morphological response of these small, rural gravel-bed rivers to discrete flood events and to put this response into the context of decadal-scale channel adjustments and river management practices.

1.3 Objectives

- To understand sediment dynamics within these rivers and how they respond to discrete flood events and river management.
- To estimate the quantity of change in sediment storage within reaches for the 20th of June 2021 flood event.
- To contextualise the river response to the flood event using longer (decadal) historical imagery and cross-sectional surveys.
- To critically appraise river management strategies.

These aims will be achieved using surface monitoring techniques to identify the locality and scale of geomorphic change in these rivers in response to the June 2021 flood event. This flood provides an opportunity to answer the questions outlined in the aims. The locality and scale of change detected will be used to evaluate the impact of the June 2021 flood event and use the impacts observed to inform effective future strategies to implement to mitigate the loss of infrastructure and risk to human life. Photogrammetry will be used to detect and quantify event-based geomorphic change. Historic imagery and cross-section surveys will put the river response captured in the June 2021 flood event into a decadal context. The history of these river's management strategies will be critically apprised, which will be used to inform suggestions for management in the future. This case study can be used to inform the management of similar short, steep gravel bed rivers in New Zealand.

1.4 Justification

- There has been little study done on small gravel-bed rivers below short, steep catchments in rural environments such as these. This study will give unprecedented insight into the geomorphological patterns and scale of change. Utilising known and well-established methods.
- The use of SFM enables us to assess the reaches of rivers for geomorphic change accurately (Westoby et al., 2012).
- These rivers are short and steep, and the slopes in the higher elevations are highly connected to rivers, making potential erosion events such as mass movements highly available to the river.

2.0 Study area

The Tauanui and Turanganui catchments are in Pirinoa, South Wairarapa, New Zealand (Figure 1). These rivers are dynamic systems known to be ephemeral over dry summers and capable of large floods in heavy rainfall events. This extreme variation in flow results in geomorphic change that brings into question the scale of geomorphic change in relation to the hydrology of these rivers and the effectiveness of management practices of these rivers.

2.1 Topography, physiography, and land-use

Both rivers are sourced from the Aorangi Range, which is classified as a 'whaleback' uplifted Greywacke range in the east, with forearc basin plains to the west consisting of Mesozoic rocks, Neogene sediments and Quaternary sediments in the lower catchment (Bertaud-Gandar et al., 2018). The main influences of erosion susceptibility within the Aorangi Range are considered to be geological disturbance due to tectonic activity, fire and introduced pests (Wardle, 1967).

The strong greywacke of which the ranges are formed has been shattered and deformed by tectonics such as thrust planes and faults. In conjunction with incising rivers, erosion, including landslides, is frequent (Wardle, 1967; Druce, 1971). Extensive anthropogenic fires have been recorded in the Aorangi Range (Wardle, 1967). Evidence showed large-scale fires in the range from pre-colonisation times through to European settlement when land clearing was done using fires, which escaped into the ranges (Wardle, 1967). The removal of vegetation by fire significantly reduces the resistance of the land to surface erosion processes such as landsliding (Girona-García et al., 2021).

By 1880, deer and goat populations in the Aorangi Range were high. The first recorded liberations of brushtail possums were in 1923, which led to a large population accumulating (Wardle, 1967). These introduced animals caused significant vegetation damage within the ranges due to animal browsing. Browsing causes younger trees to die, reducing plant succession and lowering forest cover, which can be a driver of erosion due to lower soil cohesion from reduced forest health and a lower population of vegetation (Wardle, 1967; Moseby et al., 2020).

The Tauanui and Turanganui Rivers are classic New Zealand gravel bed rivers with incised river valleys of gravel, boulders, and silt. The upper terraces of the Tauanui and Turanganui catchment were formed by wave action before tectonic uplift occurred (Woolfe, 1993). This maritime terrace is approximately 150m above the current sea level. The Tauanui and Turanganui Rivers, in forming their current course, have incised through the terrace, reducing it to a narrow strip which butts onto the steep greywacke slopes of the mountain block. On either side of the terrace, the land drops steeply to lower river terraces averaging 80m above sea level (Figure 4). These are alluvial deposits through which both rivers have further degraded to the present-day valley floor.

The Lower Wairarapa Valley, of which the Tauanui and Turanganui catchments are a part, is heavily modified by people. The lowlands have been extensively manipulated for agriculture intensification and flood protection. This systematic modification became known as the Lower Valley Development Scheme, where significant anthropogenic changes in the Ruamahanga River and surrounding tributaries were made (Trodahl et al., 2016). Lower Wairarapa Valley has been heavily modified to protect land and infrastructure from flooding, which has been a significant issue since the beginning of European settlement (Trodahl et al., 2016). The Lower Valley Development Scheme was introduced in 1968, which involved diverting the lower Ruamahanga River from its original course draining into the south-east shore of Lake Wairarapa to the northern end of Lake Ōnoke (Ferry) which is a 6.5 km² brackish Hapua-type lagoon (Kirk & Lauder, 2000 in Trodahl et al., 2016). In more

recent years, The Lower Ruamahanga catchment has been further modified through the building of barrage gates in 1974 to control Lake Wairarapa's outlet. Floodways, stop banks, and river realignments have been completed in many tributaries (including both Turanganui and Tauanui Rivers) to lower the lake levels to increase available land for agriculture and reduce lake level rise over winter which floods paddocks and residential land (Airey et al., 2000). Heslop (1996, p.2) noted on the nearby Ruamahanga River, "the emphasis on farming all available land to the river's edge, leaving no margin for natural erosion/accretion processes".

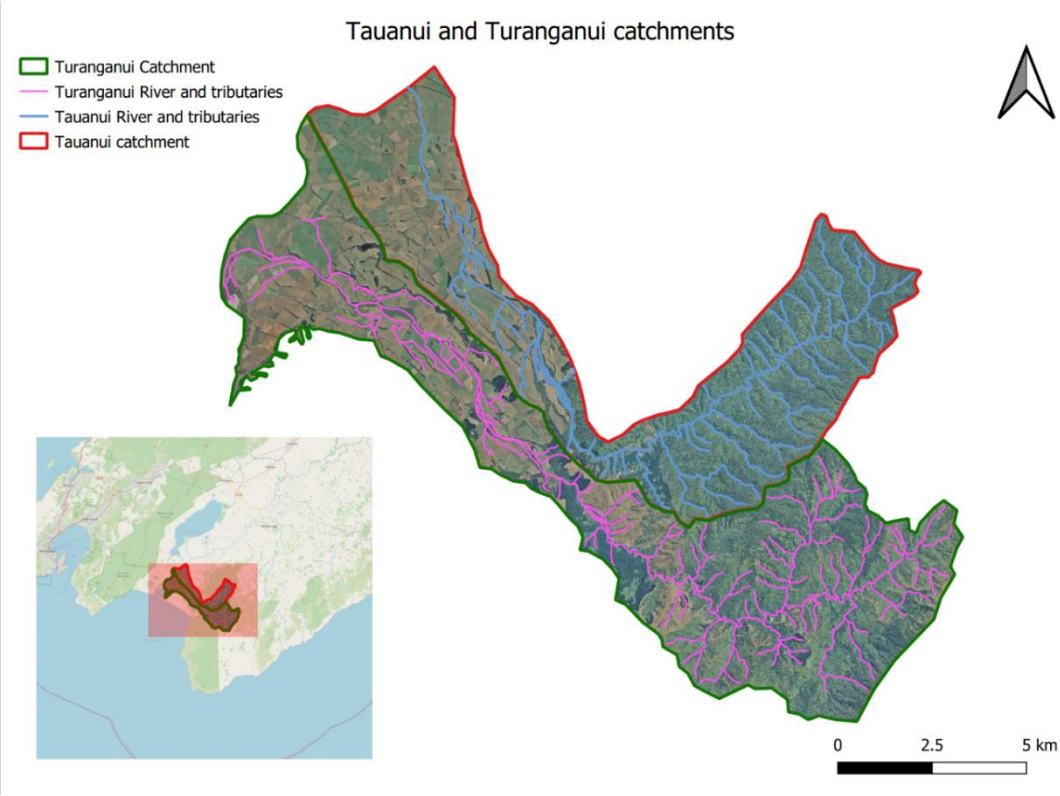


Figure 1: Study site area showing both catchments and their location in the lower North Island of New Zealand.

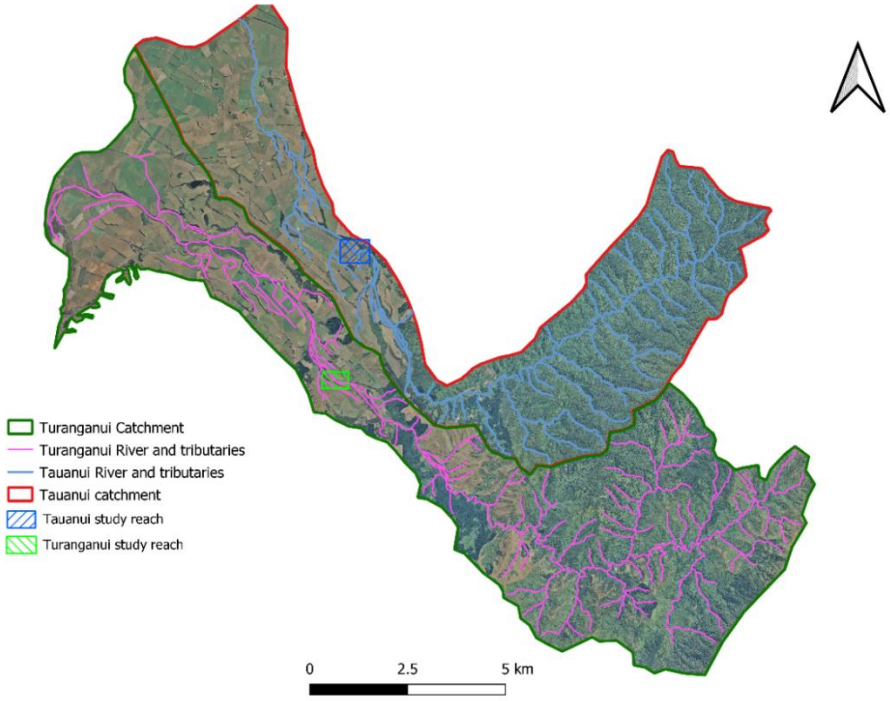


Figure 2: Study site showing both catchments and specific study reaches.

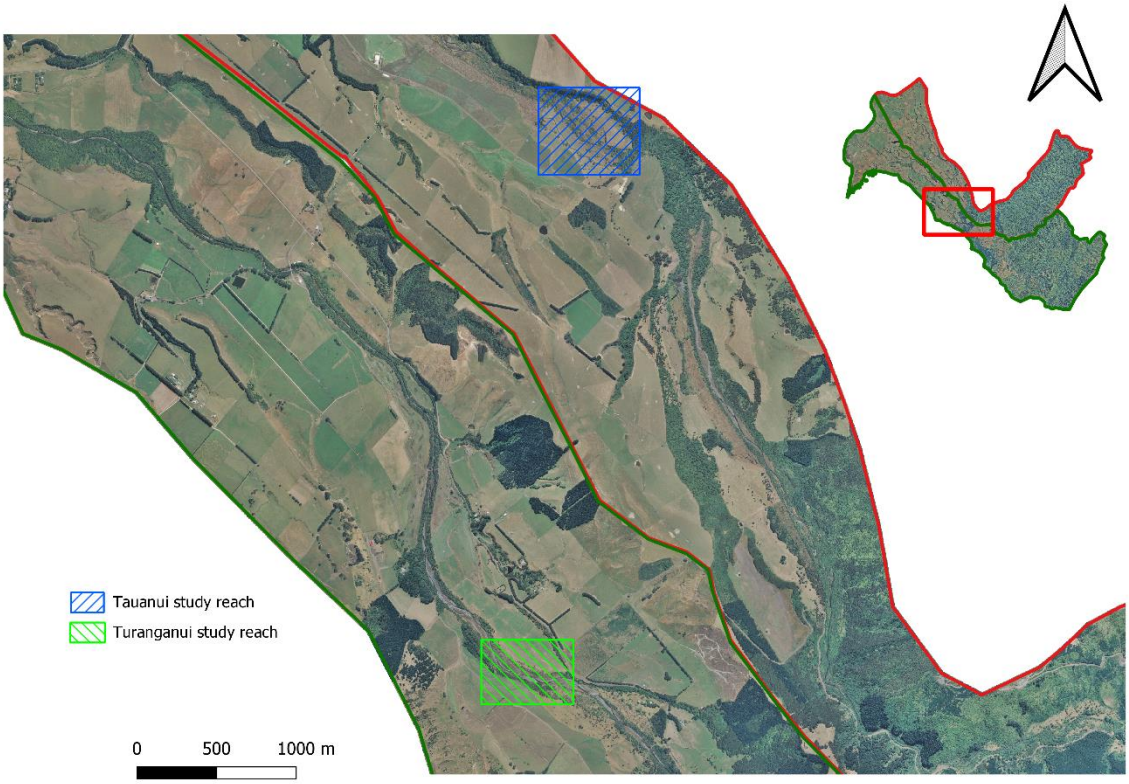


Figure 3: Closer view of both study reaches.

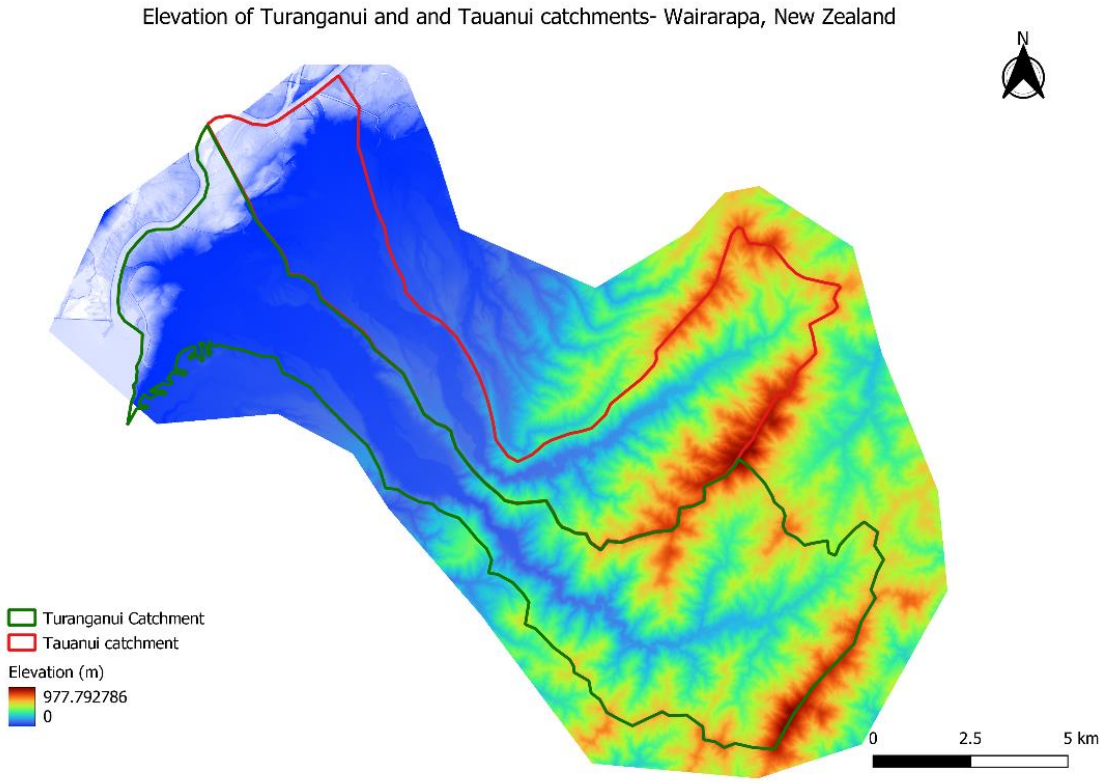


Figure 4: Elevation of the Turanganui and Tauanui catchments.

2.1.1 Catchment land use & flood mitigation

As illustrated in Figure 5, the headwaters of these catchments are primarily unmodified, with Indigenous forest and broadleaved indigenous hardwoods in the upper catchment, some exotic tree plantations, and primarily pastoral farming in the lower catchment.

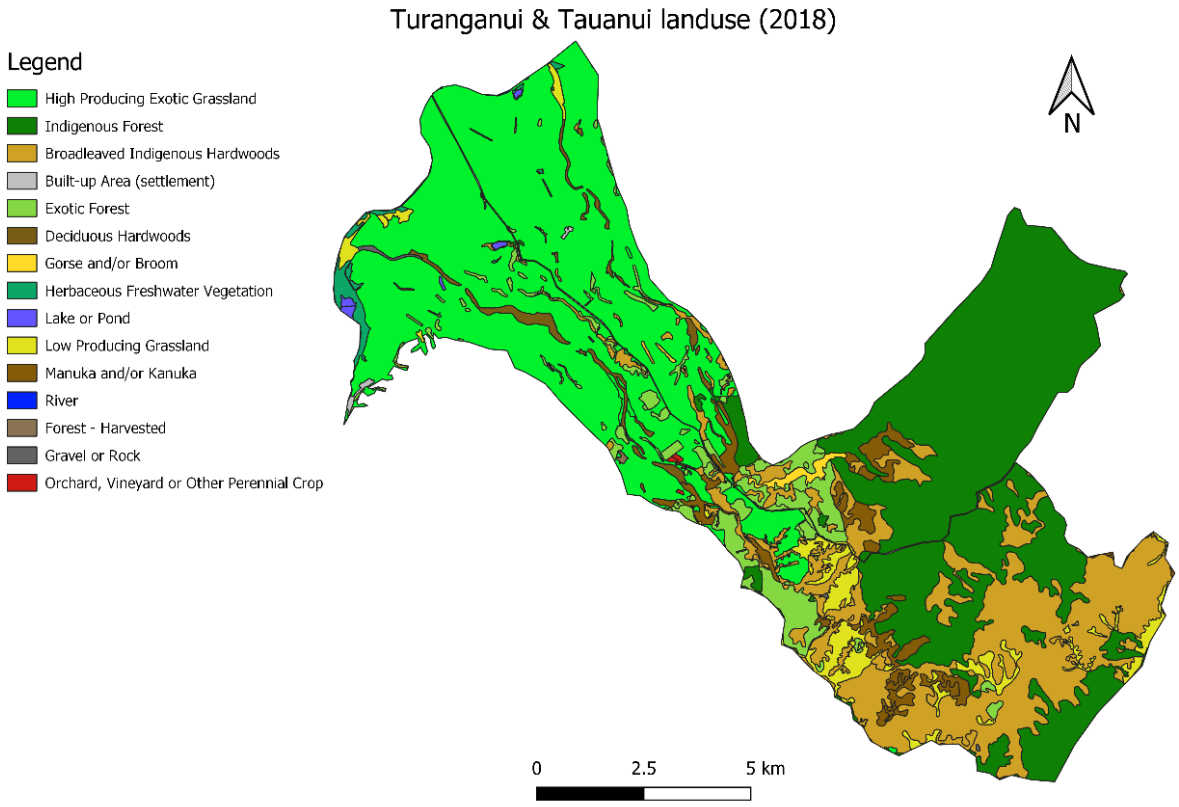


Figure 5: Land use within Turanganui and Tauanui catchments.

2.2 Tauanui River

The total size of the Tauanui River catchment is 5494 hectares. The upper catchment is located in the Department of Conservation (DOC) managed Aorangi Forest Park, an unmodified indigenous forest. Most land has been anthropogenically modified through the middle of the catchment as it is classified as exotic tree plantations with smaller portions cleared for low-production farmland. Smaller portions are reverting manuka/kanuka and indigenous forests. The lower catchment has been heavily modified to become high-production grassland and is utilised for dry stock grazing and dairy runoff. To protect farm infrastructure and to prevent erosion (Figure 6), the Tauanui had a stop bank built in the lower catchment when agriculture intensification began and is now managed by GWRC, who actively plant exotic species such as poplars and willows and utilise earthworks to channelise the river and maintain stop banks. The river channel is confined using stopbanks when the river exits the ranges and encompasses the study reach. The bottom of the catchment is where the Tauanui enters the Lower Ruamahanga River diversion through a heavily modified delta system.

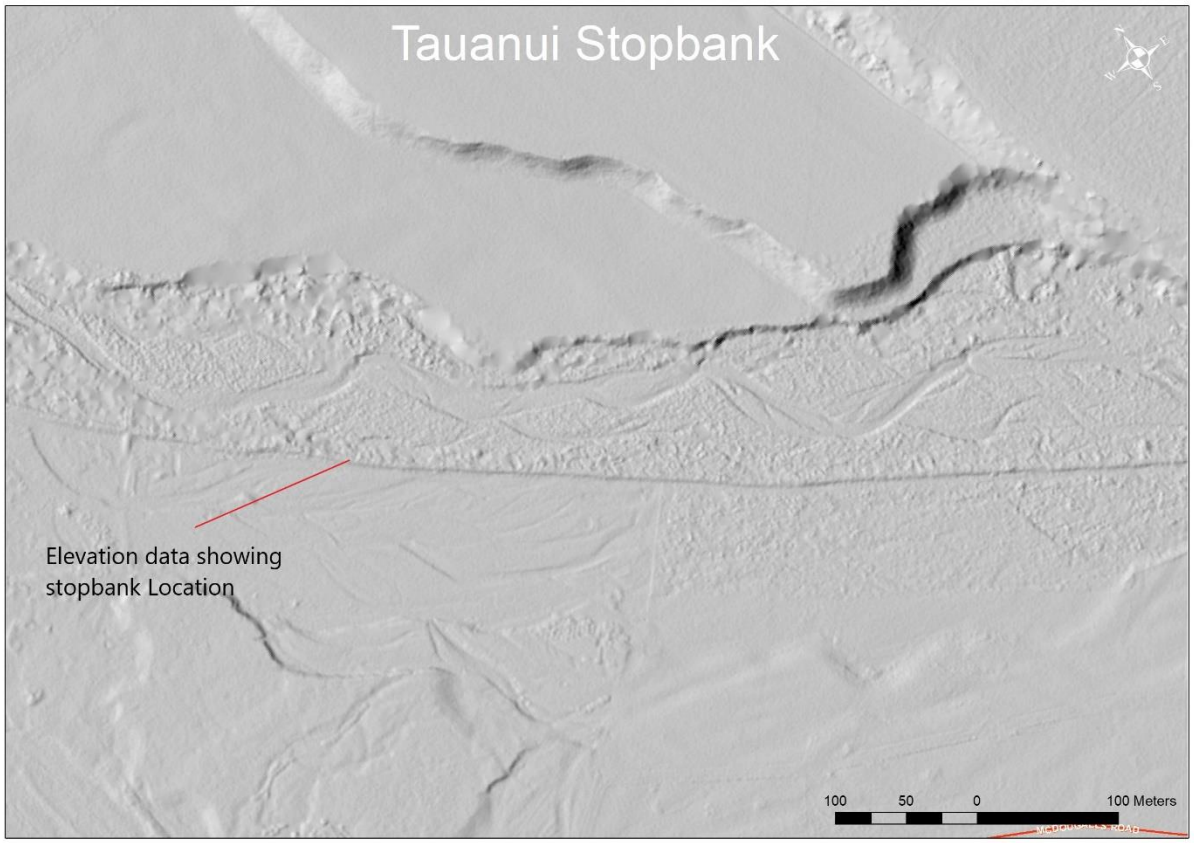


Figure 6: Stopbank position in the upper Tauanui River (LINZ, 2023).

2.3 Turanganui River

The total size of the Turanganui catchment is 7167 hectares. As seen in Figure 5, the upper Turanganui consists of mostly indigenous broadleaved hardwoods and other indigenous forest types, as it is also in DoC land. More significant portions of the farm in the mid-catchment area have been retired from grazing and are planted in pine forests, with the lower portions of the catchment taken up with high-production farmland for dry stock grazing. The lower portion of the Turanganui River has stop banks built to protect local houses and infrastructure from flooding. These assets are also maintained by GWRC. Planting exotic plant species, such as poplar and willow, is commonplace in the riparian areas of the Turanganui to maintain the river corridor. The Turanganui River enters Lake Ōnoke adjacent to the Ruamahanga River diversion, where stop banks confine alluvium depositions, forming a delta system.

2.4 Climate and hydrology

Rainfall in both catchments is considered temperate oceanic according to the Köppen-Geiger classification, experiencing warm summers with an average daily temperature of 22°C from December through to February and cool winters from June through to August with a daily average temperature of 11°C (Chappell, 2014). Due to variable topography throughout the Wellington region, airflows are manipulated, which causes a considerable variation in annual rainfall (Figure 7). Up to 2000mm of rainfall is received annually in the Aorangi Range, which is the headwaters of both rivers and approximately 1000mm in the South Wairarapa plains, where both rivers drain into the lower Ruamahanga River. A unique feature of the Pirinoa region is the raised terrace, which leaves the landscape exposed to the strong, drying northwest winds and the cold southerlies. Southerly storms can cause considerable damage on the very steep slopes within both catchments.

Figure 7: Wellington region median annual rainfall totals 1981-2010 (Chappell, 2014).

2.5 Hydrology

Both rivers have ephemeral characteristics during dry summers and respond quickly to heavy rainfall due to both catchments' steep, short nature (Carlin, 1980; Watts & Perrie, 2007). Little hydrological data was available in both rivers before 2017 when only sporadic monitoring occurred. Continuous monitoring has occurred since 2017 and shows the Tauanui River has a median flow of 0.349 m^3/s, whereas the Turanganui River is 0.441 m^3/s. Figure 8 shows both hydrographs' steep rise and fall in response to a flood event. This illustrates the steepness of the catchment and the quick response to rainfall due to proximity to the Ranges. Following frequency analysis of all available flow data of both rivers, the largest flood recorded in the Tauanui and Turanganui is 40m^3/s and 42m^3/s, respectively. Both of which were from the 20th of June 2021 flood event.

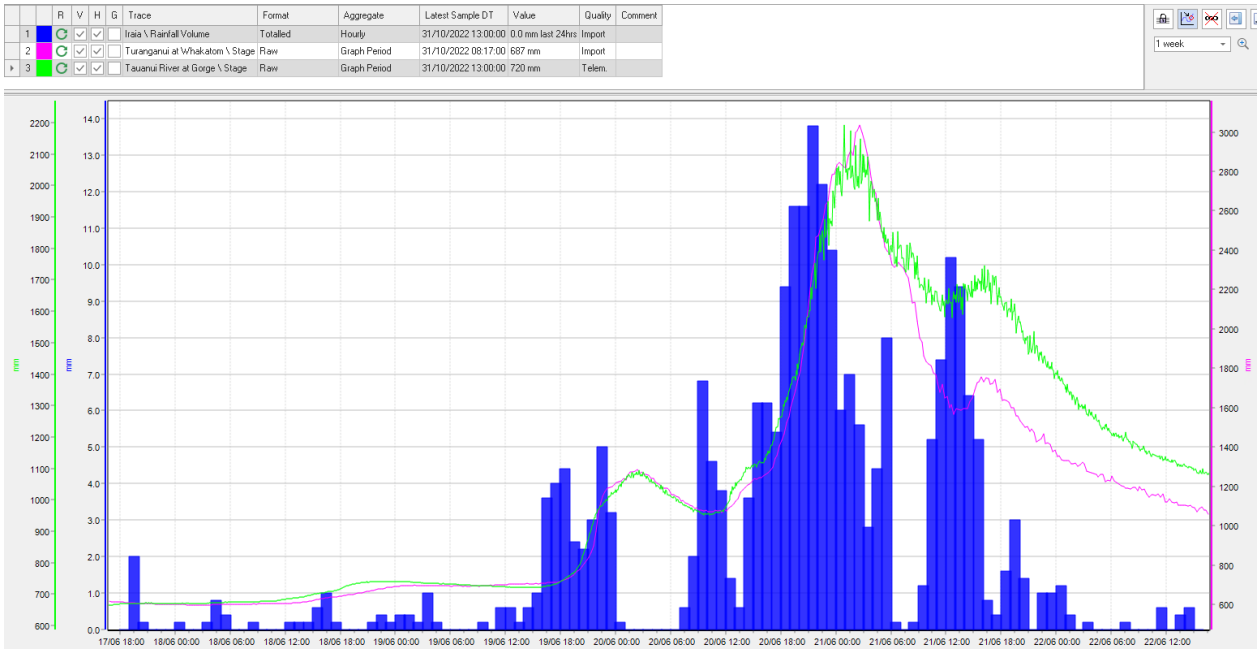


Figure 8: Hydrologic data for Tauanui and Turanganui Rivers overlaid over rainfall data from GWRC Ruakokopatuna monitoring sites.

2.6 Geologic setting

The North Island of New Zealand is situated on an active plate boundary, with the Hikurangi Subduction Zone (Figure 9) east of the North Island, where the Pacific Plate subducts beneath the Australian Plate (Ballance & Cotterall, 2017). The subduction zone transitions to a transform fault farther south, near Kaikoura. The rates of plate movement per year vary along the subduction zone. Still, as seen in Figures 9 and 10, the Pacific Plate subducts beneath the Australian Plate at a rate of approximately 40mm per year in the southeast of New Zealand (Ballance & Cotterall, 2017). The study area is in the southern East Coast Basin, an actively deforming forearc basin (Figure 10). A forearc basin is a sedimentary basin occurring due to the interaction between a subducting tectonic plate and an overriding tectonic plate, in this case, due to the tectonic activity occurring in the Hikurangi subduction zone (Hoda, 2016; Ballance & Cotterall, 2017).

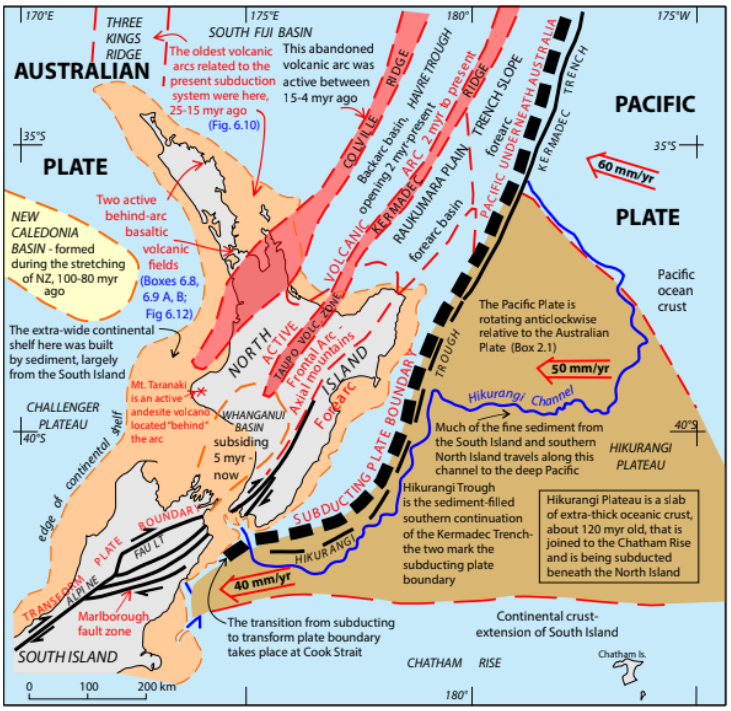


Figure 9: Tectonic setting of the North Island of New Zealand (Ballance & Cotterall, 2017).

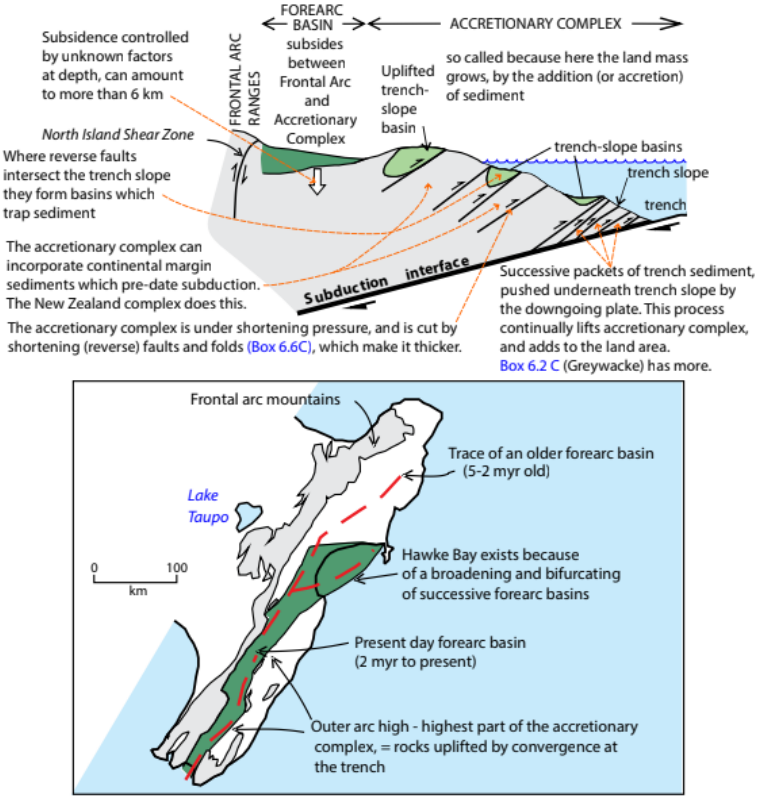


Figure 10: Tectonic setting of the eastern North Island, New Zealand (Ballance & Cotterall, 2017).

As seen in Figure 11, several active faults cross the study area. These faults run perpendicular to the rivers, the two main ones being the Dry River and Ruakokopatuna fault lines (Cape et al., 1990). Rectangular drainage patterns seen in the Tauanui River (see Figure 2) indicate the jointing and folding occurring in the headwaters (Breirley & Fryirs, 2005). Dendritic drainage patterns with slight trellis patterns indicate there is low geologic control, with slight dipping and folded sedimentary strata. This is backed up by the geologic and tectonic maps (Figures 11 and 12). Most tectonic faults in the vicinity of the Aorangi range are thrust faults due to the deformation of the Aorangi Block, one of five basement blocks forming the forearc basin on the east coast of the North Island (Tamsin et al., 2018). The major fault lines in the Aorangi range run in a northeast-southwest direction, and a period of tectonic activity in the Tertiary Period have produced sharp ridges (Wardle, 1967). Active tectonics in the area have the potential to produce earthquakes, which can provide significant amounts of sediment to the river systems. Historic earthquakes along faults weaken rocks throughout the catchment, making sediment vulnerable to erosive processes.

Figure 11: Faults and folds active now and/or were active in the late quaternary period (Cape et al., 1990).

2.6.1 Lithology

Figure 12 illustrates the geology of the study sites. The Tauanui and Turanganui catchments consist of undifferentiated Mesozoic rocks in the headwaters, changing to Neogene sediments in the middle of the catchment and Quaternary sediments in the lower end of the studied catchments (Bertaud-Gandar et al., 2018). This provides a varied bedload of sediment types in the Tauanui and Turanganui Rivers. Each study reach consists entirely of Holocene river deposits due to them being located on the floodplain.

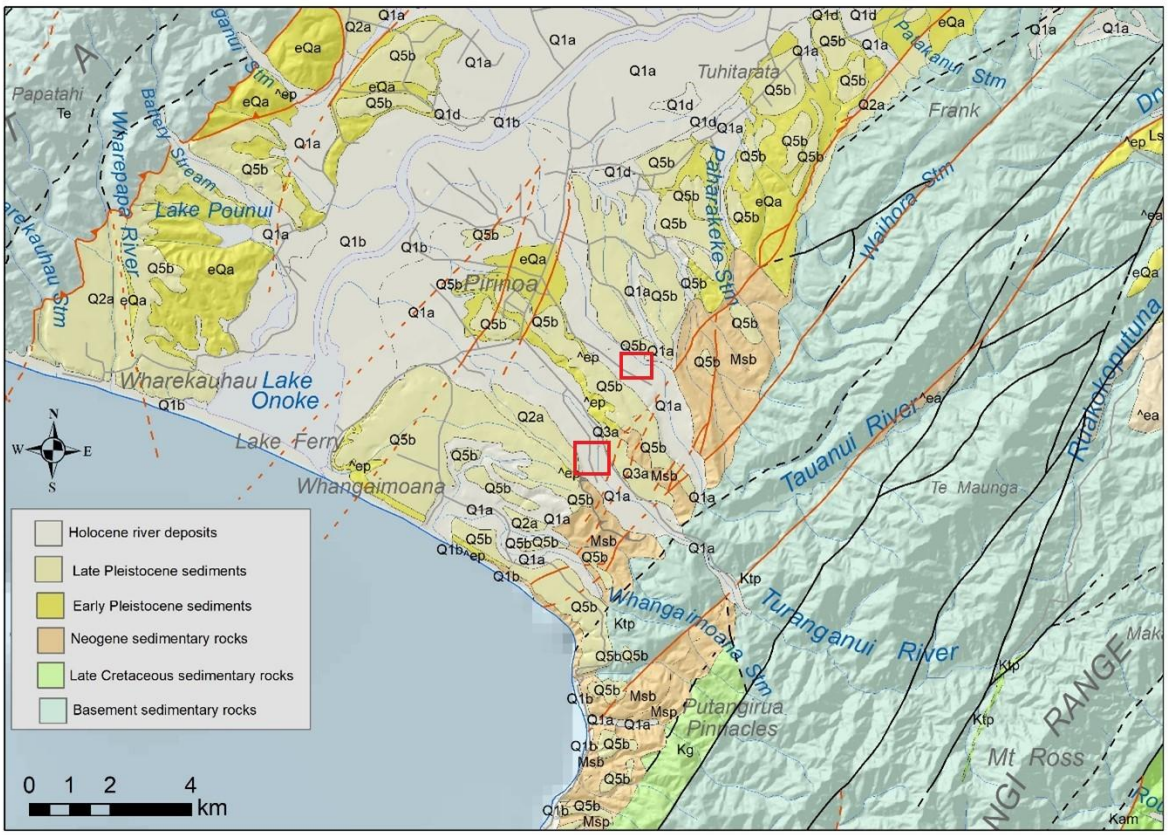


Figure 12: Geological map of the Turanganui and Tauanui Rivers with study reaches highlighted in red.

As seen in Figure 13, the Aorangi range consists of Mesozoic basement greywacke, which is hard and resistant to erosive processes when not fractured by tectonic processes (Muschamp, 2005). Neogene Rocks are classified as *soft* due to the low intact strength or low Uniaxial Compressive Strength (qu) (Muschamp, 2005). These weaker rocks are, therefore, more susceptible to erosive processes, making Neogene sediments more available sediments in these fluvial systems. The Quaternary sediments present in the Wairarapa valley floor of which both rivers flow consist of medium to fine loose Pleistocene sandstones and mudstones of marine origin (Woolfe, 1993). These rocks are classified as 'soft' as they have an unconfined uniaxial compressive strength of 20MPa or less (Muschamp, 2005). Due to their inherent weakness, these rocks are susceptible to erosive processes, especially where tectonic processes are present, such as in the study area.

Figure 13: Geologic setting of the study site (Bertaud-Gandar et al., 2018).

2.7 Matter and energy dimensional flux

Rivers are divided into three distinct zones to simplify the explanation of sediment dynamics within a fluvial system (Figure 14). These are production, transport and storage zones (Schumm, 2005; Corenblit et al., 2015). These zones represent the dominant form of sediment flux occurring within them. The production zone is the upper catchment by which water and sediment provided to the river are derived. The transport zone is a high-energy zone, often in the centre of a catchment, where the channel is often more stable due to an equilibrium of erosion and deposition. The storage (or deposition) zone is where the river profile starts to level off, and net aggradations tend to occur and develop landforms such as deltas or alluvial fans. An understanding of where a specific reach is located is important as it will give an indication of the dominant sediment process occurring. As seen in Figure 2, both study reaches are in the centre of their catchments and possess wandering and multi-threaded planforms. These characteristics indicate sediment transfer zones (Coleman & Scott, 2011). This means both study reaches are likely to be experiencing high sediment flux, comprising both erosion and deposition.

Figure 14: The Four-dimensional framework illustrating matter and energy fluxes in river systems (Corenblit et al., 2015).

3.0 Literature review

This section aims to outline a background in fluvial geomorphology processes and how they can dramatically alter landscapes and to reinforce the importance of understanding these processes and their drivers. Structure from motion photography will also be discussed, along with its role in quantifying geomorphological changes in fluvial systems.

Fluvial geomorphology is the study of rivers and their interaction with channel forms and processes (Charlton, 2007). A river channel's form depends on environmental factors such as geology, hydrology, temporal and spatial scale. The study reaches must be examined carefully to understand the rate, scale, and patterns of geomorphological change as they respond to significant hydrological events such as flooding. An effective way of quantifying fluvial geomorphic change is structure from motion (SFM) photogrammetry, which functions using the same fundamentals as stereoscopic photography, which has been used for decades to detect geomorphic change (Betts & DeRose, 1999; Chandler et al., 2002). Using a series of overlapping, offset images, a 3D structure can be built when processed using photogrammetry software (Westoby et al., 2012). However, the 3D structure must be set into a specific geographic datum to analyse geomorphic change accurately. This is done using targets photographed in the imagery of the studied landscape that have been surveyed using highly accurate RTK GPS (real-time kinematic global positioning systems) survey equipment.

Unmanned aerial vehicles (UAVs) are often used because they are cheap to use, can have pre-programmed flight paths, and provide high-quality imagery.

Factors influencing fluvial geomorphology will be discussed using well-documented New Zealand examples, focusing on sediment degradation and deposition dynamics of New Zealand's River systems.

3.1 Fluvial geomorphology and river management

Fluvial geomorphological processes are a core element of this study and have major implications for river management. Fluvial geomorphology is integral in understanding landform dynamics within a river corridor in response to flood events and assessing and informing the effectiveness of management practices implemented within a river’s catchment. Fluvial geomorphology’s role in river management is prominent in academic communities. It is acknowledged as an important applied science in advising river management practices but is not consistently applied in river management regimes (Garcia et al., 2021).

3.2 Geomorphic analysis

Geomorphic analysis is a well-established technique geomorphologists use to identify and understand the relationship between flow processes and fluvial landforms in rivers and their surrounding landscapes. Geomorphic analysis involves systematically classifying study reaches by their geomorphic characteristics based on the study's focus (Fryirs & Brierley, 2013).

Initially introduced by Sear et al. (1995), who suggested solutions to sediment-related management problems in rivers can be identified through observing fluvial geomorphology. Sear et al. (1995) developed a geomorphological survey methodology incorporating historic catchment land use and channel networks with modern maps to judge sediment supply, transport and storage within a river, from reach to catchment scale. This geomorphological insight is used to judge engineering solutions to management problems within the river, with recurring feedback on destabilising and stabilising phenomena occurring in response to implemented solutions (Figure 15).

Figure 15: Conceptual illustration of the fluvial audit process (Sear et al., 1995).

This survey methodology was utilised in the River Sence, Leicester, to give geomorphological insight into a series of river management issues observed by local authorities and explore the utility of the newly developed Geomorphic audit process. Historical maps on planform stability, land use and river management data were collated with field observations of bank erosion throughout the study reach to suggest stock exclusion and revegetation as management practices to address bank erosion issues. This methodology was then adapted for use by the environment agency of the UK as an auditing tool for advising river managers on the geomorphic history of a catchment and providing insight into sediment-related issues within the river system (Dangerfield et al., 2005). The use of spatial analysis tools such as GIS is introduced to view, analyse and process historical data such as aerial imagery and data gathered in the field (Dangerfield et al., 2005; Soar et al., 2017).

3.3 Geomorphic impacts

Geomorphic impacts are commonly witnessed as small-scale erosion and deposition of riverbanks and channels and, in larger events, as channel avulsion and large-scale channel widening and incision (Milan, 2012). Flood events are established as being controls in channel geomorphology and play a significant role in shaping valley floor morphology due to the mechanisms of erosion and deposition of sediment (Milan, 2012; Harvey, 2007). Geomorphic impacts as a response to flooding have been widely researched by Fuller (2007) and Milan (2012) and illustrate why river management needs to occur. There has been much debate over the significance of flooding in the geomorphology of river channels. Wolman and Miller (1960) suggest that the bulk of sediment transport occurs during high-magnitude events that occur infrequently. This is due to the extreme flood velocities associated with high-magnitude, low-frequency events (Wolman & Miller, 1960). Although these events transport large amounts of sediment, Milan (2012) argues that they occur too infrequently compared to the carrying capacity of lower magnitude, higher frequency events over larger temporal scales.

Wolman and Miller (1960) argued that lower magnitude, higher frequency flood events govern river channel geomorphology. This is reinforced by Leopold and Maddock's (1953, in Fuller, 2007)) argument that bankfull discharge, described as the point at which a river's flow reaches the

transition between the channel and its floodplain, is the most significant geomorphic event in-channel (Mulvihill et al., 2010). is the most significant geomorphic event in-channel. Baker (1977) suggests that most geomorphic work occurs at the modal frequency of floods, and the sediment transport rate depends on the applied stress from discharge. This theory of this is illustrated in Figure 16. Heritage and Milan (2004) further modify the product of frequency and transportation rate to account for variations in sediment size transport and bedrock channels.

Brunsden and Thornes (1979) acknowledge that more frequent events result in stable, constant fluvial geomorphology in the landscape, but extreme events occurring from 10^2 to 10^5 frequency can modify the trends in landscape evolution. In addition, the role of extreme events has been increasingly discussed in relation to significant geomorphic work, especially when the event's magnitude exceeds equilibrium thresholds (Baker, 1977). equilibrium thresholds are therefore discussed as governing the geomorphic response to extreme flood events.

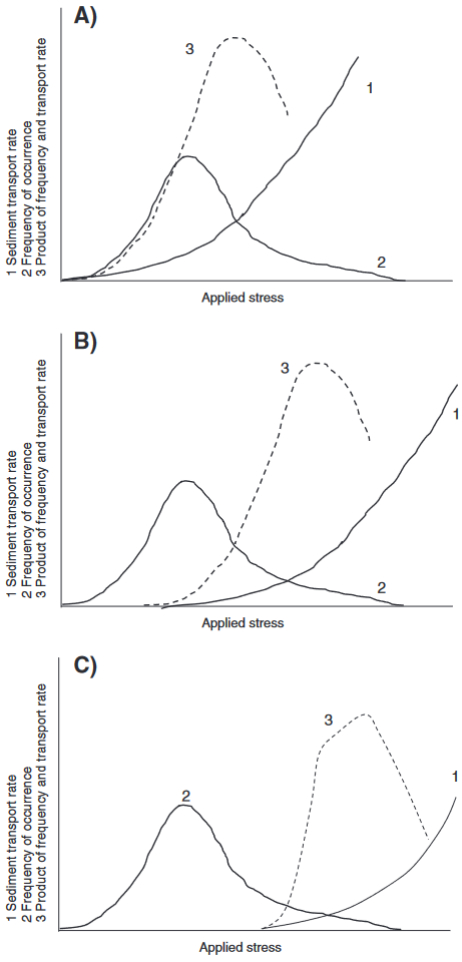


Figure 16: Wolman and Miller's (1960) relationship between the rate of sediment transport, applied stress and frequency of disturbing events; B Heritage and Milan's (2004) adaptation to account for variations in sediment size; C) Baker's (1977) Modified model for bedrock channels.

Milan (2012) illustrated the significant geomorphic impact of a significant flood event when limiting intrinsic thresholds are exceeded in the River Thinhope Burn, Northern England, where 236mm of rain fell in 24 hours, resulting in 5202 m^3 of deposition and 2125m^3 of erosion. What constituted this event as 'large' was the amount of sediment moved and the amount of geomorphic change within the river system. This helps to illustrate the importance of catchment characteristics as outlined by Miller (1995), who discusses that geomorphic impact from a large flood often depends on the

channel's shape and the catchment's size. Miller (1995) explains that large floods are likely to have a significant impact in narrow, steep valleys compared to wide, broad valleys due to the concentration of shear stress on areas where flow is concentrated, such as narrow gorges or sharp bends. Brunsden and Thornes (1979) also outline the importance of river sensitivity in geomorphic impact.

The Thinhope Burn flood was characterised as an extreme event that significantly impacted the study reach morphology. The overall catchment size is comparable to the Tauanui or Turanganui Rivers. However, the Thinhope Burn is much smaller and steeper with a deforested catchment and consists of bed material with much greater variation. Overall, the fundamentals of geomorphic response covered in this study are similar to those investigated in the Tauanui and Turanganui Rivers. However, due to the catchment and geomorphic characteristics, the Thinhope Burn constitutes a more sensitive system, more susceptible to significant channel response.

Thresholds are an essential component in determining the scale of geomorphic change. Thresholds are described by Schumm (1979) as conditioning factors that determine the scale of geomorphic change. These factors can be inherent in the system (intrinsic) and external variables (extrinsic). When an external variable outside the system progressively changes, resulting in significant changes being triggered within the system are known as extrinsic thresholds. An example is flood flows increasing in velocity and becoming turbulent, resulting in erosion and riverbed planform changes (Schumm, 1979; Milan, 2022).

Intrinsic thresholds result in geomorphic change from variables within the system, such as the mobilisation of sediment grains, or the thresholds that determine changes in fluvial landforms such as bars or banks (Milan, 2022). Fuller (2007) identified that the artificial narrowing of parts of the Kiwitea River resulted in modifying intrinsic erosional thresholds, which caused significant variation in geomorphic response at a reach scale. Milan (2012) demonstrated the result of extrinsic threshold exceedance and its importance in determining geomorphic response. How thresholds are modified, and the results of thresholds exceedance are fundamental components in understanding the geomorphic response to flood events in the Tauanui and Turanganui Rivers, as both rivers have been modified, which, according to Fuller (2007) will have modified intrinsic thresholds, and because the external force of hydrology is variable, and understanding of extrinsic thresholds will be important.

3.4 River resilience

River resilience is a term that has many different definitions with regard to river geomorphology. This is partially due to several interpretations, spreading over many scientific and engineering disciplines (Fuller et al., 2019). Resilience as a geomorphological theory is not well documented in the literature and has recently developed to encompass other geomorphological processes, such as resistance and recovery. This is due to the nature of geomorphological studies becoming increasingly ‘systems’ focused (Thoms et al., 2018). Many vital geomorphological concepts rely on resilience, such as equilibrium and the role of thresholds (Fuller et al., 2019).

River resilience is defined by the inherent ability of a river system to resist change and by the ability of a river system to recover from disturbance (Fuller et al., 2019). Resilience comprises two main components: resistance and recovery (Fuller et al., 2019). River resistance has been described by Meyer (2016) as “whether, or to what extent, system disruption will occur in response to disturbance”. Regarding fluvial systems, this means that resistance is the inherent ability of a river to resist geomorphic change when acted upon by a disturbing event such as a flood. An example of this is illustrated in Figure 17, which describes bedrock channels having naturally high resistance and

braided channels having naturally low resistance to geomorphic change during flood events. Resistance can also be impacted by human modification of river systems, either increasing or decreasing resistance to geomorphic change (Gregory et al., 2008). For example, river engineering, such as channel straightening and bank armouring, increases a river's resistance to change, whereas vegetation clearance and removal of the riverbed armour layer reduces a river's resistance to change (Gregory et al., 2008; Warman & Friedrich, 2013; Fuller et al., 2019).

Fuller (2007) highlights the importance of resistance in understanding flood response and tailoring effective management strategies following monitoring geomorphic change from a 150-year flood in the Kiwitea, Manawatu. Fuller (2007) argues that large flood events result in widely varied geomorphic responses due to varying thresholds, sensitivity, and local channel geometry and configuration differences. This is due to observations of variations in geomorphic change between reaches and catchments. Resistance is an important aspect of study in the Tauanui and Turanganui Rivers as it helps to identify the drivers behind the geomorphic response to flood events between the two rivers studied.

Figure 17: Fuller et al. (2019) theory of river resilience combining resistance and recovery, with examples from natural and anthropogenic example (Fuller et al., 2019).

River recovery is the inherent ability of a river system to return to its pre-disturbance state following a perturbing event such as a flood (Thoms et al., 2018). In natural river systems, some types of rivers, such as braided rivers, are more likely to recover to their pre-disturbance condition (fuller et al., 2019). Meandering rivers, however, have a lower potential for recovering to their original state when disturbed through natural straightening (avulsion) of meanders (Fuller et al., 2019). These scenarios are shown in Figure 17. Fryirs and Brierley (2000) explored the relationship between river recovery and human modification of rivers, where it is discussed that human modification of rivers can significantly reduce the potential for the river to return to its modified state. In some cases, when boundary conditions are breached, a river cannot return to its original state. This is the

“turning point” (Fryirs & Brierley, 2000, p. 248). This process is outlined in Figure 18. this approach can be utilised to assess the recovery potential of the modified Turanganui and Tauanui Rivers. Fryirs and Brierley (2001) highlight the role of human interactions in the process of river recovery in the Bega Catchment, Australia, where significant changes in sediment supply since European settlement have reduced river recovery capacity. This applies to both Tauaui and Turanganui rivers as they have highly modified catchments that have permanently affected sediment supply.

Conversely, human interaction can contribute towards the recovery of fluvial systems. Órbigo and Ibisate (2012) show how applied geomorphology in river management in the Órbigo River in the northwest of Spain can contribute towards river recovery. By implementing strategies informed by applied fluvial geomorphology, such as reforesting the headwaters and removing confining structures such as stopbanks, the Órbigo River changed from a wandering, mainly single-channelled river back to a more natural braided form that has a more natural sediment flux and has more capacity for floodwaters.

River recovery can vary between reaches and catchments depending on intrinsic properties within the system, such as geomorphic thresholds and sediment supply (Harvey, 2007). Harvey (2007) demonstrated by highlighting the differential recovery of two different streams within the Howgill Fells, northwest England, following an identical 100-year event. Harvey (2007) records that the Bowderdale Beck largely recovered, whereas its neighbouring stream has only partially recovered due to the sediment influx from stronger hillslope-channel coupling (Figure 19). This illustrated the inherent variability in river recovery, and it can contribute towards understanding rehabilitation pathways for potential changes in management regimes.

Figure 18: Conceptual framework for assessing river condition and potential for recovery (Fryirs & Brierley, 2000).

Figure 19: Geomorphic maps of the Bowderdale and Langdale following a flood in 1982 and state of recovery in 2002 (Harvey, 2007).

River resilience is defined by Fuller et al. (2019) as the ability of a river system to resist and recover from disruption or perturbation. It thus comprises both river resistance and recovery as a bivariate

theory. As illustrated in Figure 17, the resilience of a river system relies on the system having either high resistance and/or high recovery characteristics.

Resilience is an important concept in this study as it helps to explain the natural and anthropogenic influences contributing to contrasting geomorphic responses to a singular flood event between different river reaches (Brunsden & Thornes, 1979). This is pertinent when comparing flood response between the Turanganui and Tauanui Rivers, as resilience helps to evaluate the effectiveness of river management for the two rivers. This is achieved by understanding what combination of resistance and recovery characteristics each river has and whether these characteristics stem from human actions or are inherent in the systems. Management can be assessed and tailored to reduce anthropogenic interference detrimental to river resilience and the bivariate characteristics it derives from. Natural traits that contribute towards higher river resilience can also be identified and utilised in management to reduce the adverse effects of flood events.

An example that illustrates resilience being utilised to understand river response and inform future management is highlighted by Fuller (2008), where it was identified that due to human modification of river corridors (confining and straightening), catastrophic channel widening occurred following a flood event, which subsequently partially recovered by reducing, but not to its previous extent. This resulted in a wider river corridor that is more resilient due to resistance being improved by increasing flood capacity and improving the likelihood of recovery due to a more braided channel system (Figure 20). This applies to the Turanganui and Tauanui Rivers, as they have also been significantly narrowed through management.

Figure 20: Channel changes on the Kiwitea 11 km north of Feilding, with cross-section profiles (Fuller, 2008).

Fuller and Hutchinson (2007) showed the role of remediation works on sediment flux following willow planting and groyne construction. The effectiveness of willow planting and groyne construction in reducing bank erosion was illustrated but suggested this resulted in accelerated channel scour. This highlights that river management practices play a role in fluvial geomorphic

processes, both in reducing erosion and increasing it in some circumstances and need to be better understood. This will help to inform effective river management going forward.

3.5 Morphological budgeting

Morphological budgeting is a useful tool for detecting geomorphic change in fluvial environments. Morphological budgeting has often been used to quantify the impacts of floods on river channels and surrounding floodplains. Wheaton (2008) defines morphological budgeting as quantifying sediment fluxes and storage in a designated area over a specified period. Morphological budgeting has been established as an accurate means of establishing geomorphological trends and quantifying changes in sediment storage over time. Using sequential georeferenced aerial photographs, Fuller (2008) quantified the morphological impacts of a 100-year flood in the Kiwitea stream and discovered the spatially variable nature of geomorphic change from the event (figure 20).

Ashmore and Church (1998) observed changes in channel morphology and displayed the connection between hydraulic processes and river geomorphology. Ashmore and Church (1998) observe sediment storage changes throughout river channels over several spatial and temporal scales and are used to inform river engineering practices. Sediment budgets were calculated in three Canadian rivers utilising cross-section surveys, bedload transport monitoring stations and observational morphologic methods to understand sediment movement patterns and volumes. Ashmore and Church (1998) found cross-section surveys effective at establishing large-scale trends in sediment flux but lacked the resolution to identify smaller-scale changes between survey sections. Morphological observations were useful in identifying areas of change but lacked quantitative calculations as too many variables were involved in erosional and depositional processes. This shows that the use of SFM is an important monitoring technique to utilise in the Tauanui and Turanganui Rivers, as the existing cross-section surveys may not capture smaller reach-scale sediment storage changes.

Geomorphologists and others, such as government agencies, have utilised cross-sectional surveys to monitor sediment flux in river channels. Cross-section surveys have been used since the 1920s in New Zealand (Griffiths, 1979) and have helped to identify sediment movement patterns in rivers and the source location of sediment influx into a river. This practice is still used today by organisations such as regional councils to track sediment changes in rivers and help inform flow model development (Griffiths, 1979; GWRC, 2021). The Tauanui and Turanganui Rivers have a cross-section survey program to monitor sediment changes (seen in Chapter 3.4). However, as Ashmore and Church (1998) identified, cross-section surveys lack the resolution to track sediment changes between surveys and are prone to user errors. Fuller et al. (2003) outlined these errors, where it was found that cross-sectional survey-derived morphological budgeting consistently underestimates sediment flux compared to DEM-based approaches (Figure 21). This is due to the fixed nature of cross-section surveys, where they do not identify areas where scour/deposition has been newly initiated and cannot measure areas between cross-sections as DEM-based methods can.

Figure 21: Comparison of subreach sediment transfers calculated using cross-section survey and DEM differencing (Fuller et al., 2003).

Technological advances have allowed for large-scale monitoring of sediment flux and provide much finer detail than previously available methods. GPS survey methods allowed many elevation points to be gathered in short amounts of time, and the development of digital elevation models (DEMs) allowed 3D visualisation of river morphology. Calculations of sediment change over time were made more accurate using DEMs of difference (DoDs). These allow high-resolution quantification of geomorphic changes at higher accuracy than cross-section surveys (Brasington et al., 2000; Fuller & Basher, 2012). This is highlighted by Brasington et al. (2000), where upwards of 2000 survey points were gathered per day in a 13Ha reach of the River Feshie in Scotland. A point density of 1.1 per square meter was achieved, which resulted in the development of two digital elevation models (DEM) and a digital elevation model of difference (DOD) with an accuracy of 0.1m (Figure 23).

This method enabled accurate analysis of three-dimensional channel dynamics within the survey reach. Creating a DEM using GPS surveys is time and labour-intensive and would be impractical for large-scale surveys or when surveys need to be made in quick succession. As shown in Figure 23, survey point density varies due to surveying being focused on areas of topographic variability or gynomorphically dynamic areas such as bars, riffles, and pools. Areas with sparse survey points are topographically uniform or perceived to be more stable landforms. This could reduce the accuracy of the DoD if significant geomorphic change were to occur in areas of sparse survey points such as avulsion. The manual nature of surveying data points also enables the potential for user error.

Figure 22: Survey points and DEM derived from it (Brasington et al., 2000).

Fuller and Hutchinson (2007) utilised GPS surveys to develop DEMs to show the role of remediation works on sediment flux in the Kiwitea River. The average survey point density of 0.1 points per square meter showed the effectiveness of willow planting and groyne construction in reducing bank erosion but suggested this resulted in accelerated channel scour. Fuller and Hutchinson (2007) were able to identify reach-scale trends in sediment movement but could not accurately quantify sediment movement or monitor sediment below the resolution surveyed. Fuller and Basher (2012) utilised DEMs built using GPS surveys to link morphological patterns to river management. Channel straightening, bank protection and gravel extraction were linked to bed degradation and a net loss in sediment in the Motueka River in Nelson, New Zealand. Fuller and Basher (2012) identified scour-fill compensation between surveys as a potential cause for underestimating sediment flux.

DEMs are useful for determining a detailed quantification of geomorphic change in Fluvial systems that other methods, such as cross-sections, cannot provide. The use of DEMs to estimate sediment flux and understand sediment movement patterns has highlighted the influence river management practices play in fluvial geomorphic processes (Fuller & Hutchinson, 2007; Fuller & Basher,2012). However, using DEMs can often underestimate sediment flux due to surveys not capturing sediment movement between surveys. DEMs often do not have the resolution to quantify clast-scale morphological patterns in rivers. Using DoDs in the Tauanui and Turanganui study reaches will help achieve the objectives outlined in this study.

Charlton et al. (2003) outline aerial Laser-Induced Direction and Ranging (LIDAR) for mapping river environments. LIDAR was utilised to produce DEMs with an accuracy of +-0.15m (Brinkman & O'Neill, 2000 in Charlton et al., 2003) and could cover up to 90km² per hour (Marks & Bates, 2000 in Charlton et al., 2003). This tool allows geomorphologists to gather substantial amounts of topographic data on river channel systems in less time than on-the-ground GPS surveying. Vegetation artefacts and missing data seen in Figure 24 illustrate some limitations of this method, such as the bias introduced by vegetation and submerged channels. The DEM accuracy produced by Charlton et al. (2003) is 15cm, which is too high to monitor small-scale events, especially on smaller rivers and streams such as the Tauanui and Turanganui.

Figure 23: Elevation surface produced using LIDAR of the River Coquet, Northumberland, UK (Charlton et al., 2003).

Lallias-Tacon et al. (2014) utilised sequential LIDAR scans to complete a sediment budget of the Bes River in France. Vegetation is accounted for by creating a layer associated with vegetation cover and accounting for vegetation height using a digital canopy model with three different classes (Figure 24). Water surfaces were also accounted for by utilising specific laser wavelengths that do not dissipate when they hit water surfaces. Although water needs to be transparent and less than 50cm deep to be accurate (Lallias-Tacon et al., 2014). Point density is much higher than previous works by Charlton et al. (2003) at 7-9 points per m2. The level of detection was measured to be between 19-30cm at a 95% confidence level, which is suitable for large rivers when estimating geomorphic change. However, this level of detection is too high to estimate smaller-scale changes in rivers such as the Turanganui and Tauanui Rivers. Airborne LIDAR is currently an expensive tool to utilise, which limits the ability for multiple surveys to be completed, which can result in an underestimate of morphological changes occurring between surveys.

Figure 24: Accounting for vegetation in LIDAR-derived DEMs by grouping and reducing DEM height using a digital canopy model (Lallias-Tacon et al., 2014).

More recent developments in LIDAR surveying involve UAV-based LIDAR surveying, as Backes et al. (2020) demonstrated. With a combined error of 6cm, this method produces high-quality DEMs capable of detecting geomorphic change on a significantly smaller scale than previously (Figure 25). Cost is reduced due to the LIDAR sensor being mounted on a UAV (Figure 26), enabling more surveys to be completed, reducing scour-fill compensation between surveys. Backes et al. (2020) outlined a drawback: the LIDAR point cloud had voids in snow-covered areas and standing water surfaces. A commercial drone with LIDAR sensors equipped, such as the one used by Backes et al. (2020) (Figure 26), costs significant amounts of money, which can be a limiting factor for utilisation.

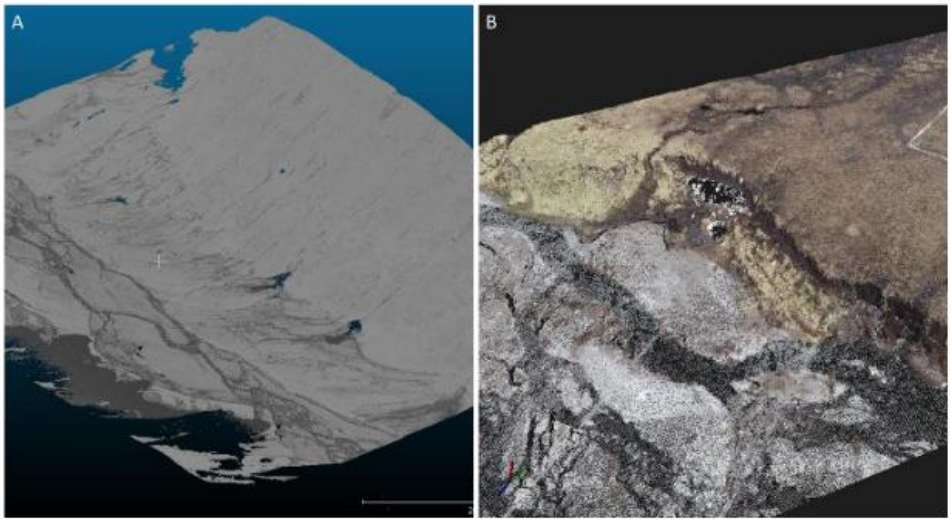


Figure 25: Digital surface model Produced using LIDAR equipped drone (Backes et al., 2020).

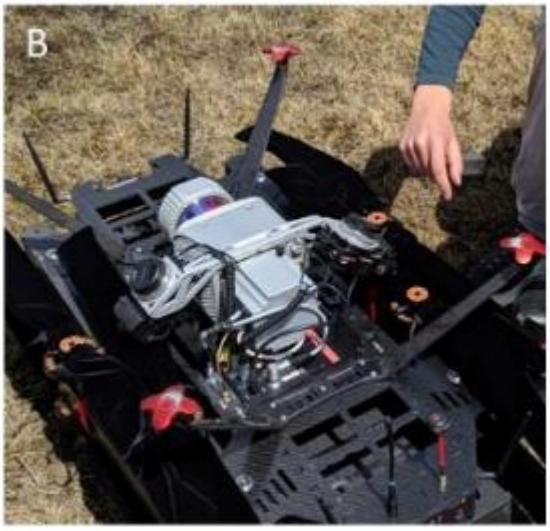


Figure 26: Drone equipped with LIDAR sensor (Backes et al., 2020).

3.6 Structure from motion

The utilisation of unmanned aerial vehicles (UAV) as a tool for morphological budgeting using Structure from Motion (SFM) has become a common tool for gathering topographical data on river systems. It has been described by Vericat et al. (2008) as a "low-cost, time-efficient alternative method to commissioned flights". SFM is the method of utilising concurrent 2D imagery at both nadir and oblique angles to produce a 3D image using computer software (Strohmaier, 2020). Combining imagery taken from low-cost consumer UAVs such as the DJI Phantom 3 (seen in Chapter 3.1.1) with millimetre-accurate Ground control point (GCP) surveyed using RTK GPS survey equipment (seen in Chapter 3.1.2) DEMs and DoDs can be produced at little cost when compared at other methods, utilising equipment readily available and portable enough to take to remote locations previously inaccessible when using other equipment (Westoby et al., 2012).

Accurate comparisons of sediment flux and storage between defined periods can be achieved, and accurate morphological budgets can be produced and visualised in the form of a DEM and DOD in a multitude of environments, such as landslides, gullies, glaciers, and fluvial environments (Holdsworth, 2018; Akay et al., 2020; fuller et al., 2020).

Akay et al. (2020) quantified flood-induced morphological changes in the Büyük Menderes River in Turkey utilising UAV and SFM surveying techniques. This resulted in three SFM-derived DEMs of six study reaches. The DEMs produced had a resolution between 5-10cm depending on flight and camera characteristics that could detect significant geomorphic changes following a significant flood event (Figure 27).

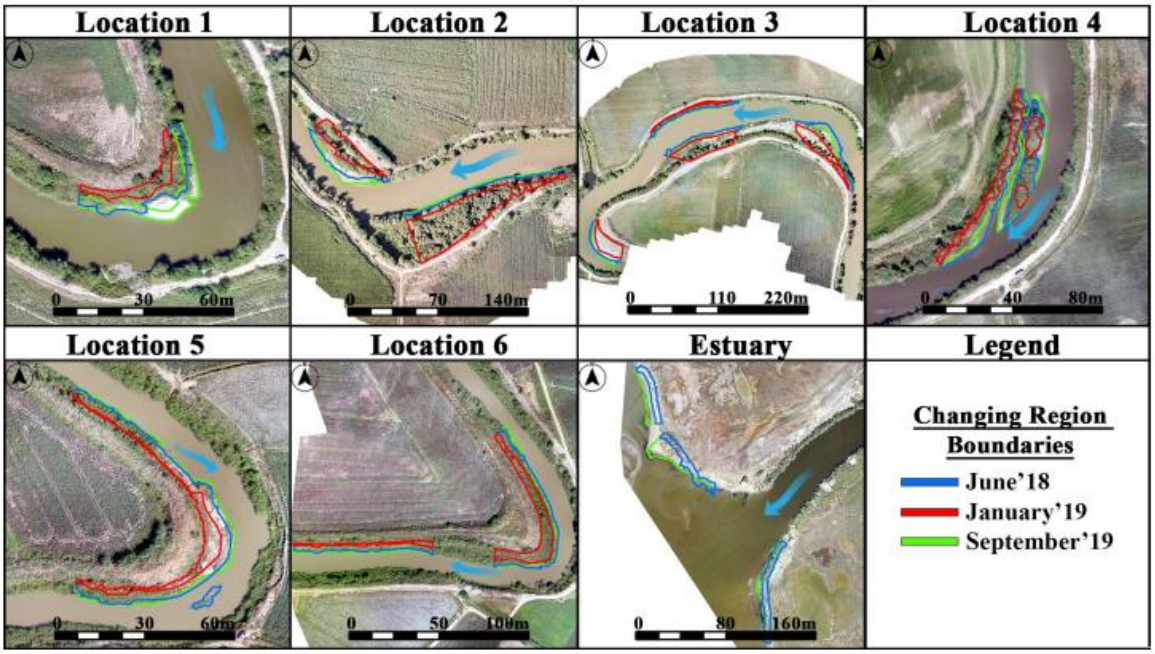


Figure 27: Geomorphic Change detection in the Buyuk Menderes River using Structure from motion (Akay et al., 2020).

Root mean square error (RMSE) is variable, as seen in Table 1 and is deemed by Akay et al. (2020) to be suitable for detecting geomorphic change. RMSE is a standard method used to measure DEM quality (Fisher & Tate, 2006; Chai & Draxler, 2014; Carrivick et al., 2016). Calculating RMSE (Figure 28) involves combining the first (mean) and second (dispersion) moment of the distribution of error (Fisher & Tate, 2006 in Strohmaier, 2020). In recent times, the suitability of the RMSE method has been discussed, as it does not represent the spatial variability of error in DEMs, and other error calculations can be used that better represent the statistical distribution of error in a model (Willmott & Matsuura, 2005; Strohmaier, 2020). Using RMSE as the measure for reporting DEM quality can misrepresent errors in a model. Due to the error throughout the model being averaged, RMSE represents model accuracy from bias and precision (from variance or standard error) (Strohmaier, 2020). Because of the spatial variability of error in models, RMSE is therefore impacted by outliers and overall bias in models (Strohmaier, 2020).

Other methods of calculating error in DEMs, such as mean absolute error (MAE), are promoted as the sole measure of precision in models (Willmott & Matsuura, 2005) due to it summarising the total error in the model (Figure 29). MAE is favoured due to its accounting for the variability of error distribution.

Table 1: Structure from motion flight specifications of the Buyuk Menderes River study (Akay et al., 2020).

Table 3. Flight specifications.

Site	Flight date	UAV type	# of Images	# of GCPs	Error (pix)	RMSEz (m)
Loc. 1	03 June 2018	P3P	143	5	0.32	0.14
	28 January 2019	P3P	314	4	0.31	0.09
	21 September 2019	P3P	142	5	0.32	0.01
Loc. 2	04 June 2018	P3P	146	5	0.25	0.06
	27 January 2019	P3P	321	5	0.28	0.03
	21 September 2019	MPP	484	6	0.27	0.01
Loc. 3	04 June 2018	P3P	259	5	0.24	0.08
	27 January 2019	P3P	405	5	0.29	0.06
	21 September 2019	MPP	409	6	0.30	0.01
Loc. 4	04 June 2018	P3P	211	5	0.24	0.02
	28 January 2019	MPP	370	6	0.38	0.03
	22 September 2019	P3P	219	5	0.13	0.01
Loc. 5	03 June 2018	P3P	280	5	0.34	0.05
	27 January 2019	MPP	468	5	0.04	0.04
	21 September 2019	P3P	280	7	0.34	0.01
Loc. 6	03 June 2018	P3P	138	5	0.25	0.09
	28 January 2019	MPP	138	5	0.26	0.05
	21 September 2019	P3P	139	6	0.27	0.01

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{n}(\hat{x} - x_i)^2 + (\hat{y} - y_i)^2}$$

Figure 28: The formula for calculating root mean square error. N is the number of GCP pairs, and X and Y are the transformed (predicted) object space coordinates of each GCP. Xi and Yi are its observed (sampled, assumed true) object space positions (Vericat et al., 2009)

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|e_i|$$

Figure 29: The formula for calculating mean absolute error (MAE). Calculation of MAE involves summing the magnitudes (absolute values) of the errors to obtain the 'total error' and then dividing the total error by n (Chai & Draxler, 2014).

Vegetation cover is also an important limitation when using SFM surveying methods. As with other air-to-air-to-surface survey methods, vegetation cover masks the true topographical surface being studied, which overestimates the quantity of sediment present. This bias can be seen in Westoby et al. (2012) and Holdsworth (2018) (Figure 30). Vegetation cover is accounted for by Fuller et al. (2020) and Strohmaier (2020) by creating masks when processing the SFM data to exclude areas of dense vegetation and to add higher levels of uncertainty to areas with lower levels of vegetation. This is illustrated in Figure 31. It is important to consider vegetation when considering the Tauanui and Turanganui Rivers, as much of the banks and stable bars are densely vegetated in places.

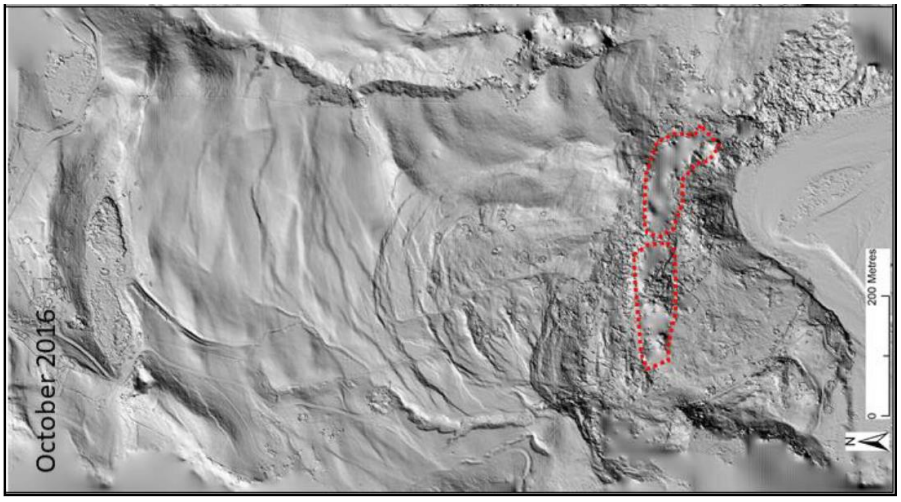


Figure 30: Vegetation artefacts in SFM photogrammetry highlighted in red (Holdsworth, 2016).

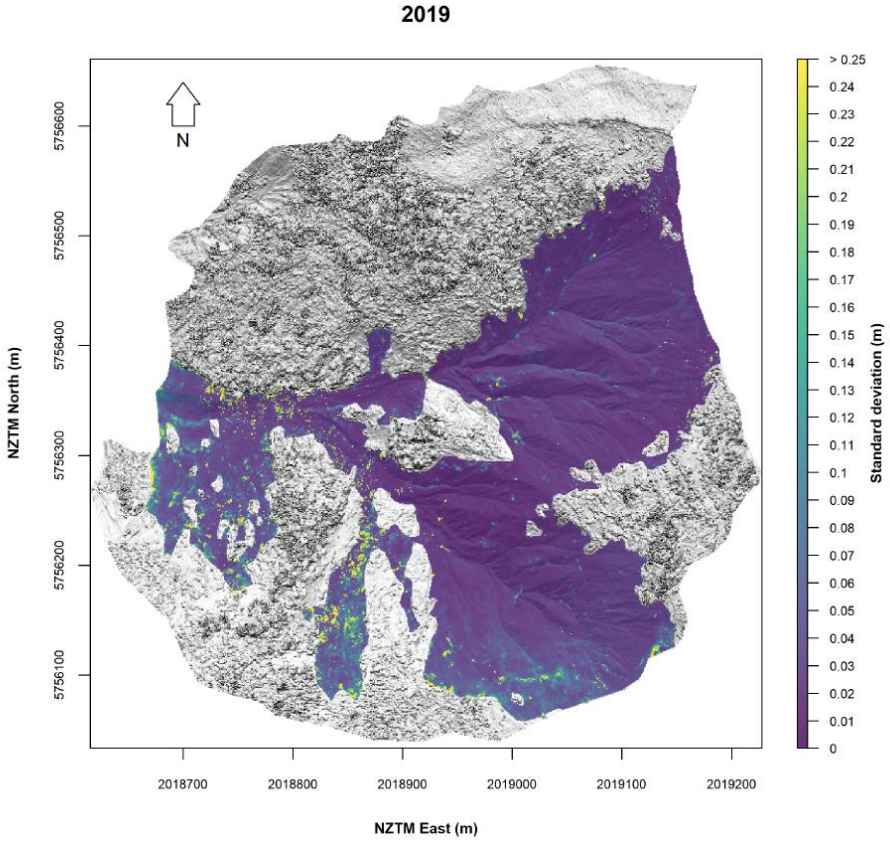


Figure 31: DEM produced by masking out densely vegetated areas (Strohmaier, 2020).

Water is also a surface that can introduce bias when using SFM methods to survey an area and is particularly important when surveying fluvial environments. High error values seen in parts of Strohmaier's (2020) model are due to the reflectivity of water surfaces when the UAV took imagery for the survey. Cook (2017) captured the performance of SFM on different water surfaces and found significant variation in the point cloud elevation data in clear water, and drone imagery could not penetrate opaque water surfaces such as white water in riffles (Figure 32). The influence of water in SFM surveys is compensated for by Strohmaier (2020) by acknowledging increased variation and standard variation in the areas where water is present in the models. Zhang et al. (2022) showed that SFM can significantly increase the accuracy of submerged gravel riverbeds if refraction

correction and underwater GCPs are used. These considerations will be important when surveying the Tauanui and Turanganui Rivers, as both contain riffle-pool sequences.

Figure 32: Cross section comparing LIDAR and SFM point clouds over different water surfaces (Cook, 2017).

SFM models can suffer from what is known as the "doming effect" due to inaccuracies in modelling the radial distortion of the camera lens, often from the camera self-calibrating. This results in systematic deformation of the reconstructed surface. This often appears as a rounded distortion of flat surfaces in the resulting model, particularly around the edges (Magria & Toldo, 2017). This introduces errors in DEMs produced and, by extension, makes any sediment volumes calculated using DODs inaccurate. James and Robson (2014) identified this doming effect in Rosnell and Honkavaara (2012) and Javernicket et al. (2014). The doming effect can be seen in Figure 33 by the increasing difference between the reference digital surface model (DSM) and the SFM-produced DSM (Magria & Toldo, 2017).

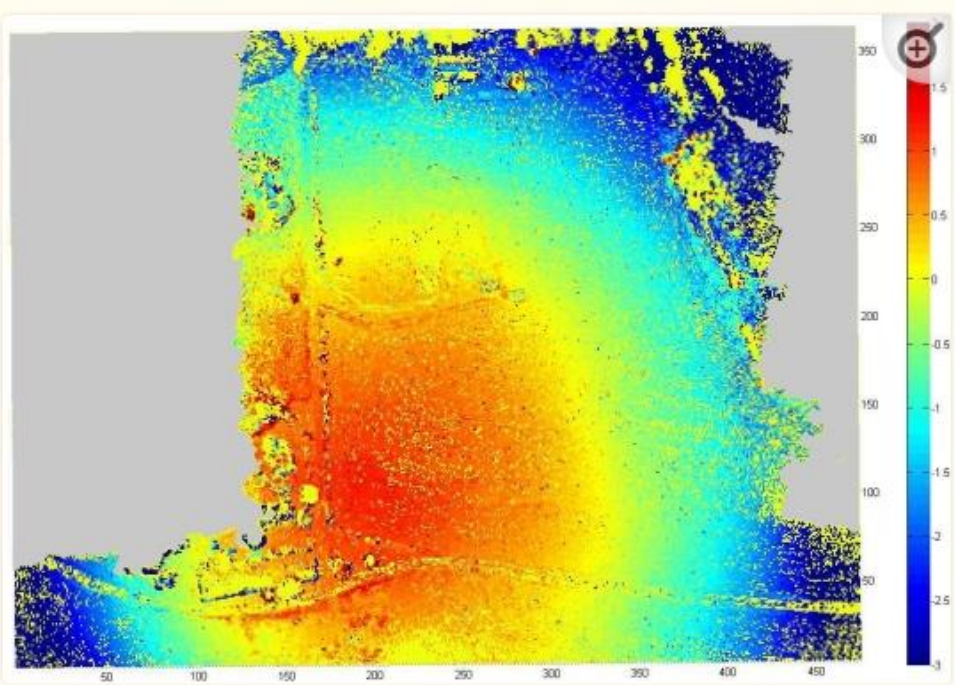


Figure 33: Difference between reference DSM and SFM DSM (Rosnell & Honkavaara, 2012).

The doming effect can be accounted for and effectively reduced using image processing methods or modifying the survey workflow when gathering field data. Magria and Toldo (2017) developed a modified bundle adjustment that uses a ground detection method to capture parts of a model that is flawed through the doming effect and correct it to the appropriate geometry (Figure 34). Lee and Han (2020) utilised the least-squares height-difference (LHD) DEM matching method with a polynomial model using a reference DEM to rectify the doming effect on an SFM DEM.

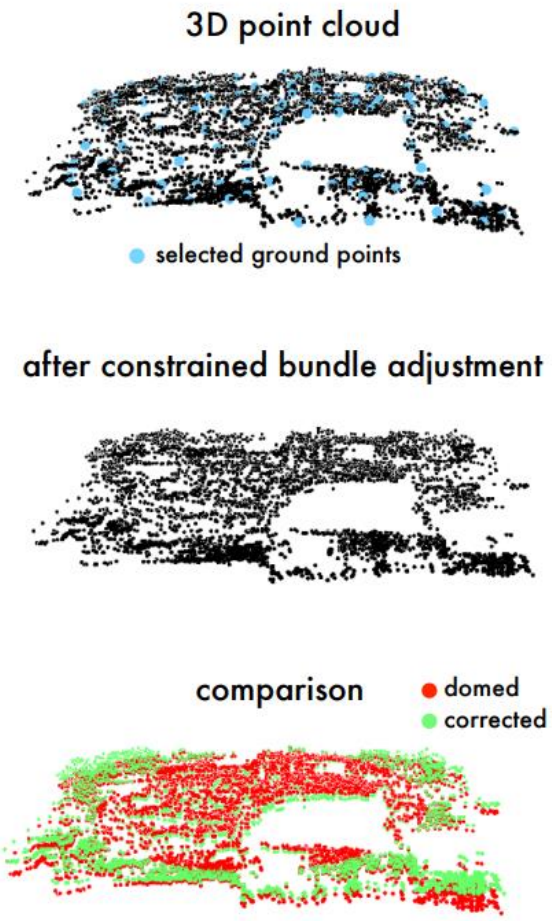


Figure 34: Point cloud data before and after bundle adjustment to correct the doming effect (Magria & Toldo, 2017).

The collection of oblique imagery and a suitably distributed network of GCPs has significantly reduced the doming effect on SFM models. When multiple images of the same target are taken at different angles (in the form of oblique images), James and Robson (2014) showed that these convergent images effectively reduce the radial distortion and thus reduce the doming effect on produced DEMs (Figure 35). James and Robson (2014) also suggested that collecting both nadir and oblique images will further reduce the doming effect. Another method known to reduce the doming effect and to increase the overall accuracy of the DEM produced is to have an evenly distributed network of GCPs (Smith & Vericat, 2015; Eltner et al., 2016). This is because GCPs represent ground truth data throughout the area being studied that is external to the set of images captured that needs to be satisfied in the adjustment process when producing the DEM, and thus reduces the need for the SFM software to interpolate images to create the DEM which produces the doming effect (James & Robson, 2014).

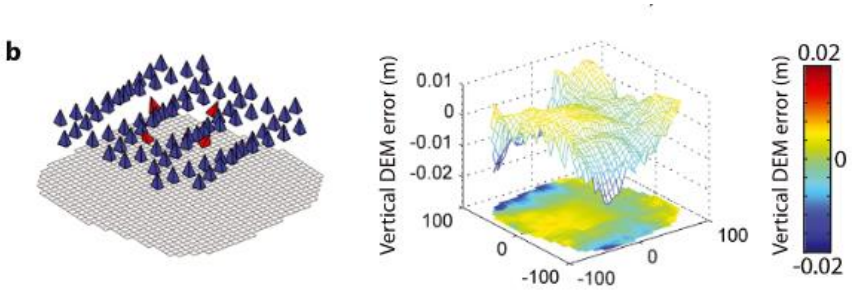


Figure 35: The effect of capturing oblique imagery on DEM error (James & Robson, 2014).

These spatial analysis tools have made sediment budget quantification more precise, allowing for a more in-depth understanding of fluvial geomorphic dynamics (Akay et al., 2020). Establishing a pattern of erosion and deposition requires collecting data at fixed temporal resolutions. Quantifying the net sediment flux requires a high spatial resolution monitoring solution. Both requirements are fit by utilising these monitoring techniques. Utilising modern technology in the form of RTK-dGPS and UAVs to develop DEMs has revolutionised the way geomorphology is monitored and quantified, which has resulted in the ability to monitor geomorphic change at a much higher frequency than what was previously achievable and at a lower cost (Eltner et al., 2016).

3.7 Hydrology

The ability of a river to erode and deposit sediment is governed by the available power of the system (Breirley & Fryirs, 2005). Steep rivers such as the Turanganui and Tauanui Rivers have higher flow velocities than more shallow sloped rivers, which equates to higher stream power. This is illustrated in the equation seen in Figure 36. By using this equation, total stream power (Ω) is a function of the specific weight of water(Y), stream discharge (Q) and bed slope (S). Higher stream power has more potential for sediment flux, particularly during flood events when water volume and velocity are increased. The scale of a geomorphic event in fluvial systems is partly governed by the catchment's hydrology (Charlton, 2007). This is because the geomorphic impact of a flood event depends on the river's stream power and, by extension, the intensity of a rainfall event within its catchment (Charlton, 2007). Rainfall leads to high stream flows, which possess more energy to erode material in the riverbed and on banks. Fluvial incision at the base of slopes can result in landslide re-activation or enable higher rates of sediment supply to the river due to increased connectivity between slope and river systems. Increased sediment supply can lead to channel aggradation and increase the chances of avulsion (Ashworth et al., 2007).

$$\Omega = \gamma Q s$$

$$\omega = \frac{\Omega}{w}$$

Figure 36: Equation for stream power and specific stream power (Brierley & Fryirs, 2005).

The relationship between stream power and erosion is well established, with clear correlations between stream power and bank erosion (Larsen et al., 2006). This is illustrated in Figure 37. Stream power is also established to be a driving factor in bed scour and deposition (Bizzi & Lerner, 2015).

Figure 37: C*orrelation between erosion and cumulative stream power* (*Larsen et al., 2006)*.

4.0 Methodology

To analyse the fluvial response to the 20th of June flood event, the surfaces of fluvial sediment before and after the flood at both study reaches need to be captured. This was completed by surveying using photogrammetry techniques, and surface changes were assessed. Historical imagery was utilised to conduct a geomorphic audit of the study reaches to facilitate analysis of decadal geomorphic changes within the rivers. Historic cross-section survey data was also analysed to capture decadal changes in bed level. In addition to this, environmental monitoring data, including rainfall and river flows, were provided by Greater Wellington Regional Council. Land Information New Zealand provided spatial data showing land use, geology, and elevation.

4.1 Photogrammetry surveys

The SFM Technique is well established and has been utilised to detect and quantify geomorphic change (Westoby et al., 2012., James et al., 2019). Using spray paint, ground control points (GCPs) were established (see Figure 38). 30-40 GCPs were planned to be used per survey; however, due to vegetation, accessibility, and survey errors, 27-35 GCPs were used per survey. Then, a drone is flown over the area of interest (AOI) using multiple nadir and oblique camera angles. Images are then processed using software to form a 3D image. GCPs are then used to georeference the resulting image to form a Digital Elevation Model (DEM). This was to identify active regions of the rivers and patterns of sediment movement and to quantify geomorphic changes occurring between surveys by creating a DoD from concurrent SFM surveys.

4.2 Survey control

To provide georeferencing and to measure the accuracy of the photogrammetry surveys, a combination of temporary benchmarks (TBMs) and ground control points (GCPs) were established at each site. GCPs provide a reference to the topography being studied and were drawn onto the ground using fluorescent spray paint (Figure 38). GCPs were measured using real-time Kinematic global positioning systems (RTK-GPS) equipment. RTK-GPS surveys are a well-established method of georeferencing and checking the quality of DEMs (Backes et al., 2020; Fuller et al., 2020). The survey equipment used was a Trimble R10 base station and rover unit (Figure 39). Three benchmarks were established at each study site using one wooden peg and two lengths of reinforcing bars hammered into the ground. This can be seen in Figure 40. These were installed to establish fixed positions throughout the study, which provided consistent and common reference between surveys and provided a way of assessing the error in the GPS data. Some GCPs were withheld from the Photogrammetry process to provide a way of evaluating errors in the photogrammetry model.

Figure 38: *Painted ground control point (GCP).*

Figure 39: RTK GPS base and river set-up prior to the first survey on the Turanganui study reach.

Figure 40: The permanent benchmark installed at the Turanganui study reach.

Before conducting fieldwork, the study reaches were assessed using aerial imagery, and a network of GCPs was mapped in both study reaches to ensure an even network of survey points at an adequate density was established in the field (Figures 41 and 42).

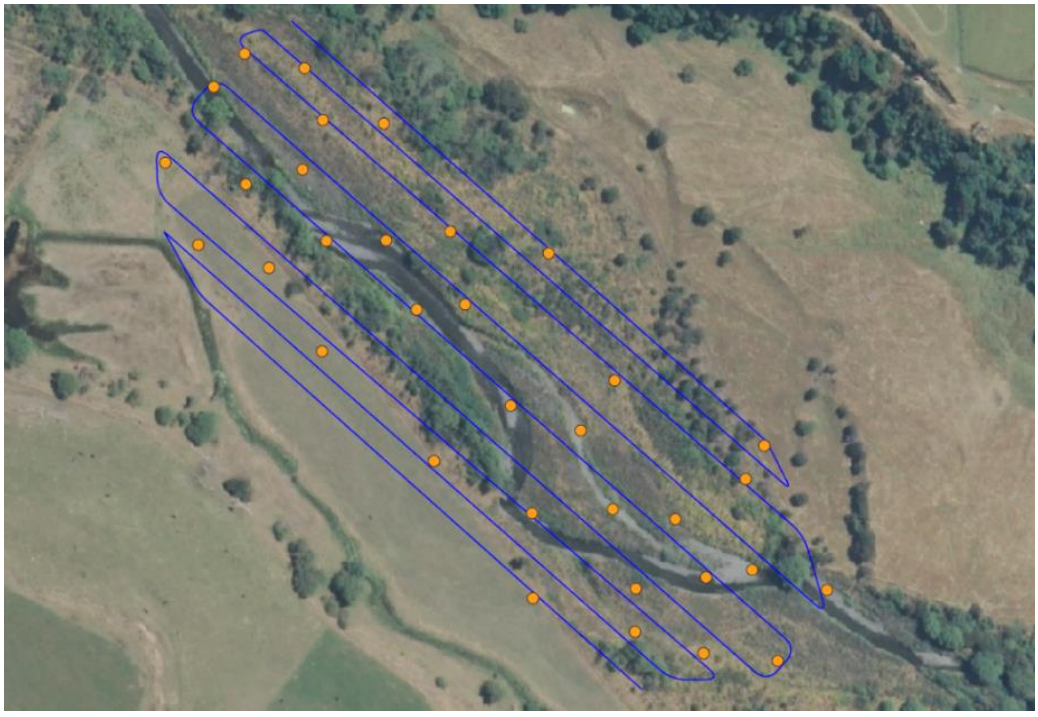


Figure 41: Programmed flight path and planned GCPs for the Tauanui study reach.

Figure 42: Programmed flight path and planned GCPs for the Turanganui study reach.

Potential GCP locations were first assessed for their ability to be seen from the air, as the UAV needed to capture the location of the survey point. Suitable sites were painted with bright marking paint so the GCP could be captured by the UAV, and the specific point where GPS data was taken could be identified. This was denoted as the centre of the cross (Figure 38). GCPs were painted on the survey reach because they could be left in place, which saves time and makes them potentially reusable for sequential surveys if they could still be seen. Points were surveyed using the 'topo point' setting on the surveying equipment. This is 15 second-averaged surveys, which were then surveyed again after rotating the survey staff 180 degrees (Figure 44). This was to reduce errors in the angle estimation of the survey equipment. The maps of planned GCPs were uploaded to A GPS-enabled map while surveying to track movements throughout the study sites and to ensure GCPs were evenly distributed across the survey reach and in appropriate numbers as planned (Figure 43).

Figure 43: *Track while surveying the Tauanui on the 7th of May 2021*.

Two surveys were completed on each survey reach for both rivers on the 7th of May 2021, while both rivers were in drought conditions and were not flowing. This ensured higher accuracy of the survey, as GCPs could be established anywhere on the channel as there was no wetted channel, as well as eliminating influence from water in the SFM survey. A major flood event occurred on the 20th of June 2021 after the first survey. Following The flood in the Turanganui River on the 20th of June 2021, significant erosion occurred, resulting in all three of the original benchmarks being lost Figure (45). Therefore, previous GCPs had to be used instead of benchmarks. Bad weather and turbid flow conditions postponed several attempts to capture sequential surveys in both rivers as weather was not conducive to drone flights, and turbid water will produce bias in the DEMs produced. When conditions allowed, the second survey for the Turanganui was completed on the 15th of September 2021 and the 11th of November 2021 on the Tauanui.

Figure 44: GPS surveying using the R10 rover unit.

Figure 45: *Bank erosion that wiped out benchmarks on the Turanganui River following the 20th of June 2021 flood event*.

4.3 Aerial surveys

A DJI Phantom 3 UAV (Figure 46) was used to collect vertical (Nadir) and 30-degree off-vertical (oblique) imagery of the Tauanui and Turanganui study sites on two separate occasions for both rivers. The Turanganui were surveyed on the 7th of May 2021 and 15th September 2021, and the Tauanui was surveyed on the 7th May 2021 and 11th November 2021. Flight paths were designed with appropriate photograph overlap (80%) for the photos to tie together accurately. Figures 48 and 49 depict the programmed flight paths for both study reaches.

Figure 46: *DJI Phantom 3 in use for the first survey on the Turanganui River*.

Flight paths were planned using the flight planning tool on www.mapsmadeeasy.com to plan the approximate flight location, altitude, and appropriate forward and side image overlap (Figure 47). In this case, prior site visits confirmed an altitude of 40m above the take-off zone provided a safe distance above trees and topographical obstacles for both sites and was low enough to produce high-quality imagery of the study reach. Eighty per cent forward overlap and seventy-five per cent side overlap was recommended as suitable. Flight speed and photo interval are set to ensure adequate images were taken and overlapped sufficiently. This was set to one photo every 2 seconds and a 15km/h flight speed. This data is then exported as a KML file and imported into Excel to check that the longitudinal values are correct, as the flight planner tool exports values suitable for the northern hemisphere and needs 360 degrees added to them for the southern hemisphere. The coordinates are then adjusted for importing into the Litchi flight programmer for DJI Drones (Figures 48 and 49).

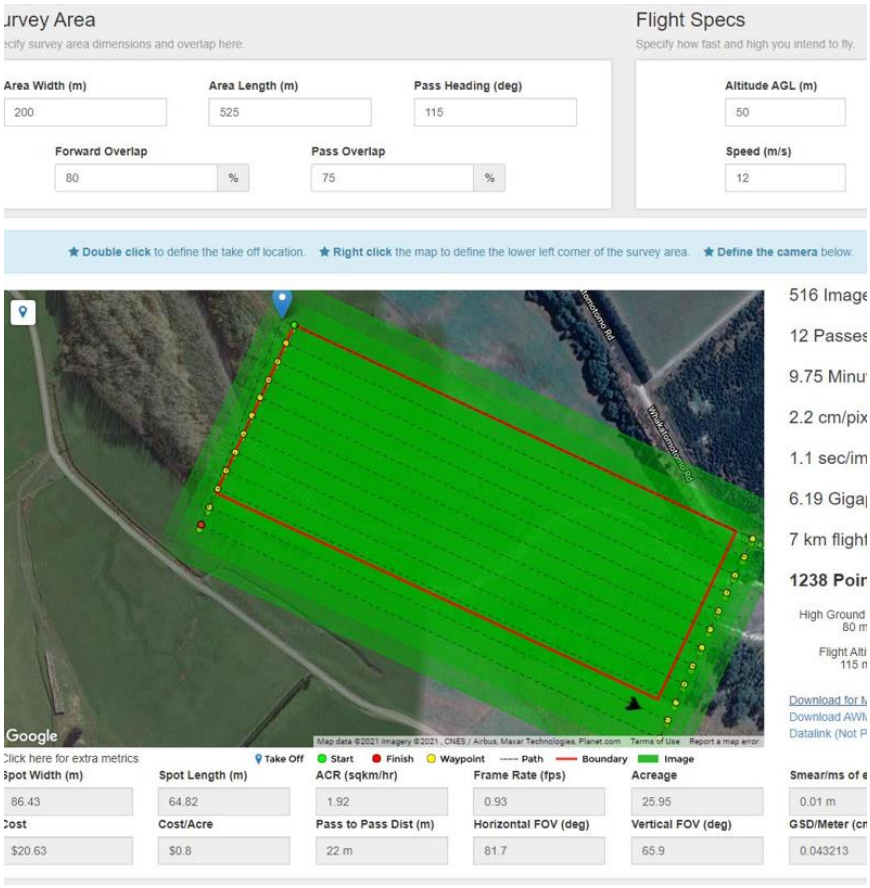


Figure 47: Mapsmadeeasy flight planning tool used for the Turanganui River.

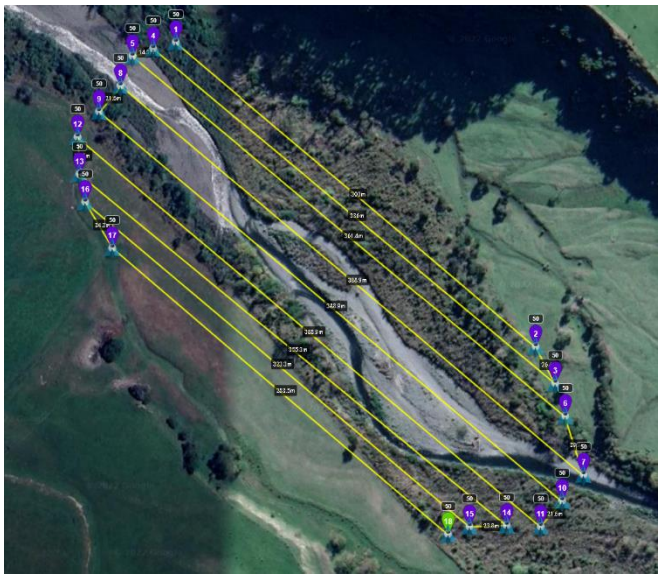


Figure 48: *Programmed drone flight path of the Tauanui River*.

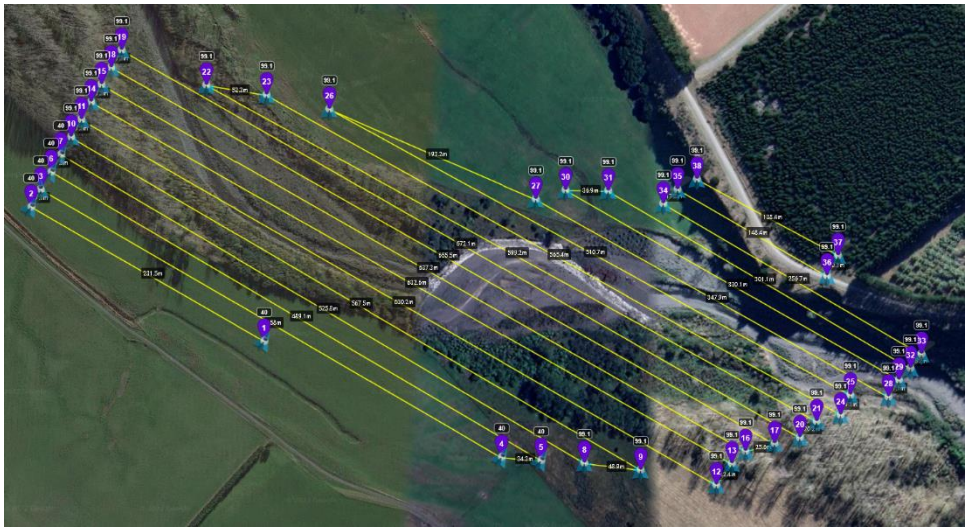


Figure 49: *Programmed drone flight path of the Turanganui* River.

On the day of the flights, weather forecasts were checked to ensure winds were calm enough for the UAV to fly, and hydrographic data was checked to ensure there was no flooding, as this would distort the SFM surface, as explained in David et al. (2021). Flight zones were checked, and all Civil Aviation (CAA) rules were complied with. The UAV was connected to the Litchi app on an iPad, and each flight was loaded onto the drone and set to fly the programmed grid, taking photos every 2 seconds, with the camera set at a nadir angle. The UAV then did two more flights with oblique angles on the camera with a 180-degree heading change between flights. After each flight, the imagery was downloaded to a PC and annotated for date, time and location. This process was completed two times for each river, totalling four surveys overall.

4.4 Photogrammetry processing

The software used to process photos taken into a 3-D model was Agisoft Metashape Professional, using structure from motion (SfM). The workflow utilised involved pre-processing the imagery collected in preparation for forming a dense cloud (dense 3-D point cloud of tied image portions, which forms the foundation of the 3-D model). Pre-processing imagery involved loading all images from a survey flight and assessing for quality; inadequate images were masked or deleted. Images were then referenced to the New Zealand Transverse Mercator coordinate system (NZTM) and aligned using key and tie point processing. Photo alignment accuracy was set to the highest, the key point limit used was 40,000, and the tie point limit was 16,000.

Key points are points in the image collection that are distinct and allow individual images to be identified, whereas tie points are identifiable features that have been identified to link photos together. This creates a network of points throughout the image collection that links them together. Alignment also involves estimating camera pose and utilising key points to extract a sparse cloud, where overlaps in imagery create a 3D image (Westoby et al., 2012). The sparse point cloud was then assessed for any outlying misrepresentations of the ground. Any points located below ground or in the air were deleted. This was completed using the gradual selection tool. Reconstruction uncertainty was set to 10, highlighting all points detected to be in the wrong position, which were then deleted. Reprojection error was then calculated, which was set to 1.1 Pixels. This highlighted all points with reprojection errors that exceeded this value, which were then deleted. The sparse cloud

was then assessed visually again, where all points below or above ground level were selected using the lasso tool and deleted. The model was then optimised using a bundle adjustment.

The RTK GPS survey data of the GCPs gathered using the rover for the survey was prepared for export in the Trimble Business Centre software by being differentially corrected against the temporary base station, which was itself corrected against the Battery Hill permanent LINZ continuous GPS station. The differential correction was processed in Trimble Business Centre. This data was exported from Trimble Business Centre and imported into Metashape, creating GCP markers on the model. GCPs were then associated with the physical survey points in the imagery. Further model optimisation was completed by refining tie points by their projection accuracy, and the dense cloud was built. The sparse cloud was then edited using a gradual selection workflow to reduce variability. An orthophoto and digital elevation model were then produced from the dense cloud, and the DEM (Digital Elevation Model) was down-sampled to a resolution of 1m to be consistent between models. Figure 50 illustrates the workflow utilised.

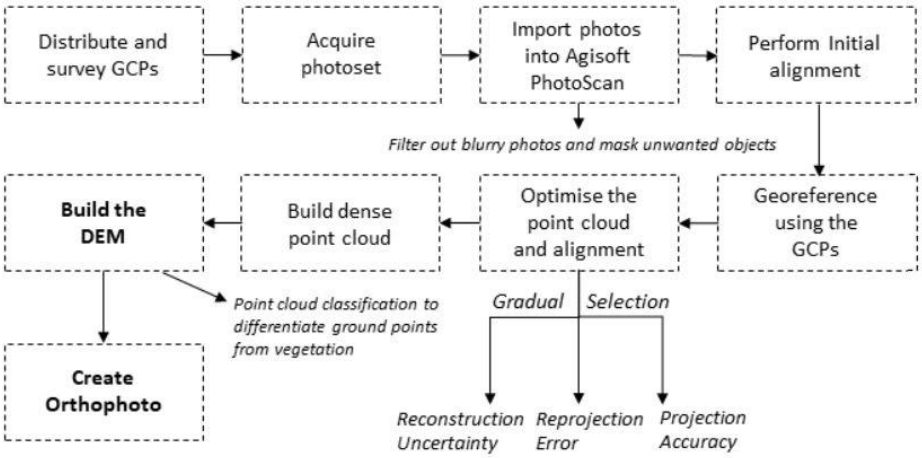


Figure 50: W*orkflow for creating 3D models, Orthophotos and DEMs (digital elevation models) using structure–from–motion. Adapted from Westoby et al. (2012) in Holdsworth (2016).*

The total error inherent in photogrammetry is influenced by the model and survey (RTK-dGPS) errors. Because GPS (global positioning systems) survey equipment was used to georeference the imagery, errors in the equipment's location estimation in 3D space are translated into the model. Model error distorts the edges of the model where poor image alignment occurs. Errors when the DEM is produced are caused by objects off the ground, such as inadequately classified trees, causing high points and pits in the DEM.

Ground control points were left out when georeferencing the models so accuracy tests could be conducted on the model's estimation of location in 3D space. Modelled coordinates were compared against surveyed coordinates to calculate an error value, which was the difference between the two. These differences were averaged using the root mean square (RMS) error. Significant elevation changes calculated in the DoD are due to either vegetation artefacts in the imagery (often on stable bars or banks) or areas that were not photographed from one survey to the next. These differences exist because each survey was tailored to the morphological changes observed on the day, meaning flight paths and resulting images were not always identical. Because the area captured in each DEM depends on the camera angle and flight path, the area captured is not always the same.

4.5 Producing the DoD map

Digital elevation models of difference (DoD) have been widely used in geomorphological studies, including those by Schwendel et al. (2011), Fuller et al. (2011) and Fuller and Basher (2012). DoDs have been concluded as an effective means of quantifying sediment movement and establishing morphological patterns. Geomorphic change detection software (GCD 7) was used to create the DoD maps for both study reaches, of which the development methodology is explained in Wheaton et al. (2010). After creating separate projects for the different study reaches, the DEMs were added into GCD and aligned with the same extent coordinates so the DEMs overlap correctly. An area of interest (AOI) was created in ArcMap as a polygon vector layer to refine the river channel and surrounding banks in both study reaches (Figure 51) and to ensure the same extent of DEMs is analysed between surveys. This was added as a mask layer in GCD software. Vegetation is noted as a source of inaccuracy when comparing DEMs produced using SFM methods (Westoby et al., 2012), as vegetation does not represent the true topography of the area being studied and produces artefacts in the imagery. To mitigate this, another AOI was further refined to the bare gravels in the first survey of both reaches using the orthophoto produced in Agisoft Metashape (Figure 52).

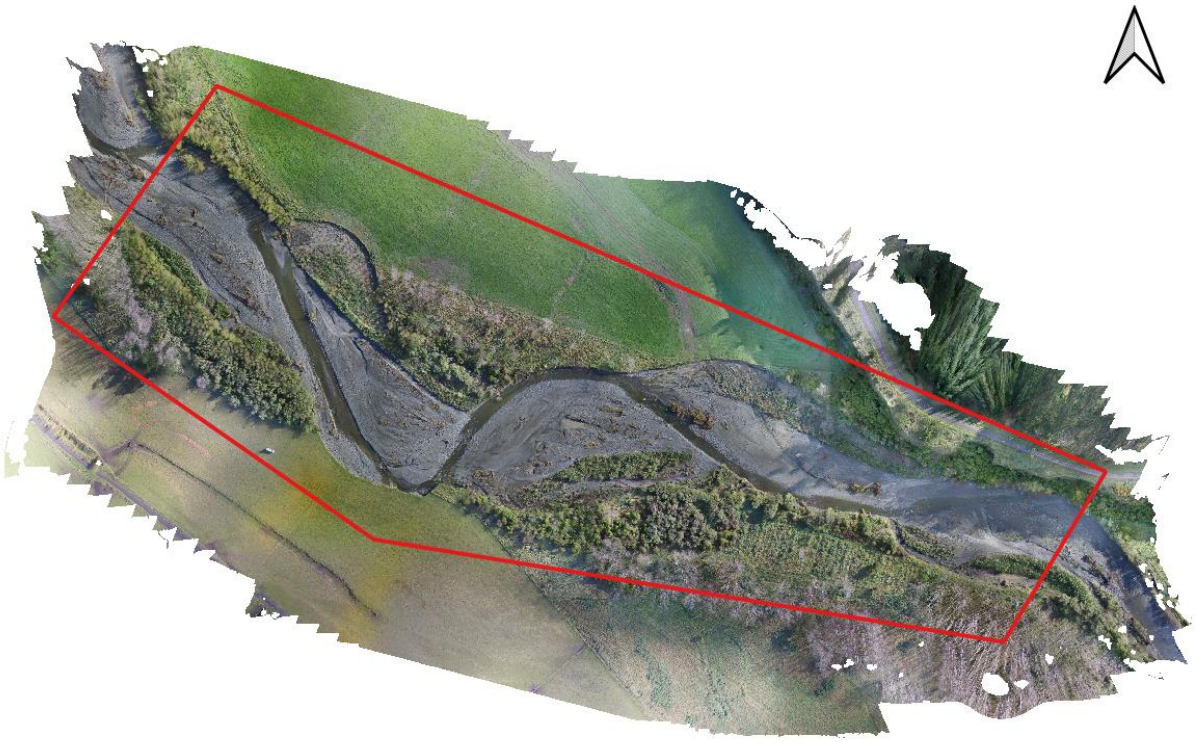


Figure 51: Area of interest (AOI) generated for the Turanganui River.

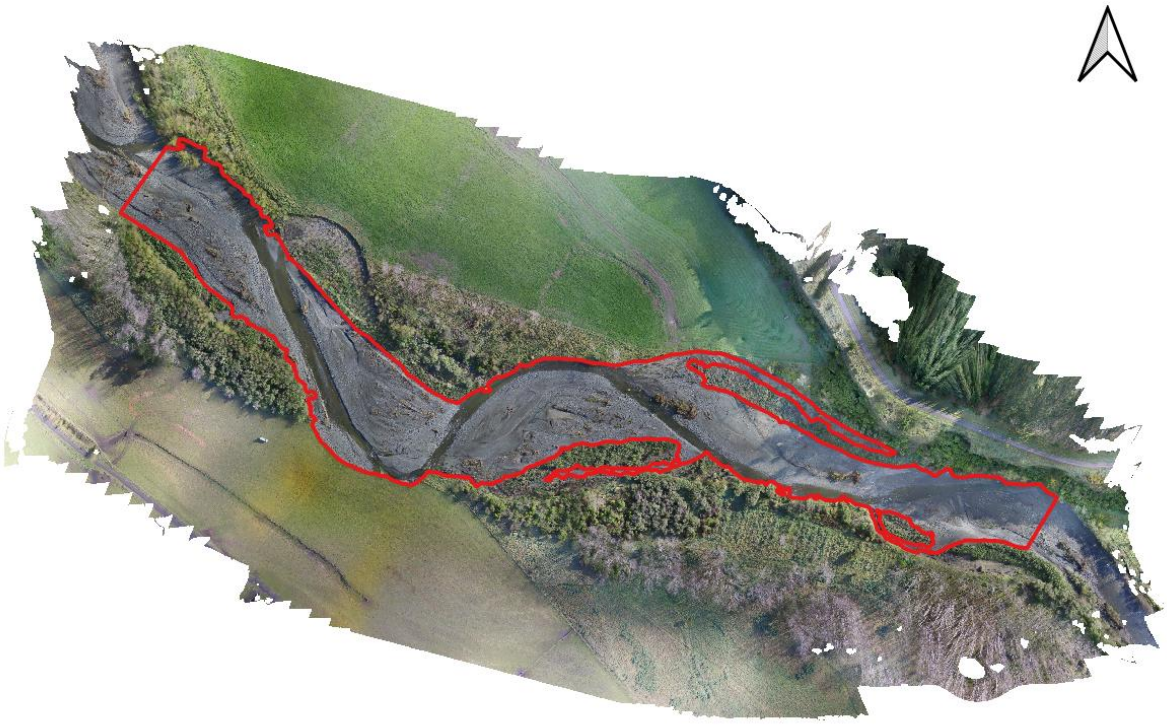


Figure 52: Bare Gravel AOI produced for the Turanganui River.

A spatially uniform error surface was then created using the Root mean square error (RMS) of the benchmarks in the Tauanui and the location of consecutive GCP survey points from each survey in the Turanganui (see Chapter 3.2.1). This is due to the flood event eroding into the paddock where the benchmarks were, resulting in them being lost. For this, the highest error was used to be conservative and to ensure geomorphic change was detected. This error surface was added to GCD as a mask layer. The final GCD layers are then created, along with tabular results of the quantification of geomorphic change calculated between the DEMs of the study reaches.

To accurately compare geomorphic change between study reaches, the total volume difference calculated in the DoDs must be divided by the size of the area of interest to produce an average geomorphic change detected per square meter. The Turanganui has a far wider and longer study reach due to its natural character and study reach selection. Therefore, any change detected would likely be greater in the Turanganui study reach.

4.6 Rainfall data and trend analysis

Rainfall data is important in understanding the scale of rainfall events occurring in the study area. This is done by recording the volume and timing of rainfall that occurred during the storm event that resulted in flooding. This analysis results in the calculation of rainfall intensity. This can then be put into historical context by comparing it to previous events to calculate a return period. This can then be used to understand rainfall's input into geomorphic change within the study reaches. Rainfall monitoring has been used to understand fluvial geomorphological patterns in many circumstances, including Fuller (2007), Milan (2012) and Akay et al. (2020). Event-based (instantaneous) rainfall was gathered using two monitoring sites maintained by the Greater Wellington Regional Council's (GWRC) Hydrology team. These sites are the Tauanui River at Pirinoa and the Ruakokopatuna River

at Iria (see Figure 53). They were chosen because they are the closest rainfall monitoring sites to the study sites, one of which is in one of the studied catchments.

The Ruakokopatuna site is also near both study reaches and represents rainfall in the headwaters of both catchments as it is in the Aorangi Range, which both rivers flow out of. Both monitoring stations have an extremely high measurement resolution (0.2mm) and, due to rainfall data being instantaneous, provide an accurate representation of rainfall event timing. Bar graphs were produced in Hilltop Manager software to recognise rainfall events that cause a hydraulic response.

Figure 53: Location of rainfall monitoring sites in relation to study reaches (Google Earth, 2021).

4.7 Flow data and analysis

Monitoring hydraulic data is important to quantify water flowing down the studied rivers and capture the scale of flood events occurring in the rivers. This enables analysis of the flood events that occur so a return period can be calculated, and connections can be made with regard to the geomorphic impacts of floods.

There is one river level and flow monitoring site on each river, both installed and maintained by GWRC. The two sites are the Tauanui River at the gorge and the Turanganui River at the Whakatomotomo Road end, highlighted in Figure 54. Both river monitoring sites are representative of the study reaches, as they are at the top end of the catchments above the study reaches, and no major tributaries enter the rivers below the monitoring sites. Therefore, the inflow through the study can be quantified and compared against the fluvial geomorphic change observed. The only consideration to be made considering the hydrology of the study reaches is that flood magnitude may be higher at the study reaches as they are located downstream of the monitoring sites and will have received more input from runoff, groundwater, and minor tributaries. Frequency analysis of the hydrographic data throughout the study period was calculated to create a cumulative percentage of discharge over the study period. Hydrographs from both rivers were produced during the study period using Hilltop Manager software. Flow data is overlaid with rainfall monitoring data

to provide insight into the relationship between hydrology and river geomorphology, as discussed in Ashmore and Church (1998).

Figure 54: Hydrology Monitoring sites for the Tauanui (left) and Turanganui (right).

Stream power is calculated by multiplying the density of water, which is typically 1000kg per meter cubed by the acceleration due to gravity, which is 9.81 meters per second. The product of this is multiplied by the peak discharge of the river. This is then multiplied by the slope of the study reach to produce stream power in Watts (w). because these rivers have different geomorphic characteristics, unit stream power (also known as specific stream power) is more suitable for comparing stream power between rivers. The Calculation of unit stream power is shown in Figure 55.

$$SSP = \frac{TSP}{w}$$

Figure 55: Formula for calculating unit (specific) stream power (Bizzi, 2015).

4.8 Geomorphic assessment of study reaches

All available historical images of both study reaches were gathered and assessed to quantify decadal scale geomorphic change. The imagery was found using Land Information New Zealand's (LINZ) website and Retrolens.co.nz. Historic imagery was analysed by adding them into ArcMap and orthorectifying them. This was done by identifying identical features between existing georeferenced imagery and the historic imagery, creating a series of ground control points. This allows the GIS to 'stretch' the historical imagery to fit the projection of the reference imagery. This

was done for the four sets of images that were not georeferenced. Geomorphic auditing was completed using the digitised AOI 'frame' for both study reaches, as seen in Figure 51, so all assessments were made within the same area for both sites and all years of imagery. Then, within each frame, the images were classified and digitised as one of 4 classes. These are heavy vegetation, light vegetation, Bare Gravels and wetted channels. This was done for all available years of imagery. These were 1996,2013, and the two aerial surveys were completed in May and September/November 2021. Figure 56 is an example of this. Analysis of these geomorphic audits was completed by quantifying the area in each image containing the four classes classified and producing graphs illustrating the change in geomorphic units over time.

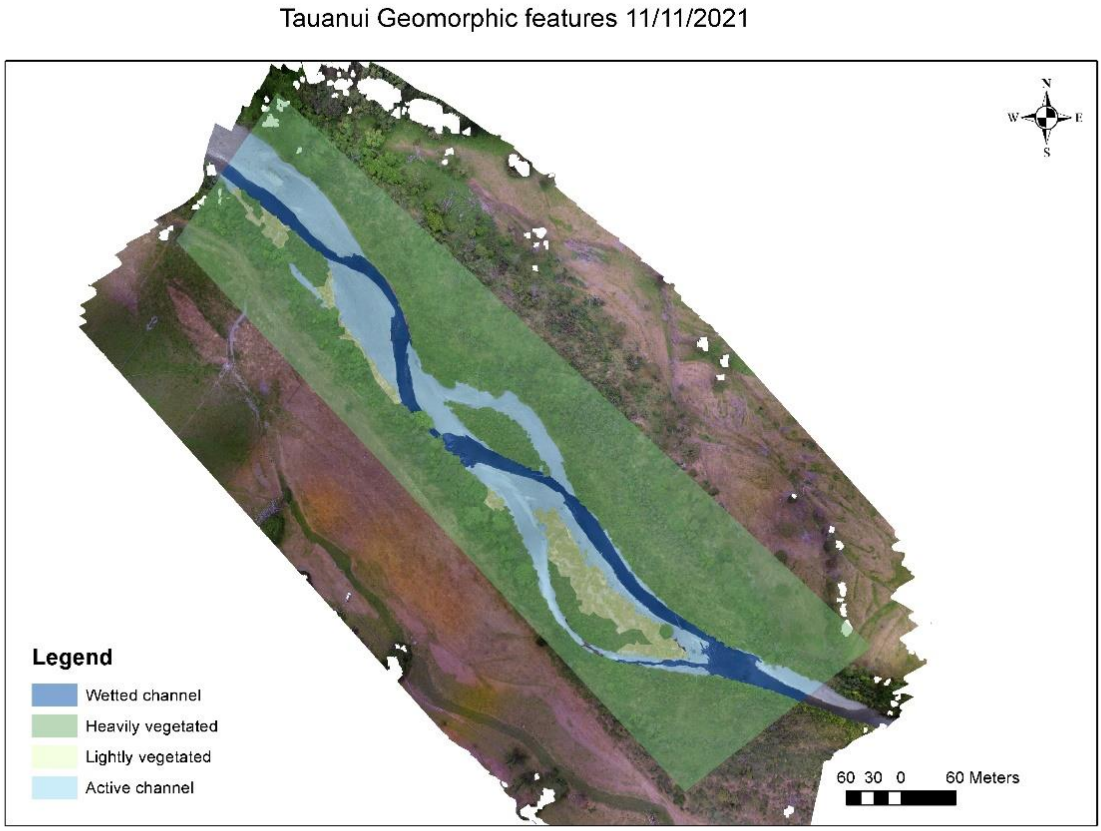


Figure 56: *Geomorphic survey of the Tauanui River overlaid over imagery to illustrate geomorphic survey methodology*.

4.9 Cross-Sectional surveys

Cross-sectional surveys have been completed in these catchments by the Greater Wellington Regional Council to monitor erosional patterns since 1991 in the Turanganui (Figures 57 and 58). In the Tauanui River, no Cross-section surveys have been completed in the upper catchment, with surveys only being completed near the roading infrastructure in the lower catchment (Figures 59 and 60). Cross-section surveys are completed by establishing a specific datum to set benchmarks down the river being surveyed and systematically surveying them in relation to the surface of the river's active bed at set durations. Therefore, patterns of erosion or degradation over time can be established when compared. These surveys were gathered from GWRC by surveying set cross-

sectional benchmarks from the mouth of the river up to where the regional council decides sediment changes are historically negligible or are not putting people or infrastructure at risk. Relevant Survey data was taken from the GWRC cross-section database and input into an Excel spreadsheet in order of cross-section and date so bed level changes could be analysed. As the data was being analysed, GWRC completed another survey in late 2021 on the Turanganui River. Some of the data received was given with high error margins as there was a possibility for human errors in the surveys when viewed by a data analyst from GWRC. Data for cross sections 20 and 21 on either side of the study reach was accepted as accurate by GWRC, which was added to the analysis. All cross-section surveys were graphed according to their cross-section so changes in bed level could be visually compared.

Figure 57: GWRC Turanganui cross-section locations in the lower catchment.

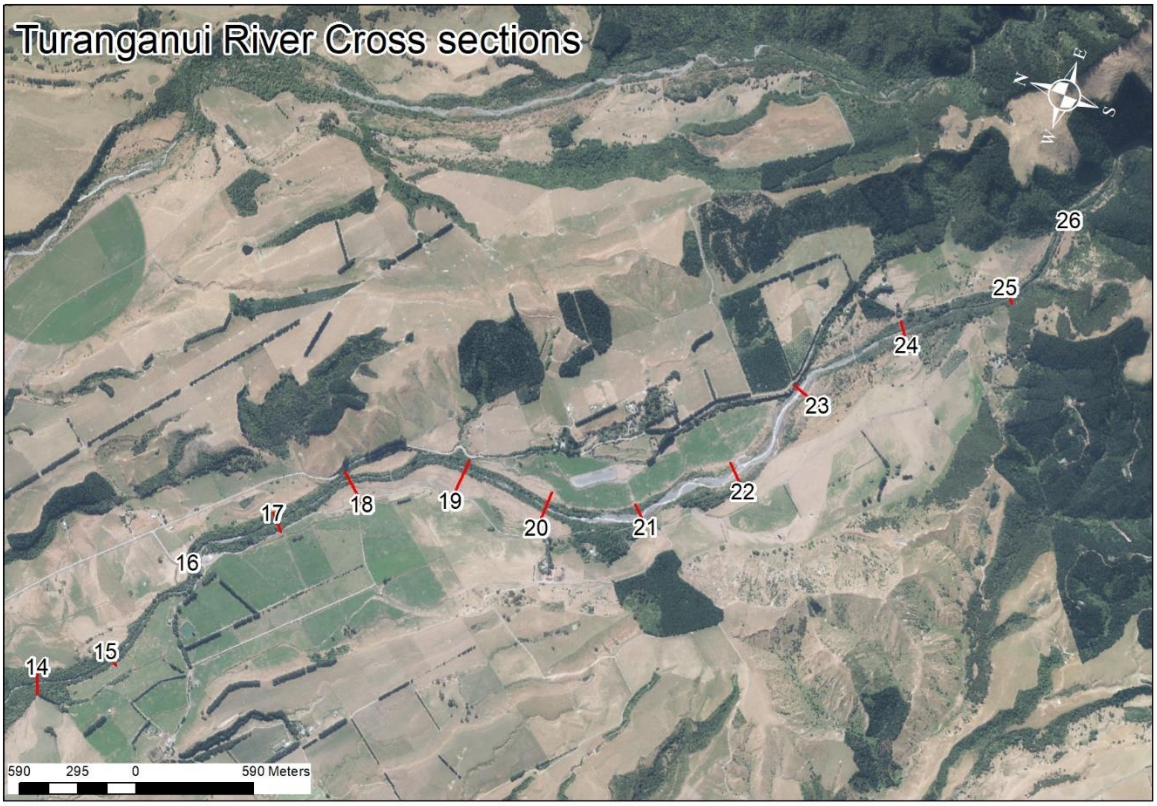


Figure 58: *GWRC Turanganui cross-section locations in the upper catchment*.

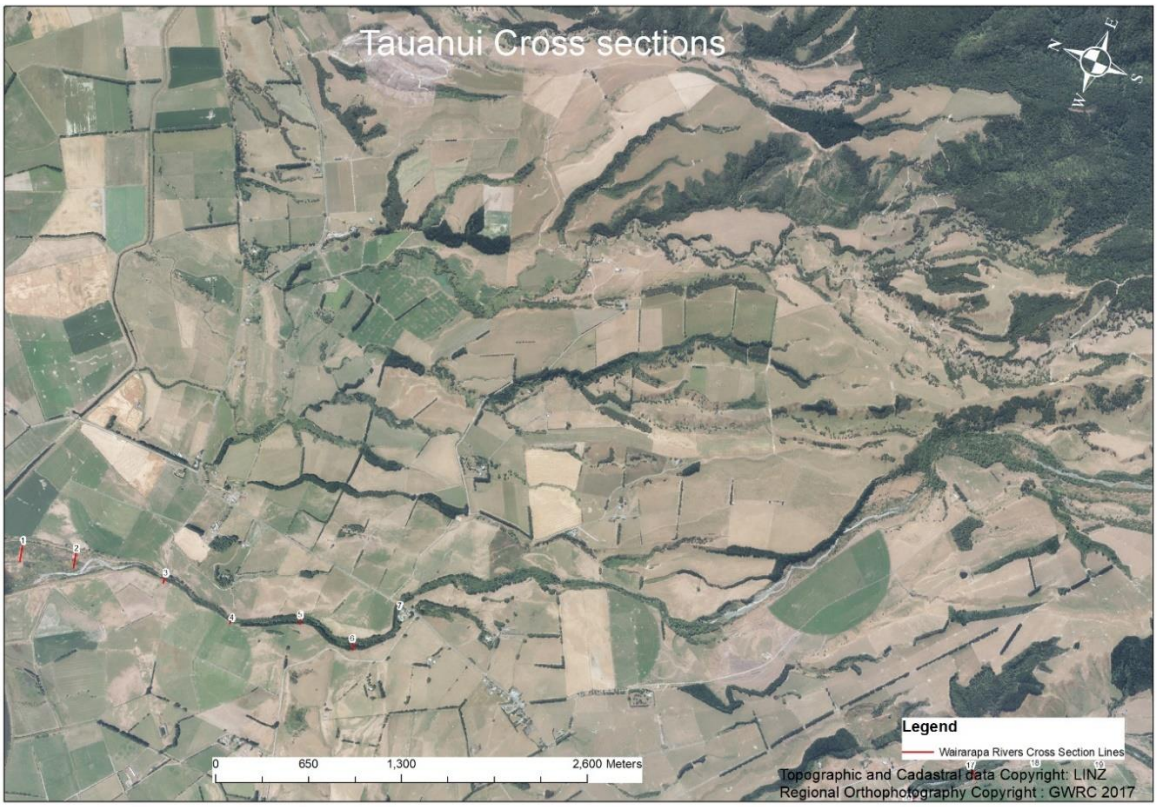


Figure 59: GWRC Tauanui cross-section locations in the catchment

Figure 60: GWRC Tauanui cross-section locations in the lower catchment (close up).

Next, the mean bed level was calculated for all cross sections to analyse trends in average bed level. This was done by calculating a weighted average of the cross-section survey using the length of the active channel. Bed levels were weighted according to the distance between survey points and the total length of the cross-section, as these were uneven between surveys and would have resulted in biased mean bed levels if not accounted for. The approach was similar to that of Sriboonlue and Basher (2003). By dividing the end area of the cross-section by the active channel width (ACW) (table 2). The distance between survey points was calculated to produce dDist, then the average RL between neighbouring survey points to produce Avg Lvl. dDist was then multiplied by the average RL to get the average area under the plot between the adjacent survey points. The total area under the cross-section was calculated by totalling all areas. The mean bed level (MBL) was then calculated by dividing the total area by the ACW. The mean bed level was calculated for all surveys and cross-sections and then graphed for analysis.

Table 2: Mean bed level calculation.

Dist (m)	dDist (m)	RL (m)	Avg Lvl (m)	dDist*AL(m²)	ACW (m)	MBL (m)
0	0	51.452				
4.4	4.4	51.317	51.3845	226.0918		
5.8	1.4	50.617	50.967	71.3538		
18.6	12.8	50.327	50.472	646.0416		
20	1.4	49.775	50.051	70.0714		
23.6	3.6	49.842	49.8085	179.3106		
27.3	3.7	50.098	49.97	184.889		
32.5	5.2	50.17	50.134	260.6968		
34.6	2.1	49.632	49.901	104.7921		
39.5	4.9	49.65	49.641	243.2409		
41.1	1.6	50.02	49.835	79.736		
42.4	1.3	50.172	50.096	65.1248		
43	0.6	52.145	51.1585	30.6951		
43.4	0.4	52.512	52.3285	20.9314		
50.1	6.7	52.659	52.5855	352.32285		
52.1	2	52.75	52.7045	105.409		
				2640.70715	52.1	50.68536

4.10 Cross-section volume calculations

Calculating volumes of a cross-section is a useful way of utilising fixed cross-sections to estimate sediment volume changes over time to make informed decisions with regard to river management. This is done using various software in New Zealand, such as RICODA, Hilltop and XSECT (Basher, 2006). Cross-section volumes were calculated by GWRC using Hilltop Hydro software. This was done by taking the cross-sectional area of two cross-sections based on a defined reduced level (RL) to calculate the volume of gravel within the reach. This method assumes cross sections are parallel to one another, which can result in values that are not absolute but relative when used over time. Volume calculations could, therefore, be completed in the Turanganui study reach as cross-sections 19 and 20 are covered by the extent of the study reach.

Data was imported into a working folder, and the volume over time function was used. Then, the dates and cross-sections are specified. Cross sections 19 and 20 over 1992, 1997, 2005, 2010, 2017 and 2022 in this case. The reach definitions were then set; this involved setting the left and right banks, the distance between the cross sections and the common datum between cross sections. The datum was set to below the lowest point of both cross sections to get a baseline for volume calculation. The end area method was used as the volume calculation method and then executed. This produced graphical and tabular volume calculations for the cross sections specified over time.

5.0 Results

This chapter presents the fluvial geomorphological analysis of the Tauanui and Turanganui study reaches, the consecutive SFM survey analysis of the Tauanui and Turanganui Rivers and cross-section survey analysis. Hydrologic analysis is also presented. Decadal patterns of geomorphic change are examined within the study reaches and are compared with the SFM surveys that occurred before and after the June 2021 flood event in both rivers.

5.1 Geomorphic assessment

Digitising imagery of the Tauanui and Turanganui River study reaches and classifying them into geomorphic units presented a timeline of changes in river layout throughout the history of available imagery. It illustrated significant changes over time, with the June 2021 flood event resulting in significant changes that contrasted in scale between rivers. However, the changes observed were significant when put into a decadal context. Geomorphic changes in both reaches show a reduction in bare gravels and lightly vegetated areas due to significant encroachment of thick vegetation.

5.1.1 Tauanui geomorphic assessment

The mapping of the Tauanui study reach can be seen in Figure 61. The epochs 1944 through 1973 display large areas of active river channel, with an overall reduction in lightly vegetated bars and banks over time. The river's wandering, laterally active nature can be seen in 1961, where the wetted channel occupies the true left of the floodplain outside of the study frame. A slight increase in heavily vegetated areas is illustrated between 1944 and 1961, with the majority developing on the left bank. Major changes occurred in 1996 when a significant reduction in the bare gravel can be seen. Light vegetation increases on both sides of the river, with heavily vegetated areas also significantly increasing. Bare gravel further decreased from 2013, with increased sinuosity and the first instance of heavily vegetated bars present. Bare gravel appears to be further reduced in May 2021 as heavy vegetation encroaches on the bare gravels, some lightly vegetated abandoned channels become overgrown with heavy vegetation, and some paleochannels are reinitiated to wetted channels. Following the June 2021 flood event, the wetted channel reverts to one dominant channel, and an overall reduction in both classifications of vegetation as a result of expanding bare gravel. The bare gravel increases to a size not recorded since 1996.

Quantification of the Tauanui study reaches morphology shows from 1944 to 1961 (Figure 61) a 26.4% increase in bare gravels to 73.1% of the study reach. This increase contrasts with a 25.5% decrease in lightly vegetated areas. Heavy vegetation increased steadily from 11.4% to 28.8% from 1944 to 1973. Conversely, light vegetation was reduced by 30.3%. Dramatic changes were recorded between 1973 and 1996 when the bare gravels reduced from 62.2% to 14.2%, and heavy vegetation began to dominate the study reach as it increased from 28.8% to 58%. This trend further proliferated in 2013 when all other geomorphic classes were reduced in exchange for a 16.3% increase in heavy vegetation, and the bare gravels nearly halved to 7.7%. Channel characteristics appear to stabilise by May 2021, where heavy vegetation is still dominant and bare gravel takes up 7.9% of the study area. Following the June 2021 flood event, the November 2021 survey shows the bare gravel nearly doubled to 13.3%, and for the first time, heavily vegetated areas reduced 3.8% to 74.5% of the study reach.

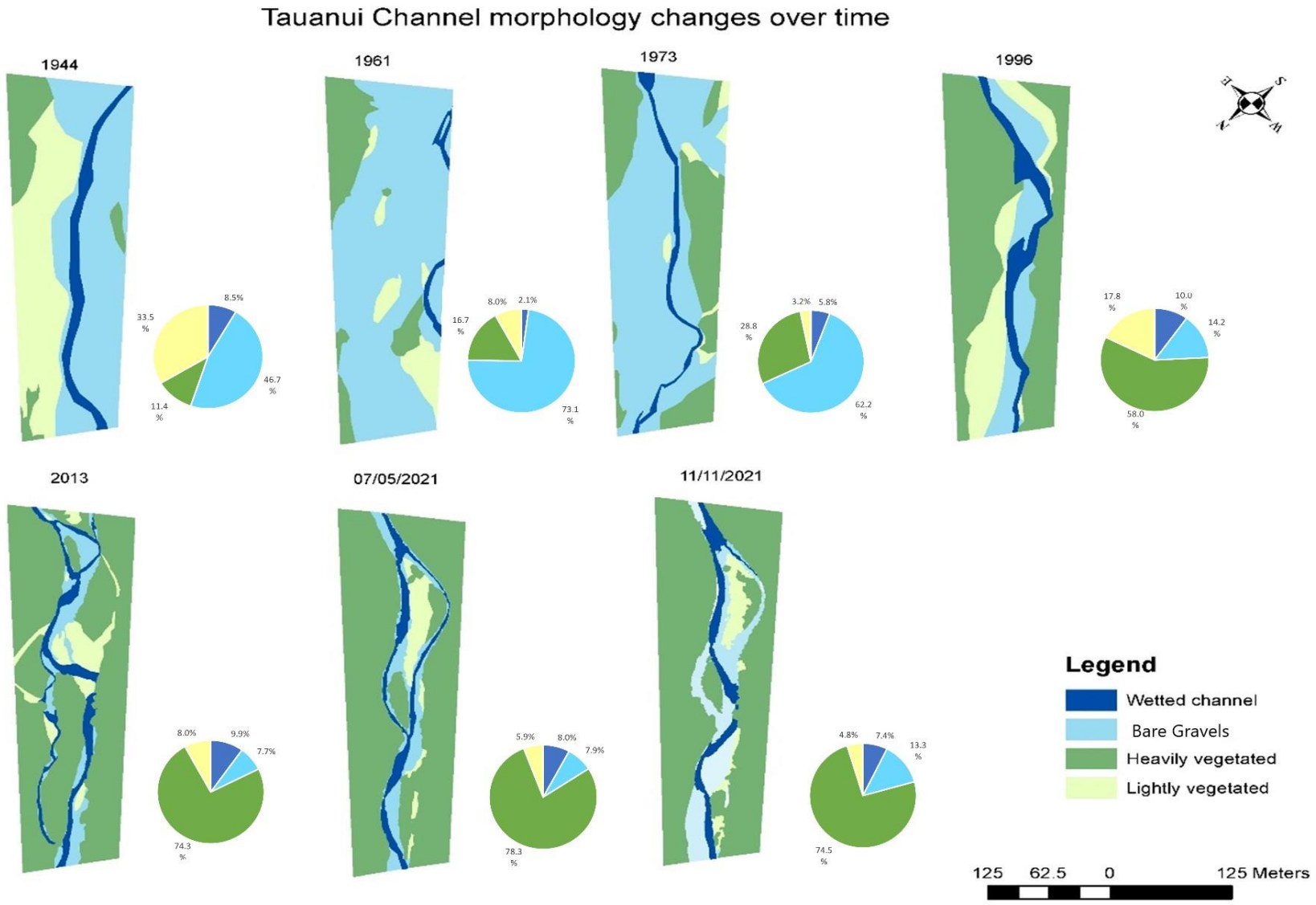


Figure 61: *Geomorphic survey for Tauanui* River *from 1944 to 2021.*

5.1.2 Turanganui River geomorphic assessment

The mapping of the Turanganui study reach can be seen in Figure 62. In 1946, the Turanganui River wetted channel followed the true right of the floodplain in a braided fashion, out of the study reach frame. Several vegetated bars can be seen, and large bare gravel areas are present. Widening bare gravels occurred in 1961, with the wetted channel migrating to the centre of the study reach, still maintaining a braided planform. In 1973, heavy vegetation began encroaching on the bare gravel, with some light vegetation growing on the right bank. The wetted channel's planform changed to a single dominant channel with low sinuosity in 1996. The bare gravels progressively reduced from 1996 to May 2021, with some abandoned meanders reverting to light vegetation. Over this period, a dominant main wetted channel is present. Following the June 2021 flood event, bare gravel significantly increased throughout the study reach to an extent not previously observed before 1996. Wetted channel sinuosity significantly increases, and previous channels are reverted to bare gravels. Both types of vegetation are reduced.

Quantification of the geomorphic assessment of the Turanganui River study reach further illustrates the changes observed (Figure 62). The Turanganui study reach from 1946 to 1961 shows dominant bare gravels that increased from 14.9% to 69.9% in 1961. Overall vegetation cover is at its lowest observed occurrence at 19% in 1961. This dramatically increased in 1973 when heavily vegetated areas became the dominant geomorphic unit, taking up 48% of the study reach. Bare gravels reduce to 41.1%. In 1996, heavy vegetation further increased and now takes up 75.6% of the study reach. Bare gravel more than halves to 16.5 % in this period. This trend continued in 2013 when vegetation increased further, and bare gravel reduced from 10.2% to 6.3%. Notable changes from 2013 to May 2021 are a reduction in lightly vegetated areas, an increase in heavy vegetation, and a slight reduction in bare gravels. Following the June 2021 flood event, the September 2021 survey shows a significant 19.3% increase in bare gravel to a level not observed since before 1996. Conversely, heavy vegetation cover reduces to 66.6%, which has not been observed since before 1996.

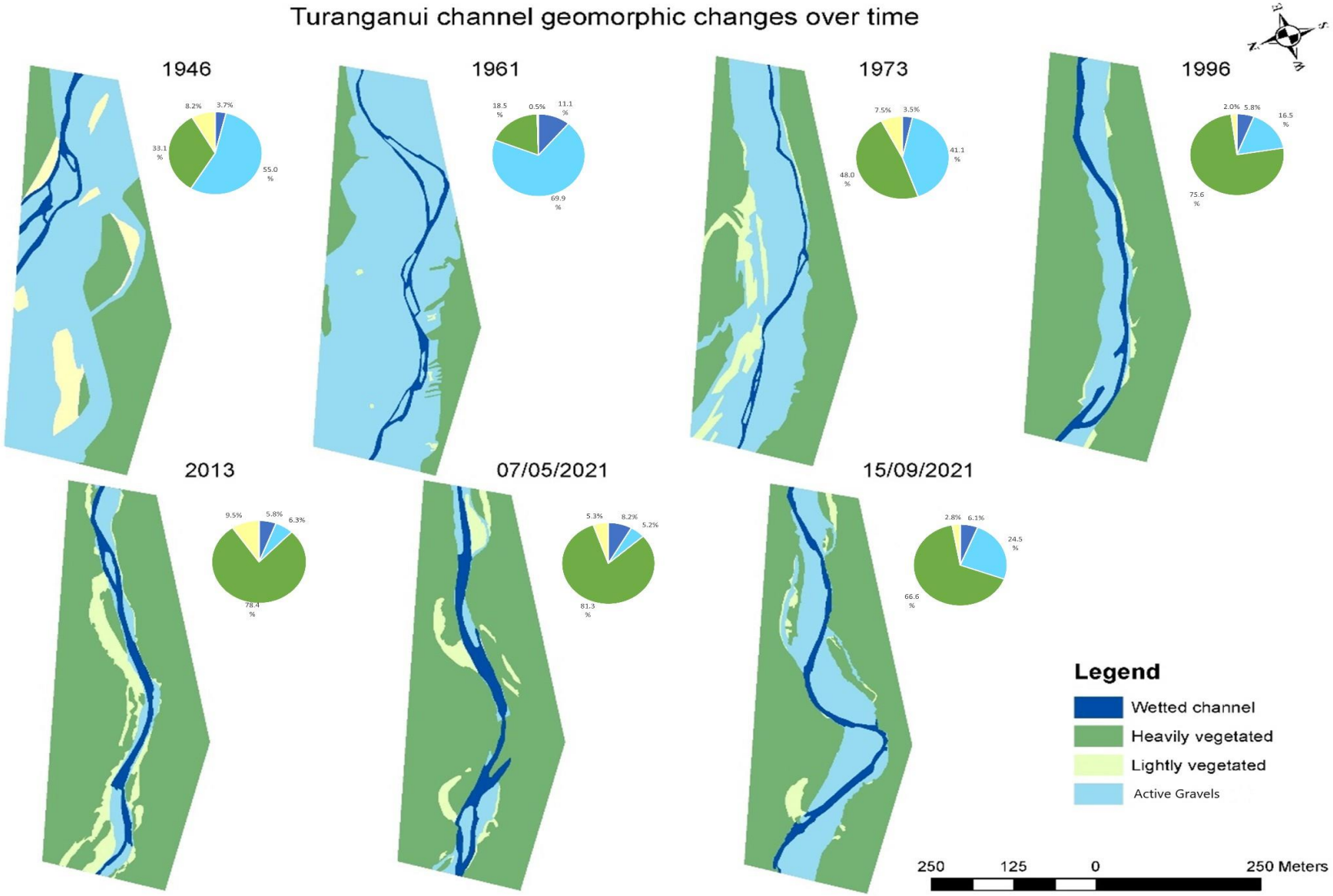


Figure 62: Geomorphic survey for Tauanui River from 1944 to 2021.

5.2 Cross-section survey analysis

Historic cross-section survey data for the Tauanui and Turanganui Rivers have been collated and analysed to show variations in bed levels over time to give insight into sediment flux throughout the areas monitored. Both rivers show changes in bed level over time, with the upper cross sections of the Tauanui aggrading and the lower cross sections degrading due to river diversion. Aside from these realignments, some other channels have migrated in recent times, with bed levels increasing and some channels narrowing. The Turanganui River cross sections show mean bed levels in the upper catchment degrading and the lower catchment aggrading. Many cross-sections show channels incising further than previously recorded, along with a narrowing of channels.

5.2.1 Tauanui cross-section survey analysis

Figures 63 and 64 display mean bed level changes throughout the history of cross-section surveying in the Tauanui River. Figure 63 shows cross-sections 1 and 2 of the Tauanui have aggraded, likely due to being diverted to the true right of the historical channel, as seen in Figure 65 and Figure 66. Cross section 3 in Figure 63 shows the channel has aggraded since surveys began, followed by channel narrowing and incision in more recent times. Cross sections 4 and 5 in Figures 63 and 64 show a similar pattern of aggradation followed by incision. However, as seen in Figures 63 and 64, channel migration has occurred in cross-sections 1,2,4 and 5. Cross sections 1 and 2 have had their channels anthropogenically modified, as seen in Figures 65 and 66. Cross section 6 shows the channel has aggraded until 2010, followed by incision and aggradation. Cross-section 7 shows that channel morphology has stayed relatively constant, with some aggradation and channel narrowing occurring in recent times.

A collation of cross-section survey data for the Tauanui River is illustrated in Figures 67 and 68. Figure 67 depicts all cross-sections except Cross section 7, aggrading from 2000 to 2010, followed by overall degradation of the cross-section beds in 2017. Cross sections 1 and 2 degrade to lower levels than the first surveys completed in 2000. Cross section 7, however, degrades from 2000 to 2005, where bed levels then slightly aggraded in 2010. In 2017, bed levels aggraded to a height greater than since surveys first began in 2000. Figure 68 shows bed level changes from 2000 to 2017. The trend observed is that the lowest two cross-sections degraded, and the rest aggraded approximately 0.2m, except for cross-section 7, which aggraded over 0.6m over this timeframe. The cross-section channel sequence seen in Figures 63-64 shows that in 2017, all cross-sections except cross-section 7 changed their channel shape. This is likely the result of GWRC diverting the lower reaches of the Tauanui River into adjacent land to form a delta system (Cyril, 2009). This was because of increasing sediment deposition seen in cross sections 1-6 posing a threat to the Ruamahanga diversion, where sediment deposition into the Ruamahanga diversion was narrowing the Ruamahanga channel, posing a flood capacity risk (Figure 65). Realignment of the channel has likely influenced sediment dynamics within these lower reaches, resulting in bed-level changes.

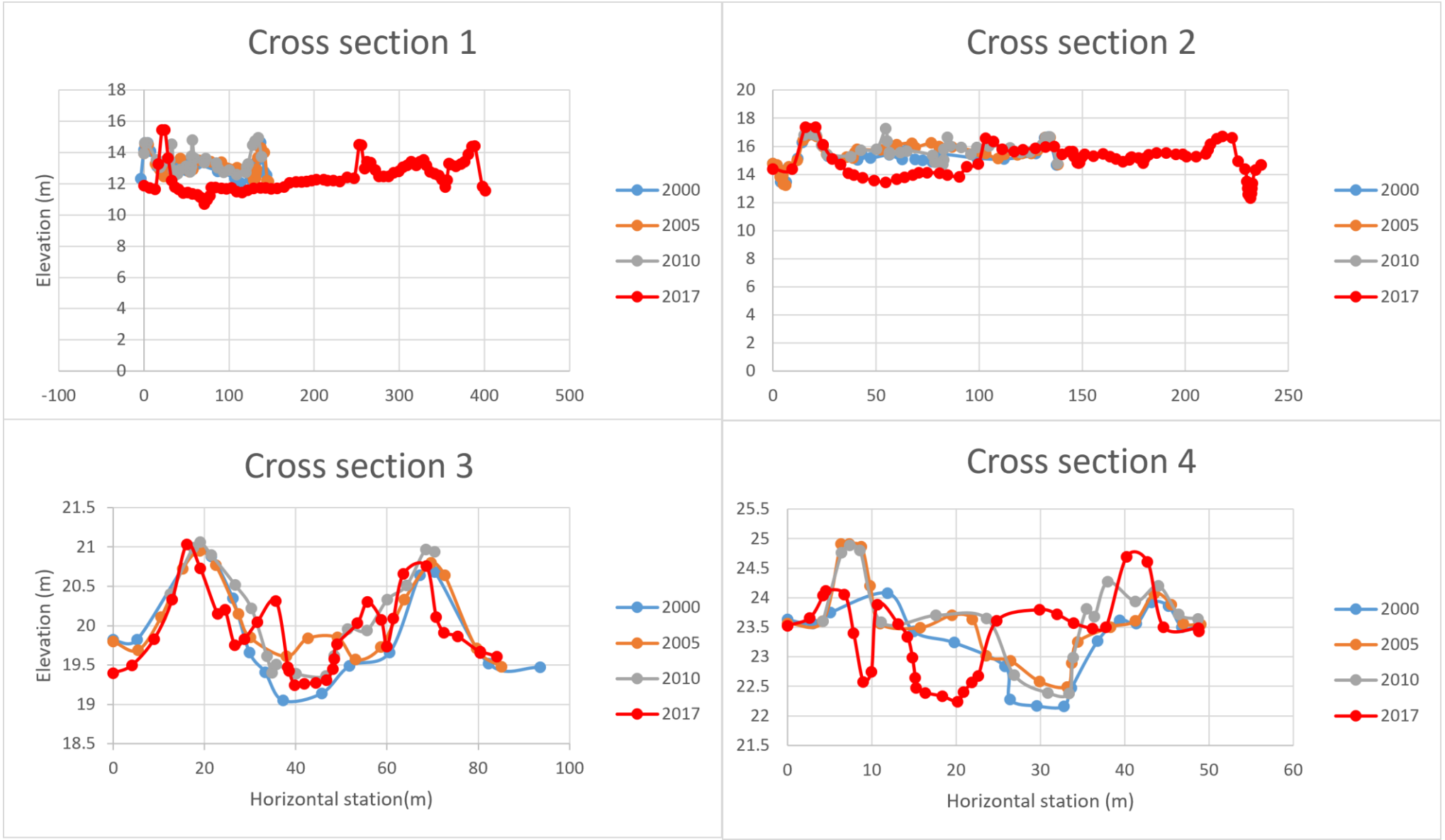


Figure 63:Tauanui Cross sections 1-4.

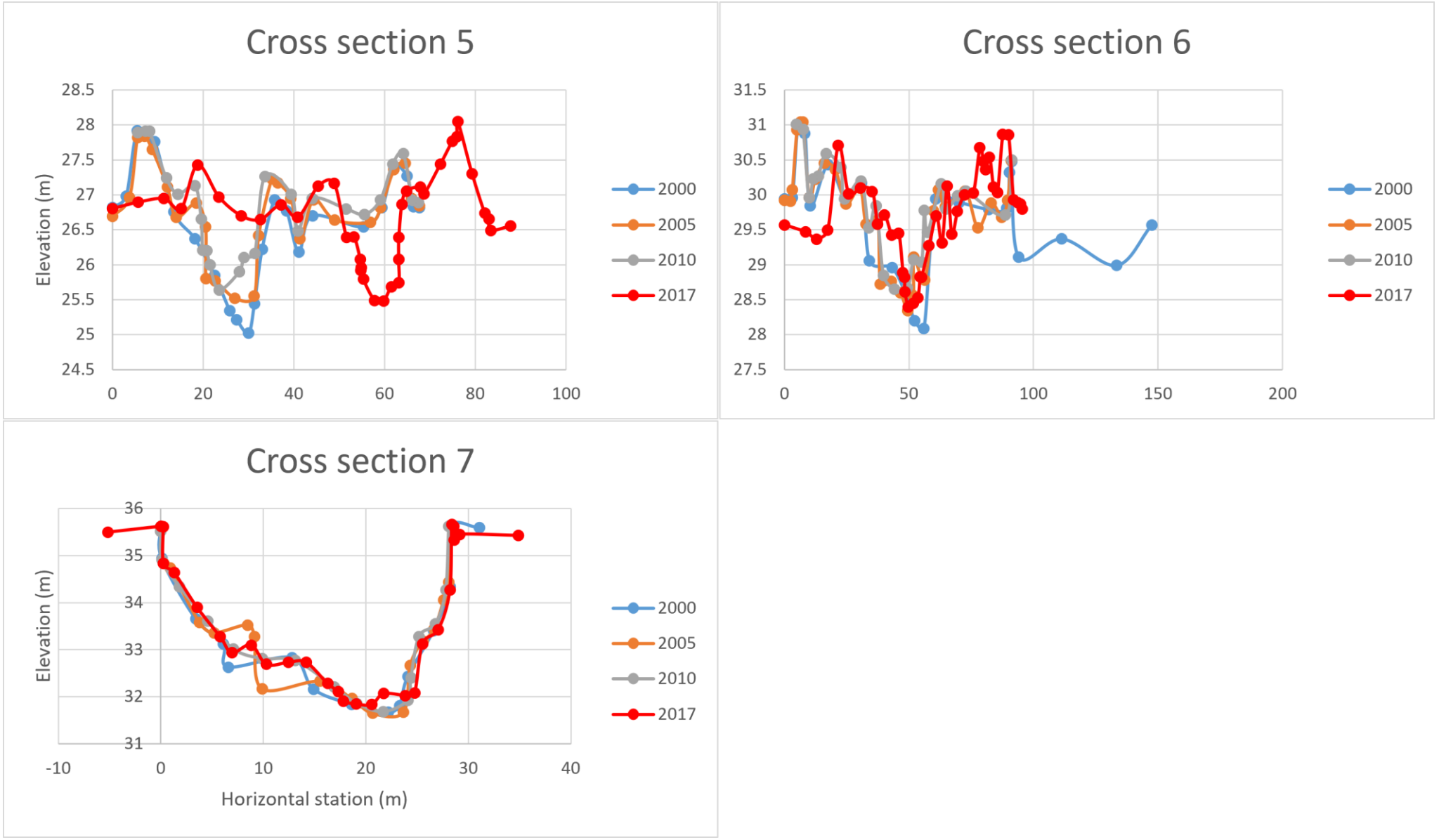


Figure 64 Tauanui Cross sections 4-7.

Figure 65: Tauanui outlet in 2012 (LINZ, 2023).

Figure 66: Tauanui outlet in 2021 (LINZ, 2023).

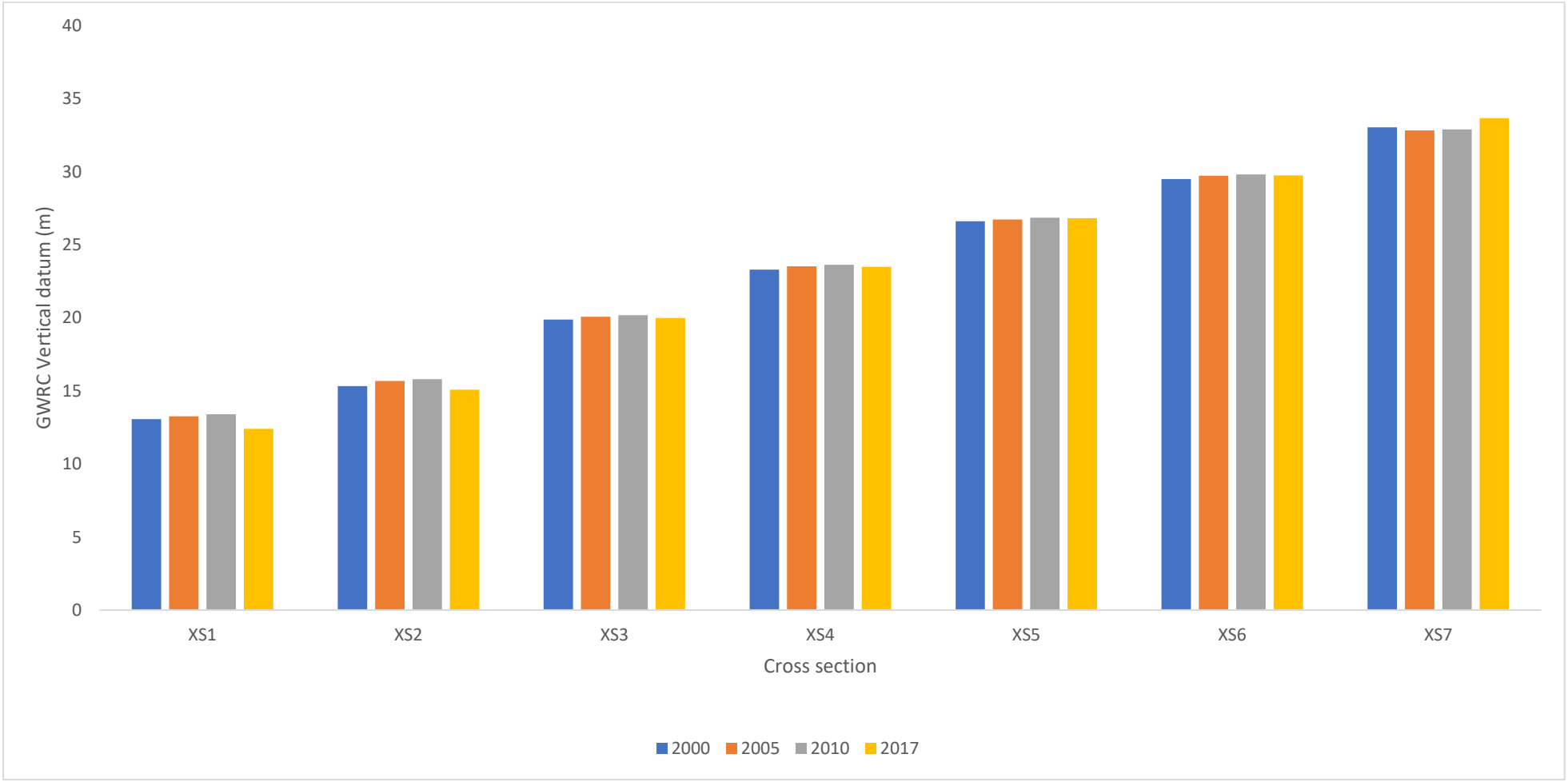


Figure 67: *Tauanui mean bed level changes over time*.

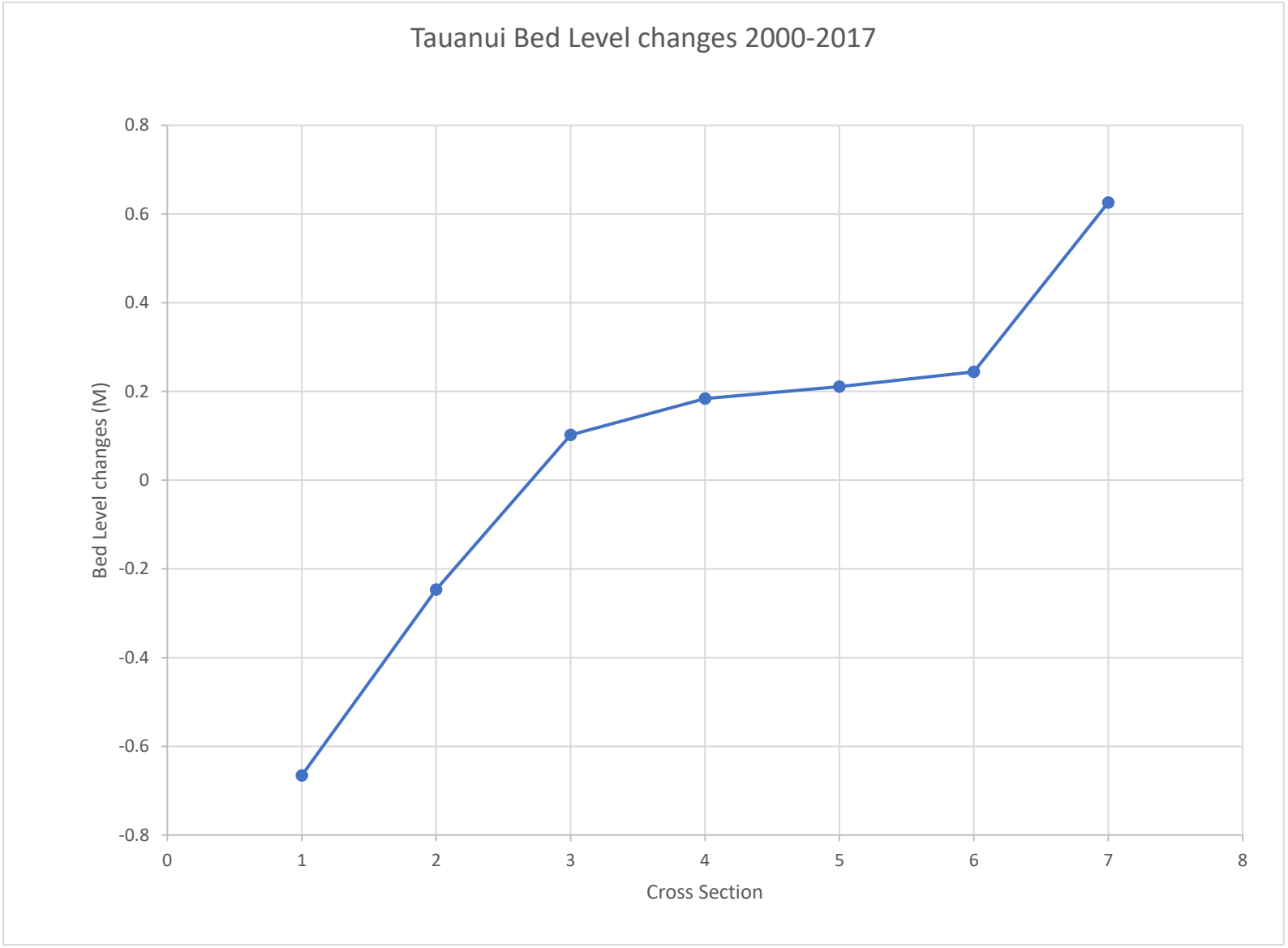


Figure 68: *Tauanui Riverbed level changes from 2000-2017*

5.2.2 Turanganui cross-section survey analysis

The collation of mean bed levels derived from cross-section survey data for the Turanganui River is illustrated in Figure 69. The overall trend observed throughout the monitored cross sections is slight degradation from the first surveys in 1991 until 2005-2007, where aggrading cross sections can be observed. This trend of aggradation continued until 2010. the general trend of the 2017 survey is degradation throughout all cross sections. Figure 70 illustrates a comparison of cross-section changes from the first survey in 1991 to the most recent in 2017. The trend is overall aggradation in the lower catchment and the opposite in the upper catchment, where a degradational trend is observed. Figure 78 shows cross-section changes between cross-sections 19 and 20 on the study reach of the Turanganui. These cross sections show steady degradation over time, with an outlying aggradation phase in 2022. Table 3 illustrates the change in cross-section sediment volume over time between cross-sections 20 and 21, which is the location of the Turanganui study reach. Bed volume decreased from a peak of 398800m³ from the 1991 survey to a low of 345873m³ in 2017. This trend then reverses as volumes increase to 369879m³ in 2022.

Figures 72 to 78 show a graphical illustration of the Turanganui River cross-section surveys. Cross sections 1 to 4 show a peak of aggradation in 2010, followed by degradation to 1991 levels or lower in 2017. Cross section 5 shows steady bed aggradation followed by a large deposition of sediment on the left bank; the right bank is also eroded. Cross-section 6 shows a highly variable bed level, with the highest bed levels observed in 2010, followed by significant erosion and channel narrowing in 2017. Cross sections 7 and 8 show aggradation from 2005 -2010, followed by erosion in 2017; cross section 8 shows incision occurring. Cross sections 9 and 10 show significant erosion since 2010/2011, with channel migration to the right. Channel migration can also be seen in cross-section 11, where the channel has moved back to its 1996 position and is significantly narrower than in 2011. Cross sections 12 and 13 show channels narrowing and degradation to levels not previously recorded. 14 through 16 show similar trends, where the bed has degraded below 1991 levels, with channels laterally migrating in cross-sections 15 and 16. The remaining cross sections from 17 to 26 show significant channel incision, many to levels not previously recorded.

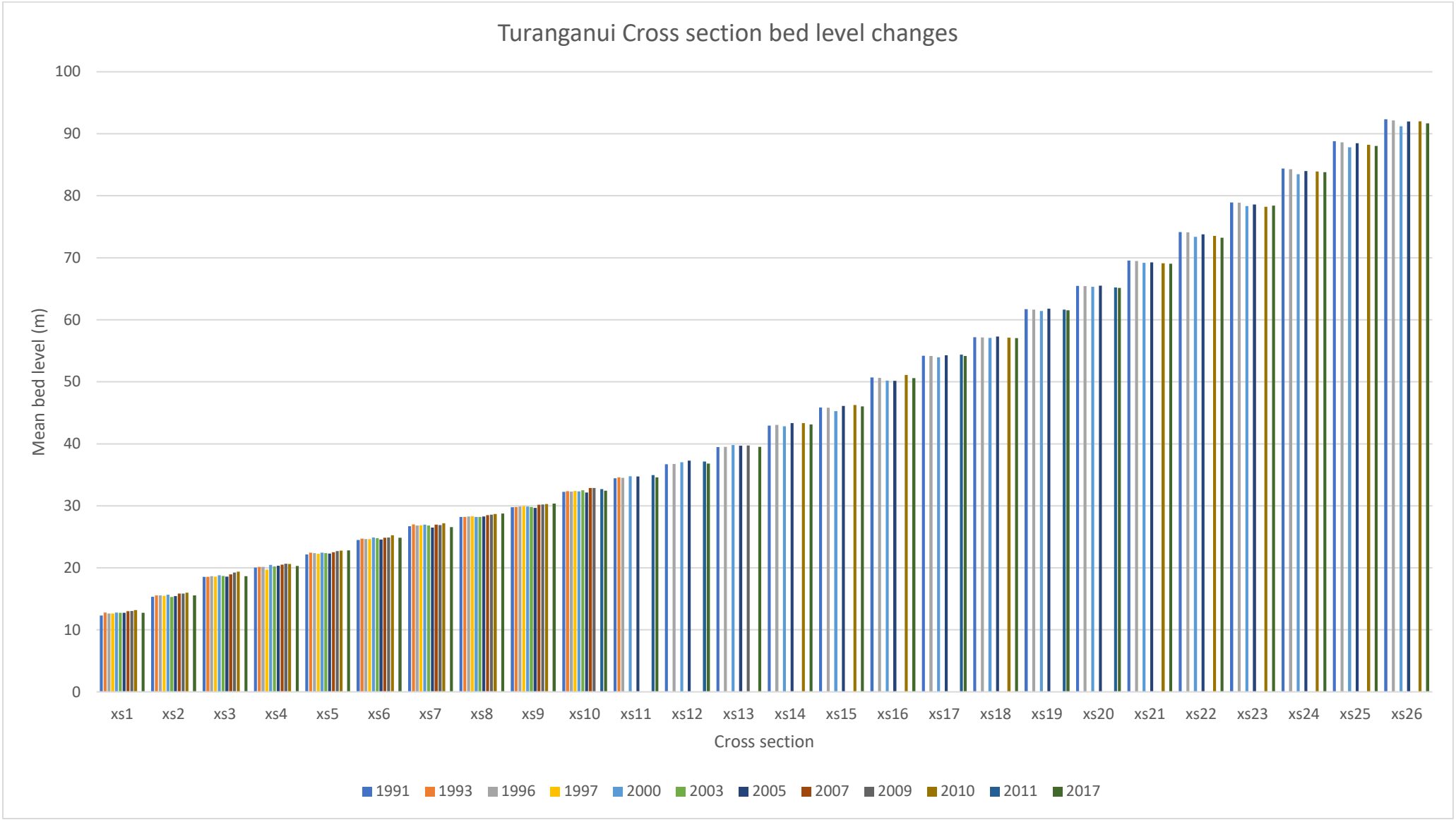


Figure 69: Turanganui mean bed level changes over time.

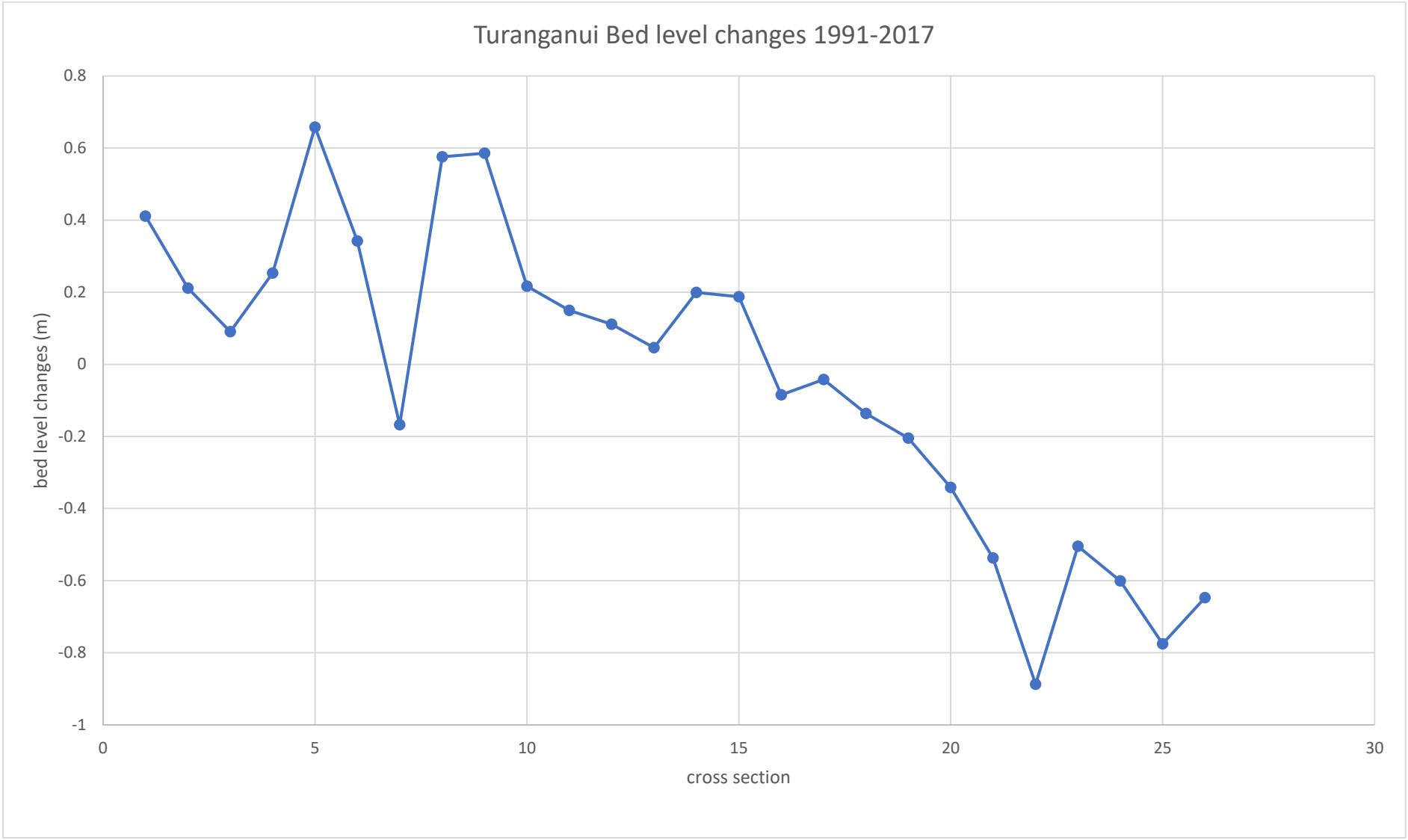


Figure 70: Turanganui Riverbed level changes from 1991-2017.

Table 3: Volume over time calculations for Turanganui cross sections 19 and 20.

```
~~~ Volume over Time Ver 1.3 ~~~
Reach study site from  1-Mar-1991 18:00:00 to 15-Mar-2022 18:00:00
Datum =   71.457 metres.
Volume calculation uses the End Area method

       Time                Volume
                          (metres)
   1-Mar-1991 18:00:00    398800
   3-May-1996 18:00:00    393860
  14-Jul-2000 18:00:00    385869
  11-Mar-2005 18:00:00    375905
  15-Dec-2010 18:00:00    363914
   2-Mar-2017 12:00:00    345873
  15-Mar-2022 18:00:00    369879
```

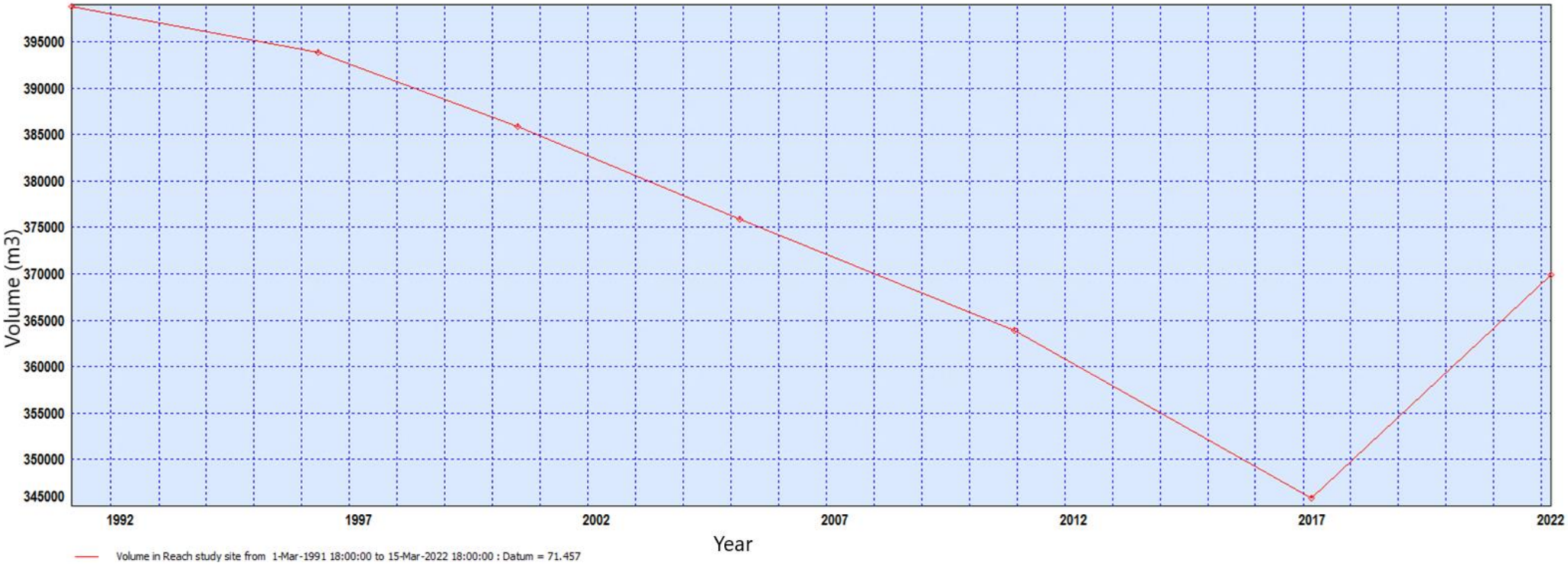


Figure 71: Volume over time calculations for Turanganui cross sections 19 and 20.

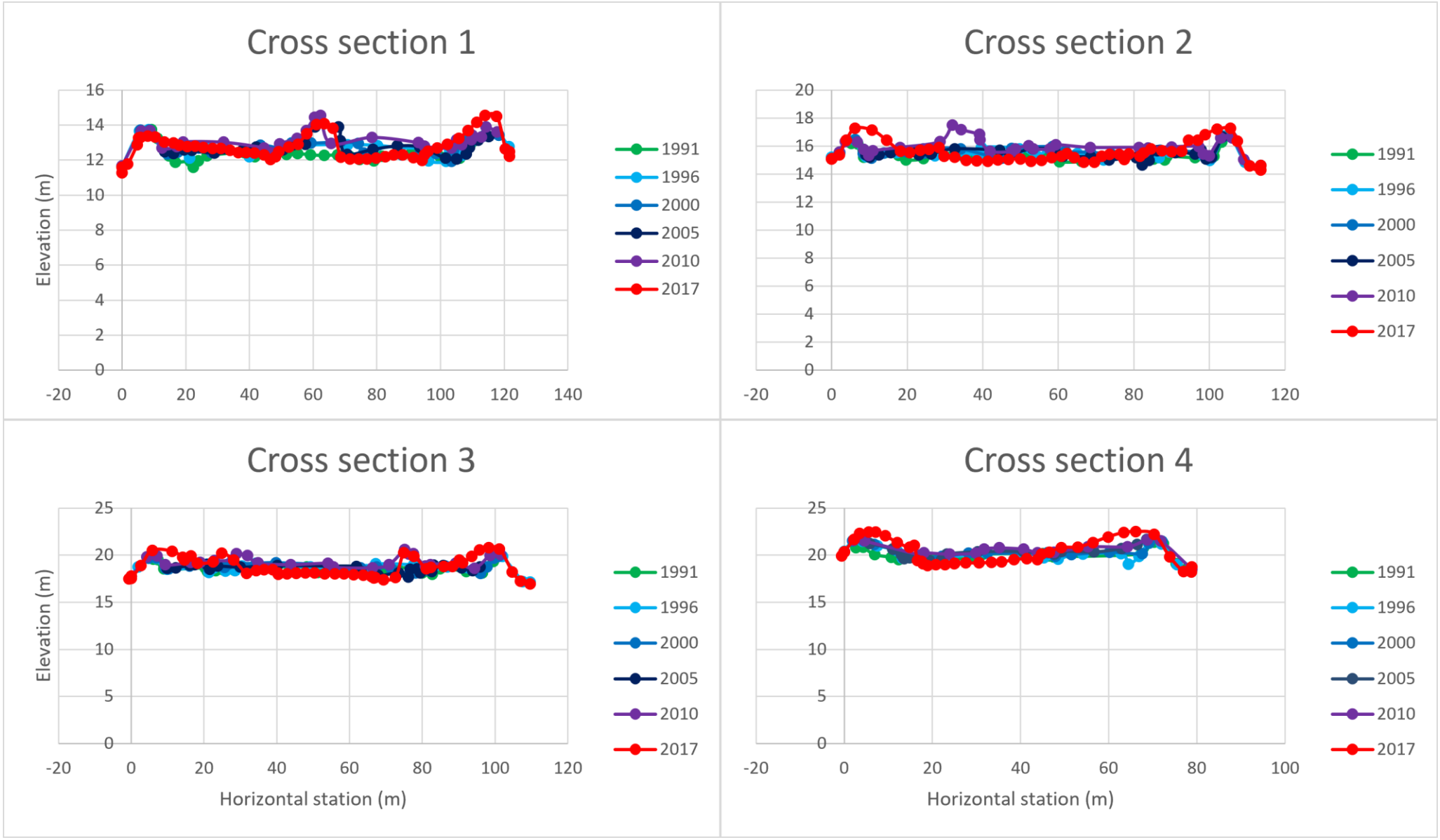


Figure 72: Turanganui cross sections 1-4.

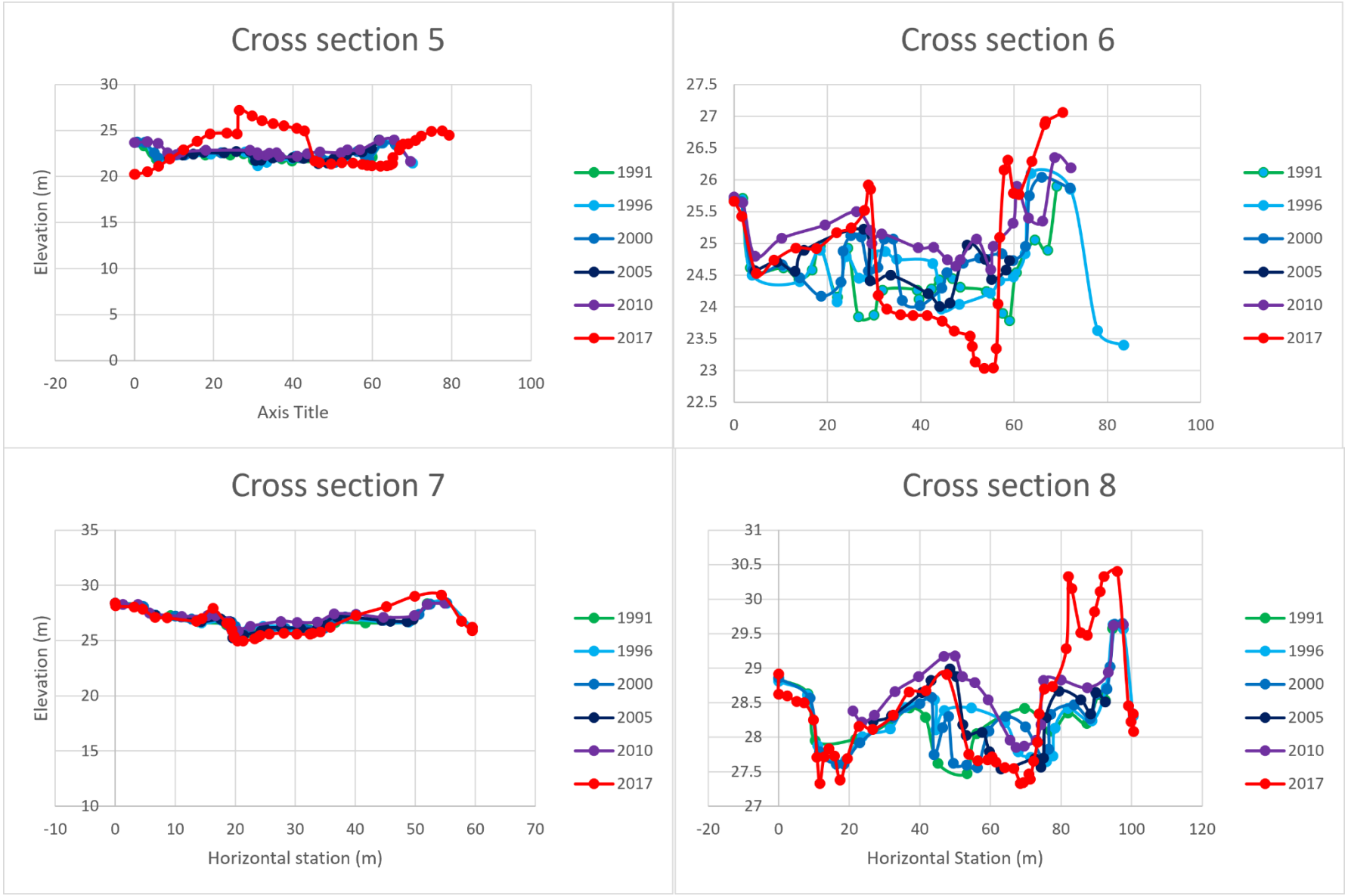


Figure 73: Turanganui cross sections 5-8.

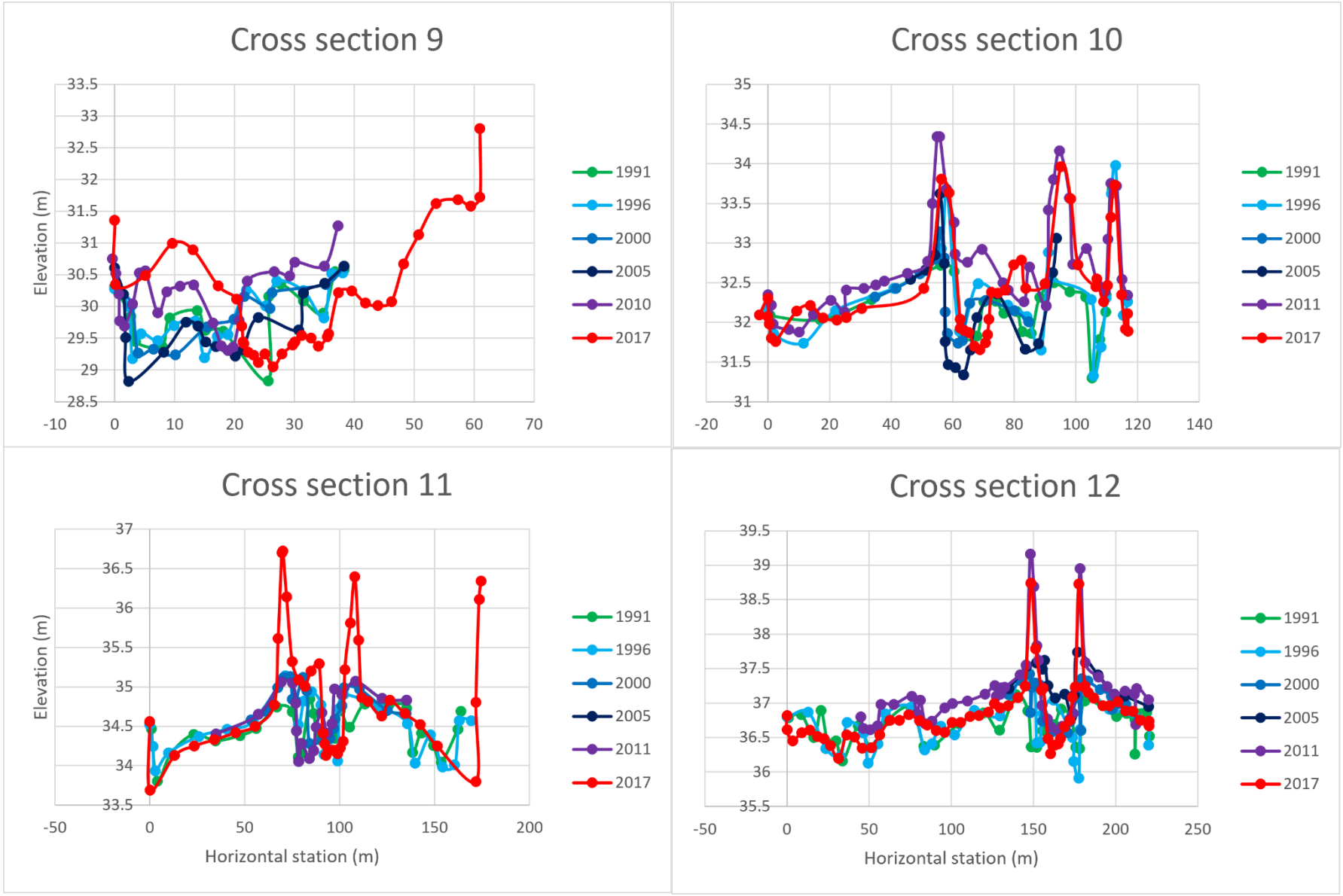


Figure 74: Turanganui cross sections 9-12.

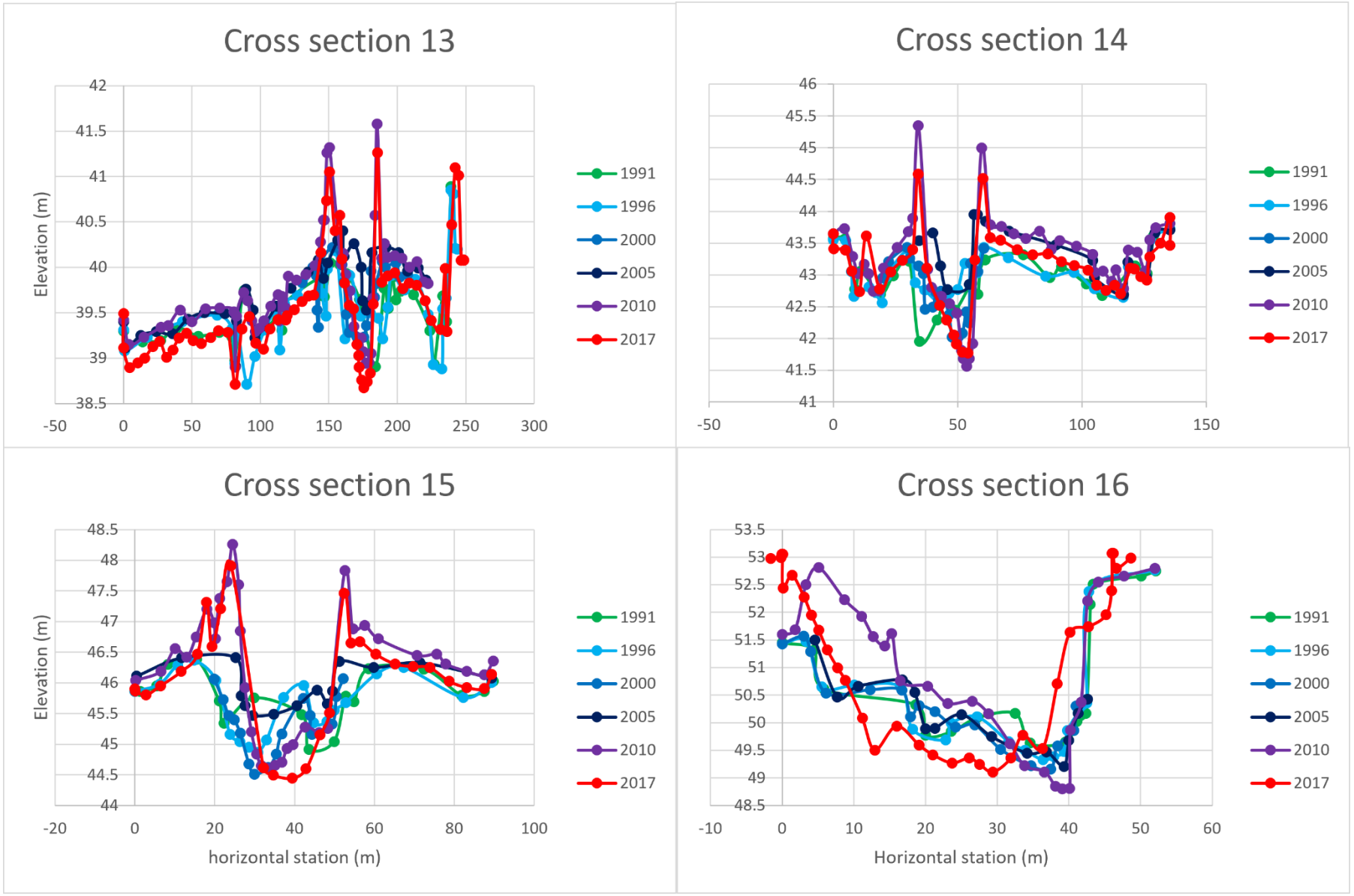


Figure 75: Turanganui cross sections 13-16.

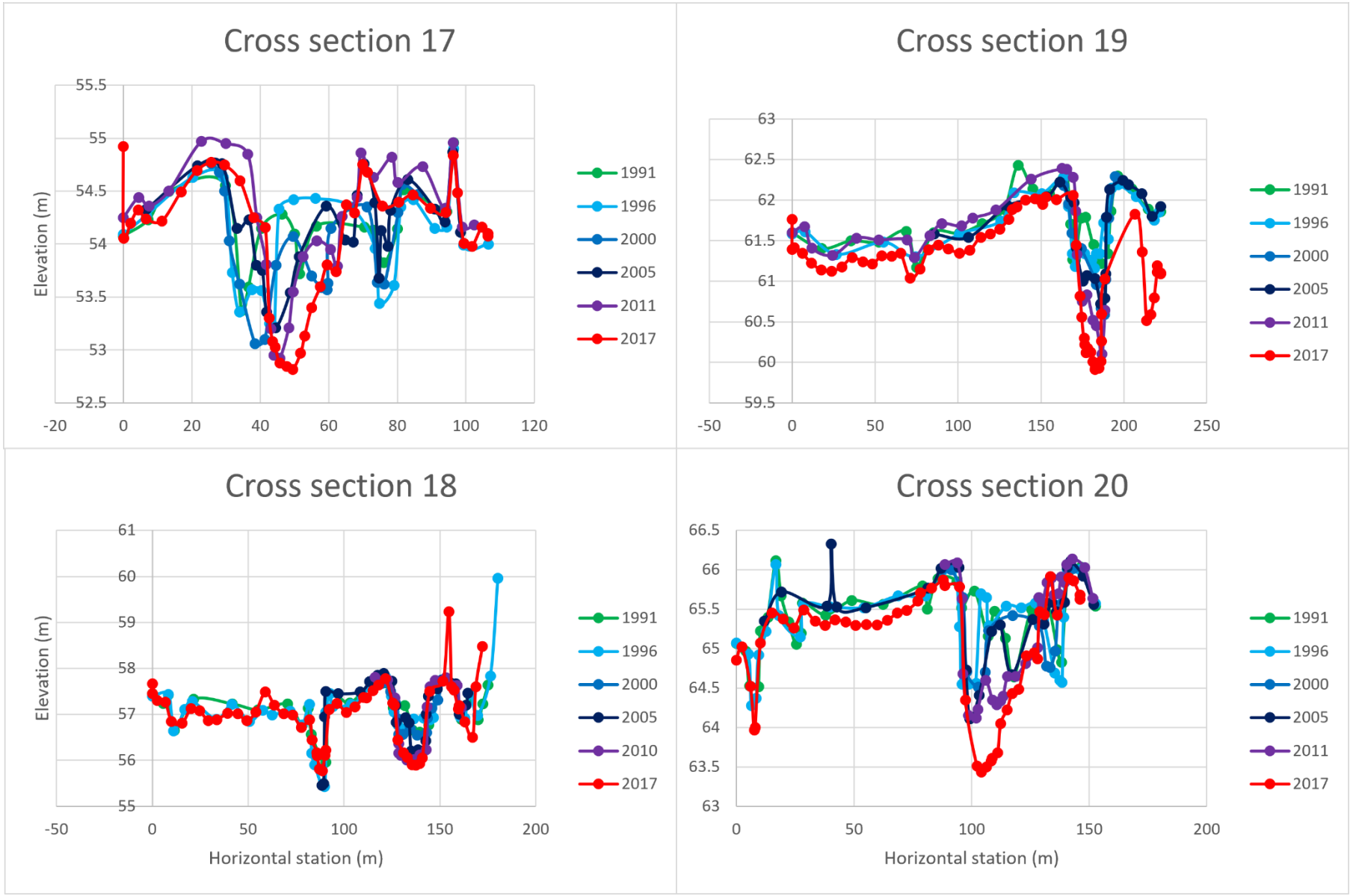


Figure 76: Turanganui cross sections 17-20.

Figure 77: Turanganui cross sections 21-24.

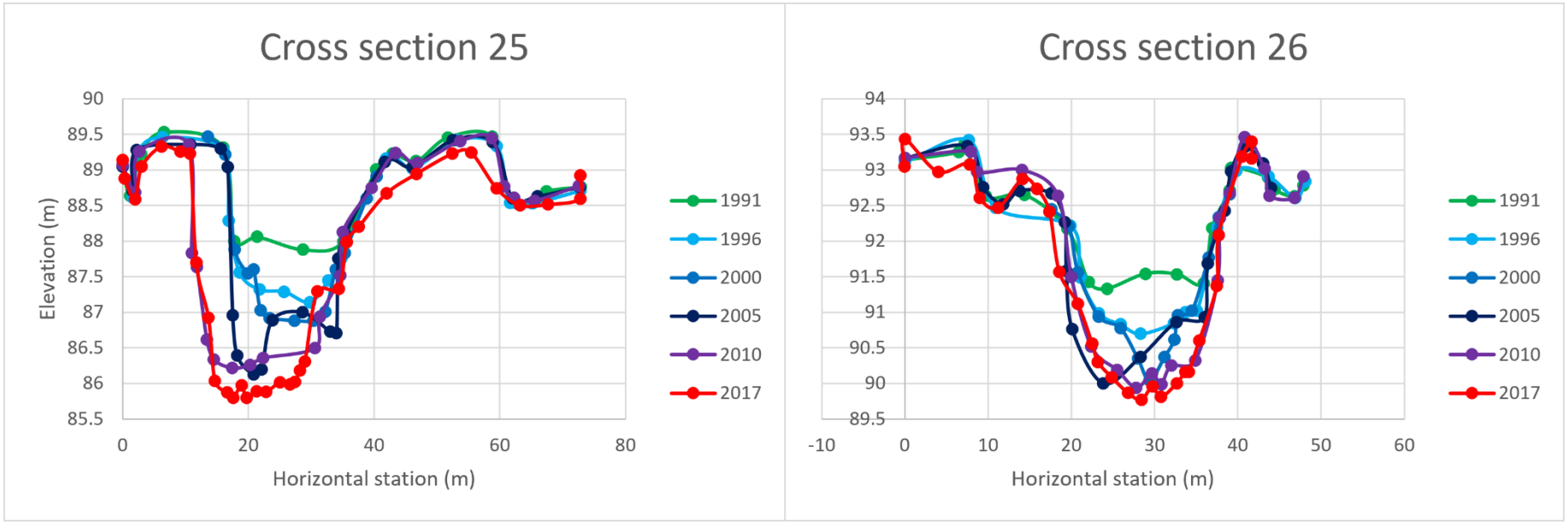


Figure 78: Turanganui cross sections 25-26.

5.3 SFM Survey RMS error

Table 4 shows the RMS error calculated for all surveys conducted on the Tauanui and Turanganui Rivers, calculated using benchmarks and ground control points when benchmarks were unavailable.

Table 4: SFM Root mean square (RMS) error calculated for both study reaches.

survey site	Benchmark Name	1st survey RMS error (m)	2nd survey RMS error (m)
Turanganui	GCP018	0.062	0.134
Tauanui	BM01	0.176	0.179

5.4 SFM survey analysis of Tauanui River

The orthophotos and DEMs produced of the Tauanui River using the SFM method can be seen in Figures 79 and 80. The May 2021 orthophoto shows a narrow, two-threaded channel with some lightly vegetated and bare gravel lateral bars. Mid-channel bars tend to be populated with light and heavy vegetation that is a mix of exotic and native species. The November 2021 orthophoto produced from the survey following the June 2021 flood event shows channel widening throughout, although most prevalent in the lower portion of the study reach with larger bare gravel lateral bars and significantly less light vegetation in the channel. Vegetated mid-channel bars appear to have been reduced in size. A previously abandoned channel has been reinitiated in the centre of the study reach, and a dominant single channel is now present.

The DEMs produced can be seen in Figure 80 and reflect the changes observed in the orthophotos. However, the DEM possesses significant vegetation artefacts on the banks, and some minor vegetation artefacts are present within the mid-channel bars. Bed Morphology can be seen in both DEMs, such as gravel deposits forming lateral bars.

The DoDs produced using the pair of DEMs of the Tauanui show the sediment flux patterns throughout the channel of the study reach (Figure 81). The DoD shows degradation at the top of the study reach that extends into the centre of the study reach, where an abandoned channel was reoccupied. Aggradation is present throughout the rest of the study reach where channel widening occurred, except for the lowest section of the study reach where degradation occurred as the river occupies the location of a vegetated bar in the May 2021 imagery. Table 5 displays the quantification of sediment movement illustrated in the DoD, which shows the Total volume difference detected is 3343m³. This is comprised of degradation of 889m³ and 2,454m³ of aggradation. This results in a net aggradation of 1564m³ in the area of interest within the study reach.

Figure 79: Orthometric photos from drone imagery for Tauanui River study reach.

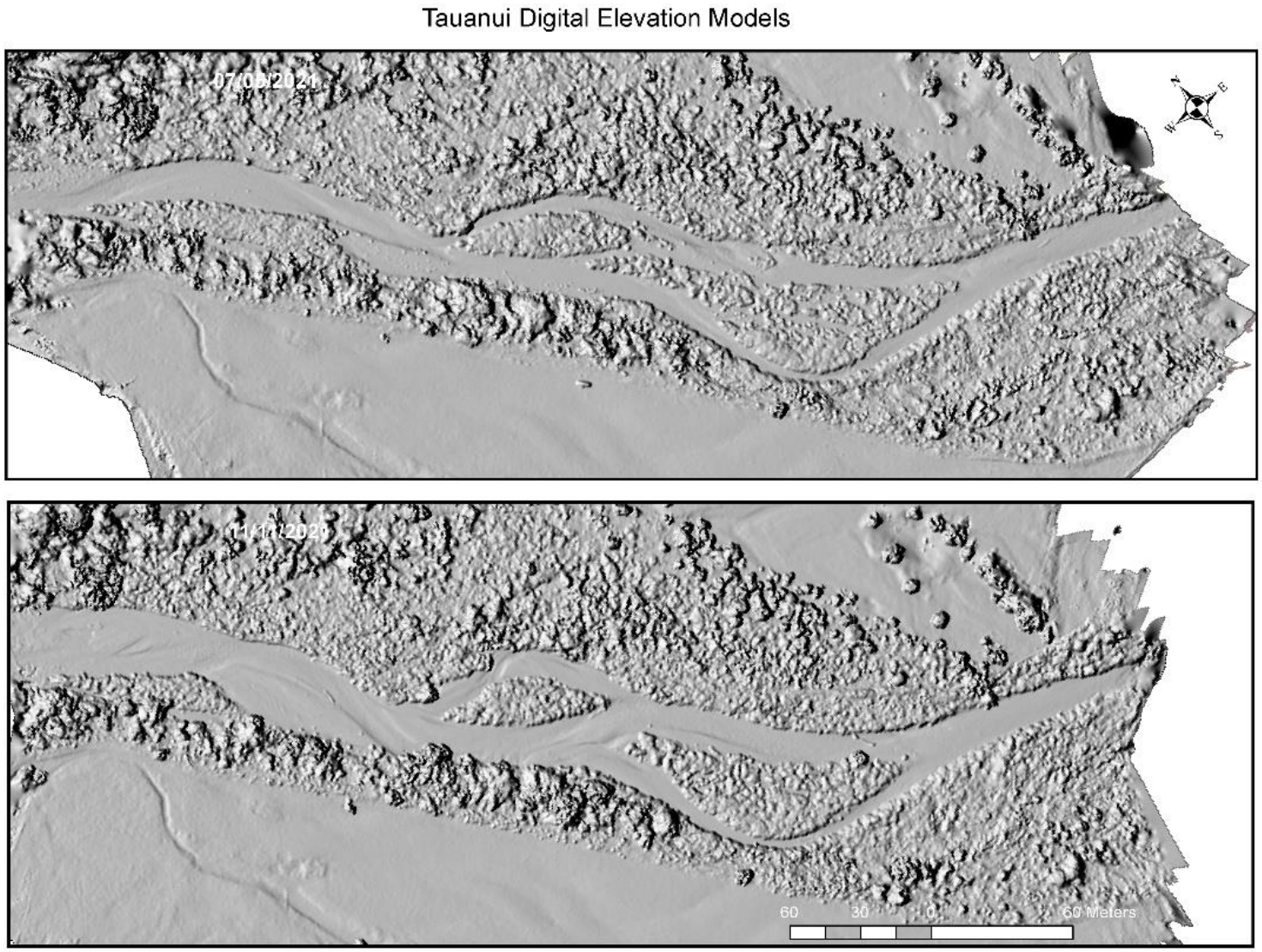


Figure 80: Digital elevation model from drone photogrammetry for Tauanui River.

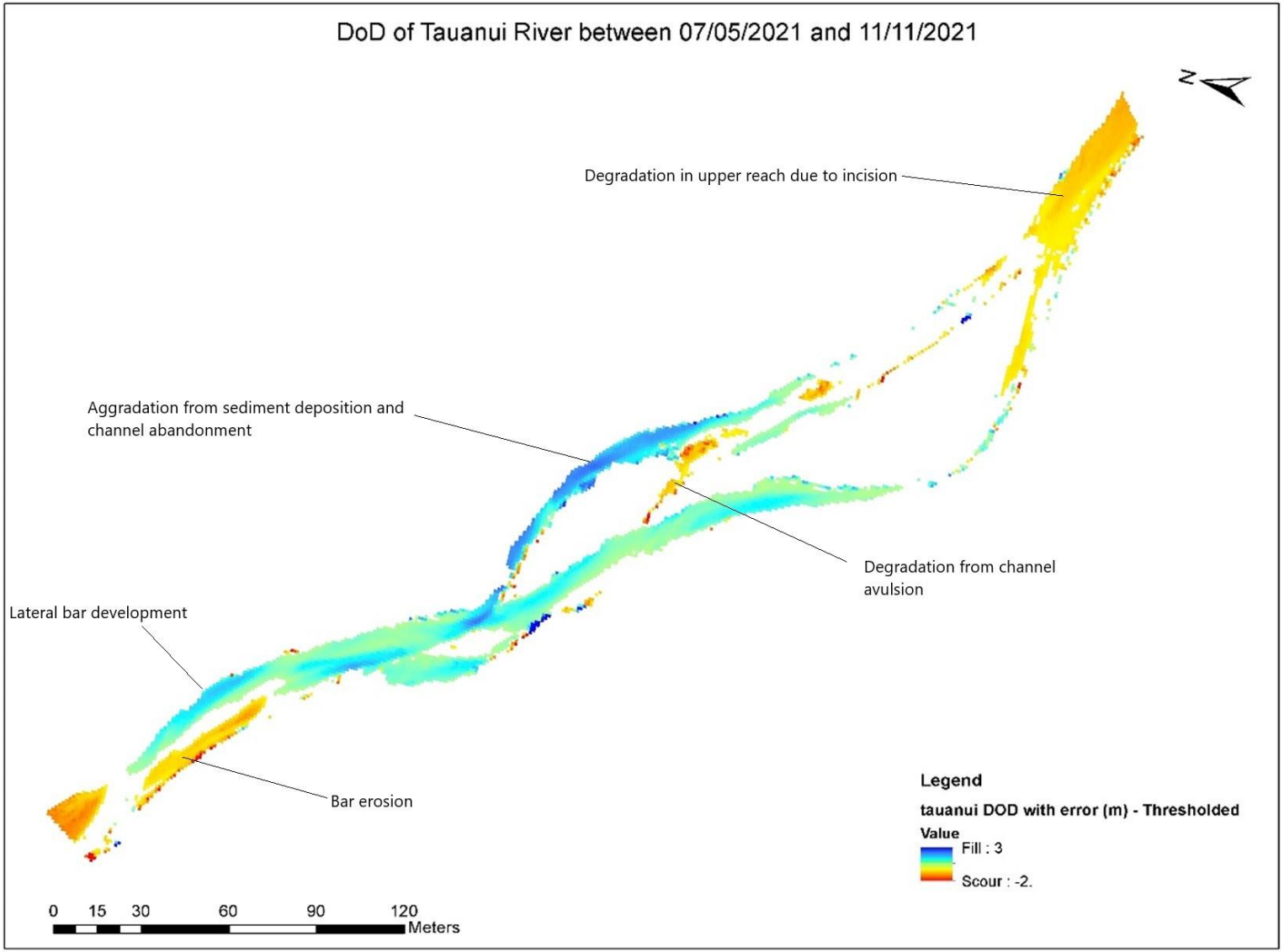


Figure 81: Digital elevation model of difference derived from photogrammetry for Tauanui River

Table 5 Tauanui study reach DoD volumetric calculations.

Tauanui DoD Summary

Attribute	Raw	Thresholded DoD Estimate:		
AREAL:				
Total Area of Surface Lowering (m²)	3,289	1,812		
Total Area of Surface Raising (m²)	4,780	3,677		
Total Area of Detectable Change (m²)	NA	5,489		
Total Area of Interest (m²)	8,069	NA		
Percent of Area of Interest with Detectable Change	NA	68%		
VOLUMETRIC:			± Error Volume	% Error
Total Volume of Surface Lowering (m³)	1,086	889	± 499	56%
Total Volume of Surface Raising (m³)	2,599	2,454	± 1,012	41%
Total Volume of Difference (m³)	3,686	3,343	± 1,511	45%
Total **Net** Volume Difference (m³)	1,513	**1,564**	**± 1,129**	72%

5.5 SFM survey analysis of Turanganui River

The orthophotos and DEMs produced of the Turanganui River using the SFM method can be seen in Figures 82 and 83. The May 2021 orthophoto shows a dry wandering multi-threaded channel consisting of several bare gravel and some lightly vegetated mid-channel bars. Some gravel lateral bars are also present. Three historic meanders can be seen that had laterally eroded historically but have been densely planted with willow species to maintain a straight planform and reduce further erosion of the farmland on the floodplain. Most of the banks are heavily vegetated with exotic tree species. The September 2021 imagery shows significant changes in the study reach. Significant channel widening has occurred, and the wetted channel has increased sinuosity as a result of lateral erosion. The increase in sinuosity has resulted in the reestablishment of two historic meanders, resulting in significant bank erosion on both sides. Point bars are significantly larger, and some of the vegetated mid-channel bars are reduced in size or gone entirely. Large woody debris can also be seen throughout the bare gravel.

The DEMs produced (Figure 83) also reflect these observations seen in the orthophotos. However, the riverbed morphology is better defined, displaying gravel formations created by riffle pool sequences in both images and flood flows in the September 2021 imagery. Significant vegetation artefacts can be seen on the banks, bars and historic meanders of both DEMs. Artefacts from vegetation debris on the bare gravel can be observed in the September 2021 DEM.

The DoD for the Turanganui seen in Figure 84 shows significant erosion in the upper portion of the study reach where the wetted channel has migrated, a side channel has been reinitiated, and vegetated mid-channel bars have been reduced. The centre of the study reach shows large amounts of aggradation from the development of lateral bars and the deposition of vegetation debris. The lower portion of the study reach displays a combination of aggradation and degradation from gravel deposition and bar removal. The quantification of the DoD (Table 6) shows that the total volume difference detected is 10,502m³. This is made up of 3,536m³ of sediment degradation and 7,087m³ of sediment aggradation, resulting in net aggradation of 3,431m³ throughout the area of interest in the study reach.

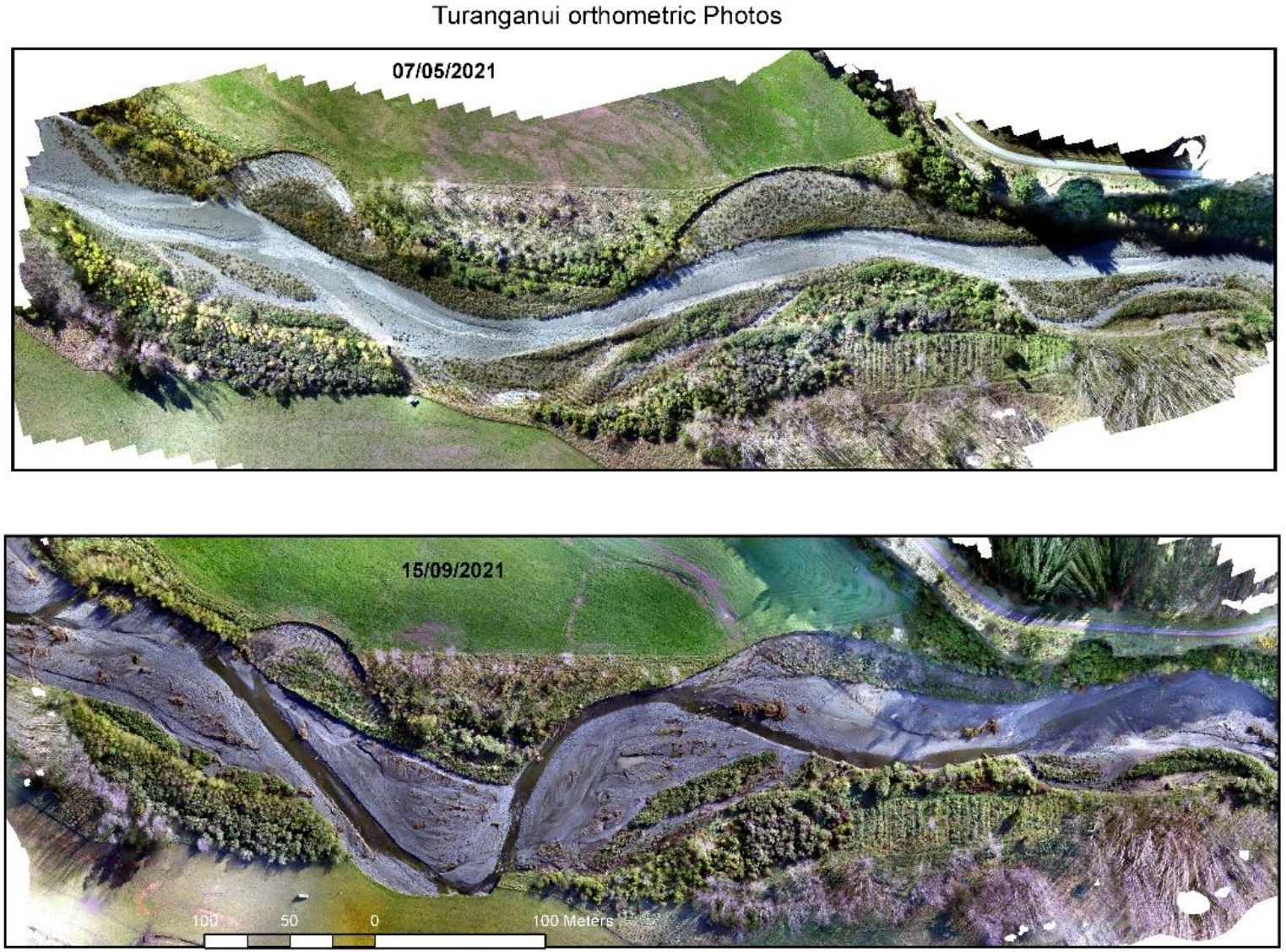


Figure 82: Orthometric photos from drone imagery for Turanganui River study reach.

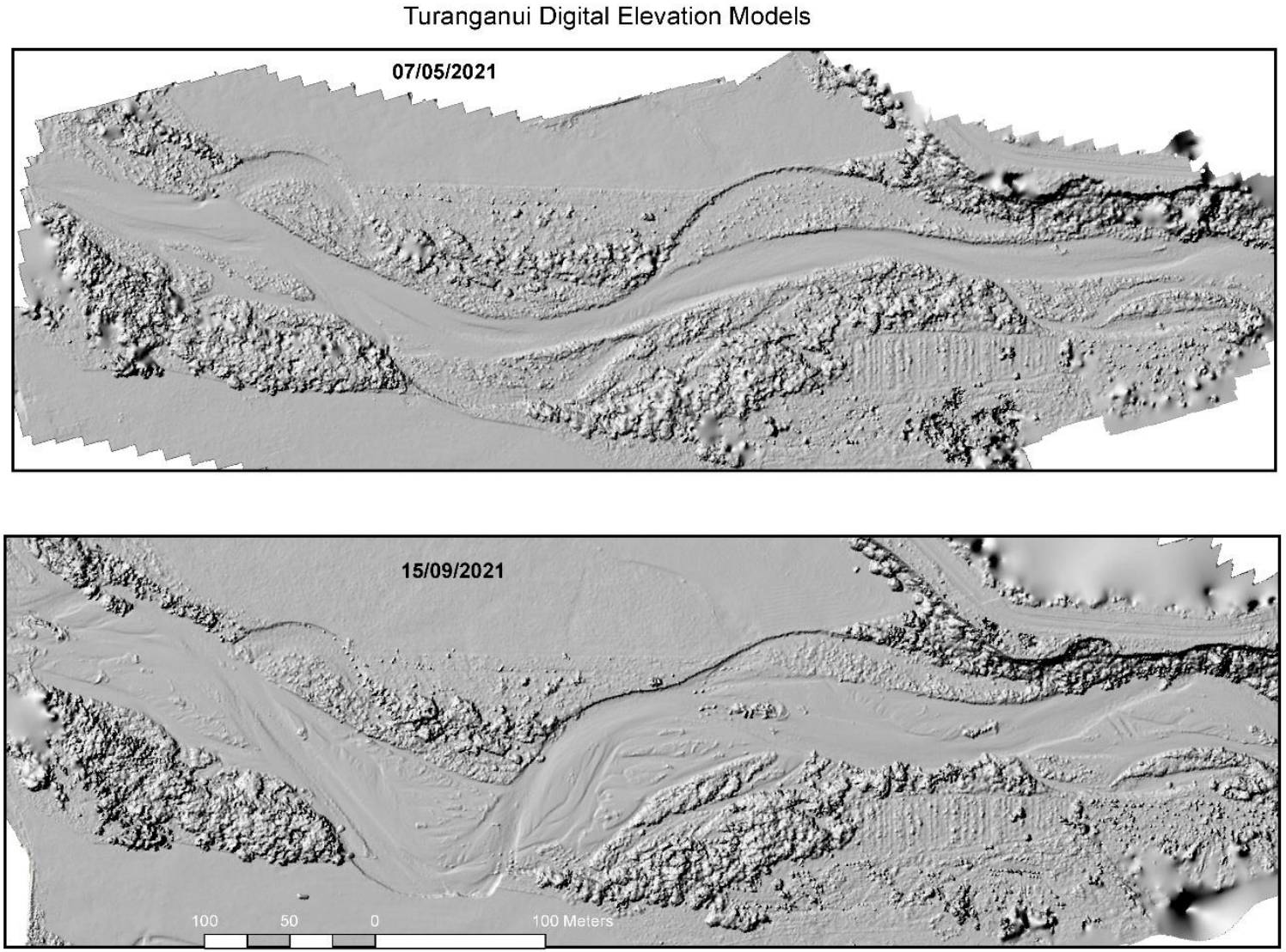


Figure 83: Digital elevation model from drone photogrammetry for Tauanui River.

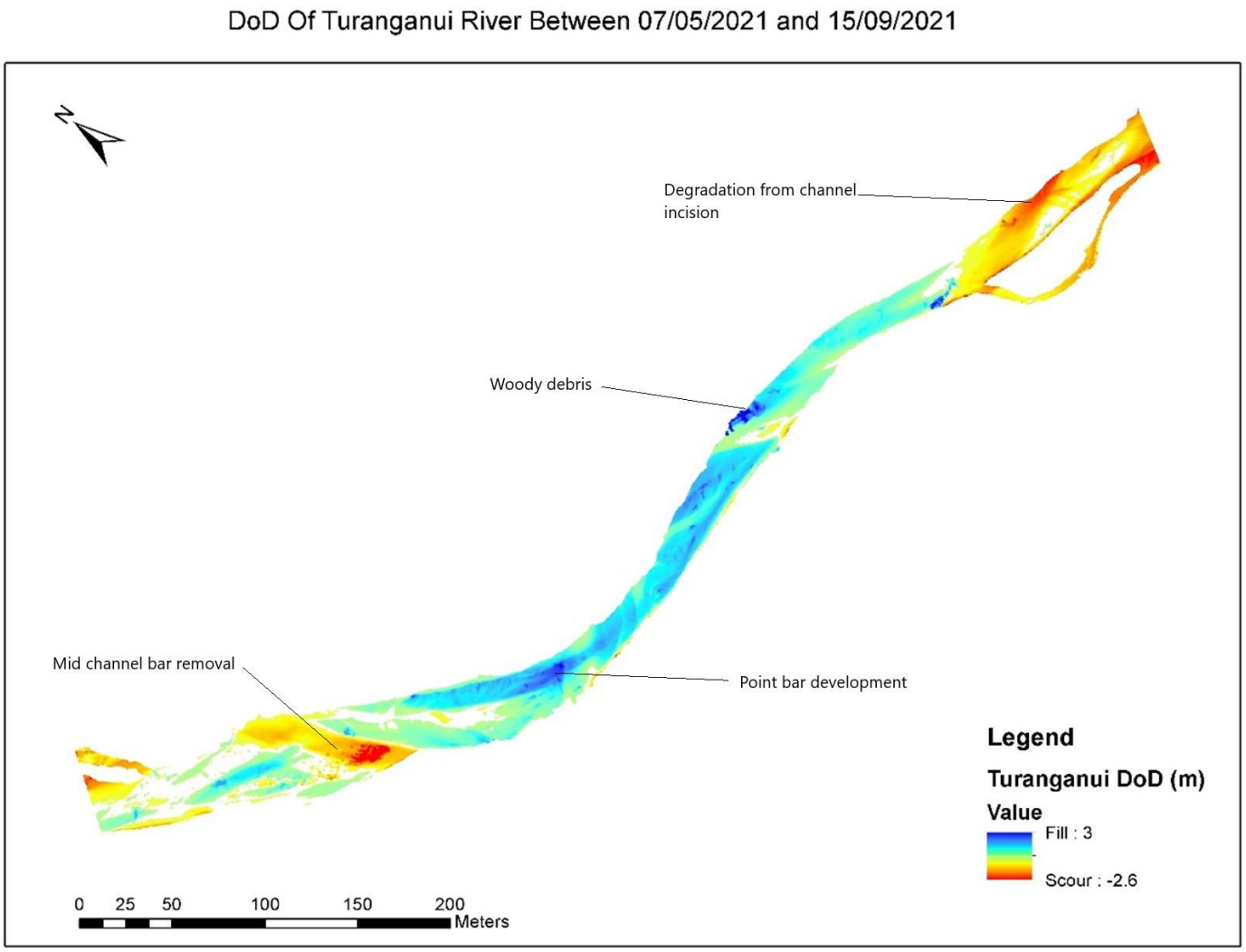


Figure 84: Digital elevation model of difference derived from photogrammetry for Tauanui River between 07/05/2021 and 15/09/20

Table 6: Turanganui study reach DoD volumetric calculations.

Turanganui DoD Summary

Attribute	Raw	Thresholded DoD Estimate:		
AREAL:				
Total Area of Surface Lowering (m²)	7,227	5,525		
Total Area of Surface Raising (m²)	11,661	9,986		
Total Area of Detectable Change (m²)	NA	15,511		
Total Area of Interest (m²)	18,888	NA		
Percent of Area of Interest with Detectable Change	NA	82%		
VOLUMETRIC:			± Error Volume	% Error
Total Volume of Surface Lowering (m³)	3,657	3,536	± 805	23%
Total Volume of Surface Raising (m³)	7,087	6,966	± 1,456	21%
Total Volume of Difference (m³)	10,744	10,502	± 2,261	22%
Total **Net** Volume Difference (m³)	3,430	**3,431**	**± 1,664**	48%

5.6 SFM surveying comparison analysis

The total volume difference for the DoDs of both river study reaches can be seen in Table 7. To compare the differences in sediment movement between the two spatially unequal rivers, an average was calculated. An average of 0.41m³ per m² of sediment movement occurred in the Tauanui study reach, and 0.56m³ per m² occurred in the Turanganui Study reach. Comparisons of these averages show that 25.49% more geomorphic work occurred in the Turanganui River.

Table 7: Volumetric comparisons of study reaches.

River	Area of interest size (m²)	Total volume difference (m³)	Total volume difference (m³) per m²
Tauanui	8069	3343	0.41
Turanganui	18888	10502	0.56
		Difference	0.14
		Difference (%)	25.49%

5.7 Hydrographic analysis

The hydrographic analysis produced a flow duration curve for the Tauanui River that illustrates the flow characteristics throughout their ranges of discharge (Figure 85). The flow duration curve calculated for the Tauanui shows the river's low flow is 0.069 m³/s, the average flow is 0.526 m³/s, and the highest flows are above 33m³/s. The Turanganui flow duration curve is seen in Figure 86, where low flows are 0.106m³/s, and the average flow is 0.812m³/s. High flows are above 22m³/s. River flow monitoring for the duration of the SFM surveys for both rivers can be seen in Figures 87 and 88. The flood event that occurred on the 21st of June can be seen in both hydrographs. Due to the short period of monitoring, the return period of the flood cannot be provided. However, the rainfall intensity return period can be and is known to be exceeded by the flow return period (Viglione & Blöschl, 2009). Rainfall monitoring data illustrated in Figure 89 shows an accumulation of 245mm of rainfall over a 6-day period. 108.2mm of rainfall fell in 12 hours, and 143mm fell over a 24-hour period in the Aorangi Ranges. 40mm fell on the lower floodplains of both rivers within 24 hours. Using Table 8 provided for the upper catchment site (Ruakokopatuna at Iria) for calculating rainfall intensity return periods, the 12-hour intensity is calculated as

exceeding a 5-year event and the 24-hour intensity as exceeding an annual event. Stream power calculated for both study reaches can be seen in Tables 9 and 10. Stream power is far greater in the Turanganui study reach than in the Tauanui. This is most likely a result of a far steeper channel gradient.

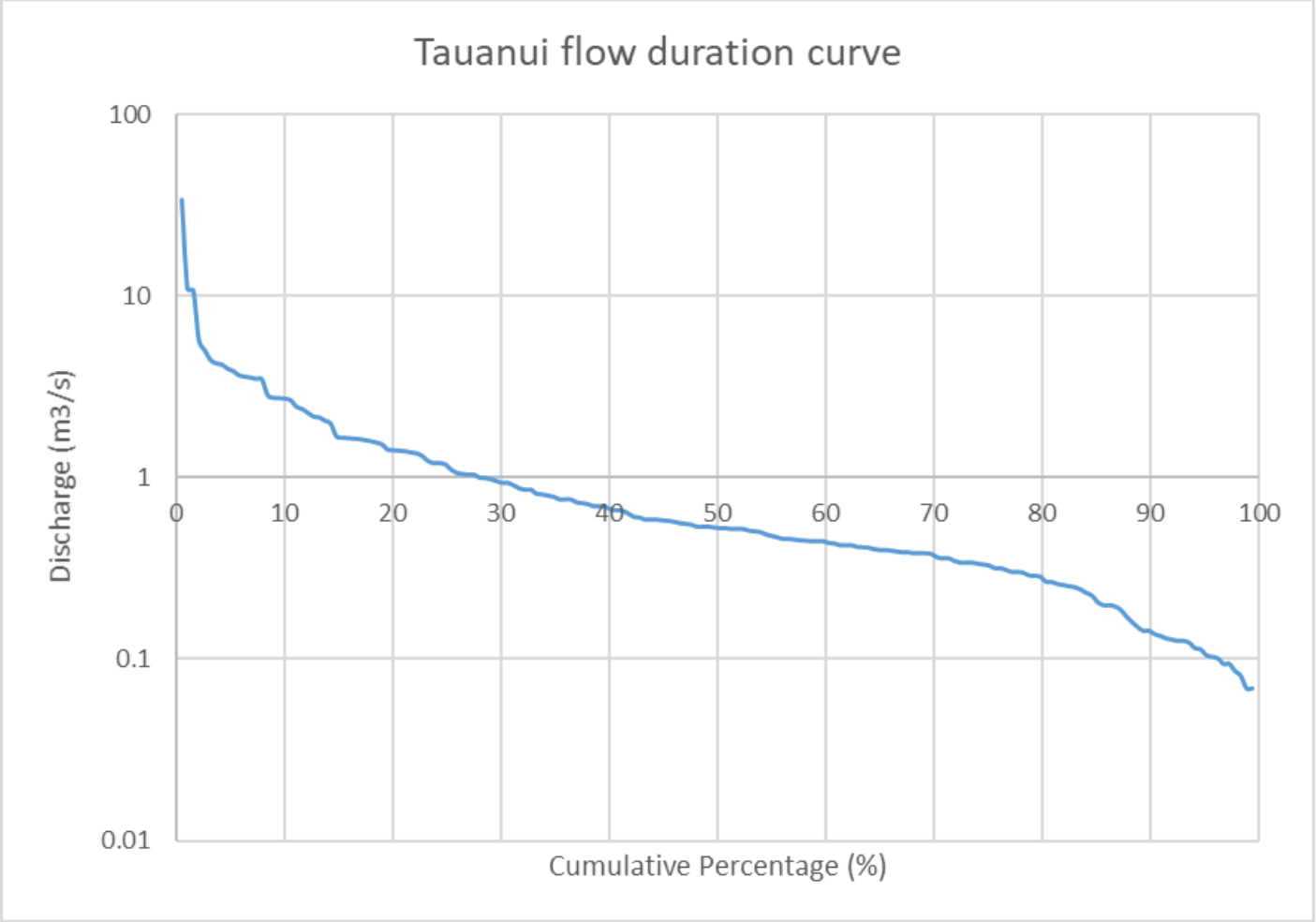


Figure 85: Tauanui River flow duration curve.

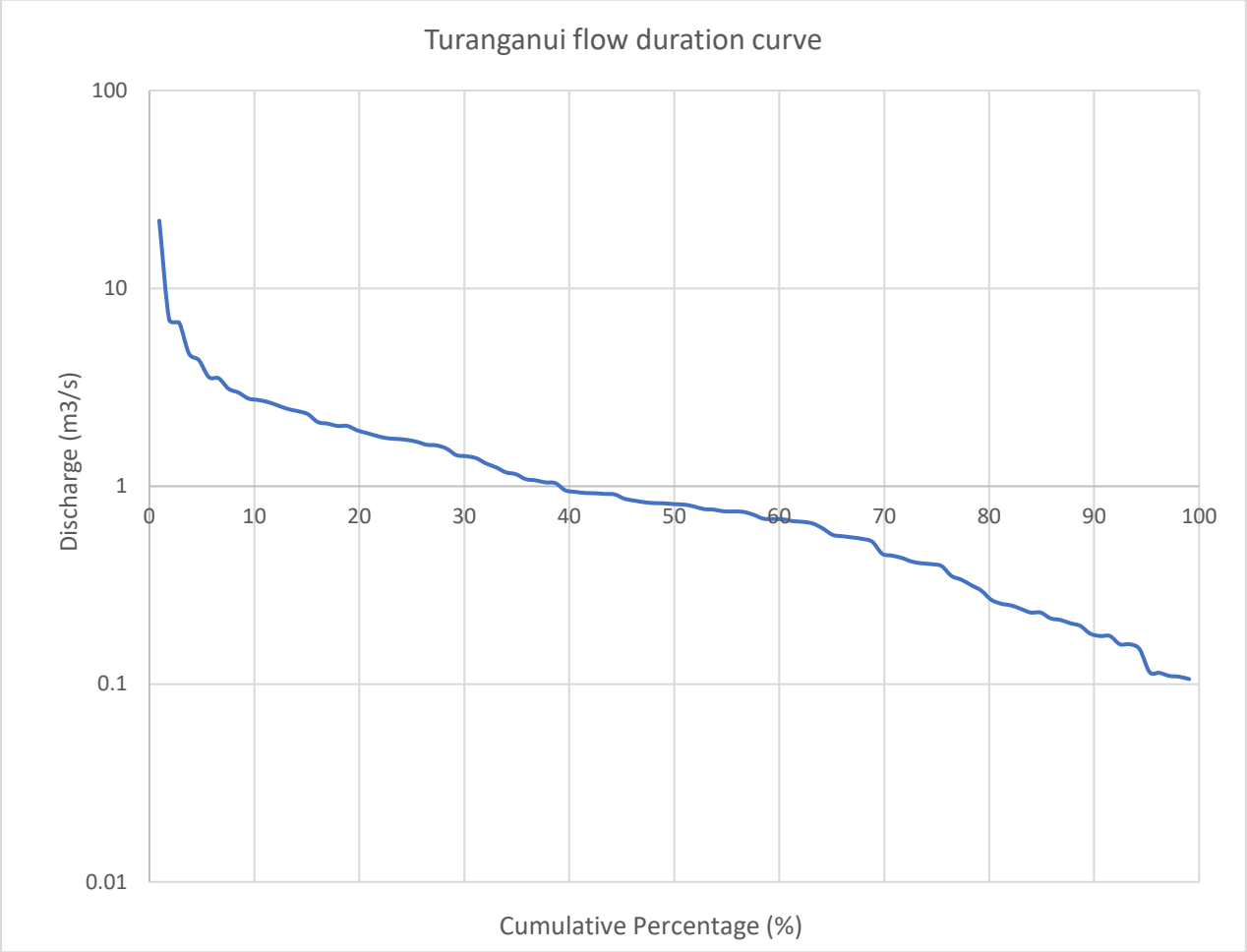


Figure 86: Turanganui River flow duration curve.

Table 8: Frequency analysis table for Ruakokopatuna River at the Iria rainfall monitoring site (Gordon, 2016).

	Storm Duration								Drought Duration	
Return Period	1 hr	2 hr	3 hr	6 hr	12 hr	24 hr	48 hr	72 hr	14 day	28 day
Mean Annual	19	27	34	52	82	119	157	177	0	14
5 year	24	33	41	64	104	156	208	235	0	6.5
10 year	30	40	49	74	122	186	249	282	0	4
20 year	37	48	57	84	140	214	288	327	0	2
50 year	48	59	70	96	162	251	339	385	0	0
100 year	59	69	81	105	179	279	378	429	0	0

Table 9: Tauanui study reach stream power calculations.

Tauanui Stream power	
density of water (kg/m^3)	1000
acceleration due to gravity (m/s)	9.81
peak discharge (m3/s)	40
slope (m)	0.003077
Stream Power (w)	1207.415
stream width (m)	27.3
Specific Stream Power (wm-2)	44.22765

Table 10: Turanganui study reach stream power calculations.

Turanganui Stream power	
density of water (kg/m^3)	1000
acceleration due to gravity (m/s)	9.81
peak discharge (m3/s)	44
slope (m)	0.00699
stream power (w)	3017.164
stream width (m)	48.4
Unit stream Power (w)	62.33809

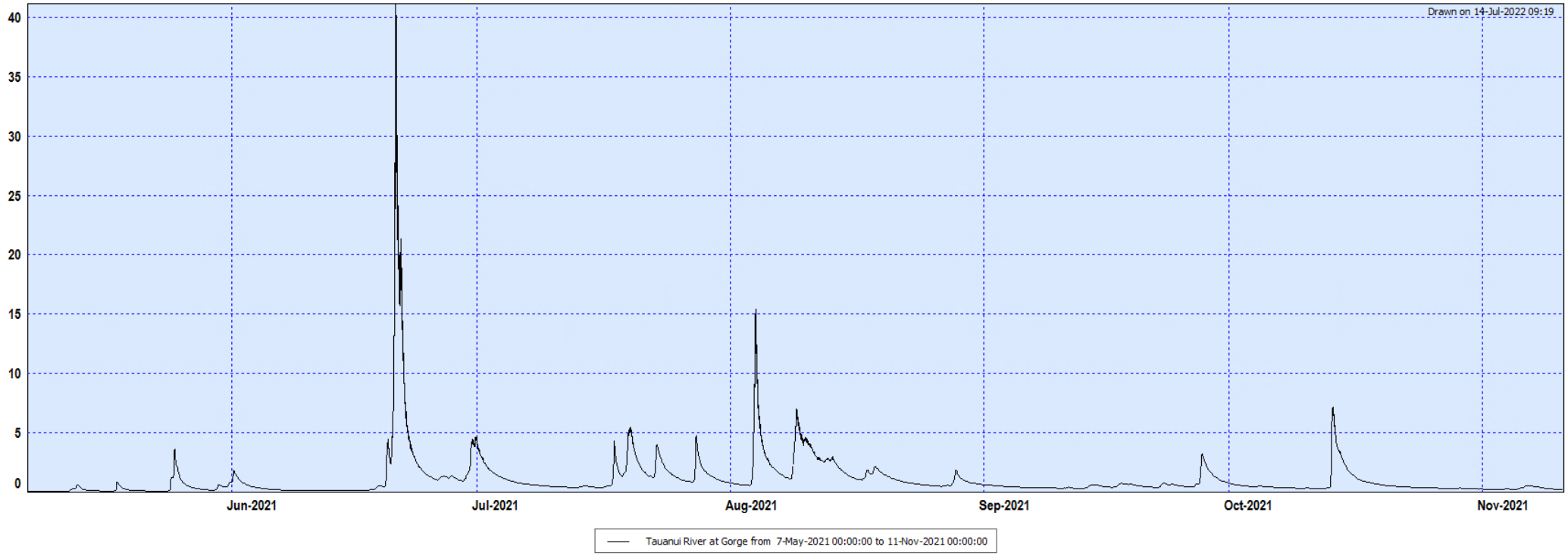


Figure 87: Tauanui River hydrograph.

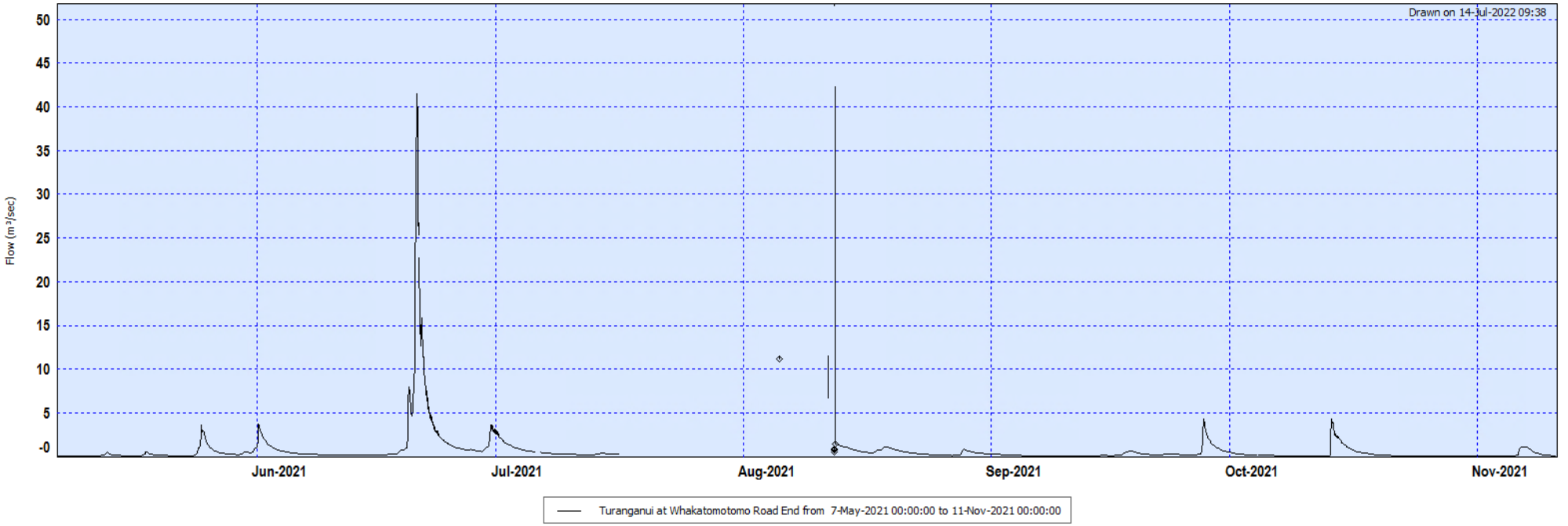


Figure 88: Turanganui River hydrograph.

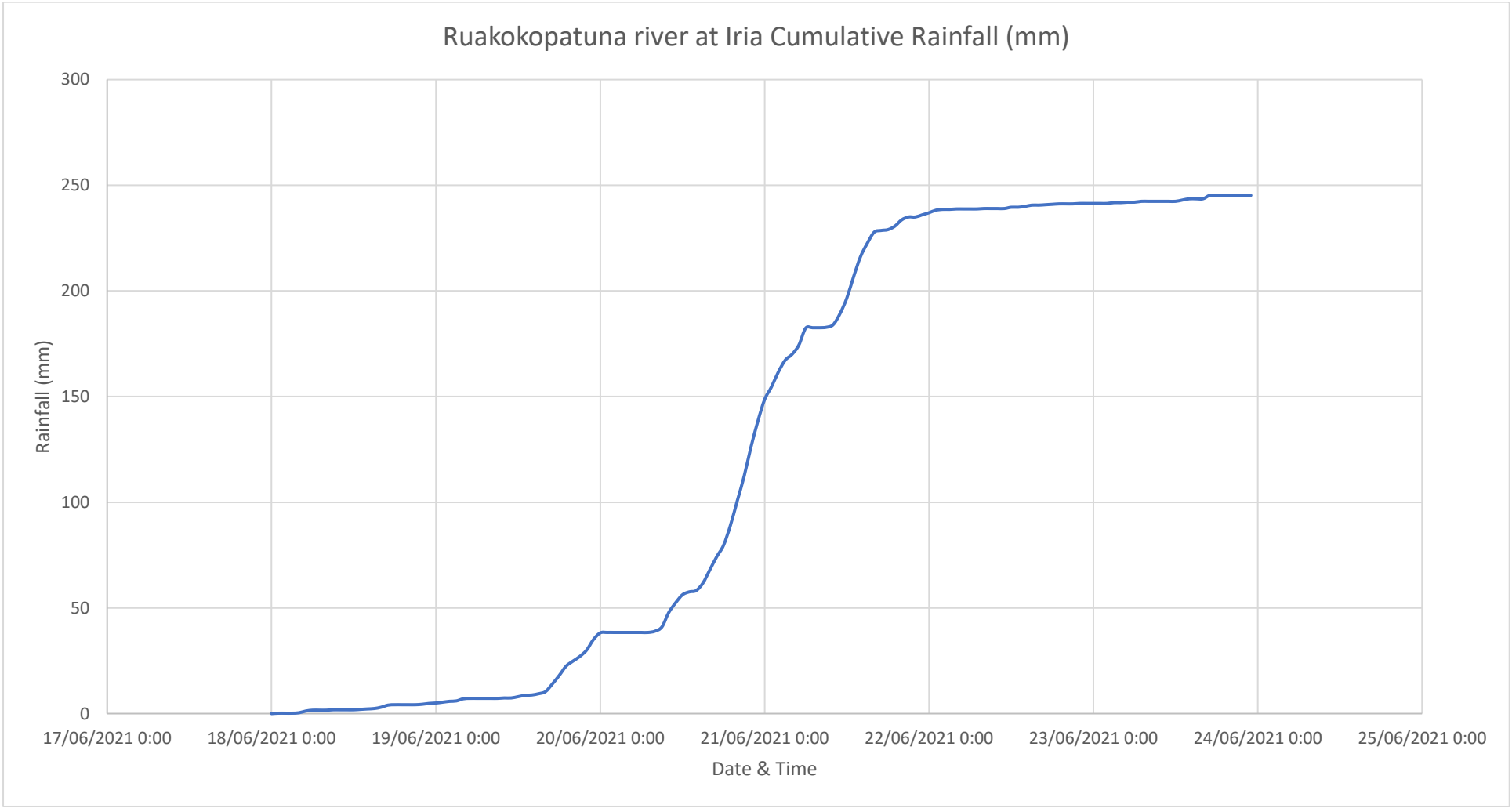


Figure 89: Ruakokopatuna River at Iria rainfall monitoring site over the June 2021 storm event.

6.0 Discussion

6.1 SFM and geomorphic response drivers

Following the geomorphic assessment of all available historical imagery of the Tauanui and Turanganui Rivers, a story of geomorphic change over time became clear. Large unvegetated active gravels are evident in both rivers, occupying large swaths of their floodplain from the 1940s until the 1960s. From the 1970s, both rivers become straightened and narrowed. The 1990s show further reductions in channel size, where the rivers now have significant amounts of heavy vegetation on their banks. The 2021 surveys show a further reduction in bare gravel and an increase in vegetated banks and bars on both rivers.

All monitoring techniques implemented show that both rivers' geomorphology has significantly changed over time, illustrating large active gravels in the 1940s, followed by a trend of progressive straightening and narrowing over time, and the proliferation of riparian vegetation on the riverbanks, mostly of which are exotic. Cross sections also show both rivers aggrading in the lower catchment (before intervention in the Tauanui) and the upper reaches of the Turanganui progressively degrading and channelising over time. Large areas of active gravel present in the Tauanui and Turanganui Rivers, along with many of New Zealand's gravel bed rivers in the 19th and early 20th century, are likely to represent enhanced catchment sediment flux in response to forest clearance and the development of land drainage in the landscape, in conjunction with tectonic activity such as the 1942 Wairarapa earthquake (Downes, 1999; Fuller & Heerdegen, 2005).

Increased sediment delivery and river discharge result in channel widening and aggradation (Fuller & Heerdegen, 2005). Decadal channel narrowing is likely a result of lower sediment influx because of reforestation of the wider catchment and accelerated by management practices implemented on both rivers. The Lower Valley development scheme that began in the 1970s and continued regional council work programs are examples of this (Cyril, 2009). Trends of river channelisation and narrowing coincide with those seen in many of New Zealand's gravel bed rivers, such as the Kiwitea Stream, Motueka, and Waingawa Rivers (Basher, 2003; Fuller, 2008; Fuller & Basher, 2012; Fuller & Conley, in press). This is illustrated in Figure 90, where significant narrowing in the lower Motueka River resulted in channel incision (Basher, 2003). These changes compare with the changes observed in the Tauanui and Turanganui because similar management practices have been implemented in their catchments, resulting in comparable geomorphic responses.

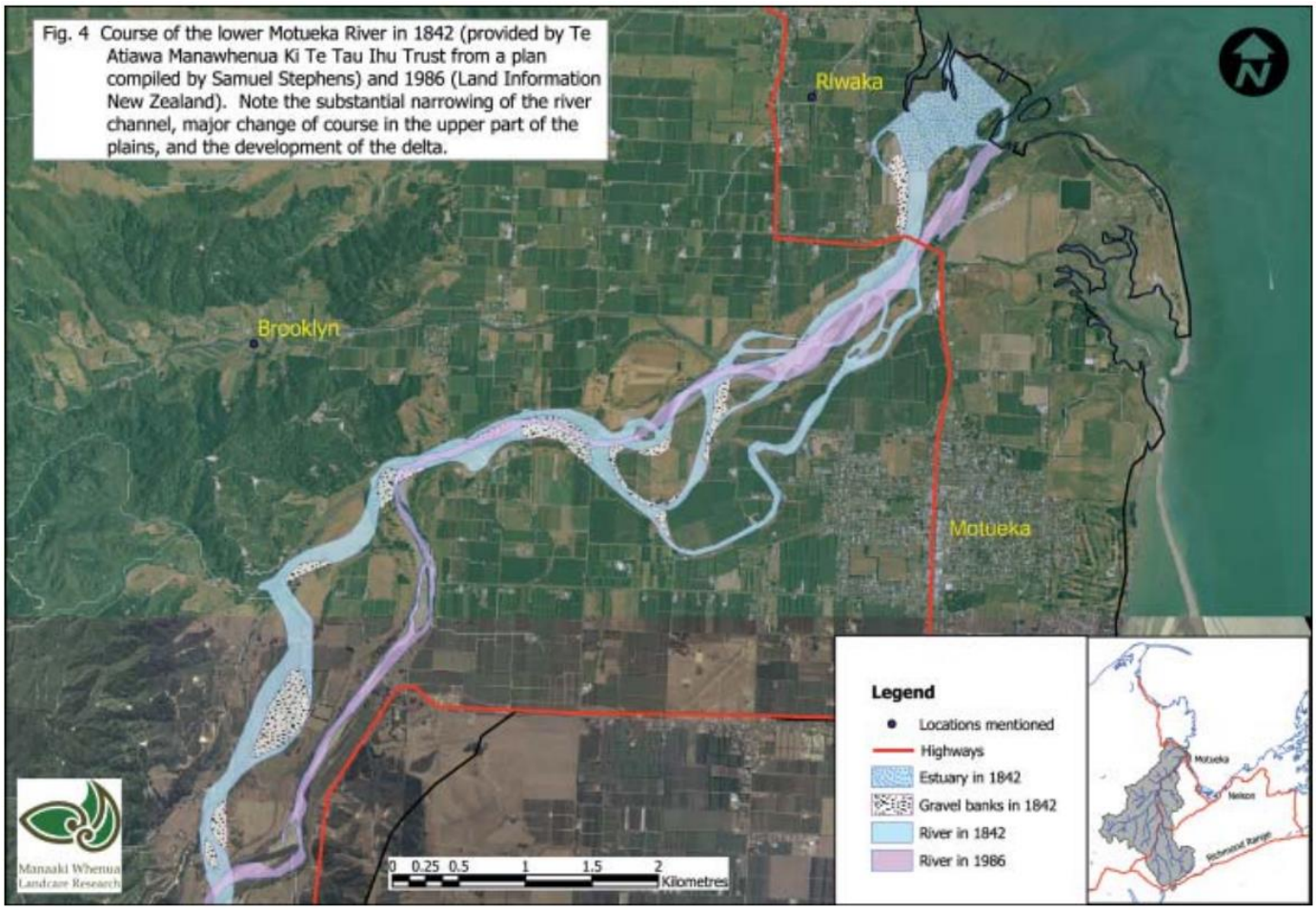
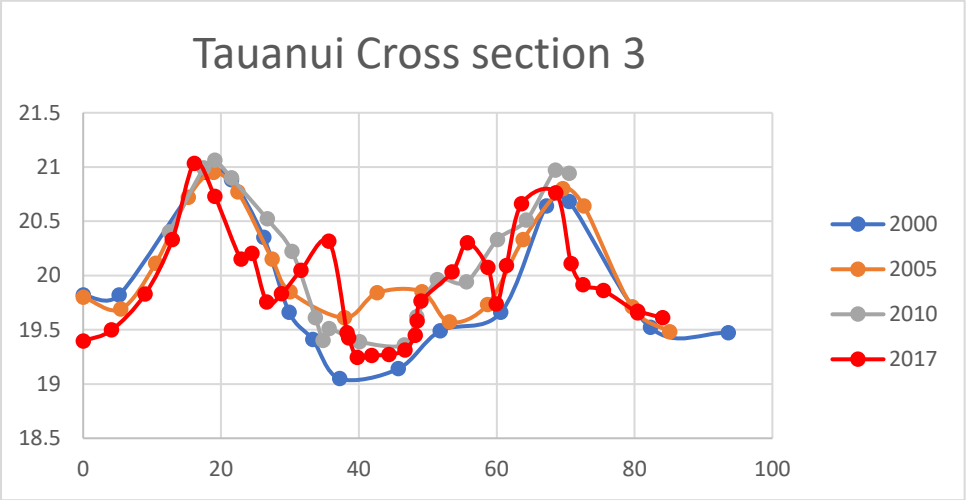


Figure 90: Changes in the Motueka River from 1942 to 1986 (Basher, 2003).

Restricting and straightening river channels are common methods utilised in rivers around the world to promote the stability of the channel and maximise floodwater conveyance. This enables the surrounding floodplain to be utilised for other purposes while not being impacted by flooding and associated geomorphic work (Griffiths, 1979; Bravard et al., 1997; Fuller & Basher, 2012; Gurnell & Downs, 2021). These methods have known implications for river conditions, thresholds and resilience, which then result in geomorphic change that is disproportionate to flood events that occur (Fuller et al., 2019; Fuller & Conley, In Press). Narrowing and straightening river channels results in confining the flow of the river and shortening the travel path of the river, causing steeper gradients and, thus, higher velocities (Erskine, 1992; Magilligan, 1992). Narrowing flow also concentrates a greater percentage of flow within the river and increases stream power, which elevates the erosive power of the river, particularly in flood conditions (Magilligan, 1992; Wyzga, 1993). Wyzga (1993) showed that the narrowing and straightening of the Raba River in Poland resulted in significant progressive channel incision of up to 3m (Figure 91a). This is comparable to bed level changes observed in the Turanganui River because channel straightening and narrowing resulted in increased gradient and thus stream power, causing incision (Figure 91c). The conclusions of Wyzga (1993) are contrary to bed level changes observed in the Tauanui cross-section surveys (Figure 91b). This is potentially due to legacy sediment from storm events causing an aggrading phase in 2005 or channel realignment and vegetation removal modifying depositional trends (GWRC, 2009). All available surveying data in the Tauanui River is in the lower catchment, where aggradation is the dominant process (Coleman & Smart, 2011). Lack of data in the upper catchment prevents the identification of channel incision or otherwise.

A

B



C

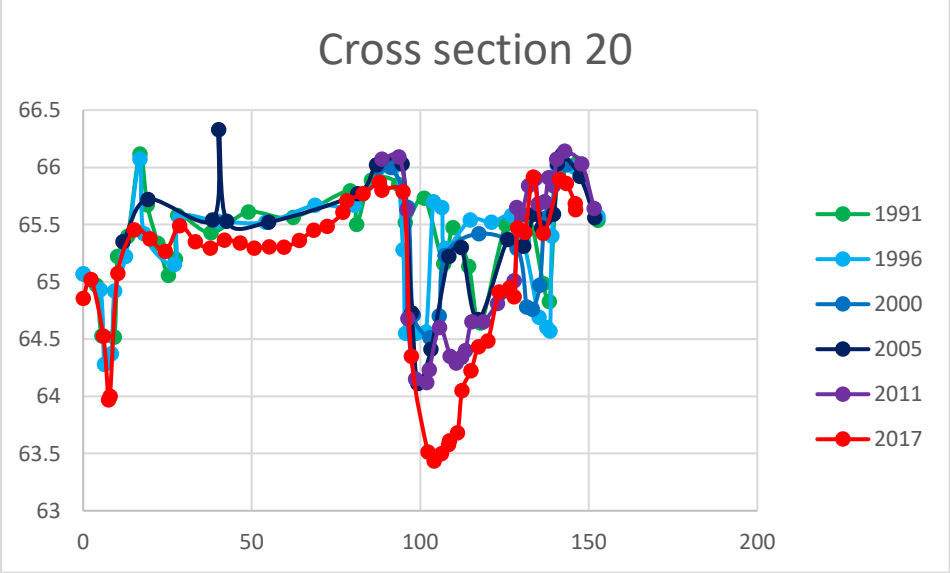


Figure 91 A: Raba Riverbed level changes over time (Wyzga, 1993). B: Tauanui cross-section three bed level. C: Turanganui cross section 20.

Steeper rivers are closer to geomorphic thresholds, which is why more geomorphic change is recorded in steeper catchments (Milan, 2012). River confinement can be both naturally occurring and artificially produced and contributes to spatially variable geomorphic change (Magilligan, 1992). When rivers have been managed in this fashion, they generally have a lower self-adjustment potential for future changes in flood magnitude, duration and frequency (Fuller & Conley, in press). Due to a lower self-adjustment potential, rivers can be near or on the brink of thresholds that, when breached, can change boundary conditions that exceed the design of these river management practices (Fuller & Conley, in press). This results in significant geomorphic change recorded in the Tauanui and Turanganui Rivers. Significant geomorphic change that occurred, such as the reduction in heavily vegetated banks and the widening active gravels in both rivers as a result of the June 2021 flood event, suggest restricting and straightening has led to increased unit stream power and thus greater geomorphic change, particularly in the Turanganui study reach. This process has been recorded in several other New Zealand Rivers (Reid & Brierley, 2015; Wheeler et al., 2022; and Fuller and Conley (in press). Higher stream power is also the result of overall land use change in both catchments. As highlighted by Brown et al. (2005), deforested catchments have reduced rainfall interception, transpiration and increased soil moisture, which contribute to increased peak discharge, which increases peak stream power. This can also drive accelerated geomorphic change. As seen in Figure 5, significant portions of both catchments have been converted to pasture, which will be contributing to this.

The SFM analysis illustrated the geomorphic impacts that occurred as a result of the June 2021 flood event in both study reaches. Management practices exacerbated the geomorphic impacts of the flood event as the increase in erosive power drove significant geomorphic work. Channel reduction and straightening result in disproportionate geomorphic change because they modify river resilience, which comprises resistance and recovery. River management practices focus on fixing rivers in straight, narrow river corridors that lack geomorphic heterogeneity (Wohl, 2016a). In doing so, river resilience is modified (Fryirs et al., 2009; Florsheim et al., 2013). Over short to medium temporal scales, these practices reduce geomorphic sensitivity until a threshold breaching flood occurs, as shown in Fuller (2007). Fuller et al. (2019) suggest that rivers in this state can have increased resilience, but this is primarily composed of resistance, and recovery is minimal as rivers are maintained in a fashion that renders them unable to adjust to significant flood events (Downs et al., 2013). There is evidence that when a catastrophic event occurs, there is an increased risk of further significant geomorphic change occurring (Lane et al., 1996; Tunnicliffe et al., 2018). The geomorphic response to the June 2021 flood event captured in the Tauanui and Turanganui Rivers suggests the management practices implemented on them have reduced sensitivity to smaller flood events but have resulted in significant geomorphic response to relatively large events, particularly in the Turanganui River.

The geomorphic change that occurred shows that the river needs more room and is trying to reclaim its natural character, which has superior resilience to engineered systems (Fuller & Basher, 2012; Fuller et al., 2019). The widening of channels and increase in sinuosity show that the recovery process is underway, and the system is becoming more resilient (Schum, 1969; Fuller et al., 2019). This is because they are more resistant to change and are more likely to recover from high-magnitude floods. Wider channels seen in both study reaches, after the June 2021 flood, increase flood capacity and reduce flow concentration. This reduces stream power and increases river resilience by making the system more resistant to change and allowing the river to be disturbed and recover from change (Thoms et al., 2018). The increase in sinuosity that was recorded, particularly in the Turanganui River, significantly increases the flow path, which decreases channel gradient and reduces stream power (Fuller & Conley., in press). This results in a more resilient river by being more resistant to geomorphic change and more likely to recover from it, as it is more likely to retain its form. This has been shown by Garcia et al. (2021), where partial recovery of the Órbigo River's floodplain (Figure 92) resulted in a more resilient river, which also reduced peak flood stage, mitigating flood damage where historic floods of equivalent magnitude had caused significant damage. This shows that the widened gravels and more sinuous channels seen in both study reaches following the June 2021 flood event are more resilient systems.

Figure 92: Morphological changes observed in the Órbigo River, Spain (Garcia et al., 2021).

Contrary to Milan (2012), the geomorphic change that occurred in the highly modified Tauanui and Turanganui Rivers suggests that more frequent, lower-magnitude flood events contribute significantly to governing channel morphology. The DoDs help to show the quantity of sediment moved, which illustrates the importance of these lower-magnitude flood events in determining the amount of geomorphic work done. As seen in the mapping of both study reaches, significant portions of the historic bare gravels are now heavily vegetated, which makes bankfull floods inundate the narrowed channels, which makes lower magnitude events capable of mobilising the alluvium stored on these vegetated banks and bars. Due to this, the cumulative work undertaken by bankfull discharges, as suggested by Wolman and Miller (1960), results in significant geomorphic work. Consecutive floods of a similar magnitude would compound the amount of sediment moved, which over time would likely surpass the geomorphic capability of high-magnitude events. This contrasts with Milan (2012) and Fuller (2007), which gives rise to the suggestions made by Richards (1999) that the geomorphological context in which the flood takes place is important in determining the scale of impacts. In this case, sensitivity and thresholds are likely controlling factors, as the modification of both rivers has sensitised both rivers and brought them closer to geomorphic thresholds, exacerbating geomorphic work done in lower magnitude events.

6.2 Contrasting geomorphic change

The geomorphic change measured in this flood event constituted significant geomorphic impacts for both study reaches as significant geomorphic change occurred, and large amounts of sediment were moved. Sediment erosion and deposition exceeded that reported by Milan (2012), which has a larger reach than those studied on the Tauanui and Turanganui, which helps to illustrate the scale of geomorphic change that occurred. Geomorphic impacts measured using geomorphic analysis and SFM DoDs show that the geomorphic impact of the June 2021 flood varied between the two rivers. The Turanganui bare gravels increased by 19.3%, yet the Tauanui bare gravels increased by 5.4%. The contrast is also evident in the enlargement of bare gravels, quantitative differences in sediment moved and visual evidence of significant variation in lateral erosion resulting in remobilisation of valley floor alluvium stored in bars and banks. Calculating unit stream power of the study reaches using slope and width showed specific stream power was greater in the Turanganui during the June 2021 flood event.

However, the Geomorphic response following the June 2021 flood event, although significant in both rivers, contrasted in scale. This is evident in both geomorphic analysis and DoDs, as bare gravels in the Turanganui increased 13.9 % more than in the Tauanui River, and 25 % more sediment was mobilised in the Turanganui River per square meter from the June 2021 flood event. There are many drivers behind this spatially contrasting geomorphic response. As Fuller and Conley (in press) highlighted channel gradient, confinement, and surface condition contribute to variable geomorphic response. The gradient is steeper in the Turanganui River, which results in higher stream power, as seen in Chapter 4.6, which results in sediment being more readily mobilised. Both rivers are significantly confined compared to their historic planform, as illustrated in Chapters 4.1.1 and 4.1.2. This increases unit stream power due to the concentration of flow (Miller, 1995). As seen in Chapter 4.6, unit stream power is more even but still higher in the Turanganui River. This is likely because the Turanganui channel width and sinuosity have been reduced further, resulting in higher unit stream power. Surface conditions appear similar in both rivers, as no human interference occurred in either channel between surveys. Different gradients and channel confinement, therefore, contribute towards contrasting responses. Knighton (1999) observed similar variations in stream power in the Trent, Derwent and Noe Rivers in England. This was due to varying channel width and gradient resulting in irregular unit stream power downstream, as was observed in the Tauanui and Turanganui study reaches. As seen in Figure 93, unit stream power upstream is higher due to channel confinement, resulting in increased geomorphic work when compared to the wider channel downstream, which spreads flood flows, lowering unit stream power.

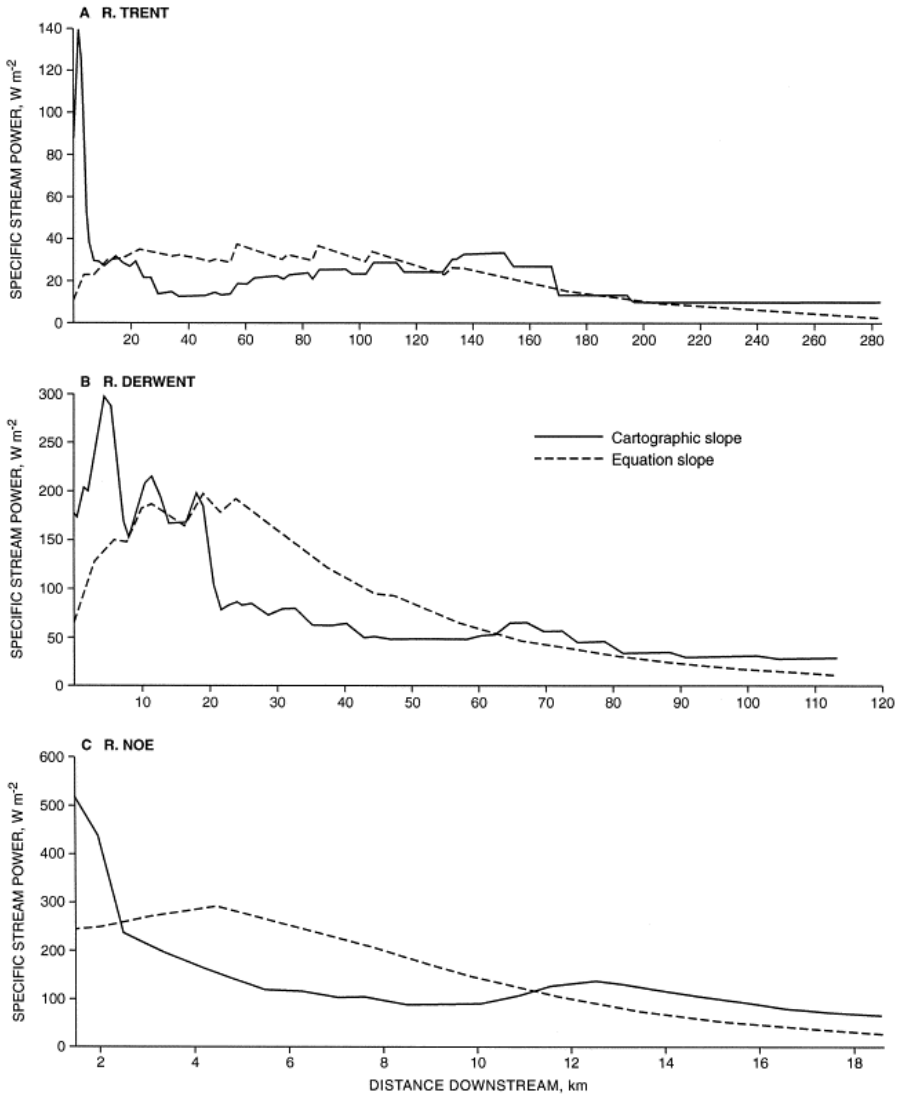


Figure 93: Variations in unit stream power along the Rivers Trent (A), Derwent (B) and Noe (C).

Variation in geomorphic work between two rivers also reflects variations in thresholds between the two rivers. Geomorphic change in river systems occurs when thresholds relating to stream power and sediment regime are exceeded (Schumm, 1979). When a river is closer to these thresholds, it is less resistant and more sensitive to change, which results in channel adjustment in flood events (Schumm, 1979; Fryirs et al., 2009; Fuller et al., 2019). The scale of geomorphic change that occurred in the Turanganui reach suggests it was closer to these thresholds, resulting in significant channel adjustment. Examples of this have been explored by Fuller (2007), whereby it was concluded that variation in geomorphic change was "conditioned by thresholds of flood power, in conjunction with the local channel configuration and planform geometry". This study presents parallels to findings presented in Chapter 4, where variations in stream power between study reaches are related to variations in the quantity of geomorphic change that occurred. This is likely due to variations in the extrinsic threshold in flood power between rivers. These extrinsic thresholds have been modified by reducing channel width and sinuosity, increasing flow concentration, gradient and thus stream power (Magilligan, 1992).

Contrasting geomorphic change between rivers suggests that river resilience varies between rivers. River resilience is known to differentiate at a catchment and reach scale (Fuller et al., 2019). Resilience is modified by inherent natural characteristics such as geology and planform or through river management. The sinuous, wandering nature and wide active gravels of both rivers seen in the 1940s-1960s demonstrate systems that have low resistance to geomorphic change but have strong recovery potential due to their ability to readily return to their pre-disturbance state (Fuller

et al., 2019). These two components combine to make up a resilient river system. Through modification of resistance and recovery potential, river resilience can be influenced by river management practices (fuller et al., 2019). Progressive straightening of river channels and planting of banks resulting in disconnecting these rivers from their floodplains seen in both study reaches increases both rivers' resistance to geomorphic change as the channel cannot readily adjust. Yet, their recovery potential is reduced as they will take longer to recover to their original sinuous, wandering state (Fuller & Basher, 2013). However, this produces a more resilient river primarily comprising resistance (Fuller et al., 2019). Gilleaver and Black (1999) showed that the embanked River Tay, Scotland, had low resilience to a heightened flood peak regime, which climate change predictions would exacerbate. This illustrates the modifications to river resilience occurring in the Tauanui and Turanganui Rivers due to river management.

Resilience varies between these two rivers because of their variation in sinuosity and wandering nature, resulting in contrasting recovery potential following a flood event. The variation in which they have been modified (i.e. narrowed and straightened) compared to their original planform also results in contrasting resistance to change, as they both will have different flood design capacities to resist change and retain their form (Fuller et al., 2019). The Geomorphic response was greater in the Turanganui study reach when compared to the Tauanui because its recovery potential has been reduced further due to straightening reducing sinuosity further than in the Tauanui. Variation in resistance between the two study reaches also presents a driver for contrasting geomorphic responses. Straightening and reduction in channel size have resulted in contrasting resistance between rivers as they have been reduced to different degrees since the 1940s, as seen in Chapters 4.1.1 and 4.1.2. channel size has reduced by 38.8% in the Tauanui and 49.8% in the Turanganui in this period. This variation in reduction shows the Turanganui River has a further reduced capacity than the Tauanui River, which reduces resistance to geomorphic change in a flood event. Therefore, the Turanganui was more sensitised to geomorphic change during the June 2021 flood event, and the significant geomorphic work that occurred reflects this. This connects with Fuller and Heerdegen (2005), where channel straightening and narrowing reduced resistance, which resulted in catastrophic geomorphic change during a flood event.

The degree of recovery in the study is likely to be a function of the frequency of these large events. As illustrated by Milan (2012), there is likely to be a ‘relaxation’ phase where sediment not transported during the June 2021 flood event is made more available for transport in future lower-magnitude flood events. The time the river is more sensitive depends on how close they are to intrinsic thresholds (Milan, 2012). Due to the degree of geomorphic change, the Turanganui study reach appears to be closer to geomorphic thresholds, indicating recovery will take longer as the relaxation phase will last longer.

Contrasting change between the two studies highlights these concepts of resilience and thresholds and the need for their consideration when implementing river management. When rivers are managed in a way that creates homogenous design channels, these concepts are not considered, resulting in spatially variable geomorphic change disproportionate to the flood event as recorded in the reaches studied. This shows a shift in approach to river management needs to take place. This is because rivers managed in this fashion are over-sensitized to larger flood events, where a disproportionate amount of unpredictable geomorphic work can occur, and recovery potential is minimal. This has been illustrated by Wheeler et al. (2022) and Fuller and Conley (in press). Resulting remediation works following significant geomorphic change are time-consuming and expensive and are likely to come under further pressure from floods as a result of climate change (Gilvear & Black, 1999).

The wider and more sinuous planforms present in the study reach, particularly the Turanganui in response to the June 2021 flood, are more resilient systems. Due to increased width, both rivers can wander laterally as they would have in the past, which results in lower stream power and more even sediment flux throughout the floodplain. This is important as aggradation seen in the lower reaches of both rivers poses an increased flood risk as capacity is compromised, and channelisation results in increased stream power and reduced floodplain connectivity (Fuller, 2007; Heritage & Entwistle, 2020). Wider, more sinuous planforms are less resistant as they are more conducive to geomorphic change but can readily recover to their pre-flood forms, which increases overall river resilience (Fuller et al., 2019). Instances of increased resilience due to wider, wandering rivers have been noted by Gilvear and Black

(1999) and Garcia et al. (2021), which suggests the wider planforms present in the Tauanui and Turanganui study reaches following the June 2021 flood event are more resilient systems when compared to their pre-flood state. Wohl (2016b) identified heterogeneous rivers as being more resilient, as well as other benefits such as biodiversity values, whereby wandering rivers produce more riffle-pool sequences and other habitats that benefit many different species. More sinuous rivers further contribute to groundwater recharge, which helps to regulate flow and water temperature, which both benefit the biodiversity and water quality (Kronenwetter, 2016; Zhou & Endreny, 2020). These benefits associated with the more heterogeneous study reaches observed following the June 2021 flood will further enhance the natural values of these rivers.

6.3 Implications for river management

As discussed, the significant geomorphic change that occurred in the two study reaches is likely to have been exacerbated by the management practices implemented on them. Management practices have reduced river resilience and over-sensitised the rivers, resulting in geomorphic change disproportionate to the flood that occurred. As discussed in Chapter 4.3.2, a significant portion of the Turanganui has incised since cross-section surveying began. This is related to the narrowing and straightening of the channel. A combination of channel incision and exotic riparian planting has disconnected the rivers from their floodplain. This has been shown to have negative implications on natural fluvial processes, such as interrupting deposition and increasing sediment transport resulting in channel incision, increasing nutrient runoff, increasing flood impacts and having negative impacts on organisms that occupy these diverse connected fluvial landscapes (Wohl, 2004; Fryirs et al., 2007; Brierley & Fryirs, 2009; Wohl, 2016). These implications suggest that the current management regime implemented in these rivers is unsuitable, as reducing geomorphic diversity impacts river resilience and has had detrimental impacts on habitat, geomorphic diversity and ecological health. This links with the findings of Wohl (2016b), Garcia et al. (2021) and Fuller and Conley (in press).

Both study reaches display low geomorphic diversity, equating to reduced habitat diversity and flood mitigation, which suggests that a change in the river management regime is appropriate. Rehabilitating both rivers to planforms, more comparable to natural systems, would provide a more sustainable approach for flood resilience and ecological health. Numerous studies have shown that river rehabilitation benefits geomorphic resilience, habitat diversity, ecological health and flood capacity (Fuller & Basher, 2012; Fuller & Death, 2018; Garcia et al., 2021). To successfully implement river restoration, rivers must be assessed at the reach scale and contextualised within their catchment (Fryirs & Brierley, 2000; Brierly & Fryers, 2009). This is because rivers have unique characteristics at the reach scale, and to restore them, their defining characteristics need to be understood. Brierly and Fryers (2000; 2005) developed the ‘River Styles’ framework to assess river character and behaviour to explain what a river looks like and how it behaves over time. This functions as the baseline for assessing river recovery potential and guides river rehabilitation (Figure 94).

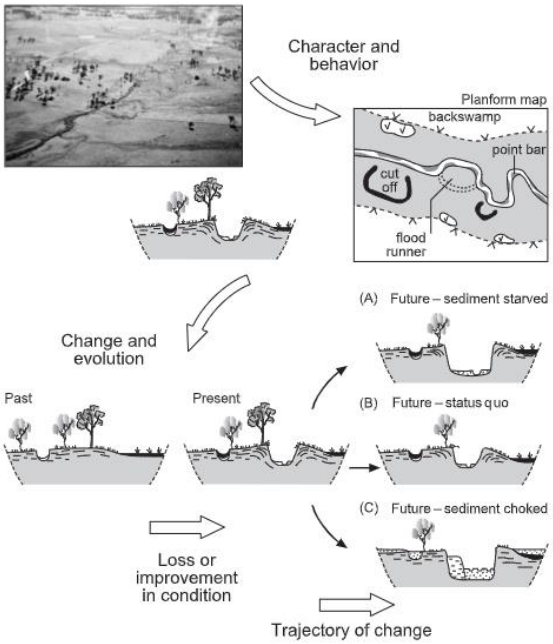


Figure 94: *An illustration of the information inputs into the river styles framework* (Brierly & Fryers,2005).

There are several indications that both rivers are in a degraded state. As seen in Chapters 4.1 and 4.2, both rivers were once closely connected to their floodplain, with wide active gravels and multi-threaded wandering channels. This geomorphic diversity has been reduced significantly due to river management. The incision in the upper catchment of the Turanganui seen in Chapter 4.3 has not been recorded to the levels present in the 2017 surveys, suggesting the river is on a degradational pathway (Fryirs & Brierley, 2000). As seen in Figure 5, portions of the upper catchment are in rotation forestry, and much of the floodplain and foothills are deforested for habitation and agriculture. This indicates that complete recovery of both rivers in the form of complete native forest cover in the catchment and active gravels occupying large swaths of the floodplain is unlikely. Therefore, both rivers are incapable of being restored to their near-original condition (Fryirs & Brierley, 2000). However, as illustrated by Fuller and Basher (2012) and Ollero and Ibisate (2012), rivers that have been significantly modified still have the potential to recover to a 'created state' that has diverse characteristics capable of benefiting resilience and ecological health (Fryirs & Brierley, 2000). Therefore, a change in management of both Tauanui and Turanganui Rivers to establish a created state of partial reconnection to their floodplains still presents many benefits. As illustrated in Chapter 4.4, both rivers increased in active gravels and sinuosity following the June 2021 flood event. As explained by Wohl (2004) and Fryirs and Brierley (2012), channel adjustment is one mechanic of the river recovery process that indicates the degradational trend is being reversed (Fryirs & Brierley, 2000).

Many initiatives introduced in recent times promote managing rivers in a way that encourages geomorphic heterogeneity due to the multiple benefits it provides. Examples of this include "erodible corridor", "Don't fight the site", and "living with rivers" (Piegay et al., 2005, p.774; Brierly & Fryers, 2009, p. 1; Garcia et al., 2021, p. 2). Piegay et al. (2005) promoted allowing natural lateral channel adjustment to occur within a defined corridor to create a balance between the environmental benefits of a more connected fluvial system and the economic benefits of protecting infrastructure and arable land on the floodplain outside of the erodible corridor (Figure 95). Williams et al. (2020) showed how allowing lateral migration in the Allt Lorgy in Scotland increased geomorphic variability following flood events, which provides many of the benefits discussed (Figure 96). Utilising approaches such as these on the Tauanui and Turanganui Rivers would provide the benefits associated with more heterogeneous systems, as well as ensure the protection of the developed floodplain.

Figure 95: Erodible corridor management regime present on the Asse River, south-eastern France (Piegay et al., 2005).

Figure 96: Development of diverse geomorphic units following restoration project allowing lateral erosion on the Allt Lorgy in Scotland (Williams et al., 2020).

The concept of 'Don't fight the site' incorporates acknowledging the inherent geomorphic characteristics and processes within a catchment to ensure the practices implemented are strategic and targeted towards guiding effective river rehabilitation (Brierly & Fryers, 2009). Garcia et al. (2021, p. 2) proposed "living with rivers" as a concept comprising not only the physical aspects of river management but of legislation and education (Figure 97). By utilising a multi-disciplinary approach, geomorphologists, engineers, ecologists, planners, and policymakers can combine their skills to effectively practice holistic river science and apply it to river management. This helps produce better overall outcomes for the environment and for protecting people and infrastructure on floodplains (Thoms et al., 2016; Garcia et al., 2021). Connected and integrated planning with regard to flood-risk management, river restoration and land planning is important in developing floodplains in a way that is sustainable, environmentally beneficial and reduces flood risk (Garcia et al., 2021). Historically, planning in these spaces has occurred in isolation from one another, so the best outcome for all disciplines is not considered (Garcia et al., 2021). For example, accelerated development in floodplains in conjunction with increasing flood frequency increases exposure to flood risk (Sofia & Nikolopoulos, 2020; Garcia et al., 2021). This requires experts to collaborate and combine their

expertise to produce an integrated plan that reduces flood risk and balances positive environmental and economic outcomes. Garcia et al. (2021) argued that there also needs to be an educational approach to river management, where it is shown that the "command and control" approach utilising hard engineering and invasive modifications is not only expensive but has detrimental effects on aquatic ecosystems and often reduce river resilience (Fuller & Death, 2018; Fuller & Conley (in press)).

The benefits of management practices that encourage geomorphic and ecological heterogeneity need to be advocated. Stories of success regarding more holistic approaches, such as Fuller et al. (2019) and Garcia et al. (2021), will contribute towards a shift in mentality concerning river management and help make legislative change more acceptable. This shows that a more collaborative approach based on the 'living with rivers' approach to river management on the Tauanui and Turanganui Rivers would benefit both the river systems and surrounding communities.

Figure 97: The illustrated conceptual model of 'living with rivers' (Garcia et al., 2021).

As shown in the Tauanui and Turanganui Rivers, the current management practices have reduced geomorphic diversity. This has negatively impacted river resilience and habitat diversity and increased the community's exposure to flood risk. As shown by Piegay et al. (2005), Brierly and Fryirs (2009) and Garcia et al. (2021), effective river management involves moving away from invasive modification and allowing the river's natural character to re-establish by allowing lateral migration and natural character to develop. Both rivers' unique characteristics must be carefully considered when considering river rehabilitation and management to make informed decisions that work with the geomorphic forms and processes present. River management needs to be integrated with other environmental planning disciplines, and the experts associated with the planning process must be collaborative to form a knowledge base that considers all implications of management practices. The community also needs to become more aware of the effects river management has on the environment and fluvial processes within these rivers.

6.4 Limitations and future recommendations

Although this research presents several findings on the drivers behind contrasting geomorphic change in response to a flood event, some limitations prevent an explicit understanding of the processes involved. Due to significant lateral erosion on the true left of the Turanganui River (Figure 45), the benchmarks for the SFM survey error calculations were lost. This resulted in relying on concurrent GCP survey points to indicate the model accuracy of the study reach. Although model accuracy is sufficient to detect geomorphic change, the margin of error is increased. Therefore, the estimation of sediment storage changes in the Turanganui River study reach before and after the 20th of June 2021 flood event has less accuracy. However, the errors calculated are still within acceptable margins. For future SFM surveys, it is recommended that benchmarks are moved further back and redundancy benchmarks installed so lateral erosion is less likely to affect them.

As seen in Chapter 4.3.1, the Tauanui River cross sections only cover the river's lower reaches. Therefore, making inferences concerning historic bed level changes in the upper catchment in the Tauanui is unsuitable. The lack of cross-section data prevented the assessment of the mean bed level in the upper catchment. However, this limitation could be overcome due to the use of historical imagery as a tool. Historic geomorphic change could then, therefore, be put into context with management practices in the upper Tauanui River. To accurately calculate bed level changes over time in the Tauanui and Turanganui Rivers, it is recommended that cross-section surveys are continued by GWRC in the Turanganui and the lower Tauanui, as well as establishing survey cross-sections in the upper Tauanui. Other tools could be utilised for bed level analysis on these rivers, such as concurrent LIDAR flights used in Backes et al. (2020) or SFM surveying as used in this research and others (Vericat et al., 2009; Javernick et al., 2014).

A well-documented limitation of SFM survey techniques is their inability to penetrate heavy vegetation (Fuller et al., 2020; Strohmaier, 2020). Although these areas were excluded from surveys, so this bias was not introduced, significant portions of the floodplain could not be monitored to detect geomorphic change, even when the orthophotos show significant lateral erosion into heavily vegetated banks. This indicates that calculations of sediment flux are underestimated. However, particularly in the Turanganui, the presence of woody debris in the survey area indicates that estimations of sediment movement may be overestimated. This impacts the estimation of sediment flux in response to the 20th of June 2021 flood event and limits the analysis of sediment dynamics within the vegetated banks and bars following the June 2021 flood. However, this did not prevent conclusions from being made as heavily vegetated areas were masked from analysis, and orthophotography allowed analysis of geomorphic change in these areas. The detectable sediment movement was also still significant in both rivers and woody debris deposited in the study reach was not significant. The development of a vegetation correction model to account for canopy cover, as seen in Enwright et al. (2021), is a potential method of detecting geomorphic change on heavily vegetated banks and bars of the Tauanui and Turanganui for future surveys.

Another variable not considered in this study is gravel extraction in both rivers. Consented gravel extraction occurs in both rivers (Cyril, 2009; Fish and Game, 2022). Also, according to regional rules, riverside landowners can extract up to 50m² of gravel per year, and others can extract up to 15m² per year (GWRC, 2014). Stockpiles of gravel seen on the private land adjacent to the river indicate this is happening, although further downstream than the study reach locations. Gravel extraction can significantly impact river morphology, such as bed degradation and channel instability (Fuller & Basher, 2012). This may be having an impact on sediment dynamics in these rivers and could be a contributing factor to detrimental geomorphic change occurring in these rivers. It is recommended that the spatial scope of this study is expanded into the areas where gravel extraction occurs to assess its impact on river morphology.

7.0 Conclusions

Analysis of the Tauanui and Turanganui Rivers using historical imagery, cross-sectional surveys and contemporary data gathered using SFM surveying identified sediment dynamics in response to discrete flood events. Narrowing and straightening of both rivers has resulted in geomorphic homogenisation, which has reduced river resilience and brought them closer to geomorphic thresholds. A flood event on the 20$^{th\ of}$ June 2021 resulted in a geomorphic change in both rivers that, when put in a decadal context, was significant. Sediment flux was quantified, revealing significant erosion and deposition, showing net aggradation in both study reaches. Although geomorphic change was significant in both study reaches, it contrasted in scale. This is related to the variations in river resilience and thresholds within geomorphic systems. River management was appraised, showing that both rivers have changed considerably over time as a result of the development of floodplains. Management has been shown to reduce resilience and bring both rivers closer to geomorphic thresholds. Including geomorphic impacts, management that homogenises river corridors also are detrimental to habitat diversity and increases the exposure of the surrounding land to flood risk. In addition, considering recent weather phenomena such as Cyclone Gabrielle and Hale resulted in significant flooding and geomorphic change that took lives and caused considerable property damage, it is clear that a new approach to river management is required. To achieve this, the role of geomorphology and the benefits of a geomorphic approach to river management should be clarified and adopted.

8.0 Recommendations

To understand the geomorphic trends occurring in the wider catchment of the Tauanui and Turanganui Rivers in response to flooding and management, further study on both rivers is required. Extending the spatial scope of the study area would achieve this and explore the implications of other river management practices occurring downstream, such as gravel extraction. Further study into historic geomorphic change and geomorphic response to flood events of both rivers in their entirety would be an invaluable addition to this research. Due to the lack of historical imagery before the 1940s, the historic planform before the deforestation of both rivers cannot be viewed for analysis. However, proxies of this can be utilised, such as written historical accounts and floodplain core analysis as used by Fuller et al. (2018) and Fuller et al. (2019), to reconstruct historical flood records to investigate geomorphic change. Extending this research into the future by completing more SFM surveys in the two study sites would provide useful knowledge, such as informing whether the 20th of June 2021 flood event flood further sensitised the rivers to consecutive erosion events. Several floods have occurred since 2021, which may have resulted in further channel widening and lateral migration.

Management strategies need to change to make these rivers more resilient to flooding and associated geomorphic change. The practices of straightening and narrowing river channels should be replaced by giving the rivers more room to laterally erode and develop a more natural character. This would involve removing or relocating the stopbanks, confining the rivers and stopping in-stream works such as channel straightening and planting. This will increase river resilience and reduce the exacerbated geomorphic change in response to floods as a result of current management practices.

An assessment of the geomorphic recovery potential of the Tauanui and Turanganui Rivers utilising a framework such as *river styles* would help inform effective implementation of future management practices that work with the inherent characteristics of each river and provide the best outcomes for flood risk management, geomorphic diversity and ecological benefits. Further study into the effectiveness of a change in management practices is also important. We have known the benefits of giving rivers more room for a long time (Wohl, 2004; Piegay et al., 2005; Fuller & Hutchinson, 2007). These theories must be put into practice, and their effectiveness must be studied and communicated. Ongoing monitoring of projects such as Te Kaueru on the Waingawa River in the Wairarapa is a good example (Harley, 2014). This information needs to be illustrated to educate landowners and government agencies to implement widespread behaviour change concerning river management practices.

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