Wairau River and Lagoon Geomorphic Assessment

Prepared for Marlborough District Council

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Executive summary

Marlborough District Council (MDC) have commissioned NIWA to help them understand the geomorphic processes of the Wairau River that have formed and continue to form the river, particularly as it flows across the lower Wairau Plains and its connection with Vernon Lagoon. This geomorphic assessment is part of a larger work package intended to enhance their understanding of the local physical landscape and inform some of their core functions, including science, policy, river management, and infrastructure management.

This report provides:

1. A high-level description of the Wairau River catchment geomorphology.
2. Trend analysis of hydroclimatic data relevant to sediment transport in the Wairau River.
3. Aerial imagery analysis of the lower Wairau River (downstream of State Highway 6) and the Vernon Lagoon over four time periods: 1924; 1947; 2005 and the 2020s.
4. River cross-section analysis to identify changes in active channel bed level, depth, and slope.
5. Consideration of the relative contribution of fluvial and coastal processes to river morphology in the lower reaches of the Waiau River.

Together, the above analyses inform recommendations for future monitoring and research that could enhance MDC's understanding of the geomorphic context of the region and enable future solutions for management, development and general wellbeing of the community.

The Wairau River catchment has complex geologic, geomorphic, and human histories. The Lower Wairau valley is home to some of Aotearoa-New Zealand's oldest and most significant archaeological sites, including the Wairau Bar and the Lagoon complex (often called Te Arapipi or the Wairau or Vernon Lagoons, which comprises the Upper Lagoon, Big Lagoon, Waikārapi Lagoon and Chandlers Lagoon).

The Wairau River initiates in the Spenser Mountains and drains a catchment area of about 4,000 km^2. As the river flows across the plains, it naturally deposits sediment as its gradient reduces. Historic, large floods encouraged early European settlers to try to manage the river through river engineering works, including:

- Blocking of the Opawa Breach at Conders Bend, near the present-day State Highway 6 (SH6) bridge (1917)
- The Peninsula Cut, near the present-day State Highway 1 (SH1) bridge (1927)
- Construction of the Wairau Diversion (1963)
- Construction of the erodible flow embankment at the head of the Wairau Diversion (2009).

The hydroclimatic analysis shows that trends in precipitation have stayed reasonably stable over the period of analysis (longest data record is about 120 years). These trends, calculated using precipitation data collected at gauging stations in the lower basin, and supplemented by flow gauge trends in the upper basin (no precipitation gauges present), suggest that rainfall has stayed reasonably consistent over the last century. At SH1, the combined records of the Tuamarina and now Barnetts Bank flow gauges provide nearly 65 years of flow data. Trends for the Wairau River at SH1 indicate reasonably strong (likely) declines in average discharge between 1961-2024. Our analysis does not investigate whether this trend is due to climatic drivers or other activities in the catchment (e.g., extraction for irrigation or groundwater pumping).

A GIS analysis of maps and aerial imagery indicates that average widths in the Wairau River between SH6 and SH1 have narrowed up to 56% since 1924, largely due to river training and engineering works to control flooding. River narrowing and straightening have also occurred in the Lower Wairau River downstream of SH1 since 1924. River narrowing can concentrate flow, which can increase the erosive potential of the flow and its ability to transport sediment. Narrowing a river also reduces the area over which it can deposit its sediment, which can contribute to sediment-build up. River straightening (e.g., engineered meander-bend cut offs) can be used to allow flood water to reach the coast more quickly, however, it also shortens the river length, which typically induces bed degradation upstream of the cut and aggradation downstream of the cut as the river adjusts its gradient.

The river cross section analysis largely aligns with previous work by Christensen and Doscher (2010) and Gardner and Sharma (2016), with some differences. Christensen and Doscher (2010) identified degradational trends in mean bed levels in the Lower Wairau River prior to 1963, indicating an "erosional" phase in the river. We consider that this trend is likely at least partly driven by blocking the Opawa Breach. Christensen and Doscher (2010) note that following the 1963 construction of the Wairau Diversion, the river experienced an "aggradational" phase, as flow energy in the lower river had been reduced by the diversion. Our analysis largely agrees with this finding, however, for the three cross sections spanning the diversion area (WR XS 20, 23 and 24.3), whilst bed levels initially aggraded (when just flow was diverted), bed levels in this area then dropped once the diversion was fully developed and bed material was also travelling down the diversion. An erodible flow embankment at the top of the diversion channel was installed in 2009 with the aim of increasing flows in the lower river whilst still enabling activation of the diversion channel during floods (Gardner and Sharma 2016). Following embankment construction, aggradation in the sand bedded tidal reach appears to have largely halted with a small reduction in bed levels at some cross sections. However, for the three cross sections spanning the diversion, our analysis indicates an increase in mean bed levels since the time of Gardner and Sharma's (2016) analysis. Aggradation in this zone is to be expected as it is within the natural gravel deposition zone. Mean bed levels in the diversion channel show a trend of upstream knickpoint migration as the channel developed and then stabilised post-construction. Minimum bed levels do not have generalisable trends and may represent infilling, deepening or changing shape of the channel. Minimum bed levels are particularly variable above the diversion, where the river is braided, and closest to the mouth, where coastal and tidal influences are greatest.

It is challenging to clearly tease apart the relative influences of natural processes versus human modifications on sediment dynamics in anthropogenically-modified rivers because such rivers may not be able to adjust naturally. Moreover, bed level adjustment can take many decades, meaning that the river may still be adjusting to one intervention when the next is initiated. Our collective analysis indicates that the most significant physical changes to the Lower Wairau River over the last century are anthropogenically driven. Between SH6 and SH1 there has been a considerable degree of river narrowing (up to 56% reduction in average width). Below SH1 the river has shown phases of aggradation and degradation (up to 1.5 m of mean bed level change) that we consider are largely phased responses to the blocking of the Opawa Breach, construction of the Wairau Diversion and construction of the erodible embankment. There is little evidence that precipitation, annual maximum discharges, or sediment delivery from the upper catchment have changed over the same period. Similarly, there is little evidence from previously conducted research included in our analysis that suggests strong coastal influence on the morphology of the Lagoon complex. Based on our analysis, we consider that, at present, fluvial processes – including fluvial response to upstream engineering interventions – may be driving more adjustments in the lower river than coastal processes.

Based on our analysis, our recommendations are that MDC continue monitoring river bed levels with cross-section surveys or bathymetric lidar to monitor any emerging trends in bed levels. MDC may also wish to consider undertaking 1-dimensional morphodynamic modelling of the river to better understand possible changes in gravel transport and bed levels under various future scenarios, including under projected climate change scenarios. Collection of bed material data would be useful to inform future morphodynamic modelling and also help identify where the river transitions from a gravel to sand bed.

The outcomes of aligned NIWA/MDC projects currently underway, including the updated flood frequency analysis, coastal flooding and sea level rise assessment, and groundwater modelling investigation, may also provide useful information for understanding the hydrologic regime of the Wairau River catchment and influences on river morphology. While outside of the scope of this work, there is potential to consider the findings of those studies to further explore the relative contribution of fluvial and coastal processes on the morphology of the Lower Wairau River.

1 Introduction

1.1 Background and purpose

The modern geomorphology (shape, form and processes) of the Wairau River in Marlborough, South Island New Zealand, reflects its unique tectonic and geologic histories, and a long legacy of river control works and engineering (Christensen and Doscher 2010). Marlborough District Council (MDC) seeks to better understand the geomorphology of the Wairau River, including the physical processes that have formed and continue to form the river, particularly as it flows across the lower Wairau Plains and its connection with Vernon Lagoon.

This geomorphic assessment is part of a larger work package commissioned by MDC to enhance their understanding of the local physical landscape and inform some of their core functions, including science, policy, river management, and infrastructure management.

This project aligns with other investigations being undertaken by NIWA for MDC, including a:

- Flood frequency update;
- Coastal flooding and sea level rise assessment;
- Groundwater modelling investigation.

1.2 Scope

This report assesses physical processes driving the morphology of the Wairau River and Vernon Lagoon, including:

1. A high-level description of the Wairau River catchment geomorphology and influencing factors, including tectonics, major weather events, land use changes and river engineering history.
2. A summary of hydroclimatic factors that may be relevant to sediment transport in the Wairau River and sediment delivery to Vernon Lagoon/river mouth, including temporal changes in the magnitude of precipitation events and in streamflow metrics.
3. A GIS analysis of maps and aerial imagery of the Lower Wairau River (downstream of State Highway (SH) 6) and the Vernon Lagoon over four time periods: 1924; 1947; 2005 and 2021/22 (most recent aerial imagery).
4. River cross-section analysis to identify changes in active channel bed level, depth, and slope.
5. Consideration of the relative contribution of fluvial and coastal processes to river morphology, in the context of previously conducted coastal analyses.

The agreed scope further requires that above assessments inform conclusions and recommendations for future monitoring and research efforts that could further enhance MDC’s understanding of the geomorphic context of the region and enable future solutions for management, development and general wellbeing of the community.

1.3 Report layout

The first section of this report (Section 2) provides a brief and high-level explanation of sediment transport principles to provide context for the geomorphic assessment.

The catchment context (Section 3) provides high-level information about the Wairau River catchment, including its underlying geology and soils, tectonic history, climate and flood history, land use and cover, and anthropogenic/human histories. It also discusses significant sites for iwi.

Section 4 describes the core new analysis undertaken for this project. We have split this section into two parts. Section 4.1 presents methods and results of the hydroclimatic analysis. Section 4.2 presents methods and results for assessing morphological changes in the Wairau River. This morphological assessment covers both the GIS (maps and aerial imagery) and cross section analyses.

Section 5 synthesises information to provide a summary of the geomorphic processes occurring in the Lower Wairau River and Vernon Lagoon. This information is then used to inform the recommendations provided in Section 6.

2 Sediment transport principles

A river's geomorphological evolution depends on the balance of river flow and the size and availability (e.g., load) of sediment from upstream, as well as the slope of the valley (Figure 2-1; Tunnicliffe and Brierley 2021).

Sediment can be supplied to rivers by discrete (e.g., instantaneous) surface processes such as landslides, debris flows, or bank erosion, or through diffuse (e.g., continuous) surface processes such as soil creep (Kondolf 1994; Tunnicliffe and Brierley 2021). Sediment ranges in size from silt and clay sized particles (<0.063 mm) to boulders (>256 mm) (Table 2-1; Wentworth 1922).

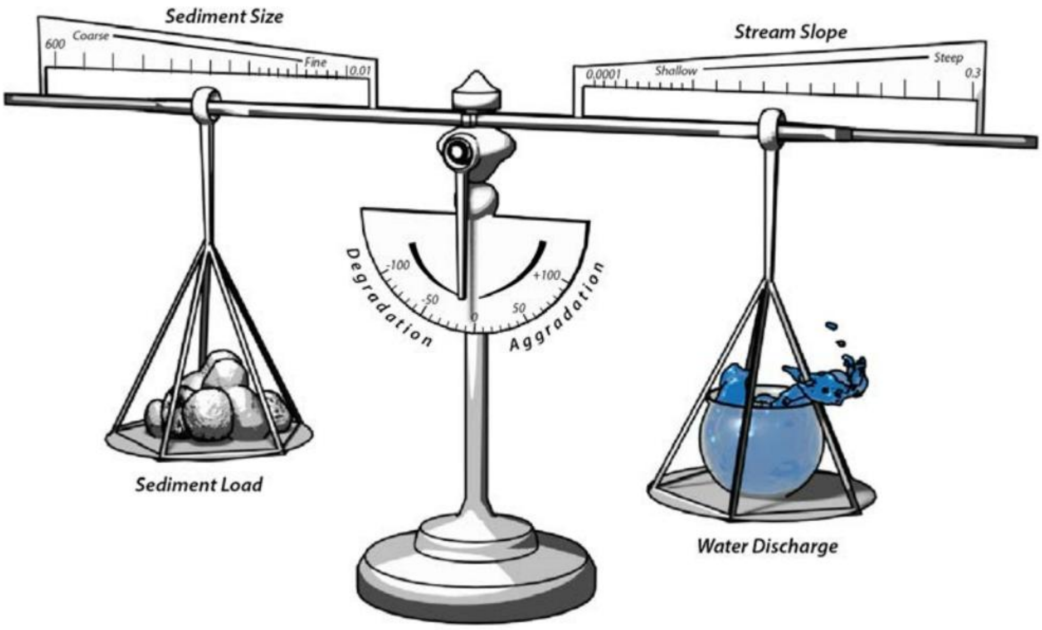

Figure 2-1: Lane's Balance illustrating the dynamic interplay of a river's form. A river's form depends on the balance of the supply of water and sediment, the size of supplied sediment, and the valley slope. From Tunnicliffe and Brierley (2021). Original conceptual model by Lane (1955).

Sediment transport in rivers tends to be discussed in two[1] categories: suspended load and bedload. The suspended load of a river includes sediment that is transported in suspension within the flowing water (generally finer sands, silts and clays), while bedload includes the heavier sediment that moves along the bed of the river (coarser sands, gravel, cobbles and boulders). Sediment particles that move as bedload can move by rolling, sliding or saltating (e.g., bouncing) along the bed (Figure 2-2).

Table 2-1: Sediment size categories based on the Wentworth (1922) scale.

Size category	Description of particle size	Size (mm)
Boulder		>256
Cobble	Large	128-256
	Small	64-128

[1] A third category, the dissolved load, comprises solutes that are typically derived from the chemical weathering of bedrock and soils. The dissolved load is generally disregarded when discussing river adjustment or sediment loads because it does not contribute to the solid load of a river (Turowski et al. 2010).

Size category	Description of particle size	Size (mm)
Gravel	Very coarse	32-64
	Coarse	16-32
	Medium	8-16
	Fine	4-8
	Very fine	2-4
Sand	Very coarse	1-2
	Coarse	0.5-1
	Medium	0.25-0.5
	Fine	0.125-0.25
	Very fine	0.0625-0.125
Silt		0.0039-0.0625
Clay		<0.0039

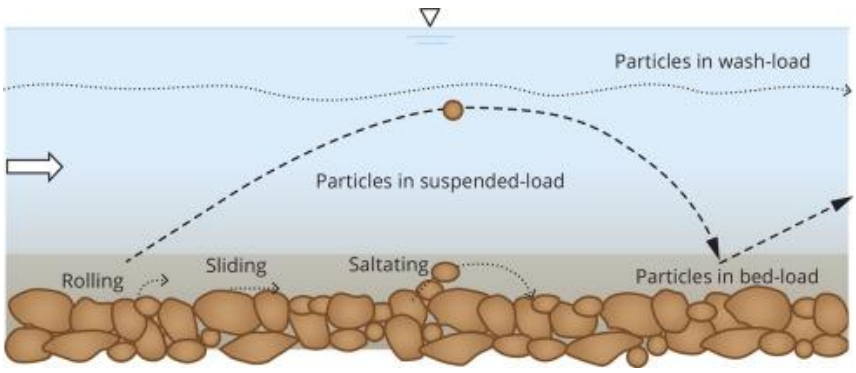

Figure 2-2: Sediment transport in rivers. From Rheinheimer and Yarnell (2017).

Together, the suspended load and bedload comprise the total sediment load of a river, which is often discussed as a metric of tonnes/year, or can be normalised by catchment area to a metric of tonnes/km^2/year. In gravel bed rivers such as the Wairau River, the majority of the annual sediment load is composed of suspended sediment (e.g., Hicks et al. 2011), and bedload makes up a relatively smaller proportion of sediment that reaches the coast. However, bedload plays an important role in shaping river morphology and habitat diversity. Gravel and other bedload materials are responsible for generating a river's morphological character, and if the river's ability to mobilise that bed material changes, the river's morphology will also change (Figure 2-1).

In the Lower Wairau River, below SH1, we have observed that the river transitions from a gravel bed at SH1 to a sand bed upstream of the lagoon. However, there is limited data available on grain size to accurately inform where this transition occurs, and the area over which the transition occurs may vary over time (see Figure 3-5 in Section 3.3).

3 Wairau River catchment context

The Wairau River drains a catchment area of around 4,000 km^{2}; [2]. The headwaters of the Wairau River extend to the Spenser Mountains, with a maximum elevation of nearly 2,300 m at Mt McKay (Figure 3-1). Braiding morphology begins as the river emerges from the Raglan and St Arnaud Ranges and flows across the Wairau Plains. As the river approaches State Highway 6 (SH6), it becomes more of a wandering channel (transitioning from braided to single thread) until it reaches the Wairau Diversion, which splits the flow of the river approximately evenly through the lower river channel and the artificial diversion channel.

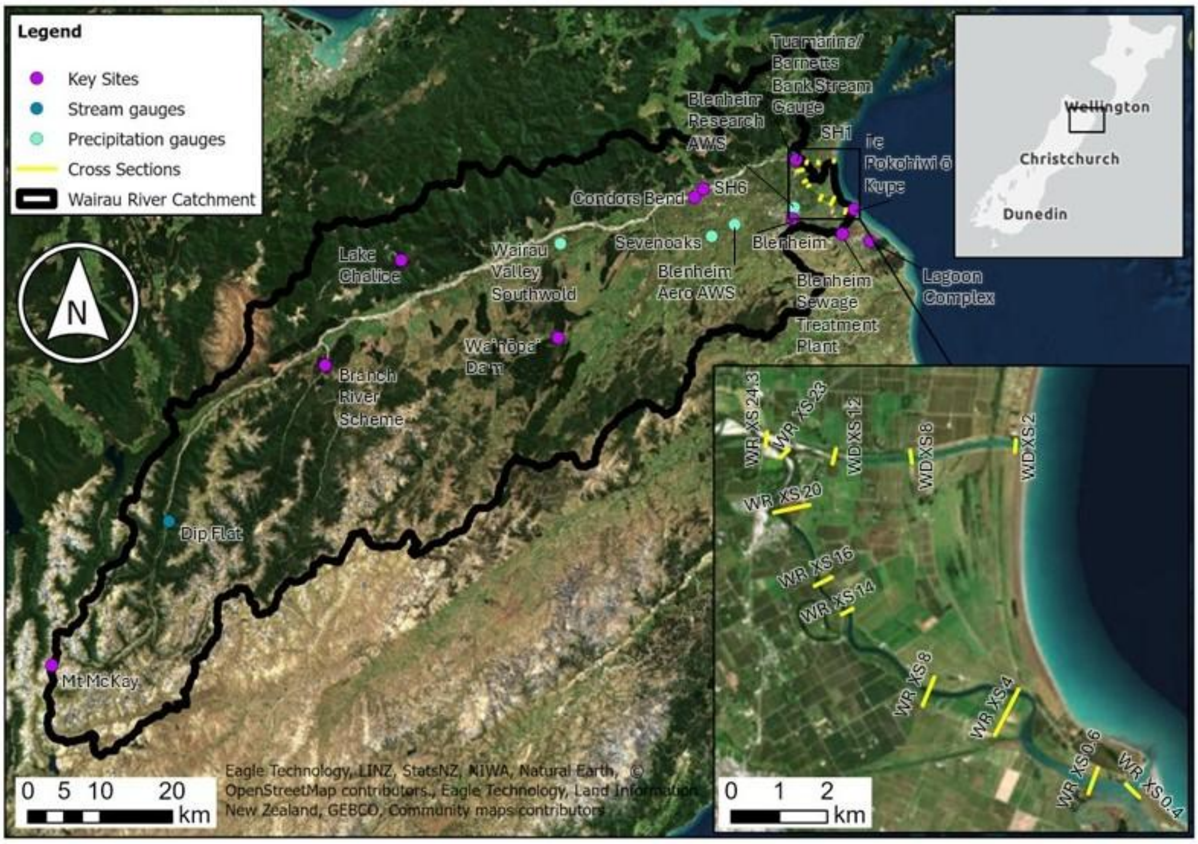

Figure 3-1: Wairau River catchment, key sites, gauge stations, and cross section locations.

The longitudinal elevation profile of the main Wairau River channel illustrates variability in river slope along the length of the river (Figure 3-2). From the point where the river emerges from the St Arnaud and Raglan ranges (about 12 km downstream of Dip Flat) to the confluence with the Waihopai River, the river has an approximate slope of 1:200 (Christensen and Doscher 2010). At the head of the Wairau River alluvial fan, slope decreases to about 1:700. Slope decreases further to 1:2,000 in the lower river, downstream of Tuamarina (Christensen and Doscher 2010).

Rates of bed level change vary along the length of the river. Christensen (2005, as cited in Christensen and Doscher 2010) found that bed levels between the emergence from the St Arnaud and Raglan Ranges to the Waihopai confluence are generally stable. The alluvial fan, from between the Waihopai confluence and Tuamarina, is a natural depositional zone (Christensen 2005; Gardner

[2] Published catchment areas for the Wairau River range from 3,430 km^{2} (Wohling et al. 2020) to 3,825 km^{2} (Basher et al. 1995; Christenson and Doscher 2010) to 4,177 km^{2} (Hicks et al. 2011). Catchment area based on the current Aotearoa-NZ national digital network (Whitehead and Booker 2020; https://shiny.niwa.co.nz/nzrivermaps/) at the river mouth is 4,040 km^{2}.

and Sharma 2016), meaning that bed levels naturally increase over time through this reach due to the lower gradient. Downstream of Tuamarina, the river is split between the Wairau Diversion channel (constructed 1963) and the Lower Wairau River, which is a lower gradient (1:2,000), tidally influenced channel (Basher et al. 1995; Christensen and Doscher 2010).

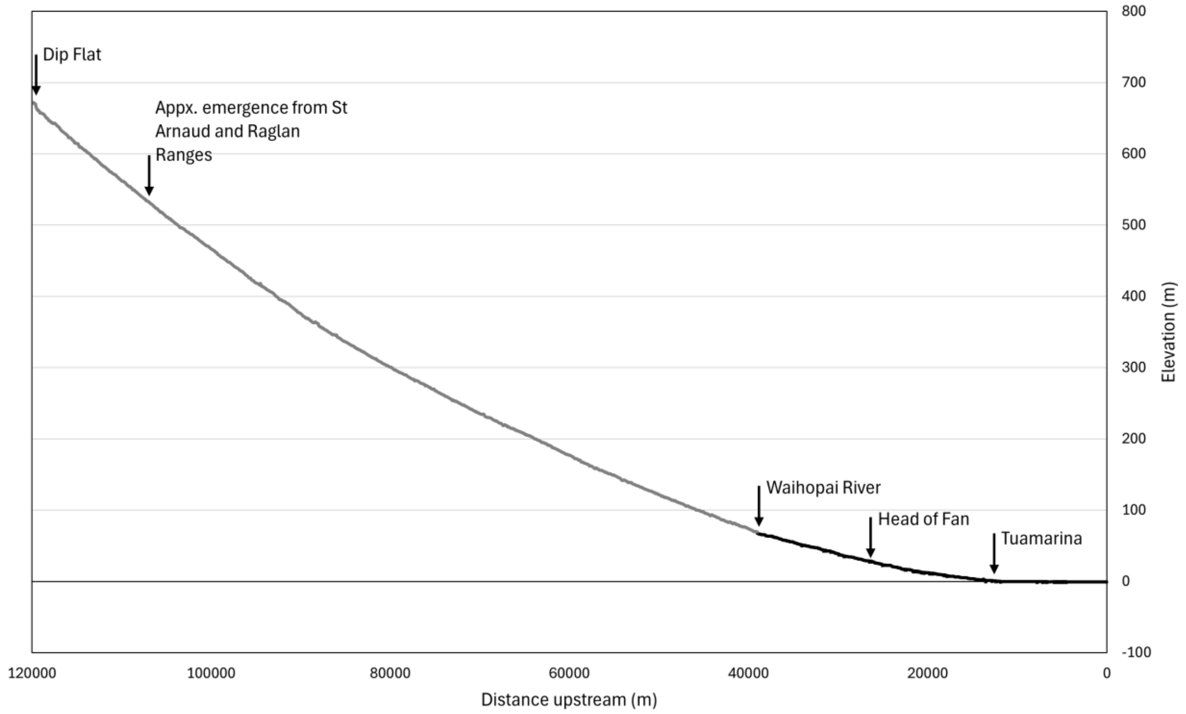

Figure 3-2: Longitudinal profile of the Wairau River valley. Data represented by the black line downstream of the Waihopai River is from bathymetry survey data collected by NIWA in 2022. Data upstream of the Waihopai River, represented by the grey line, is from a composite DEM from the Esri Living Atlas Terrane layer, down-sampled to 26 m grid resolution.

3.1 Geology and tectonic history

Contemporary surface geology and geomorphology (Figure 3-3) in the Wairau River catchment are strongly controlled by tectonic, postglacial and modern fluvial processes (Brown 1981). Earthquakes can be major drivers of geomorphic change in river systems due to cascading effects that can alter river pathways (e.g., McEwan et al. 2023), change local base level via subsidence or uplift (e.g., Hayward et al. 2010) or by delivering large amounts of sediment to the channel (e.g., Korup et al. 2004).

The main fault in the catchment is the Wairau Fault, which is the northernmost of four active strike-slip faults that comprise the Marlborough Fault System (Nicol and Dissen 2018). The Wairau Fault has not ruptured through to the surface in modern history (e.g., since 1840) but has experienced at least five surface-rupturing earthquakes over the last 6,000 years (Nicol and Dissen 2018). Such large earthquakes have the ability to generate rock avalanches that may cause landslide-dammed lakes (e.g., Lake Chalice to the north of the main valley), but the frequency of rock avalanching in the Wairau catchment is unknown (Basher et al. 1995). Tectonic controls in the catchment have resulted in the majority of Wairau River tributaries initiating in the ranges to the south (Brown 1981), draining sedimentary rocks of the Pahau Terrane (primarily sandstone with some mudstone and minor volcanics). Tributaries draining the ranges to the north were largely blocked by postglacial aggradation (sediment build-up) from the Wairau River and, combined with tectonic tilting, formed swampy areas before seeping into the Wairau River (Brown 1981). Extensive drainage of swamps across the plains began taking place in the 1870s to enable settlement and agricultural development (Basher et al. 1995).

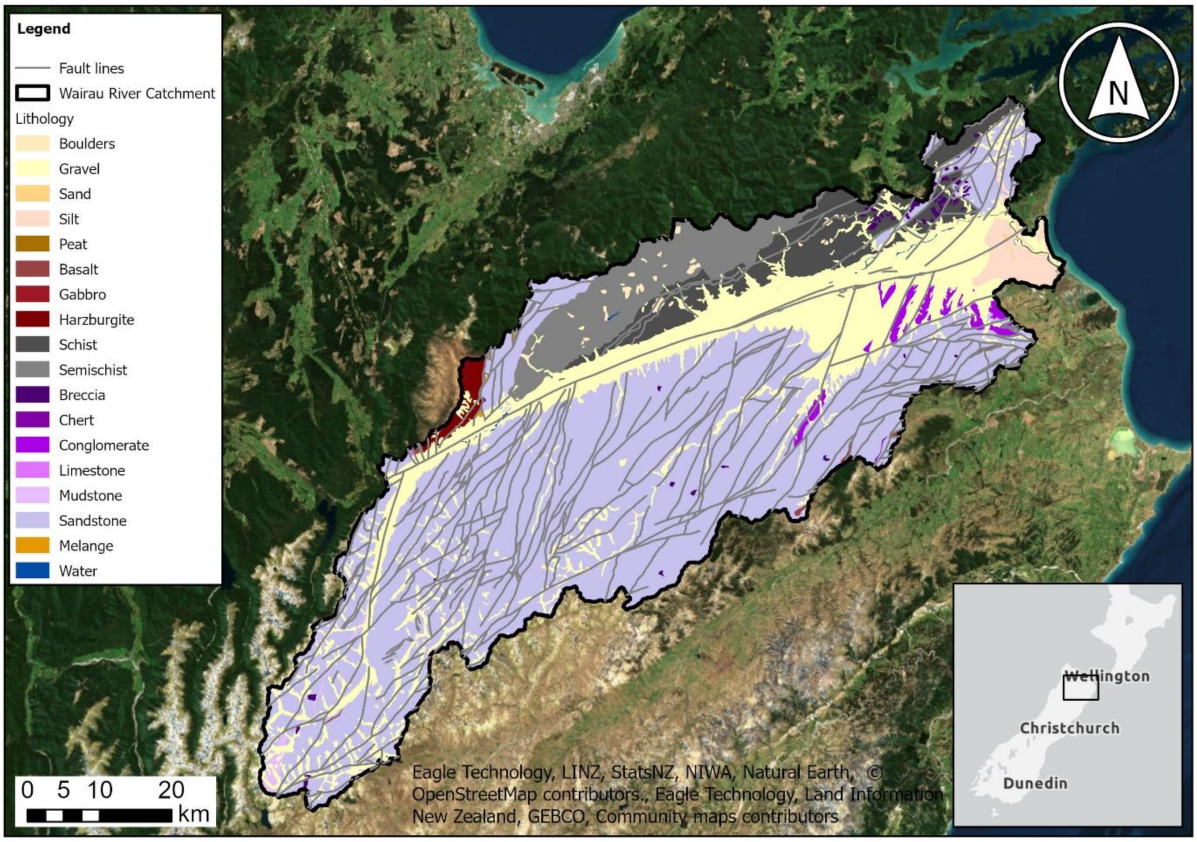

Figure 3-3: Geology of the Wairau River catchment. Geology layer modified from GNS.

The Wairau River valley and plain comprise postglacial aggradation surfaces overlying glacial outwash deposits. The oldest terraces in the Wairau Plains are 14,000 – 20,000 years old (Suggate 1988, as cited in Basher et al. 1995) and are largely overlain by postglacial sediments reworked and transported by the modern Wairau River. The upper and middle parts of the plains comprise gravels while the lower part of the plains comprises silt and sand (Figure 3-3). At Tuamarina, where the river gradient drops substantially, the Wairau River loses capacity to transport large quantities of gravel (Basher et al. 1995). Near-surface alluvial sediments associated with post-glacial fluvial deposits range in thickness between 20-35 m (Wilson 2016) and the total depth of alluvial deposits may be as large as 300 m (Hunt 1969, as cited in Basher et al. 1995).

The Marlborough region can be affected by large earthquakes on faults in both the upper South Island and the lower North Island (Grapes and Holdgate 2014). The two most notable earthquakes in modern history to affect the region include the 1848 M_w 7.4-7.7 Marlborough and 1855 $M_S \cong 8.2$ Wairarapa earthquakes (Grapes and Holdgate 2014)[3]. The 1848 Marlborough earthquake on the Awatere Fault (south of the Wairau catchment) resulted in 1.5 m of subsidence along the Cloudy Bay coast, which enlarged the Lagoon complex (often called Te Arapipi or the Wairau or Vernon Lagoons, and which comprises the Upper Lagoon, Big Lagoon, Waikārapi Lagoon and Chandlers Lagoon; here referred to the Lagoon complex (Basher et al. 1995). The 1855 Wairarapa earthquake resulted in a further 0.45 m of subsidence in the Lagoon complex (Basher et al. 1995). Cumulative subsidence including from these earthquakes and other sources – potentially from gradual subsidence or from a series of small downward displacements on local faults – has driven around 3-4 m of subsidence along the southern side of the Lagoon complex over the last 3,000 – 4,000 years (Hayward et al. 2010).

3.2 Climate and major weather events

Climate and major weather events play an important role in influencing river geomorphology, as bedload transport is driven by river flows with greatest bedload transport occurring during big floods.

The Marlborough region is characterised by dry, hot summers and cold winters (Chappell 2016). The average annual rainfall across the region varies, with some areas receiving less than 600 mm of rain per year (e.g., the Awatere Valley south of the Wairau catchment) and other areas receiving over 2,000 mm of rain per year (e.g., the Richmond and Raglan Ranges, draining tributaries to the Wairau River; Chappell 2016). Marlborough is one of three regions in the eastern South Island of Aotearoa-New Zealand that are the driest regions in the country (Chappell 2016).

Despite being one of the driest areas in Aotearoa-New Zealand, Marlborough has experienced extreme weather events in the past. Weather systems arriving from the east can bring heavy rainfall (Chappell 2016). Notable rainfall events in recent history include Cyclone Alison in 1975 and heavy rain in 1983, 2004, and 2008 (Chappell 2016). The Wairau catchment was particularly affected by the 1983 event, with widespread flooding and damage to infrastructure (Chappell 2016). River flows during this event were exacerbated by the combination of heavy rainfall, snow melt, and already saturated ground (Chappell 2016). This flooding event is the largest known flood in the Wairau River since the 1860s (Williman 2010).

Work by Wöhling et al. (2020) quantified trends in mean annual precipitation for the Wairau River basin using gridded Virtual Climate Station Network (VCSN) data available from NIWA. The Wöhling et al. (2020) analysis indicated that mean annual total precipitation had a declining trend of about 2.9 mm per year over the 1960 to 2019 period of record, but concluded the trend was ‘not significant’. Wöhling et al. (2020) further examined spatial patterns in the temporal trend by interpolating trends at individual VCSN locations and found that the majority of the basin, particularly the higher elevation areas, had negative, but non-significant, trends in annual precipitation. Wöhling et al. (2020) speculated that the trends were likely artefacts of bias in the spatial interpolation methods used to generate the VCSN data. We present an updated assessment

[3] M_W and M_S are two different scales for measuring earthquake magnitude. M_W (moment magnitude) is the most commonly used earthquake scale at present, developed to account for limitations in previously used magnitude measurements. M_W relates to the total amount of energy released during an earthquake, and it represents the amount of slip on a fault multiplied by the area of the fault surface that slips in an event. M_S is a more antiquated measurement that is a measure of surface wave magnitude. See Moment magnitude, Richter scale - what are the different magnitude scales, and why are there so many? | U.S. Geological Survey and Magnitude Types | U.S. Geological Survey for more information.

of climatic trends in Section 4.1 and discuss these new data in relation to sediment transport properties of the river system.

3.3 Land use and anthropogenic history

The Lower Wairau valley is home to some of Aotearoa-New Zealand's most significant archaeological sites, including the Wairau Bar and the lagoon complex. Te Pokohiwi ō Kupe (the Wairau Bar) is one of the earliest sites in Aotearoa-New Zealand to have been settled by early Polynesians (Te Runanga o Rangitane o Wairau 2023). The Wairau area is also recognised as one of the first sites in Aotearoa-New Zealand to have undergone modification by early inhabitants. Māori excavated an extensive canal network throughout the lagoons for navigation and food-harvesting purposes (Marlborough District Council 1994; Te Runanga o Rangitane o Wairau 2023).

Currently, about 60% of the catchment is a natural surface (e.g., alpine scree) or native vegetation, with 22% of the catchment characterised by indigenous forest (Figure 3-4). The remaining 40% of the catchment is composed of developed or modified areas (e.g., urbanised areas or exotic forestry). Most modifications to the catchment are in the central and lower parts of the valley.

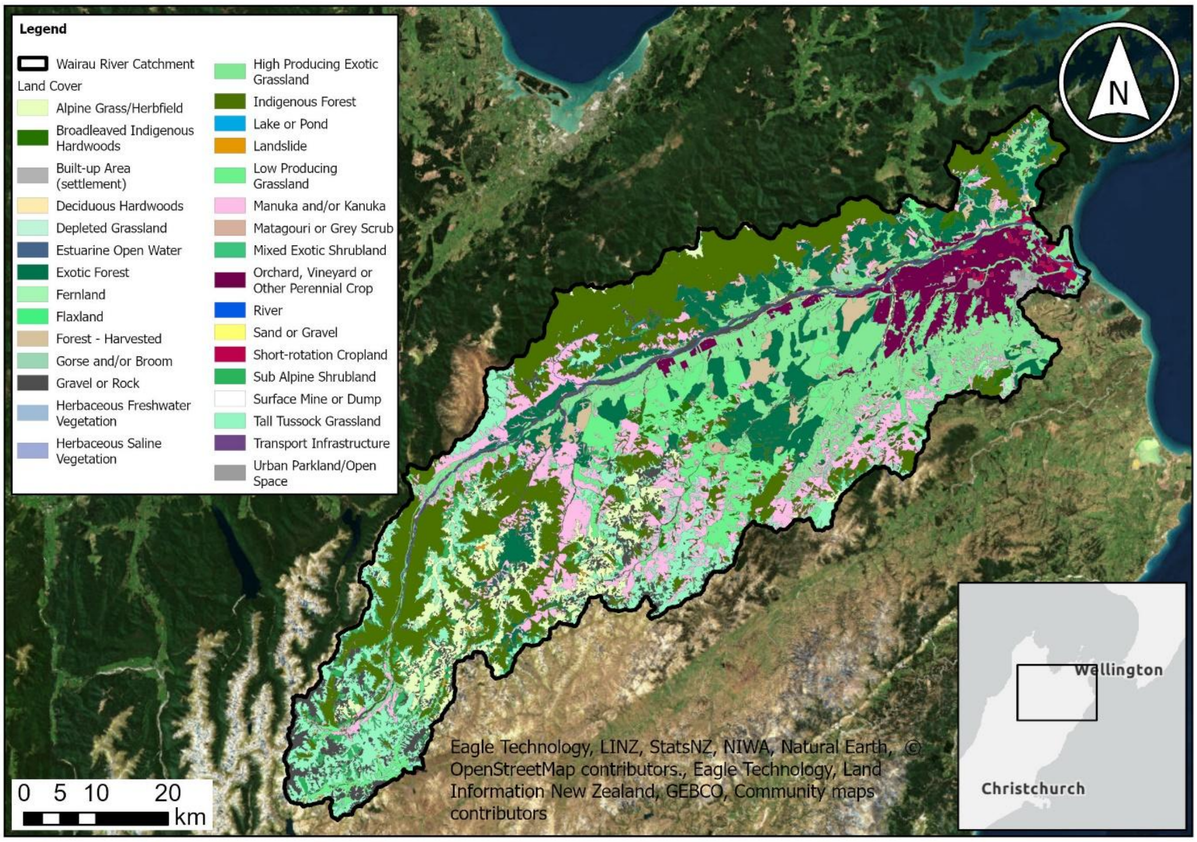

Figure 3-4: Land cover in the Wairau River catchment. Land cover data modified from the LCDBv5 from Manaaki Whenua. Data displayed represent 2018 categories.

Historically, the Wairau River had a multi-threaded (braided) channel and during high flows would overflow the banks of its primary thread and flood other channels of the lower Wairau Valley (Basher et al. 1995). Major river works on the Wairau River began taking place in the mid-1800's to enable floodplain development and support the trade industry (Christensen and Doscher 2010). There has been a series of works that affected river morphology since the early 1900's (Table 3-1; Figure 3-5).

Of these works, the two most geomorphically significant modifications to the Wairau River took place in the 1900s: blocking of the Opawa Breach (1917) and construction of the Wairau Diversion (1963), both designed to control flooding in the lower valley (Christensen and Doscher 2010).

Table 3-1: Significant river works on the Wairau River since the 1900's. This table does not capture all works on the river, but these works are likely to have had the most significant geomorphic influences on the river.

Year	River Works
1917	Blocking Opawa Breach
1927	Peninsula Cut just downstream of the Tuamarina rail bridge (near present day SH1)
1963	Wairau Diversion cut
1998	Wairau Diversion reaches full capacity (diversion channel widened naturally and mechanically)
2009	Erodible embankment installed upstream of the division cut

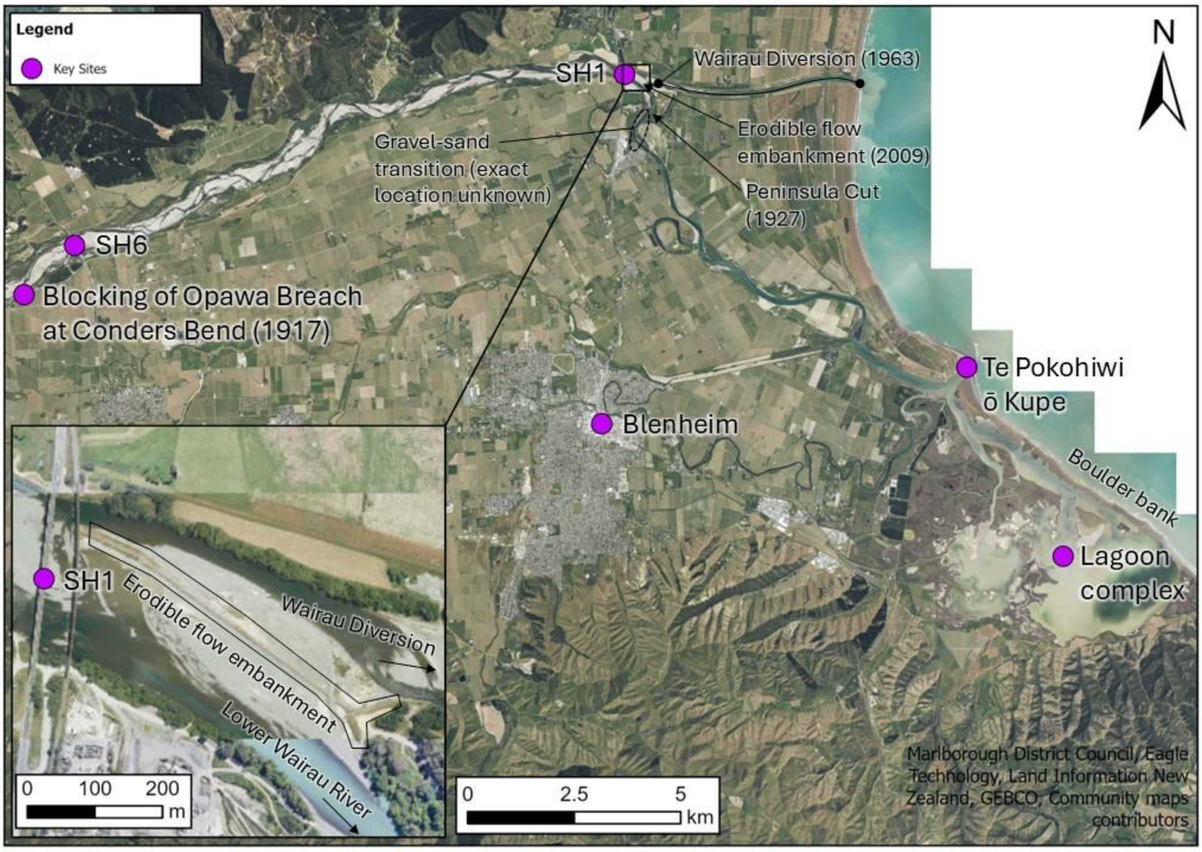

Figure 3-5: Key sites in the Wairau River downstream of Conders Bend, including the locations of significant river works.

The Opawa Breach is a location on the Wairau River near Conders Bend (Figure 3-5) where, during high flows, the Wairau River would overflow its banks and deliver floodwaters to the Opawa River via a distributary channel connecting the two rivers. Construction of the Opawa Breach forced all the flood discharge to be carried by the main channel of the Lower Wairau downstream from the Opawa Breach. This additional flow caused bank and bed erosion in the main channel (Christensen and Doscher 2010).

In the 1960s, the Marlborough Catchment Board (predecessors to MDC) carried out large scale river works to address flooding issues (Marlborough District Council 1994) which were, in part, elevated due to blocking the Opawa channel. These river works included river training and stopbanking up to the confluence with the Waihopai River (Marlborough District Council 1994). In 1963, a diversion channel was cut into the Lower Wairau below SH1 (Figure 3-5) to compensate for the increased flood flows going through the main channel after the Opawa River was blocked. The Wairau Diversion is a direct cut to the sea. When first established, the Wairau Diversion took about 20% of flood flows, but due to natural and mechanical excavation, now takes up to 60% of floodwaters in the Lower Wairau (Christensen and Doscher 2010). The borders of the diversion were built using trenched-in rock armouring, to which the channel would eventually widen.

Following construction of the Wairau Diversion channel in 1963, the Lower Wairau River experienced aggradational issues (Christensen and Doscher 2010). In 2009, an erodible flow control structure was built in the diversion area to address the aggradation that was occurring in the Lower Wairau (Figure 3-5). Downstream of Tuamarina, bed levels in the Lower Wairau River showed degradational trends between 2010-2016, which correlates to the construction of the flow control structure and suggests that it had the desired effect of reducing aggradation (Gardner and Sharma 2016).

Other infrastructure in the catchment that may influence flows and sediment dynamics includes plains-wide drainage and structures on tributaries to the Wairau River associated with hydropower generation (Figure 3-1). Via the Wairau Valley Scheme, the Wairau Drainage Plan 1996, and continual works today, a significant proportion of the previously swampy, lower and upper plains have been drained for the purposes of conversion to pastoral or agricultural uses (Calder-Steele 2024). In 1927, the Waihopai Power Station was commissioned, and a dam was built in the riverbed. The Waihopai Dam, notably, experienced rapid sediment infilling in the first decade of operations and, since the mid 1940's, the reservoir has been completely filled with river gravels (NZSOLD 1989). The dam continues to act as a river bed level control influencing bedload transport both upstream and downstream. The Branch River Power Scheme was commissioned in 1983 and is a 'run-of-river' scheme (i.e., does not include in-river storage which may obstruct bedload transport), but its influence on river flows may have impacts on sediment dynamics (Manawa Energy 2022).

3.4 Significant sites for iwi

The Lower Wairau River and Lagoon complex contain significant historical and modern cultural values. There is more than one marae in the region and three iwi that whakapapa to this area: Ngāti Toa, Ngāti Rārua and Rangitāne o Wairau. Te Pokohiwi ō Kupe (the Wairau Bar) is a particularly significant site for Māori (Figure 3-5).

Te Pokohiwi ō Kupe is the northwesternmost point on an 8 km-long boulder bar that separates the lagoon complex from Cloudy Bay (King et al. 2017; McFadgen and Adds 2019). The boulder bar formed about 6,500 years ago during stabilisation of sea levels following glacial retreat, and it likely became established in its current position about 2,000 years ago (King et al. 2017). A 1 km length of the bar on the northwestern side comprises a heritage site that contains artefacts and remains associated with early Polynesian settlers, believed to be one of the oldest archaeological sites in Aotearoa-New Zealand (Williams et al. in review).

Te Pokohiwi ō Kupe is vulnerable to climate change induced sea level rise and other environmental hazards. The heritage site on Te Pokohiwi ō Kupe is, predominantly, <3 m above mean sea level (Williams et al. in review). Under current climate and sea level conditions, approximately 20% of the heritage area is susceptible to wave inundation in a 100-year storm (Williams et al. in review). Under a scenario of 1 m sea level rise, which is likely to happen within the next decade, approximately 75% of the heritage area may become susceptible to wave inundation in a 100-year storm (Williams et al. in review). Te Pokohiwi ō Kupe may be further compromised by fluvial flooding events in the Wairau River (Williams et al. in review) or tsunami and earthquakes, as it has been in the past (e.g., McFadgen and Adds 2019). The combination of these hazards may result in the site being eroded and lost from the physical landscape within the next 100 years (McFadgen and Adds 2019; Williams et al. in review).

4 Geomorphic assessment of the Lower Wairau River and Lagoon coastal environments

Runoff during storms or snowmelt is the primary driving force determining the size and shape of a riverscape within a given geologic setting (Church and Ferguson 2015). Annual high flows, which mobilize the bed and bank material composing a channel, are strongly determinative of the stable size of a river channel, and there is an abundance of scientific literature demonstrating that channel size and mobility may change substantially with natural or human-induced changes to a river's flow and sediment regimes (Phillips et al. 2022). Thus, any changes in a channel's geomorphic character (e.g., size and shape) must be assessed in the context of both natural and human influences.

In this section, we explore trends in natural influences and implications of human influences on the geomorphology of the Lower Wairau River. We pursue three lines of investigation: hydroclimatic (precipitation and stream flow) analysis, map and aerial imagery analysis, and channel cross section analysis (Table 4-1). The map and aerial imagery analysis is focused on assessing lateral changes in morphology, whereas the cross section analysis is largely focused on vertical changes (i.e., bed level aggradation and degradation). The hydroclimatic analysis aims to assess whether there are trends that could explain observed changes in morphology. The period of analysis across the three lines of investigation varies based on availability and quality of data, as well as the scope of each individual analysis.

The earliest map available is from 1924 and the earliest aerial photos available are from 1947, both of which pre-date the daily flow record of any stream gauging station on the Wairau River. To provide additional hydroclimatic context for the periods prior to the flow gauge record (from 1951), we used available precipitation data. We also examined literature for historic accounts of flood magnitudes on the Lower Wairau, which allowed us to include additional information about estimated annual flood magnitudes in the Lower Wairau between 1920 and 1950. The map and aerial imagery analysis covers individual time stamps of 1924 (based on a historic map), 1947, 2005 and 2020s (composite imagery from 2021/22). The timeframe of cross section analysis varies by cross section, with the oldest data being from 1901. Most cross sections were first surveyed in 1927 or 1957. Together, the three lines of investigation enable a geomorphic assessment of the Lower Wairau River from the early 1900s to present.

Table 4-1: Lines of investigation employed in the present analysis.

Line of investigation	Data type and source	Date range
Hydroclimatic analysis	Precipitation data (gauge data)	1902-present
	Flow data (gauge data)	1951-present
	Historic peak flood magnitudes (written accounts)	1920s-1950s
Map and imagery analysis	Maps Past; Retrolens; LINZ	1924, 1947, 2005, 2020s
Cross sectional analysis	MDC	1901-present

A full list of data used can be found in Appendix A.

4.1 Hydroclimatic changes affecting sediment transport in the Wairau River system: precipitation and streamflow analysis

4.1.1 Precipitation

Because of its large elevation range, the Wairau River receives precipitation in the form of both rain and snow. As stated in Section 3.2, previous work by Wöhling et al. (2020) quantified trends in mean annual precipitation for the Wairau River basin using gridded Virtual Climate Station Network (VCSN) data available from NIWA. VCSM data represents spatial interpolation of data recorded at climate stations situated around New Zealand. The Wöhling et al. (2020) analysis indicated that mean annual total precipitation had a declining trend of about 2.9 mm per year over the 1960 to 2019 period of record. They also examined spatial patterns in the temporal trend by interpolating trends at individual VCSN locations and found that the majority of the basin, particularly the higher elevation areas, had negative trends in annual precipitation. However, they found that both of these negative trends were 'not significant'. Wöhling et al. (2020) surmised that the trends were artefacts of bias in the spatial interpolation methods used to generate the VCSN data. Here, we conduct precipitation trends analysis using specific climate station data, rather than the VCSN data.

Methods

We sought to identify any statistically significant trends (or lack thereof) in precipitation across the Wairau catchment, which typically requires data with relatively long (>20 years) and continuous (no major gaps) periods of record (Bayazit 2015). We identified four climate stations with daily rainfall records that were continuous for at least 20 years and extended to within 10 years of the present (Table 4-2). Unfortunately, these stations are all located in the lower elevation regions of the eastern Wairau River valley (Figure 3-1). Although a higher elevation climate station (Mahanga EWS, Agent no. 36857; elevation 1995 m) is present in the western regions of the basin, that station's period of record only extends back to 2009. Therefore, we relied on the streamflow trend analysis at the Wairau River at Dip Flat (see Section 4.1.2 below) for information on any potential climate-related changes to the hydrology of the upper Wairau River basin.

Table 4-2: Climate stations in the Wairau River valley used to test for temporal trends in precipitation.

Station name	Agent No.	Record start	Record end	Elevation (m)
Blenheim Research AWS	12430	31/12/1995	Current	4
Blenheim Aero AWS	4326	1/09/1990	Current	36
Sevenoaks	4323	1/01/1902	Current	55
Wairau Valley Southwold	4319	1/11/1917	21/2/2018	119

We performed statistical analyses on precipitation time series data to explore any trends in monthly and annual values across the four records. We applied the non-parametric (Kendall 1938) rank correlation method. The time series were created by calculating the arithmetic average for each calendar year and each month of each year (annualized monthly data) for a total of 13 datasets for each year of record. Seasons were roughly aligned to the astronomical seasons (i.e., summer in January, February, and March).

To identify the significance of any trends, we determined the slope of each time series using the non-parametric method of Sen (1968). The strength of the slope signal was considered significant if the p-value on the Kendall statistic was less than 0.10 (90% confidence). The choice of interpreting p-values less than 0.10 as significant was loosely based on the likelihood approach outlined in Hirsch et al. (2015). This approach suggests that, given that hydroclimate data often have a limited period of record, some flexibility should be used in the interpretation of trends to avoid complacency when further scrutiny may be warranted. Under the Hirsch et al. (2015) approach, a p-value of less than 0.10 would be interpreted as at least "very" or "highly" likely.

Although we used an arbitrary boundary for 'significance' with precipitation data, we also interpreted agreement in the sign of trends (increase or decrease) across stations as indicative of a somewhat strong signal that precipitation magnitudes were changing for some given month or the full year. The interpretation of these signs was strengthened by comparing them to projected patterns from climate change models (Ministry for the Environment 2018).

Results

Tests for trends in monthly and annual precipitation totals show general alignment with climate projections (Ministry for the Environment 2018). Annual trends, represented by Sen slope, show net positive trends of up to 1.5 mm per year, with autumn (Mar., Apr., May) and winter (Jun., Jul., Aug.) months tending towards positive trends of up to 1 mm per year, and spring (Sept., Oct., Nov.) and summer (Dec., Jan., Feb.) months showing declining trends (Figure 4-1). Nearly all the precipitation trends are non-significant at the 90% confidence level, but those that are significant comply with expectations put forth by climate change models. Trends at the stations with shorter periods of record (Blenheim Aero AWS and Blenheim res. AWS) tended to have stronger magnitudes than those with longer periods of record (Wairau Valley Southwold and Sevenoaks), which may be expected as the longer periods of record include much more of the decadal-scale variability in climate.

It should be noted that the magnitude of p-values is dependent on length of record and the magnitude of the slope relative to the range of data such that relatively large slopes can still have no signal.

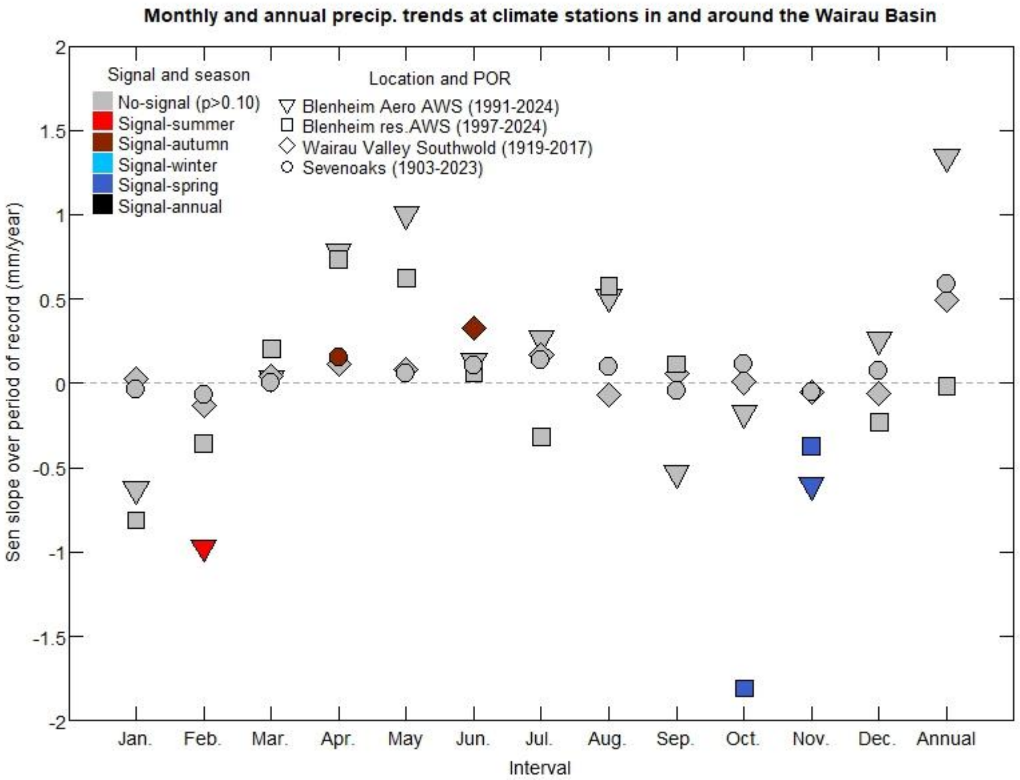

Figure 4-1: Scatterplot showing magnitude of trend in monthly precipitation for the period of record at four climate stations in the Wairau River valley. Grey colouring indicates no-signal trends, e.g., not significant at the 90% confidence level. Coloured shapes indicate a significant signal at the 90% confidence level and are colour-coded by season. In general, the data show that autumn and winter are getting wetter while spring and summer are getting drier.

Given the lack of statistically significant signals in monthly and annual precipitation trends (Figure 4-1), we compared rainfall totals with various climate oscillation phases. Below, we discuss data trends in terms of departures from the long-term median, which looks at how the median of a subset of data (e.g., monthly, annual, seasonal) compares to the median of long-term (e.g., full record) data. In the context of precipitation trends, this analysis can reveal information such as how winters associated with a specific climate cycle phase may be wetter than the median of the whole range of data that includes all phases of a certain climate cycle.

Comparison of rainfall totals with El Niño Southern Oscillation (ENSO) phase (Figure 4-2) indicates a wide range of behaviours but shows tendencies for less rain in summers during negative phases (La Niña) and more rain in spring, autumn, and winter; these behaviours are generally switched during positive (El Niño) ENSO phases. La Niña median departures during the non-summer months at the climate stations with the longest periods of record (Wairau Valley Southwold and Sevenoaks) varied from 0.45 to 9.2 mm over long-term medians (e.g., wetter than the long-term median), while summer months had departures of -7.9 to -15 mm (e.g., drier than the long-term median). El Niño median departures during the non-summer months at the same stations varied between near 0 and -13 mm (e.g., no change, to drier than the long-term median). One station (Sevenoaks) had odd behaviour in that it had negative median departures in summer rainfall (e.g., drier than the long-term median) for both La Niña and El Niño phases, but had net positive departures for the summer months during neutral phases (e.g., wetter than the long-term median; Figure 4-2). This result may be due to a trend in its data during summer months, but more time would be needed to interrogate this further because the tendences vary widely on either side of the departure line.

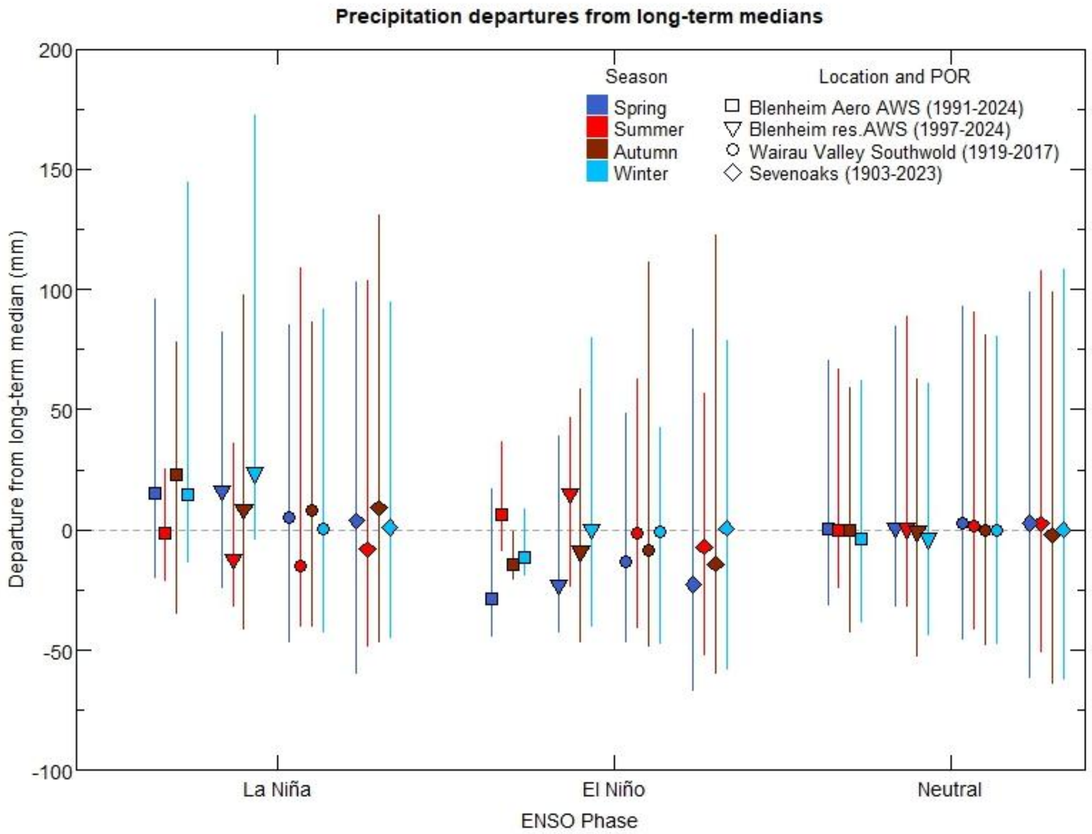

Figure 4-2: Departures of rainfall totals by season for four climate stations in the Wairau River valley over their respective periods of record. The bars represent the range of data, and points represent the medians. Data are for monthly totals grouped by season (i.e. not seasonal totals). Seasons are astronomical (Summer=Jan., Feb, Mar.; Autumn=Apr., May, Jun.; Winter=Jul., Aug., Sept.; Spring=Oct., Nov., Dec.).

Comparison of rainfall data with Southern Annular Mode (SAM) phase indicates rainfall departures tend to be higher during positive phases and lower during negative phases (Figure 4-3). The departure data have a wide range, and the median departures are small, indicating SAM has a generally weak effect on rainfall totals. Median departures at climate stations with the longest records tended to have the largest departures. Positive phase, non-summer median departures at these stations ranged from 1.2 to 9.1 mm, and from 0.3 to -3.4 mm for summer. Negative phase, non-summer median departures ranged from -1.1 to -5.1 mm, and from -0.5 to 5.5 for summer.

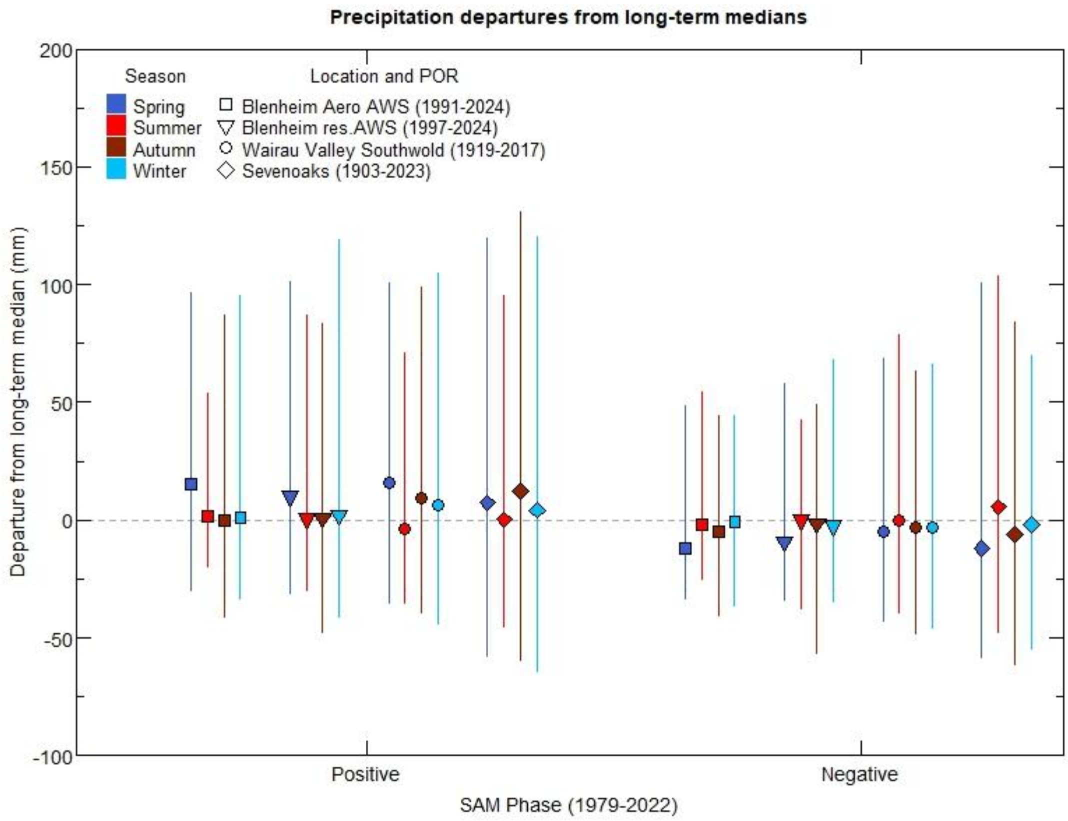

Figure 4-3: Departures of rainfall totals by season compared to the Southern Annular Mode phase for four climate stations in the Wairau River valley over their respective periods of record. The error bars are the range of the data and the points are the medians. Data are for monthly totals grouped by season.

Comparison of rainfall data with the Interdecadal Pacific Oscillation (IPO) phase indicates a wide range of behaviours, but a tendency for less rain during positive phases and more rain during negative phases (Figure 4-4). Blenheim Aero AWS appears to be particularly sensitive to IPO phase with strong median departures, while other stations, particularly the two with the longest periods of record (Wairau Valley Southwold and Sevenoaks), have weaker responses to the IPO. Positive IPO phase median departures at Wairau Valley Southwold and Sevenoaks were between -8.1 and -17 mm relative to the long-term median, and negative phase median departures were between 0 and 7.8 mm.

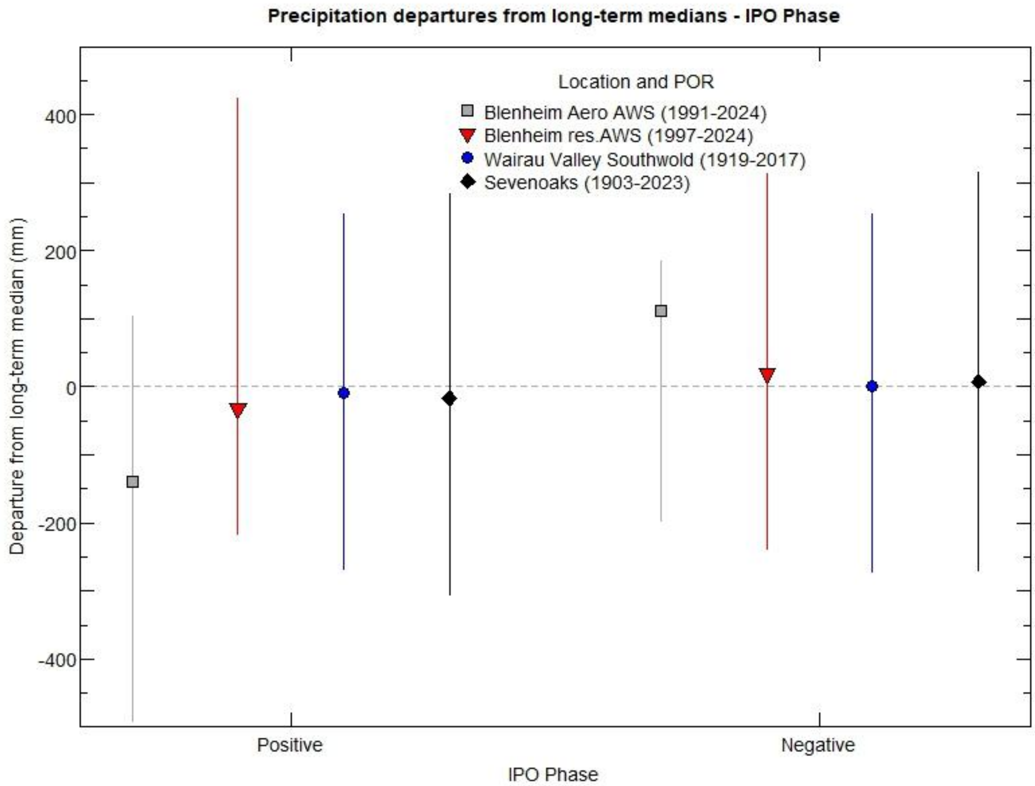

Figure 4-4: Departures of rainfall totals by Interdecadal Pacific Oscillation phase for four climate stations in the Wairau River valley over their respective periods of record compared to the long-term median. The error bars are the range of the data and the points are the medians.

Summary statement: In summary, the precipitation analysis presented here shows few statistically significant trends in precipitation over the period of analysis for the four climate stations selected. The strongest trends are in monthly and annual precipitation trends (Figure 4-1), at particular stations for specific months. Two stations show significant trends of increasing rainfall in autumn; two stations show significant trends in decreasing rainfall in spring; and one station shows a significant trend in decreasing rainfall in summer. In relation to the three climate oscillation cycles, different cycles affect certain stations more than others. However, in general, comparison of rainfall totals with ENSO phase indicates a wide range of behaviours but shows tendencies for less rain in summers during negative phases (La Niña) and more rain in spring, autumn, and winter; these behaviours are generally switched during positive (El Niño) ENSO phases. Comparison of rainfall data with SAM phase indicates rainfall departures tend to be higher (wetter) during positive phases and lower (drier) during negative phases. Comparison of rainfall data with the IPO phase indicates a wide range of behaviours, but a tendency for less rain during positive phases and more rain during negative phases.

4.1.2 Streamflow

Long-term measurements of streamflow have been made at two primary locations in the Wairau River (Table 4-3), one at Dip Flat approximately 110 km upstream from SH1 and the other near the SH1 bridge (Figure 3-1). The gauging station at Dip Flat measures flows from the upper, mountainous regions of the Wairau River basin and has been operating continuously since 1951. The combined records of the stream gauges near the SH1 bridge, previously at Tuamarina and now at Barnetts Bank, measure flows that include both the upper basin as well as the semi-arid Wairau Plains and, when combined, have a nearly continuous record since 1960 (Table 4-3).

Table 4-3: Hydrometric gauging stations on the Wairau River used to assess trends in streamflow. The records from gauges 60108 and 60109 were combined to create a complete period of record from 1960 to the present. The 60109 gauge replaced the 60108 gauge and was installed approximately 100 m upstream from the 60108 site. No tributaries intervene between the two sites, so the drainage areas are assumed to be hydrologically equivalent. Mean annual flood values are from the New Zealand River Flood Statistics online tool. Mean annual low flow values are from the New Zealand River Maps online tool.

Station name	Site No.	Record start	Record end	Drainage area (km^2)	Mean Annual Flood (m^3/s)	Mean Annual Low Flow (m^3/s)
Wairau River at Dip Flat	60114	6/1/1951	Current	505	355 ± 4%	9
Wairau River at Tuamarina	60108	4/7/1960	31/12/1999	3430	--	--
Wairau River at Barnetts Bank	60109	29/7/1999	Current	3430	1824 ± 8%	21

Methods

We used a combination of daily and sub-daily mean records to test for temporal trends in various measures of streamflow in the Wairau River. We also used published accounts of annual peak streamflow to identify trends (or lack thereof) over a longer period of record for annual maxima (SRCC 1957; Williman 1995). As with precipitation, we used the non-parametric Kendall (1976) rank correlation method to test for temporal trends in time series. We took a different approach, e.g., using a likelihood approach rather than the non-parametric method, in our interpretation of hydrologic trends as we did with precipitation trends because there are only two gauges on the Wairau with extensive periods of record, thus no ensemble with which to interpret common patterns. Prior to running trend analysis[4], we tested for serial correlation in our various time series (Box and Pierce 1970), and none of the tests were significant (p-values all greater than 0.10). All trend analysis were performed in language R using the 'EnvStats' package (Millard 2013).

Sub-daily streamflow records were the primary basis for analysis, and these records were used to extract variations of time-series used in our temporal trend analysis. The sub-daily streamflow records at both Dip Flat and near SH1 (Tuamarina and Barnetts Bank) had varying time stamps over their respective periods of record. This variation is due to changes in recording techniques used since their establishment. Early records, for example, were taken via analogue drum recorder, which was

[4] Trend analysis requires the assumption that residuals are not serially correlated. This test allows us to examine if the assumption is correct. It is standard to include these tests for time-series analysis to assure the reader that we were not simply running tests without meeting the assumptions.

later hand-digitised to create the sub-daily record. Hand-digitising required that only inflection points in the trace were recorded, and these time-stamps were not taken at even intervals. We linearly interpolated values between time stamps to the 15-minute interval across the entire period of record at each gauge, and then subsampled the entire respective record down to a consistent 15-minute records at both gauges using the 'na.approx' command in language R (R Core Team 2023). We allowed for up to a week of missing data, although such gaps were rare.

The slope of each time series was calculated using the non-parametric method of Sen (1968), and the strength of the slope signal was considered inversely proportional to the p-value on the Kendall statistic. We invoked the 'likelihood approach' of Hirsch et al. (2015) and most recently of Ryberg et al. (2024). In our interpretation of temporal trends in hydrologic time series whereby likelihood (θ) is equal to 1-p-value/2, with a trend being "likely" if θ is 0.85 or greater, "somewhat likely" if θ is between 0.7 and 0.85, and "as likely as not" if θ is 0.7 or less. This approach suggests that, given that hydroclimate data often have a limited period of record, and often seasonal to decadal-scale variability, some flexibility should be used in the interpretation of trends to avoid complacency when further scrutiny may be warranted.

The Wairau River near State Highway 1

For the Wairau River near SH1 (stations 60108 and 60109), we conducted trend analyses on the following time series:

1. Average annual streamflow (1961-2024)
2. Annual maximum streamflow (1923-2024)
3. Percentage of time each year streamflow exceeded 600 m^3/s – flows required to mobilise sand in the Lower Wairau River (1961-2024)
4. Percentage of time each year streamflow exceeded 1,200 m^3/s – flows required to fully inundate the bed of the Lower Wairau River (1961-2024).

Average annual streamflow values were obtained simply by taking the arithmetic mean of the entire, consistent (adjusted as described above) 15-minute records from each flow gauge.

Annual maximum stream flows were obtained from three sources. Records older than 1992 were obtained mainly from Williman (1995), who compiled annual maximum flood values from various newspapers and MDC documents. Additional historical records were obtained from the SCRCC Soils Conservation and Rivers Control Council (1957), which published various accounts of severe flooding in regional and district council areas for the 1920 to 1953 period. The SCRCC (1957) document includes estimated flood magnitudes in cubic feet per second (cusecs) but also includes narratives that we used to infer minimum flood magnitude in a particular year. For example, an account of a flood on the Wairau River reported that, in November of 1926, the flood magnitude near the modern-day SH1 bridge was "107,000 cusecs" (3,029 m^3/s), but that "did not allow for 40,000 cusecs passing through breaches upstream" (SCRCC 1957, pg. 151). Not all historical narratives included in the SCRCC (1957) document include values of flood magnitude, but, based on the aforementioned narrative, we assumed a value of 100,000 cusecs (2,832 m^3/s) as an approximate minimum flood[5]

[5] The value of 100,000 m^3/s accounts for a rounding-down for both error and assumption that the maximum value measured was more than needed for breaching.

value for any narrative that indicated the Wairau had breached its banks but did not include a specific estimate of the flood magnitude. Modern records are from the flow stations (Table 4-3).

Percentage of time each year stream flow exceeded a certain value was calculated as the number of time stamps when stream flow exceeded a certain value, divided by the total number of time stamps (35,040 in non-leap years; 35,136 in leap years). For the Wairau River at SH1, we chose exceedance values of 600 and 1,200 m^3/s as significant thresholds of relevance for bed material mobilisation. 600 m^3/s corresponds to the value that Christensen and Doscher (2010) identified as needed to keep fine-grained sediment (in the case of the Lower Wairau River, ≤0.165 mm) in the Lower Wairau downstream from SH1 in suspension. Christensen and Doscher (2010) reasoned that 600 m^3/s at Barnett's Bank (just upstream of SH1) was needed to suspend the fine sand because they found that 300 m^3/s was needed in the Lower Wairau River channel, and at least half of the flow at Barnett's Bank discharges through the diversion cut[6]. The percent of time the Lower Wairau exceeds 600 m^3/s thus represents the capacity of the Lower Wairau downstream of SH1 to keep finer sediments from accumulating on the riverbed approaching and within the lagoon. 1200 m^3/s is the approximate minimum stream flow magnitude that would fully inundate the streambed (flood most mid-channel gravel bars) under historical conditions (SCRCC 1957), respectively. We hypothesised that the latter of these values (1,200 m^3/s) was an approximation of the stream flow magnitude when most of the stream bed may have been near the threshold of motion before substantial channel narrowing from human engineering.

Wairau River at Dip Flat

We used stream flow data for the Wairau River at Dip Flat (station 60114) to help us identify any changes in stream flow in the upper basin. As with the Wairau River near SH1, we ran trend analyses on two primary indicators of streamflow regime at the Dip Flat stream gauge:

1. Average annual streamflow (1951-2024)
2. Annual maximum streamflow (1952-2024).

Because there are no climate stations in the higher-elevation regions of the Wairau River basin with long-term records (>20 years), we also interpreted trends in streamflow at the Dip Flat stream gauge to inform changes in mean annual precipitation in this region.

Results

Combining the daily records from the Wairau River at Tuamarina (site no. 60108) and Barnett's Bank (site no. 60109) resulted in a nearly continuous record from 1961 to 2024, with only 1967 having less than 350 days of mean flow data. Mean annual flows varied between 47 and 164 m^3/s over this period, with approximately decadal-scale oscillation periods of higher and lower annual stream flows (Figure 4-5). Trend analysis between 1961 and 2024 indicates that mean annual stream flows have a monotonic decrease at a rate of about -0.26 $m^3/s/yr$ (Figure 7). Mean annual flows for the first 20 years of record (1961 to 1980) have a mean of 108 m^3/s and the last 20 years of record (2005 to 2024) have a mean of 93 m^3/s. The p-value on the Theil-Sen trend line is 0.14, resulting in a Hirsch et al. (2015) likelihood value of 0.93, indicating the trend is reasonably strong (likely). We did not

[6] We used the value of 600 m^3/s at Barnett's Bank to identify any trends in sand-mobilising flows since 1963, using the values provided by Christensen and Doscher (2010). It is possible that this value may change based on how much base flow is diverted down the Lower Wairau River versus into the Diversion Channel. Changes in the flow split are associated with the diversion channel reaching capacity and the construction of the erodible flow embankment.

compare this trend to other water resources activities in the valley such as diversion records, so do not have a direct physical explanation for the trend other than we know that land uses have changed over this time period and groundwater pumping has increased (Wöhling et al. 2020). Likewise, we know that temperatures have increased in the basin (Ministry for the Environment 2018), resulting in increased atmospheric demand[7] for water, which could also cause a net decrease in mean annual stream flows.

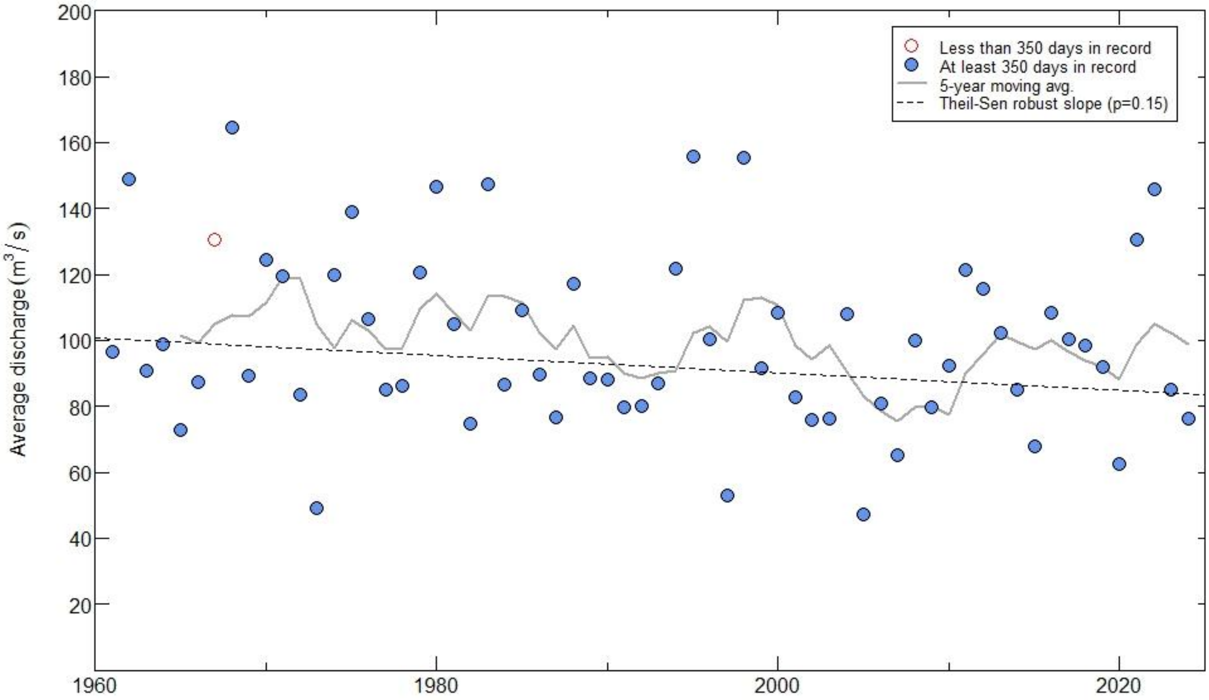

Figure 4-5: Time series showing average annual discharge for the Wairau River at SH1 from 1961 to 2024.

Comparison of the non-exceedance duration hydrographs of daily mean flows between the 1961-1999 and 2000-2024 periods (i.e., from the Tuamarina and Barnett's Bank records respectively) indicates that changes in daily stream flows closely mimic temporal trends identified in precipitation (Figure 4-1), with the largest declines occurring in the late spring and early summer (i.e., less flow), and near-zero differences or increases in the late autumn through winter (i.e., more flow; Figure 4-6). The largest declines were in the months of November and December, with a maximum difference in medians between periods of -58 m^3/s; the largest increase in median daily stream flows were in late June, with a maximum difference of medians between periods of 44 m^3/s. Median stream flows were nearly universally lower between November and May over the past 24 years compared to the period of record prior to 1999 (Figure 4-6).

[7] Atmospheric demand is the potential for the atmosphere to draw water from Earth through evaporation and transpiration. Atmospheric demand is influenced by temperatures, humidity, solar radiation and wind. See Hobbins, M., Wood, A., Streubel, D., Werner, K. (2012) What Drives the Variability of Evaporative Demand across the Conterminous United States? *Journal of Hydrometeorology*, 13(4): 1195-1214. https://doi.org/10.1175/JHM-D-11-0101.1, or Evaporation and the Water Cycle | U.S. Geological Survey for more information.

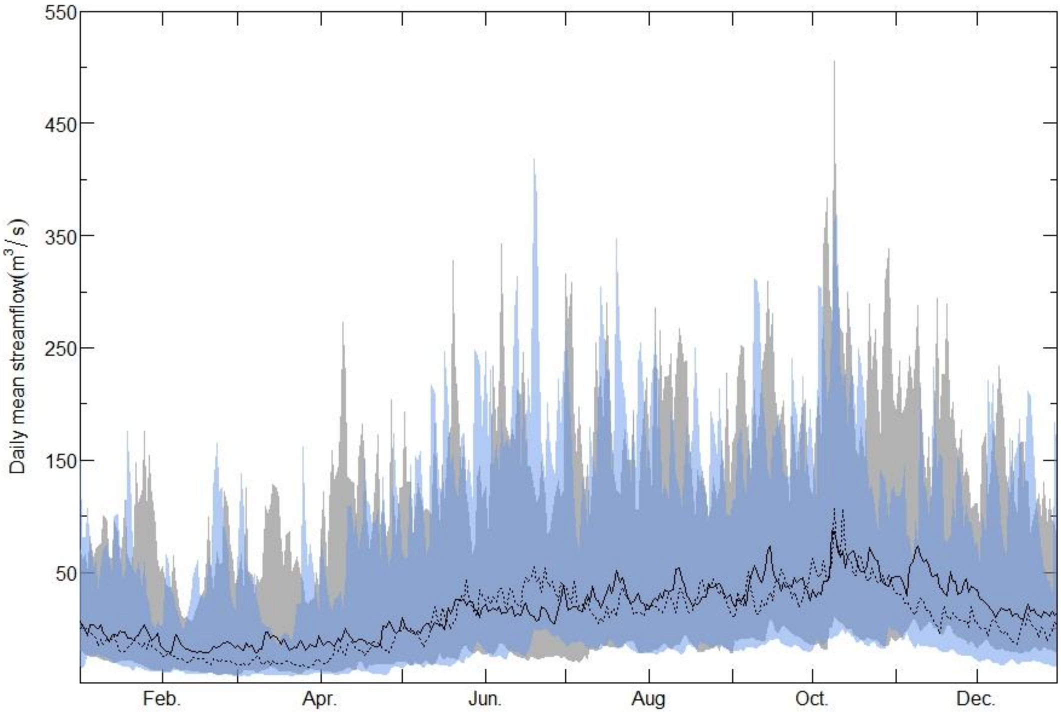

Figure 4-6: Non-exceedance duration hydrographs showing distribution of daily flows for two time periods for the Wairau River at SH1. The shaded areas represent the inner 80 percent of daily flows (10th percentile to 90th percentile) while the lines represent the medians. The grey shaded area and solid black line represent the period of record from 1961 to 1999, while the light blue shaded area and dashed black line represent the 2000 to 2024 period of record.

Annual maximum floods are indicators of a river's capacity to transport its annual bed material load, turnover its bed, and maintain its natural channel form. Time series of annual instantaneous peak flows suggest that annual maximum flows in the Lower Wairau River near SH1 have been generally steady over the past century (Figure 4-7). Peak flows varied between 587 m^3/s and 5,800 m^3/s since 1923; 5,800 m^3/s is the highest known flow on the Wairau River and occurred in the 1983 flood, during which flows exceeded the 5,500 m^3/s design capacity of the Wairau scheme (Marlborough District Council 1994; Williman 1995). Although the median value of the historic peaks appears to indicate peak flows were higher prior to 1950, these gaugings tended to occur in years when at least some flooding occurred (e.g., non-flood years are not represented) and are thus likely biased high. Likewise, the flows that were estimates prior to 1960 appear to be well within the distributions of annual maximums after 1960.

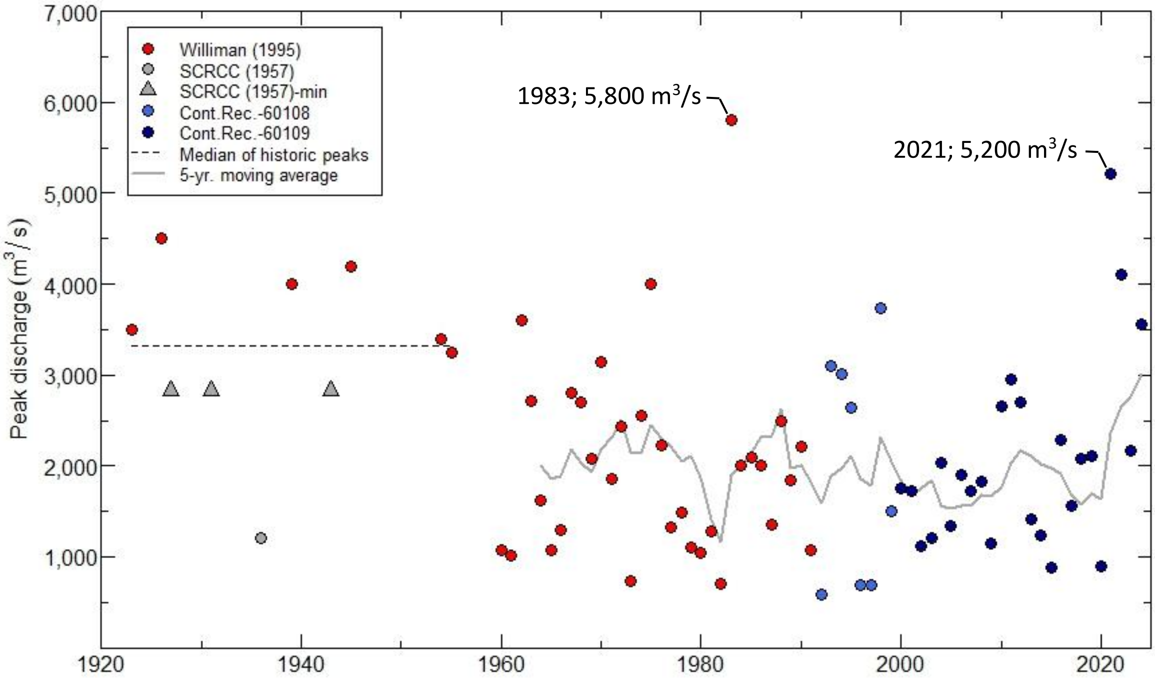

Figure 4-7: Time series showing annual instantaneous maximum (annual maximum) discharge for the Wairau River near SH1.

Examination of the 5-year moving average shows an approximate decadal-scale oscillation in annual maximum flood magnitudes, with periods of persistent higher-than-average maximums around 1975, 1995, and 2010 (Figure 4-7). Since 2020, three of the Lower Wairau's top ten maximum discharges on record have been measured and, more generally, there appears to be an increase in lower range of annual maximums since about the year 2000.

To further investigate sediment transporting capacity in the Lower Wairau River below SH1, we extracted the percent of the annual record with stream flows exceeding 600 m^3/s at the Wairau River SH1 gauge.

Our time series analysis indicates that, although annual maximum flood magnitudes have not changed, the percent of time stream flows in the Lower Wairau River at SH1 exceed 600 m^3/s is declining at a rate of about -0.01 percent per year, or about half a percent decline (or 2.3 days less) since 1961 (Figure 4-8). The p-value on the trend of these data is 0.25, translating into a likelihood value of 0.875, which is within the Hirsch et al. (2015) criteria of a 'likely downward' trend. Although the trend shown in Figure 4-8 is not visually substantial, it appears that the variance in the data is also decreasing, indicating there are fewer years when the Lower Wairau is exceeding 600 m^3/s. For example, the Lower Wairau exceeded 600 m^3/s at least 2% of the time in 8 of 20 years within the 1961 to 1980 period of record but exceeded 600 m^3/s at least 2% of the time in only 1 of 20 years within the 2005 to 2024 period of record.

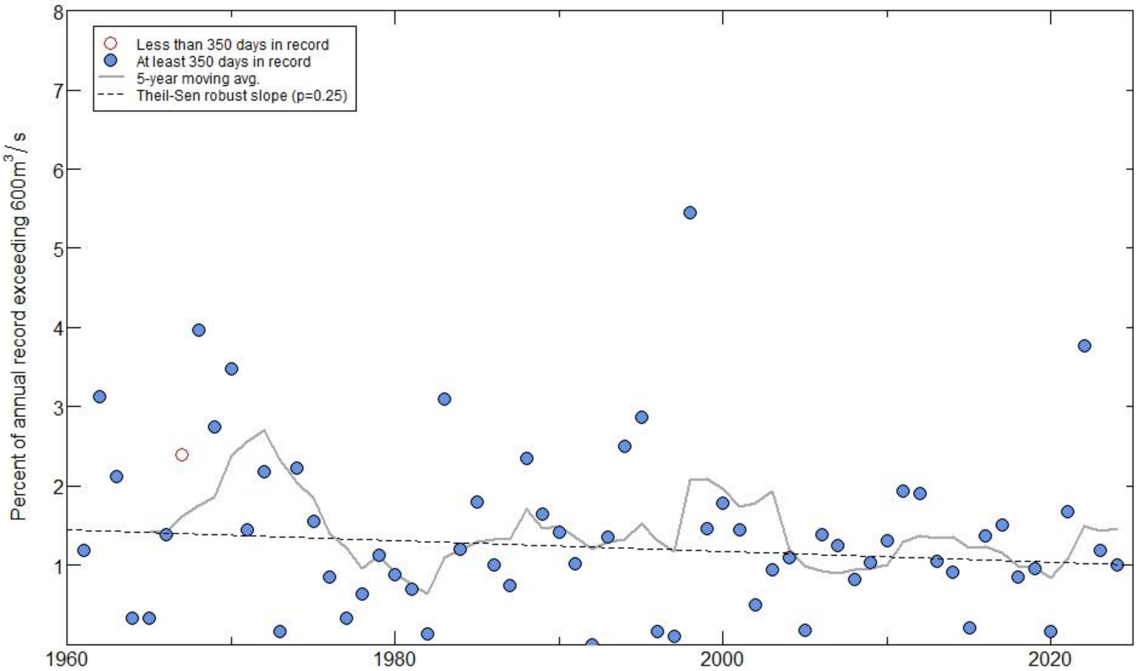

Figure 4-8: Time series showing percent of time per year the Wairau River at SH1 is flowing above 600 m^3/s.

We also examined the percentage of time the Lower Wairau River below SH1 exceeded 1200 m^3/s because this value represents a minimum bound on stream flow required to initiate full bed mobility (e.g., fully flood gravel bars in the main channel). Our time series analysis suggests little to no signal for a change in this exceedance value, with a downward Theil-Sen slope of, within rounding, 0% per year over the period of record (Figure 4-9). The p-value on the weak downward slope is 0.61, translating into a Hirsch et al. (2015) likelihood of 0.65, or 'about as likely as not', suggesting weak to no signal. Nonetheless, as with the exceedance analysis above, there is some evidence that the variance in the percent exceedance may be changing. For example, stream flows exceeded 1200 m^3/s for at least 0.5% of the time (~2 days) in the Lower Wairau River in 7 of 20 years over the 1961 to 1980 period of record; alternatively, 1200 m^3/s was exceeded in only 1 of the 20 years in the 2005 to 2024 period of record.

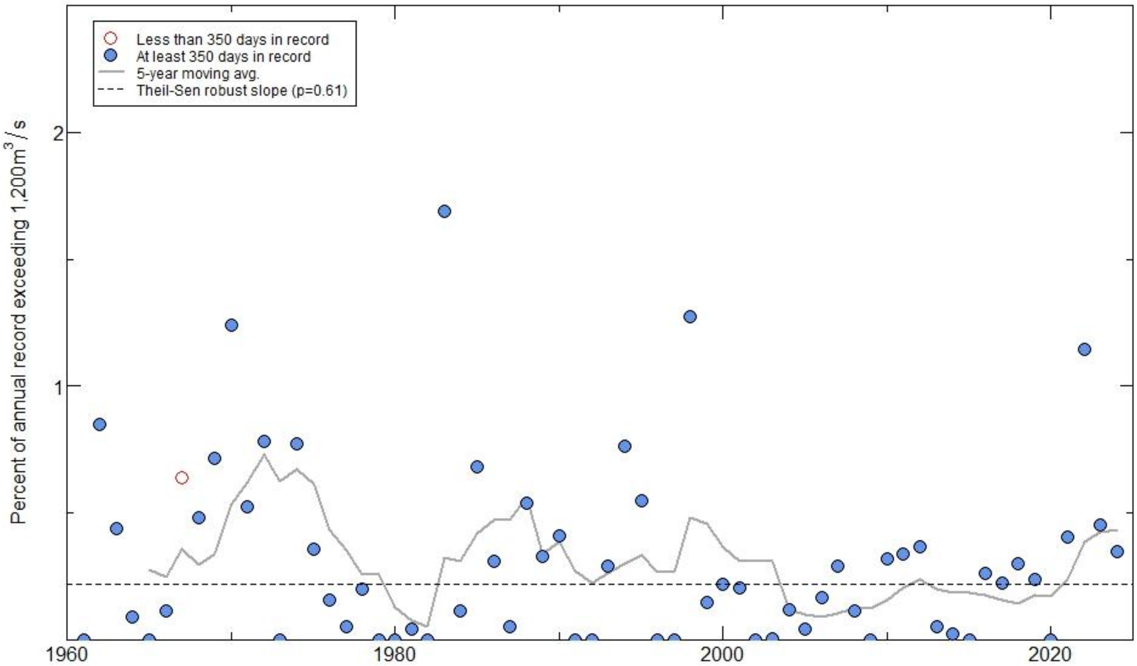

Figure 4-9: Time series showing percent of time per year the Wairau River at Barnetts Bank is flowing above 1200 m^3/s.

As stated above, we were unable to identify any climate stations in the upper Wairau River Basin that would allow us to determine if precipitation conditions have changed there. Instead, we used the flow record for the Wairau River at Dip Flat (site no. 60114) as our primary indicator of hydroclimatic change in the upper basin.

Mean annual flow of the Wairau River at Dip Flat varied between 18 and 39 m^3/s between 1952 and 2024 (Figure 4-10). Trend analysis indicates an increase of about 0.02 m^3/s/yr in annual mean flows, with a p-value on the Kendall statistic of 0.45 (θ = 0.78), suggesting the trend is 'somewhat likely upward.' These data indicate that, despite the analysis of Wöhling et al. (2020) suggesting downward trends in precipitation in the upper regions of the Wairau River Basin, stream flows in the region indicate otherwise and have, if anything, steadily increased over the last 75 years.

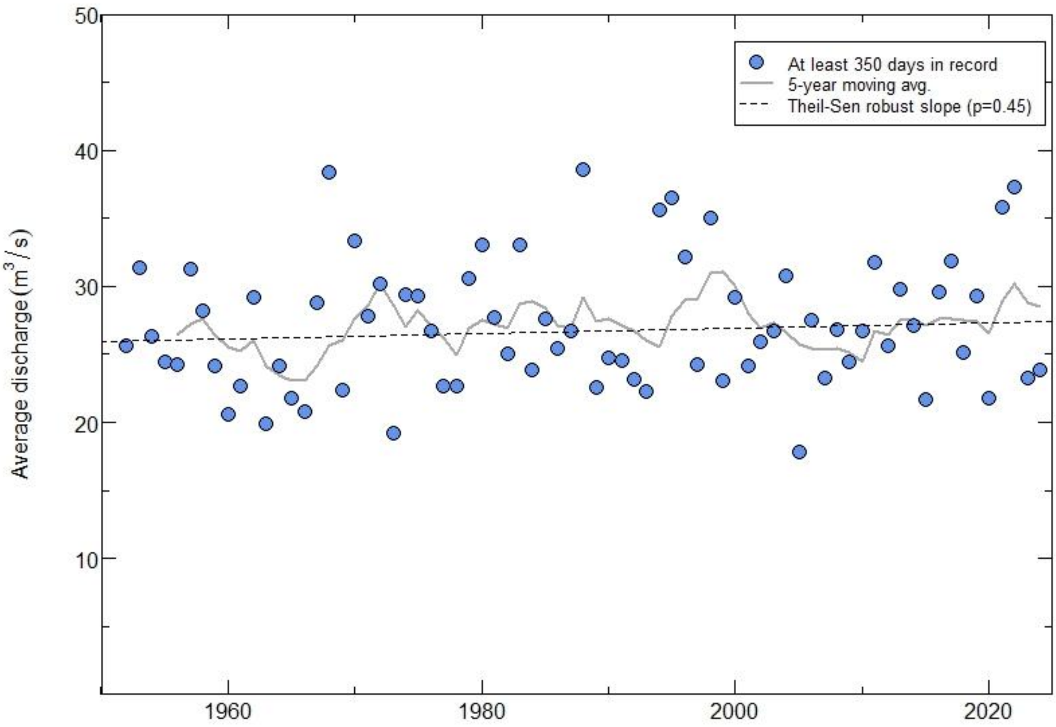

Figure 4-10: Time series showing average annual streamflow for the Wairau River at Dip Flat.

We used annual maximum stream flows as indicators of potential changes in sediment transport capacity from the upper Wairau River Basin, and therefore sediment delivery to the lower basin. Annual maximum stream flows in the Wairau River at Dip Flat varied from 123 to 626 m^3/s, with a mean value of 359 m^3/s. Trend analysis on time series analysis indicates that annual maximum stream flows of the Wairau River at Dip Flat have remained generally stable since 1952 (Figure 4-11). The slope of the robust trend line suggests a steady increase of about 0.04 m^3/s/yr but, with a p-value of 0.92 (θ = 0.64), this trend is as likely as chance. Thus, it is unlikely that the sediment transport capacity of the Wairau River in the upper basin has changed substantially, and that average ability to deliver of bed material sediment to the lower basin has been mostly unchanged.

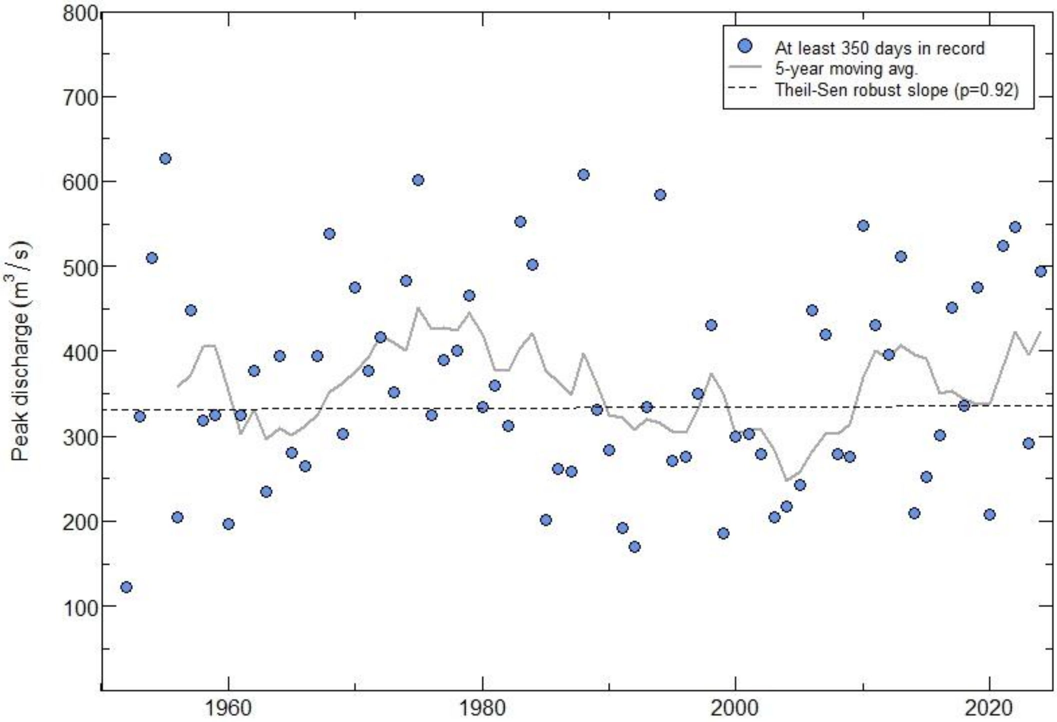

Figure 4-11: Time series showing annual instantaneous maximum (annual maximum) discharge for the Wairau River at Dip Flat from 1951 to 2024.

Summary statement and implications for sediment dynamics: In summary, trends for the Wairau River at SH1 indicate reasonably strong (likely) declines in average discharge between 1961-2024 (Figure 4-5). More detailed analysis is required to attribute this trend to climatic drivers versus activities in the catchment (e.g., extraction for irrigation or groundwater pumping).

Daily flows between 1961-1999 and 2000-2024 (Figure 4-6) indicate less flow in summer months and more flow in winter months for the latter period of analysis (2000-2024). Annual peak flood magnitudes appear to have remained steady over the historic record (Figure 4-7).

The percentage of time of each year that the Lower Wairau River spends above 600 m^3/s has decreased over the period of 1961-2024, with a 'likely downward' trend, which may indicate that the frequency of flows that can mobilise sand in the Lower Wairau has reduced, which may have contributed to deposition of fine sediment in the Lower Wairau (Figure 4-8). However, because of changes in the flow split between the Lower Wairau and the Diversion Channel over time, it is possible that the value of 600 m^3/s at Barnett's Bank does not consistently represent sand-mobilising events in the Lower Wairau.

The percentage of time of each year that the Lower Wairau River spends above 1,200 m^3/s has a non-significant trend, indicating that frequency of fully bed-mobilising flows has not changed substantially (Figure 4-9).

At Dip Flat, average stream flow indicates a 'somewhat likely upward' trend, suggesting that flows may have steadily increased at this site since 1961. Annual peak flow magnitudes at the Dip Flat gauge have no trend since the 1960's, indicating that the transport capacity of the upper Wairau River has not changed over this period.

4.1.3 Combined precipitation and stream flow analysis

Methods

To understand linkages between precipitation and streamflow and any potential impacts on sediment transport, we tested for trends in flood-inducing precipitation behaviours by examining correlations between precipitation accumulated over a certain period (n-day) and magnitude of annual peak stream flows. Analysing precipitation accumulated over set preceding periods (n-day) provides a way of assessing the effect of antecedent conditions on stream flow, i.e., if the antecedent period is wet, this can increase streamflow magnitude.

We did this by accumulating daily precipitation over a range of n-day periods up to 1-year prior to the day of each annual maximum in our records, and by using the Spearman rank correlation coefficient (herein referred to as 'Spearman R') as a measure of the strength of correlation between the two values. We performed this correlation analysis for all four of our climate stations and used the maximum of the ensemble mean correlation as the indicator of the n-day accumulation most related to peak flow magnitudes. We then performed trend analysis on the maximum annual n-day precipitation accumulation at the climate station with the longest period of record (Sevenoaks).

Results

Examination of the strength of correlation between annual maximum streamflow magnitude and accumulated precipitation shows a clear decline after about 56 days (Figure 4-12). There is some variability in this signal between the climate stations, which is likely an artifact of their different periods of record, but the overall pattern is consistent. At the two climate stations with the longest periods of record (Wairau Valley Southwold and Sevenoaks) the strength of the correlation seems to decline substantially after 14 days, whereas the correlation remains high until about 56 days at the climate stations with periods of record only dating back to the 1990s (Blenheim Research AWS and Blenheim Aero AWS). Using the ensemble average correlations for all four climate stations, accumulations of 2 days and 56 days have the two highest strength correlation values (0.53 and 0.55, respectively), indicating that high streamflow is likely to result from intense storms lasting less than 2 days, as well as from high antecedent moisture conditions extending out as far as two months (Figure 4-12).

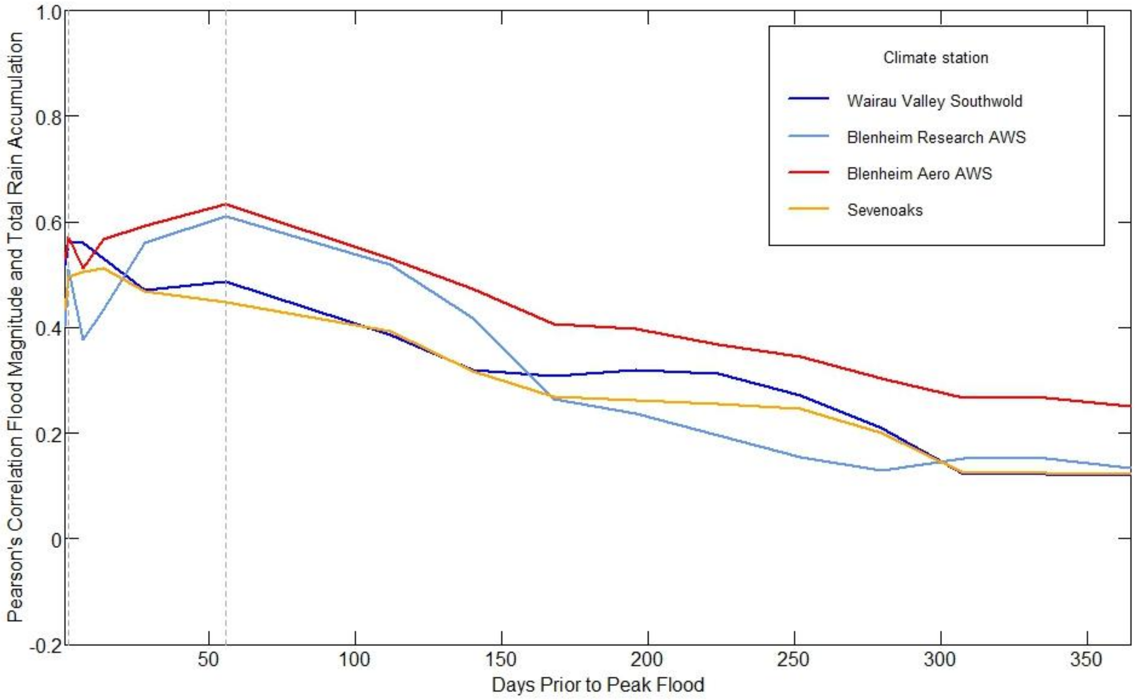

Figure 4-12: Correlation plot showing strength of correlation between the magnitude of the annual instantaneous peak discharge of the Wairau River at Barnetts Bank and the accumulated rainfall as measured at four climate stations in the Wairau River Valley. Note the highest mean correlations are at 2 days and 56 days (dashed grey lines).

Given that 2 and 56 days of antecedent moisture conditions have the strongest correlation between accumulated rainfall and annual maximum streamflow, we ran trend analysis to investigate whether there are any temporal trends in the magnitude of these precipitation accumulations. We conducted this analysis using data from the Sevenoaks climate station because it has the longest period of record.

Our time series analysis shows that maximum accumulated precipitation at these two (2 and 56 days) intervals is tending to increase since 1920, although the strength of the increase differs (Figure 4-13). The 2-day maximum accumulation time series has a slope of 0.05 mm/yr, with a p-value of 0.54 (θ = 0.73), indicating the trend is weak but 'somewhat likely upward.' This trend indicates that precipitation magnitudes in the 2 days before peak accumulation may be intensifying (e.g., individual storms are delivering higher rainfall amounts). Alternatively, the 56-day maximum accumulation time series has a slope of 0.33 mm/yr, with a p-value of 0.19 (θ = 0.91), indicating that the increase is 'likely upward.' Examination of the variability in 5-year moving average of the 56-day maximum accumulation shows a wider range of values over the past 20 years, which may explain the higher average annual maximums, as well as the higher frequency of large floods in the past five years. Likewise, these higher 2- and 56-day accumulations may translate into larger volumes of fine sediment being delivered from the broader Wairau basin, but a more detailed investigation would be needed to pursue this idea.

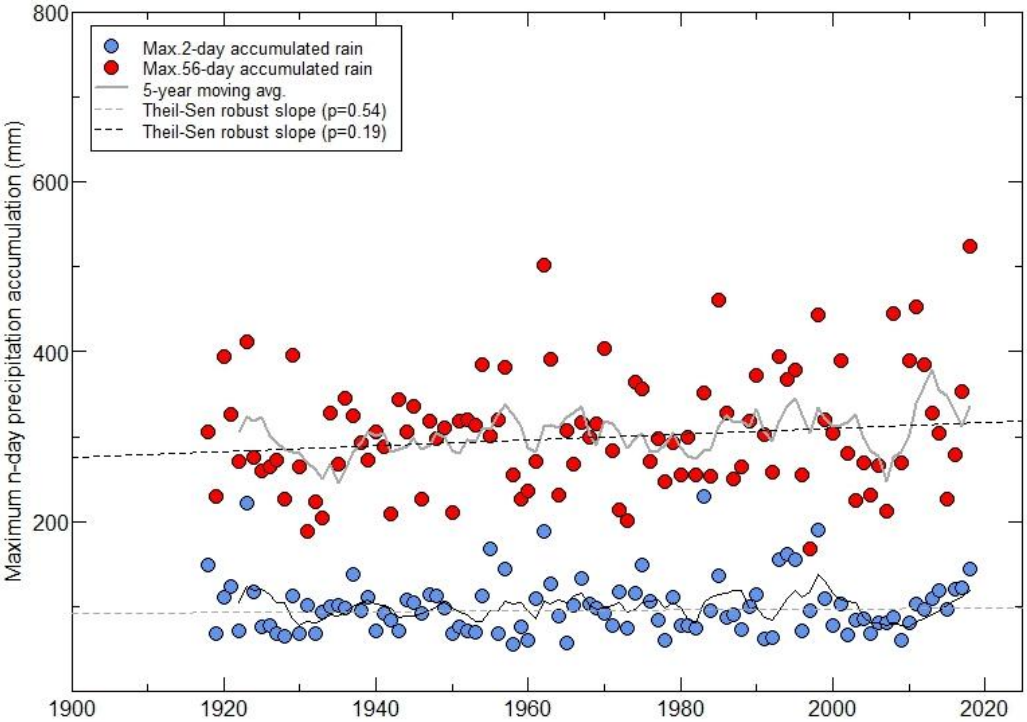

Figure 4-13: Time series showing trend in annual maximum 2-day and 56-day accumulated rainfall for the Wairau Valley at Sevenoaks.

Summary statement and implications for sediment dynamics: In summary, correlation analysis between annual instantaneous peak discharge and accumulated rainfall show strong correlations at 2- and 56- days prior to peak floods. This indicates that both intense storms lasting 2 days and high antecedent moisture conditions over a period of up to 2 months are related to high stream flows.

At the Sevenoaks gauge, accumulated precipitation amounts falling within 2 days of a flood event appear to have 'somewhat likely' increased since the 1920's. Accumulated precipitation amounts falling within 56 days of a flood event appear to have 'likely' increased since the 1920s. Both of these trends, though with varying degrees of likeliness, indicate that antecedent moisture conditions preceding flood events are increasing. Intensified storms may deliver more sediment to the catchment, but detailed analysis would be required to confirm this statement.

4.2 Temporal changes in the morphology of the Wairau River and Lagoon complex: GIS and cross section analysis

4.2.1 GIS analysis of maps and aerial imagery

Historic aerial imagery analysis is a common method for assessing changes in river planform through time (e.g., Hughes et al. 2006 and references therein). Here, we apply this approach to visually and quantitatively assess changes in active river width in the Wairau River between SH6 and SH1 as transport capacity in this section of the river has the most direct implications for sediment deposition in the Lower Wairau River channel and lagoon area. We also assess active river width between SH1 and the river mouth to relate channel width to cross sectional analysis (Section 4.2.2).

Methods

We compiled historic maps and aerial images of the Wairau River to identify changes in active riverbed width and location through time. We followed recently established methodology for identifying and mapping the extent of active riverbed (Hoyle and Bind 2017; Hoyle and Bind 2023).

The 1924 historic map and 1947 aerial imagery had been pre-georeferenced as part of a 5-year long MBIE Endeavour Programme (grant no. LVLX1901), excluding the lagoon. The 1924 map does not cover the Lagoon complex. The 1947 imagery was supplemented with images of the lagoon available online from Retrolens, which is LINZ's archive of historical aerial imagery. The 2005 imagery was received from MDC, which was already georeferenced and had full coverage of the lower river and lagoon. The georeferenced 2021/22 imagery was acquired from the MDC online GIS portal and also had full coverage of the study area.

Following image acquisition and any required georeferencing, we digitised the active riverbed extent for the selected map and sets of imagery. Digitising the active riverbed extent involved generating digital polygons that capture continuously connected bare gravel and flowing water. We digitised the river downstream of SH6, including the Wairau Diversion and Lagoon complex, for the discrete time steps of 1924, 1947, 2005 and 2021/22 (most recent imagery).

We then utilised digital topography data (digital elevation model; DEM) to correct the historic footprint polygon, where necessary. Corrections involved aligning polygon outlines with confining topography such as valley or terrace walls. These corrections enabled us to refine portions of the polygons that may have overrepresented the width of the active riverbed extent due to distortions in aerial images or in the georeferencing (e.g., Hughes et al. 2006). This process resulted in the final historic footprint (corrected) polygons for the river that represent the total, combined active area that the river occupied through the analysed period of time (Figure 4-14).

Because each image represents a single snapshot in time, we could not avoid the influences of the tide on the lower river and lagoon. We aimed to be consistent with our digitisation approach across the time steps, and used the DEM to help refine lagoon boundaries. Despite best efforts there may be some unquantified error in the digitised margins of the lagoon.

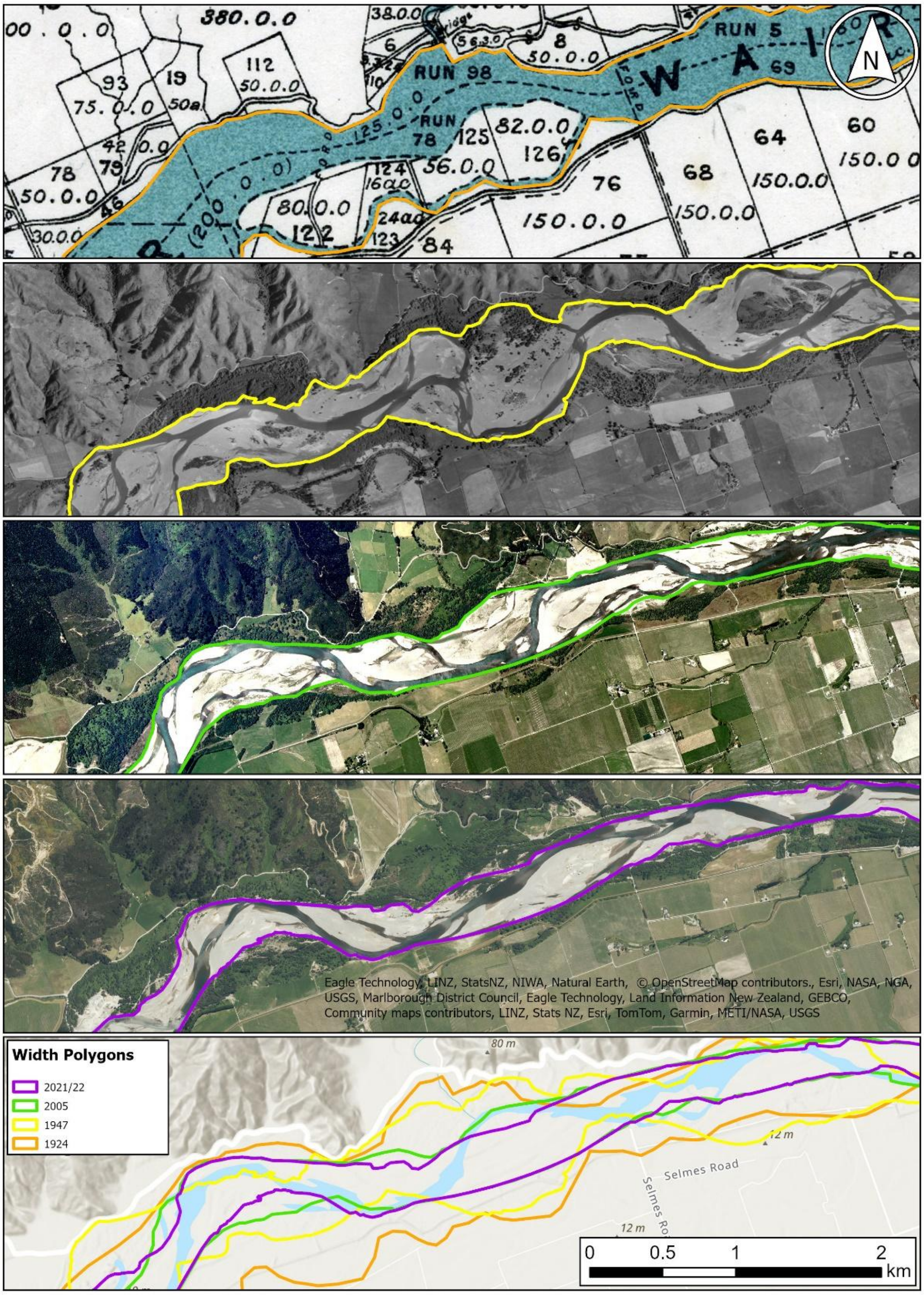

Figure 4-14: Digitisation of active riverbed through time for an example reach of the Wairau River between SH6 and SH1.

Because of the large alteration in flow and sediment dynamics introduced to the river system in 1963 via construction of the Wairau Diversion, we quantified changes in channel widths upstream of the diversion to assess potential changes in sediment transport properties in the river system upstream of the Lower River and diversion channel. We generated width transects every 100 m for the river between SH6 and SH1 for each of the periods of analysis and compared these data for the four time-steps of analysis. Using the digitised active river polygons, we generated channel centrelines for each time step. We then generated transects every 100 m on each of the different channel centrelines. This approach also captures changes in channel centreline length through time, but does not provide a direct comparison of each transect as transect location depends on the centreline length. We also quantified channel widths downstream of SH1 in the Lower Wairau channel to determine if width changes have occurred in the lower river and lagoon outlet channel.

Results

SH6 to SH1

Active river widths between SH6 and SH1 have largely reduced since 1924 (Figure 4-15). Despite overarching narrowing trends, discrete widening has occurred in some places between some time steps. Discrete widening may represent gradual channel adjustments between analysed time steps, or somewhat instantaneous widening due to engineering works or flooding that then persisted to the next time step. An example of widening can be seen between distances ~1000 m – 3000 m downstream of SH6 between 1924 and 1947 (Figure 4-15). There was substantial narrowing in this same section between 1947-2005, associated with the timing of extensive river training and stopbanking (Section 3.3), but some widening occurred between 2005-2020s.

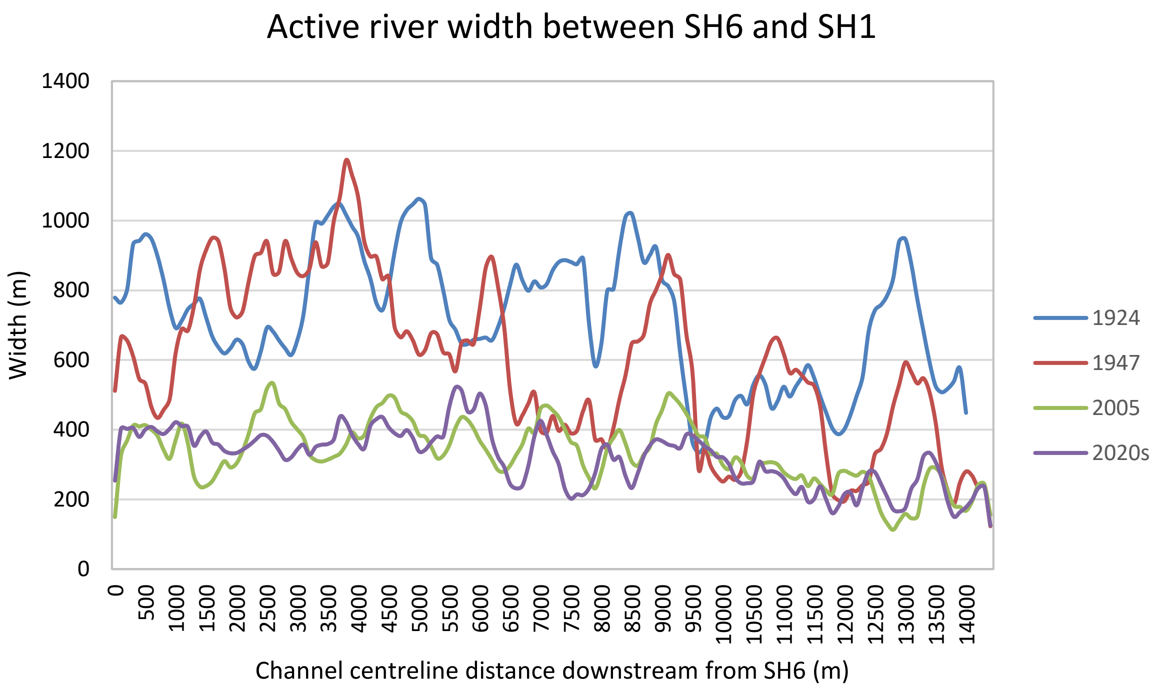

Figure 4-15: Active river widths between SH6 and SH1.

Average active channel widths in the Wairau River between SH6 and SH1 have reduced since 1924, but discrete widening can be seen in maximum width measurements (Table 4-4). For example, even though the average width in the 1947 analysis was less than that of the 1924 analysis, the maximum width of the active channel was greater in 1947.

Table 4-4: Width changes between SH6 and SH1.

Year	Average width (m)	Maximum width (m)	Reduction in average width since 1924 (%)
1924	722	1062	--
1947	590	1173	18%
2005	331	553	54%
2020s	320	521	56%

SH1 to the Wairau River mouth

Active river widths have also decreased downstream of SH1 to the river mouth since 1924 (Figure 4-16). The greatest width reduction is in the area near the Wairau diversion. However, the data suggest substantial widening of the channel near SH1 between 1924 and 1947 (Figure 4-17). This widening is due to an artificial cut called the “Peninsula” cut, which was cut in an effort to widen the floodway (Marlborough District Council 1994). The Peninsula cut would have also shortened the channel centreline length (Figure 4-16). There are also other areas along the Lower Wairau River below SH1 where old meander bends had been cut off from the active channel, further reducing centreline length (Figure 4-17).

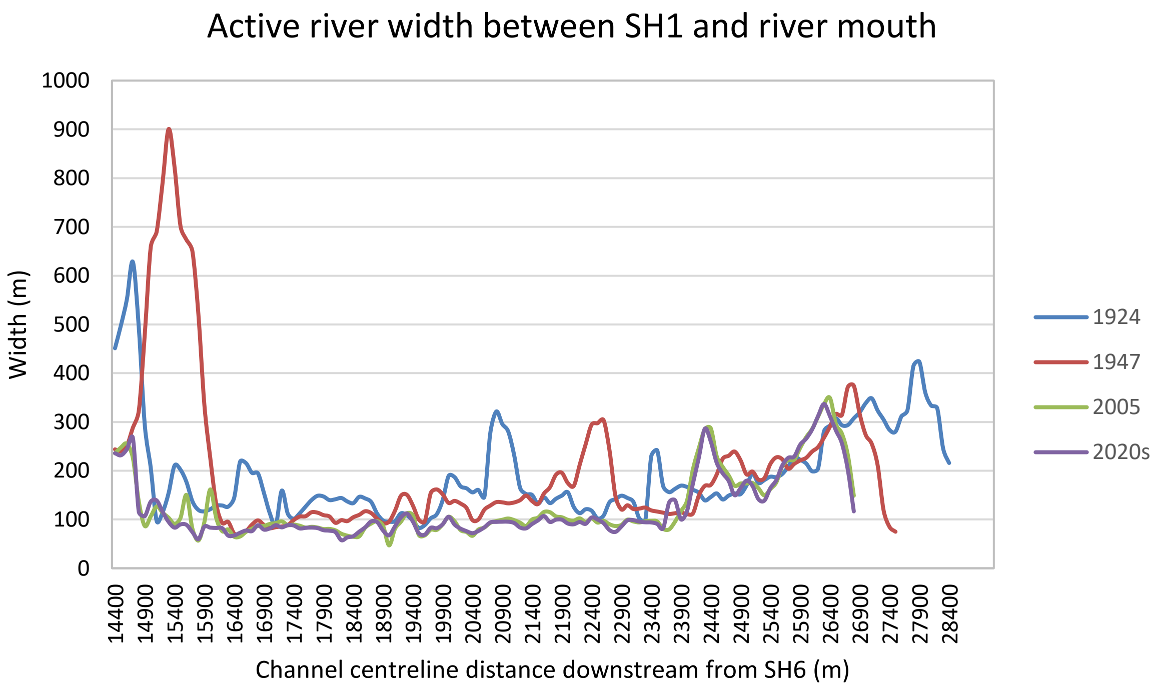

Figure 4-16: Active river widths between SH1 and the Wairau River mouth.

Figure 4-17: The Wairau River near SH1, showing differences in channel extent on historic map (1924) versus historic imagery (1947).

Average and maximum active channel widths have reduced between SH1 and the river mouth since 1947 (Table 4-5).

Table 4-5: Width changes between SH1 and the Wairau River mouth.

Year	Average width (m)	Maximum width (m)	Reduction in average width since 1924 (%)
1924	194	628	--
1947	204	901	5%
2005	127	349	34%
2020s	123	337	37%

Lagoon complex

The Lagoon complex is a highly tidal environment, and digitising the border of the lagoon shows little large-scale change through time (Figure 4-18). However, there are active sediment processes occurring in places that are influencing the margins of the lagoon (e.g., building sediment deltas where small streams enter the lagoon; Figure 4-19).

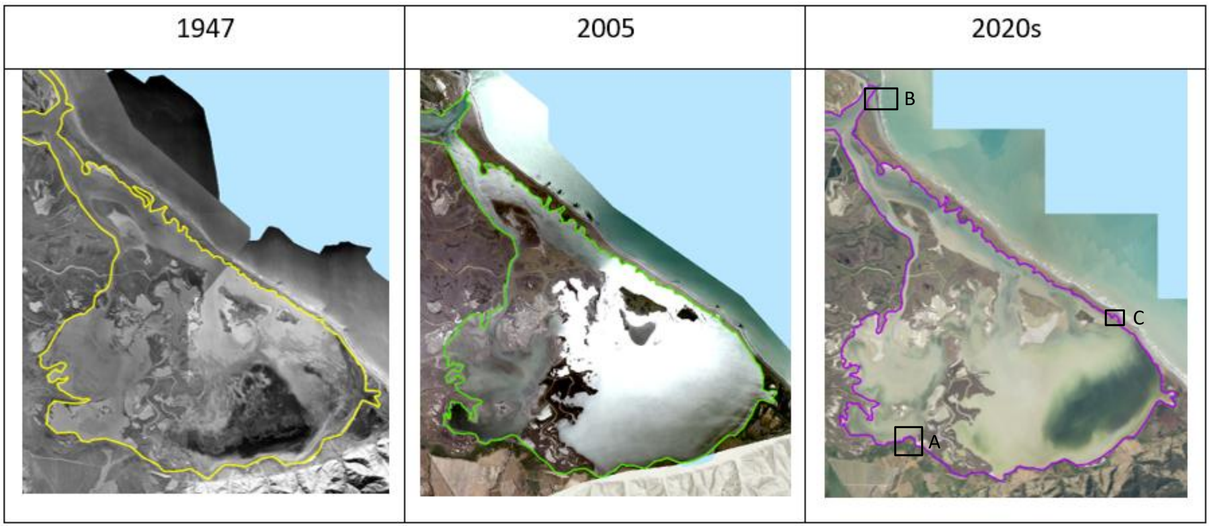

Figure 4-18: Digitised lagoon polygons and associated imagery. A) Extent of Figure 4-19. B) Extent of Figure 4-20. C) Extent of Figure 4-21.

Figure 4-19: Active sediment fan building out on the southern side of the lagoon. Coloured lines show fan extent for the corresponding year. Underlying aerial image is from 2021/22.

As part of understanding coastal vulnerability of Te Pokohiwi ō Kupe and boulder bank, Williams et al. (in review) analysed the shoreline evolution of the right bank of the river mouth and both banks of the channel entrance to the lagoon (Te Arapipi) using historical maps and imagery. They show that the northern side of the Te Arapipi channel has changed little since earlier this century whereas the southern side has retreated by more than 30 m (average 0.3m/year) (Figure 4-20). This retreat could be linked to an increase in the tidal flux across this channel and is consistent with the increase in width of the mouth.

A historical breach of Te Pokohiwi ō Kupe shows recent overwash activity (Figure 4-21). The morphology of this area appears relatively unchanged since the 1904 map from Irvine survey (Figure 4-20). Other historical maps and aerial images show periodic variability in vegetation cover, but relatively consistent morphology. These observations suggest occasional overwash events at the breach location, but that the breach has not recently been reactivated. It is likely that only a small amount of sediment is currently brought into the lagoon during overwash events, confirming that, currently, most of the sediment influx to the lagoon is from the main channel linking the Wairau mouth (via Te Arapipi) and, to a lesser extent, from the small streams. It is possible that the frequency of overwash events may increase with rising sea level.

A bathymetric survey of Wairau mouth (Hume and Williams 1981) shown in Knox (1983) indicates deeper channels between the Lagoon complex and the ocean than upstream (Figure 4-22). The presence of these deep channels suggests that, in this area, tidal flux may play a larger role in the transport of sediment and in controlling the morphology.

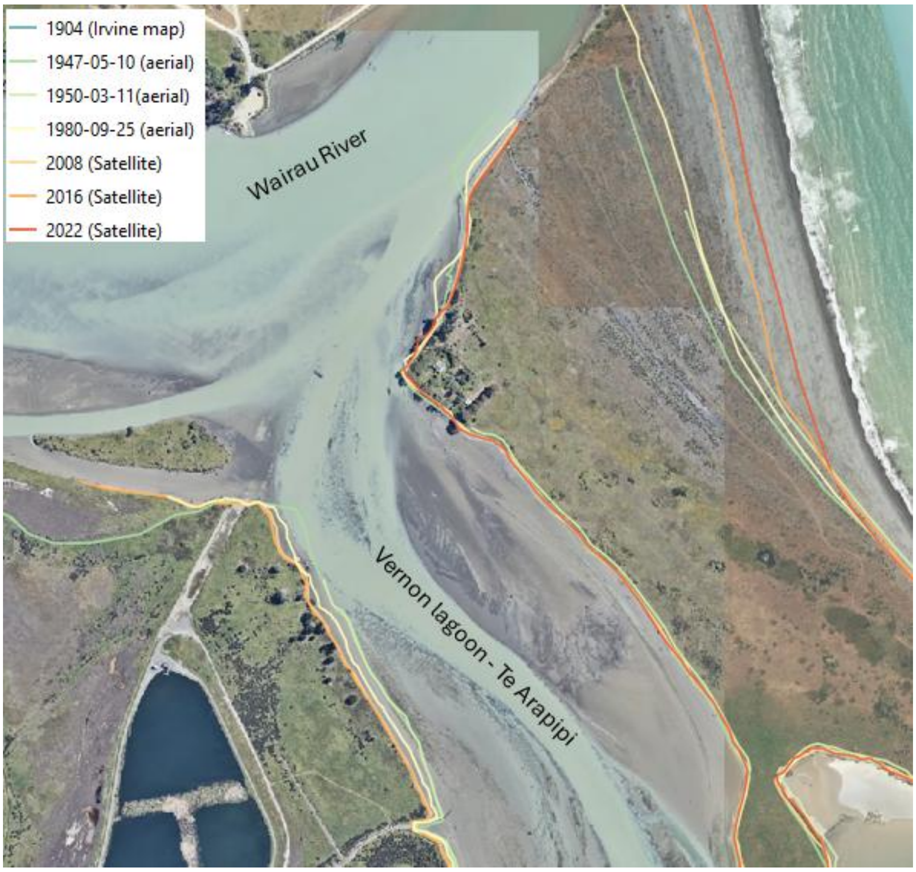

Figure 4-20: Historical shoreline position on Vernon Lagoon- Te Arapipi. Underlying aerial image is from 2021/22.

Figure 4-21: Historical breach and active overwash in Te Pokohiwi ō Kupe. Underlying aerial image is from 2021/22.

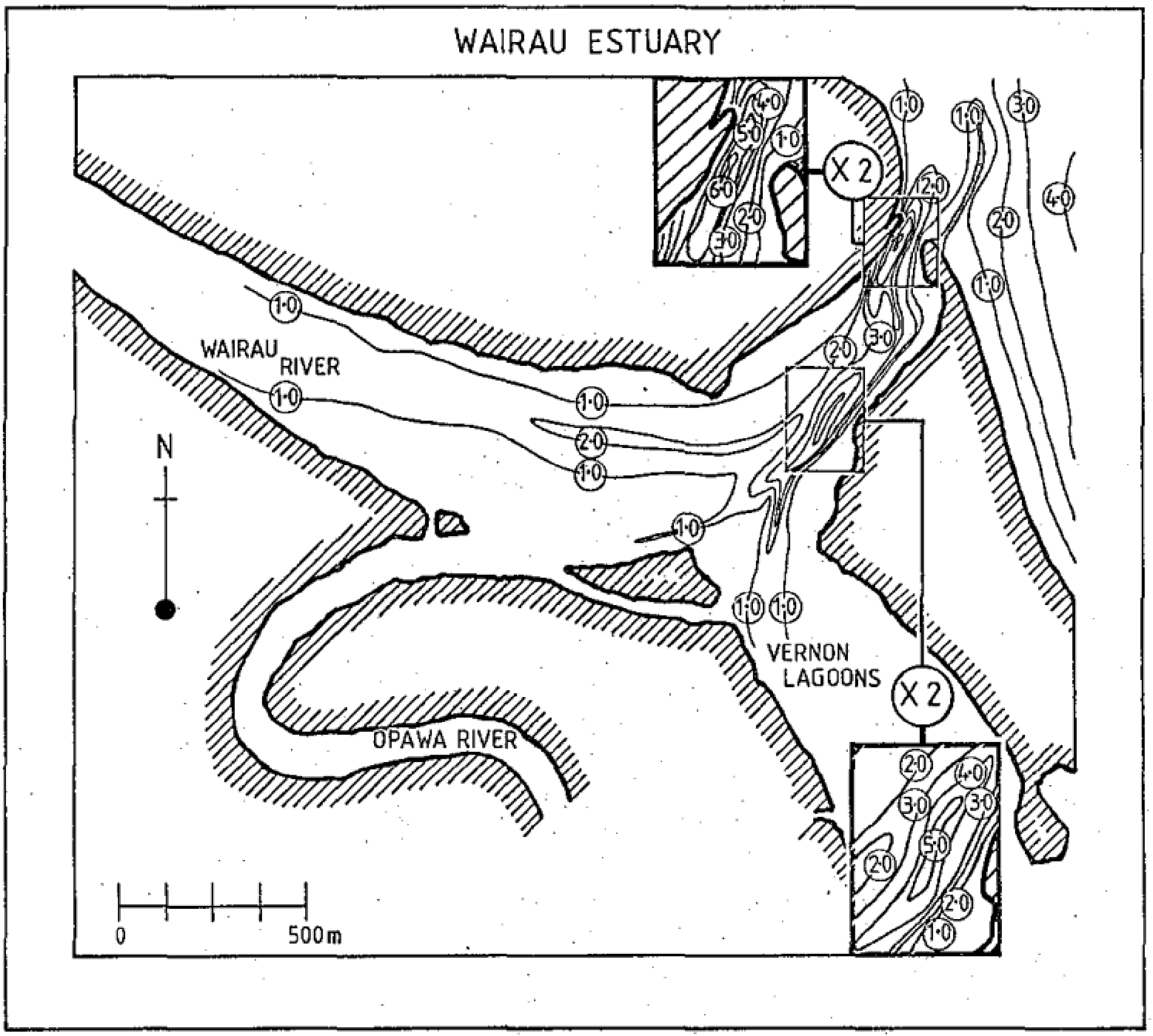

Figure 4-22: Bathymetric map of the Wairau River Estuary and Wairau Bar. Source: Knox (1983) based on data from the Marlborough Catchment, Marlborough Harbour Board and the Department of Lands and Survey.

Summary statement and implications for sediment dynamics: In summary, the width of the Wairau River's active channel has substantially reduced since the 1920s, largely due to river training and engineering works to control flooding. These engineering works have also contributed to channel centreline shortening. Narrower, shorter channels tend to have greater erosive power during mean annual flood events, but they may also experience more aggradation (sediment build up) during lower flow events because there is less lateral space for the river to deposit its sediment. Given that engineering works have substantially narrowed the Lower Wairau River but annual maximum floods have generally stayed consistent through time, it is likely that the bed mobilizing capacity during annual maximum floods has increased appreciably over at least the last 65 years. The morphology of the lagoon suggests that most of the sediment in the lagoon is coming from the Lower Wairau River and, to a lesser extent, smaller streams draining into the lagoon. Overwash events occur periodically at an area of historical breach in Te Pokohiwi ō Kupe, however, this area appears to have had fairly consistent morphology since 1904. Overwash events at the breach don't currently appear to be major contributors of sediment to the lagoon. The presence of a deeper channel near the mouth may suggest strong tidal influence.

4.2.2 Cross section analysis

Cross section analysis is a common method for assessing trends in channel bed levels through time and space. Here, we assess a selection of cross sections downstream of SH1 to identify any trends that may indicate sediment deposition (aggradation) or erosion (degradation) in the Lower Wairau River and diversion channel.

Methods

We selected a subset of cross-sections provided to us by MDC for analysis over the full duration of survey records. We selected nine cross-sections in the Lower Wairau River downstream of SH1 and three in the diversion channel (Figure 4-23). Our selection was based on aligning cross-sections with the most overlap in dates for comparisons while ensuring we had a consistent spatial distribution throughout the Lower Wairau River and diversion channel.

Figure 4-23: Locations of selected cross sections.

We plotted the raw data to determine if any corrections were needed. Historical cross section data often needs to be corrected to account for variability in start and end points (e.g., offsets) between surveys. Corrections were applied by inspecting the data and visually aligning the cross section to common locations (e.g., the top of a stopbank).

To ensure comparability of cross-section analyses across different time periods, consistent start and end points were selected for each cross-section (Figure 4-24). These points were carefully selected to encompass measurements from all surveyed years, allowing for a reliable assessment of changes over time. Offsets have been redefined relative to those from Gardner and Sharma (2016) for this study to ensure internal consistency. For surveys conducted in years where selected points lacked measured elevation data, elevations were estimated using linear interpolation between the closest measured points. In cases where the surveys did not fully cover the start and end points, extrapolation was used to estimate the missing elevations (Figure 4-24). We acknowledge that this approach is different to that employed by Gardner and Sharma (2016), who supplemented cross sectional survey data with data from other surveys. However, because our analysis extended back to early surveys, we could not supplement the cross section with additional survey data. As such, we used the linear interpolation/extrapolation method to provide synthetic data where data is missing. All offsets are shown in Appendix B.

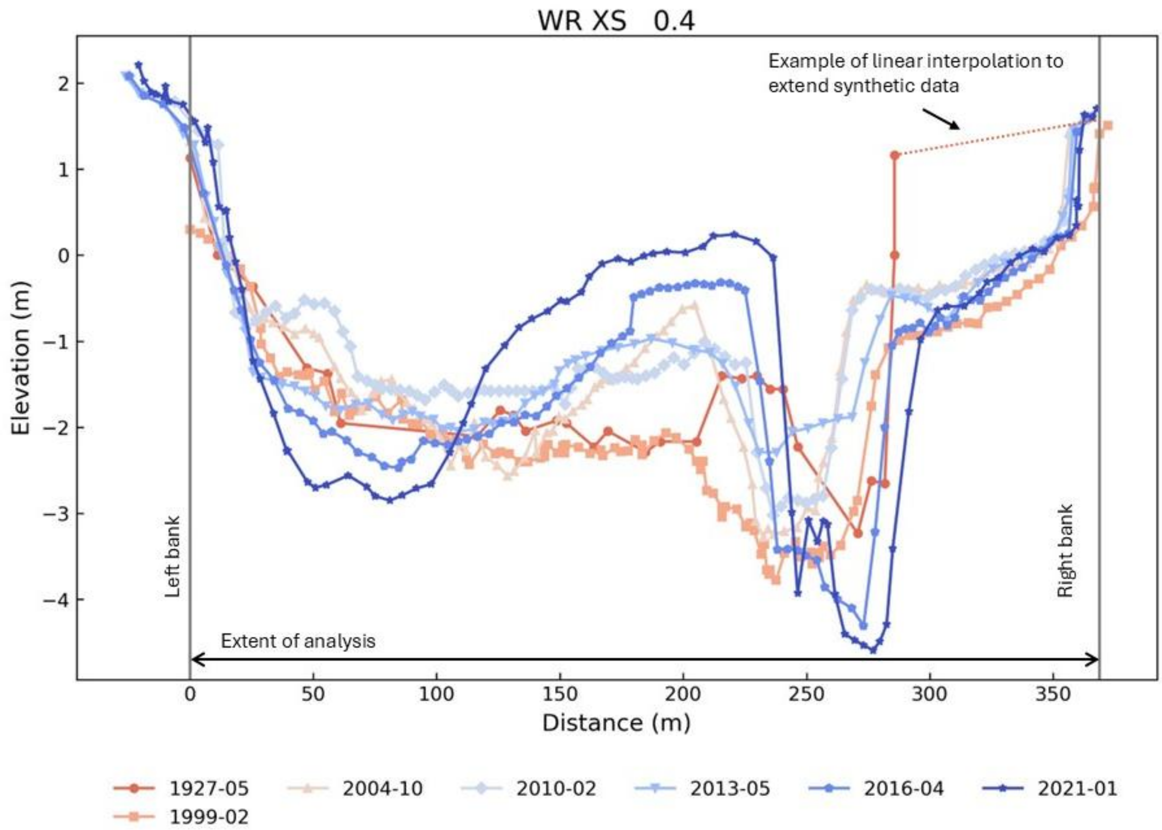

Figure 4-24: Example cross section. Linear interpolation was used to extend synthetic data. The extent of analysis within left bank and right bank delineations are specific for this study and differ for each cross section.

The mean bed level (MBL) was calculated between the same end-points for each survey (e.g., left bank and right bank lines, as per Figure 4-24), summing the area above the surveyed cross section data and then dividing this area by the distance between the end points. Tracking changes in the MBL over time allows for the assessment of long-term river stability, helping to determine whether the riverbed is experiencing aggradation or degradation across different time intervals.

The minimum bed level refers to the lowest point on the surveyed cross section. Comparing changes in the minimum bed level over time provides insights into sedimentation and erosion processes occurring in the deepest areas of the channel.

Results

Lower Wairau River

MBL analysis indicates generally consistent trends across all cross sections that align with the timing of engineering works (Figure 4-25). Below, we assess the selected Lower Wairau River cross sections in relation to two key engineering events: construction of the Wairau Diversion in 1963 and installation of the erodible embankment in 2009 (Figure 4-25). It is worth noting, though the entire Lower Wairau downstream of Tuamarina is tidal (Basher et al. 1995), we expect that the sections farthest downstream (sections WR XS 0.6 and WR XS 0.4) are the most influenced by tidal and wave activity. It is also worth noting that section WR XS 0.4 is just upstream of the surveyed deep tidal channel shown in Knox (1983) (Figure 4-22). Section WR XS 24.3 is upstream of the diversion and in between the SH1 and railway bridges, so may reflect scour or deposition associated with bridge piers dynamics. It is also important context that section WR XS 24.3 is in a braided, gravel bed, naturally depositional area. The river including and downstream of WR XS 23 transitions to a single-threaded, tidally-influenced sand bed river.

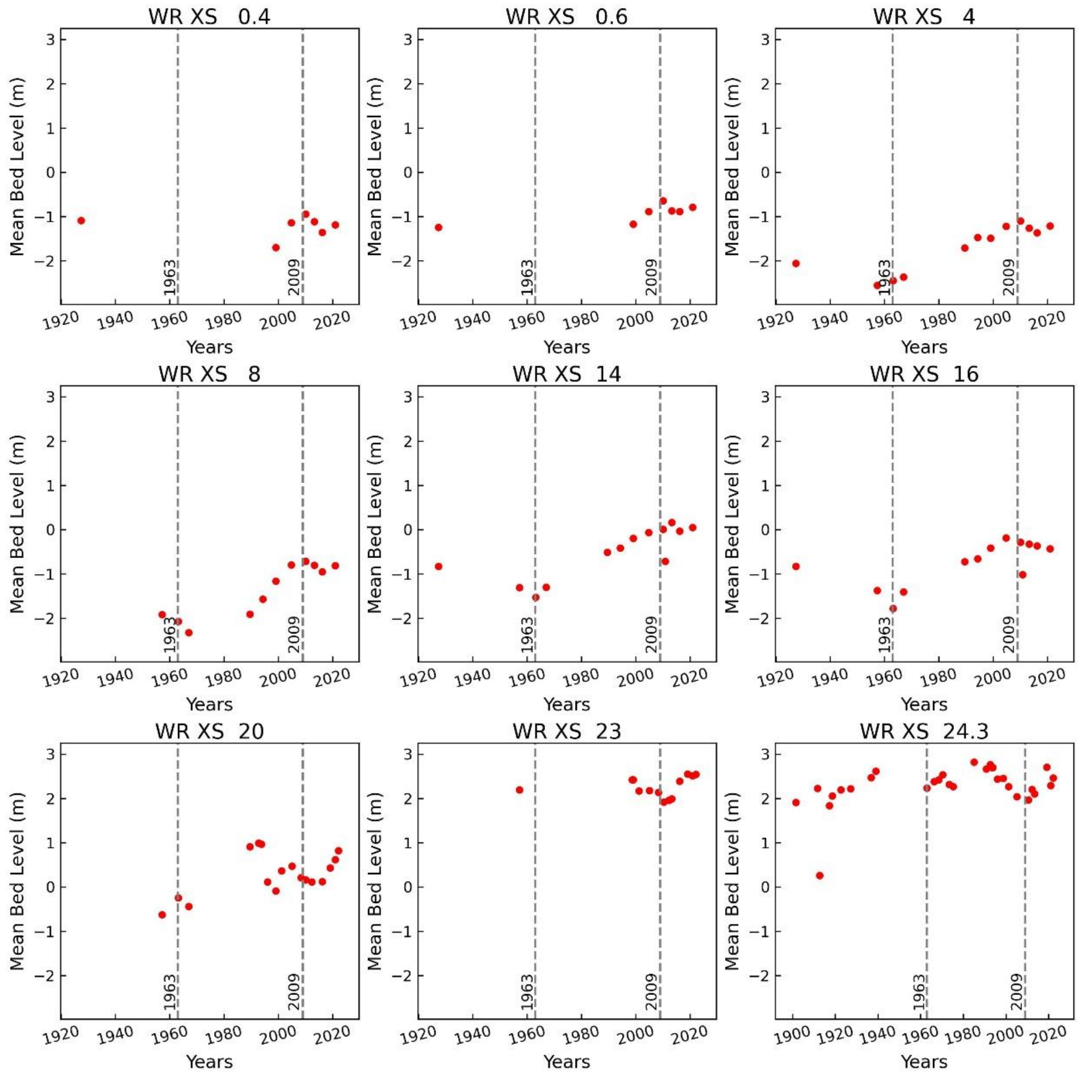

Figure 4-25: Mean bed levels for selected cross sections in the Lower Wairau River, downstream of SH1. Note that the x-axis of the WR XS 24.3 figure differs in order to show the longer period of data.

Pre-1963

For cross sections with data pre-1963, in the single thread, tidal section (i.e., downstream of WR XS 23) there appear to be trends of decreasing MBLs, which align with the “erosional” phase of the river identified by Christensen and Doscher (2010). These MBL declines may be a response of the river to the upstream blocking of the Opawa Breach, which would have prevented the dissipation of flood energy, instead keeping concentrated flood flows in the Lower Wairau River. These increased flows would likely have increased sediment transport in this section of river.

Cross section WR XS 24.3 shows a different trend, one of aggradation. Aerial imagery, as well as from personal observations, show that this cross section is braided, and it is within a natural gravel deposition zone where the river loses the energy to transport gravel. Downstream of this cross section, the river transitions to a sand bed river, although the precise area over which this occurs is unknown and may vary over time. This cross section shows a long term trend of gradual aggradation prior to 1963, illustrating those natural depositional processes. This cross section is also next to the bridges, so short term variability may be due to scour and deposition around bridge piers.

We note that bed levels in the Lower Wairau River (particularly WR XS 20 and WR XS 23) would likely have been affected by the 1927 Peninsula cut, which temporarily widened and then narrowed and straightened the channel. These two cross sections may also be influenced by shifting extent of the gravel-sand transition. However, there is too little data through the subsequent decades to distinguish between the processes at these locations.

1963-2009

Following construction of the Wairau Diversion, available MBL data largely show increasing bed level trends in the single thread, tidal section downstream of the diversion, which aligns with the "aggradational" phase identified by Christensen and Doscher (2010). Aggradation would be expected to occur as flow diverted into the diversion channel reduced the transport capacity of the flow remaining in the Lower Wairau below the diversion.

At cross sections WR XS 20, WR XS 23 and WR XS 24.3, the initial aggradation trend changes to a degradation trend in the 1990s. These cross sections are likely influenced by changes in bed levels within the diversion channel that were occurring during this period (see below and Figure 4-27). Channel geometry within the diversion was still developing until 1998. Bed level lowering within the diversion gradually progressed upstream (knickpoint migration)[8], and this upstream knickpoint migration would also have extended upstream of the diversion, resulting in bed level lowering at WR XS 24.3. These bed level changes immediately upstream of the diversion would then drive some adjustment in the Lower Wairau River.

Post-2009

To address the aggradational issues observed in the Lower Wairau River following construction of the diversion channel, an erodible flow embankment structure was constructed in 2009 to encourage more flow to go down the Lower Wairau River. After 2009, MBLs in much of the single thread, tidal section of the Lower Wairau appear to have declined, or at least stabilised, reflecting the desired outcome of the erodible embankment structure. These trends align with those in cross section analyses done in 2016 (Gardner and Sharma 2016). However, presence of the embankment structure also means that more bed material is now being directed back down the Lower Wairau River, and

[8] A knickpoint in a river is an area with a particularly steep gradient, compared to adjacent gradients upstream or downstream. Knickpoints can be stable (e.g., a waterfall in resistant rock types) or mobile/migratory (e.g., a section of river that is adjusting to a lowering in base level, for example, a drop in sea level). A knickpoint is often associated with enhanced erosion. As such, the initiation point of a mobile knickpoint can propagate upstream as the river erodes and adjusts to a reach a more stable (e.g., equilibrium) gradient. See River Knickpoints: Distinguishing Between Mobile and Fixed Steps in River Channels for more information.

natural deposition of bedload has resumed. This deposition can be seen in cross sections WR XS 20, 23 and 24.3, which show consistent aggradation trends after 2009.

Assessment of changes in minimum bed levels provides potential further insights into sedimentation and erosion processes occurring in the deepest areas of the channel. While some cross sections show changes in minimum bed level behaviour that may correspond with the timing of engineering works that appear to have influenced MBLs, others show different trends (Figure 4-26). Moreover, some cross sections show a high degree of scatter, while others are more stable. The data scatter in cross section WR XS 24.3 is likely due to a combination of bridge pier scour and braid adjustment. WR XS 23 shows reasonably stable minimum bed levels across the surveys. WR XS 20 shows a deepening of the channel between 1963-2009 when flows were diverted down the Wairau Diversion. Minimum bed levels then increase (infilling or changing shape) following construction of the erodible embankment in 2009, which is consistent with MBL trends at this section. Further downstream, trends vary spatially and temporally, and are also not always consistent with MBL changes. Further examination of the cross sections (Appendix B) shows that the most consistent change in the Lower Wairau River, (from WR XS 23 to WR XS 0.6) has been gradual narrowing over time. Bed levels at WR XS 0.4 are noisy, but perhaps show recent deepening of the thalweg (deepest part of the channel). WR XS 0.4 will be most influenced by coastal changes and tidal flows, and it is possible that bed level changes reflect an upstream migration of the deep channel mapped by Knox (1983).

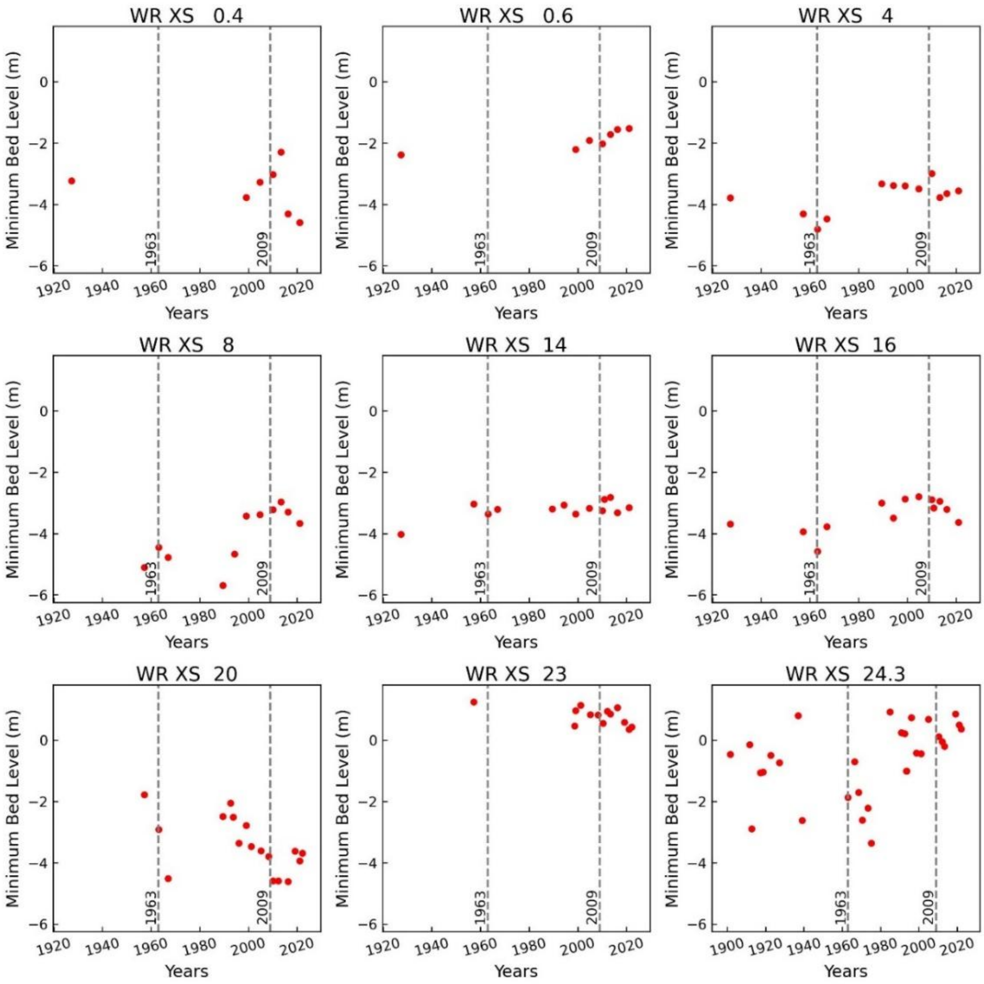

Figure 4-26: Minimum bed levels for selected cross sections in the Lower Wairau River, downstream of SH1. Note that the x-axis of the WR XS 24.3 figure differs in order to show the longer period of data.

The observed variability in mean and minimum bed levels in the Lower Wairau River makes it challenging to identify slope trends. Moreover, there are only a few cross sections that have identical survey dates, which provides limited data to use for slope analysis. We expect that trends in MBL are more robust for drawing conclusions about bed processes, so do not explore slope trends further.

Summary statement and implications for sediment dynamics: In summary, mean bed levels in the Lower Wairau River have fluctuated over the period of analysis. However, the general trend below the diversion is aggradation between 1963-2009 and degradation after 2009, with a possible upturn in MBLs in the most recent survey. For the three cross sections spanning the area of diversion works (WR XS 20, 23 and 24.3), bed levels aggraded initially, when just flow was diverted, but dropped once the diversion was fully developed and bed material was also travelling down the diversion channel. This trend continued until the erodible embankment was constructed in 2009. Since then, bed levels have begun to aggrade again as more sediment passes through the Lower Wairau River. This process is expected to continue as this section of river is a natural gravel deposition zone. Minimum bed levels do not have as generalisable trends and may represent infilling, deepening or changing shape of the channel.

Diversion channel

Mean bed levels in the Wairau Diversion channel for selected cross sections show trends associated with its construction and evolution (Figure 4-27). WDXS12, which is the farthest upstream of the selected sections – about 1.5 km downstream of SH1 – shows increasing bed levels between 1963 and the early-mid 1980s. WDXS8, the middle of the selected sections, shows an opposite trend, with MBLs decreasing from 1963 to the early-mid 1980s, when MBLs begin increasing. WDXS2, just upstream of the diversion outlet, shows declining MBLs from 1963 to the early-mid 1980s, when MBLs appear to become a bit more stable. There has been little change in MBL following the 2009 installation of the erodible flow structure, as both flow and bed material supply have been largely truncated.

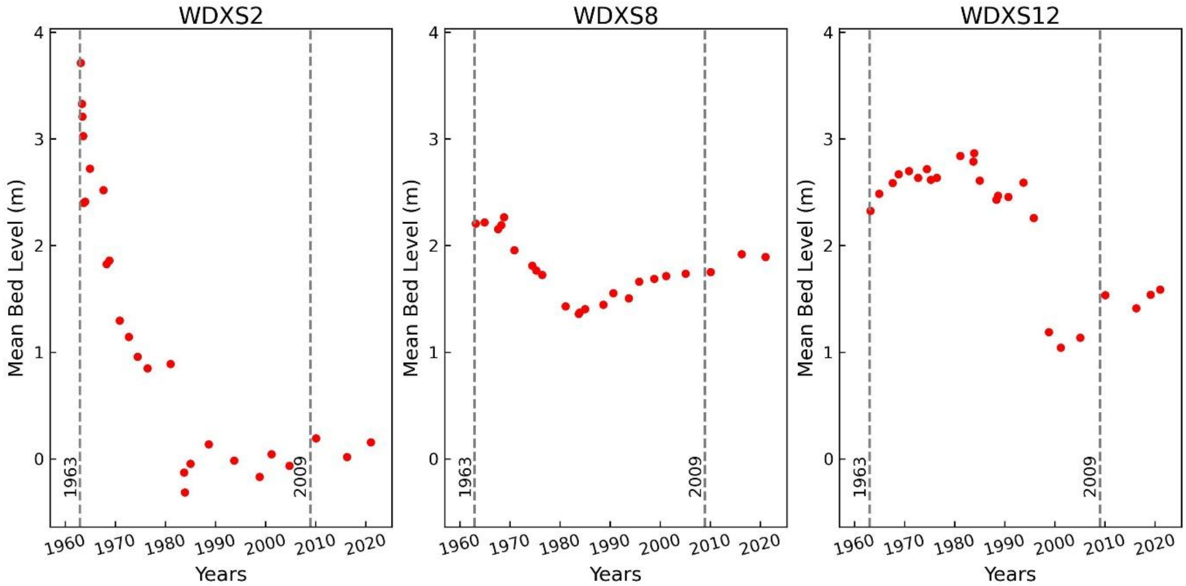

Figure 4-27: Mean bed levels for selected cross sections in the Wairau diversion channel.

As discussed in Section 3.3, the Wairau Diversion was intended to widen naturally over time, but because this widening was occurring more slowly than anticipated, it was mechanically widened to achieve the desired design outcomes. The Wairau Diversion reached full design capacity in 1998 (Christensen and Doscher 2010). The timing of the inflection in the bed level trend (e.g., around 2000-2005 for WDXS12; 1985 for WDXS8; 1982 for WDXS2) reflects the upstream migration of a knickpoint, as each cross section sequentially reached design capacity.

Minimum bed levels (Figure 4-28) decreased at WDXS2 and WDXS8 between 1963 and 2009, which aligns with the natural and mechanically aided establishment of the channel. WDXS12 shows more variability. Minimum bed levels appear to have either stabilised or increased following installation of the 2009 erodible flow embankment.

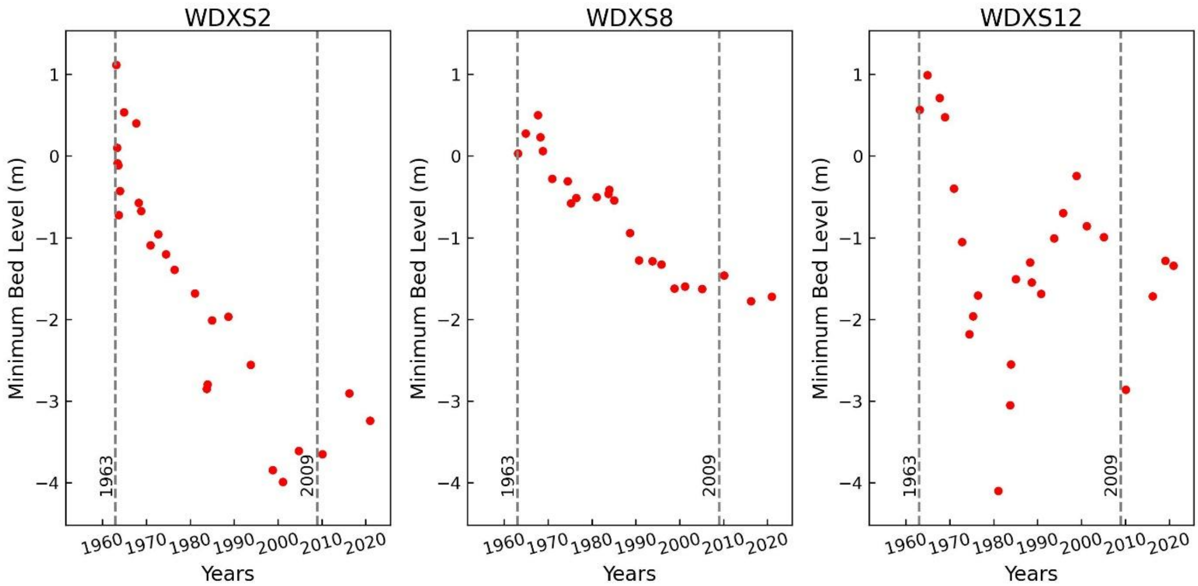

Figure 4-28: Minimum bed levels for selected cross sections in the Wairau diversion channel.

Summary statement and implications for sediment dynamics: In summary, MBLs in the Wairau Diversion indicate an upstream-migrating knickpoint as the diversion channel developed to its design capacity. The data suggest that, following the channel development phase, MBLs have subsequently shown an aggradation trend. Minimum bed levels have generally lowered over time, but have stabilised or perhaps increased following construction of the erodible embankment. Variation in the data, particularly for WDXS12, may be associated with mechanical widening of the channel.

5 Summary of geomorphic change in the Lower Wairau River

The key messages from the results of our analyses described above are:

- Our precipitation analysis (Section 4.1.1) revealed few statistically significant trends in precipitation over the period of analysis for the four climate stations selected. The strongest trends were in seasonally grouped monthly and annual rainfall: two stations show significant trends of increasing rainfall in autumn; two stations show significant trends in decreasing rainfall in spring; and one station shows a significant trend in decreasing rainfall in summer.
- Our streamflow analysis (Section 4.1.2) showed trends for the Wairau River at SH1 having reasonably strong (likely) declines in average annual discharge between 1961-2024. More detailed analysis is required to attribute this trend to climatic drivers versus activities in the catchment (e.g., extraction for irrigation or groundwater pumping).
  - There are no significant trends of either an increase or decrease in annual maximum flood magnitudes.
  - The percentage of time of each year that the Wairau spends above 600 m^3/s has decreased over the period of 1961-2024, with a 'likely downward' trend, indicating that the frequency of flows that can mobilise fine sand in the Lower Wairau River has decreased, which may contribute to deposition of fine sediment in the Lower Wairau. However, because of changes in the flow split between the Lower Wairau and the Diversion Channel over time, it is possible that the value of 600 m^3/s at Barnett's Bank does not consistently represent sand-mobilising events in the Lower Wairau.
  - The percentage of time of each year that the Wairau spends above 1,200 m^3/s has a non-significant trend, indicating that frequency of fully bed-mobilising flows has not changed substantially.
- Looking at the correlation between precipitation and stream flow data (Section 4.1.3), it is possible that antecedent moisture conditions leading up to flood events are increasing, suggesting that more rainfall may be occurring during flood-inducing storms, though more detailed analysis would be required to confirm this statement.
- The width of the active river channel downstream of SH6 has decreased by up to 56% since 1924. Though some discrete widening has taken place, the overall trend is that of narrowing in both the reach between SH6 and SH1 and in the Lower Wairau below SH1 (Section 4.2.1).
- While the lagoon shape overall does not appear to have changed substantially since 1947, there are active geomorphic processes taking place along the perimeter that may be influencing lagoon dynamics (Section 4.2.1). It is likely that increase in sea level since the 1940s has also increased tidal flux, which may be influencing widening of the Lagoon complex channel. The morphology of the lagoon suggests that most of the sediment in the lagoon is coming from the Lower Wairau River and, to a lesser extent, smaller streams draining into the lagoon. Overwash events occur periodically at an area of historical breach in Te Pokohiwi ō Kupe. However, this area appears to have had fairly consistent morphology since 1904. Overwash at the breach doesn't appear to be major contributors of sediment to the lagoon currently, but frequency of overwash may increase with rising sea level. The presence of a deeper channel near the mouth may suggest strong tidal influence.

- Our river cross section analysis (Section 4.2.2) largely aligns with previous work by Christensen and Doscher (2010) and Gardner and Sharma (2016), with some differences.
  - The data show general degradational trends in mean bed levels in the Lower Wairau River prior to 1963, indicating an “erosional” phase in the river. We consider that this may be at least partly driven by the closing of the Opawa Breach.
  - Following the 1963 construction of the Wairau Diversion, Christensen and Doscher (2010) note the river experienced an “aggradational” phase, as flow energy in the lower river had been reduced by the diversion. Our analysis largely agrees with this finding. However, for the three cross sections spanning the diversion works area (WR XS 20, 23 and 24.3), once the diversion was fully developed (i.e., from the late 1990s) and bed material was also diverted down the diversion, bed levels in this area then dropped.
  - Following construction of the erodible embankment, aggradation in the sand bedded tidal reach (Figure 3-5) appears to have largely halted with a small reduction in bed levels at some cross sections. However, for the three cross sections spanning the diversion, our analysis indicates an increase in mean bed levels. Aggradation in this zone is to be expected as it is within the natural gravel deposition zone. Mean and minimum bed levels at the most upstream cross section (WR XS 24.3) likely reflect braid adjustment and may be influenced by bridge dynamics, while the most downstream cross section (WR XS 0.4) will be most influenced by tidal activity.
  - Whilst the focus of the cross sectional analysis has been on changes in bed levels, we also note a consistent narrowing trend.
- MBLs in the diversion channel (Section 4.2.2) show variations in trends that may indicate different sections of the diversion channel responding to natural or mechanical widening at different rates and at different times, and also show an upstream migration of a knickpoint as the channel developed. MBL trends in the diversion do not appear to be significantly impacted by the 2009 installation of the erodible flow embankment.

Figure 5-1 provides a synthesis of major geomorphic influences and changes in the Wairau River catchment.

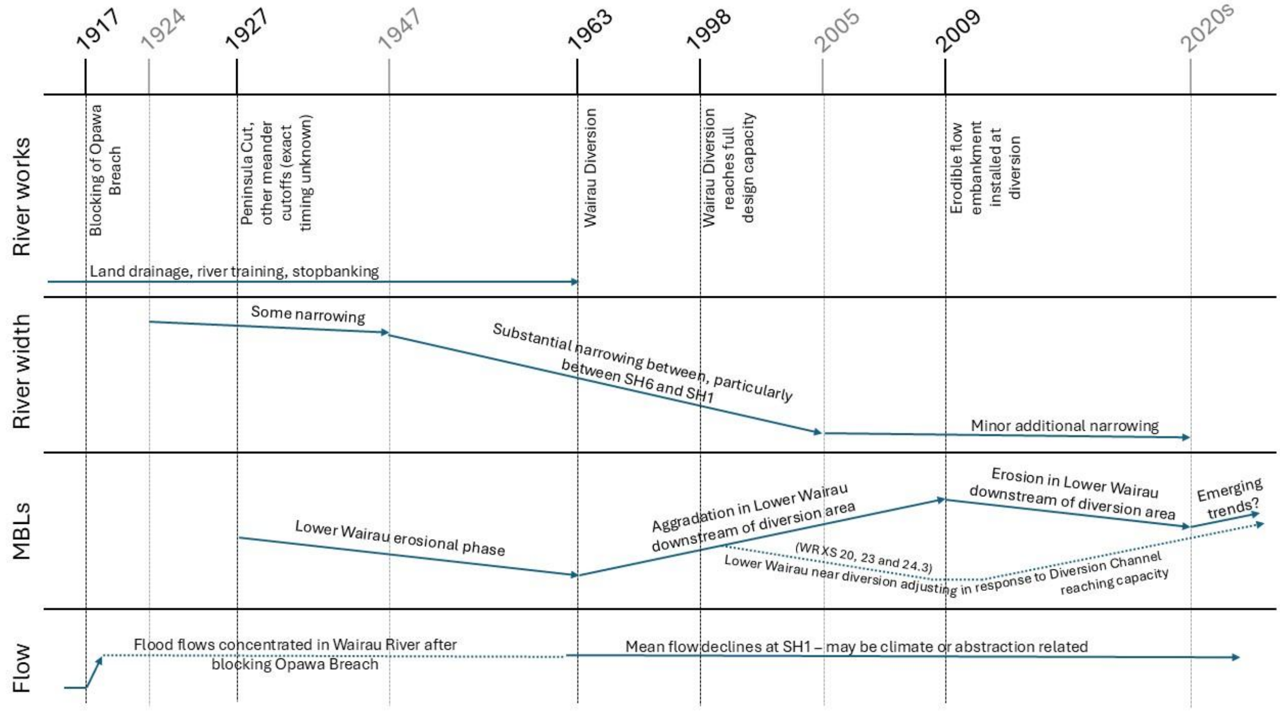

Figure 5-1: Timeline of river interventions and response in the Lower Wairau River and diversion channel. Dates in black text correspond to dates of notable engineering works; dates in grey correspond to maps and aerial imagery dates used in the GIS analysis.

The most consistent change in the Wairau River system over the last century has been channel narrowing. The data shows that narrowing has occurred from SH6 all the way to the coast. Our analysis also indicates that the physical changes to the Lower Wairau River over the last century are largely anthropogenically driven. Our analysis of the planform in the Wairau River downstream of SH6 indicates that engineering works have narrowed average width of the active channel by as much as 56% since 1924 (Table 4-4). Active channel width plays a major role in the sediment transport capacity of a river. Narrowing a river channel can concentrate flow, which can increase the erosive potential of the flow and its ability to transport sediment. Alternatively, narrowing a river reduces the area over which it can deposit its sediment, which can contribute to sediment-build up.

There is little evidence that precipitation, annual maximum discharges, or sediment delivery from the upper catchment have changed substantially over the last century. Similarly, there is little evidence from previously conducted research included in our analysis that suggests strong coastal influence on the morphology of the Lagoon complex; it is possible that increased tidal flux may be influencing the shape of the river mouth and entrance to the lagoon, but the wider Lagoon complex does not show much evidence of overwash activity (except the one historical, now inactive breach). Based on our analysis, we consider that, at present, fluvial processes – including fluvial response to upstream engineering interventions – may be driving more adjustments in the lower river than coastal processes.

In Marlborough, hazards that are most likely to be influenced by climate change are coastal flooding from sea level rise and overland or fluvial flooding. Our assessment shows little to no change in annual flood maxima over the period of analysis, which may indicate that, for the time being, flood flows are remaining relatively constant in the Wairau River. However, residual risk and overtopping of stopbanks can exacerbate the effects of flooding, and projected climate change scenarios may influence flood flows in ways that are not captured by our analysis. Under projected climate change scenarios, it is predicted that coastal flooding will become a greater issue for the region and may compromise significant sites in the catchment, such as Te Pokohiwi ō Kupe.

6 Recommendations

The Wairau River catchment has a complex geologic and geomorphic setting. A long history of river modifications and control works has further complicated the sediment dynamics in the river system.

Based on our findings, we recommend that MDC continue monitoring river bed levels with cross section surveys or bathymetric lidar. Continued monitoring will support the identification of any emerging trends in the river and will help show how the river is responding to various natural, catchment-scale changes as well as engineering interventions. We recommend MDC continue monitoring cross sections every 3-5 years.

MDC may also wish to consider 1-dimentional (1-D) morphodynamic modelling of gravel transport and bed levels to better understand possible future geomorphic trajectories of the Lower Wairau River. 1-D modelling can provide a suite of potential outcomes that may arise under future conditions to help guide planning decisions. A 1-D morphodynamic model can be calibrated using previously measured cross sections and can generate possible future scenarios 50-100 years into the future. 1-D morphodynamic modelling has the capability to generate projections of river bed changes and can help investigate the impacts of sea level rise, changes to flow regime due to climate change, the effects of gravel extraction, and could help inform what flows at Barnett's Bank are required to mobilise sand in the Lower Wairau. It would then be possible to assess how the frequency of these sand-mobilising flows may be changing.

Collection of grain size data in the Lower Wairau River would be needed to inform any morphodynamic modelling, but would be useful for clarifying the nature, extent, and dynamics of the gravel sand transition. We recommend that grain size data be collected from areas of particular management interest in the Lower Wairau River, but particularly near SH1, within the Lower Wairau River channel downstream of the diversion and within the diversion channel. The grain size data could be collected at the same time as cross section data and repeated in future to assess whether bed level changes are also associated with grain size adjustment.

The outcomes of aligned NIWA/MDC projects currently underway, including the updated flood frequency analysis, coastal flooding and sea level rise assessment, and groundwater modelling investigation, may also provide useful information for understanding the hydrologic regime of the Wairau River catchment and influences on river morphology. While outside of the scope of this work, there is potential to consider the findings of those studies to further explore the relative contribution of fluvial and coastal processes on the morphology of the Lower Wairau River.

7 Acknowledgements

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We acknowledge data from MDC and other entities that have been used in this project (Appendix A).

Finally, we thank Jo Hoyle for her thorough review that helped improve and finalise this report.

8 Glossary of abbreviations and terms

Term	Description	Resource
ENSO: El Niño Southern Oscillation	A naturally occurring climate cycle that influences global weather and climate patterns, including rainfall, temperatures and wind patterns across the world. El Niño and La Niña are the two opposite phases of ENSO.	El Niño and La Niña | NIWA
IPO: Interdecadal Pacific Oscillation	A naturally occurring, multidecadal climate oscillation that influences climate variability in the Pacific region.	Interdecadal Pacific Oscillation | NIWA
Knickpoint	A steep section of river gradient, relative to adjacent river reaches. Knickpoints can be stable or mobile. Mobile knickpoints tend to propagate upstream in response to a downstream change, allowing the river to adjust its gradient to the new conditions.	River Knickpoints: Distinguishing Between Mobile and Fixed Steps in River Channels
MBL: Mean bed level	The average elevation of a river cross section. Tracking changes in the MBL over time allows for the assessment of long-term river stability.	
SAM: Southern Annular Mode	A zone (or “ring”) of climate variability that surrounds the South Pole and extends to the mid-latitudes. The SAM influences winds and storm activity.	Southern Annular Mode | NIWA
Thalweg	The deepest, or lowest, part of a river channel.	

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Appendix A List of data and sources

Report Section	Data	Source
3	Longitudinal profile of the Wairau River valley	Data from Dip Flat to Waihopai River confluence from a composite DEM from the Esri Living Atlas Terrane layer, down-sampled to 26 m grid resolution. Data from Waihopai River confluence to the mouth is from a bathymetric survey conducted by NIWA in 2022 as part of MBIE Endeavour bid LVLX1901.
3	GIS layers:	
	Surface geology (simplified)	GNS
	Land cover (simplified)	LCDBv5 – Manaaki Whenua, 2018 values
4.1.1	Precipitation data	MDC; NIWA
4.1.2	Flow data	MDC; NIWA
4.2.1	1924 map	MapsPast
	1947 imagery	Retrolens
	2005 imagery	MDC
	2020s imagery	MDC online GIS portal
4.2.2	Cross section data	MDC

Appendix B Selected cross sections

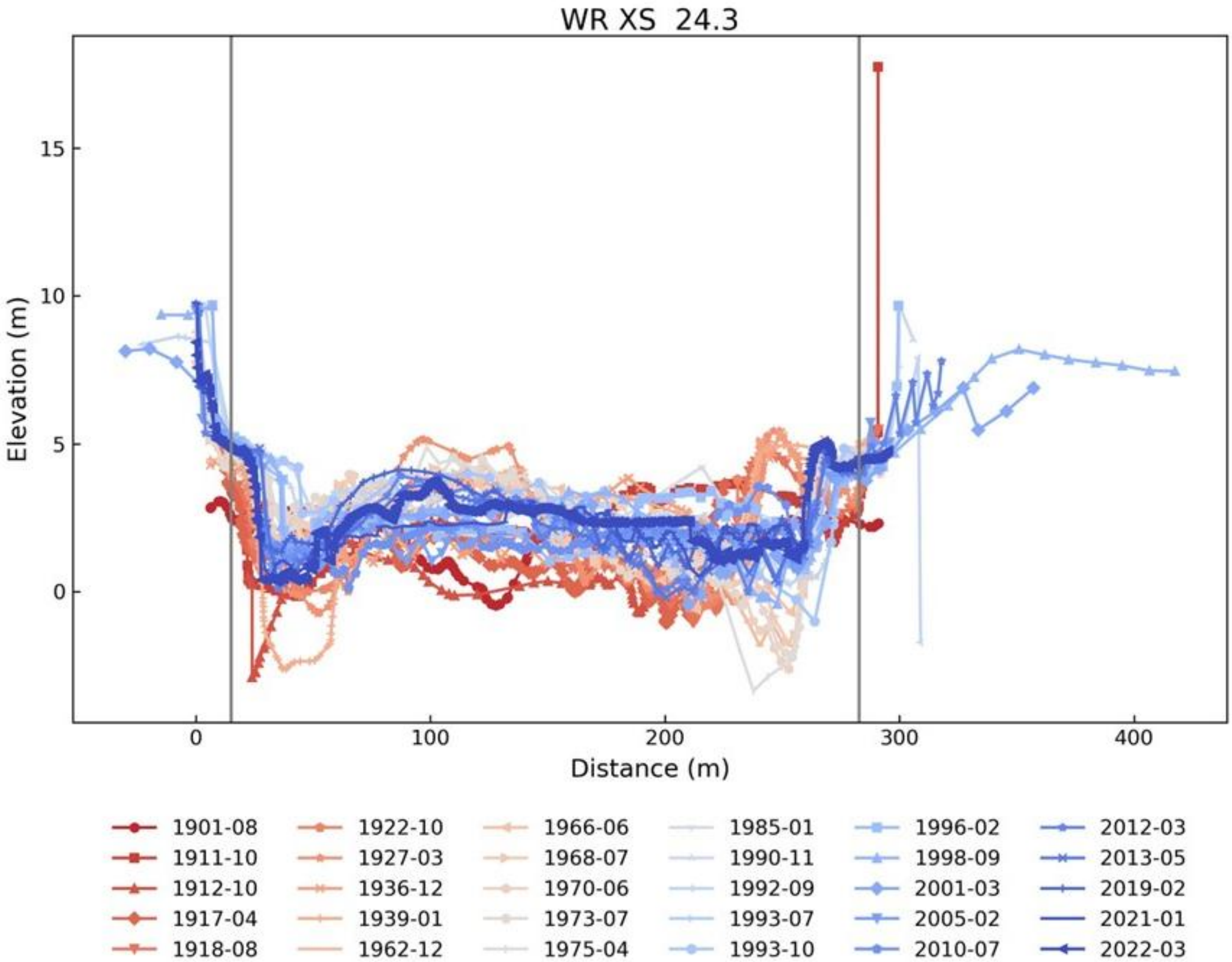

Figure B-1: Cross section WR XS 24.3.

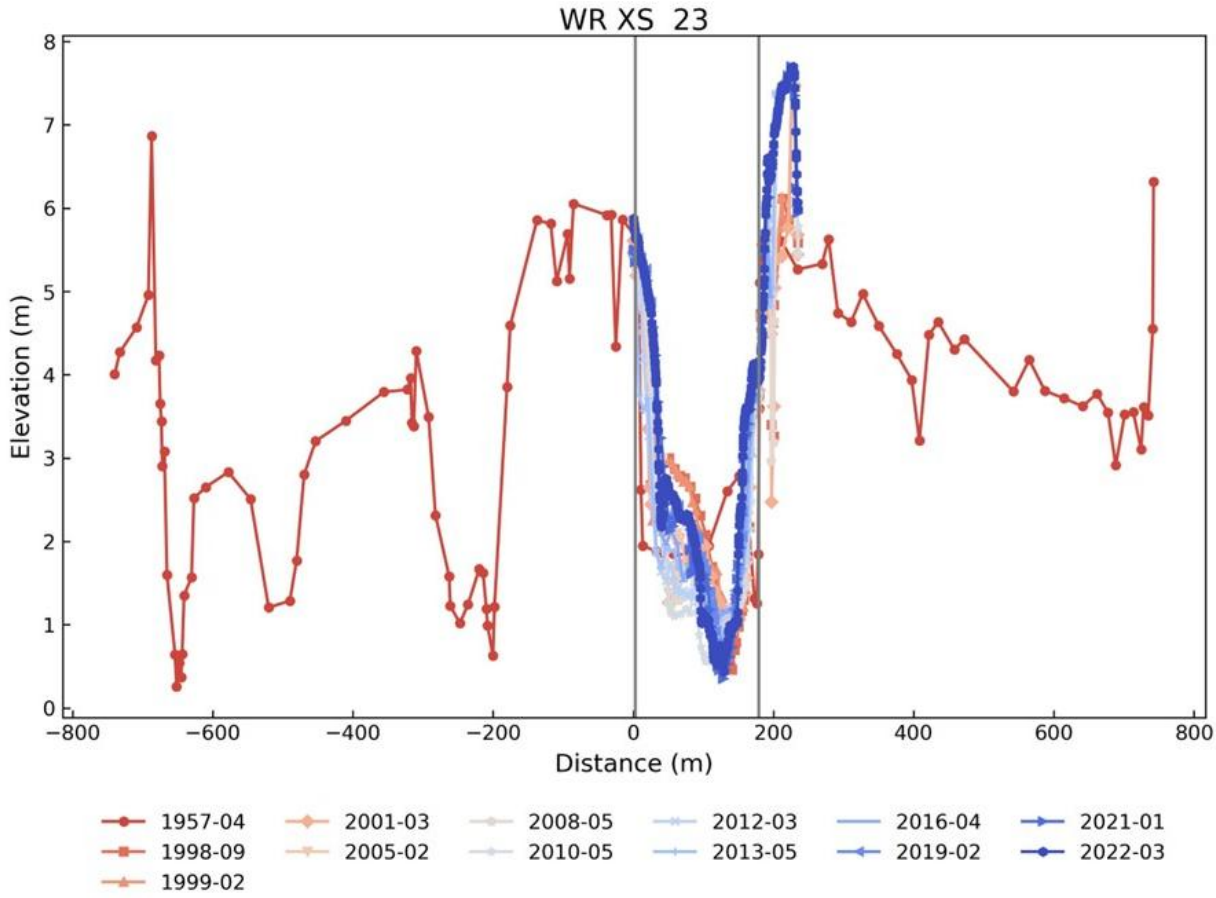

Figure B-2: **Cross section WR XS 23.**

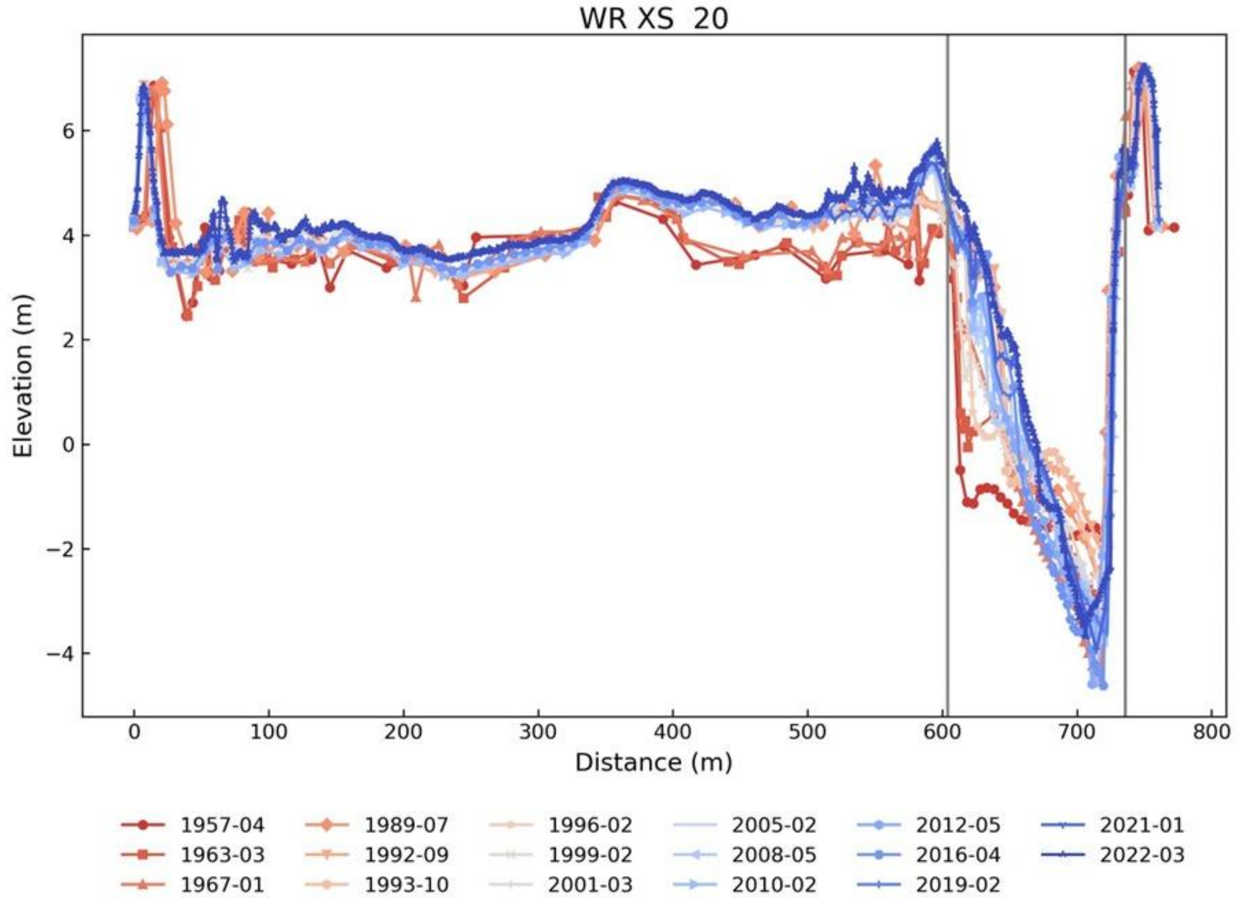

Figure B-3: Cross section WR XS 20.

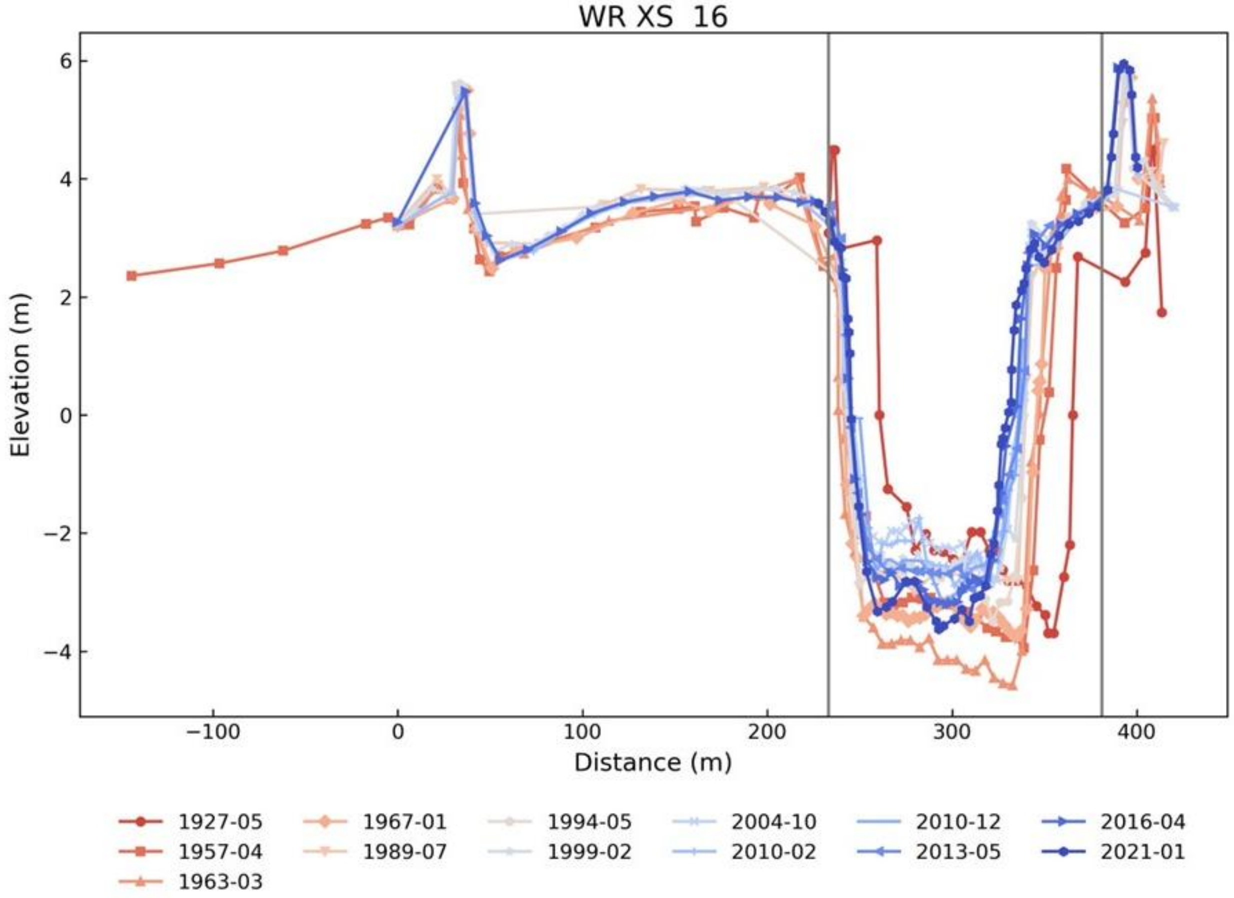

Figure B-4: Cross section WR XS 16.

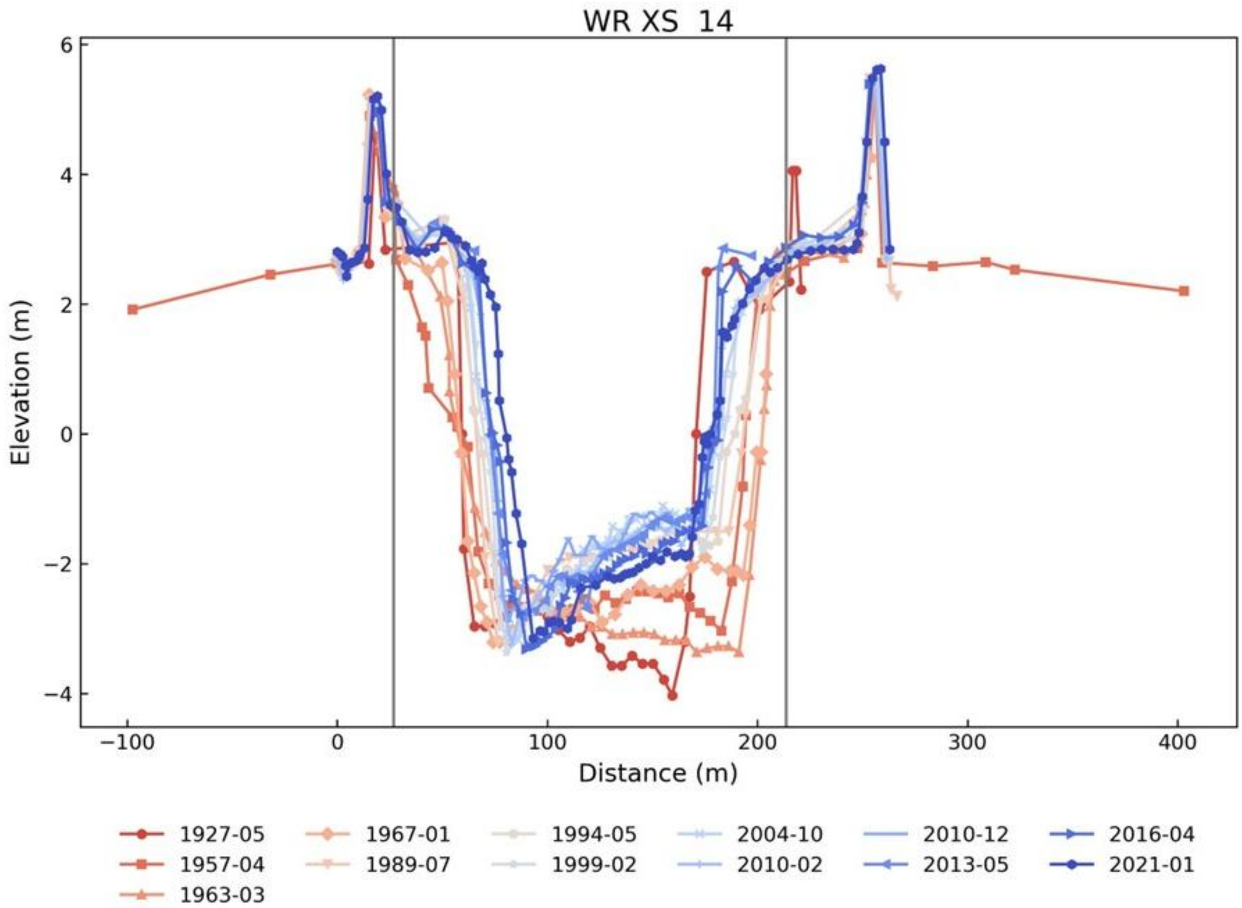

Figure B-5: Cross section WR XS 14.

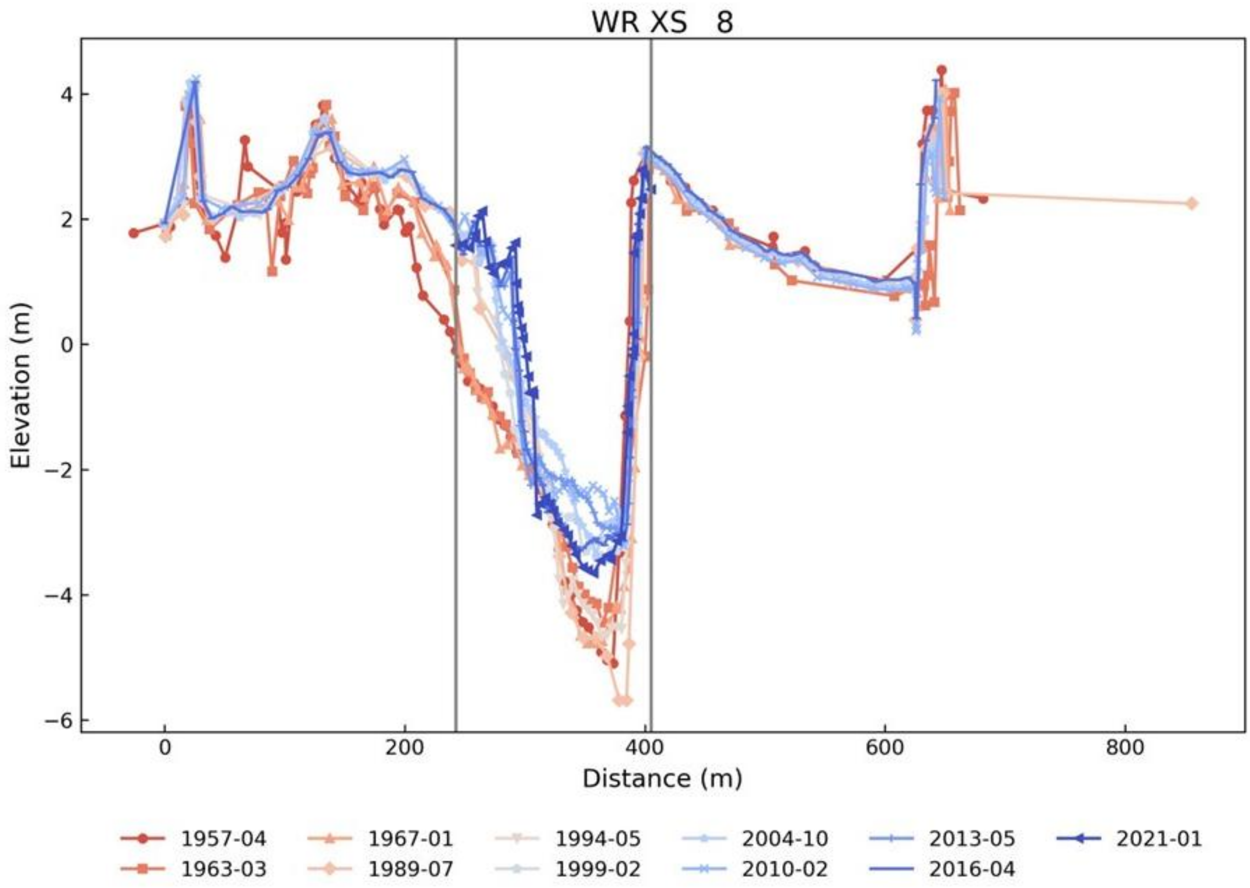

Figure B-6: Cross section WR XS 8.

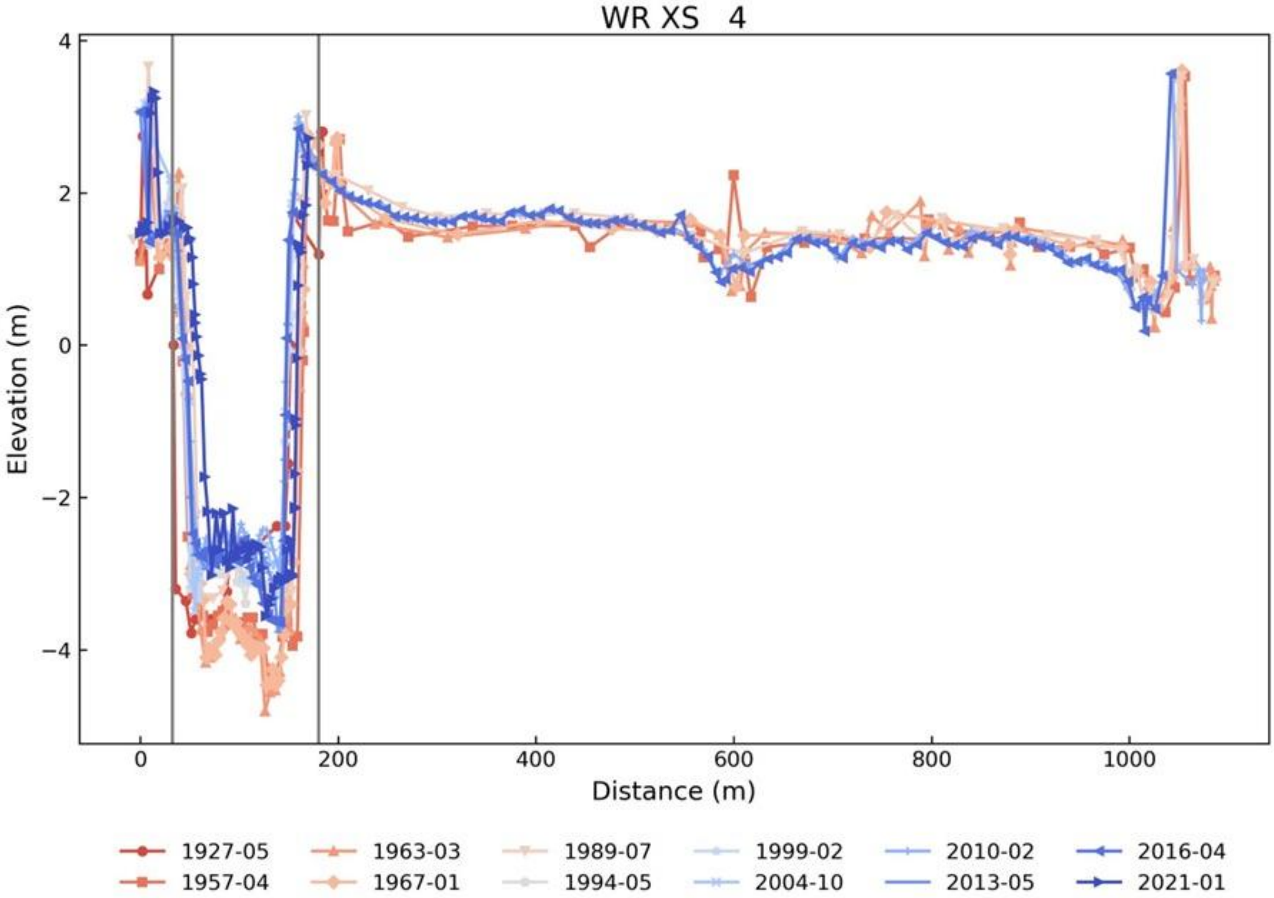

Figure B-7: Cross section WR XS 4.

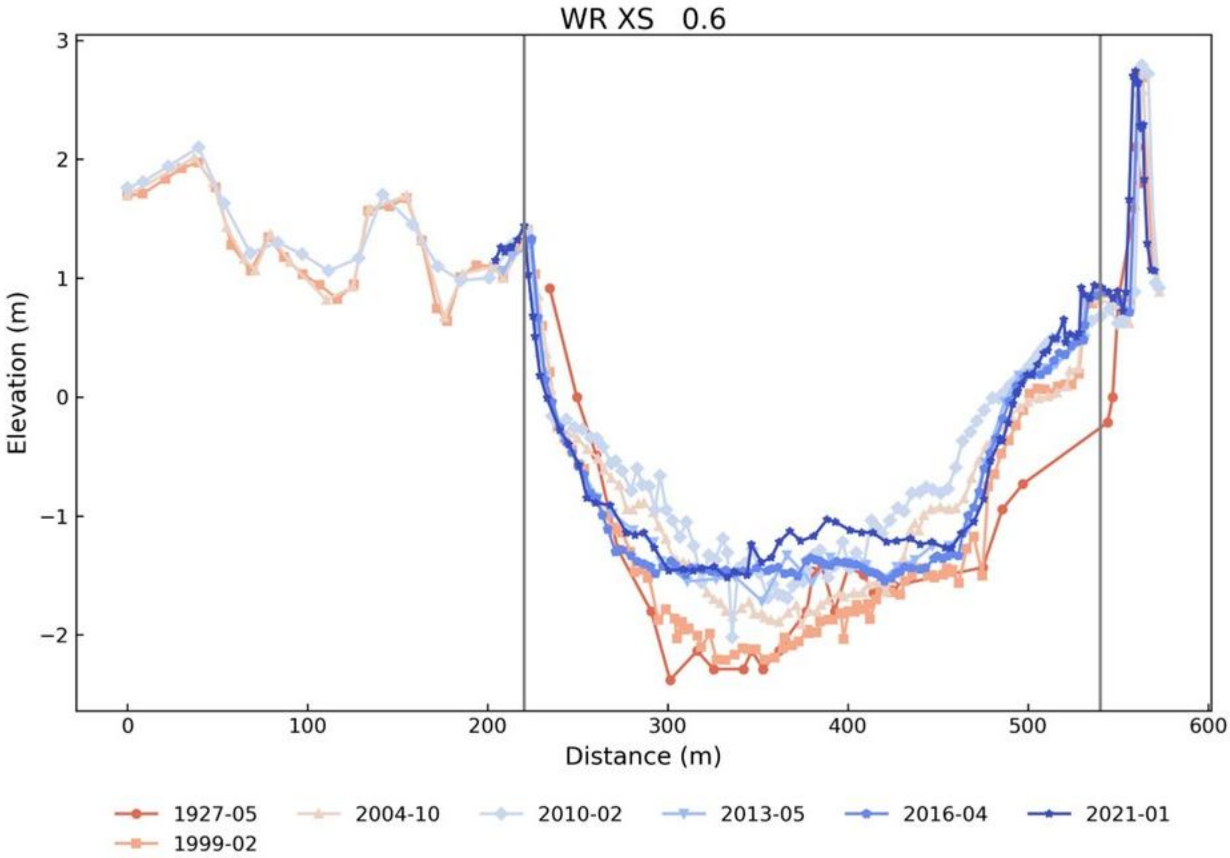

Figure B-8: Cross section WR XS 0.6.

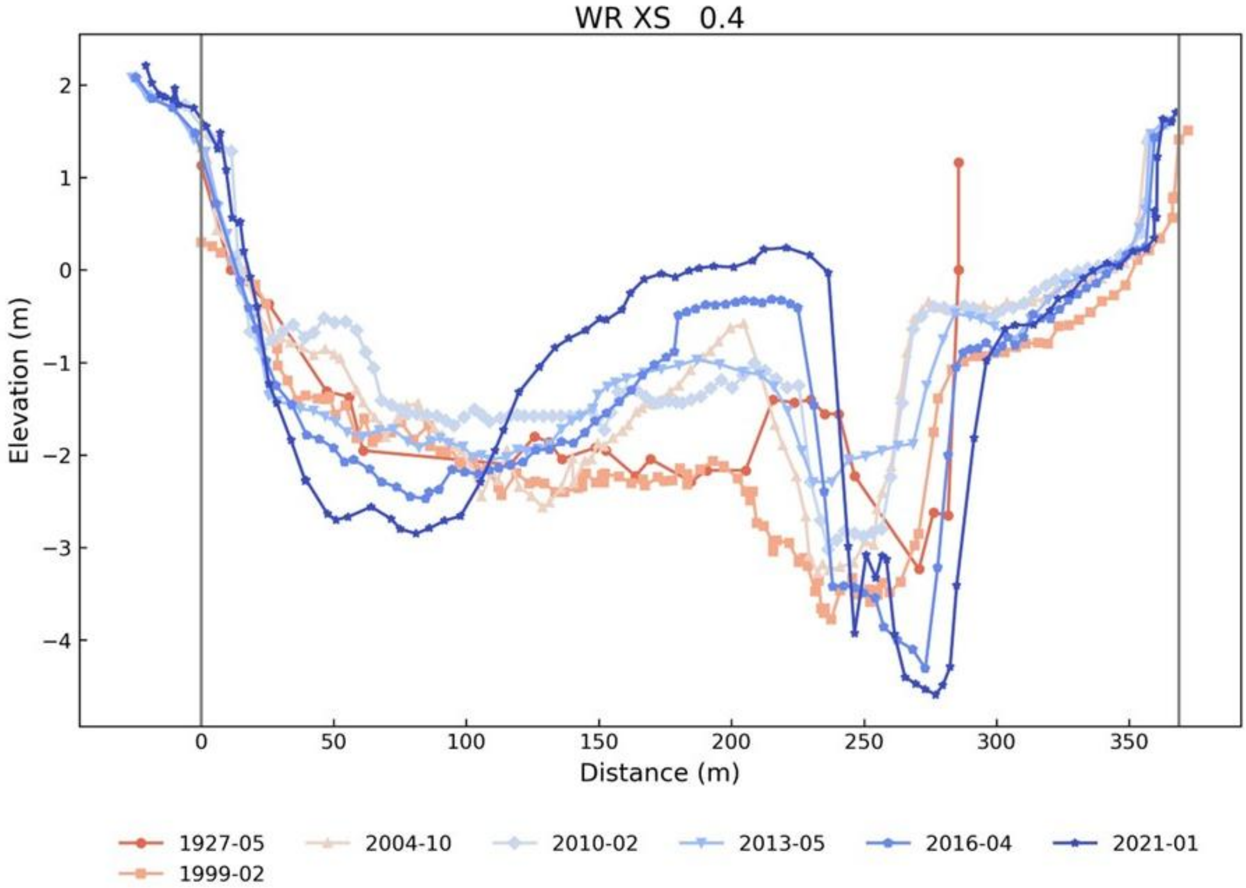

Figure B-9: Cross section WR XS 0.4.

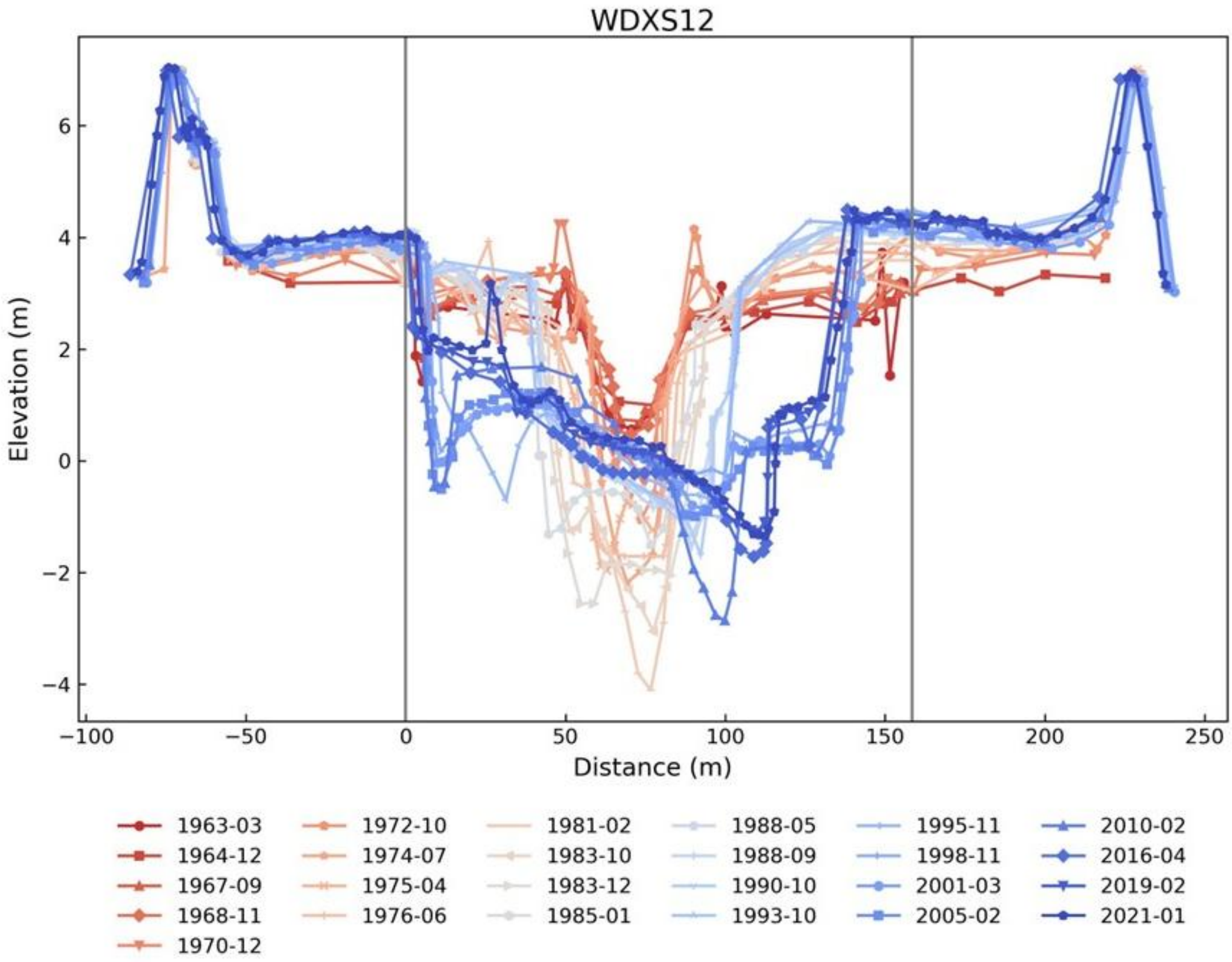

Figure B-10: Cross section WDXS12.

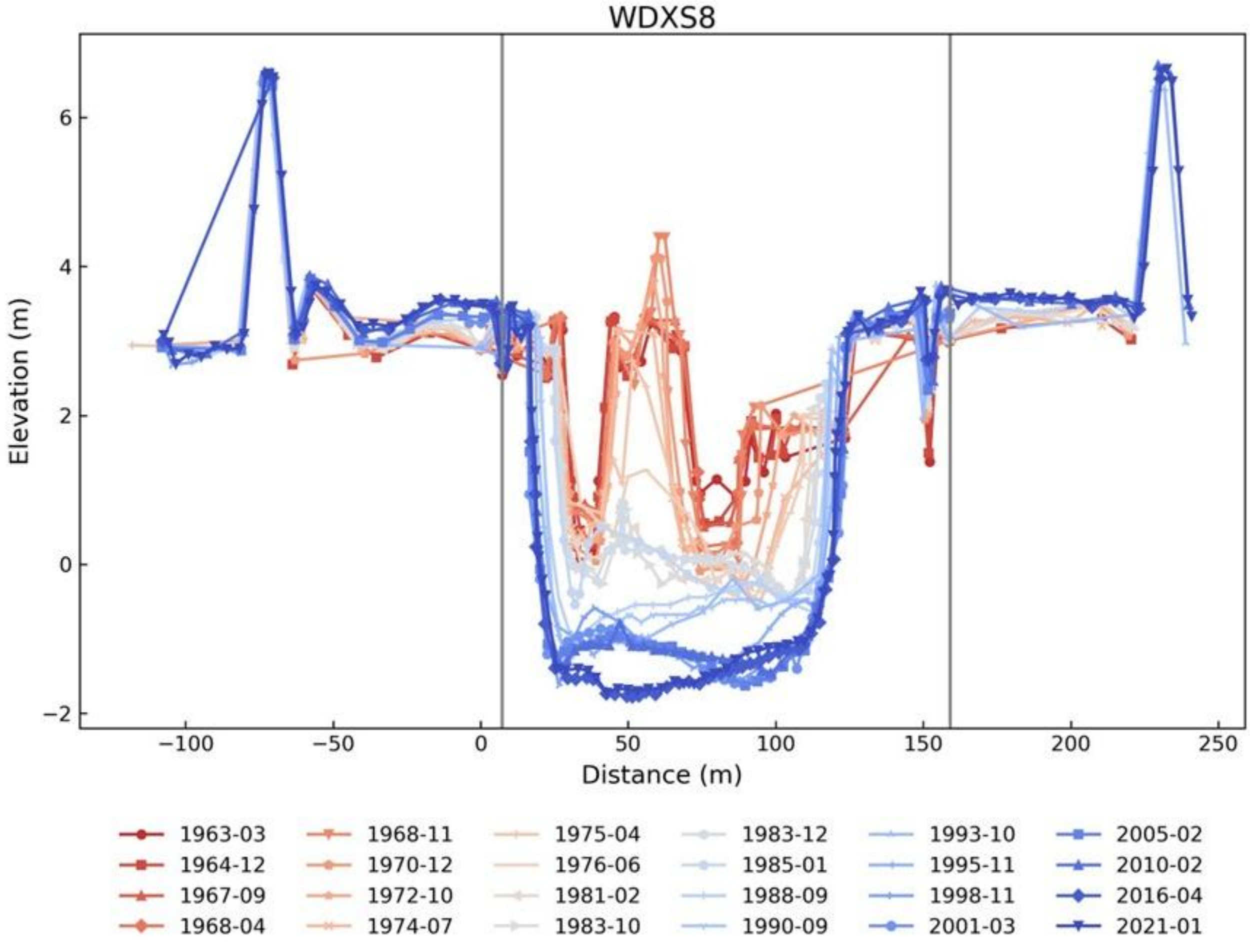

Figure B-11: Cross section WDXS8.

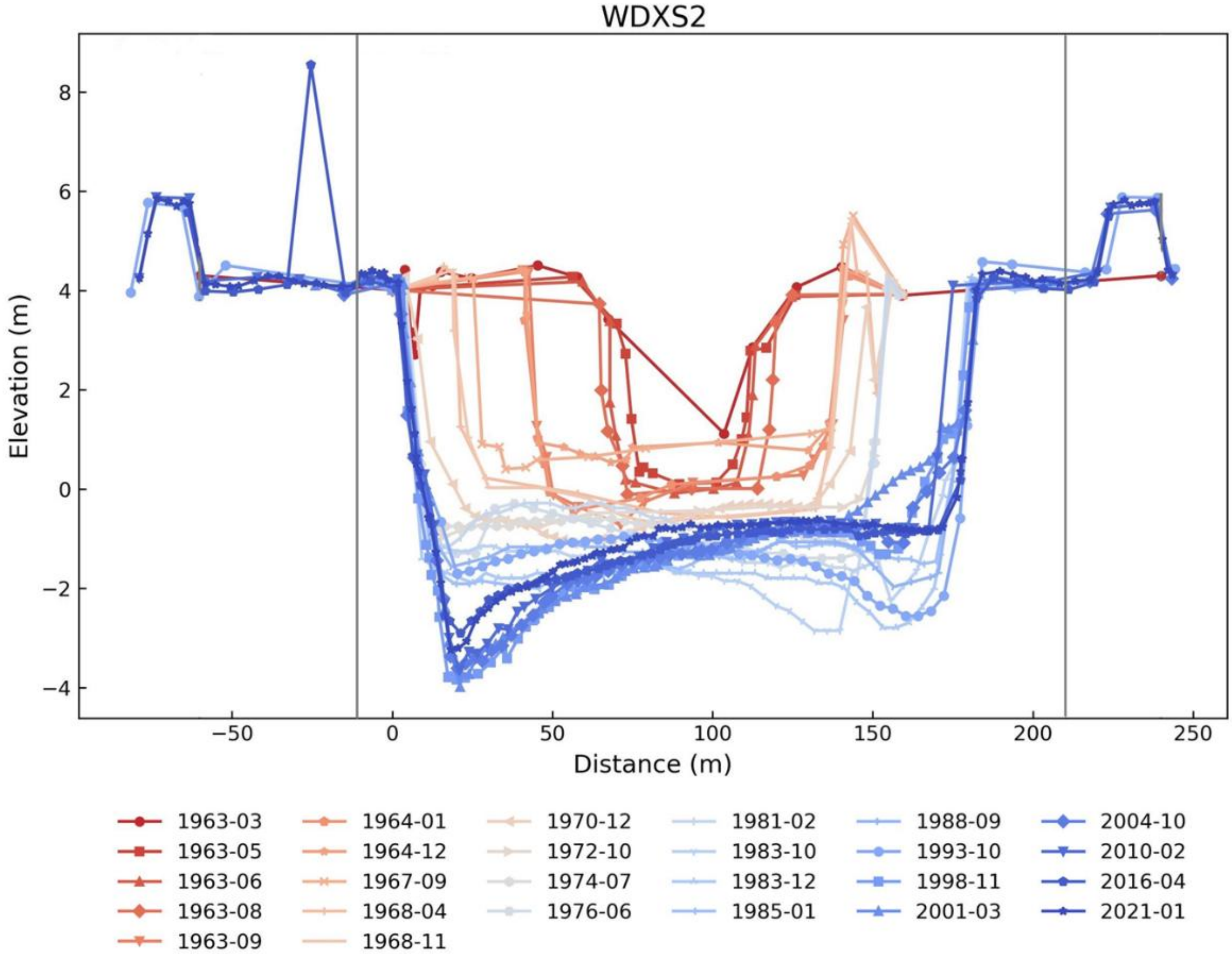

Figure B-12: Cross section WDXS2.