

The interaction of river engineering and geomorphology in the Lower Wairau River, Marlborough, New Zealand

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Abstract

The Wairau River is one of the most engineered river systems in the Marlborough region. Historical river control works, particularly the blocking of the Opawa Breach and the subsequent construction of the Wairau Diversion, have had a significant impact on flow and sediment transport in the Lower Wairau. Currently, the Lower Wairau is aggrading as a result of an increase in sediment concentration and a decrease in the duration for which flows exceed the critical threshold to keep sediment entrained. These changes are attributable to the substantial reduction in flow in the Lower Wairau that is a result of over half the total Wairau flow now passing down the Wairau Diversion. During the previous period, following the blocking of the Opawa Breach up until the construction of the Wairau Diversion, the opposite occurred, with significant increases in flow down the Lower Wairau and widespread erosion.

This paper reviews the geomorphic setting of the Wairau deposition zone and the impacts of the Opawa Breach and the Wairau Diversion on the Lower Wairau by examining historical cross-sectional data (1927 to present) and assessing the distinct flow and sediment transport regimes driving the aggradation and erosion. The effects on channel slope, width and bed level through

the different regimes are also examined, along with their implications for sustainable management decisions.

Keywords

Geomorphology; river engineering; suspended sediment transport capacity; aggradation.

Introduction

An understanding of the geomorphic setting of rivers and the effects of past river control works on their current morphology is needed to anticipate how proposed management policies or engineering works will affect current processes and the rivers' sediment transport capacity and future morphology. Such an understanding can inform the choice of management options to minimise the need for future remedial works. Both water and sediment need to be considered, as their interaction determines the morphology of the river channel, a key factor in terms of flood conveyance, land drainage, recreation and habitat.

The current form of the Wairau River system in Marlborough is a result of the interaction between catchment geological processes and the large-scale river engineering works undertaken over the past 150 years. The geologically active catchment and active slope processes, combined with significant rainfall

in the headwaters, produce a large volume of sediment which is transported through the system. The northwest tilting of the geologic block underlying the Wairau River and the deposition of erosion-resistant beach ridges 6000 years ago determined the river setting that European settlers encountered during development of the Marlborough region and Blenheim Township in the mid 1800s.

While there has been wide-scale modification of many rivers throughout the Marlborough region by channel diversions, detention dams, stopbanking, and erosion control works, the Wairau River, which is the largest in terms of flood discharge, is the most highly modified.

Historically, competing River Boards built control structures that effectively transferred flood hazard to other Boards' districts. The two most significant river control works that have affected the Lower Wairau River are the blocking of the Opawa Breach in 1917 and the construction of the Wairau Diversion in 1963.

The blocking of the Opawa Breach, which was effectively the southern channel of the Wairau River, was attempted many times, but in 1917 there was success and the flood hazard was transferred from the main town of Blenheim to the outlying settlements of Tuamarina, Spring Creek and Grovetown. Approximately 50 years later the flood hazard created by the blocking of the Opawa Breach was mitigated with a large diversion channel from Tuamarina to the sea (the Wairau Diversion). This temporarily mitigated the flood risk, but the subsequent redistribution of water and sediment has led to a 1.5 m aggradation of the Lower Wairau, which has again led to an increased flood risk in the Spring Creek, Grovetown, Wairau Pa and Lower Wairau districts. As well as increasing flood risk, aggradation has caused other adverse impacts, including reduced drainage and a reduction in recreation, habitat and environmental quality.

This paper reviews the impact of historical flood control measures on the Lower Wairau River and their effects on channel morphology. Historical cross-sectional data will be used to illustrate the changes to bed levels, channel widths, and bed volumes, and the impacts on sediment transport capacity will be discussed. Results from this study have been used in the design and evaluation of a flow control structure to address aggradation in the Lower Wairau.

Wairau River catchment

The 3825 km² Wairau catchment is located at the northeastern end of the South Island of New Zealand (Fig. 1). The 170 km long Wairau River is the main channel that transports water and sediment through the system.

The headwaters of the Wairau catchment are in the Spenser Mountains, which are the northernmost extent of the Southern Alps, and are bounded by the Richmond Ranges to the north, the Bounds and Raglan Ranges to the south and by the sea to the east.

Strong topographically-controlled rainfall gradients characterise the Wairau River catchment (Rae *et al.*, 1988). The east-to-west annual rainfall variation ranges from 600 mm at the coast up to 1800 mm in the upper reaches of the middle Wairau Valley, increasing to 2400 mm to the southwest in the headwaters. High-intensity thunderstorms are also a feature of the Wairau catchment, with an average of 5 to 10 thunderstorms per year (Simpson *et al.*, 1980). Figure 2 presents a long profile of the river.

Within the mid-Wairau Valley, the Wairau River flows on a wide braided gravel bed over the 75 km from where it emerges from the Raglan and St Arnaud Range to the confluence of the Waihopai. This reach of the river has a slope of 1:200 and flows along the fault-angle depression between the Marlborough Sounds and Awatere geologic blocks. Recent evidence suggests that bed levels are stable in this reach (Christensen, 2005a).

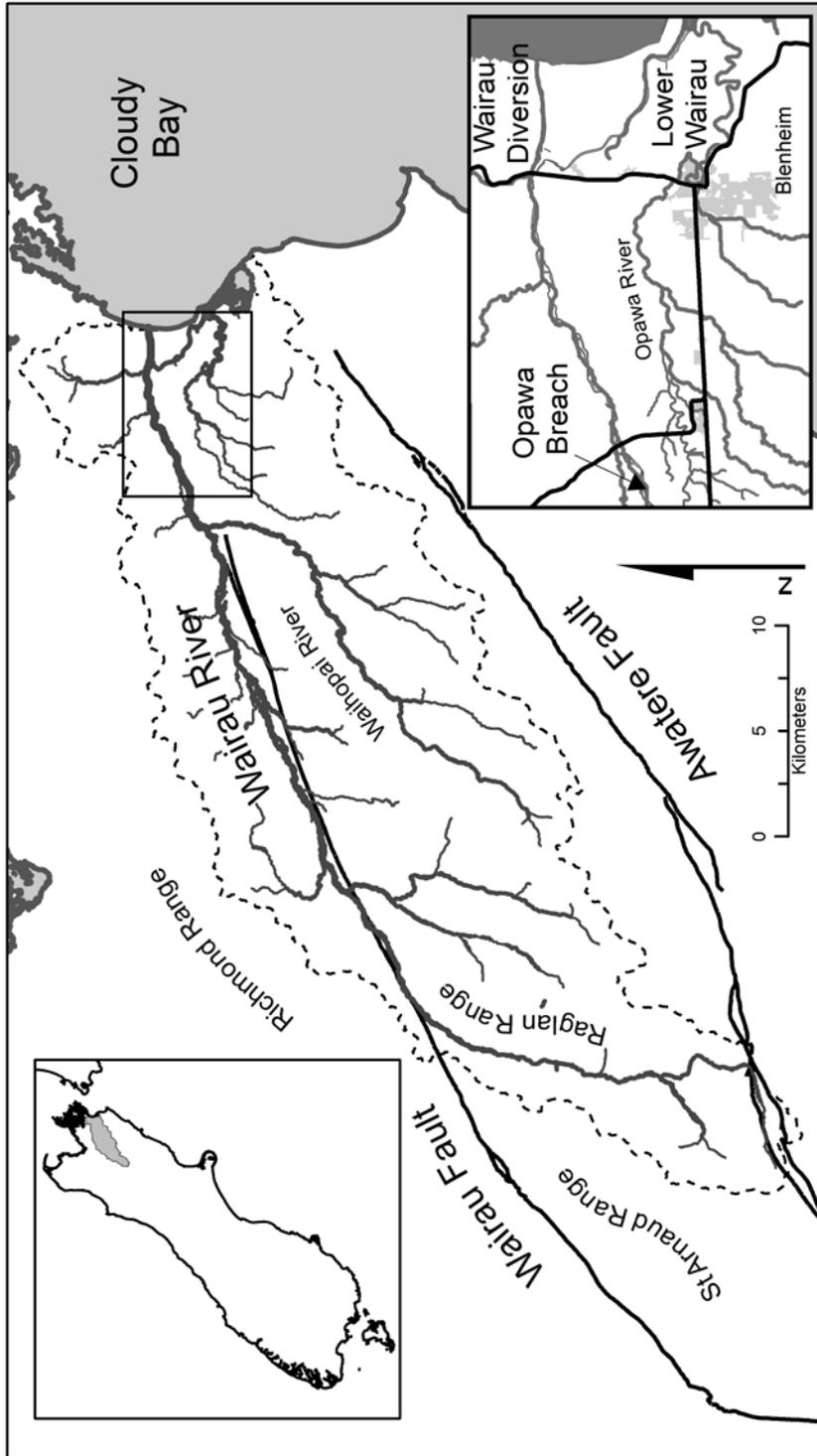


Figure 1 – The Wairau Catchment and Lower Wairau River (after Rae *et al.*, 1988).

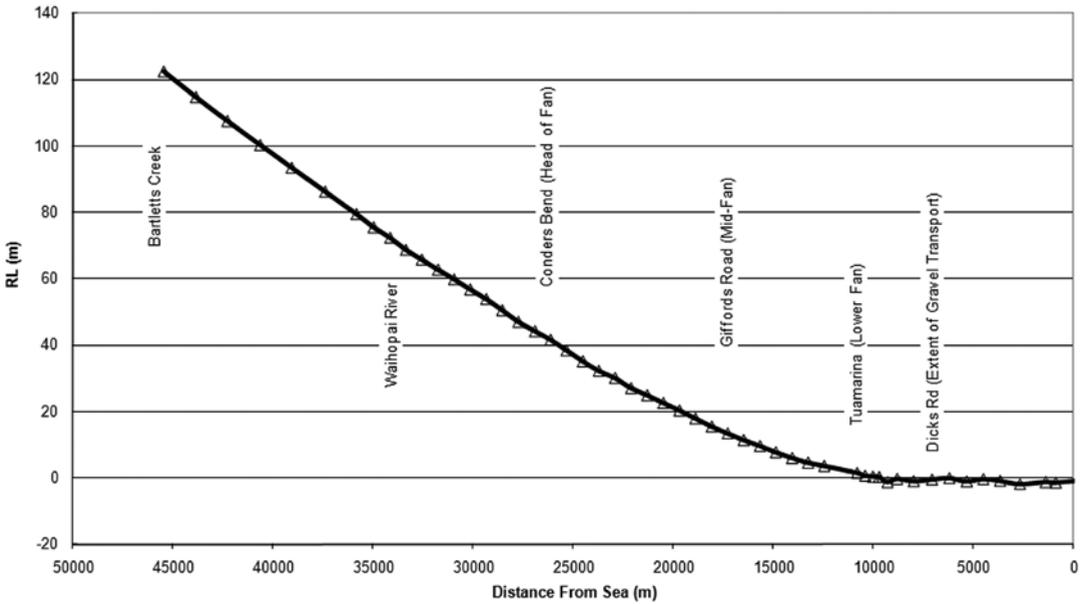


Figure 2 – Long profile of the Wairau River.

Below the Waihopai confluence the Wairau River flows on the northern flank of a 170 km² alluvial fan, originally formed by the

river during the post-glacial and Holocene period (14,000 yrs BP to present) (Rae *et al.*, 1988; Basher *et al.*, 1995). The towns of Blenheim, Grovetown and Spring Creek are located on a mixture of swamp, lagoon and beach deposits (Basher *et al.*, 1995).

The slope of the river decreases from 1:200 to 1:700 from the head of the fan to the bifurcation

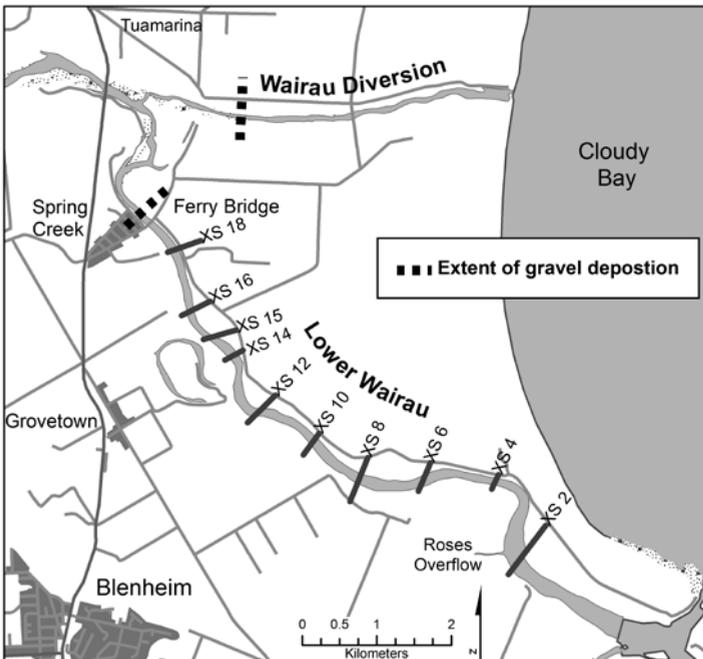


Figure 3 – Detailed map of the Lower Wairau River and the Wairau Diversion, including locations of cross sections.

of the Lower Wairau and Wairau Diversion at Tuamarina. The active, semi-braided, gravel bed channel is generally 400 m wide and is now flanked by vegetated berms and stopbanks, providing a confined floodway width of 800 m. The upstream supply of gravel bedload to the Wairau River deposition zone has been estimated at 70,000 m³/yr, based on the mapped volume of the Raupara Formation created over the current post-glacial/Holocene period (Christensen, 2007).

At the bifurcation of the Wairau River at Tuamarina, the man-made Wairau Diversion cuts a direct path to the sea. It has a flood slope of 1:1000 and a rock-lined active channel of 150 m flanked by 75-m flood berms to give a floodway width of 300 m. From this point, the Lower Wairau River flows in a southeasterly direction for approximately 12 km from the bifurcation at Tuamarina before discharging into Cloudy Bay through the Wairau Bar. The Lower Wairau has a flood slope of 1:2000 and a confined floodway width of 350 m. The permanently wetted, tidal main channel is typically 120 m wide.

The average annual flood in the Wairau River at Tuamarina is 2100 m³/sec and the 1% annual exceedance probability (AEP) flood peak is 5500 m³/sec (Williman, 1995).

Based on analysis of suspended sediment gaugings, Christensen (2007) estimated the annual suspended sediment load at Tuamarina to be 1.8×10^6 t/year. Another published estimate of the suspended load based on geological and hydrological mapping calibrated on catchments with similar characteristics and gauged sediment fluxes is given as 0.84×10^6 t/year (Hicks and Shankar, 2003). However, there is a significant error in this estimate due to underestimation of the Upper Waihopai sub-catchment, where measured dam sedimentation data provides an annual suspended sediment load of 0.83×10^6 t/yr for this sub catchment alone (Christensen, 2005b).

Geomorphic setting of the Lower Wairau River

The Alpine (Wairau) Fault is the dominant tectonic feature of the Wairau catchment and separates the southern and northern sub-catchments, which have distinctive differences in underlying geology. The fault extends through virtually the whole catchment and has experienced 70 m of horizontal and 1.2 m of vertical movement over the past 20,000 years (Simpson *et al.*, 1980). To the south the bedrock is greywacke and argillite, to the north it is schist. The ranges of the southern tributaries, the Waihopai in particular, are extremely steep, with exposed, eroding greywacke surfaces. Because of the active tectonic landscape and substantial rainfall, the river transports a significant volume of sediment. The majority of the sediment (95%) is silt and fine sand transported in suspension.

Over the current post-glacial/Holocene period the Wairau River deposition zone has received approximately 28×10^9 tons of fine-grain sand and silt and 1.4×10^9 tons of gravel (Christensen, 2005a). All of the gravel has been deposited within the landward boundary of Wairau River deposition zone, while most of the fine-grained sand and silt have been deposited out in Cloudy Bay. The gravel-sand transition is located at Dicks Road in the Lower Wairau, and alluvial gravel is present down to the Thomas Road pump station on the Wairau Diversion (Fig. 3). Over time, if the river aggraded sufficiently it could potentially avulse to the southern side of the fan. Presently this is not an issue, as gravel extraction currently exceeds the natural supply rate and the river control works are well maintained.

Two key factors have affected the present morphology of the Lower Wairau River – the first is the northwest tilting of the geologic block on which the Wairau Fan is located. This has encouraged the main Wairau River

to flow on the northern side of the fan. The second factor is the creation of erosion-resistant beach ridges 6000 years ago when sea level was higher than at present. The beach ridges are formed of coarse marine sediments and are of sufficient height and resistance to erosion that the Lower Wairau River has maintained its position without overtopping them for at least the past 2000 years (Pickrill, 1976). The beach ridges are approximately 3 km inland of the present-day coast and were deposited as the sea receded from its maximum level 6000 years ago (Pickrill, 1976).

As a result of geological tilting and the erosion-resistant beach ridges, the Wairau at Tuamarina makes an abrupt 90 degree turn to flow in a southeasterly direction for 12 km as the Lower Wairau River before flowing out to sea at the Wairau Bar, which is also the outlet for the two main lowland rivers (Lower Opawa and Upper Opawa/Roses Overflow) as well as the Vernon Lagoons and Wairau Estuary. This is a key feature of the Lower Wairau system; in the absence of the beach ridges and the geological tilting, it is likely that the Wairau would have flowed directly to the sea.

Historical river control works

There is evidence of river control and drainage works on the Wairau Plain dating back to its first occupants back in the 1100s (Williman, 1994). However, it wasn't until the mid 1800s when the Wairau/Opawa River trade became established and development of the floodplain intensified that large-scale river control works were undertaken.

Flooding was recognised as a significant problem by the early European settlers and the name given to the first trading post, 'The Beaver', was in recognition of the frequent flooding. The desire to protect property from flooding led to large-scale modification of almost every watercourse on the Wairau Plain. The two key works, in terms of their

effects on the Lower Wairau River, were the blocking of the Opawa Breach in 1917 and the construction of the Wairau Diversion in 1963 (see Fig. 1).

The Opawa Breach

Through geological time the Wairau River has occupied portions of the whole flood plain. At the time of European settlement the main channel was located at the northern edge of the floodplain, with overflows occurring into the Opawa River. In April 1861 the Wairau was in significant flood and the flow was divided between its own channel and that of the Opawa (Davidson *et al.*, 1959). This event showed the settlers that the Opawa River was a significant distributary channel of the Wairau River and posed a serious flood threat to Blenheim.

In October of 1861 the Marlborough Provincial Council made their first unsuccessful attempt to block the Opawa Breach with a timber-based groyne. Flooding continued to be a significant problem for the Lower Wairau and Spring Creek Boards, with Blenheim reported to have had nine floods in 11 weeks in 1893, and a large flood in 1904 with an estimated 2000 m³/s flowing down the Upper Opawa – at least half the Wairau flow (Williman, 1994).

In 1914 the Lower Wairau River Board began a clandestine operation to close the Opawa Breach with a groyne of stone and netting. The groyne was nearly completed before it was discovered by a member of the Spring Creek Board and construction ceased. Despite this, by 1917, the Opawa was successfully blocked. Subsequent public unrest led to the creation of the Wairau River Board.

On 9 May 1923 the board faced a major flood when one of the greatest inundations of the Wairau Plains occurred (Thomson, 2002). The flood was more remembered for the serious flooding in the Taylor, Fairhall and Doctors Creek catchments, but it was a

significant event in the Wairau, especially as the main Wairau channel now had to take all the floodwater, with little or no overflow down the Opawa. This event caused significant overtopping and failure of stopbanks in the Wairau and Lower Wairau channels.

The Wairau River Board addressed many of the issues concerning flooding on the Wairau Plains, but the critical flood threat from the Wairau River remained unresolved. The two large floods in June 1954 (5% AEP) and February 1955 (10% AEP) caused substantial damage and turned the public of Marlborough towards replacing the Wairau River Board with the Marlborough Catchment Board (Williman, 1994).

The Wairau Diversion

In January 1956, the Marlborough Catchment Board was formed under the provisions of the Soil Conservation and Rivers Control Act 1941. The Catchment Board was made responsible for the whole Wairau Catchment from 'the source to the sea' and its activities included soil conservation works as well as river control. The Wairau Valley Scheme outlined a 15-year programme with significant capital works, including the construction of the Wairau Diversion to provide an alternative flood path to the sea in Tuamarina.

The construction of the Wairau Diversion began in 1963 with a 10-m-wide (bottom width) pilot channel excavated from Tuamarina directly to the sea. The material excavated was used for stopbank construction. Trenched rocklines were also installed to limit the channel development to the desired design width. The concept of the pilot cut was that natural erosive forces would enlarge the channel from its initial capacity of 700 m³/s to the full design capacity of 3000 m³/s, while enlarging the channel width to 150 m. The natural enlargement occurred much more slowly than anticipated and had to be supplemented by mechanical excavation,

especially of the erosion-resistant beach ridges near the coast, and only reached design capacity in 1998. As the Wairau Diversion developed, flood flows were greatly reduced in the Lower Wairau. The Wairau Diversion has effectively replaced the flow capacity that was previously provided by the Opawa Breach before it was blocked off.

Impact of the Wairau Diversion

While the Wairau Diversion was enlarging and capturing an increasing proportion of flood flows, the Lower Wairau bed was aggrading with fine sand and silt and being reduced in capacity. Up until 1998 the increasing capacity of the Wairau Diversion was greater than the decreasing capacity of the Lower Wairau such that there was a net increase in the combined system capacity. With the Wairau Diversion reaching its design capacity, and further enlargement limited by erosion-control structures, it has remained stable since 1998. However, the Lower Wairau has continued to aggrade at an increasing rate and the system is now not able to pass the 1% AEP flood flow without stopbanks being overtopped. The 1% AEP flood is the specified standard of protection in the Wairau River Floodways Management Plan, a regional plan prepared under section 65 of the Resource Management Act (1991).

As well as affecting the flood flow capacity of the channel, aggradation is also adversely affecting recreation, drainage and water quality. The deposited sediment has reduced the water depth during periods of normal flow and has significantly reduced the volume of the tidal prism. The reduced tidal prism means that contaminants from the numerous rural drains and the Spring Creek waste water plant, which discharge into the Lower Wairau, are more concentrated than they otherwise would have been. The reduced tidal volume has also affected the functioning of the Wairau Bar river mouth, with longshore sediment transport more readily blocking the

mouth, resulting in perched water levels in the Lower Wairau at low tide. The loss of the lower end of the tidal cycle has a significant impact on the effectiveness of gravity drainage for the whole Lower Wairau Plain.

The reduced depth and water quality also adversely affects recreational activities, including rowing, kayaking and water skiing, which require minimum water depths. All of these activities, as well as swimming and fishing, are affected by reduced water quality.

There are also strong Iwi links with the Lower Wairau, particularly around the Grovetown Lagoon and the Wairau Bar.

After 100 years of channel diversions and stopbanking, it is now the management of the sediment build-up resulting from these works that is critical to achieve a suitable level of flood protection while providing for ecological, drainage, recreational, social and cultural values in the Lower Wairau River.

Lower Wairau flow and sediment regimes

The flow characteristics of the Lower Wairau River have changed significantly over the past 100 years. Flood flows and flow exceedance values for the Lower Wairau increased for the 1920–1963 period due to the blocking of the Opawa Breach. Since the construction of the Wairau Diversion in 1963, however, they have been gradually reverting to the approximately pre-1920s state (Christensen, 2007). Changes in flood flows and flow exceedance have a significant effect on sediment concentration, supply and transport capacity.

There have been three distinct flow regime phases in the Lower Wairau River in the recent past (1850–present). At the time of European settlement the Opawa Breach was a significant tributary of the Wairau, flowing on the southern side of the fan and swamp deposits. During floods it typically carried 30–50% of the total Wairau discharge. With the blockage of the Opawa Breach in 1917,

the Lower Wairau now had to pass 100% of the Wairau River flood flow. This significant increase in flows resulted in widespread erosion in the Lower Wairau. This regime remained until the construction of the Wairau Diversion in 1963. When first constructed, the Wairau Diversion took only 20% of flood flows, but it gradually enlarged due to natural erosion and mechanical excavation to now take up to 60% of the Wairau flood flows. Since its construction, aggradation has been observed in the Lower Wairau. The low flow split between the Lower Wairau and Wairau Diversion is dictated by the morphology of the gravel bar around the bifurcation, but this has in the past been mechanically adjusted to ensure that at least 50% of the discharge flows down the Lower Wairau to maintain water quality.

Changes to sediment transport

The sediment of interest in this study is the fine sand-sized particles transported as both suspended load and bedload (depending on the shear stress conditions) before being deposited in the Lower Wairau beyond the downstream limit of gravel deposition (Fig. 3). Samples of sediment deposits in the Lower Wairau River have been analysed to determine a D_{50} of 0.126 mm and a D_{75} of 0.165 mm. Sediment in this size range will be transported through the system in suspension during periods of high flow, but as the flow and velocity diminish particles will fall towards the bed where they may continue to be transported further downstream as bedload before being deposited on the bed (Hicks *et al.*, 2004).

The sediment transport capacity of the Lower Wairau depends on the rate and frequency of flow and the sediment entering the river. These characteristics have changed significantly as a result of channel diversions, firstly increasing then decreasing the flow into the Lower Wairau River.

An increase in flow will increase the depth and, in tidal reaches, also the slope of the water surface, with corresponding increases in shear stress and sediment transport capacity. Decreases in flow will have the opposite effect, resulting in decreases in shear stress.

In New Zealand rivers the suspended load is largely dependent on supply, not capacity (Hicks *et al.*, 2004). However the transport capacity of most rivers diminishes downstream due to the reduction in slope and resultant reduction in shear stress. In the Wairau River the slope decreases from 1:200 in the upper reaches to 1:400 in the middle reaches of the fan and floodplain. In the lower reaches the flood slope is reduced to between 1:900 and 1:1400 for the Wairau Diversion and 1:2000 to 1:3400 for the Lower Wairau River.

The suspended transport rate is likely to be limited by supply for all the reaches of the Wairau except for the Lower Wairau, where transport capacity is the likely to be the limiting factor, particularly during the recession of flood flows. This conclusion is made based on the fact that the Lower Wairau is the only reach where there has been long-term deposition of fine-grained sediment in the active channel. However, this has not always been the case, as evidenced by analysis of the Lower Wairau cross sections from the erosional regime that occurred from the 1920s until 1963.

The suspended sediment concentration in the Lower Wairau has been estimated using the sediment rating curve developed at Tuamarina (Christensen, 2007) and is shown in Figure 4 for flow at Tuamarina up to 2500 m³/s, along with sediment gauging points from a November 2006 flood event.

It is then assumed that sediment splits in proportion to the flow split at the bifurcation with the Wairau Diversion. This is a simplification of what actually occurs, as it has been observed during a sediment and flow gauging that a transverse concentration

profile develops across the bend at the head of the Lower Wairau. As the total Wairau flow increased above 1500 m³/s (Lower Wairau flow ~ 650 m³/s), the transverse pressure gradient supplied by the water surface sloping downwards towards the inside of the bend became significant, with higher sediment concentrations measured on the inside of the bend. However, it has been determined that at Lower Wairau flows greater than 300 m³/s, there will be sufficient shear stress to keep fine-grained sediment in suspension so that it is transported through the system (Christensen, 2007). This determination was made by extracting shear stress data from a calibrated Mike 11 hydraulic model and comparing it to the critical threshold required for suspension of the D₇₅ particle size entering the system. Based on a critical Shields Factor of FS = 0.6 for suspension (FS = 0.1 for initiation of motion), it was determined that there would be sufficient shear stress (1.8 n/m²) during a 300 m³/s flood for a 0.165 mm grain (D₇₅) to be transported in suspension through the Lower Wairau and out to Cloudy Bay.

It is therefore concluded that the increase in sediment concentration that occurs at Wairau flows greater than 1500 m³/s, due to the bend at the head of the Lower Wairau, is not a factor that contributes to the deposition that is occurring. This consideration, as well as the lack of data available to quantify the sediment split, provides justification for using the simplification of assuming that the sediment splits in proportion to flow.

It is likely that the total sediment supply from the catchment has remained relatively constant over this period, although soil conservation plantings in the 1960s and sediment trapped in the Benhopai Dam between 1926 and 1948 may have had a minor impact.

The significant change that has affected sediment transport capacity in the Lower Wairau is that of flow regime.

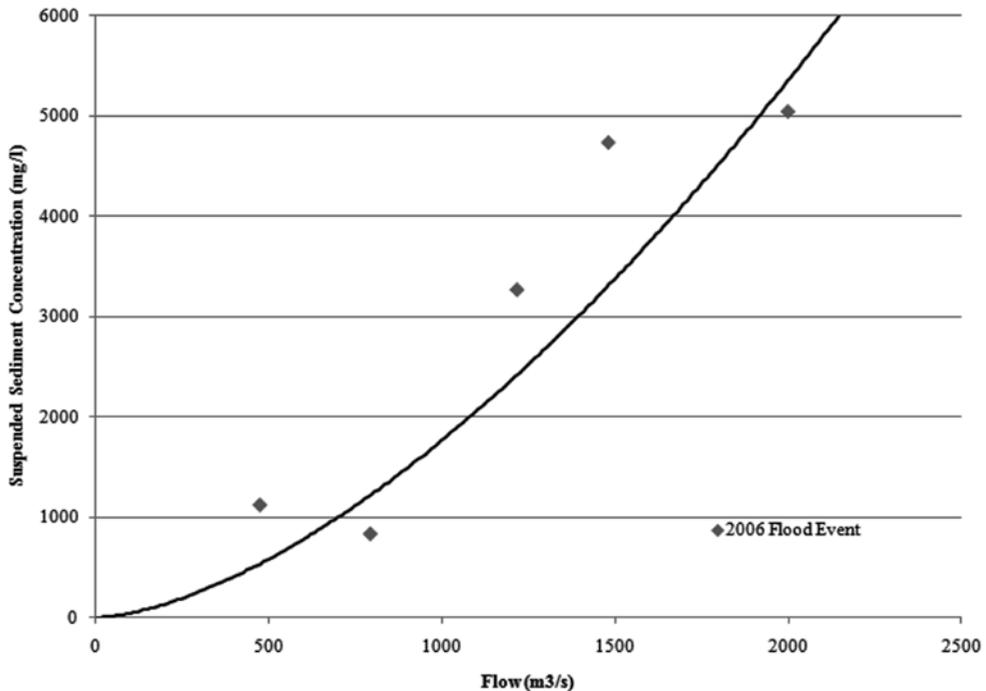


Figure 4 – Estimated suspended sediment concentration rating curve at Tuamarina.

With the Wairau Diversion now capturing over 50% of flood flows, there has been a significant reduction in flows down the Lower Wairau River. The number of days that there is sufficient flow ($> 300 \text{ m}^3/\text{s}$) to keep the D_{75} sediment in suspension and transported through the system has decreased from 18 to 5 (Christensen, 2007). More significantly, the sediment concentration during these periods of likely deposition (flow $< 300 \text{ m}^3/\text{s}$) has increased substantially. Following the blocking of the Opawa Breach and prior to the Wairau Diversion being constructed, the Lower Wairau carried the total river flow, such that a Lower Wairau flow of $300 \text{ m}^3/\text{s}$ had an estimated sediment concentration of 250 mg/l (see Fig. 4). With the Wairau Diversion capturing over 50% of the total Wairau flow, a Lower Wairau flow of $300 \text{ m}^3/\text{s}$ now requires a flow at Tuamarina in excess of $600 \text{ m}^3/\text{s}$. For a total Wairau flow of

$600 \text{ m}^3/\text{s}$, the sediment concentration is over 300% higher, at 850 mg/l .

Morphological changes in the Lower Wairau

Changes in the Lower Wairau will be examined through the lens of cross-sectional data, focusing on channel slope, channel width and bed level changes over the three flow and sediment regimes.

Overview of available cross-sectional data

Historical cross-sectional data were used to gain a better understanding of the impacts of the river control works on channel morphology, particularly channel slope, main channel width and bed volume.

The earliest cross section survey data available for the Lower Wairau River is from a survey in 1927. This survey, however, is

not considered particularly accurate due to uncertainty in the actual locations of the surveyed sections. The next comprehensive survey was in 1957, with surveys also carried out in 1963 and 1967. There is then a significant break in the data due to the focus on monitoring the natural enlargement of the Wairau Diversion. The 1989 survey revealed significant changes, and the Lower Wairau has been surveyed every five years since. The most recent cross section survey was undertaken in October 2004, with sixteen cross sections surveyed over almost the whole of the Lower Wairau. Of these sixteen cross sections, nine could be used for comparative analysis with historical surveys back to 1957 (see Figure 3 for the cross section locations on the Lower Wairau.)

Method of analysis and limitations

The method of calculating bed level changes is based on determining the mean bed level defined between an active channel width at each cross section. This information can then be used to determine the change of area at a cross section between two survey dates. Using the average change of area between adjacent cross sections, the volume of deposited or eroded material between cross sections over a survey period can be calculated.

A significant point to note on using discrete survey data to determine bed volume changes is that none of the changes that occurred between the survey periods are picked up; it is simply the difference in bed volumes at two points in time. Care must be taken in interpreting results from this method, as sediment inflows and outflows are not necessarily reflected in the cross sections (Fuller *et al.*, 2003). Lindsay and Ashmore (2002) note that calculated volumes may be negatively biased when bed changes have occurred between surveys. Though sparsely spaced cross sections provide few insights into the bed level changes (Brasington *et al.*, 2003), the volumes calculated here can

still provide a useful measure of how much material is actually there, but caution is needed in using these data for estimating sediment supply.

Also, the distance between each of the nine cross sections is typically 800 m, so the calculations of bed level changes are assumed to be indicative of that reach of the river, although there may be variation between cross sections due to localised effects. Reach characteristics may be misrepresented when the cross section is on a bend. Scour holes often develop on the outside of bends and beaches can build up on the inside of a bend. Also propagation of meander patterns up or downstream can affect cross section profiles. This is not such a problem with the post-1957 data, but it is one of the reasons that the earliest survey (1927) cannot be used for comprehensive comparative analysis. The timing of the survey, whether before or after a significant flood, can also have a significant effect on the rates of change calculated from deposited or eroded material.

Due to these factors, the changes in bed level and volumes of material should be considered only as estimates. This is, however, the best information available and the method used to analyse this data is considered the most accurate at this time.

The slope of the river channel has been determined by linear regression of mean bed levels within the active channel over the tidal reach of the Lower Wairau.

The river cross sections at the downstream end of the reach have not been included due to the influence of coastal processes.

Erosional Phase – 1927–1963

From around the early 1920s until 1963, the Lower Wairau was in an erosional regime, as 100% of the Wairau flow was entering the Lower Wairau River during this period. Quantifying the erosional rate during this period provides very good information on what can be expected when investigating the

design of flow control structures to erode sediment.

The only cross sections from the 1927 survey that are suitable for quantitative comparison with the more recent datasets are cross section 16 and cross section 14. These sections are located in the straight reach between the Ferry Bridge and the Grovetown Lagoon, which has maintained a relatively constant width and alignment over the survey period. Based on the average changes at cross sections 16 and 14, the mean bed level in this reach decreased by 1.404 m (0.039 m/yr) between 1927 and 1963. This depth of erosion is possibly similar to the current depth of deposition, suggesting that the river may be at a level similar to that prior to the beginning of the 1920s erosional cycle.

The 1957 cross section survey is the earliest full and reliable dataset to quantify bed level changes. Between the 1957 and 1963 surveys,

approximately 385,000 m³ (65,000 m³/yr) was eroded from the Lower Wairau channel. This lowered the mean bed level by 0.271 m (0.045 m/yr). Changes in bedslope for this period are shown in Figure 5 and a typical cross section is shown in Figure 6.

The less certain value of 0.039 m/yr from the analysis of the 1927-1963 period and the more accurately determined value of 0.045 m/yr from the 1957-1963 period give a good indication of the rate of erosion that would be expected if a similar flow regime was created using a flow control structure.

Using the mean bed level data from the accurately surveyed and located 1957 and 1963 surveys to determine the river slope shows a flattening of the slope from 1:13,000 to 1:50,000. The approximate slope in 1927 was 1:3,000. The flattening of bed slope is a typical response in an erosional channel regime where sediment transport capacity exceeds supply and the bed is erodible.

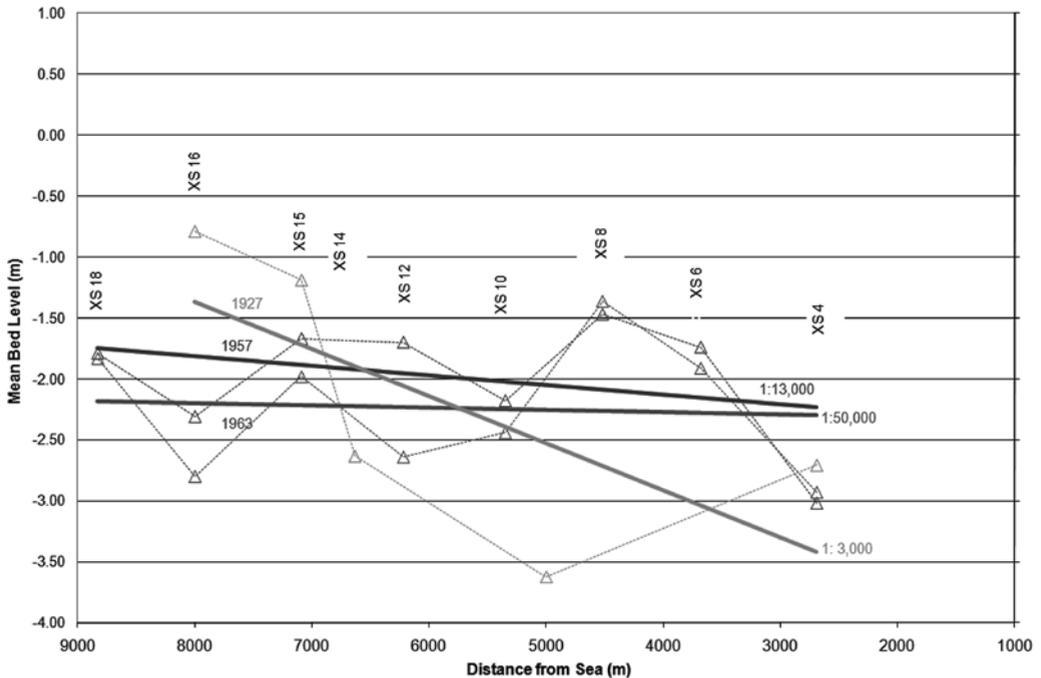


Figure 5 – Change in Lower Wairau bedslope – erosional phase (1927-1963).

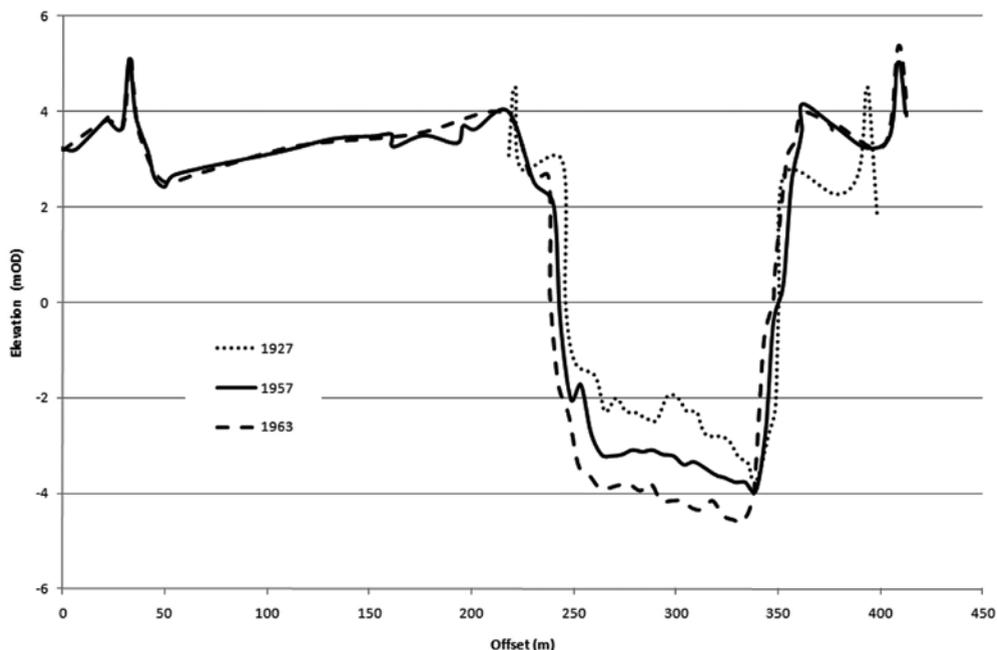


Figure 6 – Typical Lower Wairau cross section 1927-1963 (erosional phase).

Aggradational Phase – 1963-2004

The Lower Wairau River has been in an aggradational phase since 1963, which coincides with the opening of the Wairau Diversion. Since the beginning of this phase the total volume of material deposited downstream of the Ferry Bridge is estimated at $1.9 \times 10^6 \text{ m}^3$ (50,000 m^3/yr). Assuming a density of 1.2 t/m^3 , this deposition accounts for 8% of the total sediment supplied (800,000 t/yr) to the Lower Wairau, with the remaining 92% passing through the system and being deposited into Cloudy Bay. The deposition in the Lower Wairau has resulted in the mean bed levels in this reach increasing by 1.5 m (0.032 m/yr).

The whole reach of the Lower Wairau from the Ferry Bridge to the Roses Overflow confluence has aggraded over this period, with slightly greater deposition occurring upstream of the Blenheim Rowing Club at cross section 8 (Fig. 3). Figure 7 shows the bedslope changes in this phase, while Figure 8

shows a typical cross section in the aggrading reach.

The rates of change in terms of bed level over all phases are graphically presented in Figure 9.

The aggradational phase has seen the slope of the channel increase from 1:50,000 to 1:10,000 in 1989 and 1:5000 since 1999. The steepening of the channel slope through aggradation is a typical response where the sediment supply exceeds the sediment transport capacity of a river reach.

As well as the changes in bed levels and slope, the width of the channel has also changed. In the lower reaches of the Lower Wairau, the channel width has reduced by an average of 40 m since 1963. In the upper reaches the width has reduced by approximately 10 m over the same period.

The width of the channel is also important in determining sediment transport capacity, with narrower channels in the sand/silt phase typically providing greater sediment transport

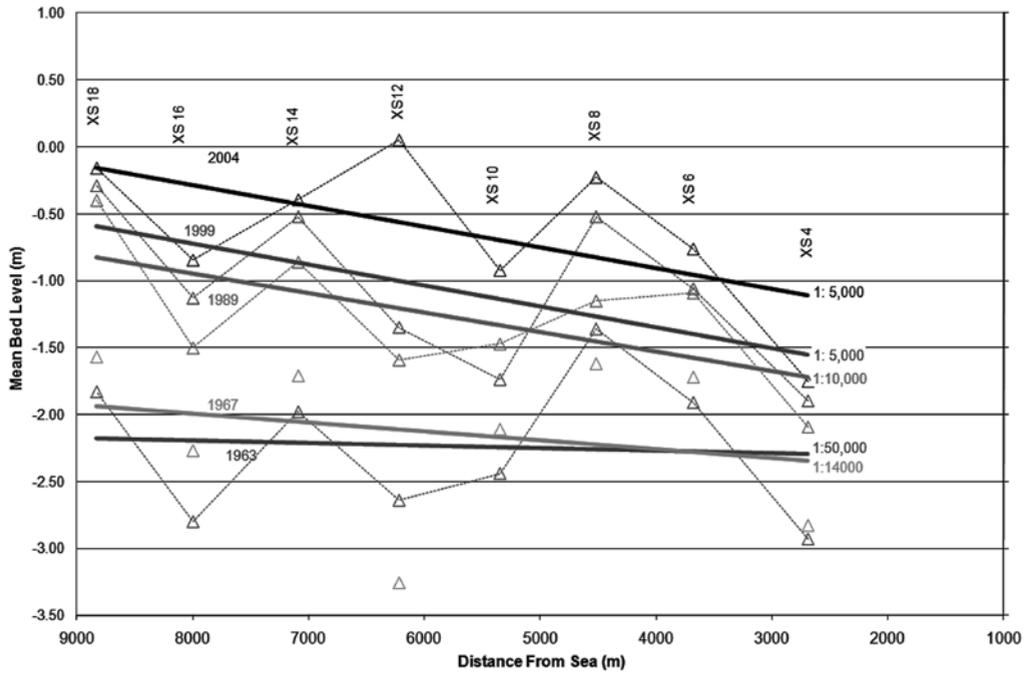


Figure 7 – Changes in Lower Wairau bedslope – aggradational phase (1963-2004).

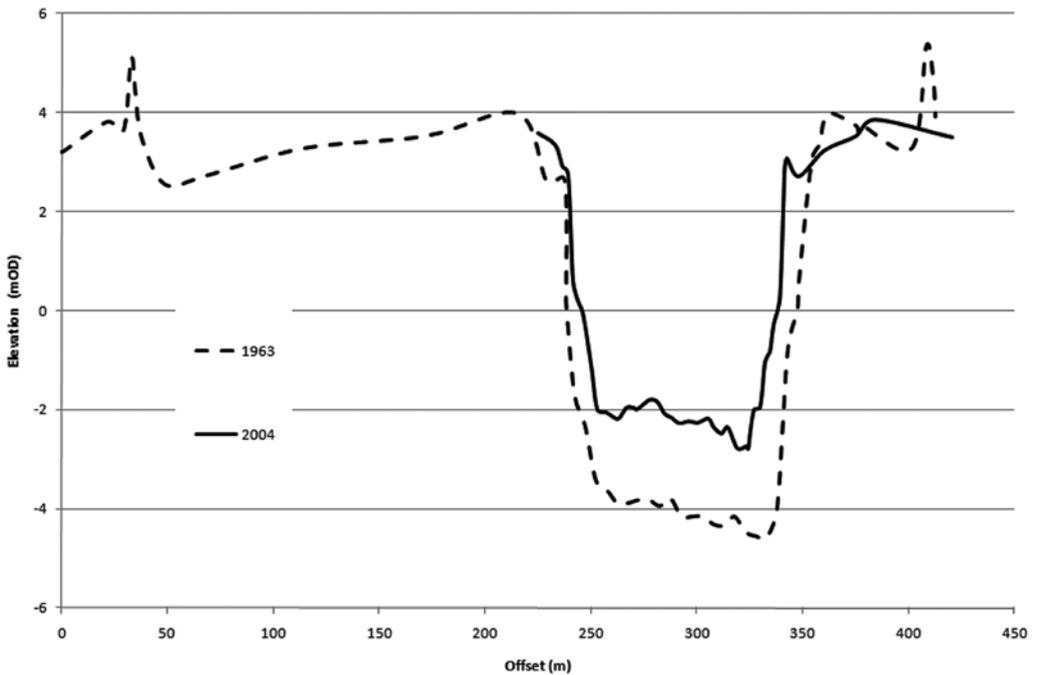


Figure 8 – Typical Lower Wairau cross section 1963 – 2004 (aggrading phase).

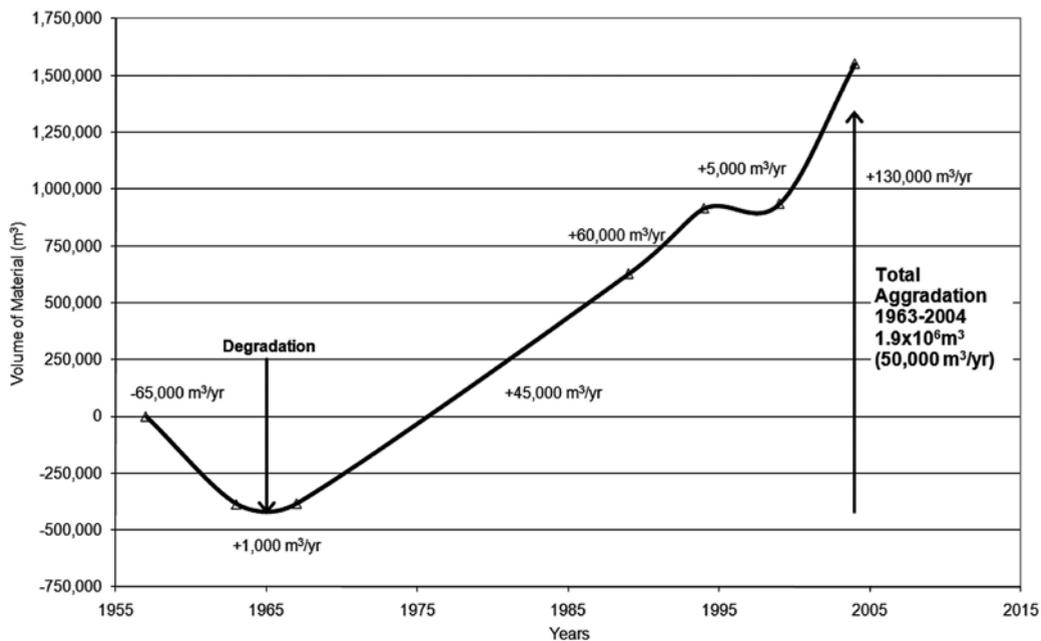


Figure 9 – Cumulative linear changes in the Lower Wairau river bed.

capacity. The opposite is generally true in the gravel phase of a river, but there are arguments and examples for both sides. The reductions in width should theoretically increase the average velocity and therefore shear stress, but the reduction in width could also amplify any deposition that is occurring. The deposition that has occurred over the period where the channel has narrowed suggests that the channel narrowing has not been sufficient to compensate for the reduction in sediment transport capacity resulting from the Wairau Diversion.

Summary of bed level changes

The present well quantified aggradational phase in the Lower Wairau River has seen nearly $2 \times 10^6 \text{ m}^3$ of sediment deposited over the 10 km tidal reach of the channel. This has raised the average bed level by 1.5 m, or on average 0.32 m/year, since 1963. Changes over the 1927=2004 period are summarised in Table 1.

The erosional phase is less accurately quantified due to the lack of survey data and uncertainty over survey locations, but erosion, possibly of a similar extent and at a similar rate, occurred from 1917 through to 1963. Within the limitations of the data, particularly pre-1927, the best estimate of the rate of erosion during this period is 0.035 myr.

It is also interesting to note the significant variation in the rates of aggradation over the past 15 years, with the highest rate of aggradation during the recent survey period (1999-2004), but the preceding period (1994-1999) showing the lowest rate. The reasons for this are related to sediment supply and/or flow regime.

The river flow over the two periods also differed significantly, with the 1994 to 1999 period (Fig. 10) having 12 freshes over 1500 m^3/s and the significant July 1998 flood of 3800 m^3/s , compared with the 1999-2004 period (see Fig. 11) with only

Table 1 – Summary of bed level changes and rates of erosion or deposition

Period	Total bed level change (m)	Annual rate of change (m/yr)	Total volume deposited (+) or eroded (-) (m ³)	Annual rate of deposition (+) or erosion (-) (m ³ /yr)
1927-1957	- 1.002*	- 0.033*	N/A	N/A
1957-1963	- 0.271	- 0.045	- 385,000	- 65,000
1963-1967	+ 0.056	+ 0.015	+ 4,000	+ 1,000
1963-1989	+ 0.782	+ 0.035	+ 1,000,000	+ 45,000
1989-1994	+ 0.173	+ 0.036	+ 290,000	+ 60,000
1994-1999	+ 0.048	+ 0.010	+ 20,000	+ 5,000
1999-2004	+ 0.428	+ 0.090	+ 615,000	+ 130,000
Erosional phase (1917-1963)	- 1.610**	- 0.035**	N/A	N/A
Depositional phase (1963-2004)	+ 1.500	+ 0.032	+ 1,900,000	+ 50,000

* Based on average measured changes at cross sections 16 and 14.

** Based on average of 1927 – 1963 annual rate

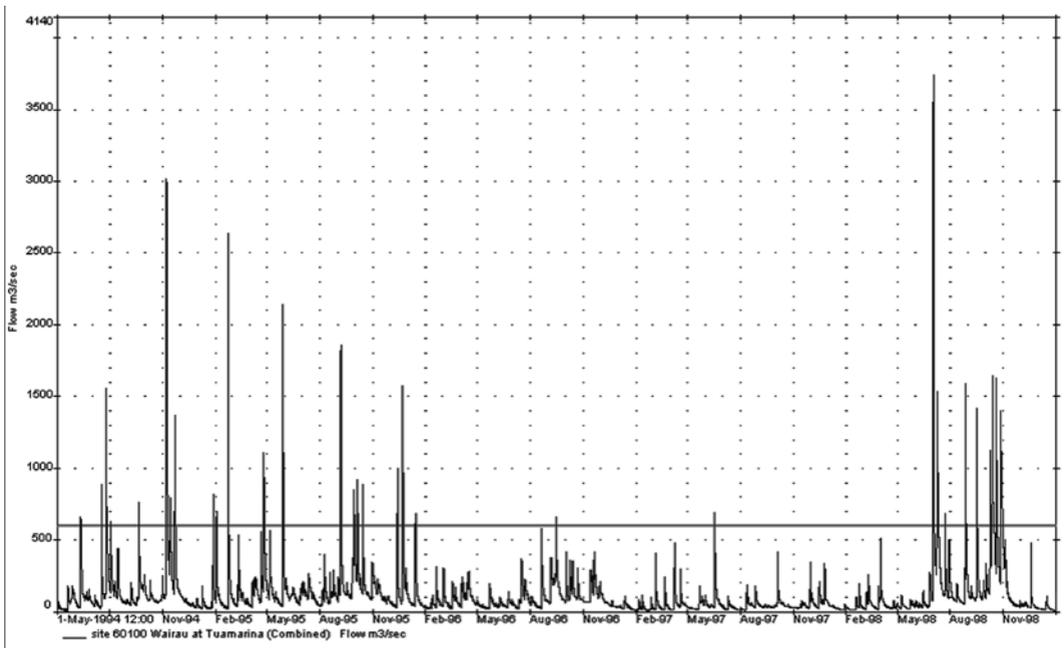


Figure 10 – Wairau River flow at Tuamarina 1994-1999.

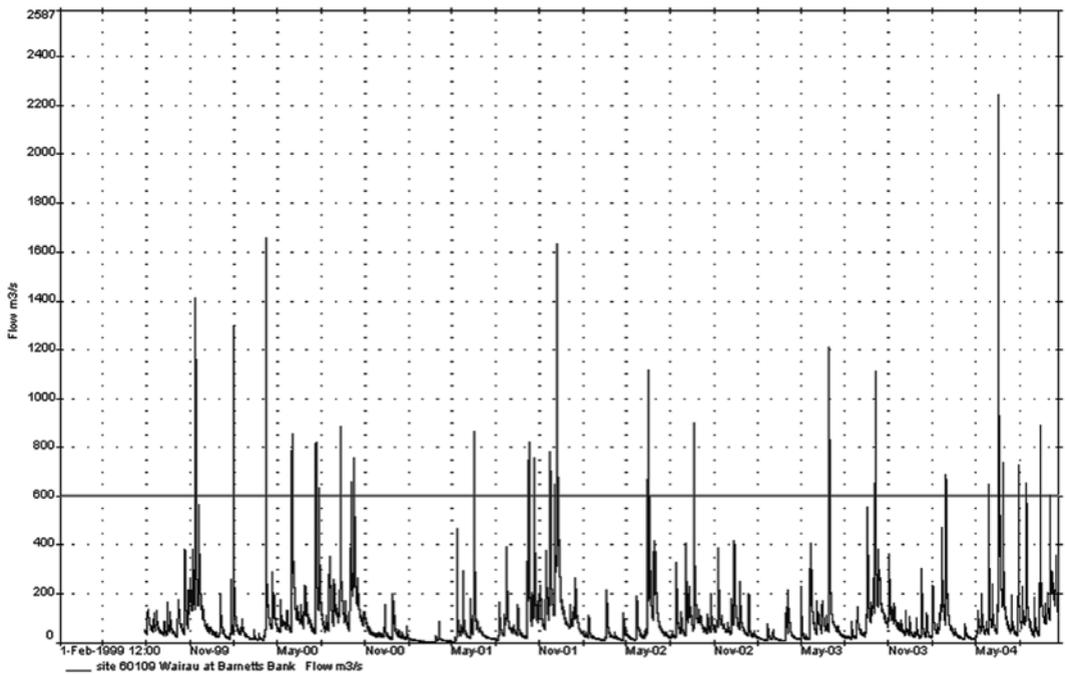


Figure 11 – Wairau River flow at Tuamarina 1999-2004.

three events greater than $1500 \text{ m}^3/\text{s}$ and a maximum of just over $2000 \text{ m}^3/\text{s}$. Another significant statistic is the percentage of time the river flow was greater than $600 \text{ m}^3/\text{s}$ (shown as a horizontal line in Figures 10 and 11). This is the flow that would be required to have approximately $300 \text{ m}^3/\text{s}$ in the Lower Wairau, which is estimated to be the flow required to keep suspended sediment entrained (Christensen, 2007).

During the 1994 to 1999 period, the flow in the Wairau was greater than $600 \text{ m}^3/\text{s}$ ($\sim 300 \text{ m}^3/\text{s}$ in the Lower Wairau) for approximately 42 days, compared with only 20 days for the 1999 to 2004 period. The period of time the critical flow for sediment transport is exceeded gives a good indication of the total sediment transported over that period. Conversely, the time that the critical flow is not exceeded gives a good indication of the likely deposition that could occur over that period.

Looking at the longer term change in bed levels, it could be suggested that the Lower Wairau is returning towards the level it was prior to the Opawa Breach being closed (see Figs. 5 and 6), although it is likely that the Wairau Diversion takes a greater proportion of Wairau flow than the Opawa Breach typically did. However, it is recent changes (in the past 10-15 years) that set the standards for evaluating recreational, ecological and flood hazard effects.

It is also likely that the present aggradational cycle will continue into the future, resulting in further reductions in flow and further reinforcing the aggradational cycle. The rate of future aggradation will depend on the sediment supply and the flow regime, but based on the past 40 years of data, it is likely that bed levels will aggrade by approximately 0.032 m per year.

The 1927 and 2004 bed levels appear to be very similar, as could be expected with the

flow regime being about the same as it was before the Opawa Breach was blocked off.

Design and construction of an erodible flow control structure

The current aggradational cycle is causing a number of problems, including increasing flood hazard, reducing water quality, limiting recreational opportunities and impairing drainage. A number of options were considered, including doing nothing, raising the stopbank, mechanical control gates, dredging, or the use of an erodible gravel embankment to control flows. These options were assessed and an erodible gravel embankment to control flows and induce erosion (Fig. 12) was selected as the optimum solution, based on its economic, environmental and social attributes, as well as future sustainability.

The erodible gravel embankment has been designed to divert a greater proportion of flow down the Lower Wairau during small floods, with the aim of flushing out deposited sediment. During larger floods it could be overtopped and eroded to allow both the

Lower Wairau and Wairau Diversion to be fully utilised for carrying flood flows.

The design of the erodible gravel embankment was analysed in detail using a numerical sediment transport model linked to a hydraulic model (Christensen, 2007).

A range of predicted erosion rates were determined from the modelling, but comparison with the estimated rate between 1927 to 1963, when there were higher flows in the Lower Wairau, suggested that predicted erosion rates with the erodible gravel embankment in place would likely be at the lower end of the range. Based on a lower range estimate of the rate of erosion, and combined with flood berm and stopbank improvement works, it was estimated that it would take at least 20 years for the Lower Wairau channel to enlarge sufficiently to achieve the required flood control standard and meet the recreational, ecological and drainage objectives.

The results of the analysis and design work were sufficiently positive and conclusive to warrant a trial period of embankment operation. Resource consent was granted in

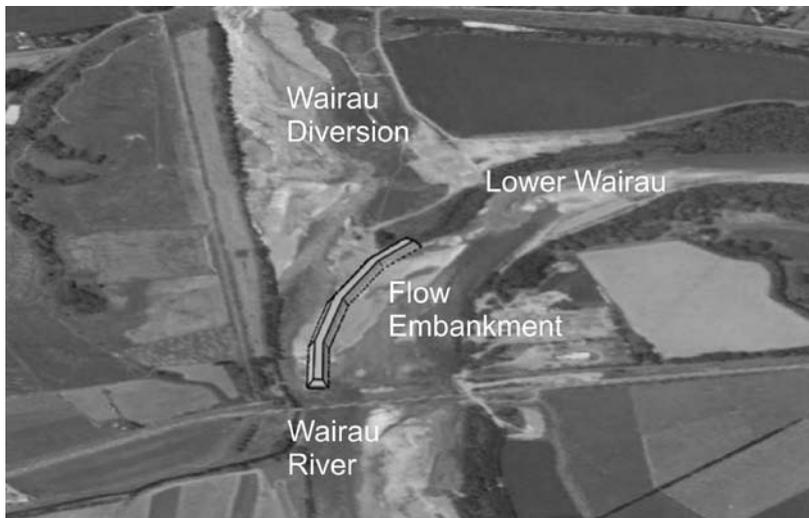


Figure 12 – Location of flow control embankment at the bifurcation of the Lower Wairau and the Wairau Diversion.

July 2009 and construction was completed soon after in August. On 26 August 2009 a small fresh of 690 m³/s occurred and the embankment performed as intended, diverting 71% of the total flow down the Lower Wairau, with the remaining 29% flowing down the Diversion. The peak water level was approximately 1 m below the crest of the embankment.

On 31 August another small flood occurred, causing the embankment to overtop and erode as intended. The erosion occurred very quickly and the within 30 minutes a substantial flow was occurring through the breach and into the Wairau Diversion (Williman pers com., 2010). The small flood peaked at 1130 m³/s and the design levels were shown to be overly conservative. The embankment was reconstructed with a crest 350 mm higher than the initial design. Another small flood occurred on 7 June 2010, which peaked at 1300 m³/s and came within 50 mm of overtopping the embankment without causing the berms of the Lower Wairau to flood. This event confirmed that the embankment height is optimised for the present state of the Lower Wairau.

It will take a number of years of operating in this manner, with reconstruction following each failure, to determine whether the Lower Wairau is enlarging as predicted by the numerical modelling and morphological analysis. The next bed level survey of the Lower Wairau is scheduled for 2014-15. If this survey shows that erosion of the deposited sediment has occurred, then the height of the embankment can be further increased to provide greater sediment transport capacity in the Lower Wairau.

Conclusions

The geomorphic setting of the Wairau River made it difficult to provide flood protection for the early European settlements. Large-scale river engineering works of the past 150

years have fallen short of providing a long-term solution that meets the communities' requirements. The changes in flow regime resulting from the blocking of the Opawa Breach and the subsequent construction of the Wairau Diversion have had a significant effect on sediment supply, sediment transport capacity and the channel morphology of the Lower Wairau River. The blocking of the Opawa Breach increased flows, increased sediment transport capacity, decreased sediment supply from minor floods and resulted in channel erosion and flattening of the channel slope. The construction of the Wairau Diversion had the opposite effect, with reduced flows, reduced sediment transport capacity and increased sediment supply for minor floods, and it resulted in channel aggradation and narrowing, with a steepening of the slope.

An erodible gravel embankment has now been constructed which diverts a greater proportion of flow down the Lower Wairau during small floods in an attempt to flush out the deposited sediment and enlarge the channel. It will be a number of years before it will be possible to determine whether this solution has been effective.

Acknowledgements

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