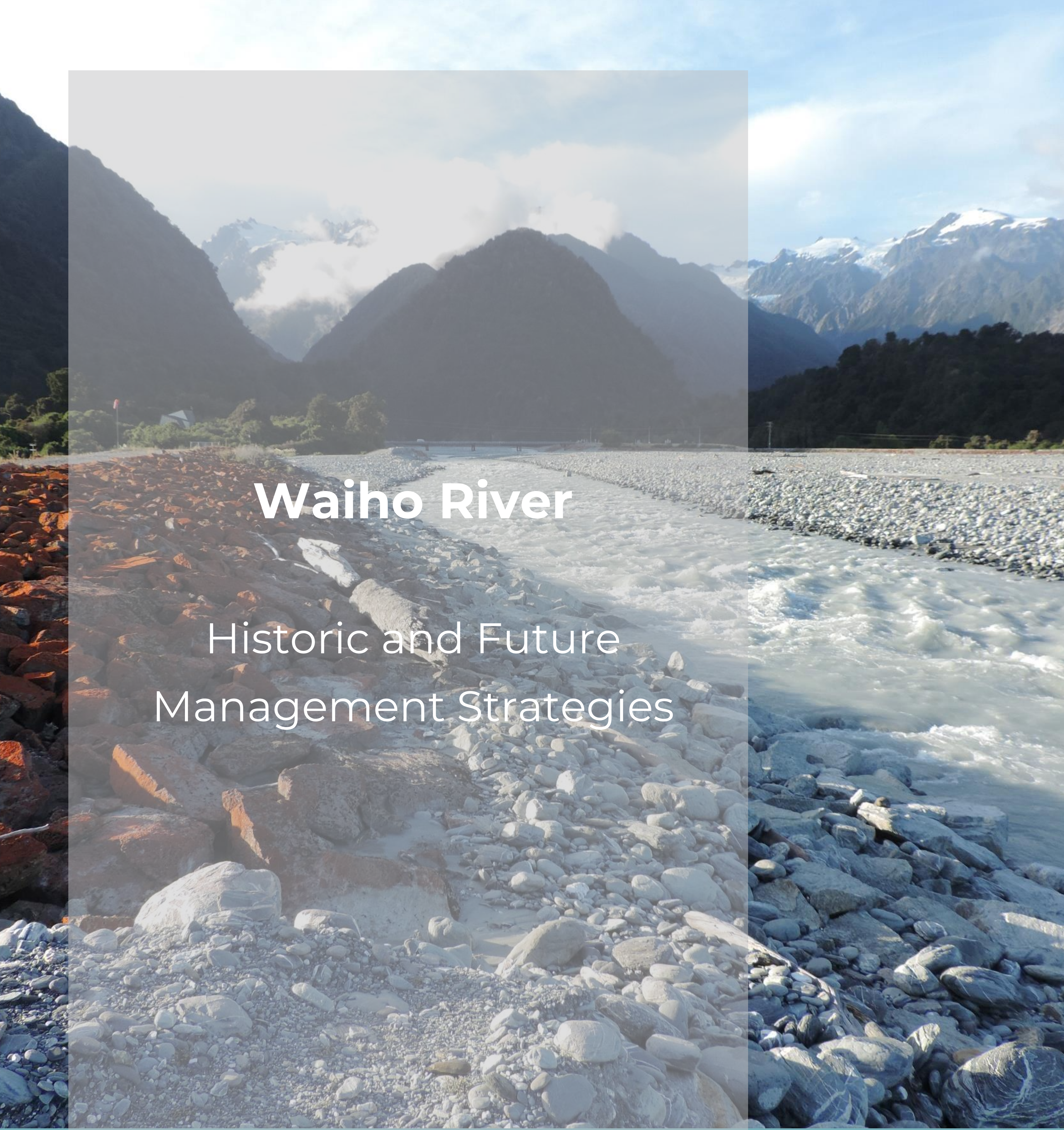

Waiho River

Historic and Future Management Strategies

10-Oct-23

Client: West Coast Regional Council

Report by: Rose Beagley & Matthew Gardner
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THE WEST COAST REGIONAL COUNCIL

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EXECUTIVE SUMMARY

Land River Sea Consulting has been contracted by the West Coast Regional Council (WCRC) to summarise the hazards posed by the Waiho River to the Franz Josef township, oxidation ponds, State Highway 6 (SH6), and surrounding community, and the historic management of these hazards; as well as provide recommendations for future management of the river.

FRANZ JOSEF TOWNSHIP AND SURROUNDING AREA

The Franz Josef township and surrounding area is home to a small community that relies largely on tourism and dairy farming for its livelihood. Tourists are drawn to the area for its very high environmental value which includes Te Wahipounamu and the Franz Josef Glacier, whilst the foreland plains between the Southern Alps and Tasman Sea provides a large area of land for dairy farming and other agricultural uses.

The only access by car to the Franz Josef area is via the SH6 which is closed on occasion due to small landslides and bridge wash outs, which can isolate the community and be detrimental to revenue as it prohibits access to tourists. As a result of its small population, the funds available from rates, even with district, regional and central governmental support, are inadequate to maintain and upgrade the stopbank network that protects the community from the hazards posed by the Waiho River.

GEOMORPHIC BACKGROUND

The Waiho River is a very dynamic and powerful bedload dominated river that experiences frequent high flow flood events. From where it departs the mountains it has formed a steep alluvial fan that is partially (and naturally) blocked at its downstream end by the Waiho Loop – a terminal moraine wall, and to the south by Canavan's Knob.

Since at least 1948, the river has become increasingly active and braided, occupying a far greater area of its fan surface than what it did in the early 20th century. Furthermore, the river has been increasing the elevation of its fan surface through deposition of its bedload (aggradation – a natural process), however since the 1970's, the rate of vertical increase in elevation has been occurring at a much faster rate than before. This behaviour is believed to be the product of confinement of the river at its fan head by the protection network, which restricts it from accessing two thirds of its fan surface.

As a result, the fan surface has now reached unprecedented levels, such that the Waiho River has already started to change paths (avulse) to the north into the Tatare valley. The consequences of a full avulsion for the upstream farmland, oxidation ponds, SH6, protection structures and Franz Josef township, though not easily predictable, are high, as is the continued pressure on the entire network from the increasing fan surface elevation.

HISTORIC AND CURRENT MANAGEMENT STRATEGY

The management strategy for the Waiho River, has always been one of control through protection structures such as stopbanks (otherwise known as levees, dykes, or flood embankments), rock gabions, revetments, and groynes. The construction of significant structures started in the 1970s; undertaken by the state roading authority and the West Coast Catchment Board.

The present day network is owned and managed by several agencies, and bounds the very active fan surface on the true left (south, herein) from just upstream of the SH6 bridge down to just below the Waiho Loop, and on the true right (north, herein), from just upstream of the SH6 bridge to just below the oxidation ponds.

Over the last five decades, the network has experienced repeated damage during flood events, and although the stopbanks been repaired and raised multiple times to keep up with the rapidly aggrading fan surface, the relatively new stopbanks downstream of Canavan's Knob are already threatened.

CHALLENGES OF CONTINUED CONFINEMENT

If the current management strategy is continued and the river remains confined to just one third of its fan surface, the network will face an array of challenges. These include:

- A decreasing stopbank capacity to handle flood events as a result of the aggrading fan surface;
- The risk of a full avulsion of the Waiho River into the Tatare Stream and the consequences for the upstream land and infrastructure;
- The increasing vulnerability to breach and/or overtopping of the Waka Kotahi stopbanks on the south side, between the SH6 bridge and Canavan's Knob; and
- The increasing vulnerability to breach and/or overtopping along the stopbank from Canavan's Knob down to Rata Knoll and at the highly confining rock lined Milton's stopbank.

RELAXATION OF THE BOUNDARIES RATIONALE

The option of relaxing the southern boundary of the Waiho stopbank protection network is based on over forty years of extensive reports and studies investigating the aggradational behaviour of the river, and modelling of the response of a river to confinement and changing width.

Traditionally, confinement of a river has been designed to increase the depth of flow, thereby increasing transport capacity, and subsequently promoting degradation. However, downstream of the mountains the Waiho River has formed a depositional fan that has a braiding character and is now confined from the Callery confluence to downstream of the Waiho Loop on the south side and to the oxidation ponds on the north side. This confinement prevents the Waiho River from laterally migrating across its natural fan surface, whilst reducing the surface area available to deposit sediment.

A microscale model study of the Waiho system and stopbank network has shown that the rate of vertical sediment deposition decreases when the modelled river was given access to a greater portion of its fan surface. A mechanism and response which was replicated in a more recent numerical model study. Therefore, whilst relaxation of the southern boundary will not stop the volume of sediment accumulating on the Waiho fan, it is likely to slow down the rate at which this sediment accumulates vertically i.e. it will slow down the vertical increase in bed surface elevation.

Even if the southern stopbanks are retained, there is a high chance the Waiho River will break out to the south by itself, with catastrophic consequences, involving loss of life, livestock, and property. A managed removal of the stopbanks and controlled release of the river will reduce the likelihood of these consequences occurring.

IMPACT OF RELAXING THE SOUTHERN BOUNDARY

The relaxation of the southern boundary option involves the removal of all of the south side stopbanks, with the priority being the removal of the Waka Kotahi stopbanks between the SH6 bridge and Canavan's Knob, and then the removal of Milton's and the Rubbish Dump stopbanks.

This will reduce the pressure on the north side stopbanks and the likelihood of the Waiho River avulsing into the Tatare Stream in the immediate future, and provide the Waiho River access to its entire fan surface and lower flats on which it can then deposit its high bedload.

However, there are significant financial costs to this option. The dynamic and braided nature of the river means that it will continue to shift around even once flowing to the south, placing the entire land to the south at risk of scour and deposition of gravels and sediment. Further, hydraulic model results with the stopbanks removed have shown that a considerable portion of this land will be underwater during an estimated 1 in 100 year annual recurrence interval flood event.

Thus, this option requires the buyout of all of the land to the south of the Waiho River, the removal of all infrastructure, and the realignment of the SH6.

RECOMMENDATIONS

Relaxation of southern boundaries

Based on the extensive reports and scientific papers that have investigated the Waiho River, and our understanding of its likelihood to continue to aggrade into the future, we recommend a release of the Waiho River to the south.

This will give the Waiho River access to its entire fan surface. In doing so, the horizontal spread of sediment will be increased, slowing down the rate of the vertical increase in height from the aggradation. This will also serve to reduce the pressure along the north side network which protects the township, heliport, and oxidation ponds, as well as reduce the likelihood of an avulsion into the Tatare valley, but given the aggraded state of the Waiho fan, does not rule this out.

Ultimately, the relaxation of the southern boundary will provide time to relocate the township, heliport, and oxidation ponds out of harm's way.

Management of north side stopbanks

Due to the very high consequence should the heliport stopbank fail or overtop, urgent consideration needs to be given to the relocation of the Heliport, especially with the stopbank being raised by an additional 2m, further increasing the consequences should it fail.

Engineering works to prevent a permanent avulsion into the Tatare are likely to be expensive as well as futile in our professional opinion now that a partial avulsion has significantly developed. Consideration could be given to ongoing physical channel works to divert the main braid to the south side, to attempt to delay a permanent avulsion. However, this will only be temporary and likely overwhelmed every time there is a fresh in the river. Therefore, consideration may need to be given to bringing forward the relocation or replacement of the oxidation ponds with an onsite treatment plant as had been previously proposed prior to 2016.

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1. INTRODUCTION

1.1. SCOPE

Land River Sea Consulting Ltd have been contracted by the West Coast Regional Council (WCRC) to:

- Summarise the hazards posed by the Waiho (Waiau) River to the township of Franz Josef and the surrounding community (Figure 1-1); and
- Provide an overview of the historic and current management strategies for these hazards, and recommendation/s for long term and sustainable future management.

Figure 1-1 - Waiho River downstream of its junction with the Callery River, with the township of Franz Josef on the north side and surrounding farmland, community and SH6.

1.2. PREVIOUS REPORTS AND STUDIES

The Waiho River system has been studied extensively since at least 1983 in an attempt to better understand the behaviour of the river and the risks it poses to the Franz Josef township, SH6 and bridge, oxidation ponds and farming community.

A list of all the reports, modelling studies, theses, and scientific papers known to us has been compiled into Appendix A.

2. FRANZ JOSEF TOWNSHIP AND SURROUNDING AREA

Franz Josef is a small town on the West Coast of the South Island of New Zealand approximately 135km south of Hokitika and 145km north of Haast. It lies within the 2.6 million hectare UNESCO-recognised World Heritage site, Te Wahipounamu, and is the local tourist hub for the Franz Josef Glacier – a major South Island attraction.

The township has a resident population of 510 people, but the day-to-day number is much higher as a result of a high tourist flow, with the visitor night to resident ratio estimated to be around 2.9:1 (i.e. 2.9 visitors for every 1 resident)(Tonkin+Taylor and EY, 2017). The township provides services for the local agricultural industry, and smaller communities either side of the river between Potters Creek to the north and Docherty Creek to the south.

The area is administered by the West Coast Regional Council and the Westland District Council, with the WCRC having two rating districts – A and B (Figure 2-1). These rating districts were created in order to maintain the flood and erosion protection works that have existed on the Waiho River since the 1950's (West Coast Regional Council, 2023). However, given the small populations in these districts, funds for ongoing maintenance and further works are limited.

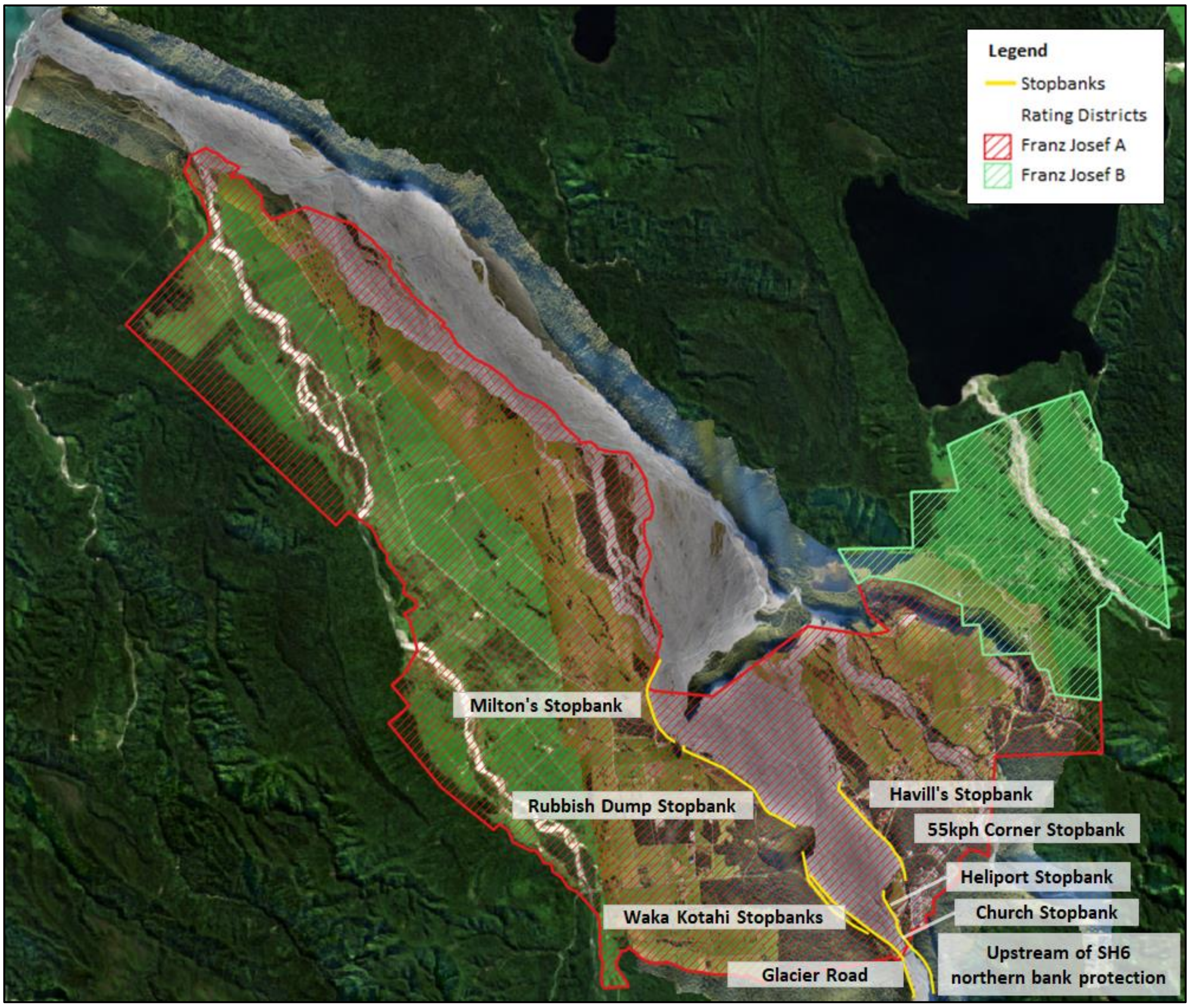

Figure 2-1 – Franz Josef rating districts A and B, and stopbank names.

2.1. ACCESS

The only access by car to Franz Josef, is via the State Highway 6 (SH6) which passes through the township before crossing the Waiho River 750m downstream of its junction with the Callery River (Figure 1-1). It is the main and only traffic artery along the length of Westland and is vital to the economy of the township and area, providing the only means by which town supplies, tourists, residents, and agricultural produce can move.

On occasion the highway is closed for up to a few days or even weeks at a time due to small landslides and bridge washouts. For example in March 2019 the SH6 bridge over the Waiho River was washed away during a flood. It took several weeks for the bridge to be repaired, with diggers and helicopters utilized to transport supplies, people and even cars across the river. During this time, visitor numbers to the area plummeted, highlighting the importance of this highway and its susceptibility to damage by the Waiho River.

2.2. INFRASTRUCTURE AND UTILITIES

Within the Franz Josef township area, there are approximately 144 properties comprising one- and two-storey residential and commercial buildings (Tonkin+Taylor and EY, 2017). These properties have a capital value of around $113 million, with the wider area from Docherty Creek to Potters Creek providing an additional $76 million in value (Tonkin+Taylor and EY, 2017). Included in this count are a volunteer fire station, Department of Conservation workshop and fire depot, petrol station (and underground storage tanks), community hall, police station, health centre, Catholic and Anglican churches, kindergarten, and primary school.

The township runs on a centralised town potable water supply, wastewater and stormwater network which includes the wastewater treatment oxidation ponds on the edge of the Waiho River (Figure 2-2). It receives electricity from the national grid in Hokitika via the Westpower 33 kV line, with generation capacity on this line at Wahapo Lake (16km north of the town) provided by Trustpower (Tonkin+Taylor and EY, 2017).

There are also two telecommunication towers within Franz Josef which provide all major mobile companies coverage.

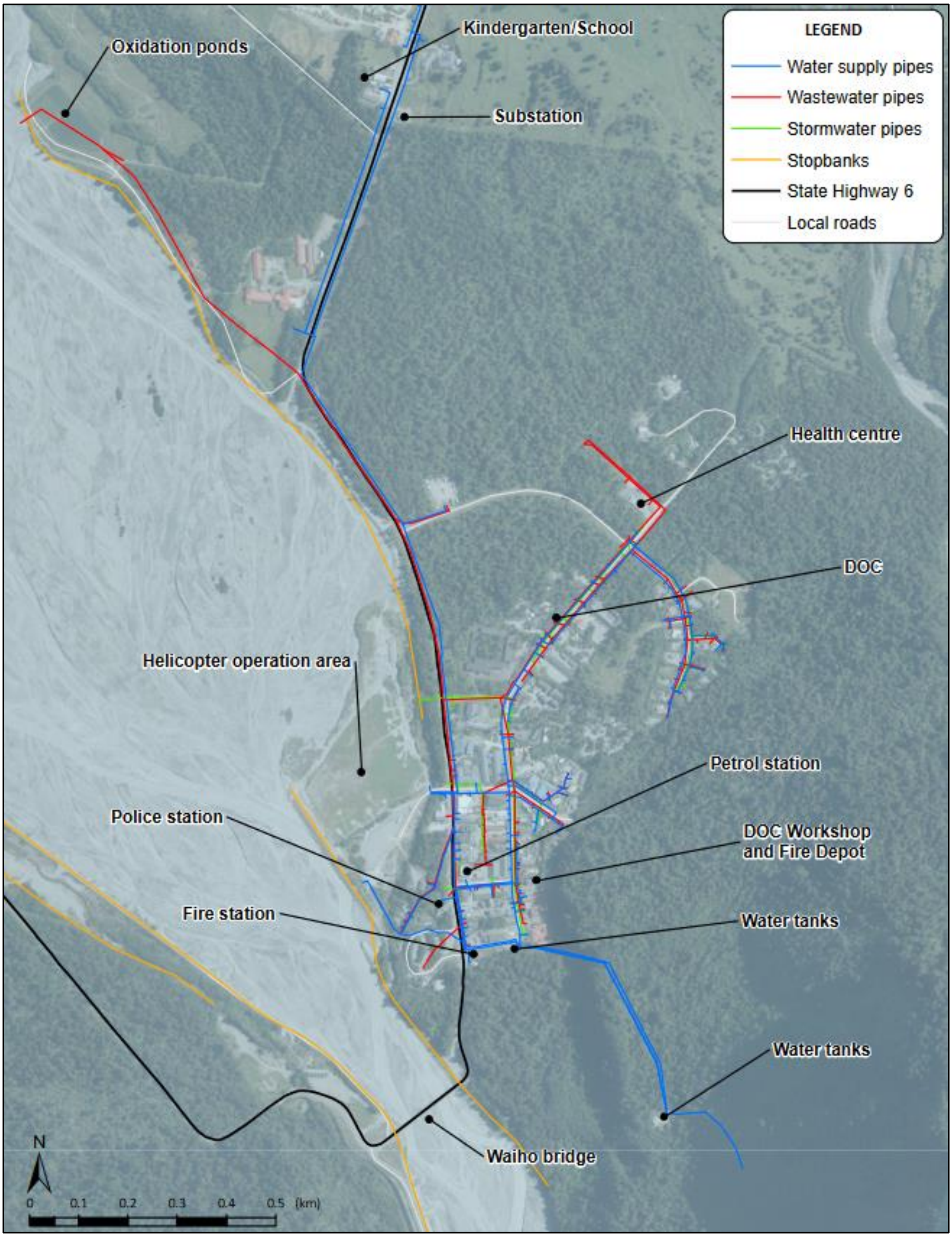

Figure 2-2 – Franz Josef township amenities (Tonkin+Taylor and EY, 2017).

2.3. ECONOMY

Tourism provides the main source of income for much of the population through commercial operations and the government-run Department of Conservation, with tourists drawn to the area for its high environmental value. This influx of tourists provides invaluable support for the local restaurants, cafes, accommodation providers and only supermarket.

Though there are range of activities available within the Franz Josef area such as guided nature walks, walking tracks i.e. to Alex Knob or the Callery Gorge, hot pools, and kayaking on Lake Mapourika; the Franz Josef Glacier is the major drawcard.

Of the over 3,100 glaciers in New Zealand (Chinn, 1999), fewer than 1% are used by tourism operations, with the Tasman, Franz Josef, and Fox glaciers the most intensively utilized (Purdie, 2013). It is estimated that 20% of the total visitor arrivals to New Zealand (700,000 people) arrived at the Westland glaciers in 2016, with total expenditure in the township by both domestic and international tourists estimated to be around NZD 122 million for that year (Tonkin+Taylor and EY, 2017).

However, like other mid latitude glaciers, the Franz Josef Glacier is very sensitive to changes in climate (Anderson et al., 2008; McKinzey et al., 2004). Over the past century aside from small re-advances due to slight changes in the climate such as El Nino episodes (increased precipitation, cooler temperatures; (Chinn et al., 2005; Hooker & Fitzharris, 1999)), the general trend of the Franz Josef Glacier has been to retreat. This corresponds with warming of the climate over the last 100 years (Oerlemans, 2001). As the climate is projected to increase both in temperature and precipitation, it has been predicted that the Franz Josef Glacier will continue to retreat. Simulation modelling suggests a further 5 km retreat of the terminus up the valley (Anderson et al., 2008).

Figure 2-3 shows a simplified version of how the warming of the climate can impact glacier tourism. When applied to the Franz Josef glacier, it follows that:

- Warming of the climate will continue to cause the glacier to retreat.
- As a result, access onto the glacier will become increasingly difficult unless via helicopter, the risk to visitors from hazards such as rockfall, crevasses, and ice avalanches will increase, the difficulty of activities on the glacier will also increase, and the quality of the glacier scenery will decrease (Wang & Zhou, 2019).
- Therefore, there will be a general decline in the reward to risk ratio for tourists accessing the glacier, with the balancing act for tourism operators between safe access and client satisfaction becoming increasingly challenging (Purdie, 2013).
- This is likely to have a negative effect on tourist numbers (Wang & Zhou, 2019), with the Intergovernmental Panel on Climate Change predicting that shrinkage and retreat of glaciers will reduce visitor numbers in tourism-dependent towns like Fox Glacier and Franz Josef (Hennessy et al., 2007).

Should the glacier see a decline in visitor numbers, there will also be a loss of revenue for the tourism operators and other businesses within the Franz Josef area, which will present difficulties for the community, given its reliance on tourism as its main source of income.

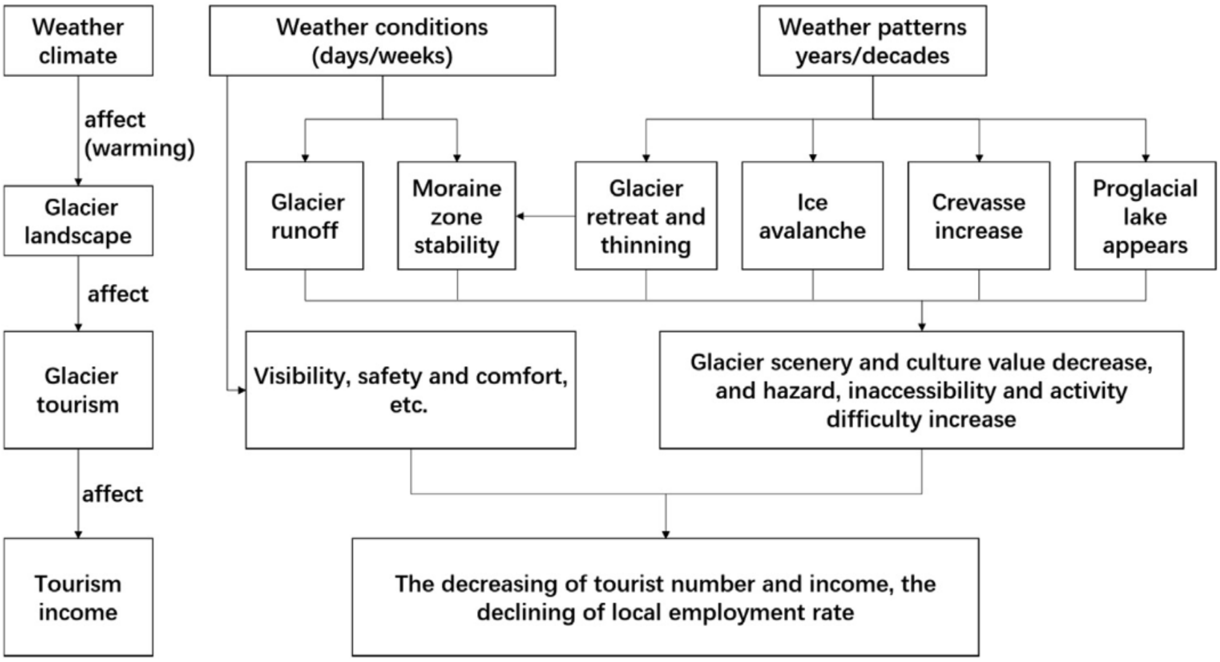

Figure 2-3 – Flow on effects from changing climate on glaciers landscapes and glacier tourism activities. Figure from Wang and Zhou, 2019.

Agriculture provides an additional source of revenue for the Franz Josef area. In the 2,500 ha of land to the south of the Waiho (the Waiho flats), dairy farming (the dominant current land use) generates a revenue of around $4,500 per hectare, with additional land uses including cattle and sheep grazing, wool, deer and velvet, goat and fibre, and manuka (Vorster & Hart, 2020). The proposed option of releasing the river to the south, would result in the loss of this revenue.

3. GEOMORPHIC BACKGROUND

3.1. LOCATION

The Waiho River flows from the actively uplifting Southern Alps (~5 to 10 mm per year) to the Tasman Sea on the West Coast of the South Island of New Zealand, with the township of Franz Josef located immediately to the north of the river just after it exits the mountains.

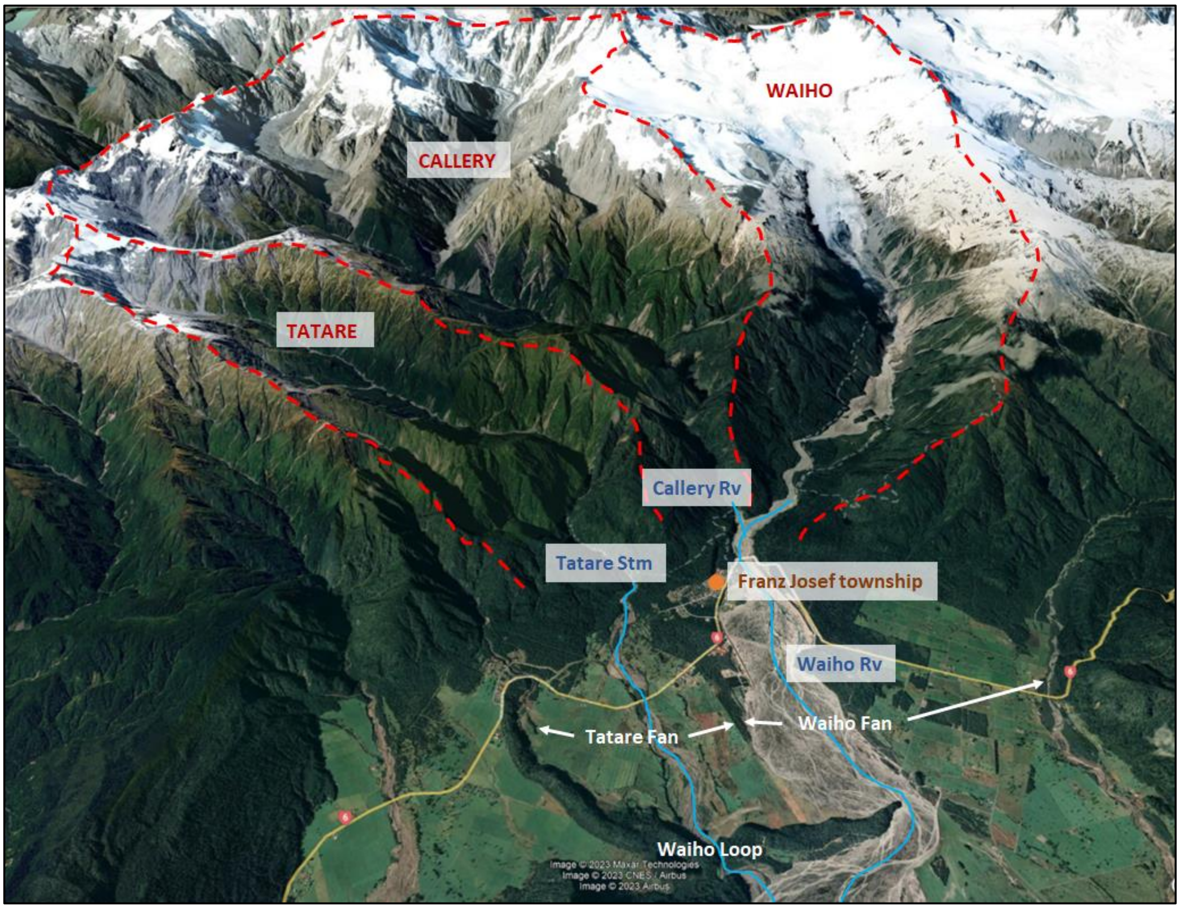

Figure 3-1 - Waiho catchment with main tributaries and geomorphic features labelled.

The river is fed by a relatively small catchment comprised of the Waiho ($77km^2$), Callery ($92km^2$) and Tatare ($28km^2$) main sub-catchments (Figure 3-1). However, given its origin amongst the glaciated and metamorphosed schist/gneiss and greywacke dominated Southern Alps, and exposure to the roaring forties (prevailing moist westerly winds), the river receives a high supply of both sediment and water. This is evident by its braided nature and very active alluvial fan surface.

The steep alluvial fan that has been formed downstream of where the Waiho River departs the mountains, is partially (and naturally) blocked at its downstream end by a terminal moraine formed from a rock avalanche around 11,000 years ago – the Waiho Loop (Alexander et al., 2014). Another major obstruction to the fan is Canavan's Knob on the south side, which affects both the fan activity and distribution.

The Waiho River currently flows across the fan to the northeast of Canavan's Knob, and then through a gap between Rata Knoll and the southern end of the loop, before being joined by the Tatare Stream and continuing down a 11.5 km long elongated valley of glaciofluvial deposits (valley train) to the sea.

3.2. AGGRADATIONAL BEHAVIOUR

Since at least 1948 when the first aerial imagery was taken, the Waiho River has been actively increasing the elevation of its alluvial fan surface. The fan is a natural aggradation (depositional) reach, as the sediment supply from the mountains cannot be contained within a defined channel, and hence spreads out as a fan across the open valley downstream of the mountains. This process gives rise to an increasing fan height as the supply is distributed across the fan surface. The rate at which the Waiho has been aggrading its fan surface has rapidly increased from the 1970's onwards.

Aerial imagery, cross section and LiDAR data sets, documented observations, and photographs provide extensive evidence on the aggrading trend of the river and fan, which is believed to be currently occurring at rates averaging between 0.16 m and 0.2 m in vertical elevation per annum (Beagley et al., 2020; Gardner & Brasington, 2019; Tonkin+Taylor and EY, 2017).

- The aerial imagery in Figure 3-2 shows the pronounced change in channel pattern between 1948 and 1997, with the 1997 imagery showing a far more braided river system downstream of the Callery Junction compared to the 1948 imagery. Further, in the 1997 imagery, all of the vegetated and grass covered islands and land in the open area between bush lines in 1948, is now covered by river sediment.

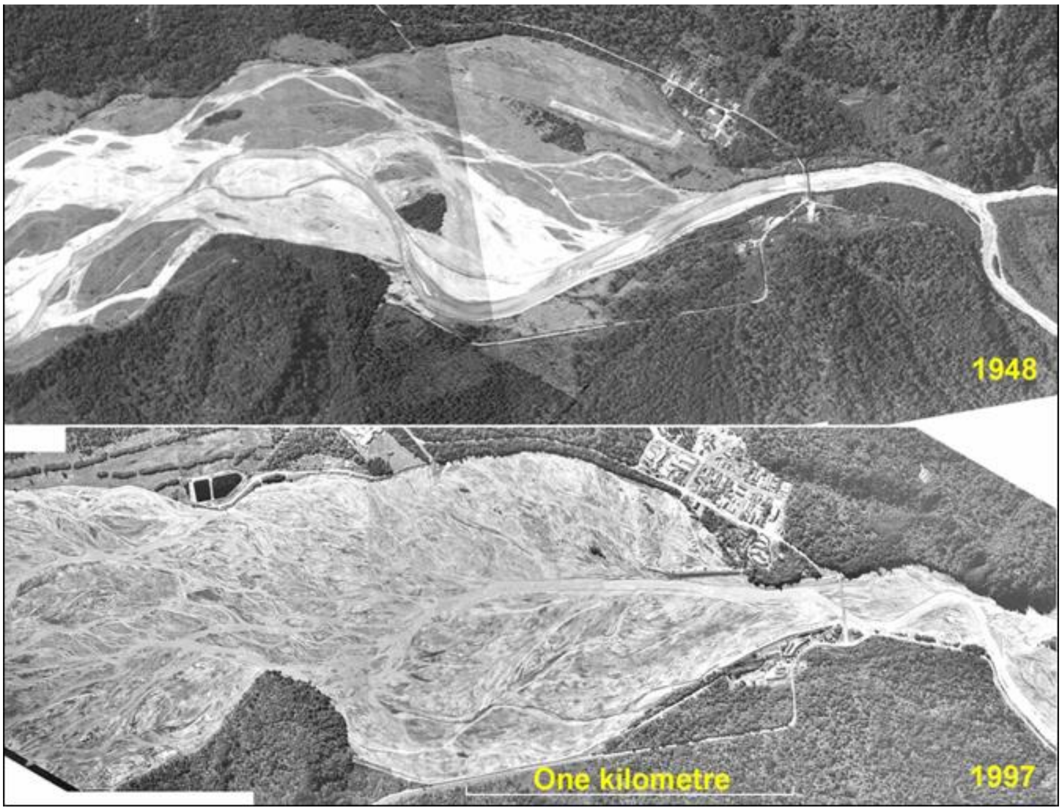

Figure 3-2 - Aerial imagery of the Waiho fan from 1948 and 1997. (Davies & McSaveney, 2001)

- In Figure 3-3, bed surface elevation data along cross sections 14 and 17 has been compiled from 1999, 2012 and 2023. The data clearly shows an increase in bed surface elevation from increased aggradational supply and stopbank heights over time, with notable narrowing of the riverbed and fan surface between 1999 and 2012 as a result of the construction of the Heliport (north side) and the innermost Waka Kotahi (south side) stopbanks.

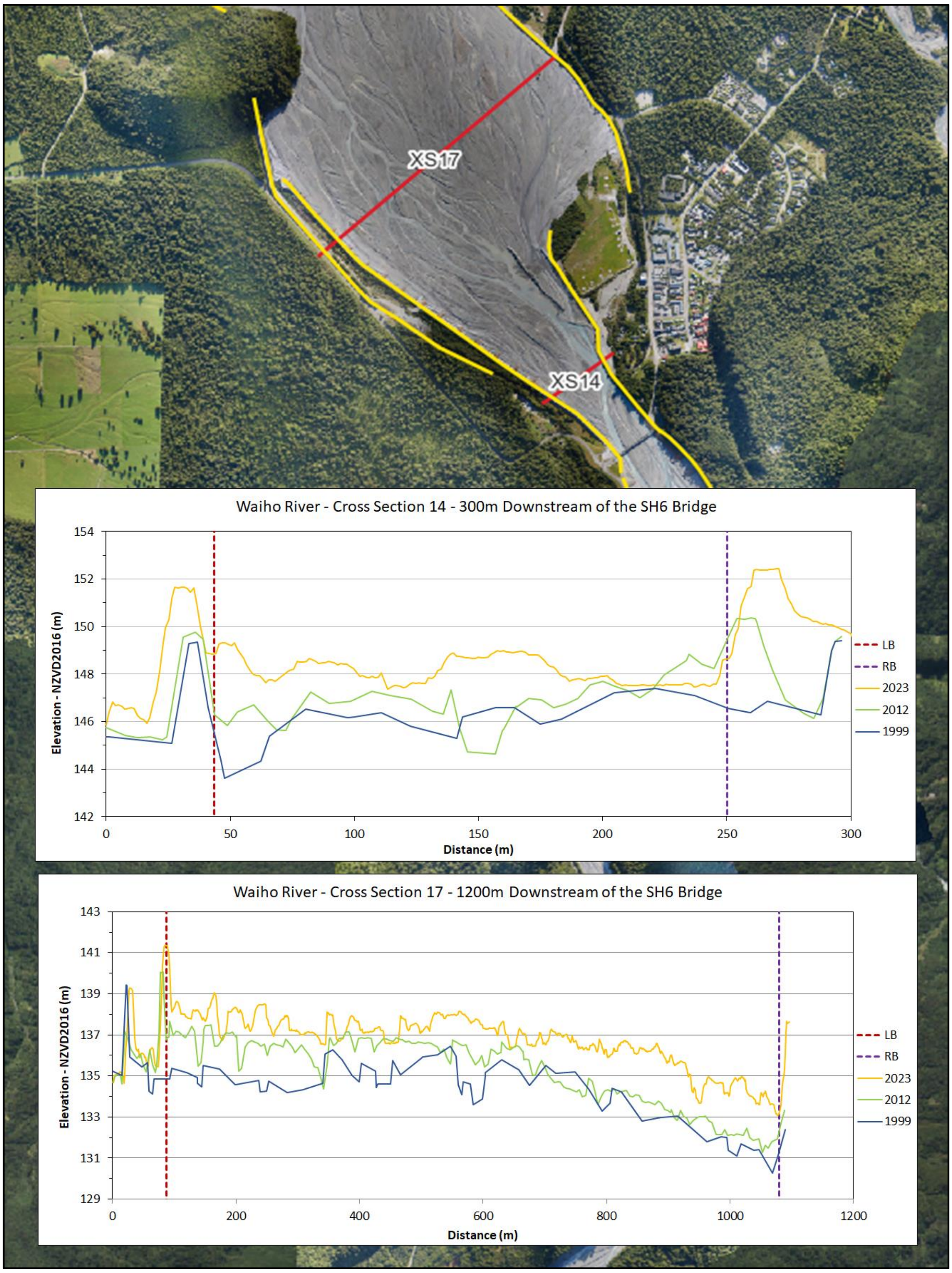

Figure 3-3 - Cross section surveys from 1999 and 2012, and the latest LiDAR (2023) showing the increasing bed elevation and confinement over time.

The earliest known report discussing the aggradational behaviour of the Waiho River was in 1983, when Mosley was contracted to investigate the recent history of the Waiho River in order provide an indication of its likely future behaviour (Mosley, 1983). The investigation was prompted out of concern for the SH6 bridge given that the riverbed below had aggraded by 4 m since 1948 with 1.4 m alone in 1982, and for the Franz Josef Glacier access road, which had been washed out on at least six occasions between 1965 and 1983.

Mosley provided reasons for both the incised (deep channel formed through erosion of the bed material) and aggrading states of the river, which he associated with a change in sediment supply between the Franz Josef glacier and Waiho River as a result of the relationship between the location of the glacier terminus, and it's advancing/retreating behaviour.

- The river incision observed from European settlement through to the 1930s was related to the existence of a terminal lake that formed as the glacier retreated from its 1820's position between 1923 and 1950 (Figure 3-4). This created a large sediment trap therefore reducing the immediate supply of sediment to the river system.
- From the 1950's onwards, once this lake had filled up, sediment was able to pass directly from the glacier into the river. Though the glacier had small readvances in the 20th century it had remained in the narrow bedrock gorge part of the valley, where there was negligible sediment storage available, meaning that the effects of extreme events (major rock falls or floods) was attenuated to only a limited extent. This rapid transfer of sediment, combined with an increased volume of sediment from the increasingly exposed valley walls, meant that sediment supply between the glacier and the river was high.

Figure 3-4 – 1948 aerial imagery showing the remaining part of the terminal lake on the south side just upstream of Sentinel Rock and Teichelmann Rock (imagery provided by Mark Healey, WSP).

Mosley concluded that the aggradation trend of the river and fan was likely to continue. He also observed that the "*river control structures such as groynes and rock training banks* [stopbanks] *may be completely inappropriate in the high energy environment provided by the Waiho.*" An observation proven true in 1982 with the failure of the long stopbank constructed down the centre of the confined fan, less than two years after completion (Figure 3-5). By 1994, no trace of this stopbank remained in the aerial imagery.

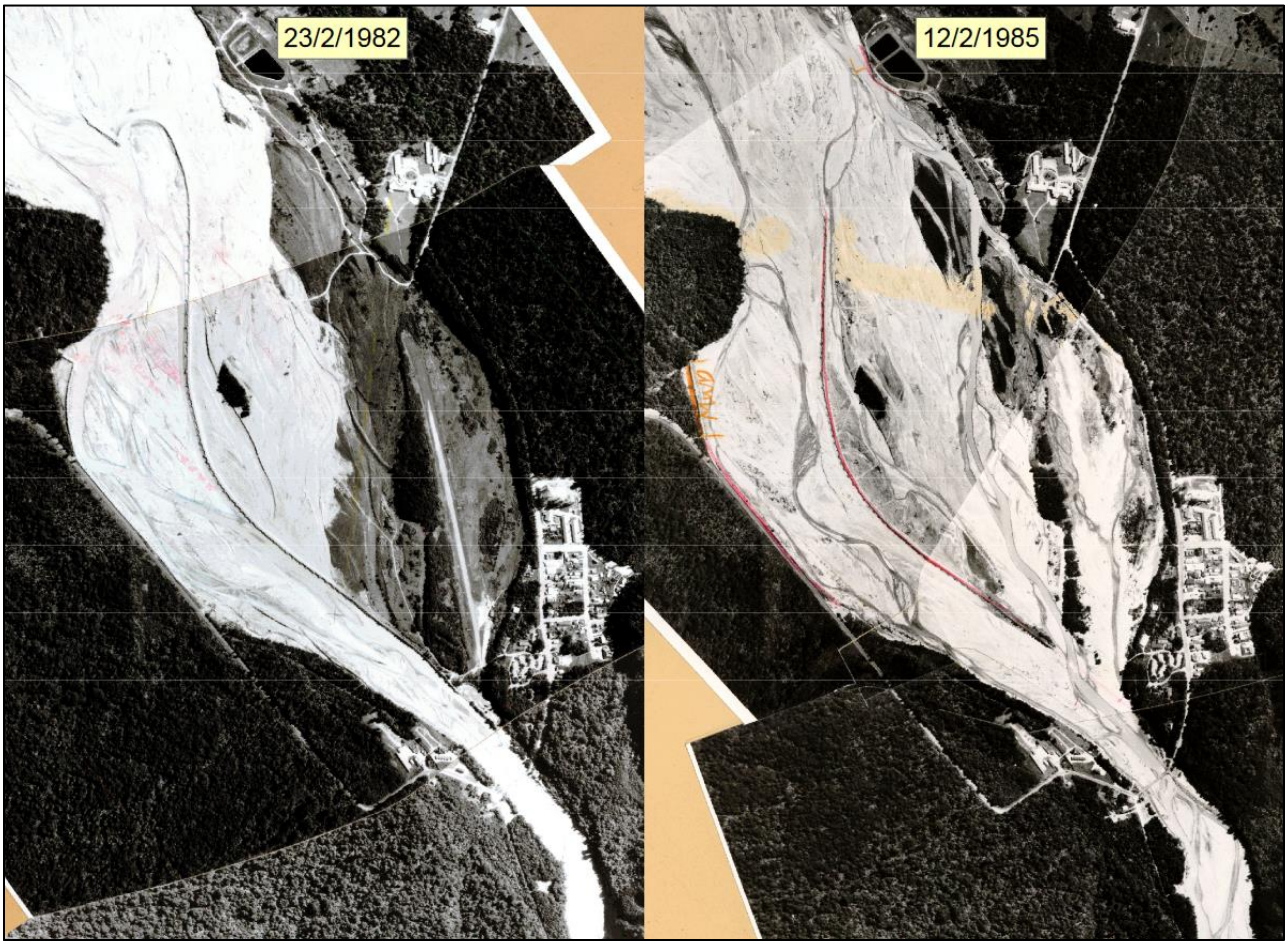

Figure 3-5 – Comparison of the upper Waiho fan between 1982 and 1985 (the most recent aerial imagery after the stopbank failure) showing the long central stopbank in place, and then breached at its upper end, and hook groyne destroyed at its lower end.

As predicted by Mosley, the aggradation trend did continue, and in acknowledgment of this, in 1990 the WCRC contracted Hoey to investigate the probable and maximum extents of riverbed aggradation over short, medium, and long term timescales (2, 20 and 50 years).

Hoey's report (Hoey, 1990) reinforced what Mosley had said. Through investigating the factors that control aggradation at different timescales (flooding, sediment supply, river channel adjustments and glacier fluctuations) and providing estimates of the volume of sediment supply from both the Callery and Waiho sub-catchments, he concluded that the aggradation was likely to continue in all three of the timescales, affecting the Waiho riverbed area both upstream and downstream of the bridge.

Further he referred to the conclusions made by Griffiths and McSaveney (1986) in regard to the Waitangitaona River avulsion in 1967 which he perceived were relevant to the Waiho case. Griffiths and McSaveney concluded that though there was a high probability that the Waitangitaona River could be contained over a thirty-year period or so, at longer timescales, the local community must accommodate the erosion, deposition, and flooding hazards, as would, Hoey noted, the Franz Josef community.

In 1998, with the situation only worsening and compounded by the ongoing need to raise and repair the stopbanks to keep up with the rapidly aggrading bed, the WCRC contracted McSaveney and Davies (1998) to complete a natural hazards assessment of Franz Josef and its environs. Whilst the report was to include all hazards, there was a heavy focus on the Waiho River itself, with the authors providing a detailed insight into the history of the Waiho, and an understanding of its sub-catchments as well as hydrologic and geomorphic features. From the in-depth analysis, McSaveney and Davies concluded that the protection network, which Mosley (1983) had already suggested was probably not an appropriate management strategy for the river, was rather the cause of the aggradation. They deduced that the well intentioned and constructed protection structures, in restricting the river to a small portion of its historic fan surface, had prompted the aggradational behaviour. In the following years, this hypothesis was tested through microscale modelling (Beagley et al., 2020; Davies et al., 2013; Davies et al., 2003) allowing it to be further developed and redefined, with better understanding of how fans respond to confinement.

McSaveney and Davies also drew attention to the fact that the aggraded fan surface had now reached an unprecedented elevation, such that it was level with the Tatare fan, and therefore in the near future the Waiho River could break out (avulse) to the north and flow into the Tatare Stream above the Waiho Loop. They were particularly concerned about this, as unlike breakouts to the south, a northern break out into the Tatare hadn't occurred before, and so the outcomes could not easily be predicted but would likely have significant consequences for the oxidation ponds, SH6 and Franz Josef township.

They went on to provide six options for future management for the river including doing nothing, maintaining the status quo, and selecting/making new courses or restricting the river from accessing a particular course.

In 2012, Hall refined these to four options:

1. Do nothing; or,
2. Status quo; or,
3. Acceptance of avulsion to the Tatare Stream; or,
4. Boundary relaxation.

Hall's options followed a comprehensive summary (Hall, 2012) of the preceding reports and literature on the aggradation hazard which included multiple studies led by Davies (1994, 1997, 1998, 2000, 2001, 2002, 2003a, b, 2006a, b, 2008). Hall also forecast that if the river continued to aggrade the fan surface, the Mueller Wing of the Scenic Circle Hotel and oxidation ponds were at risk of flooding, and that within ten years it was highly probable that the Waiho River would avulse (reroute) into the Tatare Stream.

Both the Scenic Circle Hotel and oxidation ponds were inundated in the March 2016 flood, whilst in February 2023, the Waiho River began the process of avulsing its flow into the Tatare Stream. Figure 3-6 shows the 2016 and 2023 bed surface elevation data of a cross section from the south side of the Waiho fan all the way to the edge of the Tatare Stream on the north side. The 2023 data shows considerable aggradation across the Waiho fan surface, which has served to push the flow of the Waiho River towards the north side, resulting in the avulsing behaviour that has formed the breakout channel/s down to the Tatare Stream. This avulsion process has been discussed in detail in Section 3.3.

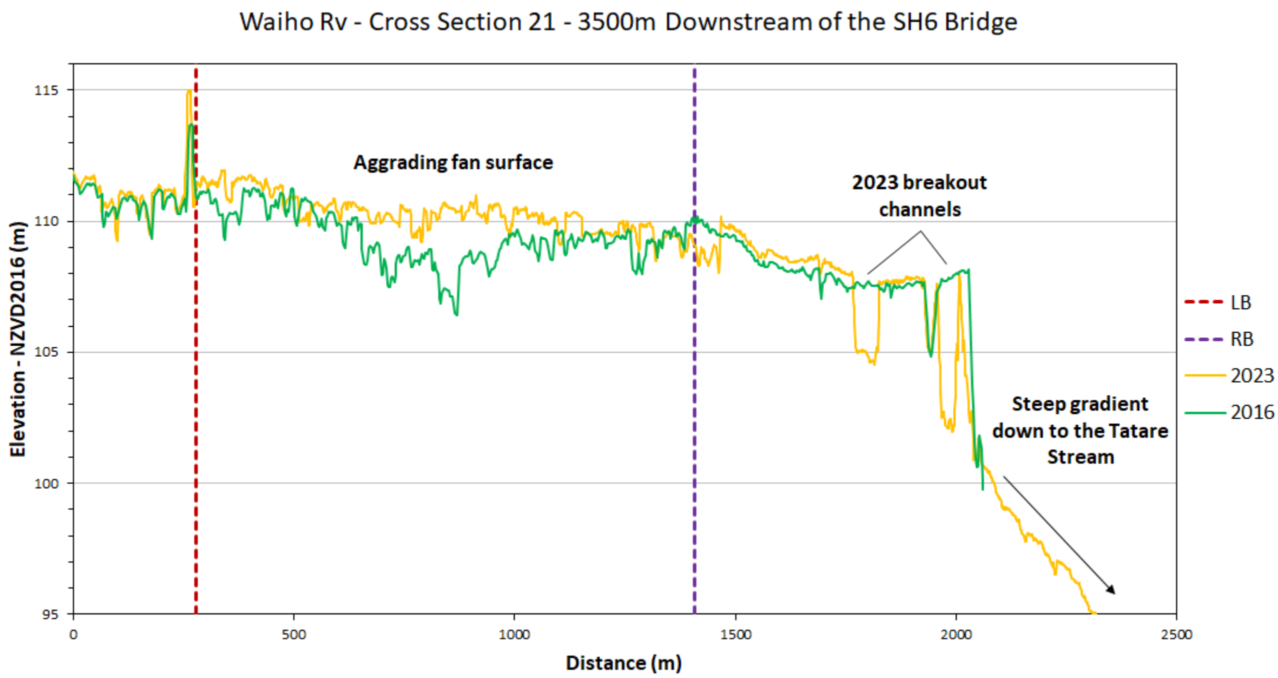

Figure 3-6 – 2016 and 2023 bed surface elevation data from cross section 21 adjacent to the avulsion site.

In 2016, after the March event that flooded the Scenic Circle Hotel and oxidation ponds, a workshop was held on the 27th and 28th of July. The workshop brought together the affected agencies, as well as the experts in the field of river engineering in order to develop a long term strategy for managing the river and its aggradational behaviour.

The attendees agreed that the river would continue to aggrade without intervention, and though it was unclear what the rate of future aggradation would be, in the next 5 to 10 years it was likely to be severe as there are millions of cubic metres of gravel and sediment in the Callery and Waiho catchments available for transport down onto the Waiho fan (Meehan, 2016).

They also addressed the role the stopbanks play in the aggradation of the fan, agreeing that by constricting the river, the stopbanks accelerate the rate at which the fan surface elevation increases, with subsequent impact on stopbanks and edge protection measures. Further they noted that the Waiho River needs to occupy a large fan for deposition of its high bedload (Meehan, 2016), as it did prior to human intervention. Therefore, digging the gravel out, or realigning the river channel, will not provide the relief needed for the community and infrastructure. In the long term, the river needs to be able to occupy its full fan surface, which involves relaxing the southern boundaries (Meehan, 2016).

The following year, Tonkin and Taylor (2017) released a WCRC funded report assessing the management options and providing a cost benefit analysis. They forecast that within thirty years, unless a new approach was taken, the fan surface would be equal to or higher than the level of the Franz Josef township (upstream of the SH6).

In cross sections from the latest LiDAR (8th of June 2023), whilst the river channel upstream of the SH6 is still lower than the Franz Josef township, downstream of the SH6 bridge the fan surface is already considerably higher than both the SH6 to the south, and the heliport, SH6 and parts of the township to the north (Figure 3-7).

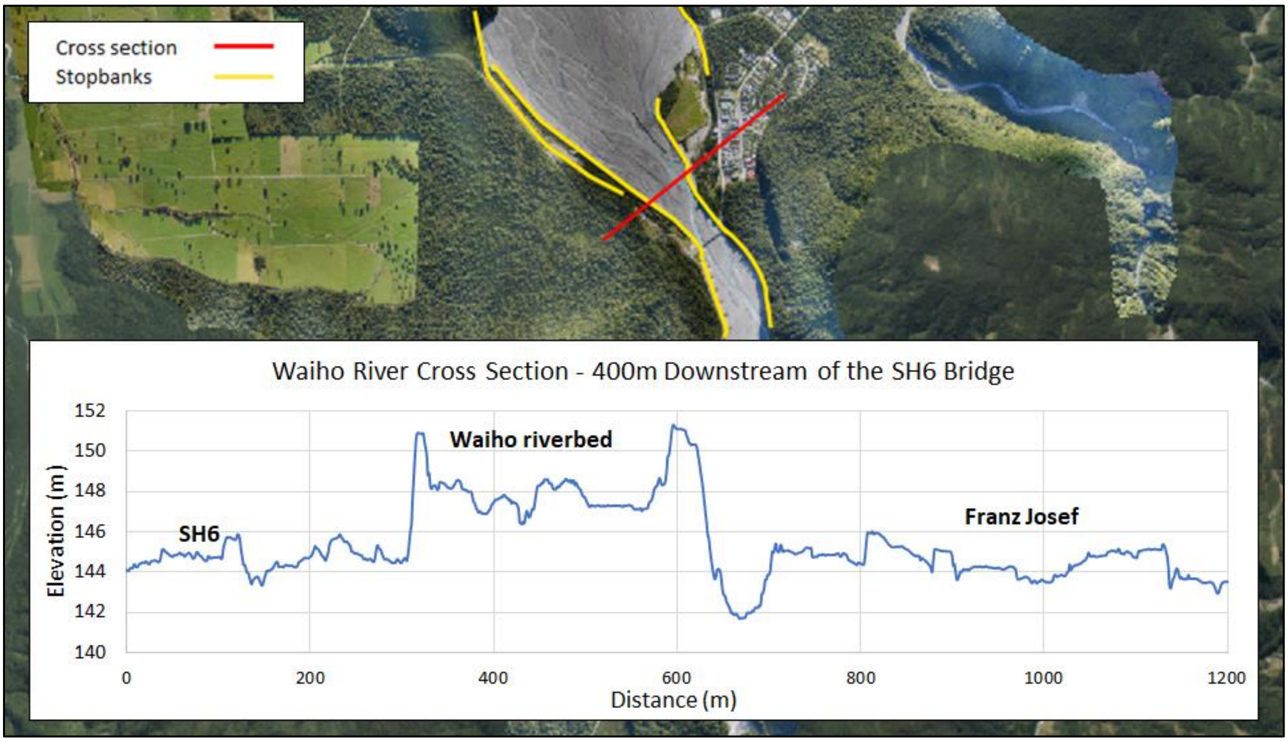

Figure 3-7 – A cross section taken 400m downstream of the SH6 bridge showing the height of the confined Waiho riverbed above the SH6 and township of Franz Josef.

At the same time, in 2017, a microscale modelling experiment was investigating the option of relaxing the boundaries of the protection network as recommended by the 2016 workshop (Beagley, 2017). Part of this investigation involved studying the response of the microscale fan to confinement. In doing so, Beagley et al (2020) were able to show that in an already aggrading fan, confinement increases the rate of vertical accumulation of sediment on the confined area.

The underlying theory behind this is that fans naturally distribute sediment laterally, accessing different segments of their large surface at different times (Blair & McPherson, 1994; Reitz & Jerolmack, 2012; Zarn & Davies, 1994). When confined, the distributional channel network no longer has the space to spread its load out horizontally, thus it must accrue the same volume of sediment vertically over a much smaller area. Therefore, the rate at which the bed surface elevation increases is faster in a confined setting compared to an unconfined setting.

These findings are applicable to the Waiho River and fan.

- In the early 20th century, as discussed by Mosley (1983) and Hoey (1990), the Waiho River would have been naturally aggrading (albeit at a much slower rate).
- Then, in the 1970's, when the state roading authority and the West Coast Catchment Board began construction of the significant edge protection structures, they confined the river to the northeast of Canavan's Knob.
- More significant confinement was then attempted in the early 1980's, when a long stopbank was constructed down the centre of the confined fan, restricting the river to the south side, and away from the growing infrastructure and community on the north side. However this central stopbank was quickly destroyed by the river.
- Therefore, for much of the mid to late 20th century and the last twenty-two years, the river has been confined to just one third of its natural fan area.
- In this time, sediment supply has increased, most likely because of glacial retreat up the Waiho valley, resulting in an increased rate of aggradation, which is restricted to this confined area.

Thus, from the 1970's onwards, the Waiho River has been depositing its high volume of sediment over a much smaller area, and hence, the fan surface elevation has been increasing at approximately three times its natural rate (when accessing its entire surface).

Since this study, high resolution geomorphic change detection (GCD) analyses have been conducted on the Waiho for the WCRC using the 2016, 2019 and 2023 LiDAR data sets (Gardner, unpublished; Gardner & Brasington, 2019). These studies support the continued aggradation of the fan surface between the SH6 bridge and Waiho Loop (Figure 3-8), and the accumulation of an upstream supply of sediment for the fan.

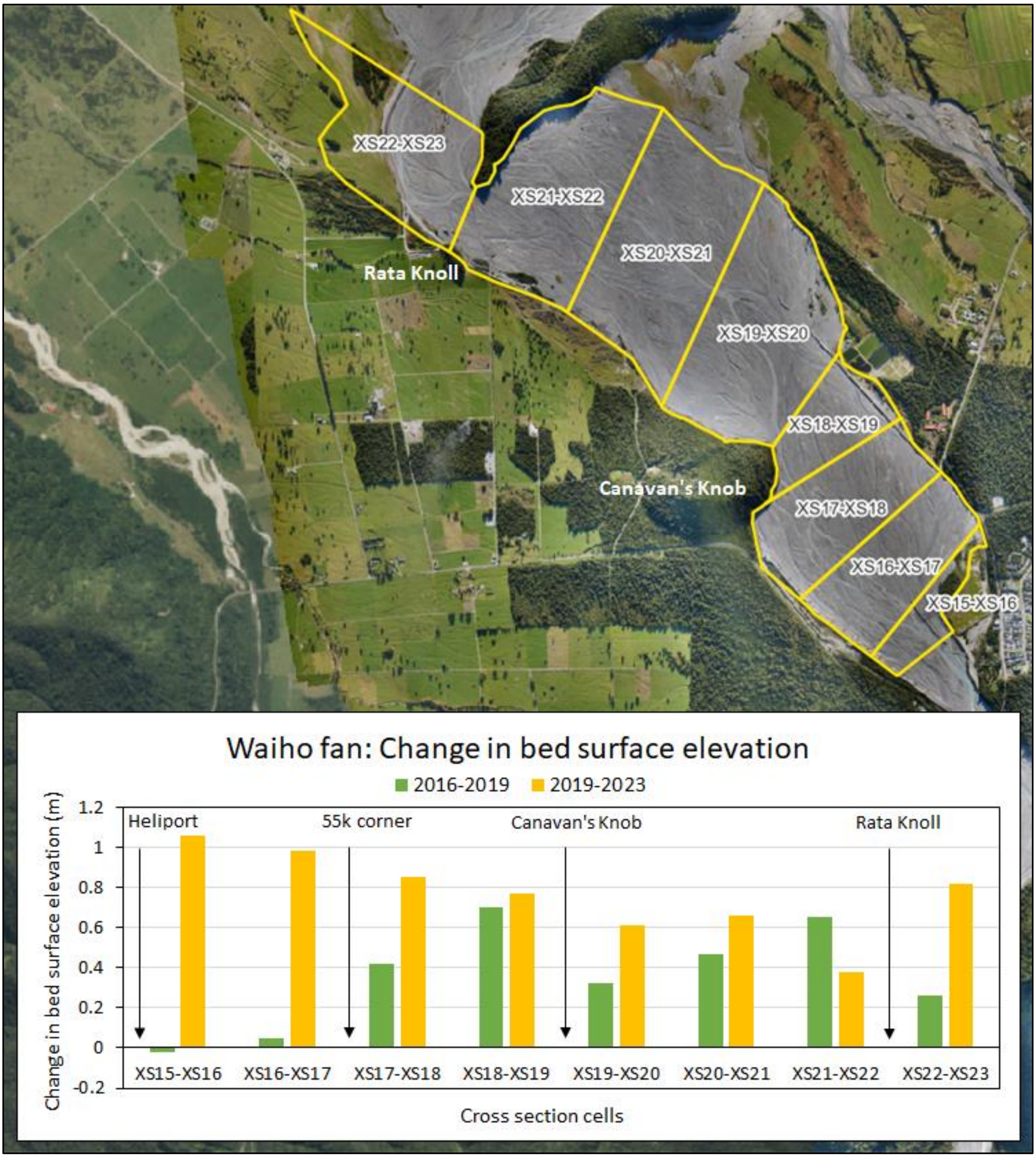

Figure 3-8 – Net change in bed surface elevation per cross section cell between 2016 and 2019, and 2019 and 2023.

Figure 3-9 shows the 2016 to 2019 net change in sediment volume for the four reaches between the glacier terminus and Waiho loop:

- In the upper valley which lies between the Franz Josef Glacier terminus and just downstream of the Sentinel and Teichelmann rocks, there was a net gain of ~1.1 million cubic metres of sediment. A large portion of which was likely the product of the March 2019 flood event which resulted in several metres of aggradation at the terminus of the glacier.
- The two narrow river reaches between the upper valley and the Waiho fan, experienced net losses of sediment. Due to their narrow nature, these reaches often act as good conduits for sediment transport. However, active erosion at the channel edges, suggests they are also sediment sources for the fan aggradation.
- The Waiho fan itself, experienced a net gain of ~0.98 million cubic metres of sediment which equated to local increases in bed level of 0.3 m to 0.7 m.

Figure 3-10 shows the 2019 and 2023 net deposition and erosion of sediment for the four reaches between the glacier terminus and Waiho Loop.

- The upper valley experienced a net loss of sediment, notably just downstream of the glacier terminus. This resulted in just under half of the sediment that accumulated here in the previous three years, to be transported downstream.
- Some of this upper valley sediment was deposited in the first of the river reaches, between the bottom of the upper valley and the Waiho-Callery junction, and as a result, this first river reach experienced a net gain of sediment (~0.16 million cubic metres). However, the river reach between the Waiho-Callery junction and bottom of the heliport stopbank, again experienced a net loss.
- The Waiho fan experienced a net gain of considerably more sediment to the previous three year change, aggrading by ~1.57 million cubic metres of sediment. This aggradation occurred over the entire (confined) fan surface, with Figure 3-8 highlighting the pronounced increase in volume in the lower half of the fan adjacent to where the Waiho River has started to avulse into the Tatare Stream (cross sections 19 to 21).

The extensive number of reports and studies discussed above unequivocally show that the aggradational behaviour of the Waiho River is not slowing down. If anything as indicated by the 2016 to 2019, and 2019 to 2023 GCD analyses, aggradation across the Waiho fan is increasing with the average change in bed surface elevation across the fan surface increasing from 0.12 m per year between 2016 and 2019, to 0.19 m per year between 2019 and 2023.

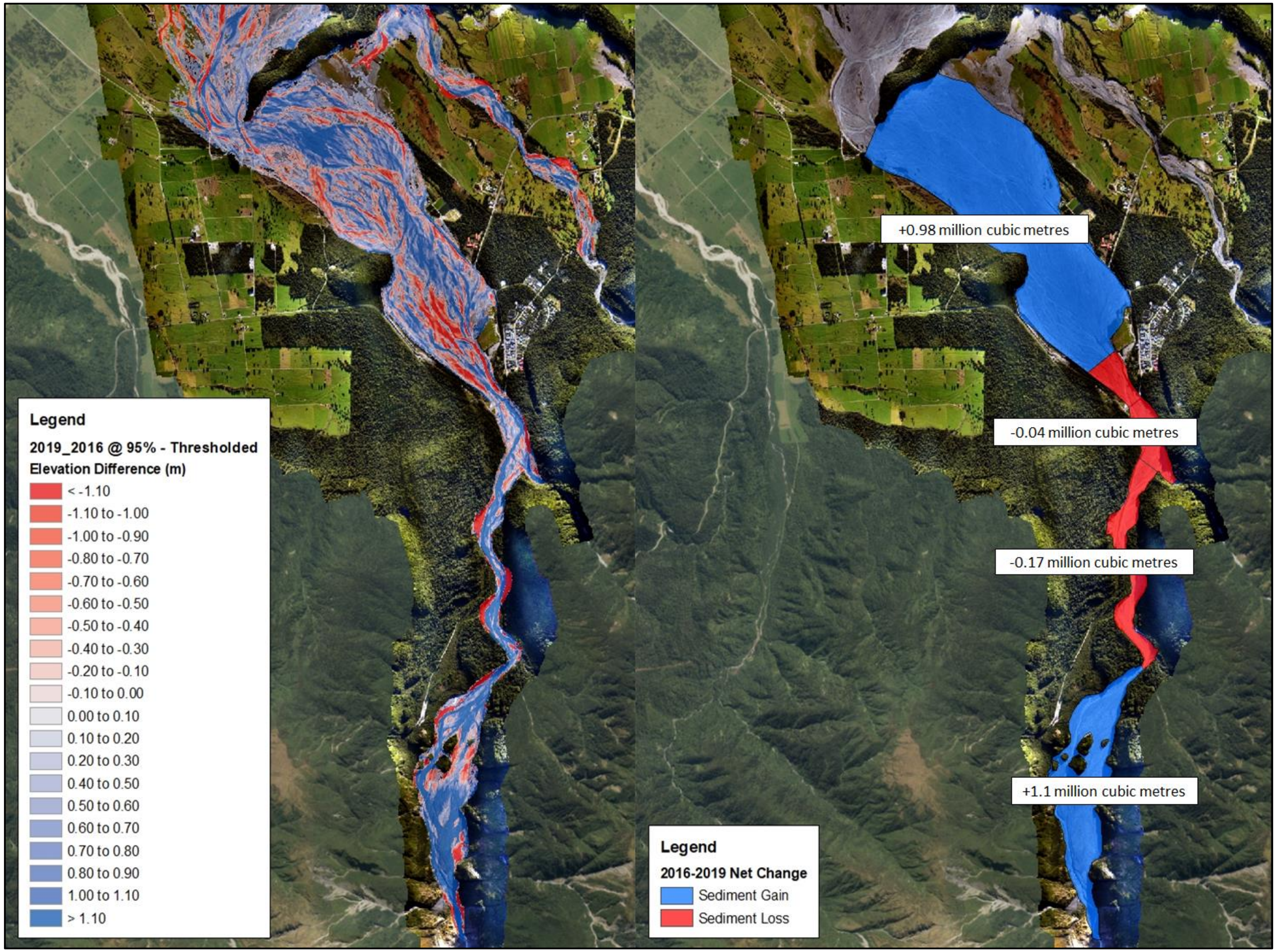

Figure 3-9 – Elevation difference (erosion and deposition) and the net change between 2016 and 2019

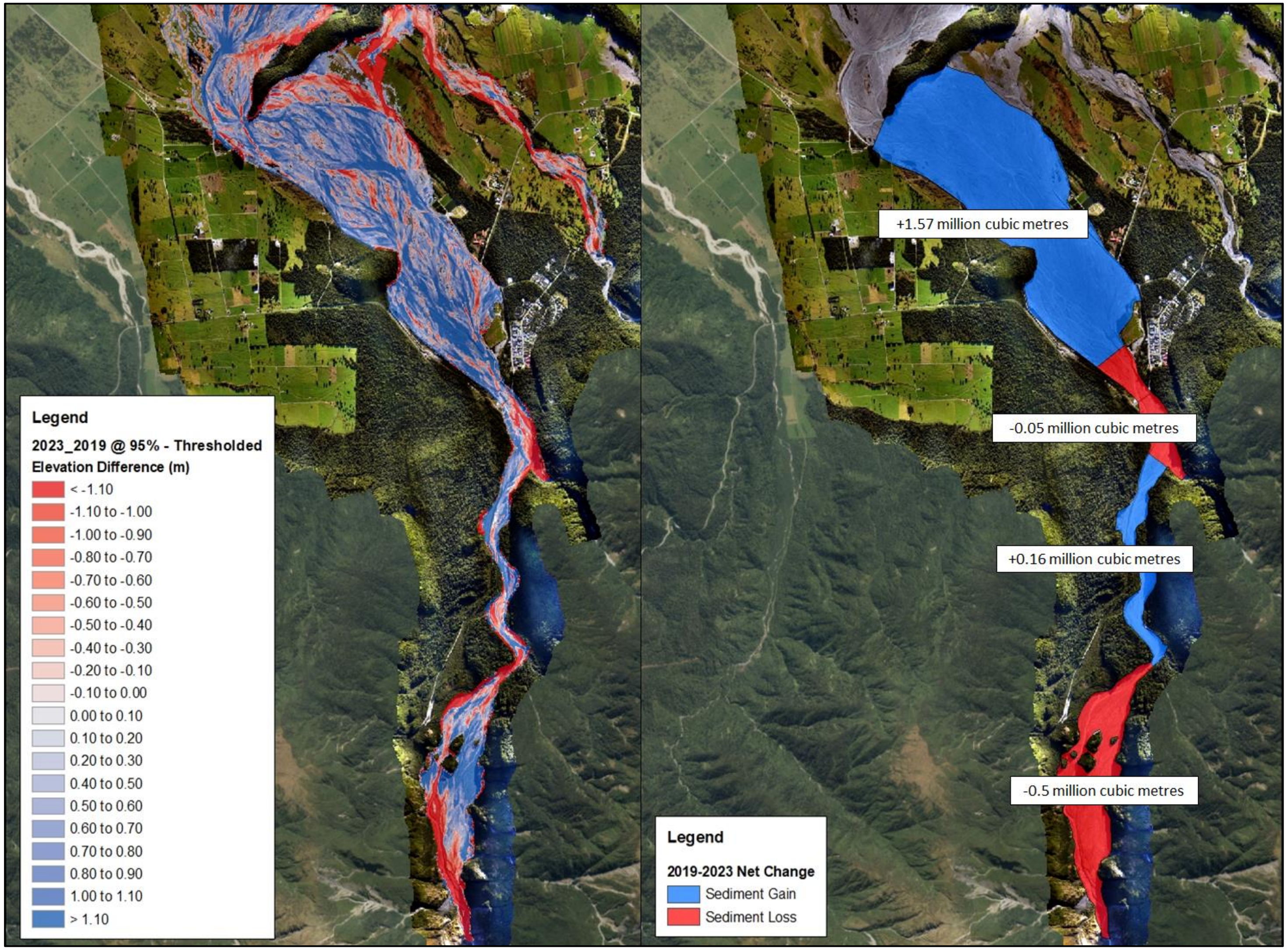

Figure 3-10 - Elevation difference (erosion and deposition) and the net change between 2019 and 2023

3.3. AVULSION INTO THE TATARE STREAM

The ongoing confinement of the Waiho River has allowed the river to aggrade its fan surface to a level where the surface is higher than that of the Tatare fan surface, such that the avulsion scenario first discussed in 1998 by McSaveney and Davies, and frequently since, is now possible.

Over the last ten years, small breakouts from the Waiho River into the Tatare Stream have occurred, but the river was always able to be rediverted away from the Tatare stream and fan and these did not last. This activity did not go unnoticed, and in January 2015, during an emergency meeting held by the Franz Josef stakeholder group (i.e. Waka Kotahi, Scenic Circle Group, Rating District, WCRC, WDC, and Electronet) to look at options for future management of the river, Land River Sea Consulting and G & E Williams Consultants proposed a cutoff embankment be constructed to prevent the Waiho River from avulsing into the Tatare Stream (Figure 3-11)(Gardner & Williams, 2015). At the time, the natural high land (farmland) would have made for a relatively straightforward design and construction process.

Figure 3-11 - The January 2015 proposed cutoff embankment to prevent the Waiho River avulsing into the Tatare Stream. (Gardner & Williams, 2015)

In 2021, the WCRC began the resource consent process to build this rock lined cutoff embankment on the northern bank of the Waiho River. In January 2023, construction began, however this was soon halted (in February) with the onset of the developing avulsion eroding the farmland that the embankment would have been built along, and in the months that followed, the Waiho River established a significant channel into the Tatare Stream (Figure 3-12).

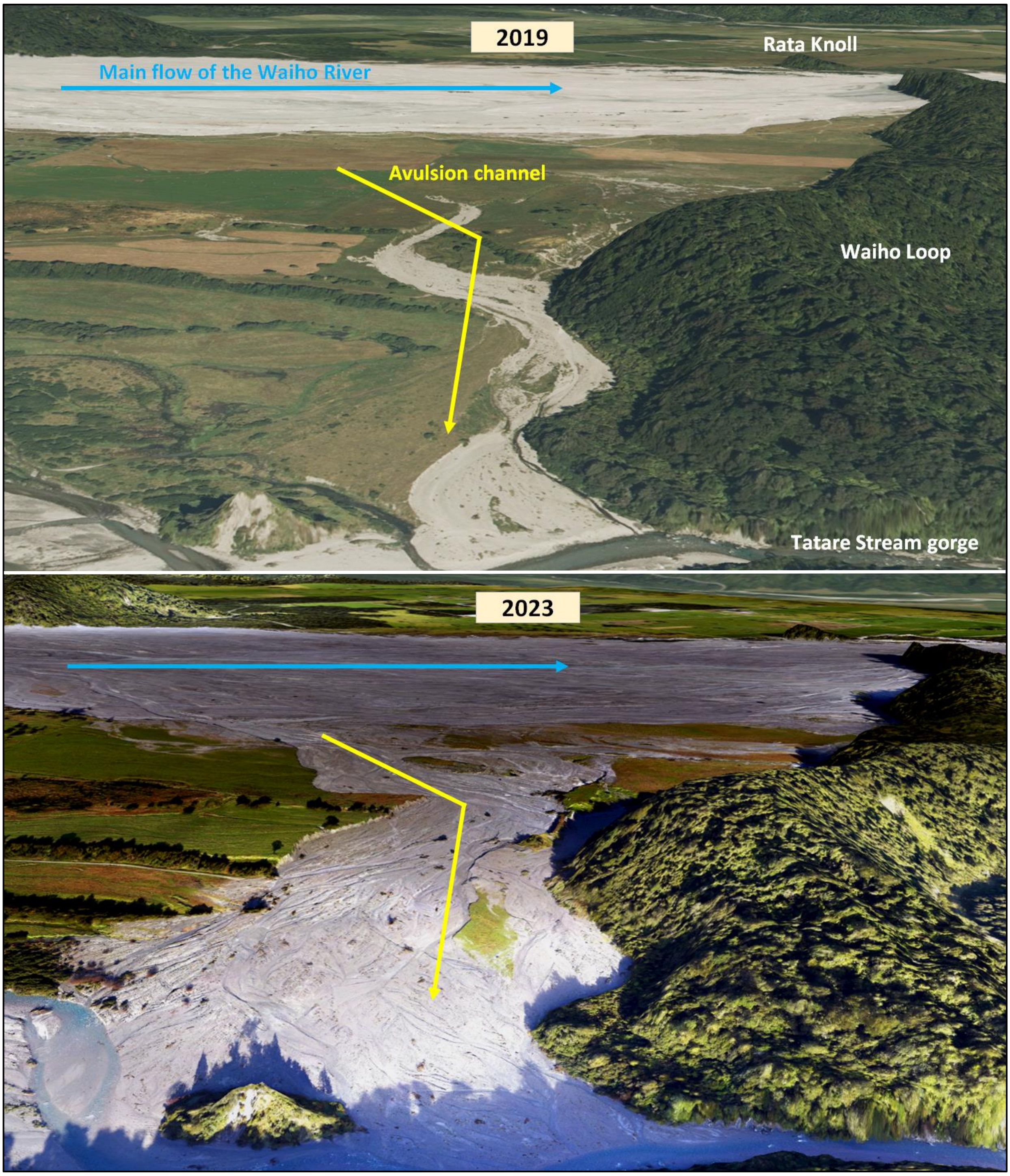

Figure 3-12 – Images comparing the Waiho avulsion site before (2019) and after (2023) the February 2023 event. At the bottom of each image, the Tatare Stream can be seen flowing into its gorge through the Waiho Loop.

Figure 3-12 shows 2019 and 2023 imagery of the north side of the lower Waiho fan just above the Waiho Loop. In the 2019 image, the breakout channel has yet to completely form, and the area is covered in farmland. The 2023 image shows the newly formed breakout channel (avulsion) into the Tatare Stream which flows along the bottom of both images and then through the Waiho Loop. In this 2023 image, a large portion of the farmland from 2019 has been lost to the river, and offers a very steep pathway for the Waiho River to take from its fan down into the Tatare valley.

This steep gradient (approximately 1.9%) is made obvious in a long profile of the 2023 avulsion channel (Figure 3-13). In Figure 3-13, surface elevation data from 2019 and 2023 has been taken from the top of the avulsion channel at the edge of the Waiho fan and down the channel (the yellow line in Figure 3-12) to where it joins the Tatare Stream. The Waiho River has eroded a considerable amount of farmland between the edge of the Waiho fan and the 851 m distance mark, creating a channel of relatively consistent gradient down to the Tatare Stream.

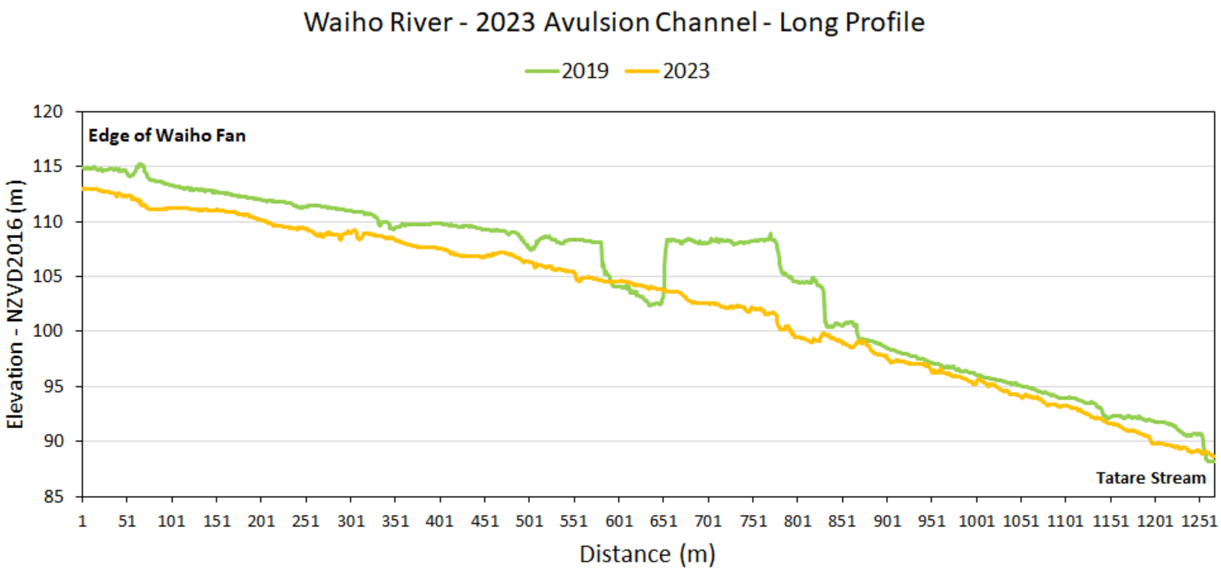

Figure 3-13 – Long profile of surface elevation data along the 2023 avulsion channel between the edge of the Waiho fan and the Tatare Stream.

The current state of the avulsion as of the 8th of June 2023 LiDAR shows the channel to be 2.5 m deep and 64 m wide at its upper end just after it departs the active Waiho fan surface, and 7.0 m deep and 226 m wide at its downstream end just before it joins the Tatare Stream (Figure 3-14).

At present, only one braid has been captured, with the main braid of the Waiho River still flowing out to the sea via the gap between Rata Knoll and the southern end of the Waiho Loop (Figure 3-1). However, as this channel becomes more entrenched, the risk of a full avulsion (where the main flow of the Waiho River is re-routed into the Tatare Stream) is high with considerable implications for the upstream land and infrastructure. These implications have been discussed in depth in section 4.2.2.

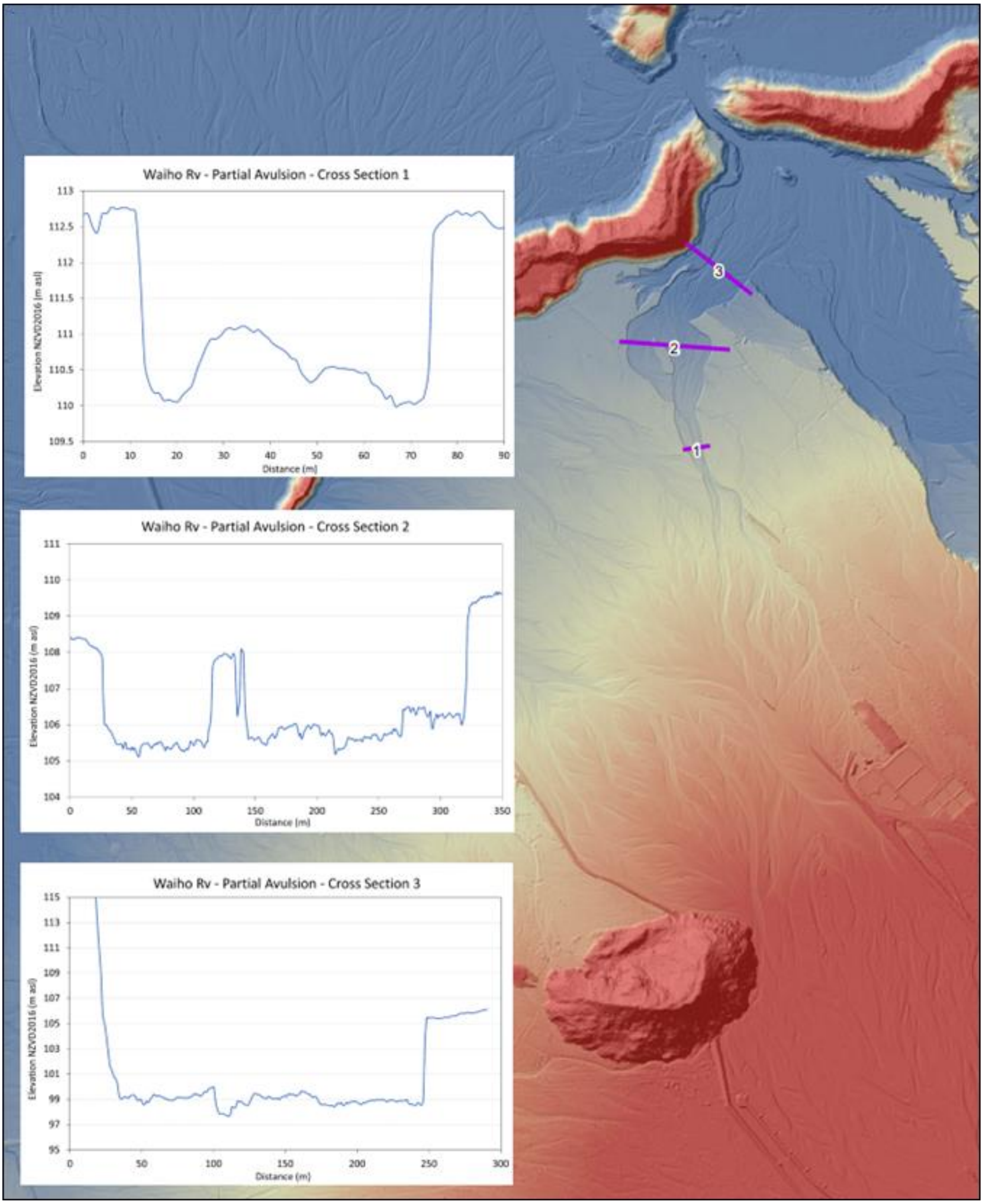

Figure 3-14 – DEM and hillshade layer of the LiDAR flown on the 8th of June 2023 showing the partial avulsion of the Waiho River into the Tatare Stream. The three cross sections on the left show the increasing depth and width of the breakaway channel as they precede downstream.

4. STOPBANKS AS A MANAGEMENT STRATEGY

4.1. HISTORICAL MANAGEMENT OF THE WAIHO RIVER

Since European occupation of the area around the 1890's, the management strategy for the Waiho River and its fan surface, has always been one of control through protection structures such as stopbanks (otherwise known as levees, dykes, or flood embankments), rock gabions, revetments, and groynes.

The location of the township of Franz Josef was originally chosen as it was considered safe from flooding, and provided close access to what was believed to be a reasonably safe and stable river crossing, as at the time, the riverbed consisted of very large glacial lag boulders (Davies & McSaveney, 2001). However, this was proven not to be the case.

- A photo in the 1920s shows a rock gabion (wire crate) on the south side of the river just upstream of the footbridge, presumably to control riverbank erosion and protect the footbridge.
- In 1927, a hotel was moved off the lower terrace on the north side, because of flooding.
- During the 1930's repeated flooding of the former airstrip, prompted construction of a series of rock gabions along the north side to protect the lower terrace and airstrip.
- In 1947, after the river broke out in a flood above Canavan's Knob and flowed down SH6 to Docherty Creek, a temporary low scrub and boulder wall was put in place to prevent overflow and protect the river bank.
- From 1948 onwards (the first available aerial imagery) in order to keep up with and protect from the aggrading fan and very active and powerful river, the number of stopbanks gradually increased, and on occasion decreased. An indication of the power of the Waiho River was its decimation of the 1980 long central stopbank which spectacularly failed after being breached during a flood event.
- Short term river diversion works using the riverbed sediment have also been used to direct the main braid of the Waiho River away from the stopbanks and in an attempt to keep it running down the middle of the active fan surface (Figure 4-1). However, given the nature of the river and fan, these do not last long.

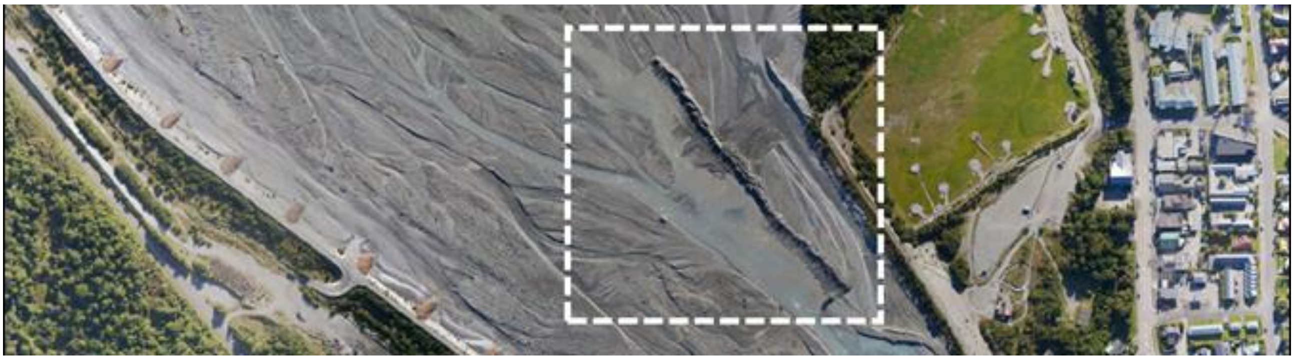

Figure 4-1 - short term diversion works to keep the main braid away from the true right on the 8th of June 2023.

The present day protection network is owned and managed by several organisations including the West Coast Regional Council (WCRC), Waka Kotahi - New Zealand Transport Agency (NZTA), Hokitika Airport Authority, Department of Conservation, and Westland District Council (WDC) (Figure 4-2).

The network is extensive, with stopbanks bounding the very active fan surface on the south side from just upstream of the SH6 bridge down to just below the Waiho Loop, and on the north side, from just upstream of the SH6 bridge to just below the oxidation ponds.

Over the last five decades, the network has experienced repeated damage during flood events, and although the stopbanks have been repaired and raised multiple times to keep up with the rapidly aggrading fan surface, the relatively new stopbanks downstream from Canavan's Knob are already threatened.

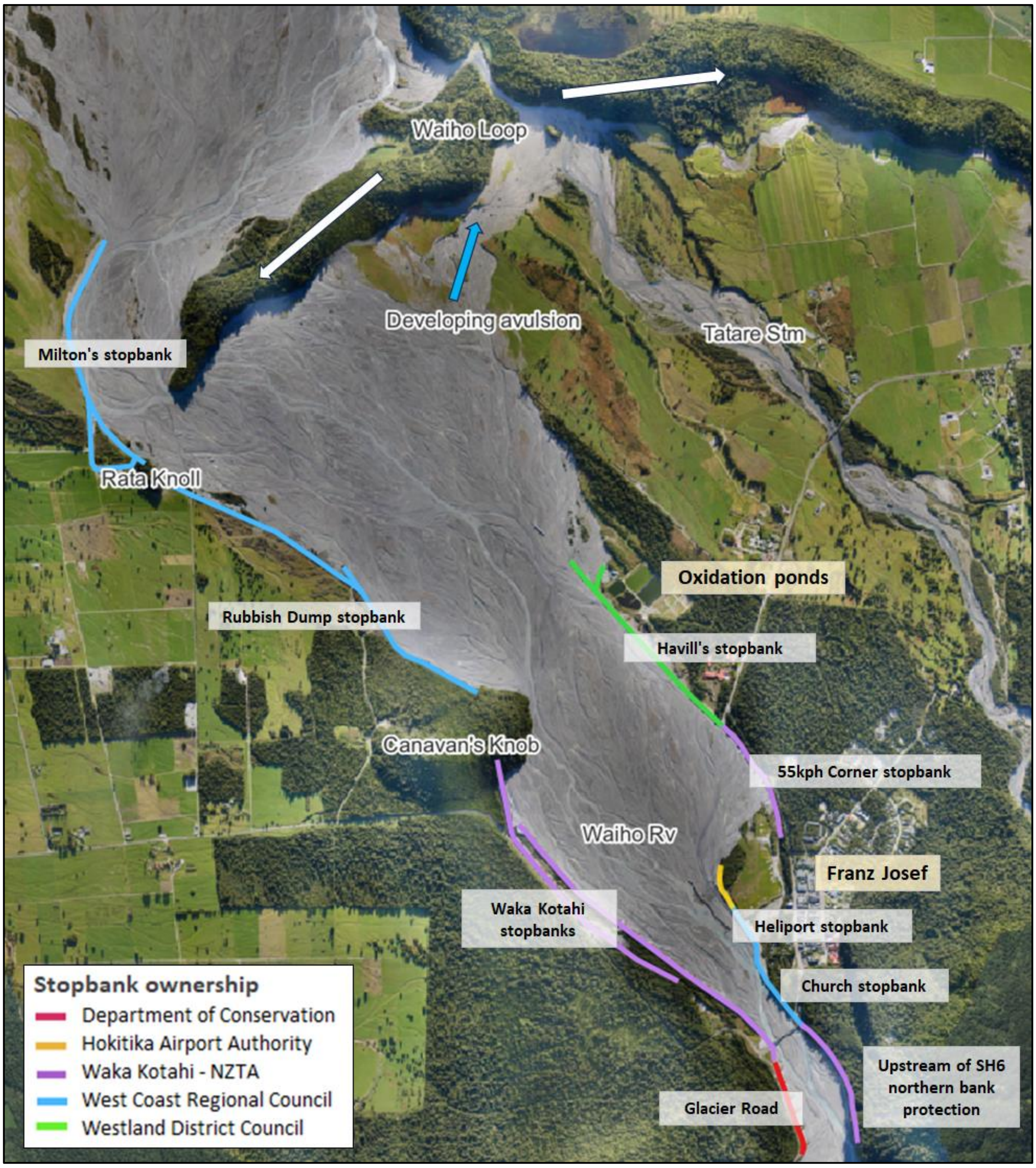

Figure 4-2 – Waiho protection network and ownership as at June 2023

4.2. CHALLENGES OF CONTINUED CONFINEMENT

The current state of the Waiho River along its fan reach between the Callery-Waiho junction and the Waiho Loop has serious implications for flood risk mitigation, with the network facing an array of challenges should it continue to confine the river to only one third of its full fan surface.

The most salient issues are:

- The decreasing capacity of the stopbanks to handle flood events as a result of the aggrading fan surface, that is showing no signs of slowing down.
- The formation of an avulsion channel from the Waiho fan into the Tatare valley which threatens the upstream oxidation ponds and stopbanks.
- The increasing vulnerability to breach and/or overtopping of the Waka Kotahi stopbanks on the south side of the river between the SH6 bridge and Canavan's Knob.
- Problems with the south side rock works in terms of the vulnerability of the highly confining Milton's stopbank, and the risk to the stopbank and rock works between Canavan's Knob and Rata Knoll.

4.2.1. AGGRADATION OF THE FAN SURFACE

The Waiho River is unequivocally still aggrading its fan surface, with no indication of slowing. If anything, given our understanding of the system, and in light of climate oscillations, general climate change and the impending magnitude 8 earthquake on the alpine fault (AF8 earthquake), sediment supply is likely to increase, meaning that the current rate of aggradation will likely continue if not also increase.

Previous studies suggested that there was a link between sediment supply and glacier retreat, as this leaves behind exposed unstable valley sides and scree deposits, which can then be transported directly into the river system by storm rainfall and runoff (Hoey, 1990; Mosley, 1983).

- The Franz Josef glacier has now retreated to the steep dip slope at the end of the valley, and as suggested, there are now large areas of unsupported valley sides, exposed to rain events. As a result this upper valley between glacier terminus and just downstream of the Sentinel and Teichelmann rocks contains a ready supply of sediment for the downstream reaches of the Waiho, in the future.
- The GCD analysis between 2016 and 2019 showed that ~1.1 million cubic metres had accumulated in this upper valley. The analysis between 2019 and 2023, showed that just under half of this was transported downstream, this leaves behind at least ~0.6 million cubic metres of sediment available for future transport downstream and onto the fan.
- It is also likely that the glaciers in the Callery sub-catchment (i.e. Spencer and Burton glaciers) will be retreating too in response to the changing climate, thus increasing the volume of sediment available to be rapidly transported downstream through the Callery River gorge during flood events.

In addition, sediment supply from both the Waiho and Callery sub-catchments is likely to be increased as a result of multi-decadal climate oscillations, and climate change.

- The Interdecadal Pacific Oscillation (IPO) is the long-term oscillation of sea surface temperatures in the Pacific Ocean which affects the strength and frequency of El Niño and La Niña cycles. When in a positive IPO phase, New Zealand receives stronger west to southwest winds which means the West Coast is wetter than average. So, it experiences more extreme rainfall and therefore more frequent flooding than average (Wratt et al., 2022). The IPO is believed to have switched to a positive phase around 2020, with fluctuations between positive, negative, and neutral phases since 2016.
- Coupled atmospheric-ocean general circulation models and physically based downscaled projections for New Zealand forecast an increase in temperature and precipitation on the West Coast, with a mean increase in precipitation of 3.7% by 2050 and 8.0% by 2100 (Anderson et al., 2006, 2008; Mullan et al., 2001; Rutledge et al., 2017).

As rainfall frequency and intensity increases, so too does the volume and frequency of sediment supply to river and fan systems, as a result of increased mobilization of sediment and an increase in the frequency of mass movement events such as shallow landslides (Jakob & Owens, 2021). Therefore, given the shift into a positive IPO phase and the climate change projections, there is likely to be an increase in sediment supply in at least the short to medium term, with subsequent effect on fan surface aggradation volume and rate.

In addition, there is a 15% chance of the AF8 earthquake rupturing in the next 10 years. The impact of a major earthquake and its aftershocks on the Waiho River include immediate and severe damage to the stopbanks and therefore their ability to contain floods, and greatly increased sediment supply from the shaking-induced landsliding, which will rapidly increase the rate of fan surface aggradation.

The consequences of this aggradational behaviour continuing at or increasing from its current rate, will be continued high levels of activity across the fan surface and a reduction in the capacity of the stopbanks to withstand the flows they were 'designed' for, and therefore increasing vulnerability to breach or overtopping.

Land River Sea Consulting Ltd have run their Waiho River hydraulic flood model (Gardner, 2021) with the 2016, 2019, and 2023 LiDAR and the current protection network to show how the aggrading fan surface is affecting peak design water level along the stopbanks and therefore the capacity of the network.

The model results indicate an increase in peak water level along the south side Waka Kotahi stopbank (SH6 Bridge to Canavan's Knob), and north side Church/Heliport and 55pkh Corner/Havill's stopbanks over time, with a pronounced increase between the 2019 and 2023 LiDAR model results (Figure 4-3, Figure 4-4 and Figure 4-5). The GCD analyses suggest, that this pronounced increase is likely due to the transport of just under half of the 1.1 million cubic metres of sediment that had accumulated between 2016 and 2019, downstream between 2019 and 2023.

Further, the 2023 model results show that in places along the stopbanks on both sides of the river, the peak water level is within a metre of the crest level, putting it at risk of overtopping or failure. The upper end of the Waka Kotahi stopbanks and the lower end of the 55kph Corner/Havill's stopbank have minimal to no freeboard, and are therefore very vulnerable to overtopping (Figure 4-3 and Figure 4-5).

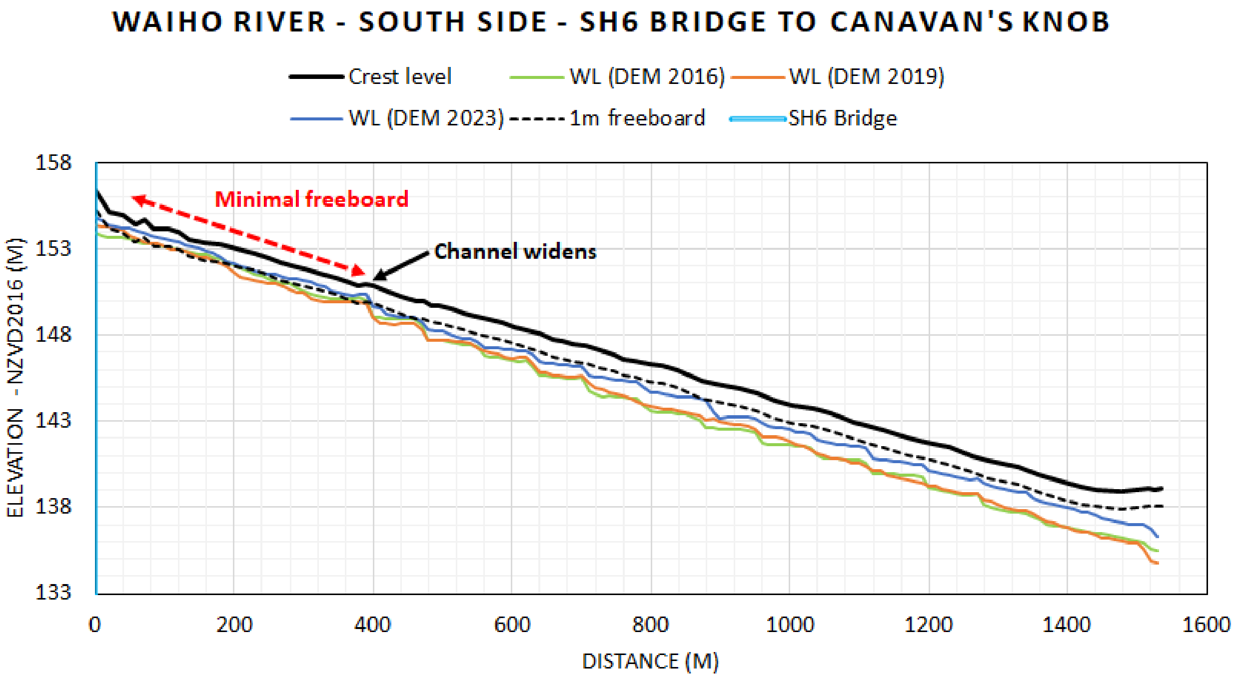

Figure 4-3 – Modelled peak water levels along the SH6 bridge to Canavan's Knob stopbank using the 2016, 2019 and 2023 bed surface elevations.

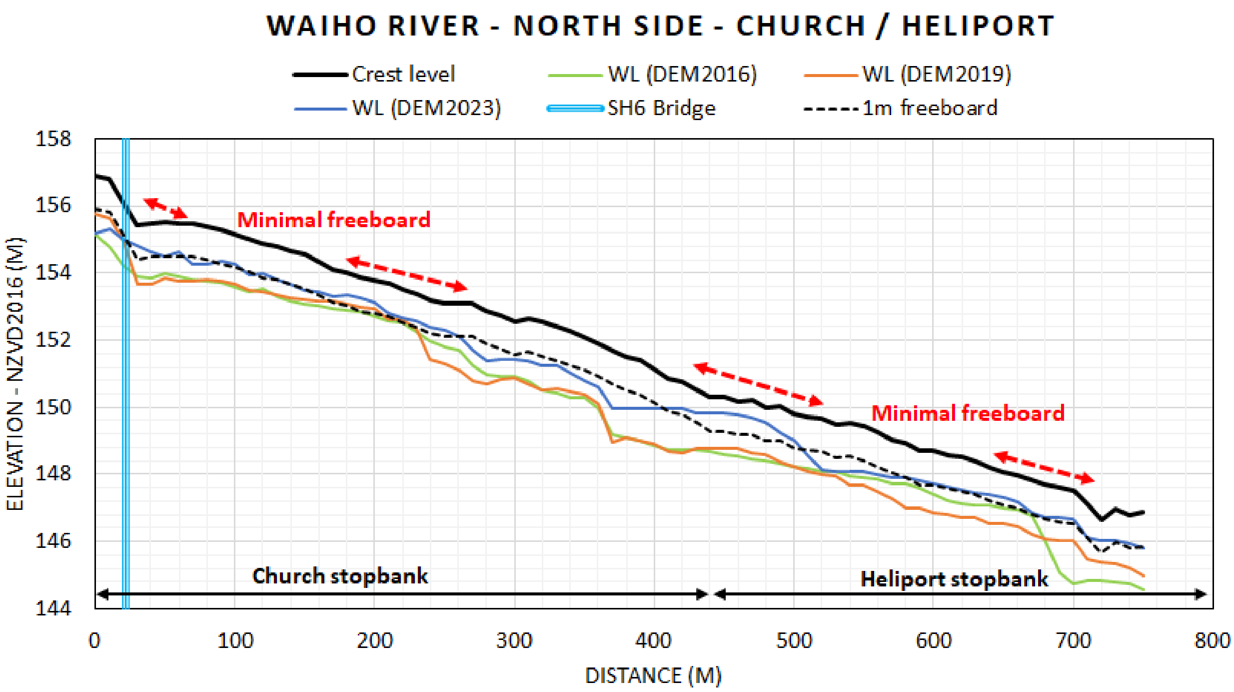

Figure 4-4 - Modelled peak water levels along the Church/Heliport stopbanks using the 2016, 2019 and 2023 bed surface elevations.

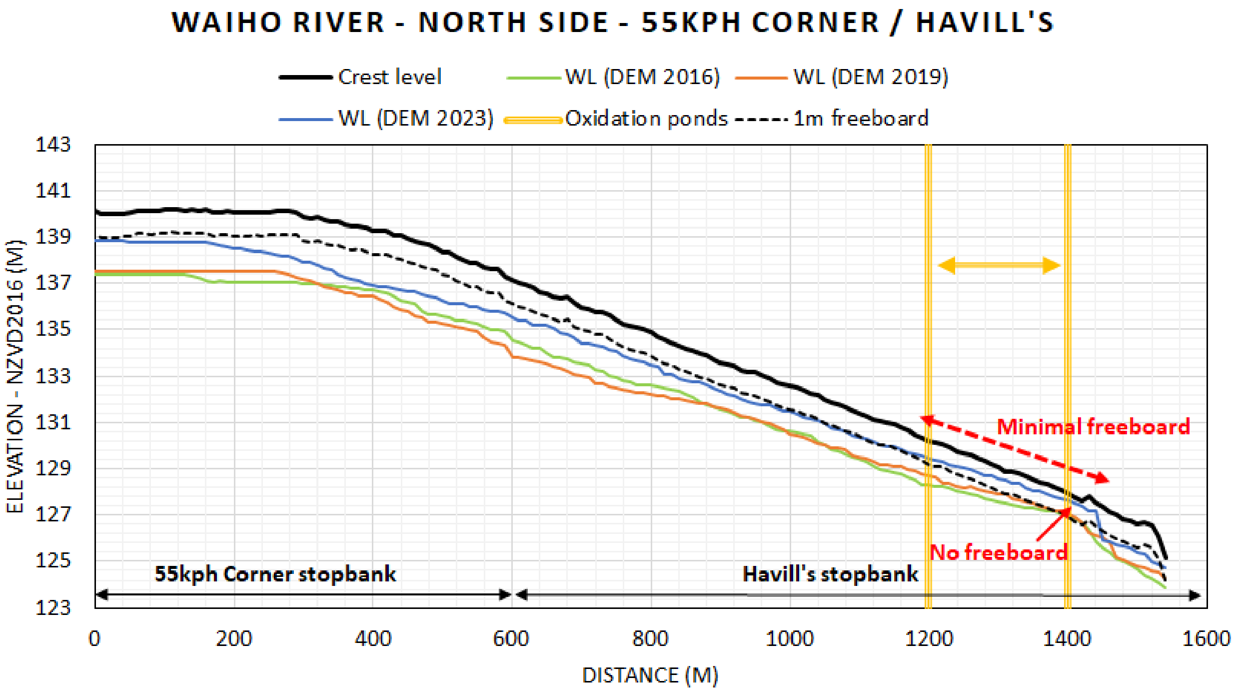

Figure 4-5 - Modelled peak water levels along the 55kph Corner/Havill's stopbank using the 2016, 2019 and 2023 bed surface elevations.

If the aggradation continues as predicted, it will continue to reduce the capacity of the network, increasing exposure to the flood risk and vulnerability of the stopbanks to breach or overtopping during flood events. Whilst in the past this has been dealt with by increasing the crest level of the stopbanks, this requires ongoing and substantial expenditure, increases the residual risk and consequences of failure, and as has been shown does not solve the problem, instead it allows it to continue.

Additionally this aggradational behaviour is also resulting in high levels of channel activity with frequent changes of the main channel and its distributional network through the build-up and erosion of sediment. These changes often result in channels running directly beside the stopbanks or directing flow into them, which places increased pressure on the stopbanks, increasing the risk of underscouring and/or failure.

An example of this can be seen in the Land River Sea Consulting hydraulic model results, which show how recent accumulation of sediment has formed an island in the middle of the river adjacent to the 55kph Corner/Havill's stopbank (Figure 4-6). As a result of this island, flow is diverted to the right, and forced up against the stopbank. It is likely that this island is causing the high water levels along the lower end of the 55kph Corner/Havill's stopbank and therefore the loss of freeboard discussed earlier. However, how the river will respond to this island to future flood events, is relatively uncertain as the hydraulic model uses a fixed bed, and therefore cannot account for the sediment movement that would normally take place during a flood event. It is worth noting though, that the March 2016 breach which saw the Scenic Circle Hotel flooded, occurred when the Waiho River was still confined within a single channel, but that channel was directed towards the 55kph Corner stopbank, forcing the water into it.

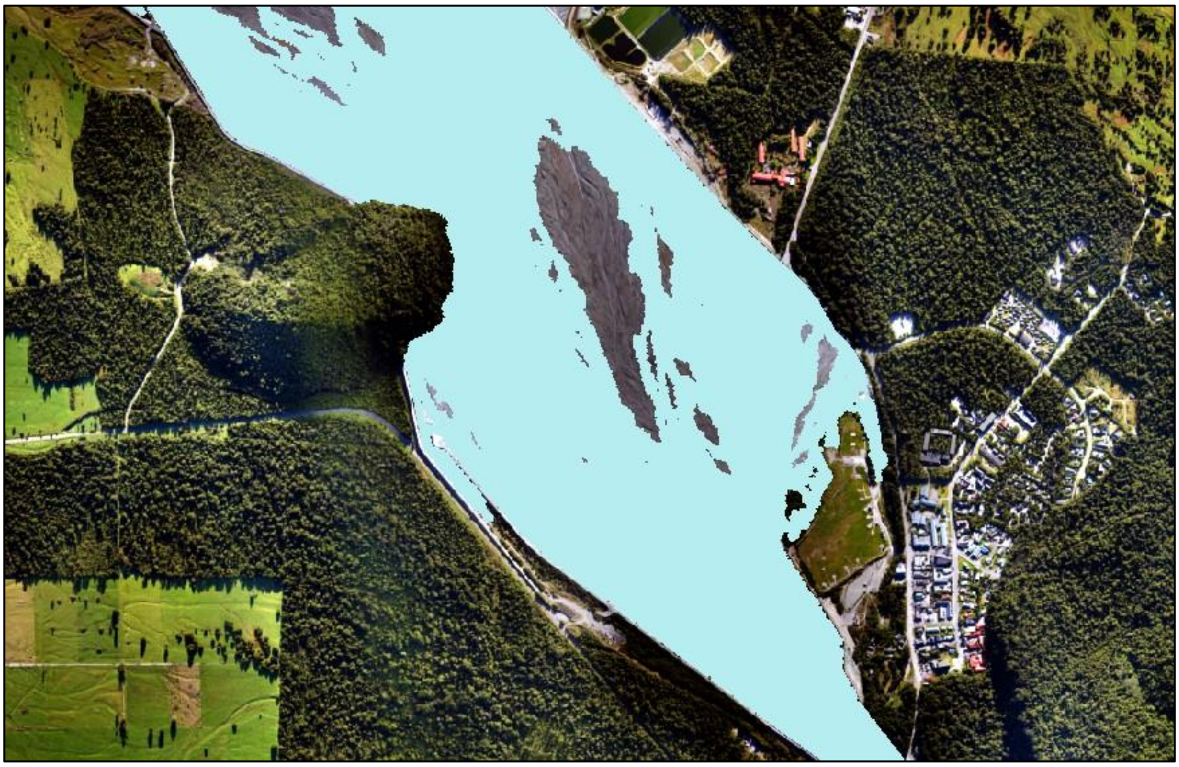

Figure 4-6 - 2021 hydraulic model base run (2500m3/s) using the 2023 LiDAR DEM.

4.2.2. AVULSION INTO THE TATARE

As discussed in section 3.3, the Waiho River has aggraded its fan surface to the point that an avulsion (breakout) into the Tatare Stream is now possible and has been in development since early 2023. There is now a well-defined channel down to the Tatare River, which is wide and well-entrenched. The riverbed upstream of this breakout shows high levels of activity, with both deposition and scouring occurring as a back channel develops upstream towards the oxidation ponds, forcing the north side riverbank to retreat as it does so.

The consequences of a full avulsion have been discussed in reports and papers repeatedly since its first mention in 1998 (McSaveney & Davies, 1998) and have been supported by a microscale model experimental study (Campbell, 2012; Davies et al., 2013). These suggest that should a full avulsion occur, headwater erosion (degradation and widening of the active channel bed) will progress upstream towards the oxidation ponds. And whilst the exact path of the degrading and widening channel, and the timescale of progression cannot be predicted with certainty, the consequences of this behaviour are high (Hall, 2012). Already, onsite observations found back scour progressing upstream towards the oxidation ponds.

4.2.3. LEFT BANK ROCK WORKS

A consequence of the high level of channel activity and aggradation across the fan surface has been an increase in pressure along the Rubbish Dump and Milton's stopbank on the true left side of the fan downstream of Canavan's Knob.

The main channel on occasion now runs alongside the gravel stopbanks between Canavan's Knob and Rata Knoll resulting in progressive erosion of sections of unlined bank which are very prone to failure. An example of recent erosion of the banks is shown in Figure 4-7. As a result of the threat to the stopbanks, there has been progressive lining with rock, resulting in a continuous rock lined wall that joins with the tightly confining Milton's stopbank.

Figure 4-7 – Example of erosion on true left bank (photo taken in October 2022)

Maintaining this long length of rock, with on-going aggradation requiring stopbank raising, and hence adding rock all along this length, would require substantial expenditure. It would also give rise to an increasingly risky structure with each increase in height.

Recent inspections of the rock linings have also noted that the placing and selection of the rock is not in line with industry best practice making it more prone to failure. Site inspections have identified that the rock linings have been placed like a stone masonry wall, using large and elongated rocks that are fixed into an interlocking surface that cannot move without unravelling. While this provides a strong surface, the greatest vulnerability of rock linings comes from bed scouring that undermines the rock lining. Rock lining practice in New Zealand has evolved toward a standard of a well-graded mix of rock sizes that is placed as a mixed rock matrix that can self-heal damaged areas and settle as a whole into localised scour holes and therefore be less prone to failure. If needed the bank can simply be topped up if the crest levels have dropped, however the bank will still be structurally sound.

An example of relatively recent slumping on the Milton's stopbank is presented in Figure 4-8 where it can be clearly seen where the rock work is coming loose from the face and falling into the channel. This is likely a result of bed scour beneath the toe of the bank, and therefore the bank is settling into the scour hole and coming apart due to the nature of the rock placing.

Figure 4-8 - Visible stopbank slumping (highlighted in yellow)

This rock lining shows the disadvantages of a fixed rock lining, where bed scouring has given rise to (localised) dropouts of the lining rock, leaving a steep opened face, very vulnerable to direct damage from turbulent flood flows. While aggradation may cover over the lower parts of rock linings on the fan, the rock wall and the tight bend of Milton's stopbank are at risk of underscouring. Further, with the bend bar opposite Milton's stopbank building up, scour depths along the Milton's stopbank are likely to increase. Any scouring to the underside of the rock here will result in an immediate collapse of the stopbank, with a sudden release of floodwaters from a narrow channel carrying a substantial part of the flood flow. The failure and resulting flooding is likely to be catastrophic.

Additionally, the rising bed levels in the lower fan which resulted in the breakout channel into the Tatare valley, have also given rise to a wide depositional front along the length of the Waiho Loop with a channel forming in between. This channel allows a high flow capacity up against the moraine wall, which means that substantial flood flows will run down the right side of the fan before passing along the length of the Waiho Loop where they will then be directed straight into the Milton's stopbank, further increasing the risk and consequences of failure.

An incidence of such failure occurred in 2019 during the March flood which took out the SH6 bridge as well as breached Milton's stopbank (Figure 4-9). Floodwaters from the breach destroyed the Franz Josef airstrip as well as a large area of farmed land (Figure 4-10).

Figure 4-9 - Milton's stopbank breach location, and downstream inundation of farmland.

Figure 4-10 - Aerial image showing the flooding of the Franz Josef airstrip as a result of the Milton stopbank failure. Photo by Wayne Costello/DOC.

A recommendation was made by Land River Sea Consulting at the time that the Milton's stopbank was unsustainable in its current location and needed to be realigned and shifted back to lower the scour potential. This was considered by the council, however due to insurance, we were advised that this was not possible, and it needed to be rebuilt in the same location. As described above, the continued aggradation and high channel activity is putting the existing structure under threat, and it will also require significant expenditure to extend the lifespan of the structure.

5. FUTURE MANAGEMENT

The Waiho River and fan has been confined by protection structures for many years, and this confinement has been maintained through a very prolonged period of aggradation. However, this confinement is becoming increasingly expensive, and will continue to do so as the aggradation continues, especially as there is justification to believe that the rate of aggradation will increase in the short to medium term. Therefore, to continue to maintain the stopbanks is not just going to become too expensive, but increasingly unsafe.

Each time the crest level of the stopbanks is raised it increases the residual risk and consequences should a stopbank failure occur.

- With each increase in height, the fall from the crest level down to the adjacent land increases.
- This results in increased water velocities should the stopbank be breached or overtopped, a relationship that is not linear, but exponential.
- As velocities increase so too does the potential for floodwaters to erode land and damage buildings, as well as risk to life.

Additionally, ongoing maintenance and upgrades of the network are impractical. The dynamic and powerful nature of the Waiho River and its fan has created a situation in which making realistic design decisions is very difficult - even untenable - and where the continued use of structural measures to mitigate the flood hazard has now reached its practical limit.

The ongoing aggradation, the predicted increase in frequency and intensity of flood events and therefore sediment supply, and the recent avulsing behaviour of the river highlights the fact that another management strategy is needed. The relaxation of the southern boundary option provides the river with more room for its very high level of activity and aggradational behaviour, and allows time for retreat of the Franz Josef township, heliport, and wastewater treatment plant.

It is an option that is based on an understanding of the aggradational behaviour of the Waiho River which is backed by over forty years of extensive reports and studies, and the response of a river to confinement and changing width.

Further, it is an option that has been previously considered, with the cost to buy out the land, realign the highway and remove the landfill also priced (Hall, 2000; Vorster & Hart, 2020). However, one problem when assessing historic cost estimates is that differing methodologies have been adopted and the scope of works being proposed for each assessment has not always been clearly documented. We have sighted three quite different cost estimates for the relaxation of the southern banks, two of which are almost an order of magnitude different when pricing the same works. We have therefore left costings out of this report and recommend that a detailed and clearly documented costs assessment is put together in collaboration with all agencies involved to ensure accuracy.

In order to carry out a proper economic cost / benefit assessment of relaxing the southern stopbank boundaries and allowing the river to flow to the south, it would also be essential to gather accurate economic data in relation to the contribution to the economy from the land use. We do not currently have this data available to us.

5.1. RELAXATION OF THE BOUNDARIES RATIONALE

As discussed in section 3.2, the Waiho River has been aggrading its fan surface since at least 1948 and more rapidly since the late 1970's. At the same time as this change in aggradation rate, the depositional area of the fan has been confined to one third of its natural fan surface, through the use of stopbanks and edge protection works.

Traditionally, confinement of a river has been designed to increase the depth of flow, thereby increasing transport capacity, and subsequently promoting degradation, not aggradation. However, in the case of the Waiho River, it still functions as a fan with a fully braiding channel within its confined reach between the SH6 bridge and the Waiho Loop. Therefore, confinement has not resulted in an increase depth.

Instead, confinement of the Waiho has limited the ability of the river to laterally migrate across its fan surface – a critical function of any river and fan relationship – whilst reducing the surface area available for it to deposit sediment. As a result, with less space to spread its sediment load horizontally, the Waiho began to accrue it vertically at a faster rate than before.

Subsequently, it follows that by relaxing the boundaries to the south of the Waiho River and therefore increasing the area of fan surface available to it, the Waiho River will have more space to spread its sediment load horizontally, thus slowing the rate of vertical increase.

In 2017, using a microscale model, Beagley et al (2020) investigated two alternative stopbank alignments which increased the area of fan surface the Waiho River has access to (Figure 5-1).

- An intermediate alignment which doubled the area the Waiho River could access whilst still protecting a large portion of the farmland for continued human use.
- An extreme alignment which allowed Waiho River to access its entire fan surface to the south i.e. all of the farmland.

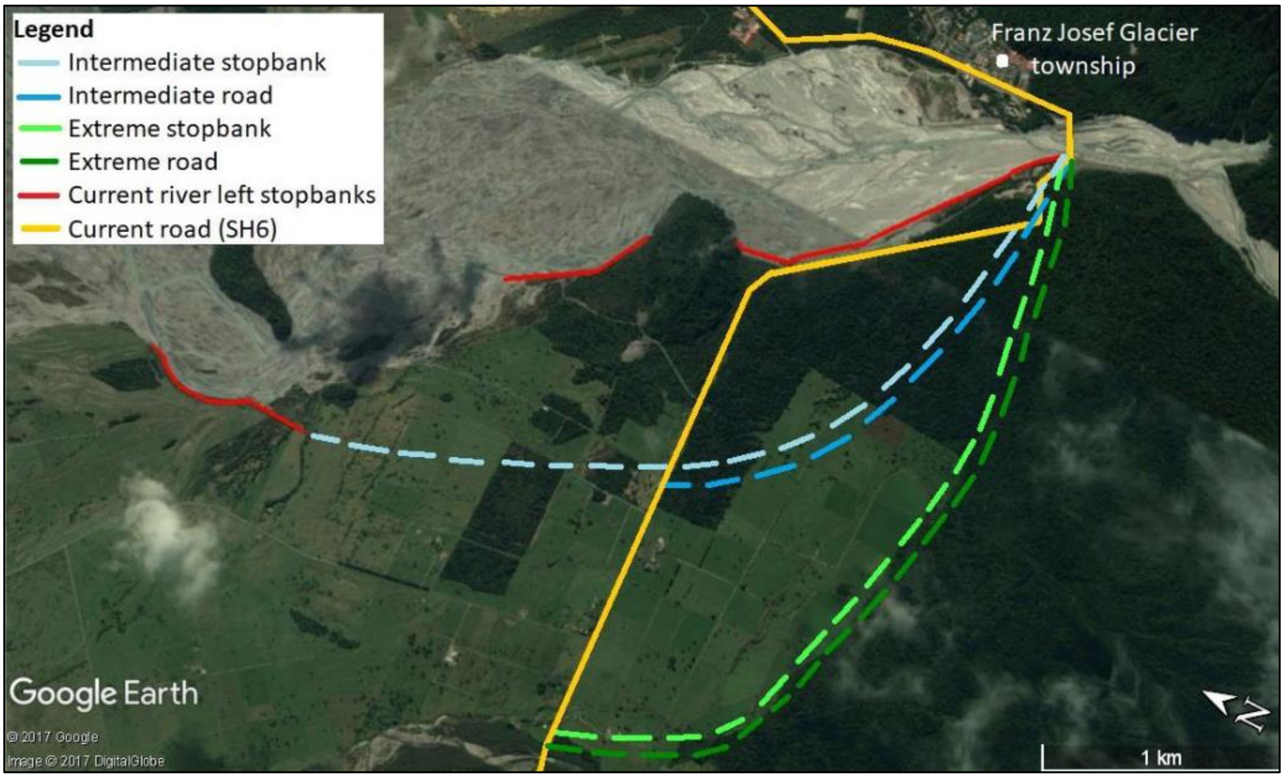

Figure 5-1 - The three stopbank alignments simulated in the 2017 microscale model study.

For each scenario, the microscale model was allowed to aggrade from a sloped and smoothed out planar surface, before the current (2017) stopbank network was installed and aggradation rates recorded. Then, after a period of time the south side stopbanks were removed and the response to the sudden increase in fan surface area was observed.

In both scenarios, the removal of the south side stopbanks resulted in some initial degradation at the fan head i.e. just downstream of the SH6 bridge which was likely the result of the increased velocities due to the steeper gradient between the aggraded and newly released areas. This was then followed by net aggradation across the whole fan surface, however the rate of vertical rise occurred was slower compared to that of when the modelled river was restricted by the south side stopbanks.

This response has been corroborated by a more recent numerical model study investigating how changing river width impacts bedload transport and aggradation rate (Measures et al., 2021). By comparing the results of 15 different constant-width domain model runs, between 200m and 3000m wide (Figure 5-2), Measures et al. were able to show that:

1. In a severely narrowed width (300m and below), where a river functions as a single thread during flood events, confinement leads to increased transport and reduced aggradation, therefore resulting in net erosion.
2. In more moderate widths (400m to 2000m), where the river can braid, the net volume of aggradation remains similar, however as width increases, the vertical increase in bed level elevation slows, as the volume of aggradation is able to be spread out across a greater surface.

3. The model showed that the widest widths (2500m and above) have higher transport rates and less aggradation. However, the modellers were uncertain as to whether or not the model was run long enough to fully develop the braided initial planform prior to starting the simulation.

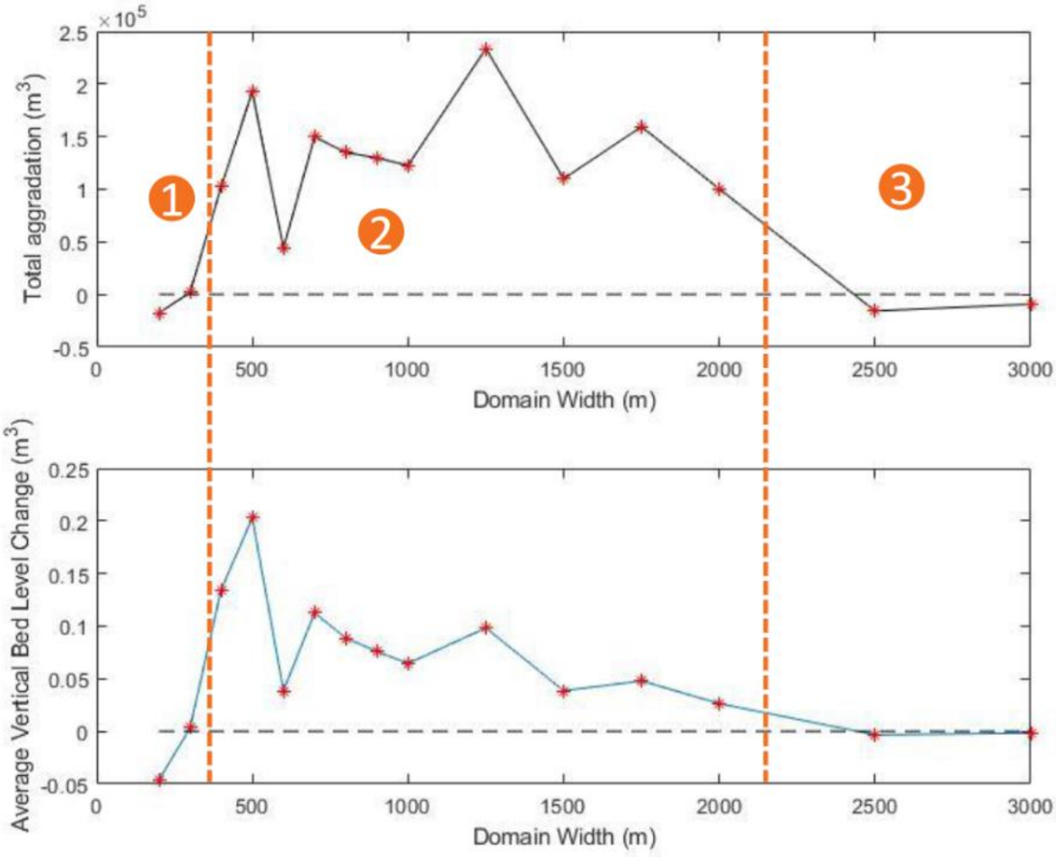

Figure 5-2 - Results from the different constant width experiments.

Measures et al. also used their calibrated numerical model of the Waiho to test the response of the river to the removal of the south side stopbanks. However, given the findings are yet to be formally published, and the authors have stated that the results warrant further analysis to build confidence in the modelling, we have erred on the side of caution, and only discussed the constant width experiments which were conducted in greater depth compared to the testing of the Waiho stopbank realignment.

Regardless of this final point, the implications of the other findings remain. Relaxation of the southern boundary will not stop the aggradational behaviour of the Waiho River nor will it prompt a return of the fan surface to some lower elevation. However, it will slow the rate of surface rise from the aggradation.

This reduced rate of rise is important for the future management of the area, as it will provide the Franz Josef community with the time for a managed retreat of the oxidation ponds, heliport, and township away from both the flood and avulsion hazards posed by the Waiho River.

Furthermore, even if the existing management strategy was continued, and the southern boundary of stopbanks were retained, there is a high chance that the Waiho River will break out to the south by itself, as it has done previously in the 20th century. The consequences of this would be catastrophic, with the likelihood of loss of life, livestock, and property, high. By actively managing a relaxation of the southern boundary and controlling the release of the Waiho River to the south, the impact on life can be reduced.

5.2. IMPACT OF RELAXING THE SOUTHERN BOUNDARY

The relaxation of the southern boundary option involves the removal of the south side stopbanks both upstream (the priority) and downstream of Canavan's Knob. These include:

- The Waka Kotahi stopbanks upstream of Canavan's Knob;
- The Rubbish Dump stopbank; and
- Milton's stopbank.

In doing so, the river will be able to access its entire fan surface, and the downstream Waiho Flats. However, the impact of this will be considerable.

The main channel of the Waiho River will not simply shift to the south and occupy just one location. The highly dynamic nature of the river means that the main and distributional channels will continue to change as they have always done within the current confinement. Therefore, the entire area of land to the south of the Waiho River will be at risk of scour and deposition of gravels and sediment.

We have modelled the removal of all of the stopbanks on the south side of the Waiho River with an estimated 1 in 100 year ARI flood flow. The results show considerable inundation of the land from the Southern Alps range front down to the Waiho River mouth (Figure 5-3). Though there is an island of relatively untouched land in the centre of the lower flats, it is unlikely that this would stay that way. The ongoing movement of sediment, erosion of the existing farmland, and different channel alignments would place all of the land downstream of the Waiho Loop at risk.

Thus, this option requires the buyout of all of the land to the south of the Waiho River, the removal of infrastructure to prevent this from being washed downstream and out to sea, and the realignment of SH6. Trying to control how much of the southern land the river has access to in order to minimise costs, will not be possible, given the dynamic, powerful, and braided nature of the river. Nor is just removing the stopbanks downstream of Canavan's Knob.

The Waiho fan begins just downstream of the SH6 bridge, and as a result experiences high levels of activity and therefore considerable aggradation in this upper reach between the bridge and Canavan's Knob. This puts pressure on the north side stopbanks that protect the Franz Josef township and heliport, and therefore risk to land, infrastructure, and life. In order to reduce (though not remove) this pressure, the stopbanks upstream of Canavan's Knob must be removed, giving the river space to move south away from the northern banks.

Additionally, this should also reduce the risk of a full avulsion into the Tatare valley occurring in the immediate future, as the main flow of the river will be diverted to the southern side of Canavan's Knob and therefore away from the Tatare. Just releasing the river downstream of Canavan's Knob, will not do this.

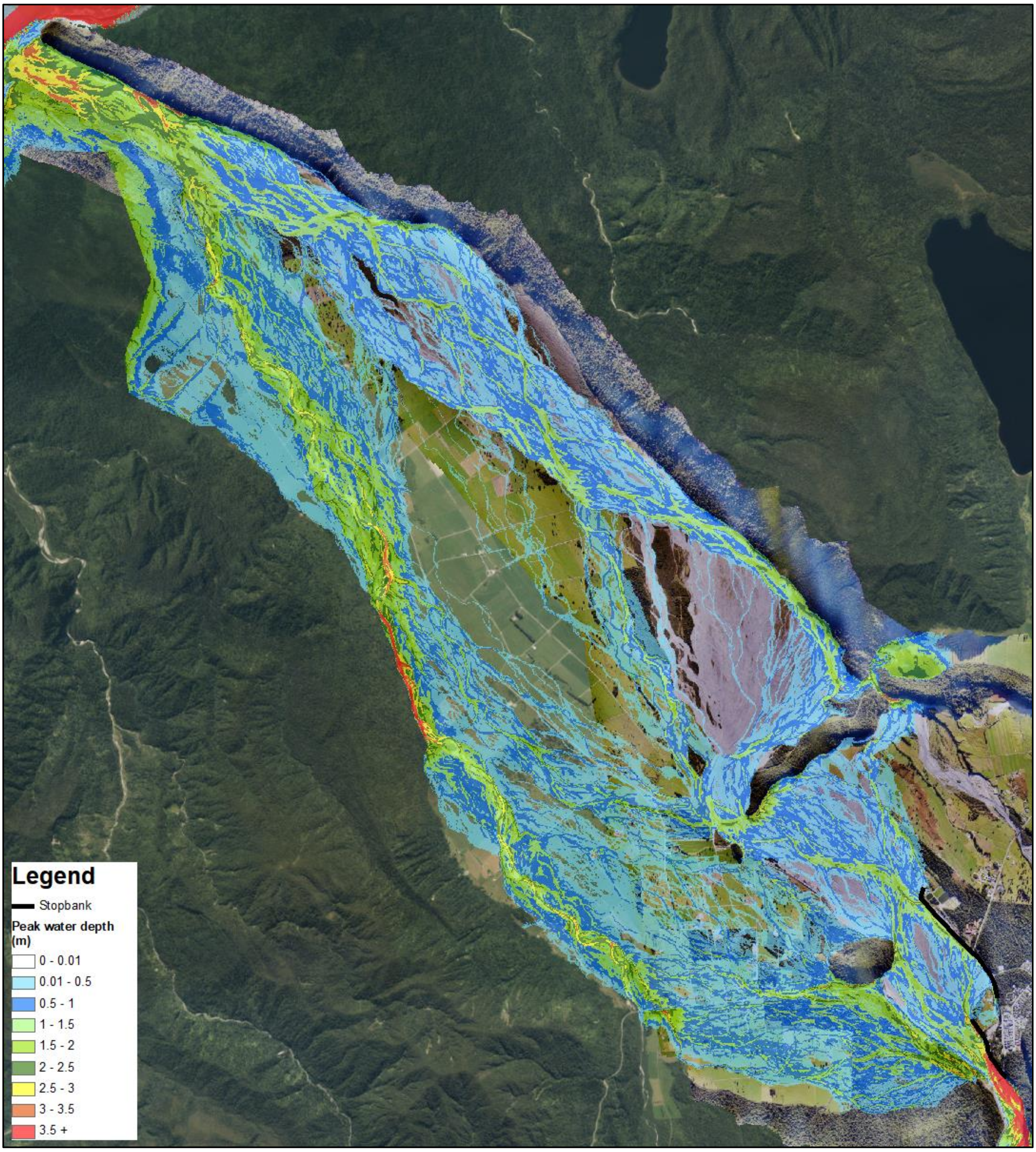

Figure 5-3 - Land River Sea Consulting hydraulic model result of the 100 year flow – no south bank scenario.

5.3. MANAGEMENT OF NOTHERN STOPBANKS

5.3.1. HELIPORT STOPBANK

Regardless of what happens with the relaxation of the southern boundary, it needs to also be acknowledged that the current location of the Heliport is unsustainable and consideration to relocating these assets must be given priority.

Even without further increase to the stopbank crest levels, the residual risk and consequences of breach or overtopping of the current stopbank in this location are very high. The crest of the stopbank is already between 7 m and 8 m higher than the immediately adjacent land (the heliport), and the council is proceeding with construction under emergency works provisions prior to receiving consent, to increase the crest level by ~2 m. This will increase the vertical fall to between 9 m and 10m in this location, with significant increase in consequences should the banks overtop or fail (Figure 5-4).

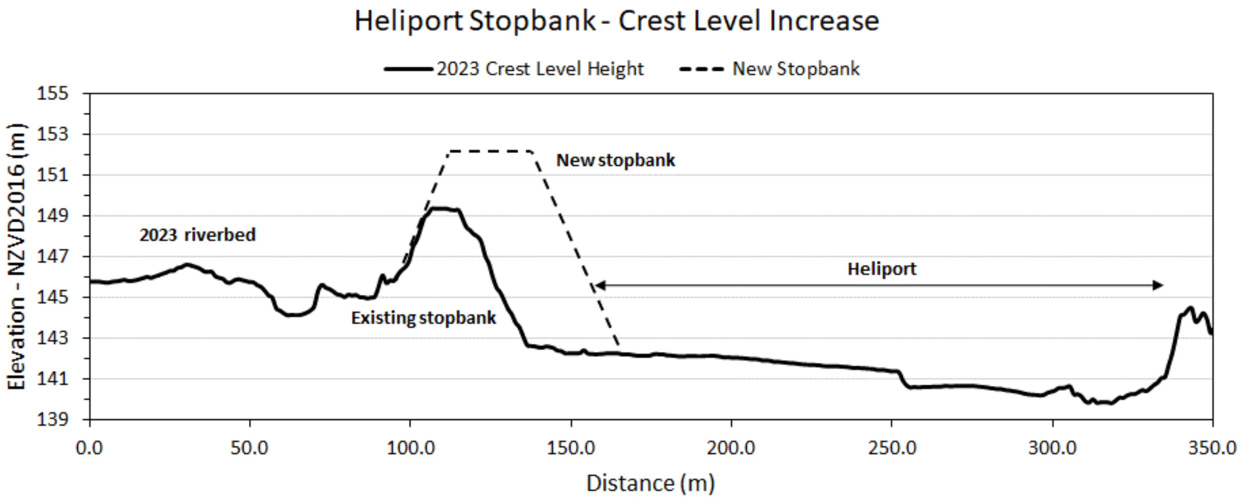

Figure 5-4 – Cross section at the heliport showing the existing stopbank and the proposed crest level and width increase.

The consequences of failure of this wall would be catastrophic with certain destruction of any assets in the way of floodwater and certain loss of life if anyone was unfortunate enough to be in the vicinity at the time of a flood.

5.3.2. TATARE BUND / HAVILLS WALL

John Ellis, Gary Williams and Matthew Gardner have all visited the location of the partial avulsion into the Tatare and made comment on the potential for engineering options to mitigate the effects of the diversion. It is clearly evident on site that the headcut is already advancing rapidly towards the oxidation ponds. This is very serious as should the channel reach the oxidation ponds, scouring will likely undercut the protection measures around the facility. At the same time the general aggradation taking place on the fan surface will reduce the effective height (capacity) of the defence measures. This combination of scouring and depositional activity would make any reinstatement of the stopbanks impractical and of ill-defined but short period effectiveness. Further, continued headwater erosion upstream of the oxidation ponds, would likely affect both the township of Franz Josef and the stopbanks on both sides of the river (Hall, 2012).

This development makes it difficult to determine what the right course of action is for the upstream north side stopbanks. Work has already started on the 55kph Corner stopbank to increase its crest level height, with the plan to also increase the crest level height of Havill's stopbank.

Considering the current avulsing behaviour of the Waiho River, consideration will need to be given to the best course of action in regard to raising Havill's stopbank.

As of February 2023, when the avulsion began to develop at pace, construction had not started on the Tatare Bund, as first proposed by Williams and Gardner in 2015 and consented in 2021. As a result of the significant changes to the topography due to the partial avulsion, our assessment is that this is no longer worthwhile, nor technically feasible.

The primary purpose of the bund was to prevent overflow from heading to the north towards the Tatare and from allowing the predicted back scour to begin to occur. Now that significant back scour has already occurred and is likely to rapidly progress upstream, works to prevent further back scour are likely to have high risk of failure. The primary reason for this being that the natural high land where the bund was proposed to be constructed on, no longer exists. If a new stopbank was constructed to block this overflow path, it would have to be built in the riverbed, and to at least the same standards as the existing upstream stopbanks which are being currently raised. Preliminary back of the envelope cost estimates place this at a minimum spend of $10 million, likely higher due to the requirement for additional toe rock to try and prevent undercutting.

Whilst this report is not intended to be an engineering options assessment, other alternative options which could be considered in this location, could include but are not limited to:

- Managing the braid alignment through physical intervention in order to keep the main braid on the left of the fan and flowing against Milton's stopbank as it has done until now. It must be noted that this would also come at significant ongoing cost, and every time there is a fresh in the river, the braid is likely to align itself back towards the Tatare, due to the current fall of the fan surface to the north. Active management of the braids may have limited success, and if anything would only delay the natural processes whereby a permanent avulsion into the Tatare will fully develop. Managing river alignments can also have unintended consequences, causing more harm in other locations.
- Moving the oxidation ponds away from the river, either by constructing a self-contained wastewater treatment plant in the town, as previously recommended by Opus International Consultants (now WSP) or finding a more suitable location for the ponds. It is our understanding that when built in 2016, these ponds only had an intended lifespan of 15 years, to be reassessed when the existing consent was due to expire. Consideration could be given to using some of the funds currently set aside for constructing the Tatare Bund and raising Havill's stopbank, for relocation of the existing ponds, knowing that any engineering works to protect them, may be very prone to failure due to the exceptionally dynamic nature of the river in this location.

- If the southern stopbanks are removed, it may be possible to keep the river flowing to the south for many years and therefore significantly delaying a permanent avulsion into the Tatare. It must be acknowledged however that this will realistically require significant time to put into action, and even if the process of purchasing properties and realigning the highway etc. started today, it may be too late to prevent a full avulsion into the Tatare.

6. CONCLUSIONS

The following conclusions can be drawn from this study:

- The Waiho River system has been studied extensively since the 1980's to better understand it's behaviour and the risks it poses to the surrounding community and infrastructure.
- These studies describe a very dynamic and powerful river fuelled by a high supply of sediment and frequent high flow events, which has been confined by stopbanks to just one third of its natural fan surface.
- Cross sectional and LiDAR datasets present a rapidly aggrading fan surface, with analyses indicating that the surface is likely to continue to aggrade by at least the same rate if not faster in the short to medium term.
- In its current state the crest level of the stopbanks are in places up to 8 m higher in elevation than the adjacent land. Additionally, the aggrading bed is reducing the capacity of the stopbanks to handle the flood flows they was designed for. This presents a significant risk to land, infrastructure, and life. If the stopbanks are breached or overtopped during a flood event, catastrophic flooding is likely.
- The heliport is particularly vulnerable due to the rapidly aggrading adjacent riverbed, and from the planned increase to the crest level height of its stopbank (already underway) which will only further increase the fall from crest level to land. The consequences of breach or overtopping are significant. Consideration to relocating the heliport must be given high priority.
- In recent months, the aggradation of the fan surface has led to a partial avulsion of the Waiho River into the Tatare Stream. A full avulsion places the upstream oxidation ponds, stopbanks and township at risk of undercutting and erosion, and once occupied by the main flow of the river, is believed to be irreversible.
- Increasing pressure on the south side of the network, particularly at the tightly confining Milton's stopbank due to increased channel activity and the aggradational trend, indicates that risk of another breach or overtopping event similar to that which occurred in March 2019, is likely.
- The rating district is small, therefore so are the funds relative to the size of the network and the ongoing maintenance and upgrades required to keep it functioning effectively, even with district, regional and central government support.
- Continuing to maintain the current stopbank network with upgrades to crest level heights to manage the aggradational behaviour, is an expensive and impractical exercise, and increases the residual risk to the Franz Josef community and infrastructure, with catastrophic flooding likely should the stopbanks breach or overtop.
- Further, continuing to confine the river within the current stopbank alignments whilst increasing the crest level does not solve the problem of the aggrading fan surface, only allows it to continue.

- Microscale model and numerical model studies indicate that increasing the area of fan surface available to the river will provide it with a greater surface to deposit sediment which will therefore slow the rate of rise of the fan surface from the aggradation.
- Even so if no action is taken, there is a high chance that the Waiho River will avulse to the south by itself. If it does so, the consequences will be catastrophic with a high likelihood of loss of life, livestock, and property.

7. RECOMMENDATIONS

To continue to manage the aggradational and avulsing behaviour of the Waiho River through rigid confinement is no longer sustainable or safe. Nor is it justified given our understanding of how confinement of a fan surface affects the rate of rise of the surface from aggradation.

Instead, we recommend a different management strategy, one which has been suggested on numerous occasions, which allows a relaxation of the southern boundary protection structures, and shifting of SH6 between the Waiho River and Docherty Creek back to the edge of the mountains.

By removing the south side stopbanks that extend from the SH6 bridge down to Rata Knoll, the Waiho River will be able to access its entire fan surface. This will:

- Allow a greater horizontal spread of its high bedload, which should slow down the rate of rise of the fan surface.
- Reduce the pressure on the north side stopbanks which protect the township and oxidation ponds; and
- Reduce the chances of a full avulsion into the Tatare Stream in the near future. However, given the aggraded state of the Waiho fan surface, a full avulsion into the Tatare valley cannot be ruled out.

This management strategy effectively reduces exposure from, and the risks of, the hazards posed by the Waiho River, whilst providing time for a relocation of the Franz Josef township, heliport, and oxidation ponds, out of harm's way.

In addition to removing the southern stopbanks, urgent consideration needs to be given to relocating the heliport. At present, there is an extremely high risk to the land and infrastructure protected by the Heliport stopbank. Should this stopbank overtop or fail, especially after it has been raised a further 2 m, the consequences will be catastrophic.

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9. APPENDIX A – PREVIOUS REPORTS, ARTICLES, AND STUDIES.

Year	Authors	Title	Type
1983	Mosley	Response of the Waiho Rv to variations in Franz Josef Glacier	Internal report – Hydrology Centre
1987	Davies	Problems of bedload transport in gravel bed rivers	Book section
1990	Benn	Summary of flood events on the West Coast from 1846 to 1990	Report
1990	Hoey	Aggradation in the Waiho River	Report
1991	Thompson	SH6: Waiho River Bridge Waterway Requirements	Report
1994	Zarn and Davies	The significance of processes on alluvial fans to hazard assessment	Scientific Paper
1997	Davies	Long-term management of facilities on an active alluvial fan – Waiho River Fan, Westland, New Zealand	Scientific Paper
1997	Davies and Scott	Dambreak flood hazard from the Callery River	Scientific Paper
1998	Davies	Franz Josef Glacier access road-security of end facilities	Report
1998	McSaveney and Davies	Natural Hazard Assessment of the township of Franz Josef Glacier and its environs.	Report
1999	Clarkson	Small-scale hydraulic modelling of alluvial fans.	Master of Engineering - Thesis
2000	Davies	Sediment production, transfer, and deposition in the Waiho River system	Report
2000	Hall et al	Evaluation of options for the management of the Waiho River Aggradation Threats	Report
2001	Rouse et al	The Transit New Zealand Waiho Workshop	Workshop report
2001	Gough	Changes in understanding, awareness and preparedness for natural hazard risk in Franz Josef Glacier	Report
2001	Davies and McSaveney	Anthropogenic fanhead aggradation, Waiho River, Westland, New Zealand.	Scientific Paper
2002	Milligan	Waiho River flooding risk assessment	Report
2002	DTec Consulting	West Coast Natural Hazards Review	Report
2002	Davies	Landslide dambreak floods at Franz Josef Glacier township: a risk assessment	Scientific Paper

2003	Davies et al	Anthropogenic aggradation of the Waiho River: Microscale Modelling	Scientific Paper
2003	Davies et al	Water and sediment outbursts from advanced Franz Josef Glacier, New Zealand	Scientific Paper
2004	Korup	Landslide-induced river channel avulsions in mountain catchments of southwest New Zealand	Scientific Paper
2005	Goodsell et al	Outburst flooding at Franz Josef Glacier	Scientific Paper
2006	Davies and McSaveney	Geomorphic constraints on the management of bedload dominated rivers	Scientific Paper
2006	Davies and Korup	Persistent alluvial fanhead trenching resulting from large infrequent sediment inputs	Scientific Paper
2008	Tovar et al	Evidence for a landslide origin of New Zealand's Waiho Loop moraine	Scientific Paper
2008	Good Earth Matters	WCRC – Waiho River Flood Protection – Design Flood Levels	Report
2008	Davies and McSaveney	Principles of sustainable development on fans	Scientific Paper
2009	Carrivick and Rushmer	Inter- and intra-catchment variations in proglacial geomorphology: an example from Franz Josef Glacier and Fox Glacier.	Scientific Paper
2011	Good Earth Matters	WCRC – Waiho River Flood Protection – Updated flood modelling.	Report
2012	Trayes	Franz Josef – Waiho – A multiple natural hazard area	Report
2012	Hall	Waiho River Future Management	Report
2012	Campbell	A microscale modelling experiment to investigate the effects of an avulsion of the Waiho River into the Tatare River, South Westland, New Zealand	Honours Dissertation
2013	Davies et al	Recent behaviour and sustainable future management of the Waiho River	Scientific Paper
2014	Alexander et al	Formation of the Waiho Loop terminal moraine	Scientific Paper
2014	Purdie et al	Franz Josef and Fox glaciers: historic length records	Scientific Paper
2014	Gardner	Waiho River Hydraulic Modelling and Analysis	Report
2015	Gardner and Healey	Waiho River - Long Term Monitoring	Memo to WCRC
2015	Gardner	Waiho River Stopbank Extension Helipad	Memo to WCRC
2016	Langridge et al	A Natural Hazard Assessment for the Township of Franz Josef, Westland District	Report
2016	Gardner	Waiho River Mean Bed Level Analysis (1983 to 2016)	Memo to WCRC
2016	Gardner	Waiho River Potential Options	Memo to WCRC

2017	Tonkin and Taylor	Franz Josef natural hazards options assessments and cost benefit analysis	Report
2017	Beagley	Effect of alternate stopbank alignments on the Waiho River, Westland, New Zealand: a microscale modelling investigation	Master of Science - Thesis
2019	Gardner	Franz Josef Glacier Road Access – Assessment of Effects	Memo to WCRC
2019	Gardner and Brassington	Waiho Loop Cut Investigations	Report
2019	Gardner and Brassington	Waiho Change Detection Analysis	Report
2019	Dunant	Quantification of multi-hazard risk form natural disasters	Doctor of Philosophy - Thesis
2020	Beagley et al	Past, present and future behaviour of the Waiho River: a new perspective	Scientific Paper
2020	Vorster and Hart	Franz Josef cost benefit analysis of options for improved resilience	Report
2021	Blagen	A dendrogeomorphological study of aggradation hazards in Westland, New Zealand	Doctor of Philosophy - Thesis
2021	Gardner and Williams	Waiau River Valley Hazard Assessment	Report
2021	Gardner	Franz Josef Stopbanks Preliminary Design	Report
2021	Measures et al	Modelling the influence of river confinement on aggradation in the Waiho River	Conference poster
2022	Gardner	Tatare Bund – Assessment of Effects	Memo to WCRC
2022	Nandhini	Assessment of potential suitability of land for town growth – Franz Josef	Master of Science - Thesis
2023	Beagley	Waiau Rv: risk of avulsion into Tatare Stm	Memo to WCRC
2023	Gardner	Waiho Rv – Assessment of Effects of New stopbanks	Memo to WCRC
2023	Gardner and Beagley	Analysis of seven breach scenarios: Waiho 2021 2D hydraulic model	Memo to WCRC
2023	Davies	Comparative hazard and risk assessment of existing and proposed Franz Josef town sites: report for Westland District Council	Report