Future Management of the Waiho River

This report has been compiled by the 2023 Waiho Technical Advisory Group upon the request of the West Coast Regional Council

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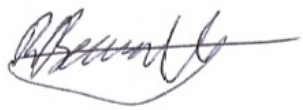
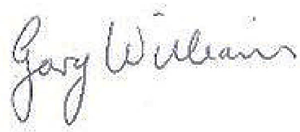
Signature:	     
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EXECUTIVE SUMMARY

Six specialists in the fields of river science and river engineering have been contracted by the West Coast Regional Council to form a Technical Advisory Group to provide direction for the future management of the Waiho River in Westland, New Zealand.

CONTEXT

The Waiho River drains from the Western Southern Alps and across a 16 km long *floodplain* to the Tasman Sea. In the upper *reach* of this *floodplain*, the river has formed a steep and large *alluvial fan*. *Alluvial fans* are flattened conical landforms that are found where a sediment-laden stream or river exits a steep confined channel to a more gently sloping surface where the channels are free to spread out laterally and can increase the *fan* surface elevation through a process called *aggradation* (*deposition* of sediment).

Since settlement by Europeans in the mid to late 1800s, a large portion of the true left side (south, herein) of the Waiho *alluvial fan* has been developed for agricultural use, whilst the true right side (north, herein) has been occupied by the Franz Josef township and amenities. To protect these areas from flooding, protection structures ("stopbanks"; raised banks along the river side) have been constructed to contain the river (Figure 3-9). However, these structures also restrict the Waiho River to about one third of its available *fan* surface area, and therefore reduce the area it has to deposit its high sediment load on. As a result, the river is rapidly increasing the elevation of its bed. This is problematic as it is progressively reducing the *capacity* of the protection structures, which makes them vulnerable to failure during *flood* events.

In the years 2000 and 2016, workshops were held to develop a sustainable long-term management strategy for the river. Both of these workshops concluded that maintaining the entire protection network is unsustainable, and that the only realistic option is to allow the river access to the whole of its *floodplain* by removing the south side stopbanks. Although it was agreed at the 2016 workshop to recommend that a plan be put in place to release the river to the south, and efforts were made by the council alongside central government, this has not happened, and since 2016 the situation has deteriorated.

The Waiho River has continued to aggrade its bed, and as of 2023 has developed a major break out (avulsion) channel into the Tatare Stream to the north. This is a fundamental change in behaviour for the river, which will have serious consequences for the oxidation ponds, SH6 and bridges, and ecological value of Lake Pratt, and for the occupation of Stony Creek, Tatare, and the Top 10 holiday park.

GEOMORPHIC BACKGROUND

The Waiho River, like other major West Coast rivers, flows from steep, rapidly-uplifting, and equally rapidly-eroding mountains with approximately 10 m of rainfall per year and frequent intense *flood* events. As a result, the rivers are steep, and gravel-bedded, with high coarse sediment loads, braided *alluvial fans* and floodplains.

Sediment supply to the river systems fluctuates which impacts on river behaviour across their fans and floodplains. Higher sediment input periods (e.g. following earthquakes, landslides, major glaciations) cause the rivers to aggrade and deposit sediment across the *fan* surfaces, elevating the surfaces and extending the fans downstream over less steep floodplains, whilst lower sediment input periods cause river beds to incise into the fanheads.

The Waiho River has been aggrading its bed level since the river was incised at a low bed level in the late 1800s. This *aggradation* paused between 1923 and 1950 when a *proglacial lake* trapped much sediment and caused a period of stable bed level, however, it recommenced in the 1950s and has continued to the present, with the current rate of bed level rise near the state highway bridge about 0.2 m per year (2 m per decade).
This *aggradation* is due to increasing sediment supply caused by:

(i) Changing climate (including the *Interdecadal pacific oscillation* and *Southern annular mode*) increasing winter rainfall and temperature, *permafrost* reduction, and glacial retreat; and/or
(ii) Increasing tectonic stress in the Western Southern Alps due to plate motion.

However, since the 1970s, stopbanks have confined the Waiho River to approximately one third of its natural *fan* area, preventing it from occupying its whole *fan*. The rate of increase of the bed level is therefore currently about three times faster than it would be if it was allowed to spread over the whole *fan* area. This has resulted in increasingly active and expanding bed channels, and a break out channel (*avulsion*) developing from the Waiho River into the Tatare Stream. This *avulsion* behaviour was foreseen in 1998 and has occurred earlier than it would have, had the Waiho not been laterally confined by the south side stopbanks.

In the future, the rate of bed level increase is expected to continue or accelerate. In addition, there is a 15% chance of a magnitude 8 earthquake on the Alpine fault within the next 10 years. This will likely cause:

(i) Severe damage to all stopbanks.
(ii) A major *aggradation* episode (metres in height, decades in duration)
(iii) Possible landslide dam(s) in the Callery River and/or Tatare Stream with consequential dambreak floods
(iv) Multi-decade river *avulsion* and flooding.

RIVER MANAGEMENT

The management strategy for the Waiho River, has always been one of control through protection structures such as stopbanks, rock gabions, revetments, and groynes. The construction of significant structures started in the mid 20th century, 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 river bed on the south side from upstream of the SH6 bridge to just downstream of the Waiho Loop, and on the north side, from just upstream of the SH6 bridge to just downstream of the oxidation ponds.

Over the last five decades, the network has experienced repeated damage during *flood* events, and although it has been repaired and raised multiple times to keep up with the rapidly aggrading river bed, the relatively new *stopbank* downstream of Canavan's Knob is already threatened. Furthermore, the ad hoc development of the network, and inconsistencies in design and construction standards, means that there are sections of unlined *stopbank*, poorly constructed rock linings, minimal to no *freeboard*, and inadequate *toe embedment*s which make these sections vulnerable to failure during floods.

Additionally, works are sometimes undertaken within the river bed in order to maintain existing and build new protection structures, or undertake other consented activities. These works often involve techniques and practices that have been used successfully on other rivers.

However, the Waiho is an unusually powerful river with complex behaviour and *fan* geometry. In addition to its highly dynamic nature, the Waiho River does not flow over a simple inclined plane downstream of the SH6 Bridge, but rather across multiple adjacent surfaces such that the natural fall is in not just one, but multiple directions. This is compounded by the rapid *aggradation* of the riverbed. As a result, the river behaves differently to what may be expected or commonly understood. Therefore it is easy to misinterpret the river and undertake works that have unintended consequences on its behaviour and on privately or publicly owned assets.

RIVER HAZARDS

The main *hazard* posed by the Waiho River to the Franz Josef community and surrounding area, is flooding; the *risk* being that a *stopbank* may be breached or overtopped during a *flood* event. Moreover, the ongoing aggradational behaviour of the river is reducing the *capacity* of the stopbanks that confine it such that ever smaller floods can *overtop* them.

Additionally, since February 2023, the Waiho has established a significant channel (*avulsion* path) into the Tatare Stream. This developing *avulsion* offers the Waiho a very steep pathway from its own *fan* down to the Tatare Stream bed, and as it continues to develop may result in channel *degradation* and widening progressing upstream towards the oxidation ponds, the Tatare valley infilling with sediment and backing up towards the SH6 Tatare Bridge, and a *fan* forming downstream of the Tatare gap in the Waiho Loop which will cause floodwaters to enter Lake Pratt.

Over the next ten years, these flooding and *avulsion* hazards are likely to be exacerbated by all or any one of a major non-seismic induced landslide, landslide dambreak, changing climate, positive phase of the *Interdecadal pacific oscillation*, and the Alpine Fault magnitude 8 (AF8) earthquake or other earthquakes in the mountains. The latter will severely damage stopbanks, and, like the others will increase sediment supply and/or *flood* frequency and intensity. In doing so, these events will affect the degree of channel change and the rate of *aggradation* of the river bed, and therefore the *likelihood* of a *stopbank* breaching or overtopping, and the rate at which the *avulsion* into the Tatare develops.

RISK ASSESSMENT

A formal *risk* assessment was undertaken for all key *flood* protection infrastructure and three presently unprotected areas (upstream of the SH6 Bridge on the north side, the area of the developing *avulsion* into the Tatare Stream, and the lower valley downstream of Milton's *stopbank*), for the flooding and *avulsion* hazards described above. The results are presented in Table 5-5 and show that:

- All areas have a *risk* rating of High or Critical for failure over the next 10 years.
- Adding or upgrading the protection in these areas is likely to come at significant financial cost, and where it reduces the *risk* rating, it generally only does so by one category as the

high rate of bed level rise nullifies the impact of the work by the end of the 10 year time period.
- The only options that make a meaningful and permanent impact on *risk* reduction are those that allow the river to occupy more of its *floodplain*, by relaxing (i.e. removing stopbanks) on the south side of the river.
- The High to Critical *risk* of most options indicates that failure is likely and that it is critical to ensure that there is effective emergency management and contingency planning in place.

The effect on *risk* in the various areas of an *avulsion* of the Waiho River into the Tatare Stream, and relaxing the Waiho to the south above (upstream of) or below (downstream of) Canavan's Knob are shown in Table 5-6.

- Over the short-term the *avulsion* into the Tatare Stream seriously increases *risk* to Havill's *stopbank* and the oxidation ponds, and moderately increases *risk* to the 55kph Corner and Link stopbanks. There is a minor *risk* increase to the Heliport *stopbank*.
- Over all timeframes as the *avulsion* continues to develop the *risk* from Canavan's Knob to Milton's *stopbank* reduces slightly due to the smaller amount of time the river will flow there. However, immediately downstream of Milton's *stopbank* the *risk* will increase slightly due to the combined Waiho River / Tatare Stream flow through the Tatare Stream gap in the Waiho Loop being more directed toward this area than at present.
- The assessment results also show that *risk* is partially reduced by relaxing the river to the south downstream of Canavan's Knob. This outcome shows that there is an opportunity to stage the "relax to south" strategy (relaxing first downstream then upstream) and thereby gain some benefits within a 10-year timeframe.
- Notwithstanding that, the results clearly show that substantial *risk* reduction is only realised once the Waka Kotahi stopbanks from the SH6 Bridge to Canavan's Knob are also removed.

JUSTIFICATION FOR A CHANGE IN STRATEGY

The Waiho River has been confined by structural protection works for many years through a long period of *aggradation*, with no signs that the rates of *aggradation* will decrease in the future. As a result, maintaining the protection network is proving increasingly challenging, and is likely to get more difficult and less reliable due to the ongoing *aggradation* as well as a changing climate.

The rapidly rising bed levels are continually decreasing the level of service of the stopbanks, however raising the stopbanks only serves to increase the residual *risk* with the consequences of an overtopping or *breach* failure increasing significantly with each raise.

A *risk* assessment of each *stopbank* in the network has shown that upgrading and/or building additional protection measures would have significant initial and on-going costs while not significantly reducing the *risk* of failure over a ten-year period. However, removing all of the stopbanks on the south side of the river will:

- Reduce the *risk* of *stopbank* failure.
- Reduce the number of assets exposed to the *flood hazard*.
- Provide the Waiho River with more surface area to deposit sediment (and hence decrease the rate of bed level rise).
- Increase the lifespan of the north stopbanks and reduce their *risk* of failure during *flood* events.
- Reduce the pressure on the overflow path on the north bank upstream of the SH6 Bridge.
- Reduce the pressure of the developing *avulsion* into the Tatare Stream.

- Reduce the impact of the *aggradation* and flooding that will follow an Alpine fault or other earthquake.

If the river is not released to the south, then it is very likely that the river bed will continue to rise by at least the current rate, putting the future of the township at ever greater *risk*. As a minimum, giving the river more space is expected to reduce the rate of *aggradation* to the order of one-third, providing the present township site with a longer lifespan. By contrast, there is a high *likelihood* that if the current protection strategy is maintained, then there would be a significant and increasing *risk* of a *breach* or overtopping along the south stopbanks, resulting in catastrophic flooding of all people, livestock, properties and infrastructure in the path of the floodwaters. *Risk* of a north *stopbank* failure would also increase with time.

Removal of the stopbanks will also provide additional resilience when the AF8 earthquake happens, by making more room available for the vast quantities of sediment expected to enter the system, also because the river-bed elevation will in that case be much lower than it would be if the present stopbanking were maintained.

This is not a new proposal and has been considered for many years, with an economic assessment of this option first being undertaken in the year 2000.

FUTURE MANAGEMENT

A 10-year management plan has been drawn up, based on past studies of the Waiho River system and the assessments undertaken for this study. The primary recommendation in this plan is a retreat (retirement from human use in terms of occupation and livelihoods) from the south side of the Waiho River valley, because of the long-term and continuing *aggradation* of the river bed and *fan* surface downstream of the mountain exit.

The management plan has followed the four responses of the PARA framework for managing *flood risk*, outlining measures for each response. However, the emphasis of the plan is on the south side retreat, with interim protection measures for river management over the time that will be required to fully implement the proposed retreat.

A five phase programme for this south retreat has been drawn up, with the land retirement starting in the lower valley, below the Waiho Loop, and then progressing up valley. At the same time the re-alignment of State Highway 6 would proceed from design and consenting through to construction, with the south side of the valley being fully retired once this realignment is completed.

However, given the time required to implement the retreat there is a high *likelihood* of flooding occurring in the interim due to breaches or overtopping of the existing stopbanks. Protection upgrades have thus been considered in terms of the *likelihood* of failure and consequential loss or damage for each of the stopbanks over the next 10 years. The timing of these interventions will depend on the actual changes in the Waiho River bed from the on-going *aggradation*, and there is a wide range of uncertainty in what might be required at what time, and what the costs of interventions might be.

To provide a general idea of possible protection costs, order-of-magnitude estimates are given for the proposed *stopbank* improvements and on-going channel management measures. The total over the next 10 years may be around $15 million for protection structures, with another $15 million of provisional sum, and around $10 million for channel management.

RECOMMENDATIONS

We recommend that the Waiho River be fully released to the south to allow the river to distribute its sediment load over the whole *fan* area and reduce the rate of bed level rise, in order to reduce the critical risks posed by the flooding and *avulsion* hazards to the Franz Josef township, and its adjacent land and infrastructure.

Additionally, we recommend that emergency management measures be prioritised given the current and future threats from the Waiho River, that new developments or intensified land uses on the southern *floodplain* be prevented with immediate effect, and that improvements be made to the existing protection network in order to provide protection whilst the staged release to the south is implemented.

We propose that the 10-year management plan be completed in a five phase approach as outlined below, noting that following this report, in depth investigations and consultation with all involved stakeholders will be needed to develop each phase.

Phase 1:

- CDEM management planning, and preparing personnel as well as local community members for their responses to potential *flood* scenarios
- Upgrade stopbanks on the north side from the SH6 bridge to the oxidation ponds to maintain protection for the Franz Josef township
- Undertake holding works along the southern stopbanks and Glacier Road to provide protection for the southern *floodplain* while preparatory works for the release are undertaken.
- Begin investigations into the likely impact of the *avulsion* into the Tatare Stream, response of the south side *floodplain* to *stopbank* removal, the extent of infrastructure on the southern *floodplain*, residual *risk* of *overtopping* on the north stopbanks and Glacier Road, and the relocation of the oxidation ponds and heliport.

Phase 2:

- Land procurement, and removal / relocation of infrastructure, and council and farm landfill sites within the identified flood hazard zone.
- Remove Milton's *stopbank* and the unlined section of the Rubbish Dump *stopbank* on the south side.

Phase 3:

- Land procurement, and removal / relocation of infrastructure, and council and farm landfill sites within the identified flood hazard zone
- Remove lined Rubbish Dump *stopbank* on the south side.

Phase 4:

- Placeholder for the realignment and construction of State Highway 6 on the south side, and realignment of services (power, telecom, etc).

Phase 5:

- Remove the remaining southern stopbanks between SH6 bridge and Canavan's Knob.

TABLE OF CONTENTS

1. INTRODUCTION

1.1. SCOPE

The West Coast Regional Council (WCRC) contracted the authors of this report to form a Technical Advisory Group (TAG; 12. Appendix A) to provide direction for the future management of the Waiho River in Westland, New Zealand.

The TAG was tasked with:

1. **Defining the existing and future hazards** that the Waiho River poses to the Franz Josef township and surrounding community and *floodplain* area.
2. **Assessing the capability of the protection structures in their current state** to reduce the risks from these hazards.
3. **Providing guidance on the available management options for the river** in terms of what actions or non-actions can be taken to reduce or remove the risks these river hazards pose to the community, infrastructure, and land.
4. **Recommending a ten-year river management plan** for the WCRC to implement, that leads into a long-term management strategy.

In order to complete these tasks, the TAG has drawn upon:

- A pre-2023 workshop report contracted by the WCRC and completed by Beagley and Gardner (2023) which reviewed all the Waiho-related literature dating back to 1983, provided an update on the *aggradation* rate, mean bed surface levels, recent river behaviour, and current state of the protection network, and gave recommendations for future management of the river.
- The substantial volume of reports, modelling studies, theses, and scientific papers on the Waiho system known to us (refer to Appendix A of the Beagley and Gardner, 2023 report for the full list).
- The authors' extensive and long experience (since the 1990s) of the Waiho (Section 12 - Appendix A).
- The conclusions and recommendations from the previous workshops held in 2000 and 2016 (Section 1.2.3).
- A field visit to the area on the 9th August 2023 to view the impact of the ongoing *aggradation* on each of the protection structures, and the developing break out channel (*avulsion*) of the Waiho River into the Tatare Stream above the Waiho Loop.
- A round table discussion on the 10th of August 2023 on the behaviour of the river, the historic and present management of it, and future management options.
- Intensive drafting and discussions since the workshop.

The TAG note that the pre 2023 workshop report completed by Beagley and Gardner (2023) contains salient information relevant to the conclusions and recommendations of this report, and should therefore be read in conjunction with it.

> A Glossary has been provided at the end of the main section of this report (Section 10), with the defined terms formatted in *italic type* throughout the report.

1.2. CONTEXT

1.2.1. FRANZ JOSEF AND THE 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, accessed by state highway 6 (SH6) (Figure 1-1). The town is located 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.

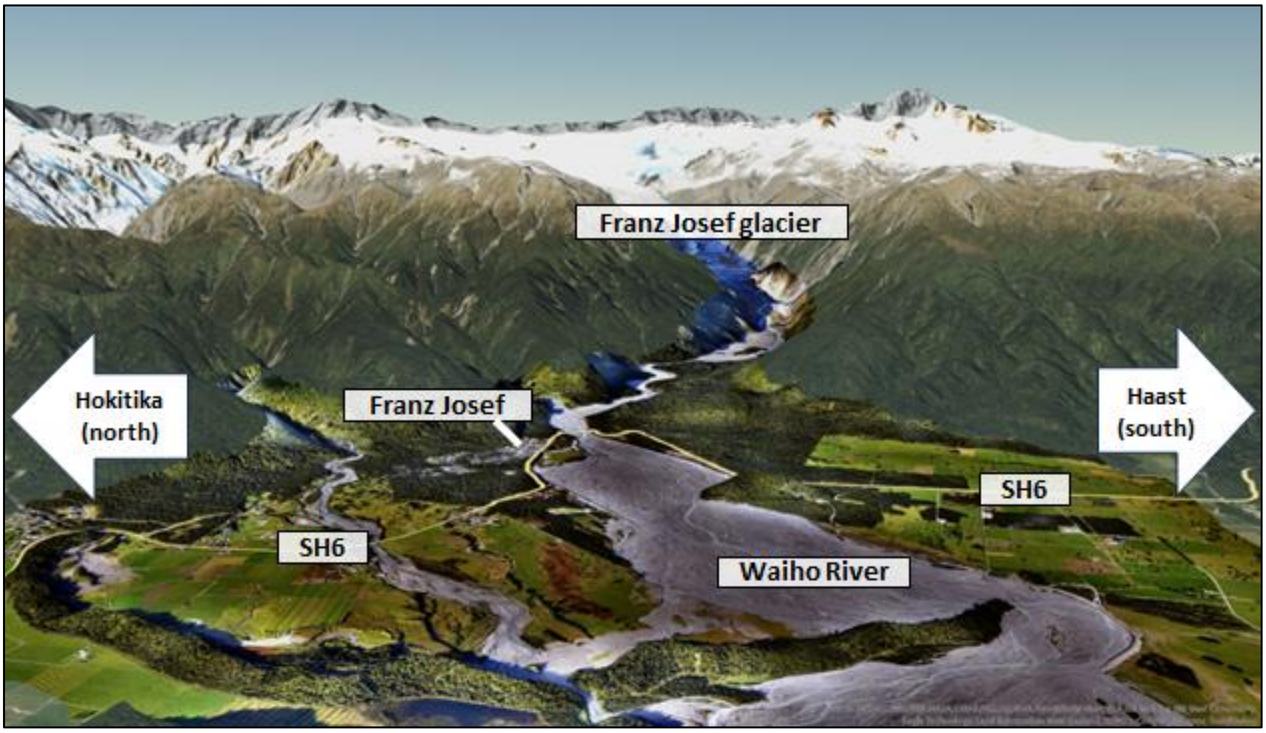

Figure 1-1 - Location of the Franz Josef township and glacier and the Waiho River.

The main source of income for much of the town's population is from the influx of tourists drawn to the area for its high environmental values, and the road-trip circuit to Wanaka and Queenstown. The town also provides services for the local agricultural industry, and smaller communities 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. These rating districts were created in order to maintain the WCRC-owned *flood* and erosion protection structures that have existed on the Waiho River since the 1940s (West Coast Regional Council, 2023).

Further detail about the township and area can be found in the Beagley and Gardner (2023) report.

1.2.2. THE WAIHO RIVER AND FAN

The Waiho River drains a catchment of about 170km^2 on the western side of the main divide of the Southern Alps, before flowing across a 16 km long *floodplain* to the Tasman Sea. In the upper *reach* of this *floodplain*, where the river leaves the mountain front, it has formed a large, steep *alluvial fan* (Figure 1-2).

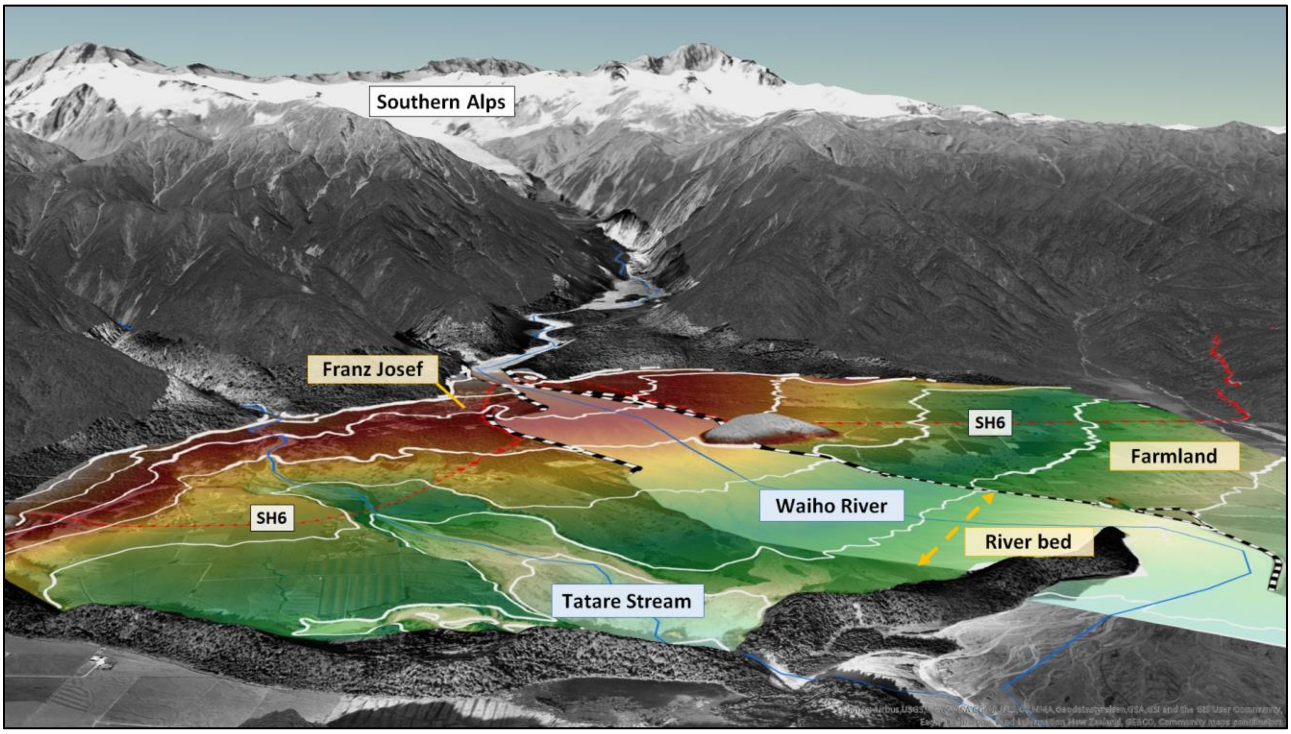

Figure 1-2 – The Waiho and Tatare *alluvial fan* surfaces shown with white 10 m contour lines and a coloured DEM from the most recent LiDAR survey (8th June 2023). The Waiho river bed has been delineated by a white layer beneath the fan DEM, with the width indicated by the orange arrows. The protection structures are shown by the black-white dashed lines.

- ***Alluvial fans*** are flattened conical landforms found where a sediment-laden stream or river exits a confined valley (e.g. at the *rangefront*) and formed where the river channels are free to spread their sediment load laterally (Whitehouse & McSaveney, 1990). Channels on the *alluvial fan* migrate and switch back and forth across the *fan* surface, building up the fan through a process called *aggradation*.
- ***Aggradation*** is the progressive accumulation of sediment deposited in river environments as a result of sediment supply to a *reach* exceeding the *transport capacity* within and from a *reach*, leading to an increase in surface elevation of river beds and *floodplains*. Where the sediment supply cannot be contained within a defined river channel, the rising channel will widen, and the sediment load spreads out over the adjacent land (e.g. *floodplain* or *alluvial fan*).

  Particularly important to this process, is that the rate at which a *fan* surface level increases is directly proportional to the area available for *deposition*. For a given excess of sediment supply over *transport capacity*, a greater surface area results in a slower surface level increase as the sediment is spread out farther, whilst a smaller surface area results in a faster surface level increase.

Since settlement by Europeans in the mid to late 1800's, a large portion of the true left (southwest) of the Waiho *alluvial fan* has been developed for agricultural use, whilst the true right (northeast) has been occupied by the Franz Josef township and amenities (Figure 1-2). We note here that though it is technically correct to refer to the sides of the river as southwest and northeast, colloquially these sides are known as the south and north, respectively, and so we will refer to the sides of the Waiho River by south and north, herein.

Like all Westland rivers, the Waiho River experiences frequent and intense sediment-laden *flood* events. These have prompted the construction of protection structures to contain the river and protect the township and southern farmland from flooding. Thus the natural aggradational behaviour of the Waiho River has been restricted by the protection network to about one third of its available *fan* surface area, and as a result, the rate at which the river is increasing the level of its bed is about three times that when it had access to its entire *fan* surface – in the mid-19th century prior to European settlement.

The river has become increasingly difficult to manage under the existing strategy of attempting to contain the river within the protection network, because:

- The river bed *aggradation* has reduced the *capacity* of the protection structures to contain *flood* flows, and they now require an upgrade (crest level and width increase) if they are to provide the level of service needed to protect the land, infrastructure, and community, that they were designed for.
- The Waiho *fan* surface is now level with the adjacent Tatare *fan* above the Waiho Loop, and a growing breakout channel (*avulsion*) now flows from the Waiho River into the Tatare Stream. At present only one braid has been captured and only during *flood* flows, so the main flow of the Waiho still passes through the gap between Rata Knoll and the southern end of the Waiho Loop. However, this is a fundamental change of behaviour for the Waiho River, and further development of this channel will have serious consequences for the oxidation ponds, SH6, ecological value of Lake Pratt, and the occupation of Stony Creek, Tatare settlement, and the Top 10 holiday park.

The March 2019 *flood* further demonstrates the need for urgent action. During that event, the flooded Waiho River destroyed the SH6 Bridge and Milton and Other's *stopbank* (Milton's, herein). Destruction of the bridge severed the only through road in Westland reducing visitor numbers to the township and glacier, with an estimated $54 million loss of tourism revenue to the community and wider region. Failure of Milton's *stopbank* caused considerable *flood* damage to the airstrip, farmland, homes, and infrastructure. Fortunately, there was no loss of life in this event. However, in its current state, the protection structures are even more, and increasingly, vulnerable to *flood* flows, (which given the regional climate, are both frequent and intense), and to the impact of the expected AF8 earthquake that will severely exacerbate river flooding hazards.

1.2.3. PREVIOUS WORKSHOPS

Since the 1980s the Waiho system has been repeatedly studied, in order to better understand the river behaviour and the hazards it poses as documented by Beagley and Gardner (2023), with many published reports and two workshops conducted to develop a suitable long-term management strategy for the river.

In 2000 the 5th International Gravel-Bed Rivers Workshop was held at Franz Josef (in the now destroyed Mueller Wing of the Scenic Circle Hotel). About 100 of the world's top river scientists stayed 4 days, taking part in a ½-day fieldwork session on the Waiho and in an evening workshop sponsored by Transit New Zealand and chaired by the WCRC CEO (Terry Day), at which about 40 local people were present. The evening comprised talks by the scientists on the management issues of the Waiho, followed by an open-ended discussion. While no formal recommendation resulted, the following points were agreed on (Rouse et al., 2001):

- It was not clear whether the Waiho *fan* was in long-term equilibrium as assumed by some researchers, and it would be prudent to expect the *aggradation* to continue;
- In considering river management it was important to include the effects of a major earthquake;
- The status quo of continuing to build stopbanks was unsustainable;
- The relaxation option, allowing the river to access the whole of its *floodplain* by removing the stopbanks on the south side of the river (Figure 1-3), was the "best and most realistic" option available.

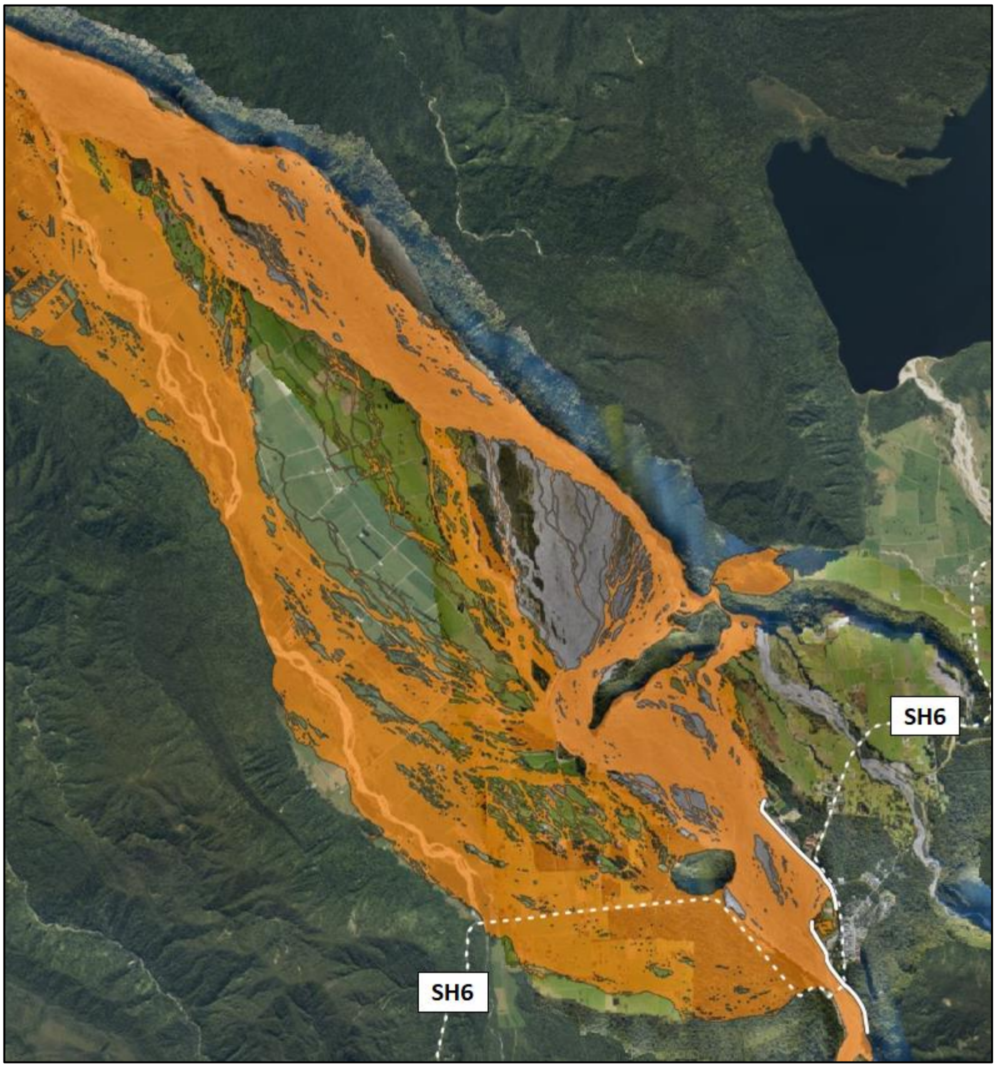

Figure 1-3 - Land River Sea Consulting modelling of the Waiho River with a 2,500m³/s flow, and all of the stopbanks on the south side removed.

In 2016, after the March event that flooded the Mueller Wing of the Scenic Circle Hotel and the oxidation ponds, another workshop was held. This was run by WCRC and brought together the affected agencies as well as 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 concluded 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* surface (the *floodplain* between the SH6 Bridge and Waiho Loop).
- By constricting the river, the stopbanks accelerate the rate at which the *fan* surface elevation increases, with subsequent impacts on stopbanks and edge protection measures.
- The Waiho River needs to occupy a large *fan* for *deposition* of its high bedload, as it did prior to human intervention.
- Digging the gravel out, or realigning the river channel using diversion works, 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 (south of Canavan's Knob), which involves relaxing the southern *stopbank* boundaries.

However, though it was agreed and recommended that a plan be put in place to release the river to the south, and efforts were made to this end by the council alongside central government, this has not happened, and since 2016 the situation has deteriorated.

As predicted, the Waiho River *fan* surface has continued to aggrade, and the *aggradation* rate has been maintained or increased as documented by Beagley and Gardner (2023). Furthermore, the 2023 workshop concluded that there was no obvious reason to expect the *aggradation* rate to reduce in the future; indeed there are good reasons to expect it to increase. The occurrence of an Alpine fault earthquake (1 - 2% probability every year) will cause an additional massive, long-term *aggradation* episode.

2. GEOMORPHIC BACKGROUND

2.1. PHYSICAL SETTING

2.1.1. GEODYNAMIC SETTING: TECTONICS, EARTHQUAKES, GLACIATION; ANCIENT HISTORY

The Waiho River (including its larger (92 km^2) tributary the Callery River; Figure 2-1) drains a mountain catchment of about 170 km^2 west of the main divide of the Southern Alps. Due to persistent warm westerly winds this area receives up to approximately 10 m of water-equivalent precipitation per year. The two rivers combine about 500 m upstream of the Southern Alps *rangefront*, which is defined by the Alpine fault. SH6 crosses the Waiho at the *rangefront*, and Franz Josef township is sited here on the north-east side (north, herein) of the river. The smaller adjacent catchment of the Tatare River (28 km^2 in area) lies north of the Callery; its river flows parallel to the Waiho and about 1.5 km north of it, joining the Waiho downstream of the Waiho Loop terminal moraine about 4.5 km downstream of the township. After leaving the Southern Alps, the Waiho River flows northwest across 16 km of *floodplain*, confined on either side by lateral moraines hundreds of metres high (Figure 2-1). In the 4.5 km *reach* from the Alpine fault to the Waiho Loop it has formed a steep *alluvial fan*, whilst downstream of the Loop is a much less steep *longitudinal valley train*.

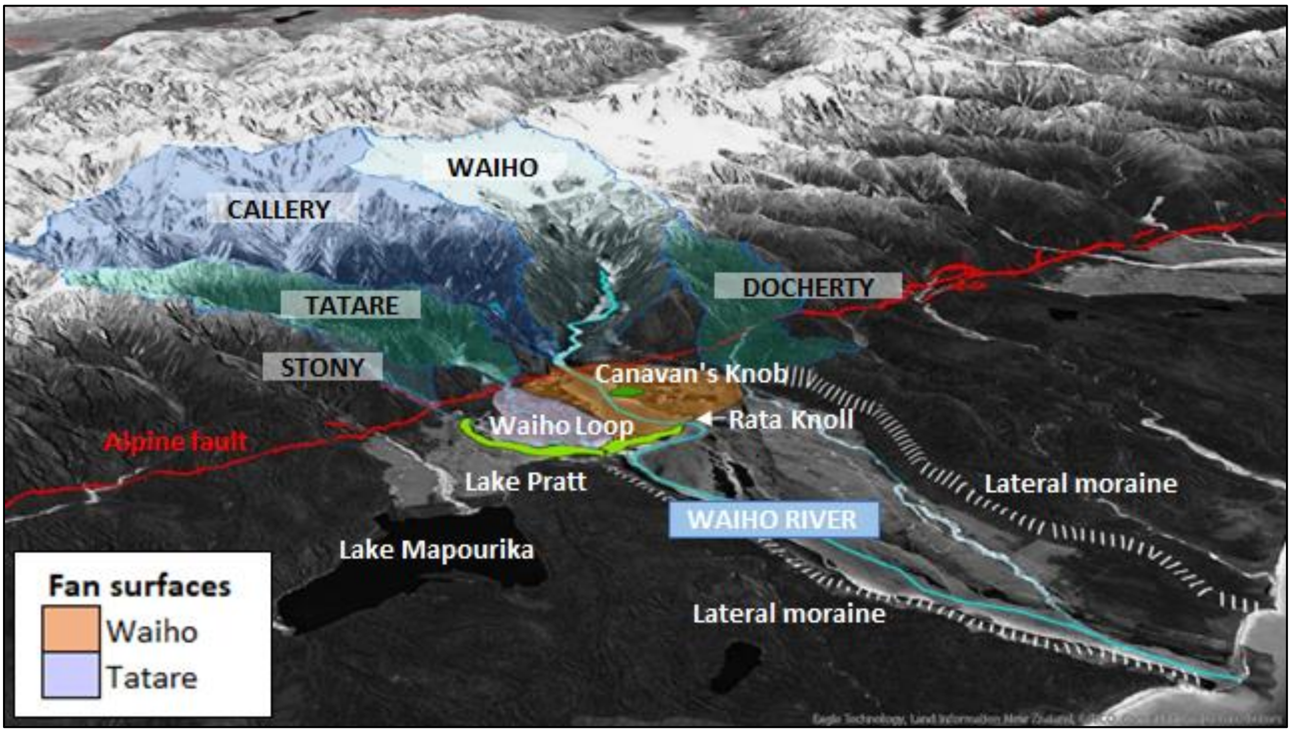

Figure 2-1 - Waiho catchment and key geomorphic features.

The Southern Alps have formed over the past several million years due to tectonic uplift east of the Alpine fault, resulting from collision of the Australian and Pacific tectonic plates; this uplift is ongoing and causes large earthquakes on the Alpine fault several times per millennium and, less frequently, on other faults west of the main divide. This uplifting landscape causes rivers to cut deep gorges and valleys within the mountain ranges, from whose steep slopes landslides of all sizes deliver sediment to the rivers; sediment delivery is approximately equal to uplift, so the landscape is in general long-term, large-scale dynamic equilibrium.

The occasional major earthquakes (and their *aftershock* sequences) can generate large numbers of landslides – some of which can be up to cubic kilometres in volume – that cause exceptionally large volumes of sediment input to the rivers. This causes rivers to aggrade their *rangefront* fans and avulse across their floodplains west of the *rangefront*, this behaviour lasting for decades before the rivers eventually degrade again into their newly-elevated fans. There is also some evidence that increasing tectonic stress prior to earthquakes can cause increased landsliding and cause rivers to aggrade for a few decades before major earthquakes. The last major earthquake was in 1717 AD (Alpine fault), with preceding ones in approximately 1620 AD (not Alpine fault) and approximately 1420 AD (Alpine fault).

During the past two million years or so, glaciations have occurred at approximately hundred thousand year timescales. For tens of thousands of years prior to about 20,000 years ago Westland was covered by ice, which extended several kilometres into the Tasman Sea from the Waiho valley. By about 18,000 years ago deglaciation was underway. Around 10,000 years ago, a large ($10^8 m^3$) landslide fell onto the receding glacier when its terminus was at the position of the Waiho Loop, causing the Loop to form. The last significant glacial event was the Little Ice Age which caused a moraine to form close to the Douglas Bridge in the Waiho valley in about 1750 AD; the Franz Josef glacier terminus then retreated to Sentinel Rock by the early 20th century. During the last major glaciation, sea-level fell by about 130 m, returning to its present-day level about 6,000 years ago.

The setting of the upper Waiho River is thus an actively-uplifting and -eroding, frequently-seismic landscape, which is overwhelmed by glacial conditions at about hundred-thousand-year intervals.

2.1.2. GEODYNAMIC PROCESSES

Here we describe the components of landscape behaviour in the geodynamic setting outlined above.

Tectonic uplift: The land east of the Alpine fault is steadily increasing in elevation due to tectonic plate motion. The maximum uplift rate is approximately 5-10 mm per year. However, at the Alpine fault itself, because the two plate boundaries are locked together at the fault between earthquakes, the annual uplift is zero there. With increasing distance from the fault the uplift increases.

West of the fault uplift is much less, and variable; major valleys may be *downwarping* due to the weight of sediment accumulation, while minor uplift may occur in other places (approximately 1 mm per year).

Seismic shaking: An earthquake occurs when the tectonic stress on a fault exceeds its frictional resistance, and sudden relative plate motion can then occur at metres-scale; for example, horizontal offset on the Alpine Fault in 1717 AD was approximately 8 m with vertical offset of approximately 3 m. A rupture starts at the epicentre and travels along the fault at several km per second. This sudden motion generates violent three-dimensional shaking of the land surface, which radiates away from the fault as the rupture propagates; in any given location the shaking may last one to several minutes. Shaking intensity can cause ground accelerations exceeding 1g (gravitational acceleration on Earth) close to the rupture. Shaking intensity is altered by topography (higher at ridge crests) and stratigraphy (the order and position of layers of rock in the ground). Every large earthquake is followed by an *aftershock* sequence as the crust readjusts to its new stress regime; following a major event (e.g. magnitude (M) 8+ on the Alpine fault), the *aftershock* sequence may extend over a decade, gradually dying away but including events of up to M7+ early in the sequence. A major earthquake could also cause a substantial ice collapse on Franz Josef glacier, which could affect the river downstream.

Landslides: Sustained high-intensity shaking can destabilise parts of mountainsides that are otherwise stable, so major earthquakes can cause large numbers of landslides. In the steep mountain topography these landslides supply unusually large quantities of sediment to rivers, which respond by increasing their gradient causing local *aggradation* which progresses downstream. Intense rainstorms also cause many landslides, but in individual storms they are usually fewer and smaller than those caused by earthquakes. Over the long term (millennia) the rate of erosion due to landsliding matches the rate at which the mountains uplift (grow).

Landslide dams: A large landslide in a narrow valley (such as the Callery or Tatare) can cause a natural dam to form blocking the river. A lake forms and grows behind the dam. When the water level overtops the dam, erosion of the downstream face can cause rapid failure of the dam, releasing the stored water and the dam sediment as a landslide-dambreak *flood*; however this can also occur before overtopping. Either way, the resulting *flood* can far exceed the flow rate of a major rainstorm *flood* (though over a shorter time period), and together with the transported sediment and vegetation, can be devastating to downstream assets. Landslide dams usually fail soon after emplacement (e.g Poerua River 1999; 6 days; Figure 2-2), but some (e.g. Young River 2008) do not.

Figure 2-2 – Poerua River *alluvial fan* three years after the 1999 Mt Adams landslide-dambreak *flood* (Davies and Korup, 2007). *Aggradation* of the river bed is causing avulsions and sediment *deposition*.

Jökullhlaups: During a rainstorm large water flows take place in the drainage tunnels within glaciers. If these become blocked due to ice collapse or sediment buildup, water accumulates within the glacier until the pressure at the terminus exceeds the ice strength, whereupon the front of the glacier fails, releasing the stored water, ice and sediment as a "glacier-burst". One of these occurred in the Franz Josef glacier in December 1995 and was responsible for the failure of the SH6 bridge. Unless the glacier readvances, this phenomenon is unlikely to repeat in the future.

River processes: Coarser sediment (gravel-cobble-boulder sizes) is transported as "bedload" – that is, it is maintained in motion above the stationary bed by contact stresses with the bed (rolling, bouncing or sliding motion). Erosion and *deposition* of bedload alters the bed shape during floods. Suspended load comprises finer materials (sands-silts) that are maintained above the bed by fluid turbulence. While erosion and *deposition* of suspended load do occur they tend to balance out, and suspended load has little effect on bed shape during floods.

The capability of a river to erode and transport bedload sediment varies with the water flow rate and the pressure gradient or slope of the water surface. Thus if excess sediment is supplied from landsliding the slope will increase to enable the available water flow rate to transport it thus increasing the transporting power of the river. Additionally, during *flood* events, the active bed may widen and/or increase braiding which can also increase the bed load *transport capacity*.

Further, while the slope is increasing the river bed level is increasing, i.e. aggrading. The wider the river, the slower the rate of bed level rise along the aggrading *reach* for a given sediment volume accumulation rate.

The Waiho *fan* appears to be undergoing long-term (century-scale) *aggradation*, so (bedload) sediment supply exceeds the *capacity* of the river to transport it. Reasons for the excess sediment input are unclear, but may be related to (i) glacier retreat; (ii) increased slope failures due to increasing tectonic stress in the landscape as we get closer in time to the next Alpine fault rupture; or (iii) the changing climate (more intense storms causes more slope failures, and *permafrost degradation* weakens high slopes). Whatever the reason, there seems to be no reason to expect the *fan aggradation* to reduce, cease or reverse in the foreseeable future. Further, the lower Waiho valley (Waiho Flats) has also started to aggrade, sloping evenly at about 0.7% to sea level at the coastline. The *fan* gradient is about twice this value, and the *fan* seems to be slowly enlarging and overriding the upstream end of the lower Waiho *reach*, just downstream of the Loop.

Debris flows: In small steep catchments in which plentiful sediment is available to the river, intense rainstorms can cause phenomena in which multiple surge waves of highly-concentrated sediment (similar to wet concrete and twice as dense as water) carry boulders and debris out onto *alluvial fan*s. These surges can be devastating to buildings and infrastructure and are a common cause of highway closure.

2.1.3. SEDIMENT AND WATER SUPPLY

The behaviour of a river system (such as *aggradation*, braiding, erosion and *avulsion*) results from the rates at which water and sediment are delivered to the system. In this section we outline the ways in which these deliveries occur and the factors which affect the rates of delivery.

In general terms every particular combination of water and sediment supply rates would, if maintained unchanged for long enough, give rise to a particular river state (width, depth, slope, planform). However, because the water input rates vary continuously with time due to changes in rainfall and snow/ice melt, and the sediment inputs occur very intermittently following landslides and riverbed and bank erosion, no particular river state is ever maintained for longer than hours or days. The river is thus in a state of continuous dynamic adjustment towards a series of never-attained steady states, driven by ever-changing rates of water and sediment supply.

Water supply to the Waiho-Callery system occurs mainly by rainfall in the 170 km^2 mountain catchment; this falls onto sloping land or ice, and flows rapidly over these surfaces to enter the river system. The rapidity of entry following precipitation depends on the surface slope and nature; runoff on the steep rocky slopes of the Callery gorge is rapid, whereas rain falling on snow or on the wide bed of the upper Waiho may move much more slowly. Snowfall may accumulate on surfaces and cause no runoff until it melts; if snow turns to ice it can be stored in a glacier for many years. Ice melt can also increase water input.

Rainstorms in the catchment can be very intense; 750 mm of rain in 3 days is not unknown. The different natures of the Waiho and Callery catchments mean that flow rate in the Callery River usually increases faster, and declines sooner, than in the Waiho. The generally rapid runoff in these steep catchments means that floods are usually of short duration, rising rapidly with rain onset and falling rapidly following rain cessation. Annual rainfall in the catchment is probably about 5,000 – 10,000 mm, so the long-term average flow rate in the Waiho below the Callery confluence is about 40 m^3s^{-1}.

Sediment supply to the river system originates from:

(i) Erosion of rock and soil from steep slopes, in the form of landslides of all sizes from less than a cubic metre (very common) up to cubic kilometres (very rarely); the largest landslides are probably triggered by earthquakes, which also generate other types of slope failures of all sizes. Rainfall also causes slope failures, generally smaller but much more frequent than those caused by earthquakes. Occasionally a major landslide occurs with no obvious trigger, as in the ten-million cubic metre event in the Poerua gorge in 1999.

(ii) Erosion of sediment from river beds and banks. This occurs in particular locations during floods, resulting from local variations in river channel flow rate and direction. If a high river bank is eroded the input can be large.

(iii) Rock from boulders to silts emanating from glacier termini during high flows; this is poorly understood, depending as it does on how rock debris deposited onto the ice surface by landslides moves through the glacier. Ice-motion erosion of rock surfaces also occurs but is probably a minor contributor.

The uplift rate in the Waiho-Callery catchment is about 5 mm per year. As the uplift rate is approximately equal to the erosion rate, the annual sediment supply rate to the Waiho *fan* is about a million cubic metres, and the average sediment concentration in the Waiho is of the order of 1,000 ppm (0.1%) by volume.

While the long-term tectonic uplift rate is probably steady, climate is certainly changing in both the short and long terms. It appears that winter rainfall may be increasing, so rainfall-generated landsliding may be increasing and with it, sediment supply. Further, increasing temperatures cause *permafrost degradation* at high altitudes, further contributing to sediment delivery. Additionally, in the short term, the *Interdecadal pacific oscillation* (IPO) and *Southern annular mode* (SAM) can affect the intensity and frequency of storm events, with positive IPO and negative SAM phases resulting in increased rainfall-generated landslides, and therefore increased sediment supply. Also, there is evidence that spontaneous landsliding may be increasing because of tectonic stress buildup as the time since the last major earthquake increases, so slopes may be getting weaker and sediment supply may be increasing. The recent onset of landslide-induced *aggradation* in the Wanganui and Fox Rivers may result from these processes.

Delivery of catchment-generated sediment to the *fan reach* of the Waiho is very rapid in the Callery, which flows at the bottom of a very narrow gorge. By contrast, sediment delivered to the Waiho from the Franz Josef glacier moves relatively slowly through the 0.5 km-wide upper Waiho valley where sediment can be retained in storage in the *floodplain*. Between 1923 and 1950 a lake formed in the upper Waiho valley that trapped most of the sediment supplied from the Franz Josef glacier.

Furthermore, because the Callery catchment is larger than the Waiho catchment, the majority (54%) of the water and sediment moving along the Waiho downstream of the Callery confluence originates in the Callery. However, because the upper Waiho valley leading to the Franz Josef glacier is much better known than the (inaccessible) Callery valley there is a tendency to neglect the significance of processes in the Callery to the behaviour of the lower Waiho, but this is clearly erroneous.

2.1.4. NATURAL BEHAVIOUR OF THE LOWER WAIHO

In the absence of human influence i.e. *stopbank* and river edge protection works, the Waiho River downstream of the Callery confluence would exhibit the following behaviours:

(i) Short-term (decades): In the absence of the effects of glacial changes or earthquakes, the Waiho would *flood* during every rainstorm, and would generally flow in a series of braided channels distributed across its whole *fan* from Docherty Creek to the south to the (higher) Tatare *fan* to the north. The individual channels would be relatively mobile and could alter their positions with every *flood*. The lower Waiho would similarly occupy all locations across the valley over time.

(ii) Medium-term (centuries): Every few hundred years a major earthquake would occur. The several decades prior to this might see increasing sediment input volumes. The earthquake itself would cause the input of exceptionally large sediment volumes (approximately 10 million cubic metres) into the system, and the *fan* would respond by aggrading rapidly by several metres over a decade or so. Post-1620 AD *aggradation* of the Waiho *fan* amounts to several metres. The *fan* would extend downstream during this episode. Once the excess sediment supply ceased the river would incise a main channel into its new *fan* surface. After enough earthquakes, *fan aggradation* would lead to the Waiho avulsing into the Tatare when its level exceeded that of the inactive Tatare *fan* surface; without stopbanking this would not be happening yet. Note that a very large non-earthquake-triggered landslide (millions of cubic metres) in the Waiho - Callery catchment would have a similar effect to an earthquake.

(iii) Long-term (millennia): At ten-thousand to hundred-thousand-year intervals a major glacial advance would deliver very large sediment volumes to the *fan* because the Franz Josef glacier advancing to cover the upper Waiho *floodplain* would excavate the whole *floodplain* sediment to some depth. This advance would occupy many decades or centuries and would cause a correspondingly slow – but massive - *aggradation* episode of the *fan*, and perhaps even overrun it with ice. A major glaciation would also cause sea level to reduce, probably lowering the base level of the system because the offshore seabed slope is steeper than the lower Waiho gradient; this would tend to cause *degradation* of the lower Waiho. However, given that the rainfall during a glaciation would probably reduce, *aggradation* would probably dominate - and indeed overwhelm - the system. The last significant glaciation was the Little Ice Age from approximately 1450 to 1850 AD, which caused a very minor (km-scale) advance; its aggradational effect on the *fan* would have coincided with those of the approximate 1420 AD, 1620 AD and 1717 AD earthquakes.

2.2. RIVER BEHAVIOUR

2.2.1. AGGRADATION

Beagley et al. (2020) describe the historical behaviour of the Waiho River and *fan*.

Briefly, prior to the first bed-level measurement at the SH6 bridge site in the 1920s, it was known that in the late 1800s the river bed was at a very low level, and was characterised by large smooth boulders of glacial origin. However not long before this a high terrace (approximately corresponding to the present *fan* surface) was present at the Callery confluence on the north side of the river (Mosley, 1983), possibly reflecting the *aggradation* resulting from the 1717 AD Alpine Fault earthquake and the Little Ice Age advance of the Franz Josef glacier. This would have corresponded to a SH6 bridge level of 148 m asl, so *fan incision* prior to the late 1800s must have been quite rapid.

In 1906 and 1924, two data points at the SH6 bridge site show the bed at about 140 m asl. A terminal lake was present in the upper Waiho valley from 1923 to 1950, and it is thought that this would have trapped the majority of the sediment issuing from the Franz Josef glacier, so that the bed would have aggraded little if at all during this period. However, from the 1950s onwards, sediment from the glacier would have passed directly into the river system, and as a result the river began to aggrade its downstream *fan* surface. Aerial imagery from the 1950s onwards show an increasingly active and expanding *braidplain*.

Bed level surveys recommenced in the early 1980s with a level of 143 m asl at the SH6 bridge site. Since then regular surveys have shown the bed level at the bridge to be increasing at an average of about 0.17 m per year with a short-term variation of ± 1.5 m (Figure 2-3; which has been related to minor glacier advances and retreats). The confined bed is now at about 150 m asl with the *fan* surface on either side of the river protected by stopbanks at 148 m asl.

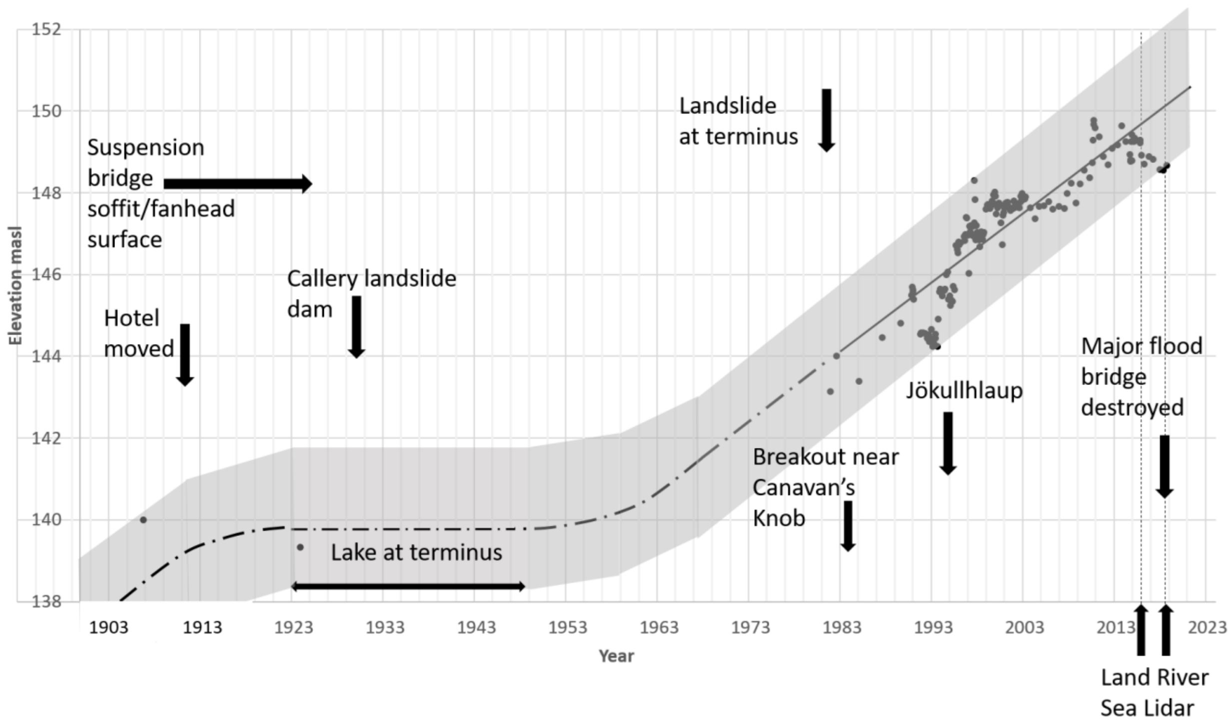

Figure 2-3 – Mean bed level (elevation in metres above sea level) at the SH6 bridge cross section. Bed level data from NZTA and NIWA, with significant events indicated by arrows. Dates of Lidar acquisition shown at right. Chain dashed line indicates inferred approximate trend from 2 data points; full line is based on post-1980 data trends. Shaded area suggests envelope of possible historic mean bed level variations corresponding to known variation from trendline observed from post-1980 data.

Further detail on the aggradational behaviour of the river has been documented by Beagley and Gardner (2023).

2.2.2. INCREASINGLY ACTIVE AND EXPANDING BRAIDPLAIN

Aerial photos from 1948, when the bed level at the SH6 bridge was about 140 m asl, show a mainly single-thread channel with overflow channels crossing adjacent vegetated *floodplain*. By contrast aerial imagery in 1997, when the bed level at the SH6 bridge was about 146 m asl, shows an intensely braided bed occupying the full available width, with no vegetation visible (Figure 2-4). Between 1985 and 2021 the river has widened by about 200m to the east downstream of the oxidation ponds as it has aggraded.

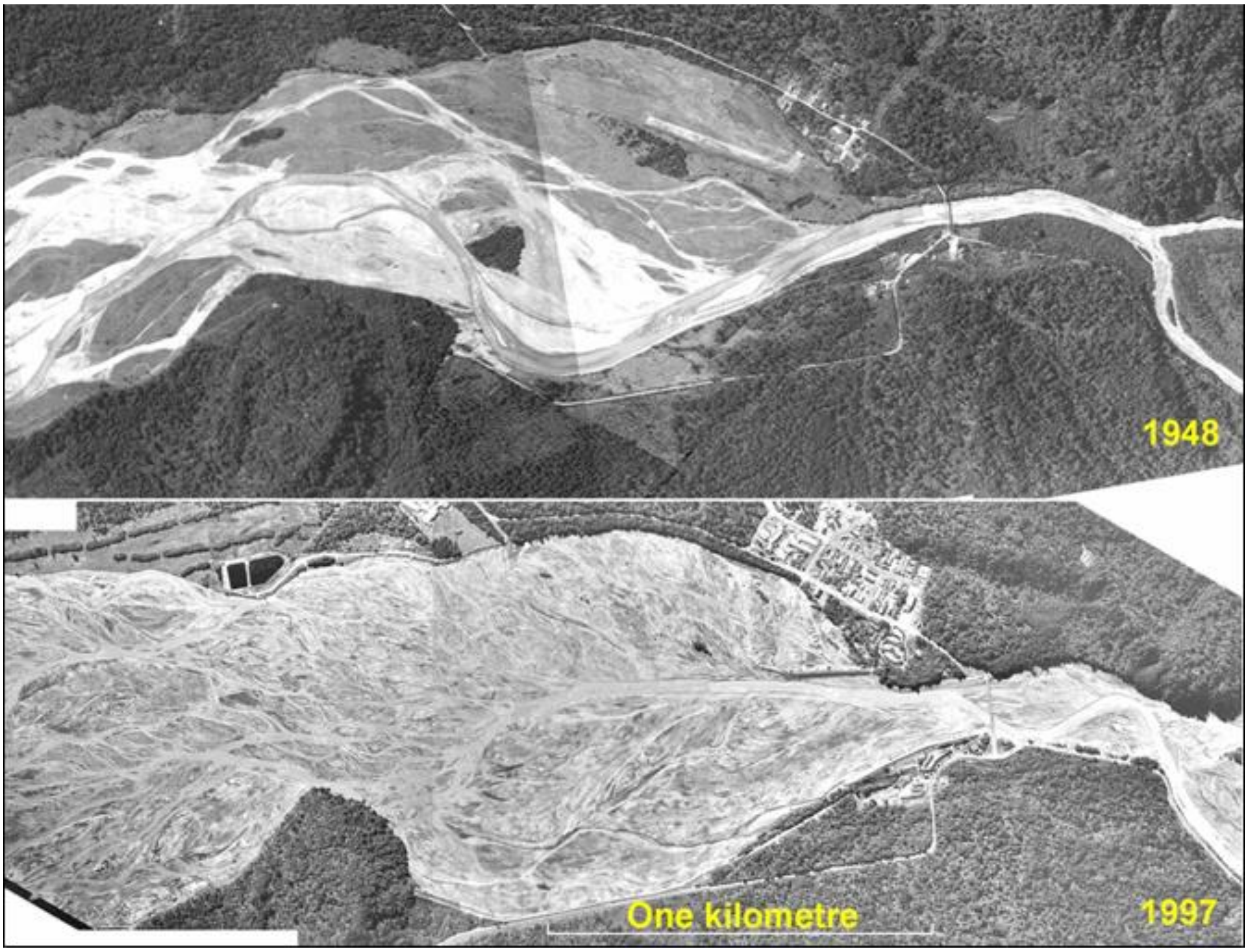

Figure 2-4 - Aerial imagery of the Waiho *fan* in 1948 and 1997.

2.2.3. DEVELOPING AVULSION INTO THE TATARE STREAM

Since about 2010 the Waiho bed downstream of the oxidation ponds has been at such a high level that *flood* waters can spill north into the Tatare Stream, the river bed of which is approximately 15 m lower than the Waiho *fan* surface. These flows have been increasing because of the continuing *aggradation* of the Waiho, and have led to increasingly deep and wide overflow channels resulting from overspill and *headcutting* during floods. In recent floods a several-metre deep and hundreds-of-metres wide breakout channel (*avulsion*) has developed that can cause *headcutting* back up the Waiho bed (Figure 2-5).

It is worth noting that the present *avulsion* into the Tatare shows that never since the last interglacial period has the Waiho *fan* previously been at its present level.

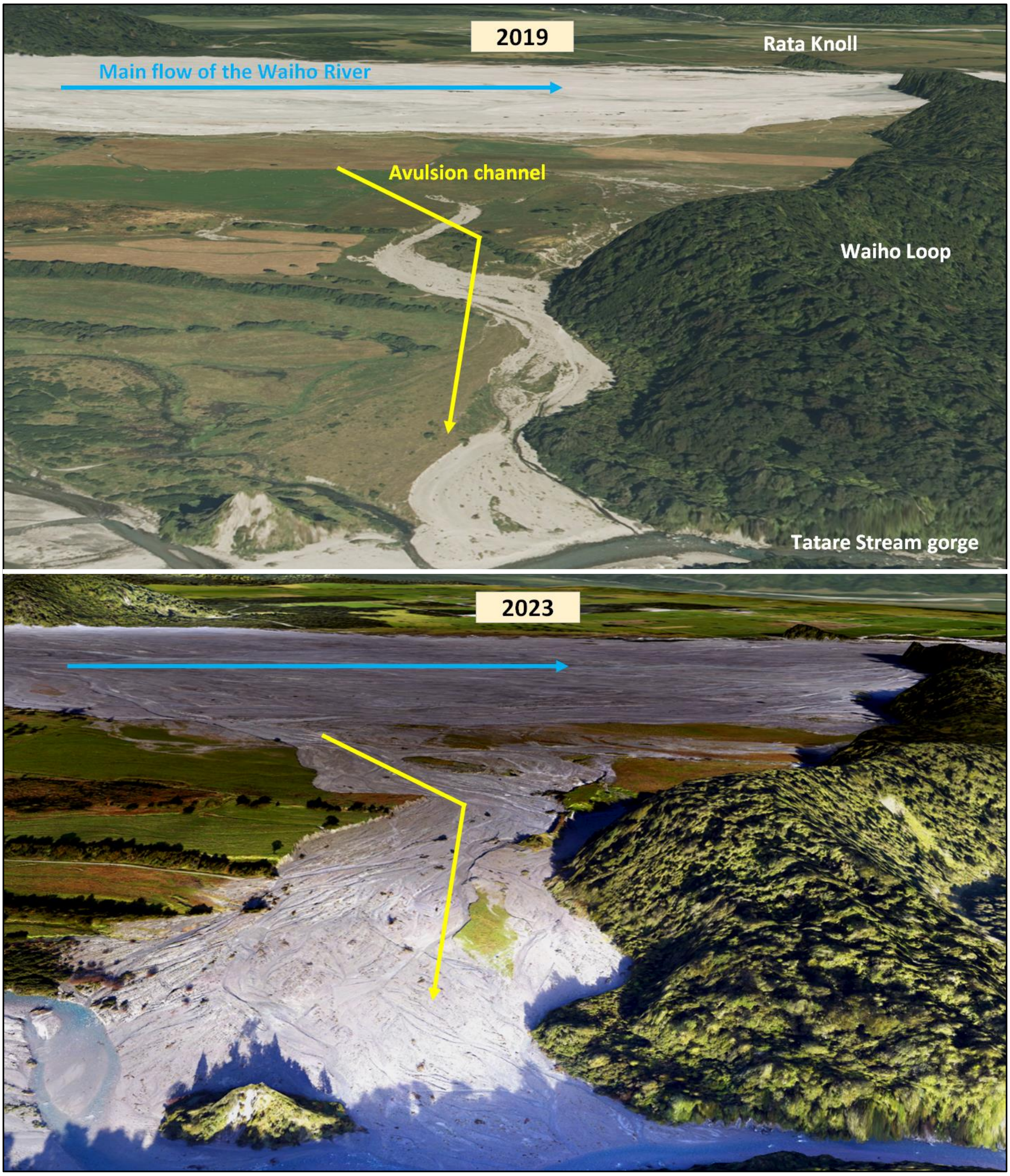

Figure 2-5 - Images comparing the Waiho *avulsion* site before (2019) and after (2023) the February 2023 event. At the bottom of each image, the Tatare Stream can be seen flowing into its gorge through the Waiho Loop.

2.2.4. EFFECTS OF STOPBANKS ON RIVER BEHAVIOUR

Since the 1970s, the behaviour of the Waiho River between the SH6 Bridge and Canavan's Knob has been constrained by stopbanks, on the south side to protect the SH6 and Motor Camp, and on the north side to protect the airstrip (later the heliport) and Tourist Corporation Hotel. In this *reach* the result has been that the river has been prevented from accessing the full width of its *fan* when it had aggraded sufficiently to spill out of its previously incised channel. Had the river been allowed to spread across the *fan*, the area over which sediment deposited would have been much greater than that available within the stopbanks, so the increase in bed elevation would have been slower. The bed elevation increase rate is inversely proportional to the bed area available for *deposition*, thus the post-1970s *aggradation* rate has been about three times what it would have been in the absence of confinement by stopbanks (Figure 2-6). As the *aggradation* has subsequently extended downstream it has been necessary to also install stopbanks on the south side downstream of Canavan's Knob and on the north side from the heliport to the oxidation ponds.

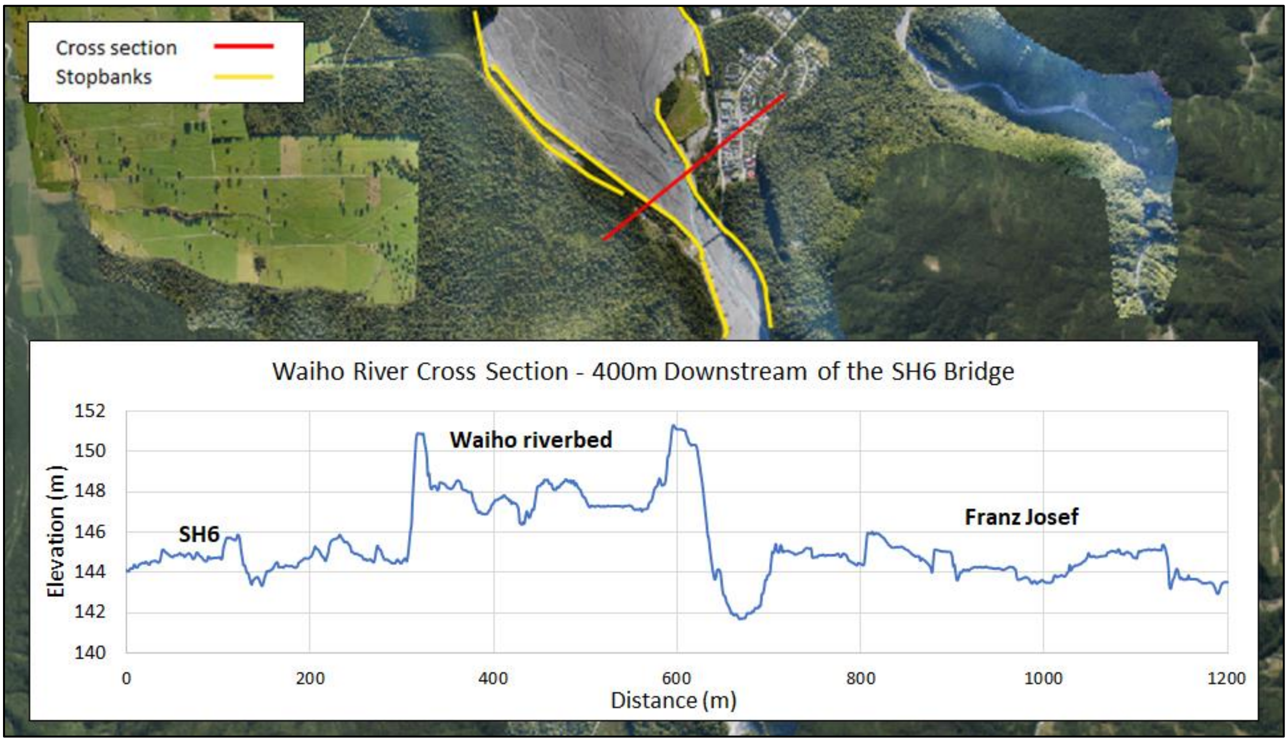

Figure 2-6 - Cross section showing the Waiho river-bed and adjacent land and township elevation.

The Milton's *stopbank* adjacent to the southern end of the Waiho Loop protects the airstrip (relocated in the 1980s from the northern *floodplain* just downstream of the Franz Josef township) and downstream farmland from flooding. However, it also diverts the Waiho River to the north, whilst causing a major constriction to the Waiho bed width that undoubtedly influences river *flood* behaviour. While growth of the *avulsion* into the Tatare above the Loop would reduce the pressure on the Milton's *stopbank*, this *stopbank* will continue to direct flow towards the *fan* now developing downstream of the Tatare gap in the Waiho Loop.

When considering future stopbanking measures, it is important to note that due to the steep river gradient, altering stopbanking downstream of Canavan's Knob will have little or no effect on *aggradation* in the reaches upstream of Canavan's Knob.

2.3. FUTURE OUTLOOK

2.3.1. AVULSION INTO THE TATARE STREAM

The development of the Waiho *avulsion* into the Tatare has been investigated by a microscale model (Campbell, 2012; Davies et al., 2013). While the model is at best an approximate indicator of real river behaviour, the following outcomes seem possible (Figure 2-7):

(i) The growth and *headcutting* (upstream extension) of the Waiho overflow channels will continue to increase, causing *degradation* in the vicinity of the oxidation ponds and heliport and possibly farther upstream.

(ii) The Waiho flow into the Tatare Stream during floods will continue to increase, and may become perennial (i.e. permanent flow all year).

(iii) The bed of the Tatare River immediately upstream of and through the Waiho Loop will aggrade rapidly.

(iv) A *fan* will develop downstream of the Tatare gorge through the Waiho Loop, building out into the Waiho and towards Lake Pratt, and increasingly push the Waiho away from its northern bank downstream of Milton's *stopbank*.

(v) The bed level of the Tatare Stream upstream of the Waiho Loop will aggrade rapidly; this *aggradation* will progress upstream to and past the SH6 Bridge, which may need to be raised to above the level of the Tatare *fan*.

(vi) Eventually the valley in which the Tatare presently flows from SH6 to the Waiho Loop will fill completely and the Tatare Stream and Waiho River will flow on a surface at the same level as the Waiho *fan*.

The timescale of these changes is unclear at present. However, given that overbank flows first entered the Tatare Stream about 2010, the recent very rapid increase in these flows, and the possibility that the *avulsion* may move upstream, it would be prudent to envisage complete infilling of the Tatare valley within a decade.

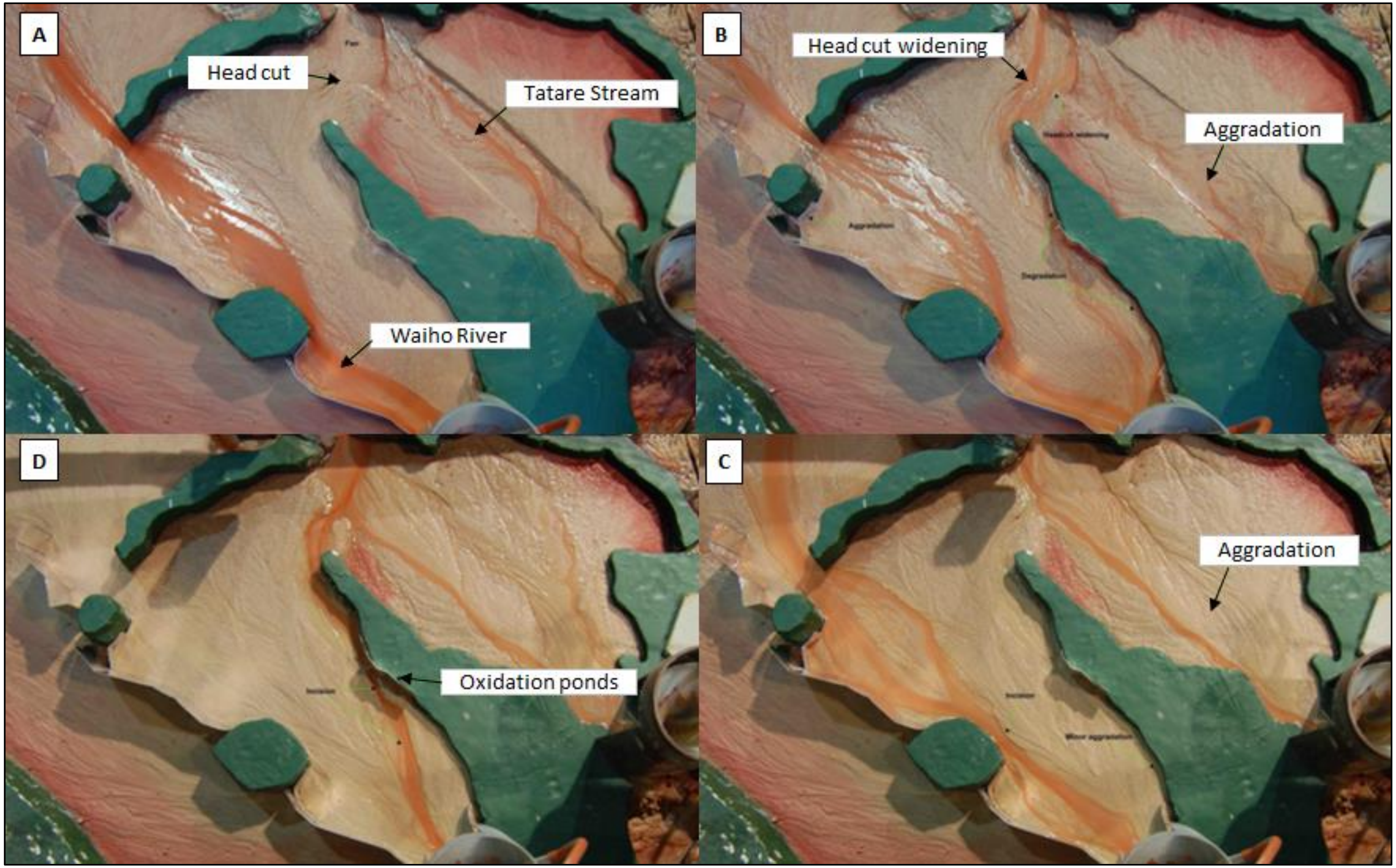

Figure 2-7 - Davies et al (2013) microscale modelling of the Waiho River *avulsion* into the Tatare Stream. Images to be viewed in clockwise order from A to D showing the head cut developing, and the Tatare valley filling in.

2.3.2. CALLERY AND TATARE LANDSLIDE DAMBREAK FLOODS

The magnitudes of the landslide dambreak floods that can occur from the Callery (Davies, 2023; Dunant, 2019; Davies, 2002; Davies & Scott, 1997) and the Tatare (Davies, 2023; Nandhini, 2022) catchments have been estimated. In both cases the flow rate of the 100-year return interval landslide dambreak *flood* is about three times that of the 100-year return interval rainstorm *flood*. Bearing in mind that a landslide dambreak *flood* will carry much larger quantities of sediment and vegetation than a normal rainstorm *flood*, the former can be expected to be much more damaging than the latter. While some landslide dams do not fail before they are filled in with sediment, and end up forming valley flats, most fail within a short time (27% within 1 day, 50% within 10 days, 85% within a year).

A major component of the *hazard* resulting from these landslide dams is the possibility that a dam could form during a major overnight rainstorm, and could fill, *overtop* and fail in a few hours before its presence had been detected. This situation was the main reason for the relocation of the Franz Josef Holiday Park in the early 2000s, but while that specific vulnerability has been remedied both rivers still pose major landslide dambreak *flood* hazards to parts of the township.

2.3.3. INTERDECADAL PACIFIC OSCILLATION PHASES

The *Interdecadal pacific oscillation* (IPO) is the long-term oscillation of wind and ocean current circulations around the Pacific Ocean, including sea surface temperature differences across the ocean, which affects the strength and frequency of El Niño and La Niña cycles.

In a positive IPO phase, New Zealand receives stronger west to southwest winds which means the West Coast is wetter than average, experiencing more extreme rainfall and therefore more frequent and intense flooding than average (Griffiths et al., 2009; McKerchar & Henderson, 2003; Thompson, 2006; 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 (Figure 2-8). The long term record shows oscillations over decadal timescales.

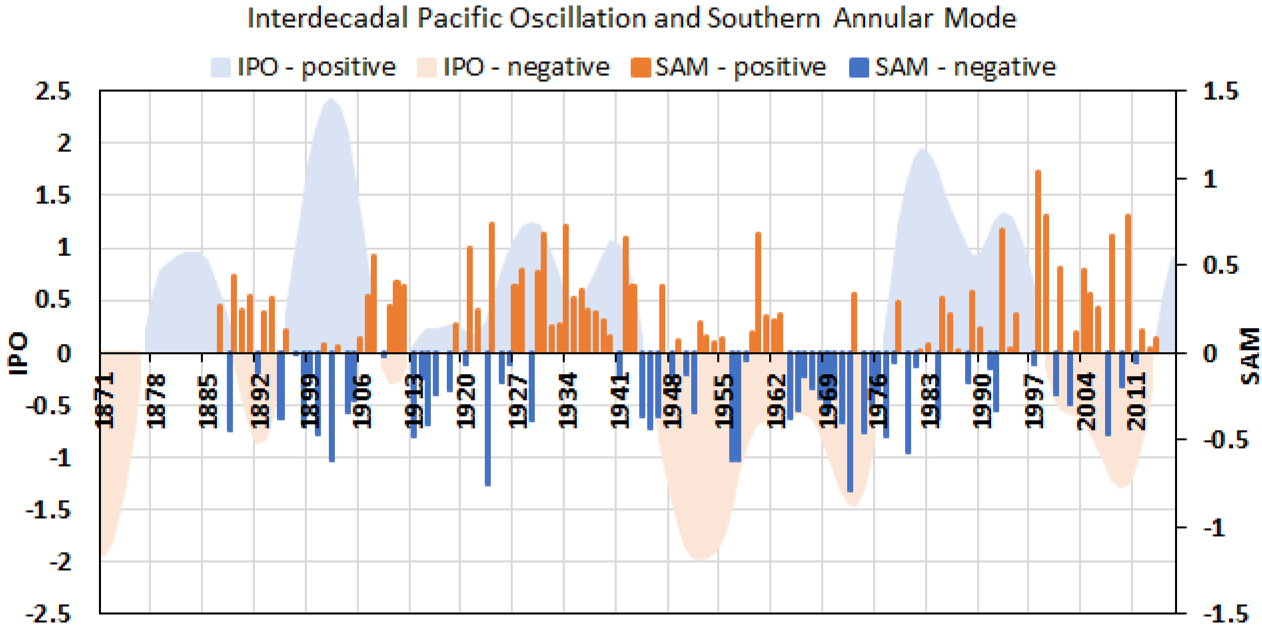

Figure 2-8 - Positive and negative phases of the IPO and SAM since 1871. Note, blue is indicative of generally wetter weather on the West Coast, and orange of more stable, drier conditions.

In addition to the IPO, regional climatic variations in New Zealand are also affected by oscillations in the Southern Ocean's circulation around Antarctica (*Southern annular mode*; SAM; Figure 2-8). Variations in the vortex circulation over the South Pole affect the position of the depression track around the southern hemisphere. This gives rise to either more south-westerly low troughs (negative SAM) or more north-easterly rainfall with blocking highs (positive SAM). The former results in similarly enhanced rainfall and therefore floods as the positive phase of the IPO.

In both cases (and even more so when the positive IPO and negative SAM align), as rainfall frequency and intensity increase, so too do 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). Studies of other Westland rivers such as the Wanganui (Gardner & Beagley, 2023) have shown a distinct change in river behaviour during positive and negative IPO phases as a result of changes in sediment supply and *flood* frequency and intensity.

Given the shift into a positive IPO phase coupled with climate change predictions and at times negative phase of the SAM, there is likely to be an increase in the frequency and intensity of *flood* events as well as an increase in sediment supply to the Waiho River in at least the short to medium term, with consequent effect on river bed *aggradation*.

The consequences of this aggradational behaviour continuing at or increasing from its current rate, will be continued high levels of channel change across the river bed and a reduction in the *capacity* of the protection structures to withstand the flows they were 'designed' for, and therefore increasing vulnerability to *breach* or overtopping.

2.3.4. CLIMATE CHANGE; EFFECTS OF WARMING

The warming of the global environment is now well established, and recent events seem to indicate that impacts may appear more rapidly than previously thought. These impacts include:

- Under all representative concentration pathways (RCPs) except 2.6, winter rainfalls and *flood* flows increase in Westland prior to 2100 (Collins, 2021).
- During any given storm event there will be less snowfall and more rainfall than hitherto. This means an increase in storm runoff from high levels; it also means less snow accumulation on glaciers and more ice-melt caused by water runoff. Both of these lead to higher river flows.
- Increase in temperatures at high levels will lead to reduction in rock faces reinforced by *permafrost*. This in turn will lead to an increase in the frequency of rockfalls and landslides, which causes increase in sediment supply to rivers.
- Rising sea levels will have a coastal impact only, due to the steep gradients of Westland rivers

2.3.5. ALPINE FAULT EARTHQUAKE (AF8)

The expected rupture of the Alpine Fault will occur along the *rangefront* of the Southern Alps, passing through Franz Josef township itself and crossing the Waiho in the vicinity of the SH6 Bridge. There will be uplift of 2 to 3 m across the fault, and horizontal offset of about 8 m. This event has a probability of about 75% of occurring within the next 50 years, 30% within the next 20 years and 15% within the next decade; thus it is as likely to occur as a 50- to 100-year *flood*. The *mainshock* will be followed by a series of aftershocks up to M7 in magnitude on the Alpine and other faults, lasting for up to a decade and gradually decreasing. An earthquake on a fault within the western Southern Alps will be smaller but all its radiated energy will affect mountains causing landsliding, whereas at least half of the energy released by the Alpine fault will only affect the low land west of the fault.

Assuming that no landslide dams form in the Waiho-Callery and Tatare systems as a result of a major earthquake and its aftershocks, the following impacts are to be expected:

(i) Immediate and severe damage to all Waiho stopbanks due to intense shaking, especially in the vicinity of the *rangefront*; this will particularly affect the heliport *stopbank* and the southern stopbanks upstream and downstream of the SH6 bridge, however, all stopbanks down to Milton's will be severely affected. The stopbanks will be structurally damaged (Figure 2-9) and reduced in elevation and the risks of overtopping and seepage failures in floods after the earthquake will increase dramatically, increasing further as *aggradation* progresses.

Figure 2-9 – Example of an earthquake damaged *stopbank* after the 2010 and 2011 Darfield and Christchurch events (Bainbridge, 2013)**.**

(ii) Greatly increased sediment input from shaking-induced landsliding, including large quantities of vegetation (Figure 2-10). This will be reworked down through the *fan* and lower valley over the course of weeks to decades, causing substantial (metres-scale) *aggradation* of the river bed with associated risks of bank overtopping and river *avulsion*.

Figure 2-10 – Example of seismic induced landsliding. Gelt River valley after the 2016 Kaikoura earthquake (GeoNet, 2023)**.**

(iii) Metres-scale uplift on the eastern side of the Alpine fault causing a waterfall that will retreat upstream (Figure 2-11); this will probably be rapidly obscured by *aggradation*.

Figure 2-11 – Example of seismically uplifted land. Waia fault scarp after the 2016 Kaikoura earthquake (Science Learning Hub – Pokapū Akoranga Pūtaiao, 2017)**.**

The regional consequences of a major earthquake will also substantially impact the societal environment of Franz Josef. Given the high probability of this event its broader consequences form a relevant context for decision-making around Waiho River management. These regional consequences are expected to include (Blagen et al 2021):

- Metres-scale river *aggradation* and *avulsion* on many Westland fans and floodplains over the course of several decades
- Severe damage to stopbanks within 10 km of the Alpine fault.
- Debris flows in many small steep streams in the years following the earthquake.
- SH6 will be impassable south of Ross through to Makarora, likely for up to several years or even decades. Road access to Franz Josef may be open within 6 months; access to Fox will take much longer.
- The Lewis, Arthurs and Haast pass roads are expected to be blocked for at least many months, perhaps for several years.
- Lack of access will mean temporary evacuation of populations from Harihari to Haast. This is expected to last for months north of Franz Josef, extending to years farther south.
- Re-establishment of economic activity south of Ross will be correspondingly delayed.

2.3.6. WAIHO RIVER BEHAVIOUR SCENARIOS OVER NEXT 10 YEARS (NO MAJOR EARTHQUAKE)

Assuming that the expected Alpine Fault earthquake does not occur within the next decade, the following river behaviour scenarios are possible (likelihoods are relative not absolute):

(i) No change of water and sediment inputs.
Likelihood medium.

- *Aggradation* will continue at approximately 0.2 m per year so the bed level at the SH6 bridge will increase by approximately 2 m, and the downstream *fan* surface will also continue to aggrade.
- Tatare *avulsion* will develop greatly (unless prevented); *aggradation* of Tatare bed will increase rapidly, moving upstream towards the Tatare SH6 Bridge. The Tatare *fan* downstream of the Waiho Loop will grow rapidly and cause increased *aggradation* and flooding downstream of Milton's *stopbank*. Lake Pratt will also be badly affected by intrusion of Waiho River flow. The existing lake will become entirely covered by silt and a new, much larger, glacial water lake will take its place.
- *Headcutting* from the Tatare *avulsion* may progress upstream to the vicinity of the oxidation ponds and Havil's *stopbank*. If the overspill itself moves upstream this *degradation* may develop rapidly.

(ii) Sediment inputs increase gradually due to warming/tectonic stress, no clear change in water inputs.
Likelihood high.

- The above effects in (i) will develop more rapidly.

(iii) Water and sediment inputs both increase gradually due to warming/tectonic stress.
Likelihood high.

- *Aggradation* continues at present rate but increased water flows cause increased damage to Milton's *stopbank* and other stopbanks. Effects otherwise as in (i) above.

In addition to the above, the following may occur:

(iv) Major (million cubic metre) non-seismic landslide in the Waiho/Callery catchment.
Likelihood approximately low
(*Aseismic* approximately 1% per year, *coseismic* approximately 2% per year)
Sudden metres-scale increase in *fan aggradation*; effects in (ii) above occur rapidly (weeks-months). If in Callery, landslide dam may form and fail causing major *flood* & sediment event threatening township.

(v) Major (million cubic metre) non-seismic landslide in Tatare catchment.
Likelihood very low
(*Aseismic* < 1% per year, *coseismic* approximately 1% per year)
Sudden *aggradation* in Tatare; SH6 Tatare Bridge needs to be replaced. Tatare *fan* downstream of the Waiho Loop grows rapidly. Landslide dam may form and fail causing major *flood* and sediment event threatening lower Stony Creek *fan* and Tatare settlement.

3. RIVER MANAGEMENT

During European settlement of the Waiho area in the mid to late 1800s, the location of the Franz Josef township was chosen as it appeared to be 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 was well incised into its fanhead and consisted of very large *glacial lag boulders* (Davies & McSaveney, 2001).

However, since settlement, ongoing flooding exacerbated by bed *aggradation* has forced the removal of the airstrip and original hotel out of the *floodplain* and lower terrace, respectively, and the Waiho River has had to be actively managed through the use of protection structures such as stopbanks (otherwise known as levees, dykes, or *flood* embankments), rock gabions, revetments, and groynes, as well as ongoing diversion and channel works.

3.1. HISTORIC PROTECTION NETWORK

The WCRC has documented the majority of the history of the Waiho River protection network including construction, damage, repairs, and upgrades in the various asset management plans that have existed over time (West Coast Regional Council, 2010, 2014a, 2014c, 2014b, 2021). We have converted this into a timeline (13. Appendix B) with the main developments of the network outlined below.

The earliest evidence of a river protection structure along the Waiho River is in a photo from the 1920s which shows a rock gabion (wire crate) upstream of the footbridge, presumably to prevent riverbank erosion (Figure 3-1).

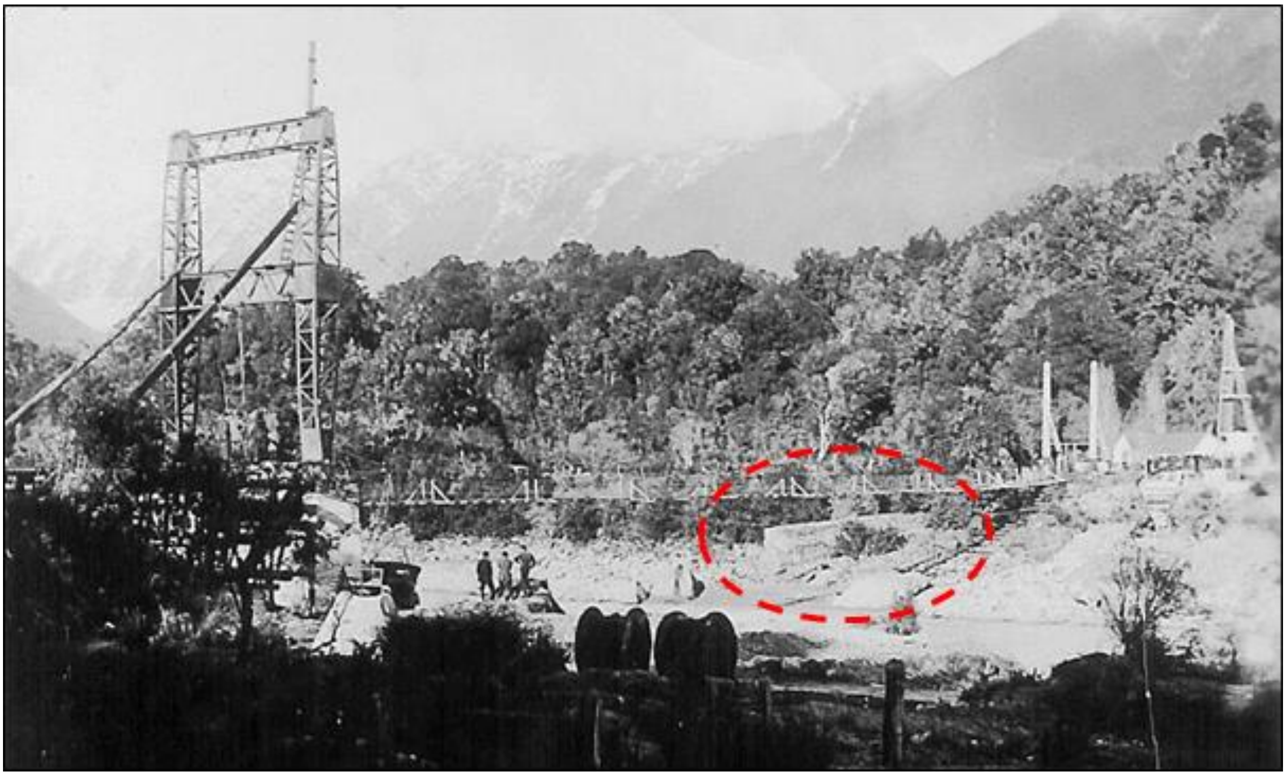

Figure 3-1 – Photo from the 1920's looking upstream at the swing bridge with the Southern Alps and Franz Josef glacier behind, and the rock gabion circled by the red dashed line.

In the 1930's further rock gabions were placed on the true right downstream of the SH6 bridge to protect the airstrip. However, construction of stopbanks didn't begin until 1947, when the Waiho River flowed over the southern riverbank upstream of Canavan's Knob and flooded across SH6, running parallel to it for 3 km to Docherty's Creek. A temporary low scrub and boulder wall to check the overflow was put in place, however erosion over the next twenty years resulted in ongoing repairs and rock additions to protect this wall, riverbank and SH6.

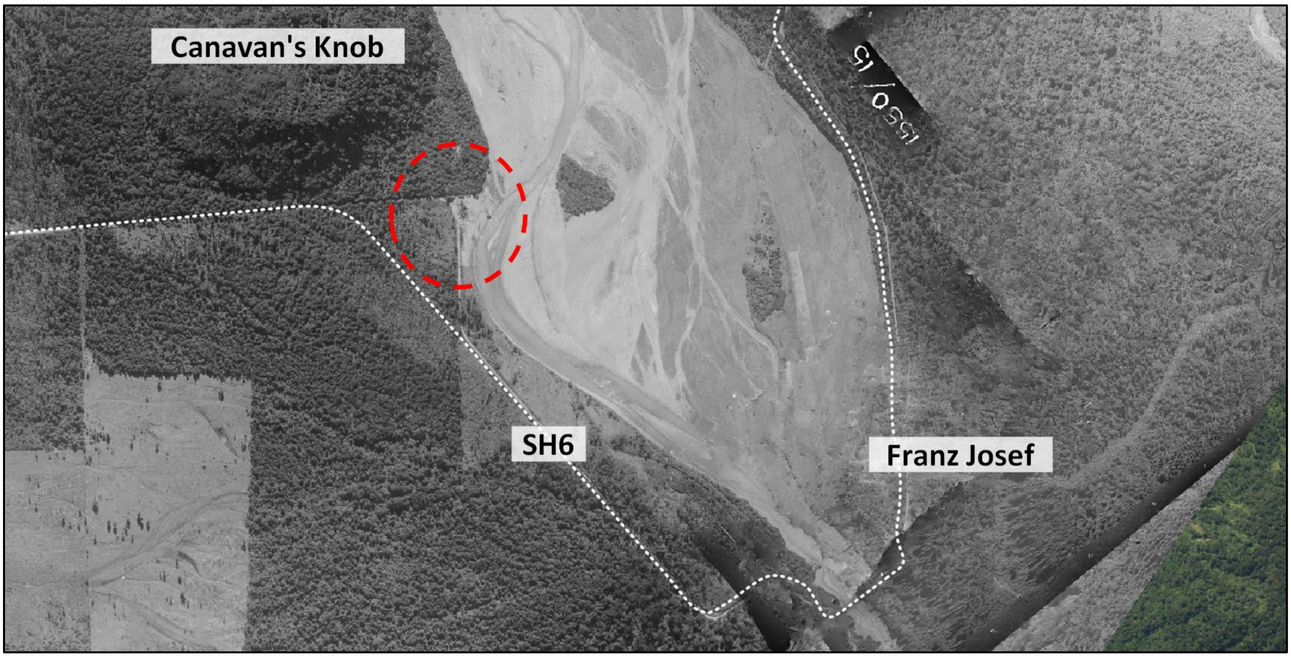

Figure 3-2 – Aerial imagery from 1948 with the location of where the river broke out in 1947 circled.

The next addition to the network was in the 1950s, with the first "permanent" *stopbank* was built on the south side just downstream of Rata Knoll in 1954. This *stopbank* (to become known as Milton's) was designed as a 'cut-off' bank to prevent the Waiho River from flooding the farmland between it and Docherty's Creek. Over the next ten years this was raised, and then repaired multiple times, with the present-day alignment considerably different to that in 1954 due to repeated damage (Figure 3-3), substantial breaches during the 1967, 1982, and 2019 floods, and erosion of the riverbank.

Figure 3-3 – Aerial imagery of Milton's *stopbank* in 1965 and June 2023.

In 1968, the first *stopbank* on the north side was constructed. This 350 m long, heavily rock armoured *stopbank* was designed to protect the airstrip and the Tourist Corporation Hotel from floodwater.

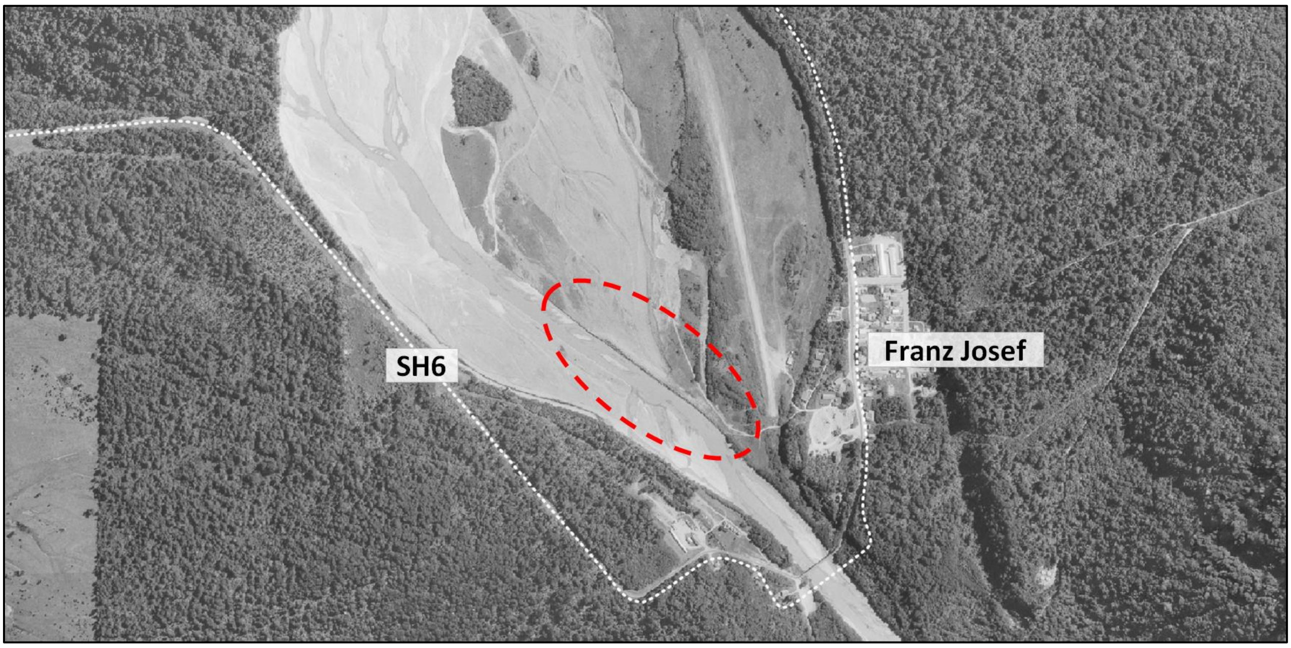

Figure 3-4 – Aerial imagery from 1973 after the construction of the first *stopbank* on the north side.

However, over a twenty-year period, this *stopbank* was breached on multiple occasions, and required ongoing repairs, and additions. In its most substantial form, it extended from the SH6 Bridge to just downstream of Canavan's Knob, confining the river to an approximately 400 m wide corridor. This particular alignment lasted only two years, with a *flood* in 1982 breaching the upstream end and obliterating the downstream hook groyne (Figure 3-5), as well as destroying the airstrip.

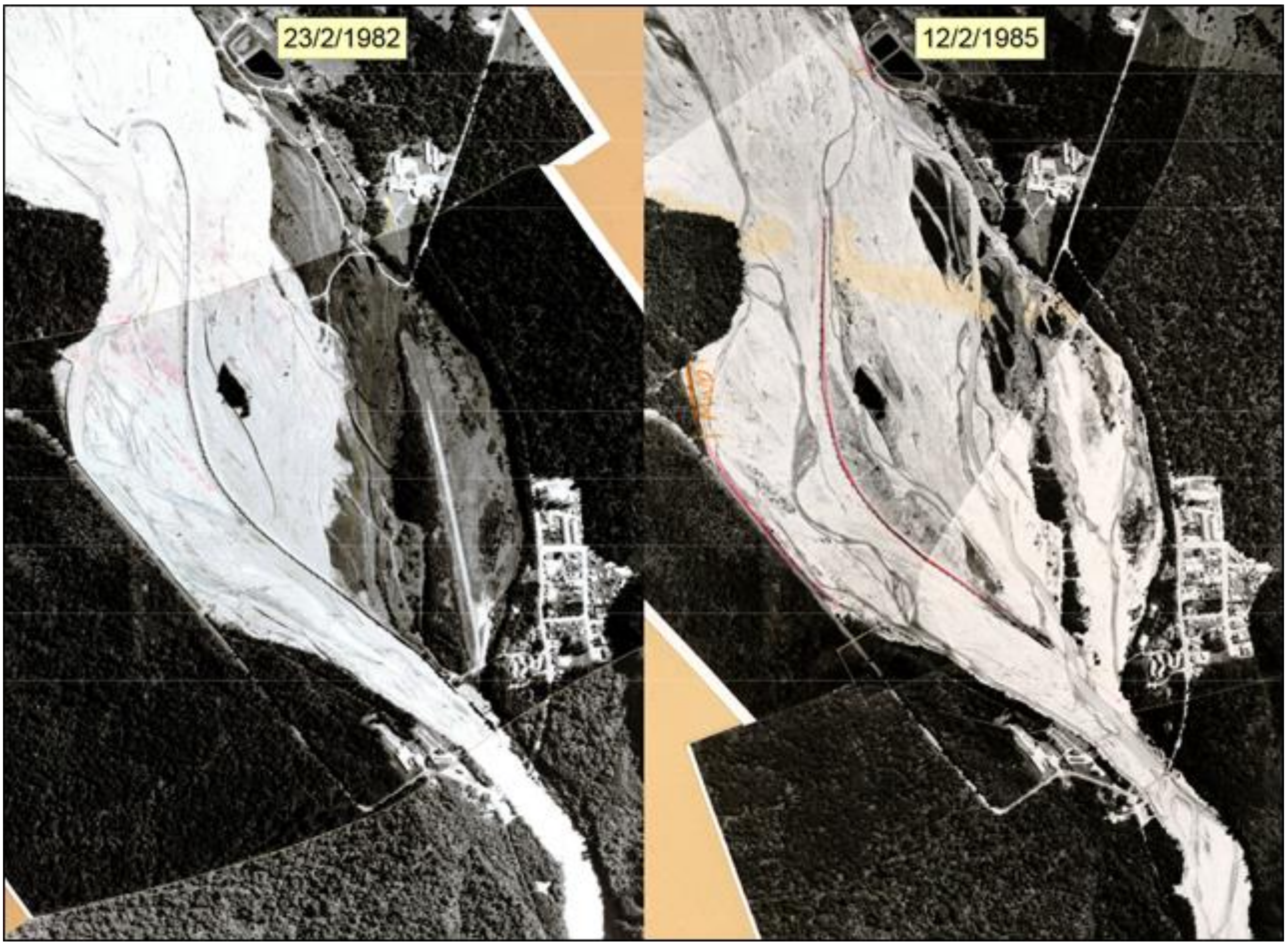

Figure 3-5 - Comparison of aerial imagery from 1982 and 1985 which shows the extended true right *stopbank* in 1982, and what remains in 1985.

By 1979, the aerial imagery also shows a substantial *stopbank* present on the south side just upstream of Canavan's Knob where SH6 runs along the southern bank of the Waiho River (visible in the 1982 and 1984 imagery above in Figure 3-5). This is a notable improvement from the various rock protection measures and temporary wall that existed previously. However, it did not prevent the Waiho from breaking out to the south above Canavan's Knob in a 1982 storm and flooding SH6 down to Docherty's Creek. It has been reported that it then took a month to get the river flowing back into its current course.

In 1985, a 140m long *stopbank* was constructed downstream of Canavan's Knob on the south side in an attempt to protect farmers in the Lower Waiho Flats from similar flooding to that of 1982 when Milton's *stopbank* breached (along with the southern *stopbank* upstream of Canavan's Knob and the northern *stopbank* protecting the airstrip and hotel).

In 1990 it was decided to abandon the northern *stopbank* in favour of pushing the works back to the existing riverbank. A year later, in 1991, the Heliport *stopbank* had been constructed and with the addition of the WDC access track *stopbank* (unlined) in 1995 and the Church *stopbank* in 1996, the original northern *stopbank* had effectively been replaced.

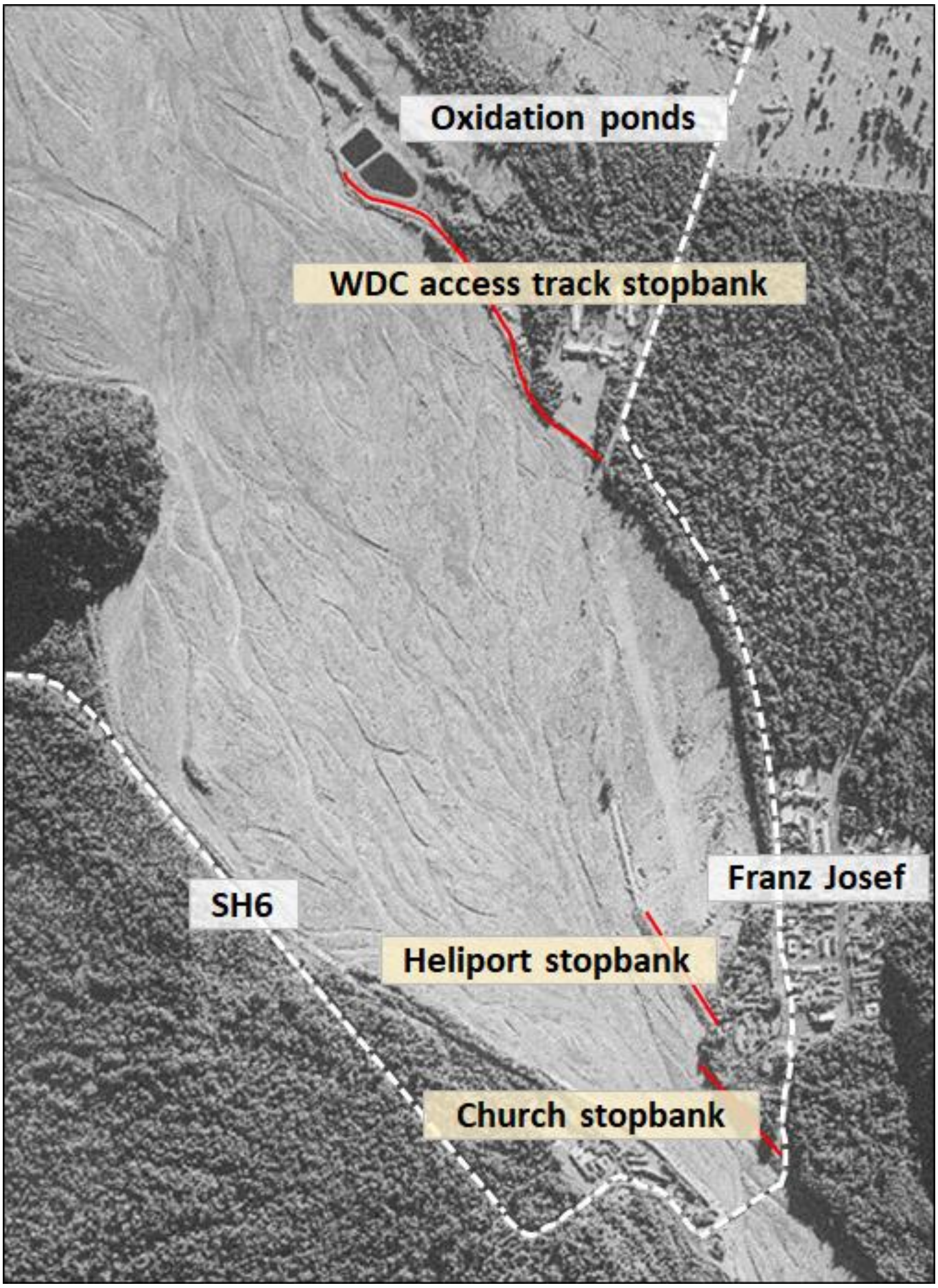

Figure 3-6 – Aerial imagery from 1997 showing the protection network on the upper *fan*, with the newly constructed stopbanks on the northern side shown by the red lines.

Between 2004 and 2011, a substantial secondary *stopbank* was constructed on the river bed inside the existing *stopbank* along the south side between the SH6 bridge and Canavan's Knob to provide a stronger frontline defence to prevent the Waiho breaking out to the south while allowing Wombat Creek to exit into the Waiho.

Figure 3-7 – Aerial imagery from 2012 showing the two Waka Kotahi stopbanks upstream of Canavan's Knob (red lines) and Wombat Creek (blue line).

On the north side, the last of the stopbanks – the 55kph Corner *stopbank* – began construction in 2014 when the river began to actively attack this location and was then gradually extended over the next two years in order to protect the highway and downstream properties (Figure 3-8).

After the 2016 *flood* event during which the oxidation ponds access track *stopbank* was breached and the Scenic Circle (previously the Tourist Hotel Corporation) Hotel flooded, a substantial rock lined *stopbank* (Havill's) was built in front of the access track (Figure 3-8).

A significant *flood* event occurred in March 2019 destroying the SH6 bridge and breaching Milton's *stopbank*. The bridge was replaced with a new Bailey bridge, the *stopbank* repaired, and the Waka Kotahi stopbanks on the south side (upstream of Canavan's Knob) were raised and in places widened so as to prevent the seepage that occurred during the 2019 event.

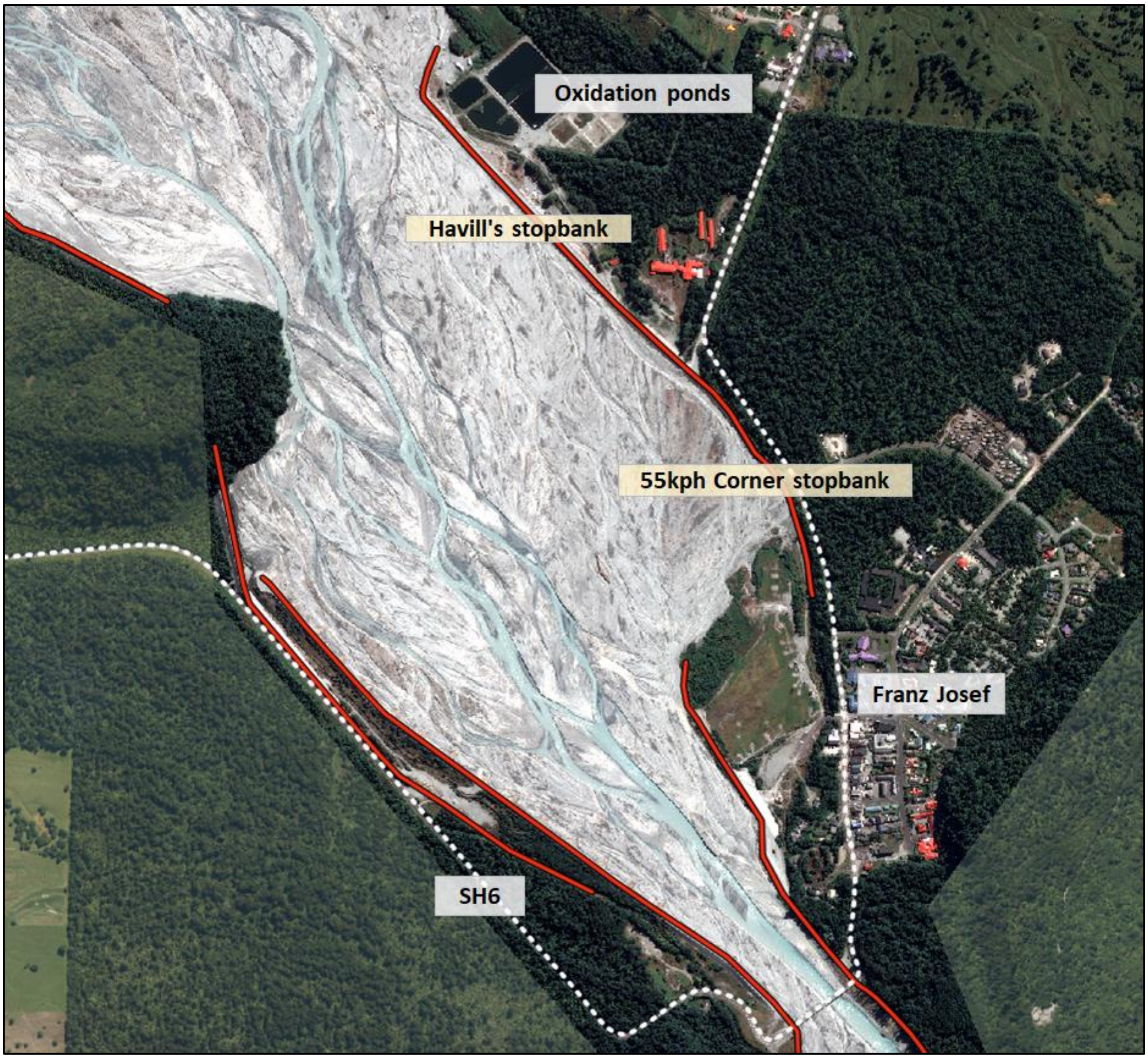

Figure 3-8 – Aerial imagery from 2021 showing the Havills and 55kph corner stopbanks.

In 2021, the WCRC began the resource consent process to build a rock lined bund on the northern bank of the Waiho River to prevent it from flowing into the Tatare Stream above the Waiho Loop. In January 2023, construction began, however this was soon halted with the onset of the developing *avulsion* eroding the farmland that the bund would have been built along.

3.2. CONTEMPORARY PROTECTION NETWORK

The present day *flood* protection network is owned and managed by several organisations including the West Coast Regional Council, Waka Kotahi - New Zealand Transport Agency (NZTA), Hokitika Airport Authority, Department of Conservation, and Westland District Council (Figure 3-9).

The network is extensive, with stopbanks bounding the very active river bed 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.

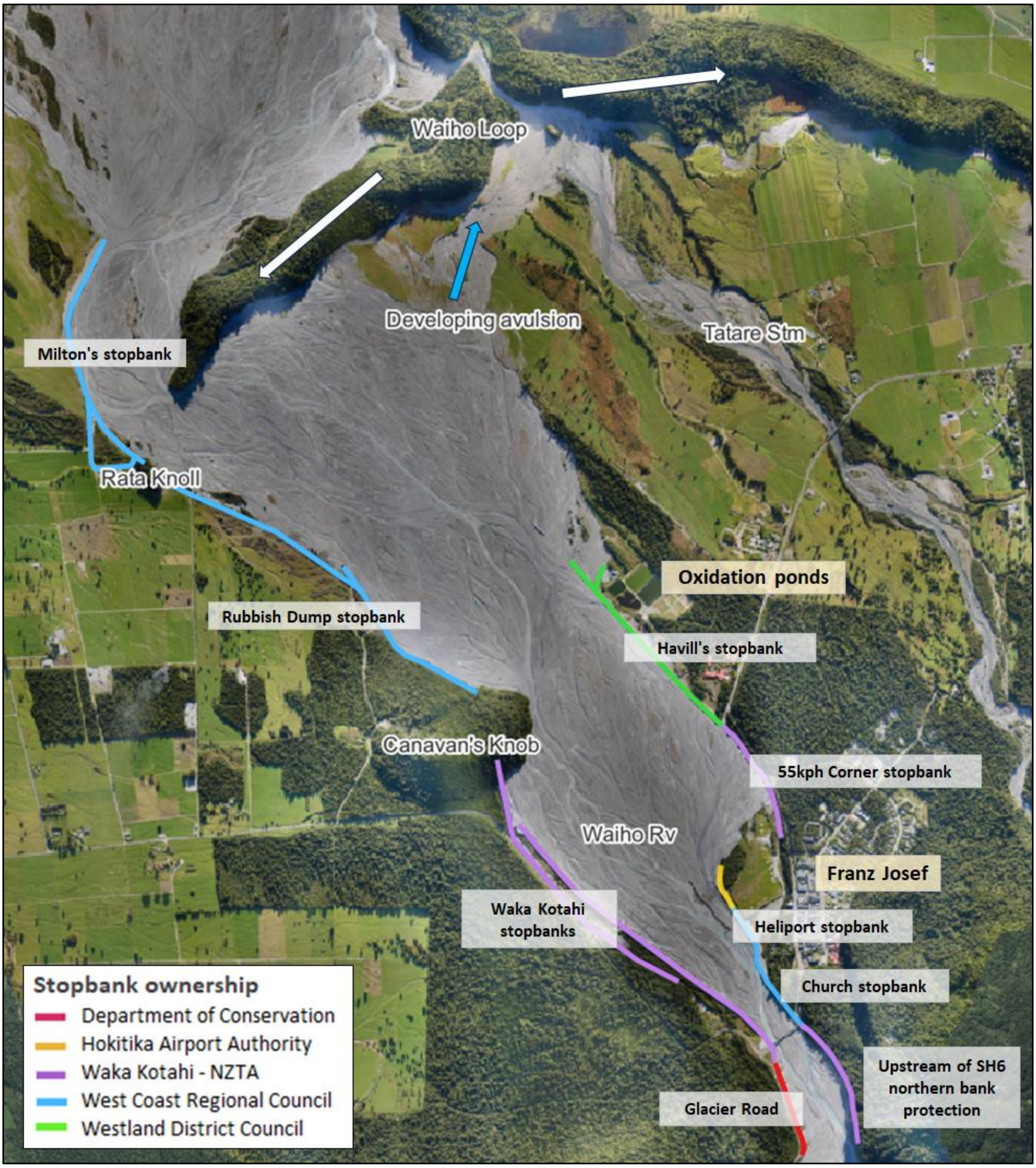

Figure 3-9 - Waiho River *flood* protection scheme with the name of each *stopbank* and key geomorphic features labelled and *stopbank* ownership denoted by colour.

However, there is very little documentation of how each of the stopbanks was designed, nor is there a consistent standard of construction across the network. As a result of this, and the rapid *aggradation* and high level of channel activity across the river bed, several issues exist within the current network.

3.2.1. UNLINED STOPBANKS

The Rubbish Dump *stopbank* is a partially unlined gravel *stopbank* on the south side of the river, which extends from the downstream side of Canavan's Knob to the upstream side of Rata Knoll where it joins Milton's *stopbank*. As a result of the *aggradation* and high level of channel activity across the river bed, the main channel on occasion now runs alongside this *stopbank* and due to its unlined nature this has resulted in progressive erosion of sections that are very prone to failure (Figure 3-10).

Figure 3-10 – An unlined section of the Rubbish Dump *stopbank* between Canavan's Knob and Rata Knoll.

Consequently, there has been progressive lining of this *stopbank* with rock. However, maintaining this long length of rock (approximately 1.75 km) with the on-going *aggradation* requiring *stopbank* raising, and hence adding rock all along this length, would require substantial expenditure.

Also on the south side, are the two Waka Kotahi stopbanks which occupy the limited space between SH6 and Waiho River from the SH6 Bridge down to Canavan's Knob, and allow for Wombat Creek to flow between them before joining the Waiho River. The 400 m of the river-facing *stopbank* immediately downstream of the SH6 bridge has been rock lined, and fifteen rock groynes have been constructed at approximately 80 m intervals along the remaining 1150 m. However, this remaining 1150 m of the river-facing *stopbank*, and the entire secondary *stopbank* behind it, are unlined. Should the channel alignment direct flow towards this *stopbank* it would be very vulnerable to overtopping, erosion, and breaching.

3.2.2. POOR CONSTRUCTION OF ROCK LININGS

The progressive rock lining of the Rubbish Dump *stopbank*, and the existing lining of the Milton's *stopbank*, are also problematic. Recent inspections of the rock linings have noted that the placing and selection of the rock is not in line with industry best practice making it prone to failure.

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 are placed as a mixed rock matrix that can self-heal damaged areas and settle as a whole into localised scour holes, and is therefore less prone to wholesale failure. If needed the *stopbank* can simply be topped up if the crest levels have dropped, while the *stopbank* remains structurally sound.

An example of relatively recent slumping on the Milton's *stopbank* is shown in Figure 3-11 and Figure 3-12 where it can clearly be seen that the rock work is coming loose from the face and falling into the channel. This is likely the result of bed scour beneath the toe of the *stopbank*, and therefore the *stopbank* is settling into the scour hole and disintegrating due to the nature of the rock placement.

Figure 3-11 – A section of slumped rock on the Milton's *stopbank*, as shown by the yellow line.

Figure 3-12 – A slumped section (yellow dashed lined) of the Milton's *stopbank*.

This 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 *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 point 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.

3.2.3. INADEQUATE FREEBOARD

Land River Sea Consulting Ltd has run its Waiho River hydraulic *flood* model (Gardner, 2021) with the 2016, 2019, and 2023 LiDAR datasets and the current protection network to show how the aggrading *fan* surface is affecting peak design water levels along the stopbanks and therefore the *capacity* of the network as a whole.

The model results indicate an increase in peak water level along the southern Waka Kotahi stopbanks (SH6 Bridge to Canavan's Knob), and the northern Church, Heliport, 55kph Corner and Havill's stopbanks over time, with a pronounced increase between the 2019 and 2023 LiDAR model results (Figure 3-13, Figure 3-14 and Figure 3-15). The geomorphic change detection (GCD) analyses suggest that this pronounced increase is likely in part due to the transport and *deposition* of just under half of the 1.1 million cubic metres of sediment that had accumulated in the upper Waiho 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 and failure if water levels should rise due to local *aggradation* and if the flow of a main channel is directed at the bank. Stopbanks are designed to have an additional height allowance (*freeboard*) beyond the peak design water level. Given the dynamic and powerful nature of the Waiho River, the *freeboard* allowance is 1 m. However, the upper end of the Waka Kotahi stopbanks, sections of the Church and

Heliport stopbanks, and the lower end of the Havill's *stopbank* have minimal to no *freeboard*, and are therefore very vulnerable to overtopping (Figure 3-13, Figure 3-14 and Figure 3-15).

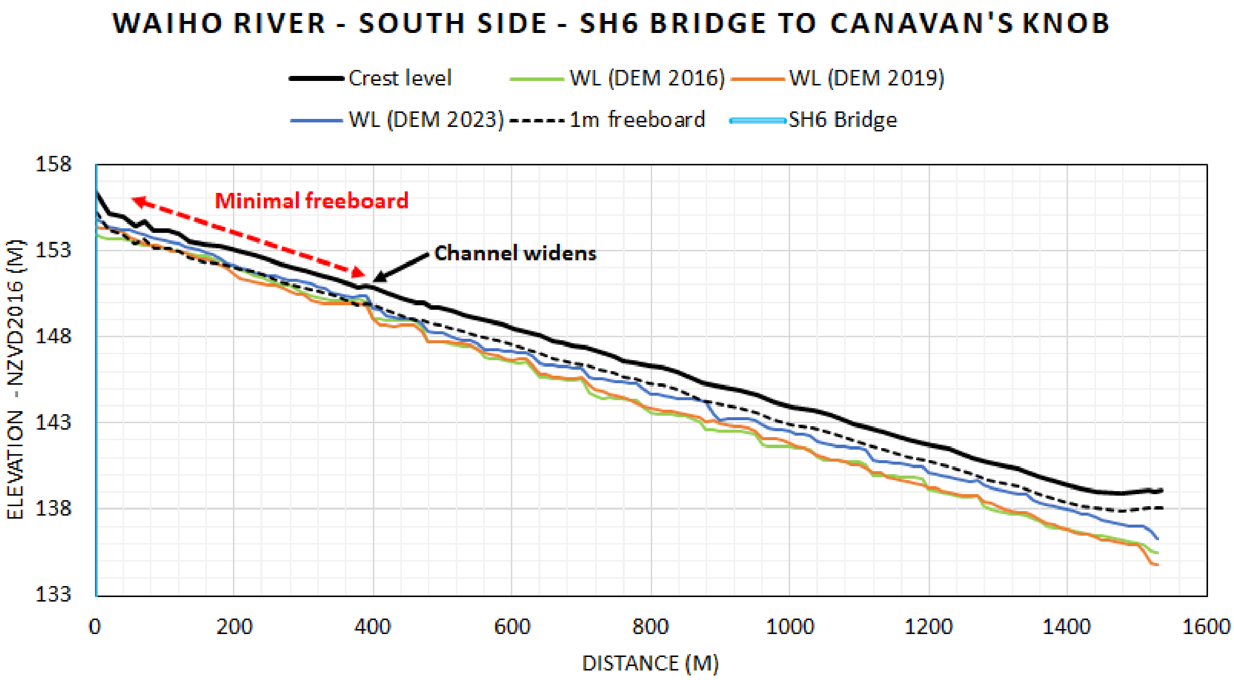

Figure 3-13 – LRS Waiho 2D hydraulic model: peak water level results with a 2,500 m³/s flow – SH6 Bridge to Canavan's Knob – south side.

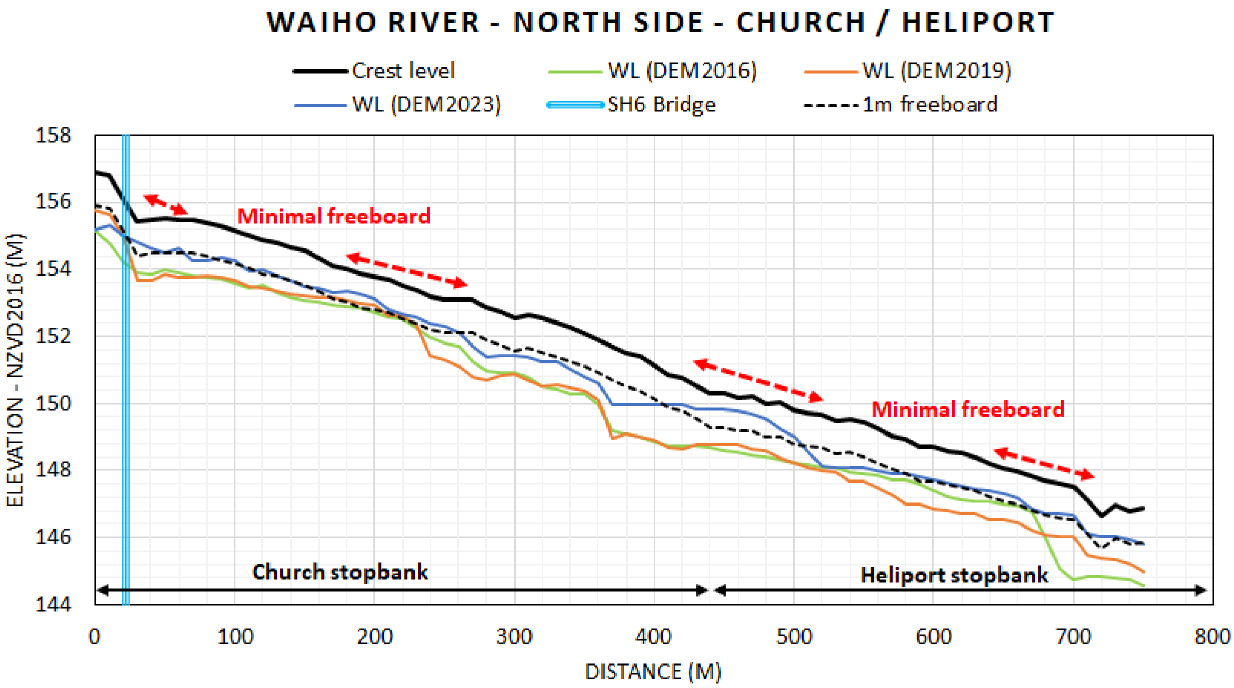

Figure 3-14 - LRS Waiho 2D hydraulic model: peak water level results with a 2,500 m³/s flow – Church and Heliport stopbanks – north side.

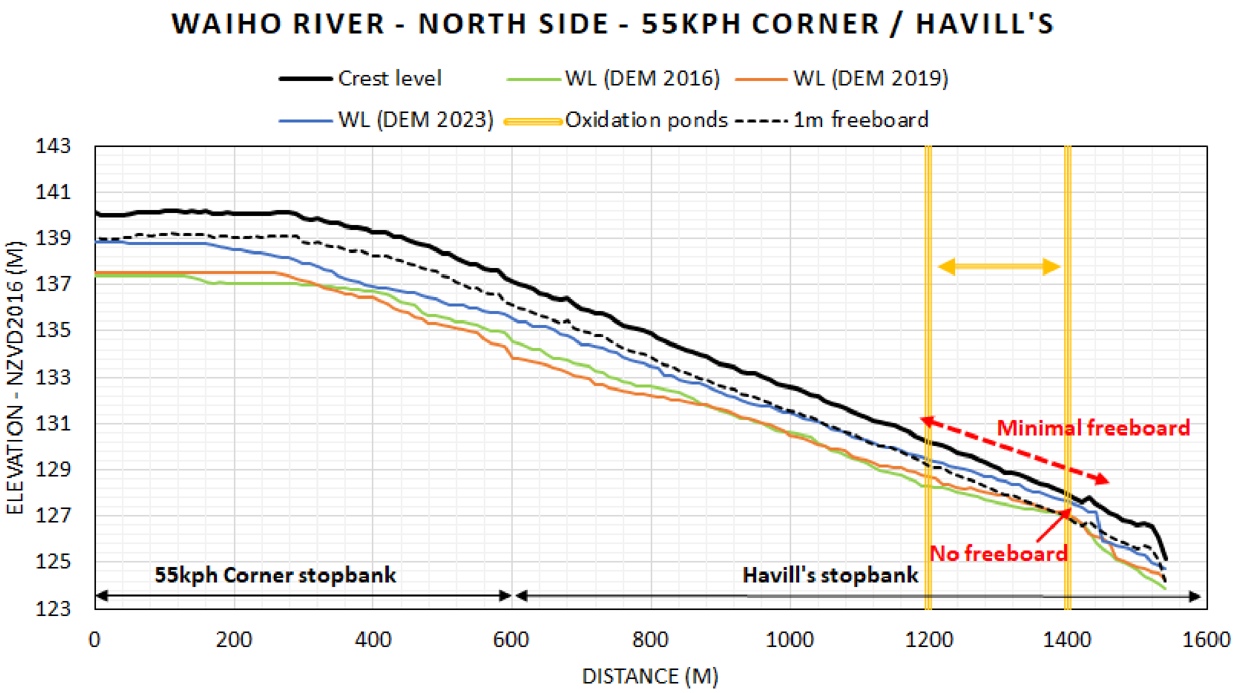

Figure 3-15 - LRS Waiho 2D hydraulic model: peak water level results with a 2,500 m³/s flow – 55kph Corner and Havill's stopbanks – north side.

If the *aggradation* continues as expected, it will continue to reduce the *capacity* of the protection network, increasing *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, and increases the residual *risk* and consequences of failure.

- 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.
- The floodwaters will also carry more sediment exacerbating potential damage.

3.2.4. LACK OF ADEQUATE TOE EMBEDMENT

Both the Havill's and Milton's stopbanks have inadequate toe depths for the river conditions that they are exposed to.

Milton's *stopbank* does not have any *toe embedment* (Figure 3-16), in a location with a high *risk* of scour. The rising surface level of the lower *fan* has given rise to a wide depositional zone 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 *flood* flows will run down the north side of the *fan* before passing along the length of the Waiho Loop where they will then be directed straight at Milton's *stopbank*. The lack of a toe means that there is no protection against the potential for scour as a result of this channel alignment, which increases the *risk* of failure.

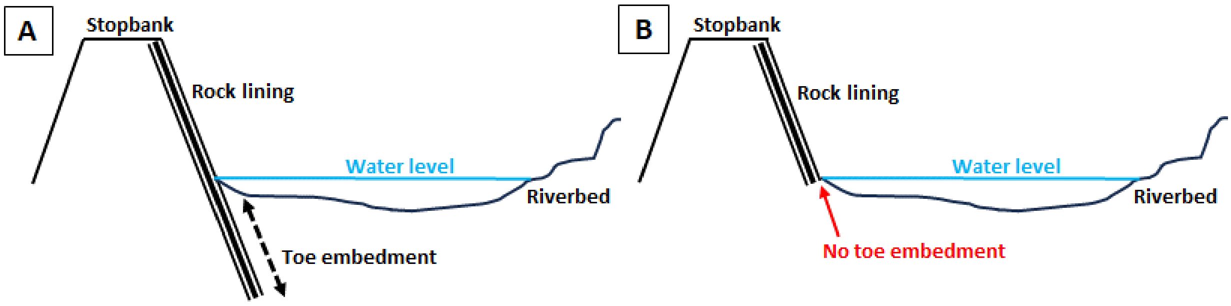

Figure 3-16 – Schematic showing a *stopbank* with a *toe embedment* (A) and one without (B).

Havill's *stopbank* toe is of unknown depth, however we understand that it is likely to be 1 m to 2 m for much of its length. This *stopbank* must protect the oxidation ponds from both upstream and downstream hazards. The high level of channel activity across the river bed means that the channel alignment can direct the full force of the Waiho River towards Havill's *stopbank* at any time, with subsequent potential for overtopping and scour. Additionally, a *consequence* of the developing *avulsion* of the Waiho River into the Tatare Stream is the *headcutting* (upstream extension) of the Waiho overflow channels towards Havill's *stopbank* and the oxidation ponds that it protects. This could result in substantial *degradation* in the vicinity of the *stopbank*, which given its shallow toe depth, will likely be undermined, resulting in failure and damage/destruction of the oxidation ponds.

3.3. CONTEMPORARY MANAGEMENT PRACTICES

The Waiho River protection network described above is designed to contain the river within stopbanks, protecting the township and surrounding area from its *flood hazard*. However, sometimes, further works are undertaken within the riverbed in order to maintain existing and build new structures, or undertake other consented activities. Such works include:

- Temporary diversion channels and bunds.
- New "permanent" banks and/or protection works.
- River training works designed to encourage a preferred channel position and alignment.
- Rock, gravel, and any other extraction activity

These works often involve techniques that have been used successfully on other rivers. However, the Waiho River is an unusually powerful river with complex geometry and behaviour (Figure 3-17). Many techniques and practices that work well on other rivers have been and are likely to continue to be unsuccessful on the Waiho. There are numerous examples of failed attempts to direct or otherwise control the Waiho River.

Aside from its highly dynamic nature, some of the key things that differentiate the Waiho River from many other rivers are:

- The Waiho River does not flow on a simple inclined plane like most other rivers.
- Downstream of the SH6 Bridge the river flows across a complex *alluvial fan* (even the portion currently constrained by stopbanks) as shown in Figure 3-17.
- The surface is fundamentally conical in shape (in fact multiple adjacent conical surfaces; Figure 3-17).

- One of several key consequences of this different surface geometry is that the natural fall is not in just one, but multiple directions (Figure 3-17).
- This complex conical surface geometry and its implications are naturally difficult to visualise and understand. Understanding is not helped by the *fan* surface being too large and curvature too great to visualise from ground level. Access to detailed survey information is needed to start to gain a true appreciation of the complexity of the surface and consequently the behaviour of the river.
- Added to this surface complexity is the ongoing natural *aggradation* of the riverbed.

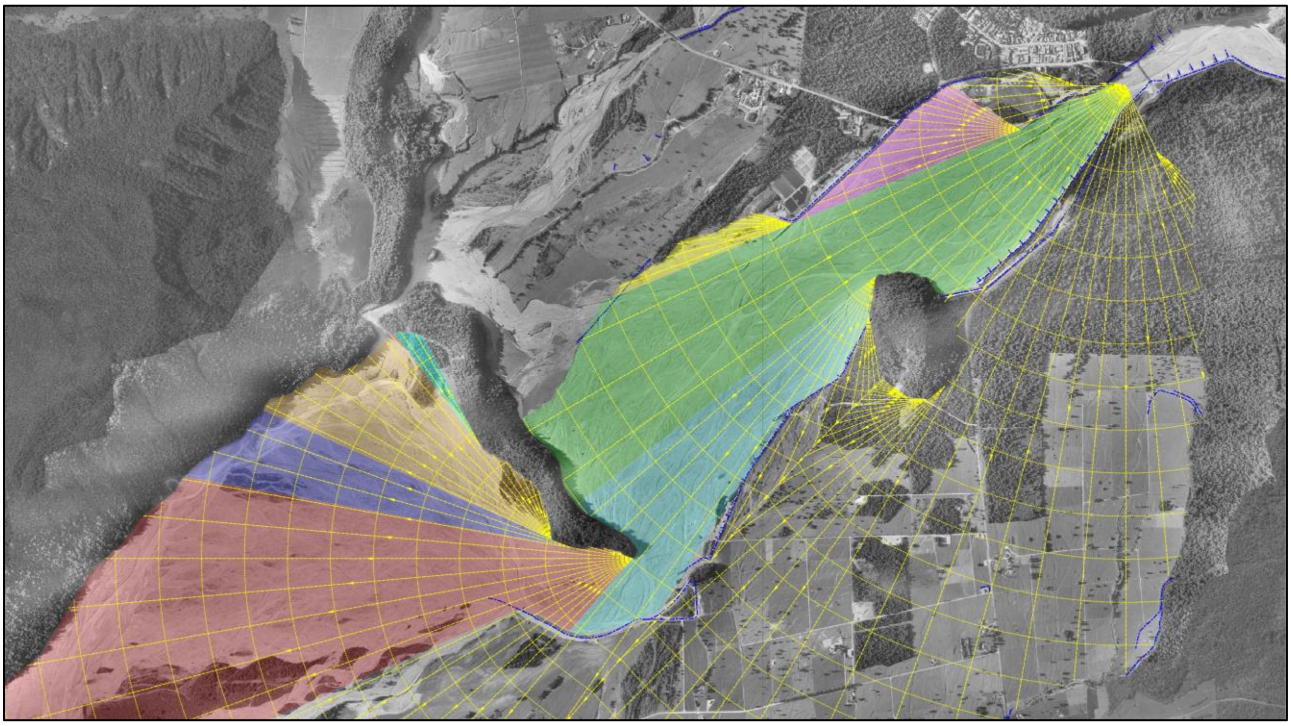

Figure 3-17 – The complexity of the Waiho *fan* shown by the multiple directions of fall created by the multiple sub-fans, with existing protection works in blue.

The key message here is that this river behaves differently to what may be expected or commonly understood. As a result, it is easy to misinterpret the river and undertake works that have unintended consequences on its behaviour and on other privately or publicly owned assets.

River management works by their nature come with very high capital and maintenance costs, high consequences of failure and potential environmental effects. Furthermore, the present Waiho River management situation could be described as ad hoc, under-resourced, precarious control of a highly complex and dynamic river system.

Operations in the river, and statutory provisions that enable them, should be mindful of the above issues. All proposed works should provide an appropriate level of detail and evidence of likely effects from those with appropriate experience and expertise in this river. Buy-in from key stakeholders (at least on-river asset owners) should also be provided for all proposed works.

Part of the solution could be to establish a formal River Management Plan to guide future works.

4. RIVER HAZARDS

Below is a summary of the hazards posed by the Waiho River to the Franz Josef community and surrounding area.

4.1. FLOODING

The main *hazard* posed by the Waiho River is flooding, with the *risk* being that a *stopbank* may be breached or overtopped during a *flood* event (or landslide dambreak *flood*) which impacts on the scheme's objective to "protect".

NZS (2008) defines a *flood* (i) and a *flood hazard* (ii) as follows:

I. A flow that overtops or flows through the natural or artificial banks in any part of a stream or river.
II. The potential for damage to property or people from flooding and the associated erosion and *deposition*. Usually quantified as an annual probability.

The Waiho River experiences frequent and intense *flood* events which the current protection structures have been designed to contain up to a specified and in some cases unspecified standard.

However, the high sediment load carried by the river, resulting in its braided nature means that at times both high and low flows may be directed at the stopbanks themselves, placing increased pressure on them.

Further, the ongoing aggradational behaviour (currently 0.2 m per year increase in riverbed elevation at the SH6 Bridge) of the river is reducing the *capacity* of the protection schemes that confine it.

4.2. AVULSION

An *avulsion* is a sudden switching of a river channel from one location to another within an *alluvial fan* or across a *floodplain* (Slingerland and Smith, 2004; Ashworth et al, 2004; Jones and Schumm, 1999). It is a natural process that assists in building *alluvial fan*s.

Since the early 2000s, floodwater from the Waiho River has at times flowed across the farmland between the Waiho and Tatare above the Waiho Loop. However, since February 2023, the Waiho has established a major breakout channel (*avulsion*) into the Tatare Stream. This developing *avulsion* offers the Waiho a very steep pathway from its own *fan* down to the Tatare Stream bed.

A microscale model study of this event (Davies et al., 2013) suggests that as this *avulsion* continues to develop:

- Headwater erosion (*degradation* and widening of the breakout channel bed) will progress upstream towards the oxidation ponds (Havill's *stopbank*), with associated river edge erosion.
- The Tatare valley will infill with sediment backing up towards the Tatare SH6 Bridge; and

- The Tatare gap through the Waiho Loop and immediately downstream will aggrade in the form of an *alluvial fan*, which may result in floodwaters entering Lake Pratt.

4.3. FUTURE OUTLOOK FOR THESE HAZARDS

Understanding how the *flood* and *avulsion* hazards, and therefore *risk* to the Franz Josef protection network, may change over time, is an important component of a *risk* assessment. Over the next ten years, the flooding and *avulsion* hazards are likely to be affected by all or any one of:

- **Alpine Fault magnitude 8 (AF8) earthquake or other earthquake in the mountains;** severe damage to protection structures, and increase in sediment supply due to seismically-induced landslides.
- **A major non-seismic induced landslide**; increased sediment supply
- **Landslide dambreak**; sudden pulse of sediment laden floodwater
- **Climate change**; increase in precipitation and temperatures, with subsequent increase of landslide occurrence and therefore sediment supply, as well as increased *flood* frequency and intensity.
- ***Interdecadal pacific oscillation* – positive phase;** more frequent and intense storm events, with subsequent increase of landslide occurrence, and therefore sediment supply.

An increase in *flood* frequency and intensity, as well as sediment supply will affect the degree of channel change and the rate of *aggradation* on the *fan* surface, and therefore the *likelihood* of a *stopbank* breaching or overtopping, and the rate at which an *avulsion* develops.

4.3.1. THE AF8 EARTHQUAKE AND RISK

The imminent AF8 (Alpine Fault magnitude 8) earthquake will also have an immediate (as well as ongoing) and devastating impact on the Franz Josef protection scheme.

Likelihood

It has been estimated from *paleoseismology* that the next Alpine fault rupture has a 15% chance of occurring in the next 10 years, and with each year that goes by the chance of it happening increases. However, unlike with *flood* events where we at least have a warning of the incoming weather, there will be no warning for the AF8 earthquake. It will happen out of the blue.

Consequences

As a result of the intense ground shaking, the unreinforced stopbanks will slump outwards and reduce in elevation, like a pile of sugar on a table that is shaken, with internal deformation and cracking taking place.

- In the M7.1 Greendale earthquake in 2010, stopbanks on the Waimakariri and Kaiapoi Rivers about 35 km distant were severely damaged (Figure 2-9) by local ground accelerations of 0.35g (Green et al., 2011).
- In the M8+ Alpine Fault rupture ground accelerations will exceed 1g, and therefore the impact on the protection scheme can be expected to be catastrophic.

- The next *flood* following the earthquake can be expected to *overtop* and/or *breach* the damaged stopbanks, even before earthquake-related *aggradation* (see below) has begun.
- Damage to the stopbanks will be greatest adjacent to the SH6 Bridge, and will perhaps reduce somewhat with increasing distance from the Alpine fault, but this reduction may not be significant. Thus it is prudent to expect all the stopbanks to be severely damaged in the Alpine fault earthquake, and to be further affected by the *aftershock* sequence.
- In the years after the earthquake, landslide sediment delivered to the Waiho, Callery, and Tatare rivers will increase the rate of *aggradation* throughout the river systems. Field investigations (Davies & Korup, 2006) and modelling (Robinson et al., 2016) suggest that at least metres-scale *aggradation* is to be expected on the Waiho and Tatare fanheads upstream of the Waiho Loop. This *aggradation* episode is likely to peak after about a decade or so following the earthquake (Blagen et al., 2022), but a return of the river to its pre-earthquake sediment regime may require several decades.

Table 4-1 - *Risk* assessment of the impact the AF8 earthquake will have on the stopbanks.

Failure scenario: rupture of the AF8 earthquake damages the stopbanks in the next 10 years.

***Likelihood*:** unlikely (15% in the next 10 years).

Consequences: extreme.

- Catastrophic damage to the protection scheme such that the next *flood* following the earthquake can be expected to *breach* or *overtop* the damaged stopbanks.
- The following floods will also carry a significant increase in sediment volume, which will increase the rate of *aggradation* through the Waiho system, further reducing the design *capacity* of any remaining stopbanks and therefore increasing their *likelihood* of failure during a *flood* event.

***Risk* rating:** HIGH

5. RISKS ASSESSMENT OF THE PROTECTION NETWORK AND OPTIONS

5.1. INTRODUCTION

To better understand the capability of the Waiho River protection network in its current state to protect the Franz Josef community and surrounding area from the hazards of the Waiho River a *risk* assessment has been completed. The assessment has been undertaken for each *stopbank* in the network, as well as on some unprotected areas, for different management options.

5.2. PROTECTION NETWORK

The following Table 5-1 lists each of the stopbanks in the Waiho protection network (see Figure 3-9 for locations) and the scenario under which each will be assessed, noting that all stopbanks, bridges, and unprotected areas will at least be assessed under the status quo scenario.

<u>Scenarios</u>

Status quo: the *stopbank* in its current state and with remedial maintenance as required following damage.

Upgrade: raise the crest levels and increase the width of the stopbanks, with additional rock work, and rock lining of all of the Rubbish Dump *stopbank*.

Build: construction of new works, including the Link *stopbank* between the Heliport and Havill stopbanks, construction of a rock-lined bund to halt the Tatare *avulsion*, and any other protection works.

Relax: remove a *stopbank* and the people/buildings it was protecting i.e. Milton's, and the south side Waka Kotahi stopbanks from the SH6 Bridge to Canavan's Knob.

The *risk* assessment of the stopbanks and areas, as listed in Table 5-1 below, has been undertaken in terms of the risks from the Waiho River of overtopping or breaching of the structures. The risks from a large AF8 earthquake on the structures, and the impact of such an event on the behaviour of the Waiho River have not been considered in this *risk* assessment. The direct and indirect impacts of this earthquake event will be so profound that the nature of the Waiho River *hazard* will be profoundly altered.

However, if the Waiho River is released to south under the "relax" options (removal of all stopbanks on the true left from the SH6 down to the Waiho Loop):

- The number of stopbanks that could be damaged by the AF8 earthquake would be reduced, so there would be fewer assets at *risk*.
- There would be significantly more area (an additional two thirds of the *fan* surface, as well as the entire Waiho Flat) for *deposition* of the earthquake-induced increased sediment supply, so earthquake-induced increases in riverbed levels will be less.

Table 5-1 - Statuses at which each structure in the protection network will be assessed.

Waiho River Protection Scheme – *Risk* Assessment			
SH6 Bridge		Status quo	
		Upgrade	
South side		**North side**	
Glacier Road	Status quo	Upstream of the SH6 bridge	Status quo
	Upgrade		Build
Waka Kotahi stopbanks (SH6 Bridge to Canavan's Knob)	Status quo	Church *stopbank*	Status quo
	Upgrade		
	Build		Upgrade
	Relax		
Rubbish Dump *stopbank* (Canavan's Knob to Rata Knoll)	Status quo	Heliport *stopbank*	Status quo
	Upgrade		Upgrade
	Relax		
Milton's *stopbank*	Status quo	55kph Corner *stopbank*	Status quo
	Upgrade		
	Build		Build
	Relax		
Lower Waiho valley	Status quo	Havill's *stopbank*	Status quo
	Build		Upgrade
			Build
Tatare River – *Risk* Assessment			
SH6 Bridge		Discussed, not assessed.	

5.3. RISK ASSESSMENT PROCESS

A *risk* assessment is the overall process of identifying, analysing, and evaluating a *risk*, with *risk* defined as the chance of something happening that will impact on objectives. A qualitative assessment of *risk* can be estimated by combining the *consequence* of the event by the *likelihood* (probability) of its occurrence (NZS 9401:2008).

$$Risk = Consequence \times Likelihood$$

Consequence

The *consequence* of a particular event or circumstance occurring (during and after), can have many dimensions such as:

> **Social**: loss of life, injury, personal stress, reductions of social and medical services, and disruption of community.
> **Economic:** costs of loss of life, business interruption, repairing/replacing infrastructure loss or damage, loss of income, loss of income production, loss of property, cost of clean-up, repair, and replacement;
> **Environmental:** cost of clean-up of pollutants (sewage, chemicals, debris), loss of amenity values, loss of habitats, modification of environments.

Likelihood

The *likelihood* of an event that causes certain consequences depends on multiple factors. For *flood* hazards, a statistical probability of a given water level and *flood* flow can be estimated from an analysis of past *flood* events. The *likelihood* of flooding, however, also depends on the *capacity* and structural integrity of *flood* mitigation measures. The *likelihood* of a failure that causes the consequences is then a combination of *flood* water level (and velocity and duration) and the potential for overtopping or *breach* flooding of the *floodplain*. The consequences then depend on the human occupation of the *floodplain* and the people, assets and infrastructure exposed to the *flood risk*.

5.4. SCENARIO LIKELIHOOD AND CONSEQUENCES

The *likelihood* of failure causing flooding and the consequences of that flooding are outlined in Section 14 - Appendix C, for all the scenarios assessed, as given in Table 5-1.

The *likelihood* of failure for each scenario depends on the specific effects at the site from a combination of *flood* event probability and *aggradation* rates. Upgrading the protection measures or re-building them affects the *likelihood* of failure, and hence flooding, but not the consequences, which remain the same regardless of when or how the flooding occurs.

The *likelihood* for *flood* events of different return periods of recurrence is given in Table 5-2, in terms of the percentage probability of occurring in any given year and over a 10 year period.

Table 5-2 - *Likelihood* of *flood* event recurrence

ARI	> 100 year	50 - 20 year	10 - 5 year	5 - 2 year	> 2 year
Annual probability	1%	2 - 5 %	10 - 20%	20 - 50%	> 50%
10 years probability	10%	20 - 40%	65 – 90%	90 – 99%	99%

The consequences of flooding depend on the extent of the flooding, the velocity and depth of the floodwaters, the scouring and *deposition* caused by the *flood* flows, and the people, livelihoods and assets vulnerable to flooding within the area affected by the floodwater.

Figure 5-1 shows the locations of potential breaches across the network, and the area of *floodplain* affected by flooding. These floodable areas overlap, as shown on the figure. However, it is important to note that these areas are only a representation of what could happen. The hydraulic model has a fixed bed so does not allow for scour, and therefore the channels cannot develop beyond their starting point, nor can new channels or sediment deposits be formed. Further, the model has used the 2021 DEM, which will have a different channel alignment and lower bed surface elevation to the present day. Thus these model *flood* extents are not to be used for *risk* mapping, but rather as an idea of where flooding may occur.

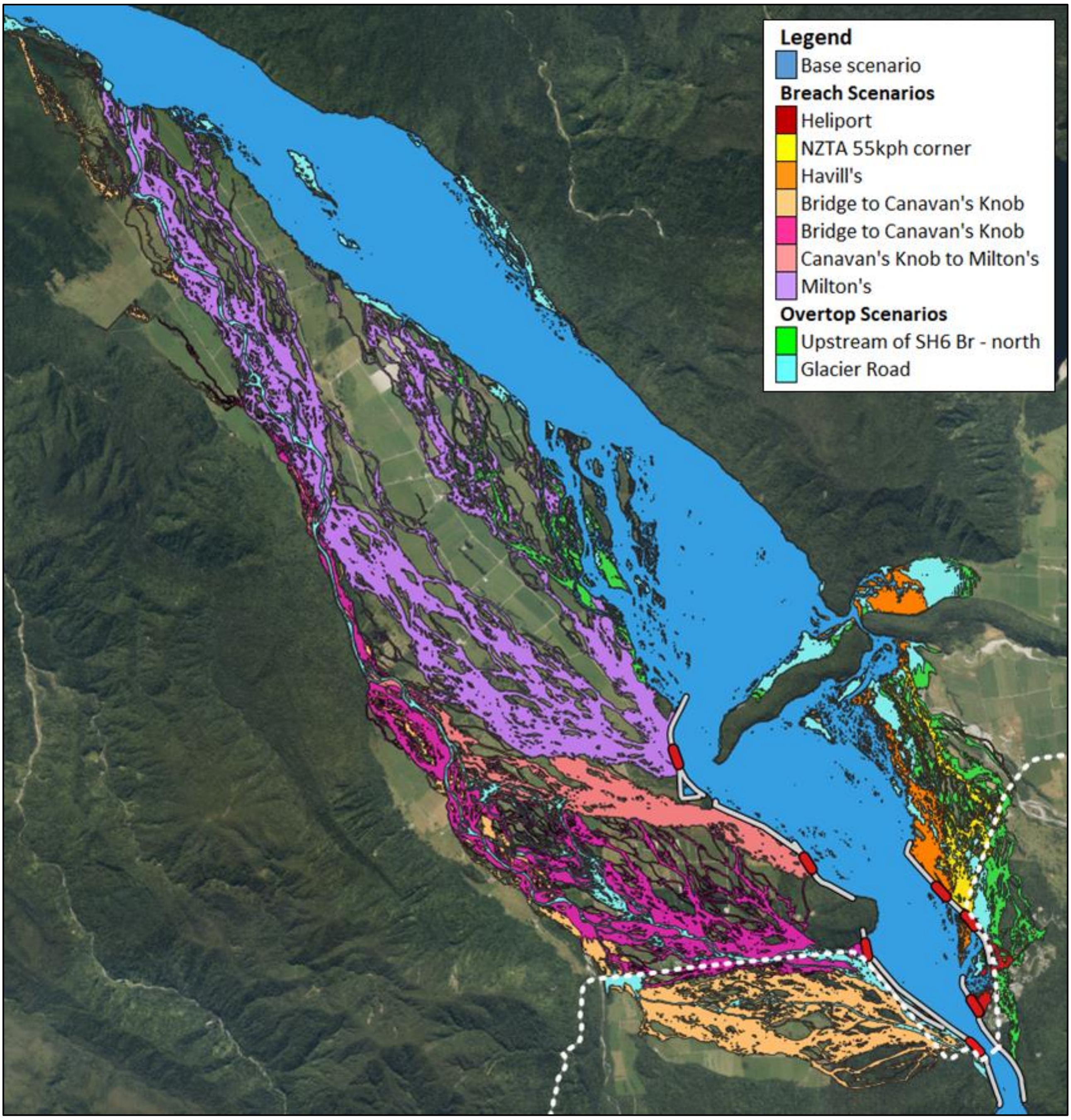

Figure 5-1 – Overlain *flood* extents from different modelled *stopbank* breaches (red) across the protection network (grey). As explained in the preceding text, these are only examples of where floodwaters may go. In reality, with sediment mobilisation, new channels may form, and the floodwaters may take completely different flow paths across the *floodplain*.

A summary of the consequences, and in particular their relative differences is given below for the scenarios of the *risk* assessment.

5.4.1. SOUTH

- **Glacier Road**: Flooding will spread over the south side of the Waiho *floodplain*, down to Docherty Creek and along to the coast, with an area below Rata Knoll between the creek and the Waiho River itself being *flood* free under present landscape conditions. *Flood* flows will follow old channels and waterways on the *floodplain*, with the areal extent of flooding depending on the size of the *flood* breakout flows. However, given the elevated riverbed level and high velocities as flow and sediment moves from the riverbed to *floodplain*, gravel mobilisation and development of new *flood* channels is likely to occur on the *floodplain*.
- **Waka Kotahi stopbanks (SH6 Bridge to Canavan's Knob):** Similar to Glacier Road, but with some of the upper *floodplain* not being flooded.
- **Rubbish Dump *stopbank* (Canavan's Knob to Rata Knoll):** Flooding will spread to Docherty Creek below the State Highway, and initially follow a previous major *flood* channel from the Waiho River to Docherty Creek, cutting off the lower *floodplain*. The upper part of the *floodplain* would not be affected.
- **Milton's *stopbank***: Floodwaters will flow across the airstrip and down to Docherty Creek, initially following old *floodplain* channels, and splitting up across the farmland of the lower valley.
- **Lower Waiho *floodplain***: Floodwater will breakout in various places and spread over varying areas of the whole lower valley from time to time.

5.4.2. NORTH

- **Upstream SH6 Bridge**: *Flood* overflows will only occur during a large *flood* event after severe *aggradation*. Floodwaters would then flow through the town, spreading out with generally low flow depths, however the potential for scour and channel development could rapidly escalate the damage potential.
- **Church and Heliport stopbanks**: A sudden release of floodwaters will flow at high velocities into the town and then down alongside the state highway to the Tatare Valley, with potential to develop the existing *avulsion* path or create a new one, with back cutting over the next few floods towards the town. The areas around the Heliport itself would have very deep flows.
- **55kph Corner *stopbank***: Floodwaters will flow along the State Highway and then to the north down to the Tatare Valley, with potential to develop the existing *avulsion* path or create a new one, with back cutting over the next few floods towards the town. The slope of the land means that flow velocities will be high, with the areal spread depending of local features and topography.
- **Havill's *stopbank***: Floodwaters will flow through the old hotel and current waste water treatment plant, and then down to the Tatare Valley, with potential to further develop the existing *avulsion* path or create a new one, with back cutting over the next few floods towards the town.

- The main *consequence* of the bridge or its abutments being swept away by floodwaters is the loss of connection of the one highway route along the West Coast. The social and economic impacts of this loss is very high and affects the whole West Coast.

5.5. RISK ASSESSMENT CRITERIA

The *risk* assessment identifies and analyses the impacts of flooding because of overtopping and/or *breach* failures of the protection structures of the Franz Josef protection network. Since limited quantitative data are available, this has been done by characterising the degrees of *likelihood* and *consequence*, in a semi-quantitative manner, to give relative *risk* rankings for the various elements of the network.

Our assessment procedure has been based on the "NZTA *Risk* Management Practice Guide (Minimum Standard Z44) version 5, February 2018" (NZ Transport Agency, 2018), adapted for *floodplain risk* assessments. Appropriate *Likelihood* and *Consequence* parameters for the Waiho River *floodplain* are given in Table 5-3 and Table 5-4, and the overall *risk* rating matrix that combines *likelihood* and *consequence* is shown in Table 5-5.

The rough order of costs of potential measures to reduce the *likelihood* of *flood* damage have been estimated. The assessment of *consequence* takes into account social and environmental impacts as well as economic losses. However, such *risk* assessments necessarily involve value judgements and reflect the knowledge and experience of the people doing the assessments.

The *likelihood* of failure has then been assessed for each scenario site based on the percentage *likelihood* criteria of Table 5-3. This is then the *likelihood* that the consequences of failure, as described below, would occur in the next ten years. This *likelihood* depends on the occurrence of *flood* events over the ten year period, and hence on a *flood* size probability function. The *likelihood* is, however, also affected by *aggradation* on the Waiho River *fan*, which is likely to continue, and potentially at an accelerating rate. The overall *likelihood* then depends on both *flood* probabilities and increases in the bed levels of the Waiho River along its valley *floodplain*.

Table 5-3 – Adopted *likelihood* rating criteria

	Rare	Unlikely	Possible	Likely	Almost Certain
Probability of occurrence in the next 10 years	≤ 5%	5 - 30%	>30 - 55%	>55 - 85%	≥85%

The consequences of failure have been assessed in terms of the potential costs of damage from flooding on the Waiho River *floodplain*, as an economic cost, with the range of costs for the consequences criteria indicated in Table 5-4.

Table 5-4 – Adopted cost *consequence* rating criteria

	Extreme	Severe	Moderate	Minor	Very Minor
Cost ($)	> $100 M	$50 - 25 M	$15 - 5 M	$2 - 0.5 M	< $0.1 M

However, the cost-based rating criteria do not directly take into account the social and environmental costs of flooding, where there is a very real threat of loss of life and of livelihoods. The *consequence* assessment has, therefore, taken into account these social and environmental costs through an overall holistic assessment of the degree or magnitude of the *consequence*, where qualitative judgements are necessary.

Given an assessment of *likelihood* and consequences for a scenario, in terms of the 1 to 5 criteria of Table 5-3 and Table 5-4, the *risk* matrix of Table 5-6 gives an overall *risk* rating. This has been done for the existing status quo, and if improvements are undertaken, as proposed, and described in Section 5.2.

The *risk* matrix of the NZTA guidelines has been used in this case, without modification. This matrix is similar to that of the Australian *Flood Risk* Management guidelines, although seven criteria are used for *likelihood* in that guideline manual. The Guidelines for *Floodplain* Management Planning of the Greater Wellington Regional Council also have a short section on *risk* assessment, using a similar 5 x 5 matrix and with 5 *risk* categories.

Table 5-5 – Adopted *risk* rating matrix (NZ Transport Agency, 2018)

		***Risk* Rating**				
Likelihood	Almost Certain	Low	Medium	High	Critical	Critical
	Likely	Low	Medium	High	Critical	Critical
	Possible	Low	Medium	Medium	High	Critical
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	Low	High
		Insignificant	Minor	Moderate	Severe	Extreme
		Consequence				

The *risk* rating for each of the scenarios considered is given in Table 5-6, where each rating is derived from the combination of the *likelihood* category and the *consequence* category. For instance, a 'Possible' *likelihood* and 'Severe' *consequence* gives a High *risk* rating, while a 'Possible' *likelihood* and an 'Extreme' *consequence* would give a Critical *risk* rating.

A full description of the structures of the Franz Josef protection scheme and potential improvements to these structures are given in Section 14 – Appendix C. The consequences of flooding from a *stopbank breach* are also outlined, with the *risk* rating shown as a combination of the *likelihood* and consequences ratings.

Table 5-6 – *Risk* assessment for the Waiho River protection, for full details refer to Appendix B.

	Asset / Area	Status Quo/Residual *Risk*			Improved/Residual *Risk*				
		Likelihood	Consequences	*Risk*	Scenario	Rough Order Costs (rounded to $0.5 M)	*Likelihood*	Consequences	*Risk*
North	Tatare *avulsion*	Almost certain	Severe	Critical	Build	$15 M+	Possible	Severe	High
North	Havill's *stopbank* (without *avulsion*)	Likely	Moderate	High	Upgrade	$5 M	Unlikely	Moderate	Medium
North	55 kph Corner *stopbank*	Possible	Severe	High	Build	$3 M	Unlikely	Severe	Medium
North	Heliport *stopbank*	Possible	Extreme	Critical	Upgrade	$0.5 M	Possible	Extreme	Critical
North	Church *stopbank*	Possible	Extreme	Critical	Upgrade	$0.5 M	Possible	Extreme	Critical
North	SH6 Bridge upstream	Rare	Extreme	High	Upgrade	$0.5 M	Rare	Extreme	High
	State Highway 6 Bridge	Possible	Extreme	Critical	Upgrade	$5 M	Rare	Extreme	High
South	Glacier Road	Unlikely	Extreme	High	Upgrade	$2 M	Rare	Extreme	High
South	Waka Kotahi stopbanks (SH6 to Canavan's Knob)	Likely	Extreme	Critical	Upgrade	$3 M	Unlikely	Extreme	High
					Build	$3 M	Unlikely	Extreme	High
					Relax	$100 M+	Certain	Insignificant	Low
South	Rubbish Dump *stopbank* (Canavan's Knob to Rata Knoll)	Almost certain	Severe	Critical	Upgrade	$5 - 15 M	Possible	Severe	High
					Relax	$50 – 70 M	Certain	Insignificant	Low
South	Milton's *stopbank*	Almost certain	Severe	Critical	Upgrade	$2 M	Likely	Severe	Critical
					Build	$5 M+	Possible	Severe	High
					Relax	$30 – 50 M	Certain	Insignificant	Low
South	Lower valley (downstream of Milton's)	Likely	Moderate	High	Upgrade	$2 - 5 M	Possible	Moderate	Medium

Table 5-7 - *Risk* assessment for the Waiho *avulsion* into the Tatare, and the release to the south.

Asset / Area	Avulse to North (Short-term)	Release to South	
		Above Canavan's Knob	Below Canavan's Knob
Avulsion into Tatare Stream		*Risk* reduces. Same outcome but over a longer period.	*Risk* reduces. Same outcome but over a longer period.
Havill's *stopbank*	High *risk* increase short to medium-term	*Risk* reduces	*Risk* reduces
55kph Corner *stopbank*	Moderate *risk* increase short to medium-term	*Risk* reduces	No change
Heliport *stopbank*	Minor *risk* increase short to medium-term	*Risk* reduces	No change
Church *stopbank*	No change	Some uncertainty*. Likely for moderate *risk* increase in the short-term then reduce below current	No change
Upstream of SH6 Bridge	No change	Some uncertainty*. *Risk* reduces.	No change
Glacier Road	No change	Some uncertainty*. *Risk* reduces.	Residual *risk* reduces
SH6 Bridge	No change	Some uncertainty*. Moderate *risk* increase short-term then reduce below current	No change
Waka Kotahi stopbanks (SH6 Bridge to Canavan's Knob)	No change	N/A	Residual *risk* reduces
Rubbish Dump *stopbank* (Canavan's Knob to Rata Knoll)	*Risk* reduces	N/A	N/A
Milton's *stopbank*	*Risk* reduces	N/A	N/A
Lower valley	*Risk* likely reduces at upstream end. No change downstream.	N/A	N/A

**Our assessments of the effects of a release to the south above Canavan's Knob on the SH6 bridge, and the assets immediately upstream and downstream of it, have been completed with some uncertainty. This is because, as the main flow switches onto the southern floodplain, it will likely transport sediment from the current riverbed onto the southern floodplain and therefore lower the bed level in the current river reach which will reduce the risk of overtopping or breach as peak water levels will be lower along the stopbanks, bridge, and river bank. However, this will also result in downcutting that may result in bank erosion and rock protection damage. We cannot predict how far upstream or downstream this downcutting may extend, but this is likely to increase the risk to both the Church stopbank and SH6 bridge in the short-term.*

5.7. INTERPRETATION OF RISK ASSESSMENT RESULTS

5.7.1. BASIC RESULTS

The results of the *risk* assessment presented in Table 5-6 show that:

- All existing areas have a High or Critical *risk* rating for failure over the next 10 years.
- Doing work in these areas is likely to cost a significant amount, and where it reduces the *risk* rating, it generally only does so by one category.

These results reflect the significant consequences of failure of these stopbanks but also the rapid rate of bed level rise nullifying the impact of the work by the end of the 10 year period.

The only options that make a meaningful and permanent impact on *risk* reduction are those that relax to the south. These options come with substantial costs and lead times.

The High to Critical *risk* of most options indicates a critical need to ensure that effective emergency management and contingency planning are in place.

Because the *risk* ratings are relatively broad in nature and consider a 10-year time period they should only be used as a guide to *risk* mitigation works. Works prioritisation within that period should be based on a more detailed assessment.

5.7.2. TATARE AVULSION AND THE RELAXATION TO THE SOUTH: ADDITIONAL EFFECTS

Table 5-7 shows the effect on the various areas of an *avulsion* of the Waiho River into the Tatare Stream, and of relaxing the Waiho River to the south above (upstream of) and below (downstream of) Canavan's Knob.

Over the short-term the *avulsion* to the Tatare Stream presents a high increase in *risk* to Havill's Wall and the oxidation ponds, moderate increase to the 55kph Corner / Link stopbanks and minor increase in *risk* to the Heliport *stopbank*. Over all timeframes the *risk* from Canavan's Knob to Milton's *stopbank* reduces slightly due to the smaller amount of time the river will flow there. However, immediately downstream of Milton's *stopbank* the *risk* will increase slightly due to the combined Waiho River / Tatare Stream flow being more directed toward this area than presently.

The results show that there is partial benefit to *risk* reduction by relaxing the river to the south downstream of Canavan's Knob as this reduces the *risk* to Havill's *stopbank* as the river will spend less time on the north side, and also reduces the number of people and infrastructure exposed to flooding should the stopbanks upstream of Canavan's Knob *breach*. This result shows that there is an opportunity to stage the relax to south strategy (relax downstream first, then upstream) and thereby gain some benefits within a 10-year timeframe. Notwithstanding that, the results clearly show that major *risk* reduction is only realised once the upstream stopbanks on the south side between the SH6 bridge and Canavan's Knob are removed.

6. JUSTIFICATION FOR A CHANGE IN STRATEGY

In order to protect the community, infrastructure, and surrounding area from the Waiho River *flood* hazards, the river has been confined by structural protection works for many years, and this confinement has been maintained (with repairs and upgrades) through a very prolonged (six decades) period of *aggradation* that shows no signs of abating.

Maintaining the protection network, however, is becoming increasingly challenging, and will become more difficult as the *aggradation* continues. The frequency and intensity of floods and landslides, and hence the rate of *aggradation*, are likely to increase in response to climate change, and a positive IPO phase, with intense *aggradation* following the AF8 earthquake.

The most salient challenges for the network are:

1. The increasing uncertainty about the intensity of the hazards, and hence the difficulties in determining appropriate design standards and the likely protection that would be provided by the structural works.
2. The decreasing *capacity* of the stopbanks to contain the *flood* flows they were designed for as a result of the ongoing *aggradation*, and the increasing *likelihood* of failure at sub-design *flood* flow.
3. Significant increase in residual *risk* each time the stopbanks are raised, with the potential impact on people and assets from any failure increasing with each increase in *stopbank* elevation.
4. The variable design and construction standards across the network, with unlined stopbanks, poor construction of rock linings, no to minimal *freeboard* allowances, and a lack of adequate *toe embedment* of rock along several of the stopbanks.
5. Potential for damage and/or failure of the stopbanks during relatively minor *flood* events.
6. The developing *avulsion* channel from the Waiho *fan* into the Tatare valley, which threatens the upstream oxidation ponds and northern stopbanks, as well as the SH6 Bridge over the Tatare Stream. This will continue to develop with each *flood* event.
7. The likely catastrophic damage to the stopbanks that will result from a major earthquake, which has a one in six chance of happening during the next decade.

These challenges mean that maintaining and upgrading structural protection measures will become increasingly expensive, with increasing residual *risk*. Further, continuing to manage the river in this way does nothing to mitigate the problem of the aggrading river bed and its exacerbation of the *flood hazard* posed by the Waiho River to the community and surrounding area.

Our *risk* assessment of each *stopbank* in the network has shown that upgrading and/or building additional protection measures would have significant initial and on-going costs while not significantly reducing the *risk* of failure over a ten-year period. The risks of failure for all of the network stopbanks under the existing status quo scenario are High or Critical. Upgrading or building more protection works serves only to reduce the ratings of some from Critical to High or in a few cases from High to Medium, whilst in others retaining the Critical or High rating.

For all of the north side stopbanks, in order to protect the community, infrastructure and land from the *flood* and *avulsion* river hazards, the only options available are to continue to maintain, upgrade or build new protection works. However, on the south side of the river, there is also the option to relax the protection boundary by removing the stopbanks and releasing the Waiho River to the south. This option will:

- Reduce the *risk* of *stopbank* failure on the south side during a *flood* event as the *stopbank* built to protect the realigned SH6 will follow the natural fall of the *fan* lateral boundary.
- Reduce the number of assets (apart from the realigned SH6) exposed to the *flood hazard* (and to the immediate impact and ongoing effects of the AF8 earthquake).
- Provide the Waiho River with more surface area (the remaining two thirds of its *fan*, and the entire Waiho Flat) to deposit sediment on, thus reducing the rate of bed level increase as the sediment will be spread out horizontally rather than vertically.
- Increasing the lifespan of the northern stopbanks and reducing their *risk* of failure during *flood* events.
- Reduce the pressure on the *flood* flow path across the terrace on the north side immediately upstream of the SH6 Bridge over the Waiho River.
- Reduce the pressure on the developing *avulsion* into the Tatare Stream.

This option is based on an understanding of the aggradational behaviour of the Waiho River and the response of a river to confinement and changing width, which is based on extensive reports and studies as documented by Beagley and Gardner (2023).

Further, it is an option that has been previously considered, with the cost to buy out the land, realign the state 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, as well as a social impact assessment and an environmental assessment.

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 about the contribution to the economy from the land use, as well as a detailed inventory of the assets and infrastructure that would have to be removed or otherwise dealt with (including landfill sites), on a property-by-property basis. We do not currently have these data.

Additionally, if river management decisions are made on the basis of a cost-benefit analysis, it is important to recognise that the time discount rate used in the analysis greatly affects the outcome. For example, allowing the river to occupy its whole *floodplain* is a once-for-all cost that may compare badly in economic terms with continued maintenance of stopbanks over, say, a 10-year period. However, when the analysis is undertaken in terms of actual costs and benefits (not discounted) over a longer planning horizon, which might be a century or longer for an important township and a national tourism industry, the outcome will be very different.

6.1. RELAXATION OF THE BOUNDARIES RATIONALE

The Waiho River has been aggrading its *fan* surface since at least 1948 and more rapidly since the late 1970's. Since the time of this change in *aggradation* rate, the depositional area of the river has been confined to one third of its natural *fan* surface, through the use of stopbanks and edge protection works, a common management practice for partially and fully braiding gravel-bed rivers in New Zealand.

However, this confinement limits the ability of the Waiho to laterally migrate across its entire (natural) *fan* surface – a critical function of any river on a *fan* – and reduces the surface area available for it to deposit sediment. As a result, now that the river has infilled from its severely incised state (that post-dates the 1850's terrace), and *flood* flows could spread out across its *fan* surface, the confinement means it has less space to spread its sediment load horizontally, and thus the Waiho *fan* surface is increasing vertically, at a faster rate than would be the case if it were not confined. We note that this a simplified version of events, and that the full complexity of the situation is detailed by Beagley et al. (2020).

By relaxing the boundaries to the southern *floodplain* 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.

Using a microscale model, Beagley (2017) investigated two alternative *stopbank* alignments which increased the area of *fan* surface the Waiho River has access to (Figure 6-1).

- 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 and the Waiho Flat to the south i.e. all of the farmland.

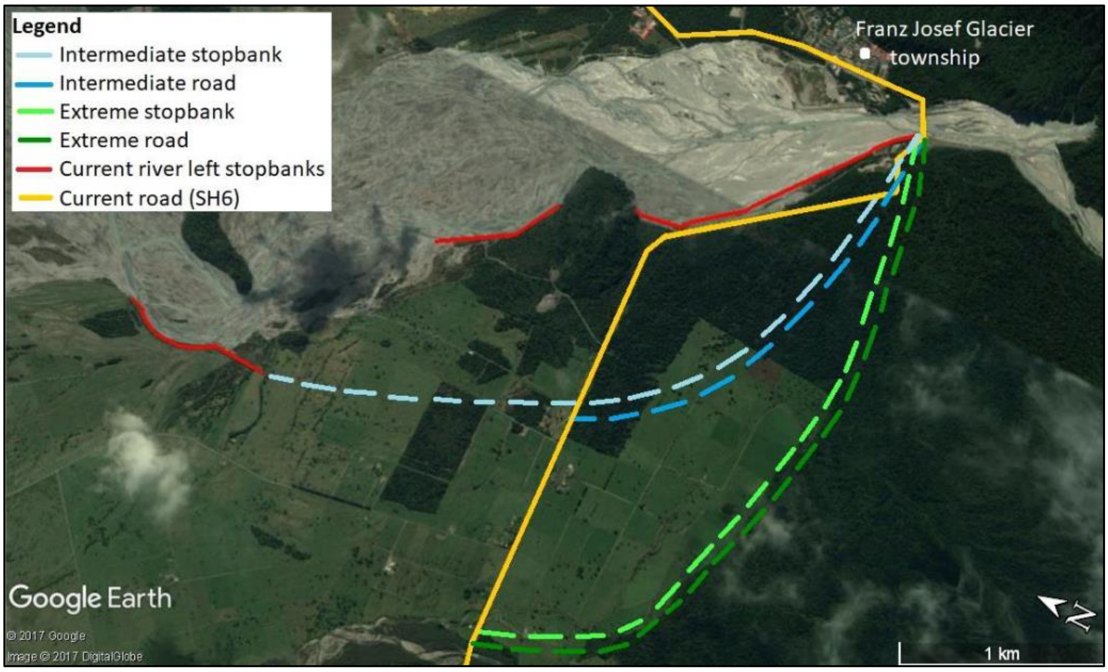

Figure 6-1 - The three *stopbank* alignments simulated in the 2017 microscale model study.

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 was slower than when the modelled river was restricted by the southern boundary stopbanks.

This response has been corroborated by past studies and more recently by numerical modelling (Measures et al., 2021). In an investigation of how changing river width impacts bedload transport and *aggradation* rate, Measures et al compared the results of 15 different constant-width domain model runs, between 200m and 3000m wide (Figure 6-2) to show that:

1. In a severely narrowed width (300m and below) where a river functions as a single thread during *flood* events such as a gorge or transport *reach*, 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.

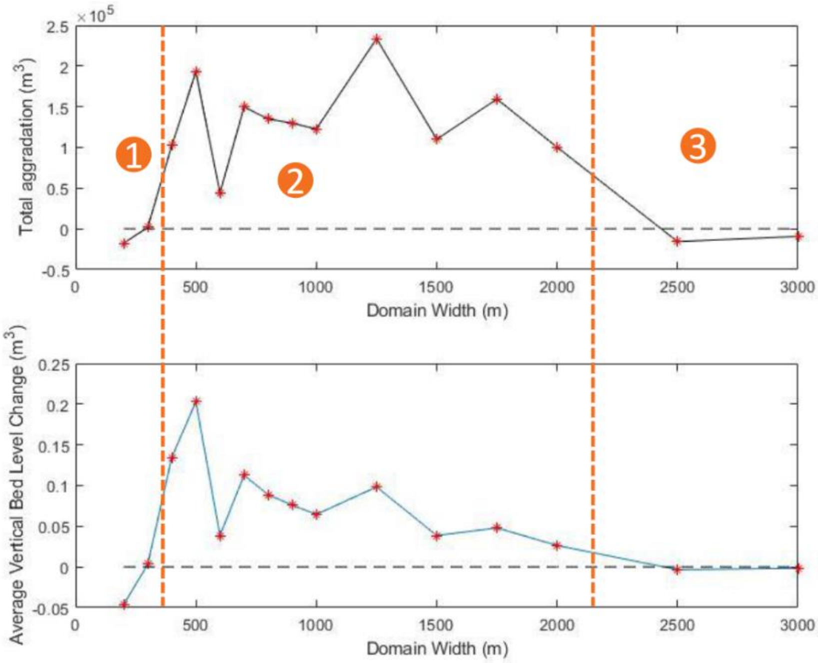

Figure 6-2 - Results from the different constant width experiments.

Measures et al. also used their calibrated numerical model of the Waiho to test the response of the river to the removal of the southern stopbanks. However, given that 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 than the testing of the Waiho *stopbank* realignment. What is significant, however, is that the Measures et al. numerical model corroborates the microscale model of Beagley et al. in showing that allowing the river to widen will reduce the rate of vertical *aggradation*.

Regardless of this last point, the implications of the other findings remain. Relaxation of the southern boundary will not stop the long-term aggradational behaviour of the Waiho River nor will it prompt a return of the *fan* surface to some lower elevation, as previous studies (Davies et al., 2003) proposed. However, it will reduce the number of people and assets exposed to the *flood hazard*, reduce the pressure on the developing *avulsion*, and the northern boundary protection works including the potential *flood* path into the Franz Josef township upstream of the SH6 Bridge, it will slow the rate of river-bed rise from the *aggradation* and it will reduce the impact of post-earthquake *aggradation* on the township.

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 required (decade) for a managed retreat of the heliport and oxidation ponds 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 stopbanks were retained, there is a high chance that the Waiho River will break out to the south by itself during a storm, as it has done previously (including at least twice in the 20th century). The consequences of this would be catastrophic, with a high *likelihood* of loss of life, livestock, and property. By actively managing a relaxation of the southern boundary and controlling the release of the Waiho River to the south, the impact on life and livelihoods can be reduced.

It is also very significant that the damage to Franz Josef township and its assets due to the expected high sediment input to the Waiho/Callery catchment following the Alpine fault earthquake (about a 50-year return period event at present) will be much less if the river has by then been allowed to occupy its whole *floodplain*, because the river-bed elevation will in that case be much lower than it would be if the present stopbanking were maintained.

7. FUTURE MANAGEMENT

Franz Josef is exposed to a wide range of natural hazards including the Alpine Fault rupture zone, possible major landslide, and flooding and *avulsion* hazards from the Waiho River. The first and second of these hazards can only be avoided by relocating the township, and Westland District Council are currently considering this. While this is outside of the scope of this report it provides a longer-term context for the decadal perspective herein.

The scope of this report is to provide recommendations for a realistic 10-year management plan for the river based on our expertise as river scientists and engineers. This must, of course, lead in to a longer-term strategy, and our opinion is that the only effective and achievable long-term strategy is to remove the south side stopbanks, allowing the river to access the whole of its *floodplain* to the south (as recommended at the 5th International Gravel-Bed Rivers Workshop in 2000 and the WCRC Workshop in 2016). This section provides an outline of the essential steps to implement this relaxation option, while managing the existing risks and river protection network in the meantime.

Whilst we acknowledge that this option will come with significant economic, social and environmental impacts, we are recommending this option based on our extensive studies of the river, as well as our understanding and engineering assessment of *risk*.

In summary, the reason we are recommending this drastic option is due to the following:

- The Waiho River *flood hazard* is currently managed by rock protected stopbanks. However, the resulting continuing rapid *aggradation* of the river bed has increased the *flood risk* to the township and SH6 to critical levels, as well as expediting the additional *hazard* of the developing *avulsion* into the Tatare Stream.
- To continue to manage the Waiho with stopbanks will not stop the rate of bed level rise nor the *avulsion*. Therefore, as the riverbed continues to rise, the vulnerability of the protection measures will increase, with an increasing *risk* to people, infrastructure, and land.
- Allowing the river to reoccupy more of its natural *floodplain* is the only viable option to slow the rate of rising bed levels and reduce the *risk* to the township and SH6 in their current and future locations from the *flood* and *avulsion* hazards

Allowing the river to occupy its natural *floodplain* on the south side will provide the following benefits:

(i) In the short-term (year - decade) some localised *degradation* (about 1 m) may occur downstream of the SH6 bridge. In the longer term (decades) the rate of *aggradation* of the Waiho River bed between the SH6 bridge and the coast will decrease, together with *aggradation* at the same decreased rate on the southern *fan*.

(ii) The Tatare *avulsion* and the infilling of the Tatare valley would be slower, and channel management measures could be used to reduce the *fan* erosion and *deposition* activity at the *avulsion* site.

(iii) *Flood* risks to the present township would be reduced in the medium term (decades) if the current south side stopbanks are retained.

(iv) The *flood* risks to the township site and potential relocation sites following earthquake, landslide and landslide dambreak events would be substantially reduced, given the much larger area available for *fan deposition* and correspondingly lower river bed levels.

(v) The retirement of the *floodplain* land on the south side would eliminate the *flood* hazards that presently exist to people living in this area, and to their assets and livelihoods.

(vi) *Flood* risks to SH6 south to Docherty Creek would reduce significantly.

Ultimately, if the removal of the south side stopbanks is combined with relocation of the township northwards (as WDC are investigating), there would be a substantial reduction to the long-term *flood* risks and maintenance requirements for the north side stopbanks, with the addition of removing the township from the Alpine Fault rupture and landslide *hazard* zones.

Thus, our proposed 10 year river management plan focuses on providing a staged release of the Waiho River to the south, while providing temporary protection for the short to medium term to the north.

It is important to note that, while we are proposing a 10 year plan that allows for managed retreat from the *floodplain*, due to the significant power of the river in *flood* (as observed on multiple occasions in recent years) and the condition of the current *flood* mitigation assets, there is still a high probability that the river may *breach* the existing protection network within this 10 year period.

A major river break out onto the south side *floodplain* prior to an effective and complete retirement of that land would cut SH6 and cause extensive damage and disruption to the assets and livelihoods of the people living in the area. The response to such a damaging event would undoubtedly be very different to the planned retreat of the proposed management plan. It would be much more stressful for the people affected, with a complicated recovery to deal with both the immediate support and assistance to people, and a sudden implementation of the buy-out and removal of assets and liabilities on the *floodplain* of the proposed retirement. The realignment of SH6 would also become more complicated, as the Waiho River might then have active channels where highway construction would need to take place.

7.1. PARA FRAMEWORK

Our approach to managing the *flood risk* and community resilience from the Waiho River is in accordance with the principles of the PARA framework (Figure 7-1), which is currently adopted by several central government agencies (Ministry for the Environment, 2022). These principles are:

- Protect – Reduce the extent and/or frequency of the *hazard*.
- Avoid – Ensure new development and property and vulnerable assets are not exposed to the *hazard*.
- Retreat – Relocate existing people, property and assets from locations exposed to the *hazard*.
- Accommodate – Reduce the consequences of the *hazard*.

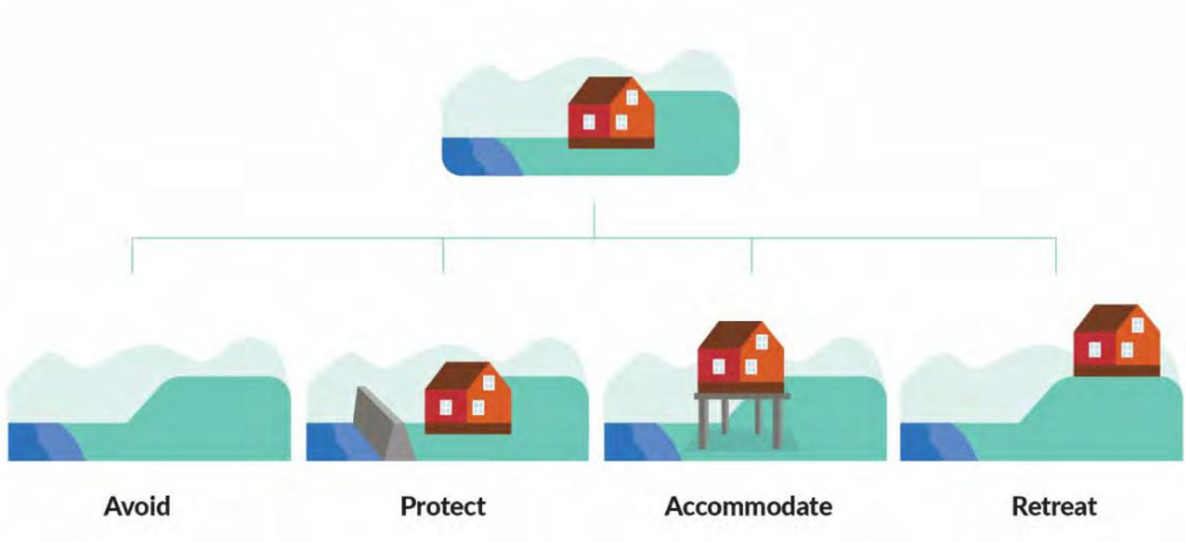

Figure 7-1 - Ministry of the Environment - adaption options

Specifically, our proposed 10-year management plan addresses each principle through the following:

- **Protect** – Strengthening and raising the protection scheme stopbanks, with an emphasis on the north side stopbanks that protect the town and key infrastructure.
- **Avoid** – Ensuring there is no new or intensification of development on the southern *floodplain*.
- **Retreat** – Implementing a managed retreat of the south side *floodplain* and the realignment of the state highway across this *floodplain*.
- **Accommodate** – Intensive civil defence and emergency management planning based on the most up-to-date information and technical understanding of the existing hazards.

7.2. 10-YEAR MANAGEMENT PLAN - OVERVIEW

The main objective of the proposed management plan is to allow the Waiho River to occupy a much larger area of its *fan* and valley *floodplain*. However, a well-considered, planned retreat from the south side *floodplain* is likely to take the order of a decade, for both SH6 realignment, and to purchase all the properties in the area and remove all assets and liabilities, such as the old council and farm landfills. Because of the continuing *aggradation* of the Waiho *fan*, and the developing *avulsion* into the Tatare Valley, there is a high *likelihood* of extreme damage and loss from a *flood* event within the 10 year time frame.

The management plan must, therefore, consider all aspects of the PARA framework, with planned measures for all four responses of this framework which we address in the following order:

Accommodate

Given the threat from the Waiho River, the highest priority is emergency management measures that protect people and reduce the losses and damages that occur from the flooding, as well as contingency planning for if a *stopbank* breaches or overtops.

Avoid

Planning controls and regulations to prevent any further new developments and intensification of land uses on the southern *floodplain* should also be put in place as quickly as the appropriate planning processes allow.

Retreat

A basic outline of what would be involved with the proposed staged retreat from the south side of the Waiho River *floodplain* has been drawn up, for both SH6 and the land retirement. How this will be implemented is, though, beyond the scope of the report. What we are emphasising is that this is the only option that will provide relief from the threats that arise from the natural *aggradation* that is occurring on the *fan* of the Waiho River.

Protect

The above measures will provide only some relief, with the threat of extreme consequences from a river breakout remaining very real. Therefore, over the next 10 years, whilst the retreat and other mitigation responses are implemented, some protection measures should also be undertaken. Improvement measures have been considered as outlined in this report, and a risk assessment has been undertaken to assist in determining priorities.

7.3. ACCOMMODATE - CDEM PLANNING

We recommend that a concerted effort is put into Civil Defence and Emergency management planning, and preparing personnel as well as local community members for their responses to potential *flood* scenarios. This should be the first step in any 10 year management plan and should begin immediately, with the TAG members providing input on the nature and extent of the *flood* threats.

Based on our current understanding of the *risk* profile to the assets, it is recommended that very specific scenarios are considered and that the realistic consequences are considered / workshopped by key personnel. We consider it important that CDEM staff / personnel understand the likely locations and nature of flooding and what they need to prepare the community for.

It is very important to highlight that the flooding that may happen now is unlikely to be similar in nature and extent to what has occurred previously, due to the significant bed level increases that have occurred in the main channel, and that these increases will continue. As a result it is likely that any floodwaters escaping the main channel in the future will have more energy due to the increased fall and are likely to take different flow paths. It is also likely that the river will be carrying more gravel than has previously occurred, causing the river to jump into new flow channels.

7.4. AVOID – FLOODPLAIN PLANNING

Given the high *likelihood* of a *stopbank* failure along the southern protection works and consequences of the resulting flooding, as well as the proposed retreat from the southern *floodplain*, we recommend no new developments and further intensification of land use on the south side (Figure 7-2) be permitted.

To do this, planning controls and regulations should be put in place as quickly as the appropriate planning processes allow.

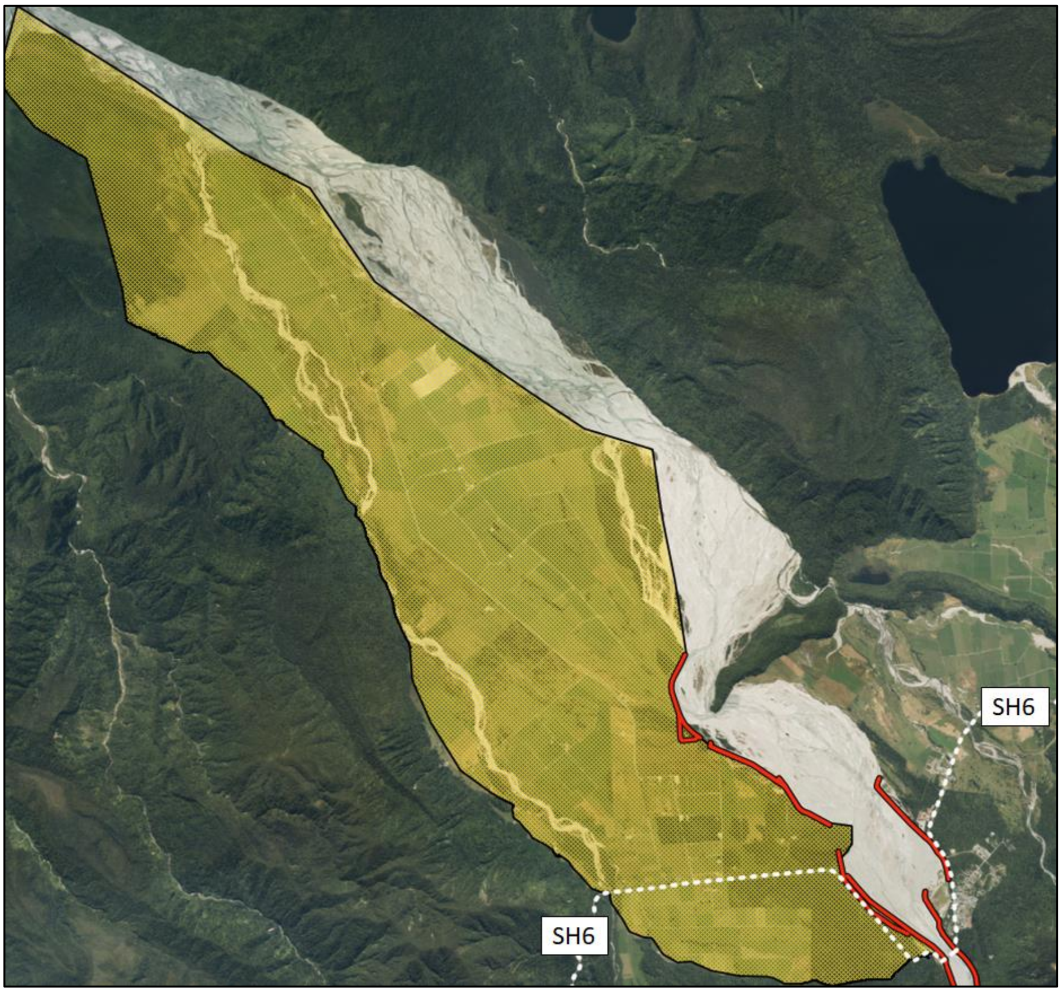

Figure 7-2 - Extent of southern *floodplain* on which any new developments and intensification of land use should be prevented. The current *flood* protection scheme is shown by the red lines.

7.5. RETREAT – RELEASE TO THE SOUTH

It is likely that the minimum timeframe required to release the river in an orderly manner to its southern *floodplain* is about 10 years, because there are many significant workstreams which will need to be undertaken including planning, consenting, land owner negotiations, purchasing of land, relocation of assets (Figure 7-3), design and construction of the highway etc.

In order to have a significant impact on the long-term bed level trends in the river, removal of the Waka Kotahi stopbanks between the SH6 Bridge and Canavan's Knob is essential. However, as this will result in the entire southern *floodplain* being inundated, all of the infrastructure, including buildings, roads, powerlines, dump sites etc., will need to be removed. This will clearly take a significant amount of time. We are therefore proposing a staged approach, with relaxation of the downstream stopbanks first, in order to allow for some of the detailed design, consenting and construction etc. to occur in parallel. As a minimum, this will involve the five phases outlined in Section 7.7.

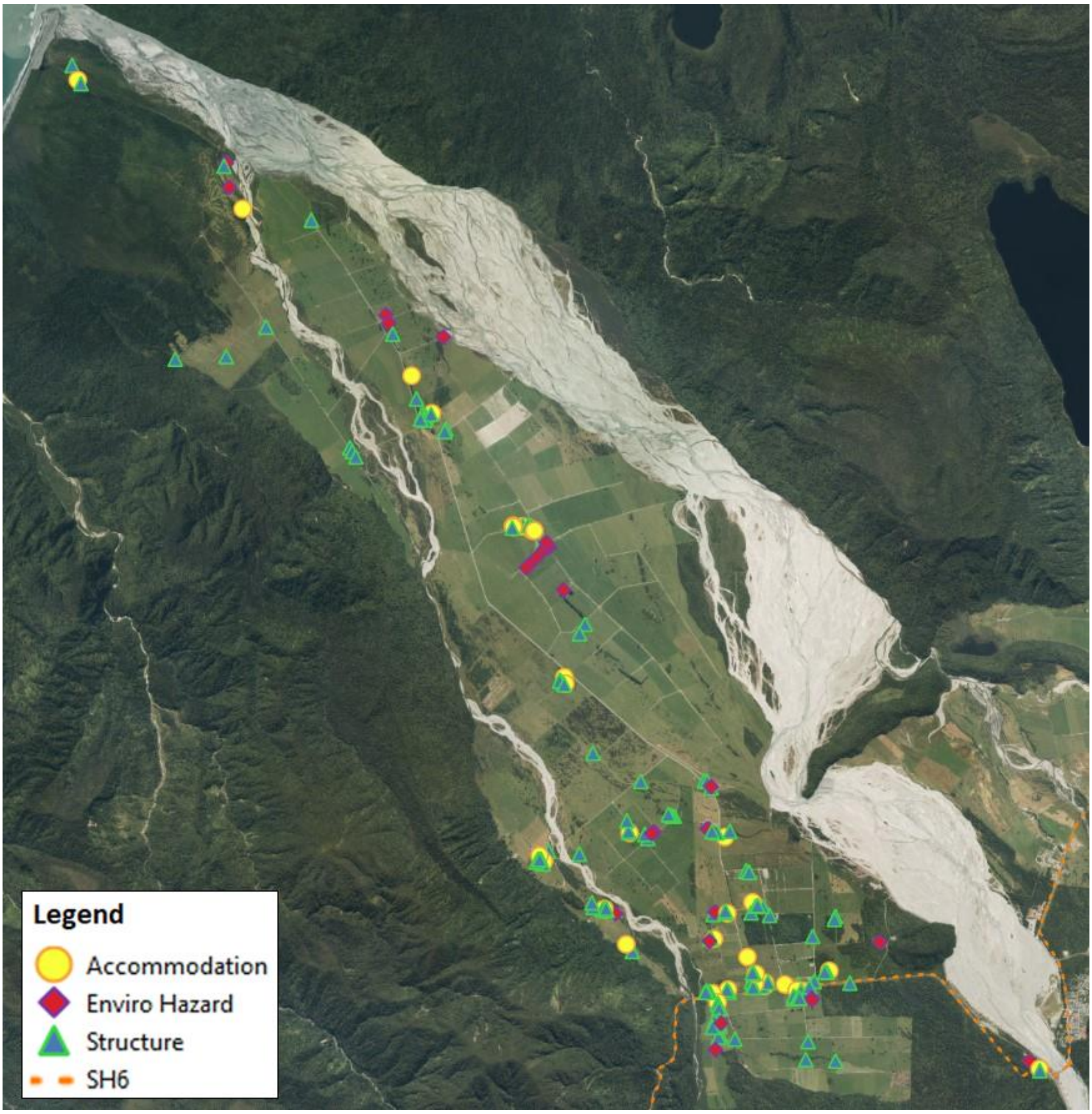

Figure 7-3 - High level overview of the infrastructure on the southern *floodplain* that will need to be relocated. The enviro *hazard* category includes effluent ponds, landfill sites, and fuel, and the structure category includes sheds, bridges, culverts, silage pits, met station, office, powerhouse, and public buildings.

7.6. PROTECT – STRUCTURAL AND RIVER CHANNEL MEASURES

The basis for undertaking improvements to the protection scheme structures is the *likelihood* of flooding and *flood* damage occurring over the 10 year time frame of the proposed retreat, and the rough cost/benefit balance for each of the specific improvement works considered by the TAG, that is outlined in this report (see Section 14 – Appendix C). The costs of these improvements have not been estimated through a scheduled engineering cost process, but rough order costs have been used to give an order of magnitude idea of costs.

Despite the impacts of the *avulsion* to the Tatare Stream, no structural works are proposed, as we consider that the continuing *aggradation* would overwhelm any measures, regardless of how robust they were. Structural works across the developing *avulsion* channel would be difficult to construct, requiring a diversion of Waiho River channels and the de-watering of the work site, with expensive rock protection measures. Then once overtopped the structure would have to be re-built at a higher level.

However, once there is some relief to the south, undertaking channel management measures may be useful in slowing down the sediment flow into the Tatare Stream.

7.6.1. GLACIER ROAD

As the river *aggradation* continues, there is the potential for floodwater to *overtop* the Glacier Road during a large event or from a landslide dam break in the Callery River. The floodwaters will flow over the southern approach to the SH6 Bridge and across the full length of the south side *floodplain*.

However, this scenario is not well understood. A detailed investigation which includes modelling and ongoing monitoring of the adjacent bed is recommended, in order to understand the *flood risk* to the road and downstream *floodplain*.

Under the *IRG* funding, this road is to be raised, and/or a new overflow cut-off bank constructed to the level of the adjacent high ground to allow Wombat Creek to be diverted across the Glacier Road into the Waiho River via new culvert or bridge.

The rough order cost for either of these upgrades would be around $2 million.

7.6.2. WAKA KOTAHI STOPBANKS (SH6 BRIDGE TO CANAVAN'S KNOB)

These stopbanks have been raised and reinforced recently (2020) to a level similar to the corresponding stopbanks on the north side of the river. With the north side stopbanks being raised by the present improvement works, overtopping and breaching of the *stopbank* would become more likely on the south side.

The south stopbanks could be raised further as well, although the intention of the present works is to give a higher standard of protection to the Franz Josef town side. It would make what are high, complex double stopbanks even higher. A failure would then develop a wider *breach*, and the outflows would be locally faster and more damaging, as a result of higher velocities created by the increased height difference between crest level and adjacent land.

The flooding from a failure of this *stopbank* would extend the full length of the south side *floodplain*, and potentially damage a large number of houses and farm assets, as well as SH6.

Undertaking this *stopbank* raising should be allowed for in the 10 year plan, with its implementation depending on actual *aggradation* trends and the nature of *flood* flow pressures along the south side below the SH6 Bridge.

The rough order cost for this would be around $3 million.

7.6.3. RUBBISH DUMP STOPBANK (CANAVAN'S KNOB TO RATA KNOLL)

The upper part of this *stopbank* is continuously rock lined, but the lower part has rock protection works only in places where repairs have been undertaken. This lower part is especially vulnerable to failure, and even more so as river bed levels rise.

The cost of fully rock lining the *stopbank* would be substantial, and further works are likely to be needed as the bed level rises. The rough order cost for an initial full rock lining would be around $5-15 million, depending on the amount of rock used and its embedment below bed levels.

A failure of the *stopbank* would result in a relatively restricted area of flooding across the *floodplain* to Docherty Creek. This would cut off access to the lower valley, but there are few assets at *risk* and the access road could be easily repaired after the event.

Despite the significant improvement in the *flood risk* from these works, they would not be a priority.

7.6.4. MILTON'S STOPBANK

This *stopbank* is protected by a substantial rock lining to the crest. However, there is little embedment of the rock below bed level, and local scour around the bend can be very deep, and is likely to increase in the future with increasing *flood* intensity and frequency. Thus, an undermining failure of the *stopbank* is almost certain in the next 10 years.

Adding rock along the toe of the *stopbank* to a deeper level would decrease this *risk*. The rough order cost for this would be around $2 million.

A failure causing flooding across the lower valley flats would cause damages much greater than this cost, and hence this work is worthwhile.

7.6.5. NORTH SIDE UPSTREAM OF SH6 BRIDGE

Flooding through to Franz Josef town would only take place after very substantial *aggradation* in this valley opening *reach* and during a large *flood* event. This would be a rare event over the 10 year period, and the terrace land could be easily and quickly raised.

This *risk* should be closely monitored.

The rough order cost to raise and protect the terrace land is estimated to be around $0.5 million.

7.6.6. CHURCH AND HELIPORT STOPBANKS

A 2 m raising of these stopbanks has been approved and is part of the present improvement works for the north side.

These improvements will not, though, bring the *risk* of failure below critical over the next 10 years. The rate of *aggradation* is such that there would still be a medium-level probability of failure.

Additional improvements to these stopbanks may be worthwhile within the next 10 years, before the river can be released to the south. However, higher stopbanks does mean that a failure would develop a wider *breach* as velocities increase exponentially with the fall from crest height to the adjacent ground, and the outflows would be locally faster and more damaging.

The rough order cost for an additional raising would be around $2 million.

7.6.7. HELIPORT TO 55KPH CORNER

A rock lined *stopbank* was constructed by NZTA between 2014 and 2016 alongside the state highway from the 55kph corner up to Franz Josef town. A link bank from the end of the Heliport *stopbank* to the upstream end of the Havill *stopbank*, at the 55kph corner, is presently being constructed. This Link *stopbank* has an allowance for 2 m of *aggradation* above present bed levels.

Given the 55kph Corner *stopbank* remains as a secondary defence, a failure in this area is unlikely over the next 10 years. However, there is some potential residual *risk* from ponded water between the Link / Heliport stopbanks and the 55kph Corner *stopbank* that may *overtop* and / or flow around the upstream end of the 55kph Corner *stopbank*.

The failure *risk* of this combined stopbanking should be investigated.

7.6.8. HAVILL'S STOPBANK

This *stopbank* was constructed in 2016 after flooding on the north side from the 55kph corner to the oxidation ponds. The raising of this *stopbank* by 2 m and the reinforcing of the rock lining is part of the present improvement works.

The combination of on-going river bed *aggradation*, and the *avulsion* to the Tatare valley that will cause channel edge erosion and the development of deep channels against the north side, means that the ponds will remain at *risk* from both *aggradation* and *degradation* scour breaching the *stopbank* at the ponds.

Further works are likely to be required over the next ten years, in addition to the present improvements, or until the ponds are de-commissioned. It is possible that it may be advisable to retain the Havill *stopbank* beyond the period required to relocate the ponds, as this structure may reduce *aggradation* and flooding risks within the Tatare valley, and consequently the scale of future management measures required there. Further monitoring and investigation is required on this matter.

The type of works required is not easily determined, given the complex river processes taking place at the site. Improvement works would, though, need to be undertaken proactively, before failure was imminent.

A rough order cost of potential measures would be around $2-5 million. These measures may be of limited effectiveness, but an allowance for some works should be included.

7.7. 10-YEAR MANAGEMENT PLAN – PHASED APPROACH

The 10-year management plan incorporates the planned measures for all four responses of the PARA framework as detailed above. We recommend that these measures be completed in a phased approach, and have drafted out a high level overview of each of the phases as outlined below. We note that following this report, in depth investigations and consultation with all involved stakeholders will be needed to develop each phase.

An example of a conceptual 10-year plan for the staged release to the south has also been presented in Gantt chart format (Figure 7-4) at the end of this section. It should be highlighted that these timeframes are only indicative (i.e. +/- 50%). Multiple streams will be running in parallel, and the exact timing of each stream will need to be flexible.

Additionally, we have included Figure 7-5 which shows a visual summary of how the protection network will change during each of the five phases in the 10-year management plan.

7.7.1. PHASE 1

- CDEM awareness workshop / planning / community liaison
- General stakeholder engagement / community consultation
- Capital work funding discussions
- Status quo management of existing banks (including raising the northern stopbanks)
- Stockpiling of rock near at *risk* infrastructure (including the Rubbish Dump *stopbank* and oxidation ponds) for emergency protection if / when required.
- Ensuring sufficient emergency response funding is readily available for bank repairs / construction etc i.e. not relying on external insurance. However, council should give consideration to establishing an agreed post-*flood* structural measures policy that would enable safe clean-up and removal of assets but not promote ongoing occupation or additional investment into high *flood hazard* areas.
- Emergency response planning for when the oxidation ponds are destroyed by the river.
- Economic, social and environmental impact assessments.

Investigations into:

- The likely impact of the *avulsion* into the Tatare Stream (including morphological modelling).
- The response of the south side *floodplain* to *stopbank* removal (using a morphological model).
- The extent of infrastructure on the southern *floodplain* that will need removal or relocation.
- The residual *risk* of overtopping along the north stopbanks between the SH6 Bridge and the oxidation ponds, as this will result in floodwater collecting behind the stopbanks with nowhere to go, so will inundate the township and SH6.
- The *risk* of overtopping of the Glacier Road through further modelling to determine trigger point for raising.
- The rapid relocation of the oxidation ponds.
- The relocation of the Heliport *stopbank*, and the construction of the secondary *stopbank*.

7.7.2. PHASE 2

- Removal of council and farm landfill sites.
- Land procurement, and removal / relocation of infrastructure within identified *flood hazard* zone.
- **Removal of Milton's *stopbank* and the unlined Rubbish Dump *stopbank*** (including reclamation of rock which can be salvaged for future use).

7.7.3. PHASE 3

- Removal of Waiho Flat Road i.e. remove seal, culverts, etc.
- Land procurement, and removal / relocation of infrastructure within identified *flood hazard* zone.
- **Removal of lined Rubbish Dump *stopbank*** (including reclamation of rock which can be salvaged for future use).

7.7.4. PHASE 4

- Land procurement, and removal / relocation of infrastructure within identified *flood hazard* zone.
- Constructing new state highway and remove old state highway.
- Realigning services (power / telecom etc).

7.7.5. PHASE 5

- **Removal of remaining south side stopbanks (between SH6 Bridge and Canavan's Knob**) and rock protection (including reclamation of rock which can be salvaged for future use)
- Ongoing management of release (i.e. river training, repairs to structures etc as river transitions to new location).

Waiho River 10-Year Plan

ACTIVITY	PLAN START (YEAR)	PLAN DURATION (YRS)
Project management		
Management, reporting and liaison	2024	10
Landfill / waste strategy and monitoring	2024	10
Milton's and Unlined Rubbish Dump stopbanks		
Investigations	2024	2
Design	2024	2
Consenting	2024	2
Landowner liason	2024	3
Floodplain infrastructure disestablishment	2025	3
Release management / benefit realisation	2027	2
Lined Rubbish Dump stopbank		
Investigations	2024	2
Design	2024	3
Consenting	2024	3
Landowner liaison	2024	5
Floodplain infrastructure disestablishment	2026	3
Release management / benefit realisation	2028	2
SH6 Bridge to Canavan's Knob double stopbanks		
Investigations	2024	2
Design	2024	4
Consenting	2024	4
Landowner liaison	2024	5
Road realignment implementation	2028	4
Floodplain infrastructure disestablishment	2030	3
Release management / benefit realisation	2032	2

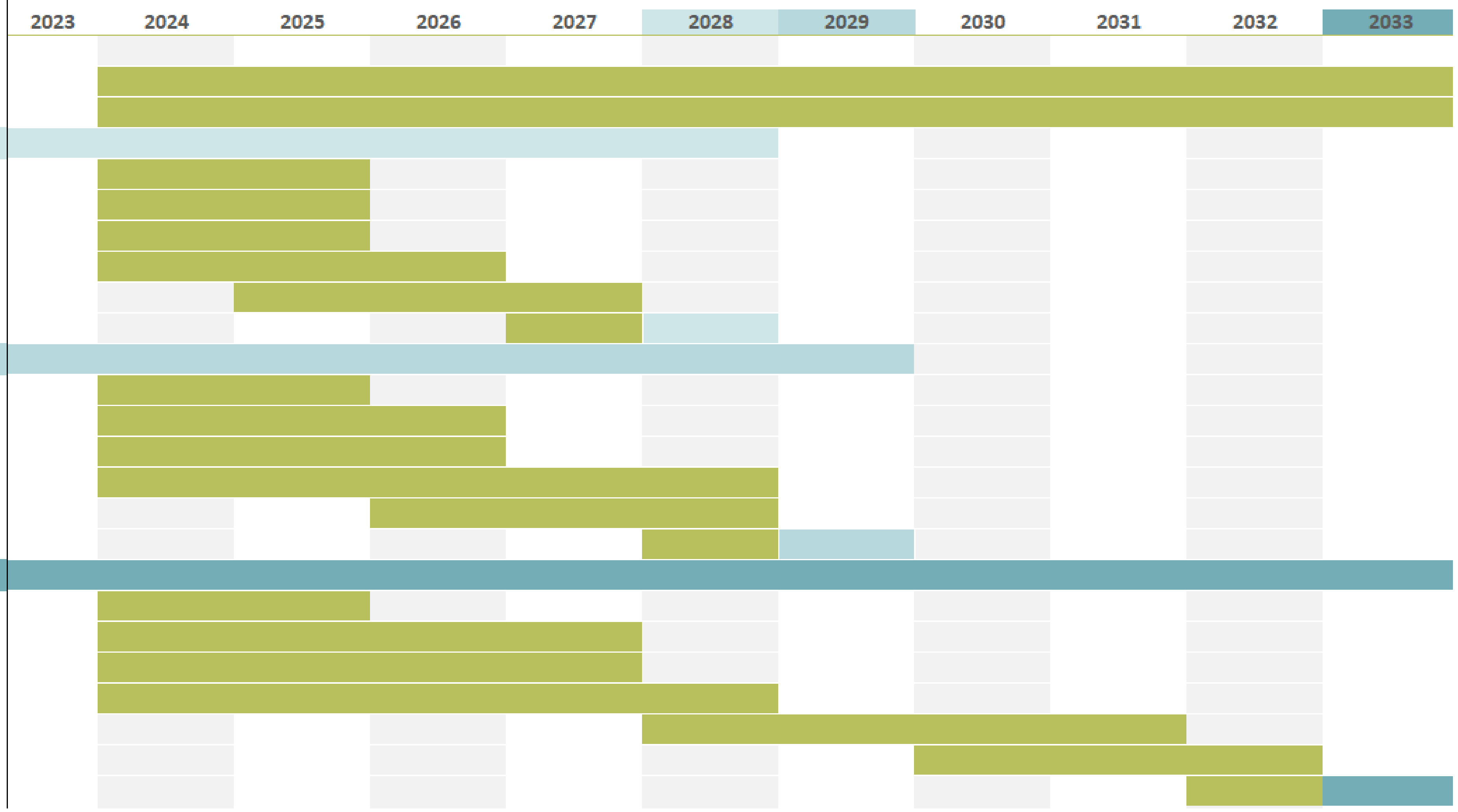

Figure 7-4 - Gantt chart of a conceptual plan for the staged approach to releasing the Waiho River to its southern *floodplain*. This is just a guide, an in depth plan will need to be developed involving all stakeholders.

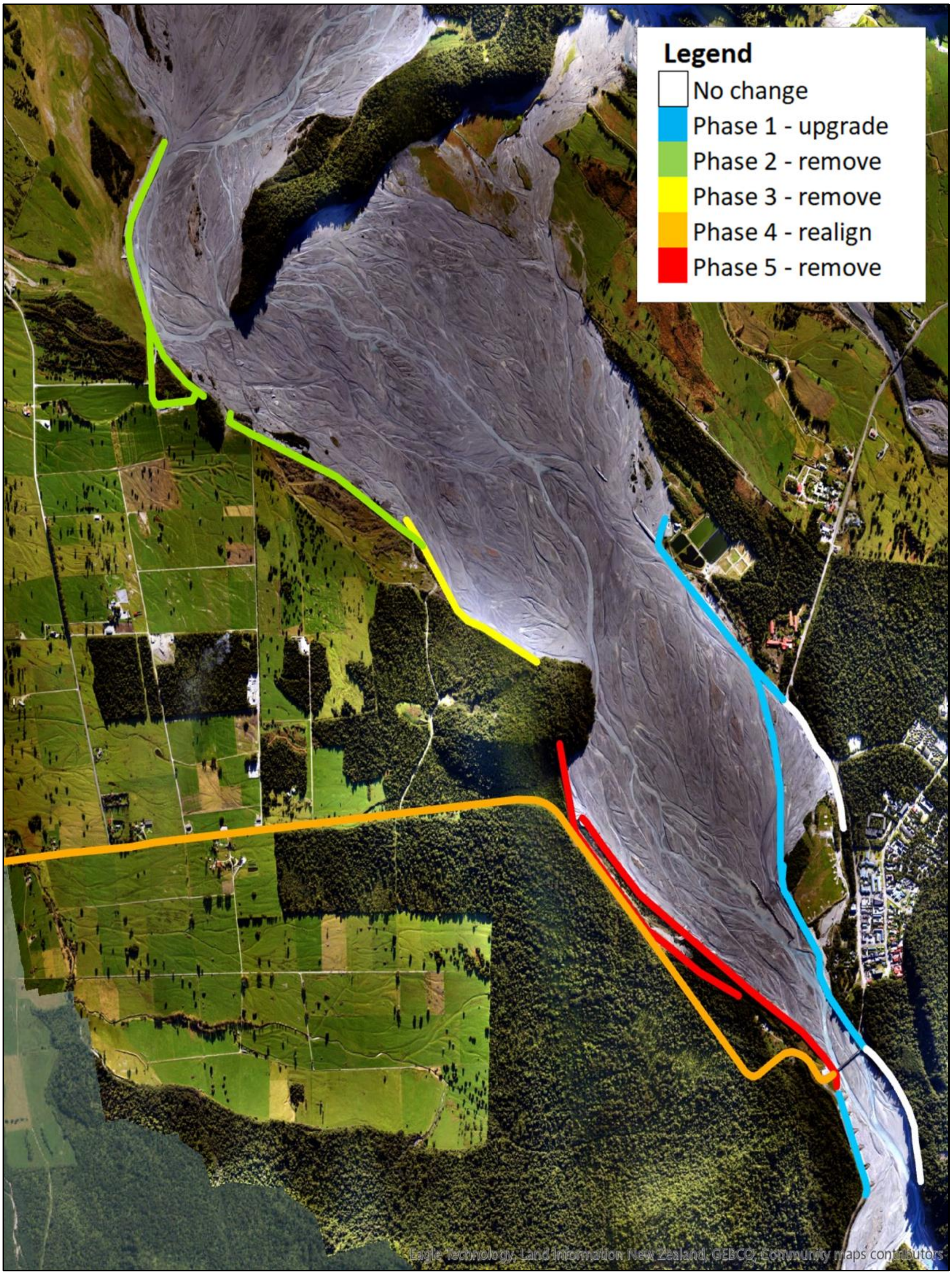

Figure 7-5 - Visual representation of the 5 phases of the 10-year river management plan.

8. CONCLUSIONS

We frame the conclusions to this report using the original scope for this work:

1. **Defining the existing and future hazards** that the Waiho River poses to the Franz Josef township and surrounding community and *floodplain* area.

   Flooding and *avulsion* hazards from the adjacent Waiho River pose significant current threat and increasing future threat to Franz Josef township and its environs. Floods in the Waiho River primarily result from unpredictable and intense rainstorms, and landslide dambreaks also pose a significant threat of sudden and extreme *flood* events.

   Flood and *avulsion* hazards are exacerbated by rapid *aggradation* on the surface of the Waiho *alluvial fan*. This *aggradation* is perching the bed of the river (between the stopbanks) at increasing elevations above the adjacent land (the natural *fan* surface). The bed of the Waiho River is now over 2 m higher than the adjacent Franz Josef township, and this unnatural elevation has also caused the developing *avulsion* of the Waiho River into Tatare Stream to the north.

   In the future, the threat posed by flooding and *avulsion* hazards will increase. *Flood* frequency and intensity will continue to increase as climate warms. Sediment supply to the Waiho will increase as landslides in the catchment become more frequent due to tectonic stress buildup and the changing climate. This increase in water and sediment supplies will increase the degree of channel change and the rate of *aggradation* across the Waiho river bed, and therefore the *likelihood* of a *stopbank* breaching or overtopping and the rate at which any *avulsion* develops. In turn as the riverbed continues to aggrade, the energy of any flow into adjacent lower-lying terrain in the event of failure of *flood* protection infrastructure will be increased, intensifying the damage caused by any *breach*. The rapidity of the *avulsion* into the Tatare Stream highlights the severity of this process.

2. **Assessing the capability of the protection schemes in their current state** to reduce the risks from these hazards.

   Rapid *aggradation* in the Waiho and rapid channel change has meant that protection structures in the Waiho have experienced a reduction in their *capacity* to contain the *flood* flows for which they were designed. There is therefore an increasing vulnerability to *breach* or overtopping of these structures, which in turn increases the risks posed from the hazards of flooding and *avulsion* in the Waiho.

   Unlined stopbanks are being progressively eroded by the Waiho and are increasingly prone to failure. Some lined stopbanks are slumping where their toe has been scoured by the river. There is now minimal *freeboard*, with peak water levels within 1 m of *stopbank* crests and some stopbanks (upper Waka Kotahi, sections of Church and Helipad and lower end of Havill's) have minimal to no *freeboard* for a current 100 years *ARI* design flow; they are therefore very vulnerable to overtopping in such a dynamic river environment.

We undertook a qualitative assessment of *risk* to the protection schemes in their current state by combining the *consequence* of failure at each protection structure with the *likelihood* of its occurrence. This highlights that all existing areas have a High or Critical *risk* of failure over the next 10 years. Seven of the twelve assets / areas were identified with a Critical *risk*. We identified ten of the twelve assets as having severe to extreme consequences of failure.

3. **Providing guidance on the available management options for the river** in terms of what actions or non-actions can be taken to reduce or remove the risks these river hazards pose to the community, infrastructure and land.

   The Waiho River has been confined by structural protection works for several decades, which coincides with a sustained and lengthy period of *aggradation* that shows no signs of abating. Our *risk* assessment indicates that further work to upgrade or build structural protection is likely to cost a significant amount, but will not necessarily reduce the *risk* rating, and where it does, generally only does so by one category. This means that maintaining the existing protection network is becoming increasingly challenging as the *aggradation* continues, further reducing *flood capacity* and increasing *likelihood* of failure. A fundamental need is an option that reduces the rate of bed level rise across the Waiho *alluvial fan*.

   On the southern side of the river, there is an option to relax the protection boundary by removing the stopbanks and releasing the Waiho River to the south. This option will provide the Waiho River with about three times more area to spread its sediment load, correspondingly reducing the rate of bed level rise. In turn this will increase the lifespan of the northern stopbanks and reduce their *risk* of failure during *flood* events, and also reduce the pressure on the developing *avulsion* into the Tatare Stream, however the *avulsion* may have fully developed before the opportunity to have this effect is realised. In order to protect the community, infrastructure and land from the *flood* and *avulsion* river hazards, the only option available is to continue to maintain, upgrade or build new protection works on the northern side of the river in combination with release to the south.

   Not releasing the Waiho to the south and retaining the southern stopbanks brings with it a high probability that the Waiho would break out to the south by itself during a storm, resulting in catastrophic loss to the community (including loss of life), infrastructure (including SH6) and land. Actively managing a release to the south reduces these impacts and averts a disaster.

   One of the highest risks to the area is a major (M_w8+) earthquake, which has a 15% chance of occurring within the next decade. This will cause major sediment inputs to the rivers, causing a high and sustained (decadal) *aggradation* episode on top of the long-term trend. It will also severely damage all river protection structures. If the river is allowed to occupy its whole *flood* plain to the south, the impacts on the township on the north side from this *aggradation* and flooding will be substantially reduced, especially if proposed relocation of assets away from the river has taken place.

4. **Recommending a ten-year river management plan** for the WCRC to implement, that leads into a long-term management strategy.

We recommend a 10-year river management plan that actively manages a release of the Waiho River to the south, while providing interim protection for the short to medium term to the north.

It must be recognised that while we are proposing a 10-year plan that allows for managed retreat from the *floodplain*, the significant power of the river in *flood* and the condition of the current *flood* mitigation assets means there is still a high probability that the river may *breach* the existing protection network within this ten year period. This situation lends a significant urgency to the implementation of this 10-year plan.

We recommend that the 10-year plan considers all aspects of the PARA framework in the following order of priority and in a phased approach to allow orderly implementation:

Accommodate: emergency management measures should be prioritised given the threat from the Waiho River. These should include specific contingency planning related to loss of key infrastructure (e.g. SH6, Oxidation ponds, power, fibre, heliport, airstrip, old WDC landfill, and others).

Avoid: planning controls and regulations to prevent new developments or intensified land uses on the southern *floodplain* with immediate effect.

Retreat: we outline briefly the requirements for an actively managed staged release over ten years, but implementation is beyond the scope of this report. In order to have a significant impact on the long-term bed level trends in the river, removal of the Waka Kotahi stopbanks between the SH6 bridge and Canavan's Knob is essential. However, as this will result in the entire southern *floodplain* becoming active river bed, all of the infrastructure, including buildings, roads, powerlines, dump sites etc., would need to be removed. This, as with the required relocation of SH6, will clearly take a significant amount of time. We therefore propose a staged approach, removing stopbanks downstream of Canavan's Knob first, in order to allow for some of the detailed design, consenting and construction, and property negotiations to occur in parallel.

Protect: we propose that improvements to the protection network be implemented alongside the staged retreat, emergency management and land use planning. These improvements have been incorporated into the five phases of the 10-year management plan, and provide guidance on each structural protection asset / area, but does not give detailed costing or design, although rough order costs are provided for context.

In summary the five phases in implementing our recommended 10-year plan are:

Phase 1:

- CDEM management planning, and preparing personnel as well as local community members for their responses to potential *flood* scenarios

- Upgrade stopbanks on the north side from the SH6 bridge to the oxidation ponds to maintain protection for the Franz Josef township
- Undertake holding works along the southern stopbanks and Glacier Road to provide protection for the southern *floodplain* while preparatory works for the release are undertaken.
- Begin investigations into the likely impact of the *avulsion* into the Tatare Stream, response of the south side *floodplain* to *stopbank* removal, the extent of infrastructure on the southern *floodplain*, residual *risk* of *overtopping* on the north stopbanks and Glacier Road, and the relocation of the oxidation ponds and heliport.

Phase 2:

- Land procurement, and removal / relocation of infrastructure, and council and farm landfill sites within the identified flood hazard zone.
- Remove Milton's *stopbank* and the unlined section of the Rubbish Dump *stopbank* on the south side.

Phase 3:

- Land procurement, and removal / relocation of infrastructure, and council and farm landfill sites within the identified flood hazard zone
- Remove lined Rubbish Dump *stopbank* on the south side.

Phase 4:

- Placeholder for the realignment and construction State Highway 6 on the south side, and realignment of services (power, telecom, etc).

Phase 5:

- Remove the remaining southern stopbanks between SH6 bridge and Canavan's Knob.

Ongoing management of the release to the south (phase 5) will be required as the river transitions to this new location.

The only effective long-term management strategy is to allow the river to access the whole of its *floodplain* on the south side. This will slow the rate of *aggradation* and reduce the *risk* posed by flooding and *avulsion* to the township and SH6. Relaxation of the southern boundary will not stop the long-term aggradational behaviour of the Waiho River nor will it result in a return of the *fan* surface to some lower elevation. However, it will reduce the number of people and assets exposed to the *flood hazard*, reduce the pressure on the northern boundary protection works and developing *avulsion*, it will slow the rate of riverbed rise, and it will substantially reduce the impact of post-earthquake *aggradation* and flooding on the township. The damage to Franz Josef township and its assets following the Alpine fault earthquake (about a 50-year return period event at present) will be much less if the river has by then been allowed to occupy its whole *floodplain*, because the river-bed elevation will in that case be much lower than it would be if the present stopbanking were maintained and there will be much greater area over which to deposit additional gravel generated by the earthquake.

Reducing the rate of rise in river bed elevation is also important for the future management of the area, since it will provide the Franz Josef community with time for a longer-term managed retreat of the township, heliport, and oxidation ponds away from the *flood* and *avulsion* hazards posed by the Waiho River.

9. RECOMMENDATIONS

We recommend that:

a. The Waiho River be fully released to the south to allow the river to distribute its sediment load and reduce the rate of bed level rise on the Waiho *alluvial fan*, in order to reduce the critical risks posed by flooding and *avulsion* to the township, adjacent land and infrastructure.

b. A 10-year river management plan be implemented to support this release, that involves planned measures for all four responses of the PARA framework.

    i. Emergency management measures be prioritised given the current and future threats from the Waiho River.

    ii. New developments or intensified land uses on the southwestern *floodplain* be prevented with immediate effect.

    iii. Retreat from the southern *floodplain* be initiated and implemented over the 10-year period to enable the earliest possible release of the Waiho to the south.

    iv. Improvements be made to the protection network in order to provide protection whilst the staged release to the south is implemented.

c. The 10-year management plan be completed in a five phase approach as outlined below, noting that following this report, in depth investigations and consultation with all involved stakeholders will be needed to develop each phase.

    Phase 1: upgrade stopbanks on the north side from the SH6 bridge to the oxidation ponds to maintain protection for the Franz Josef township, and undertake holding works along the southern stopbanks and Glacier Road to provide protection for the southern *floodplain* while preparatory works for the release are undertaken.

    Phase 2: remove Milton's *stopbank* and the unlined Rubbish Dump *stopbank* on the south side.

    Phase 3: remove lined Rubbish Dump *stopbank* on the south side.

    Phase 4: placeholder for the realignment and construction of SH6 to the south of the Waiho River. Note that this not river management, but essential to the staged release of the river to the south.

    Phase 5: remove the remaining southern stopbanks between the SH6 bridge and Canavan's Knob.

10. GLOSSARY

Aftershock: weaker earthquake following the mainshock that starts an earthquake sequence.

Aggradation: the progressive accumulation of sediment deposited in river environments as a result of sediment supply to a reach exceeding the *transport capacity* within and from a reach, leading to an increase in surface elevation of river beds and floodplains. Where the sediment supply cannot be contained within a defined river channel, the rising channel will widen, and the sediment load spreads out over the adjacent land (e.g. *floodplain* or *alluvial fan*).

Alluvial fan (or just "fan"): a flattened conical landform found where a sediment-laden stream or river exits a confined valley (e.g. at the *rangefront*) and formed where the river channels are free to spread their sediment load laterally. Channels on the *alluvial fan* migrate and switch back and forth across the *fan* surface, building up the fan through a process called *aggradation*.

Alluvium / alluvial: sediment (gravel, sand, silt) deposited by river processes.

ARI: Annual Recurrence Interval of a flood of given size; e.g. on the Waiho River a 100-year ARI flood has an estimated flow or discharge of 2,500 cumecs (m^3/s) and could be expected to occur on average once every 100-years, or with a probability (or Average Exceedance Probability [AEP]) of 0.01, or with 1% chance of occurrence in any one year. Note, the ARI does not provide a guarantee of the timing of floods.

Aseismic: not synchronous with or the result of earthquake activity.

Avulsion: a sudden switching of a river channel from one location to another within an alluvial fan or across a floodplain.

Bars: a local accumulation of sediment (gravel, sand, silt) deposited within or adjacent to a river channel.

Braidplain: the area that has been occupied over time by a braided river, which comprises both currently active, recently active, and abandoned multiple channels and *bars*.

Breach: occurs when floodwaters erode a section of stopbank resulting in a gap in the stopbank and flooding of the land it was protecting.

Consequence: the immediate or later outcome of a particular event or circumstance occurring which can include social, economic, and environmental dimensions.

Coseismic: an event or process that occurs during, and as a result of earthquake activity.

Degradation: erosion of sediment that has been deposited in river environments when the transport capacity within a reach exceeds the sediment supply to that reach, leading to a decrease in elevation, lowering the surface of riverbeds.

Deposition: the process where sediment ceases to be transported and is dropped by a river onto the riverbed or floodplain.

Design capacity: the ability of a stopbank to withstand a specific design flood event without overtopping.

Downwarping: reduction in elevation of a segment of the Earth's crust.

Flood: a flow that exceeds the capacity of a river channel to contain it and overtops or flows through any natural or artificial banks in any part of a stream or river.

Floodplain: an area of low-lying land adjacent to a river, formed mainly by deposition of river sediment and subject to flooding.

Freeboard: the additional height allowance of a stopbank beyond where the peak design water level comes to.

Glacial lag boulders: boulders left behind by a glacier.

Hazard: a source of or a situation with the potential to cause harm or loss; so a flood hazard is the potential for damage to property or people from flooding and the associated erosion and deposition that occurs during a flood.

Headcutting: progressive upstream incision and extension of a river channel.

Incision: downcutting of a river channel through erosion of the bed material.

IRG: infrastructure reference group; a group of highly experienced infrastructure leaders tasked by the government during the middle of New Zealand's COVID-19 lockdown in April 2020 with seeking out infrastructure projects that were ready to start as soon as the construction industry returned to normal in order to reduce the economic impact of the COVID-10 pandemic.

Interdecadal pacific oscillation: the long-term oscillation of wind and ocean current circulations around the Pacific Ocean, including sea surface temperature differences across the ocean, which affects the strength and frequency of El Niño and La Niña cycles.

Likelihood: probability of a particular event or circumstance occurring within a specified time.

Longitudinal valley train: deposited glaciofluvial (glacier/river) sand and gravel extending a considerable distance along a valley floor.

Mainshock: the first earthquake of a sequence – usually the strongest.

Overtop: where floodwater levels exceed the crest of a natural or artificial bank and flow over the top of it.

Paleoseismology: the study of geological sediments and rock for signs of earthquakes.

Permafrost: a thick layer of soil below the surface that remains frozen throughout the year.

Proglacial lake: a lake formed by glacial meltwater at the terminus (downstream end) of a glacier.

Rangefront: the edge of a mountain range where there is a distinct change from steep slopes to flatter ground; often defined by a fault.

RCP: Representative Concentration Pathway - a prediction of how concentrations of greenhouse gases in the atmosphere will change in the future as a result of human activities, and therefore how the climate may change. Each RCP denotes a specific climate change scenario.

Reach: a section of a river.

Risk: the chance of something happening that will impact on objectives; technically defined as the **consequence** of the event multiplied by the **likelihood** (probability) of its occurrence.

Southern annular mode: oscillations in the Southern Ocean's circulation around Antarctica affecting the position of the track of depressions around the southern hemisphere.

Stopbank: artificial raised bank along the river side to protect it from it from erosion and/or to contain floodwater.

Toe embedment: the extension of the rock protecting the stopbank face below the riverbed to prevent scour and undermining of the stopbank.

Transport capacity: the amount of sediment a river has the ability or energy to transport; a function of water flow rate and water surface slope.

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12. APPENDIX A – ABOUT THE AUTHORS

Rose Beagley, Land River Sea Consulting Ltd

BSc and MSc in Physical Geography

Rose Beagley is based in Hokitika and is currently employed as a geomorphologist / water resources scientist at Land River Sea Consulting, a small specialist engineering consultancy. Rose first worked on the Waiho River in 2017 for the research component of her Master of Science degree. She used a microscale model to investigate the response of the river to the addition and removal of stopbanks, and then used the results and an in depth study of the behaviour of the Waiho River to inform on future management options. In her previous roles, she was the data analyst and acting team leader for the Hydrology team at the West Coast Regional Council, where she was involved with *flood* response for the Waiho River and was also responsible for archiving and analysing its water level and rainfall data. Her most recent work on the Waiho has included an analysis of modelled *breach* scenarios, analysis of geomorphic change between the 2016, 2019 and 2023 LiDAR datasets, as well as a report on the aggradational behaviour and the recently developing *avulsion*, to provide context for the 2023 Waiho workshop.

Tim Davies, University of Canterbury

BSc (Hons), MSc and PhD in Civil Engineering

Tim Davies retired from a professorship at University of Canterbury, School of Earth and Environment in 2021, having worked at UC since 2003 in Engineering Geology and Disaster *Risk* and Resilience. Prior to that he was at Lincoln University, Dept of Natural Resources Engineering for 28 years, following 5 years in the Dept of Civil Engineering at Sunderland Polytechnic UK.

He has conducted research on Franz Josef and the Waiho River since the mid-1990s, including three river modelling studies and a number of fluvial geomorphology, glaciology and landslide papers; he has also conducted a number of consultancy projects for WCRC, WDC and DoC. Other investigations include the December 1995 glacier burst, the landslide dam-break *flood hazard* from the Callery and Tatare Rivers, the formation of the Waiho Loop moraine, the debris flow *hazard* at Stony Creek, the potential for a catastrophic rock avalanche from the hillslope overlooking Franz Josef and a comparative *risk* assessment for the present and proposed future Franz Josef township sites.

Tim was also a co-supervisor of a recent Auckland University PhD study in which a social science research student lived in the community and studied community perceptions of natural hazards and their management, and has interacted with the Franz Josef community in a number of exercises around hazards and emergency management.

Ian Fuller, Massey University

BSc (Hons) and PhD in Geography

Ian Fuller is Professor in Physical Geography at Massey University where he has worked since 2003. Prior to this he lectured for seven years in Physical Geography at the University of Northumbria in Newcastle upon Tyne in the UK. He graduated from the University of Wales, Aberystwyth with a BSc Honours degree in Geography in 1993, which was followed by a PhD awarded in 1996 that investigated river response to environmental change. Ian's involvement with the Waiho spans nearly 20 years. The upper Waiho from the glacier terminus to the Waiho Loop was a key field site in a final year undergraduate field course he taught that focused on geomorphic processes and hazards, which ran annually from 2005 to 2021. These regular visits provide a broad baseline knowledge of this critical part of the system. More recently, the Waiho has formed part of a research project funded by the Brian Mason Trust, in which he and colleagues at Massey and the University of Canterbury have been looking at geomorphic change in the valley floors proximal to the Franz Josef and Fox Glaciers over the past 8 years.

Matthew Gardner, Land River Sea Consulting Ltd

BE (hons) Natural Resources, CMEngNZ and CPEng

Matthew Gardner is the director and principal engineer at Land River Sea Consulting, a small Christchurch-based specialist engineering consultancy. First exposed to the Waiho River on family hiking trips as a child in the 1980's; he was then educated in the classroom and on field trips to Franz Josef by Professor Tim Davies whilst studying Natural Resources Engineering at the University of Canterbury in 2004/2005. His first professional involvement with the river began in 2014 when he was tasked with building a hydraulic *flood* model of the river for the West Coast Regional Council. Since then, he has been involved in a range of investigations and workshops on the river helping the West Coast Regional Council as well as the Department of Conservation better understand the big picture behaviour and *hazard* profile of the river. He has conducted several hydraulic modelling studies on the river as well as detailed analyses in relation to changing bed levels and behaviour of the river over time.

Mark Healey, WSP

ME (Natural Resources), CMEngNZ and CPEng

Mark Healey is a Chartered Professional Engineer with a master's degree in River Engineering. He works for WSP as Principal River Engineer based in Greymouth and has been working on and studying the Waiho River for over 20 years. In his role as engineering consultant to Waka Kotahi he has provided technical advice on the behaviour of the Waiho River and designs and strategies for river protection works. He has also been closely involved in concept design of options for realignment of SH6 to the south. Mark has also provided advice to the Department of Conservation on the risks to and management of river protection works for road and bridge assets in the Glacier Valley. In a personal *capacity*, Mark has undertaken an assessment of bed level trends at the SH6 bridge and significant research into the nature and behaviour of the Waiau River and its *fan* surface.

Gary Williams, Waterscape

BE (Hons), BSc (Physics), MCom (Hons), FEngNZ

Gary Williams is a consulting engineer in the field of water and soil engineering. He has 50 years of experience in all aspect of catchment and river management, from comprehensive investigations to final design and construction supervision. He first became aware of the *aggradation* and confinement issues on the Waiho *fan* when the international Gravel-Bed Rivers V conference was held in Franz Josef in 2000.

His professional investigations of the Waiho River system began with a site visit in November 2014, with Matthew Gardner of Land River Sea Consulting (LRS). They were commissioned by the West Coast Regional Council to investigate the nature of the river hazards and potential mitigation or protection options. Their findings were presented to interested parties in a January 2015 workshop at Franz Josef.

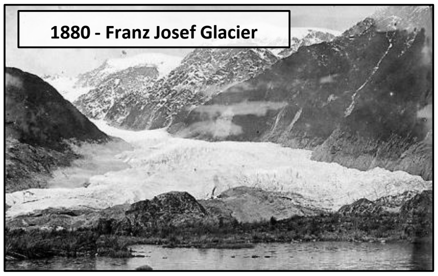
Further investigations were undertaken in 2016, following the flooding of Scenic Hotel and the district council sewage treatment ponds, with field inspections and meetings in Franz Josef in August. He was an expert witness for the council for the Environment Court case brought by Scenic Hotels. This involved detailed investigations of the 2016 *flood* event and expert conferencing with the other experts.

He was part of the design team for the *IRG* Stage 1 works along the true right bank from the SH6 Bridge to the oxidation ponds. He also undertook a review of all the *IRG* works for the Waiho River.

He has undertaken *hazard* identification and protection measures for the Department of Conservation along the Waiho valley up to the glacier, with LRS. They also studied the Fox River system for the department, following the washouts along the access roads in 2019.

13. APPENDIX B – TIMELINE OF THE WAIHO PROTECTION NETWORK

SOUTH SIDE (TRUE LEFT)



1880 - Franz Josef Glacier

Glacier Road

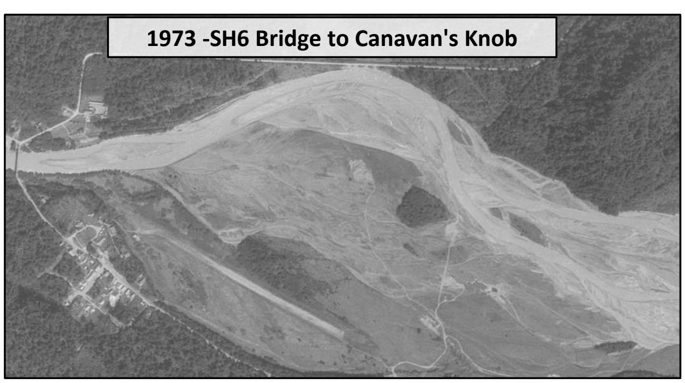
1870s – Glacier tours occurring

SH6 Br to Canavan's Knob

1947 – The Waiho overflowed the riverbank, flooding across SH6 and parallel to it for 3km to Docherty's Ck. A temporary low scrub and boulder wall to check the overflow was constructed.

1956 – Serious erosion below SH6 bridge between 1956 and 1963

1963/1965 – Between 1963 and 1966, rock protection was placed along the river bank to protect SH6.



1973 -SH6 Bridge to Canavan's Knob

1975 – Rock protection extended downstream.

Milton's

1954 – Cutoff stopbank constructed downstream of Rata Knoll

1956 – 370m of the lower end raised

1965 – 100m section damaged in 1965. Repaired with 150m riprap by 1966

1967 – Destroyed 3 times in 4 months in 1967, with repairs completed after each flood, and the alignment resited to follow the newly eroded riverbank.

NORTH SIDE (TRUE RIGHT)

Bridge/Ford

1910 – Rock gabion protecting the location of the river crossing.

1927 – First road bridge across the river

Airstrip protection

1930s – Multiple rock gabions built downstream of the SH6 Bridge

1948

Hotel protection

1968 – Construction of a 350m heavy rock armoured stopbank

1971 – 1200 tonnes of rock to top up slumped riprap.

1973 – Stopbank extended downstream by 500m. A flood in November washed out 60ms of the rock gabions; the airstrip was flooded and hotel and sewage plant threatened.

1974 – Stopbank above the airstrip was breached and the airstrip, hotel and sewage plant flooded. The stopbank was replaced with a hook groyne and rock strongead at the top end. Rock spur groynes were also placed along the reinstated bank.

Year	Milton's	Rubbish Dump	SH6 Br to Canavan's Knob	Glacier Road	Bridge/Ford	Airstrip protection	Hotel protection
1978			Floodwaters overtopped the stopbank.				
1979			During the March flood the riprap fronting the stopbank slumped.			300m and then a further 600m of the topbank destroyed in 2 consecutive floods	
1980		Three rock retards constructed	Rock protection placed along campground frontage and spur groynes placed below this.			Stopbank extended and hook groyne and stronghead constructed at the downstream end.	
1982	Stopbank completely destroyed, replaced by September 1982		The river broke out to the south above Canavan's Knob and took 1 month to retrain back to the north.			Section opposite campground damaged, and the downstream hook groyne destroyed.	
1982						Airstrip stopbank raised, groynes not reinstated.	
1983					Less than 1.8m between river bed and bridge soffit		
1984 / 1985						Breached in Dec 1984 with flooding across the airstrip and along the hotel frontage. This was repaired by 1985	
1985		140m stopbank constructed below Canavan's Knob					
1986	10 rock spur groynes built below the deflector groyne						
1989						180m breach and airstrip destroyed	

1982 - preflood, the extended stopbank

1990: As a result of the continued aggradation the stopbank was abandoned, and works pushed back to the existing riverbank.

Year	SH6 Br to Canavan's Knob	Bridge and Upstream	Church	Heliport	55kph corner	Access track
1991	300m stopbank from SH6 bridge along motor lodge and campground frontage		Four rock deflector groynes aloing the terrace toe below the SH6 bridge.	250m rock protected stopbank below DOC headquarters		
1994	**Transit NZ**					
1995		15m approach to SH6 bridge destroyed, and bank immediately below eroded.				Construction of an unlined stopbank to access the oxidation ponds.
1996	Stopbank raised by 1m over 300m, and given 2000 tonnes of rock protection		280m stopbank constructed immediately below the SH6 bridge			

1994 - SH6 to Canavan's Knob

1994 - Proposed access track stopbank

2003 - Reclassification of the Franz Josef rating district

Milton's	Rubbish Dump	Waka Kotahi	Glacier Road		Bridge and Upstream	Church	Heliport	55kph corner	Havill's

2004

2005

- Rubbish Dump: Extended upstream by 400m to Canavan's Knob
- Waka Kotahi: Secondary stopbank constructed between 2004 and 2011 to provide stronger frontline defence

2011


2011- completed secondary south stopbank


2011- extended heliport stopbank

2014

- Heliport: Stopbank extended to provide greater protection to heliport
- 55kph corner: Stopbank constructed between 2014 and 2016

2015

- **Waka Kotahi**

2016

- Havill's: Breached and Scenic Circle Hotel flooded.

Following the 2016 March flood, stopbanks on both sides of the river below the SH6 Bridge were raised.


2019 - destroyed SH6 bridge

2017

- Havill's: A substantial rock lined embankment was constructed from the SH6 55k corner along the hotel grounds to the oxidation ponds

2019

- Milton's: Breached with considerable downstream flood damage, but repaired within days.
- Waka Kotahi: Seepage just above Canavan's Knob
- Glacier Road: Large section of road washed out.
- Bridge and Upstream: SH6 bridge destroyed and upstream bank eroded. It took several weeks to replace.
- Church: Erosion immediately below bridge.

2020

- Waka Kotahi: Raised by 1m, with the downstream end of the bank joining Canavan's Knob by 2m to 4m, and also widened substantially.

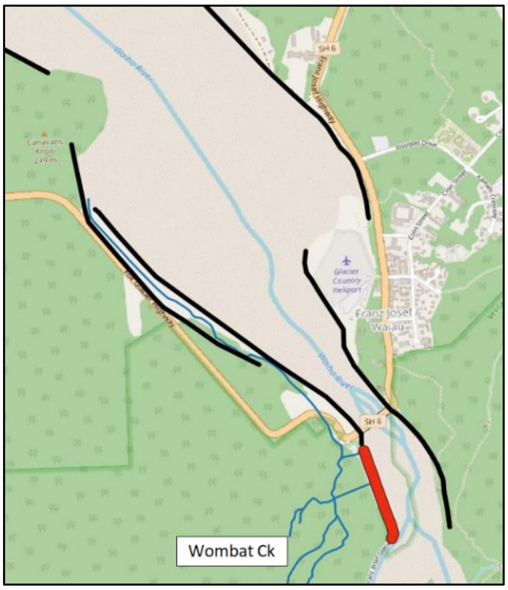
Link Wall

2023

- Milton's: Poor construction of the rock linings has resulted in localised slumping.
- Rubbish Dump: Ongoing erosion of this originally unlined bank has required progressive rock lining.
- Waka Kotahi: Aggradation in the adjacent river reach has reduced the design capcity of both of these stopbank such that they require raising.
- Glacier Road: Callery junction to the SH6 bridge to be raised by up to 2m.
- Heliport: Due to ongoing aggradation, this bank is currently being raised by 2m
- 55kph corner: Due to ongoing aggradation and river activity, a link wall is currently in construction between the top of Havill's stopbank and bottom of Heliport stopbank.
- Havill's: This stopbank has minimal to no freeboard, and requires raising.

14. APPENDIX C – RISK ASSESSMENT DETAILS

14.1. GLACIER ROAD (CALLERY JUNCTION TO SH6 BRIDGE) - SOUTH



The Glacier Road between the Callery junction and the SH6 bridge provides significant *flood* protection for the southern *fan* surface, all the way to the downstream end of the Waiho Flat. The road has been built on low lying riverbank, and if overtopped would see floodwaters flow over the southern approach to the SH6 bridge, in behind the Waka Kotahi stopbanks (SH6 bridge to Canavan's Knob) and across the southern *fan* surface.

Rough modelling of this overtopping scenario using the LRS hydraulic model with a 2,500 m^3/s flow and 2 m of aggradation between the Callery junction and the downstream end of the Heliport stopbank, results in only a small amount of floodwater overtopping the road and flowing across the southern floodplain (Figure 14-1). Further modelling of this scenario with additional levels aggradation should be completed.

Upgrade: There are two upgrade options that would reduce the current *risk* rating of this road, including raising the road, and / or a diversion of Wombat Ck which would cut off the overflow path to the southern *fan* surface.

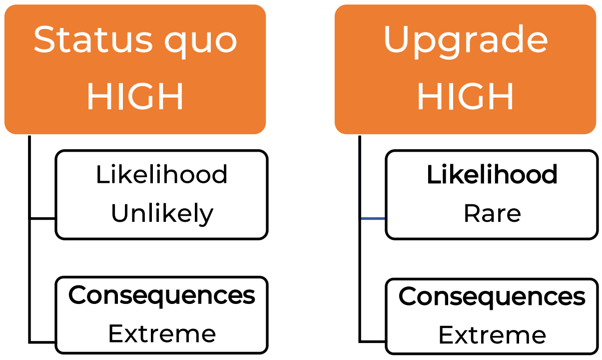
Presently allocated *IRG* funding includes an allowance to lift the downstream end of the Glacier Road. The exact timing of this work is not presently clear. However, this funding may be better allocated to a localised lift near the SH6 bridge and diversion of Wombat Creek. Regardless, the current and residual *risk* after treatment will be the same.

***Consequence* of overtopping:**

- Damage and possibly severance of the only through road (SH6) in Westland, and only road to the Upper Waiho valley (and Franz Josef glacier).
- Loss of life and/or injury if there are pedestrians/vehicles on the road during the *breach* and if residents and visitors in the modelled *flood* extent area are not evacuated before the *breach* occurs.
- Damage and/or loss of homes, buildings, and other infrastructure.
- Damage to farmland and fencing.
- Significant cost and time to retrain the river back into its current confines, rebuild the stopbanks, repair SH6, and repair/replace belongings, homes, stock, and other infrastructure.
- Loss of revenue to the community and region as there would likely be a reduction in tourist numbers whilst the road is being repaired.

***Risk* Rating**

Failure scenario: overtopping failure leading to outflow onto the southern *floodplain*.



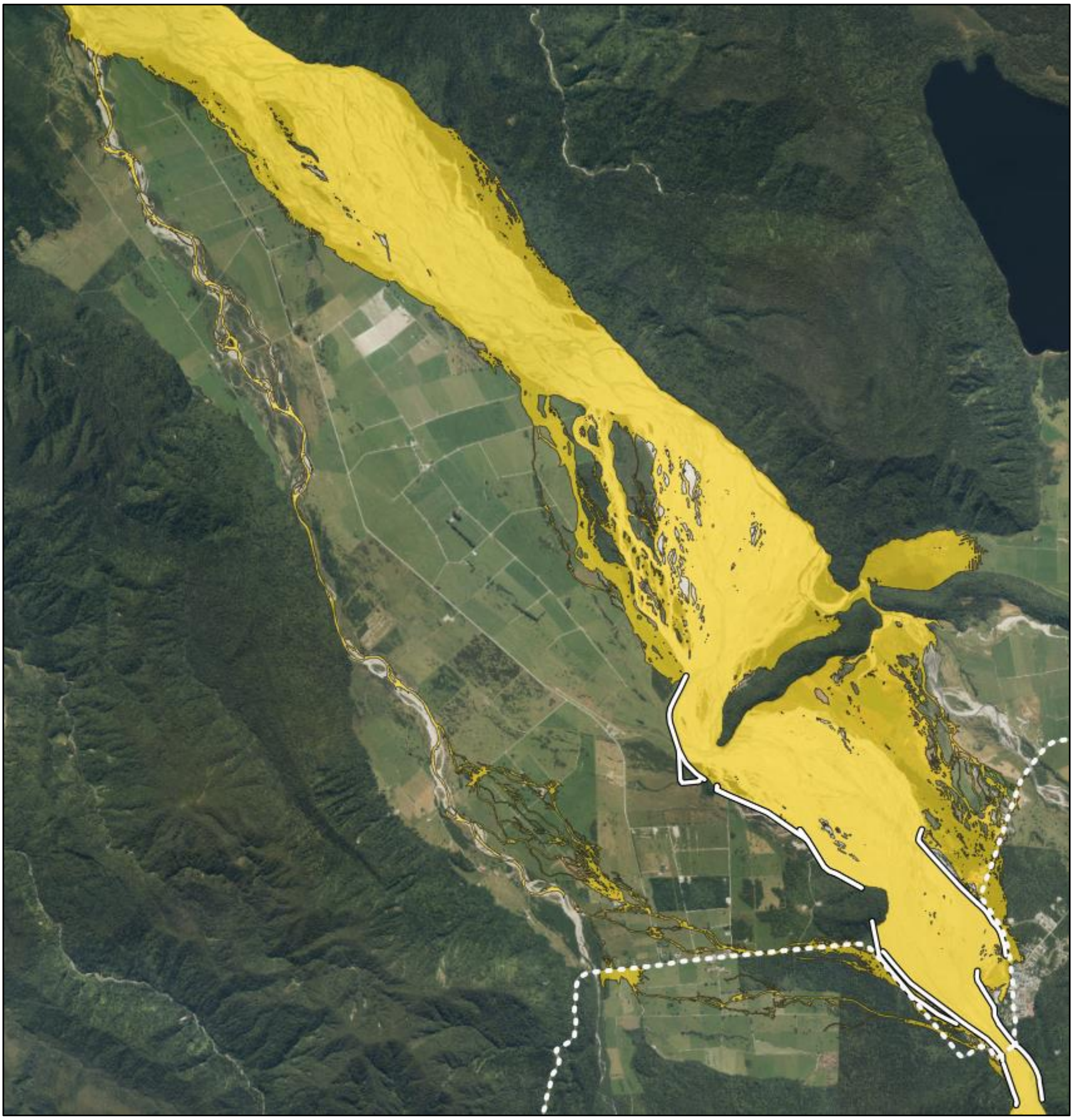
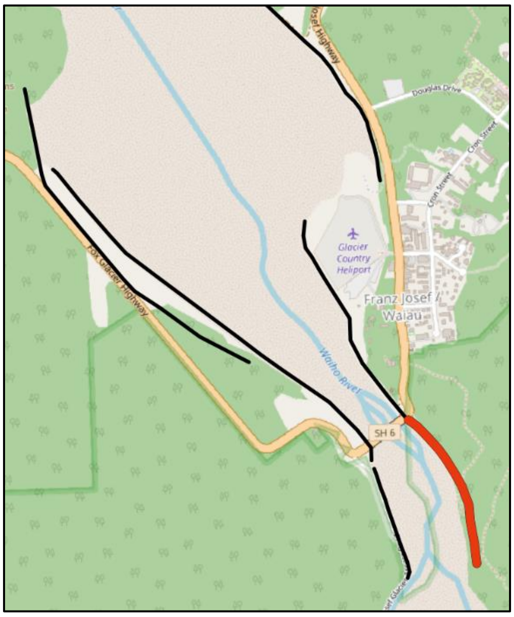


Figure 14-1 - Example of a *flood* extent across the southern floodplain (and to the north) and downstream area from a 2,500 m^3/s flow with 2 m of *aggradation* between the Callery junction and the downstream end of the Heliport *stopbank*. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.2. UPSTREAM OF THE SH6 BRIDGE - NORTH



The northern bank upstream of the SH6 bridge is a vegetated terrace composed of river sediments, and partially protected by rock revetments and groynes. The terrace represents a flow path the Waiho River (pre-European settlement) would have taken whilst building a higher *alluvial fan* surface than the present one.

In its current state, the riverbed in this adjacent *reach* is approximately 10 m below the top of the terrace. It has been hypothesised that the long term aggradational trend and short term fluctuations of the riverbed, could lead to a *flood* event overtopping this terrace, with considerable consequences for the Franz Josef township (Hall, 2012). Modelling of this *reach* with 4 m of *aggradation* and the overtopping path to the south blocked off, does result in flooding of the township, with inundation depths largely less than 0.25m, and in a few places up to 0.5m but no deeper. However, the modelling uses a fixed bed, so does not allow for scouring and therefore the overflow channel cannot develop further, and new channels cannot form. Additionally, this area is covered by thick vegetation which would have been difficult for the LiDAR to penetrate and provide accurate ground measurements for the existing channels. Therefore, given the potential for a *flood* path to become significant and for loss of life and damage to homes, businesses, and other infrastructure, we have taken a conservative approach for this *risk* assessment, and assumed consequences of overtopping to be extreme.

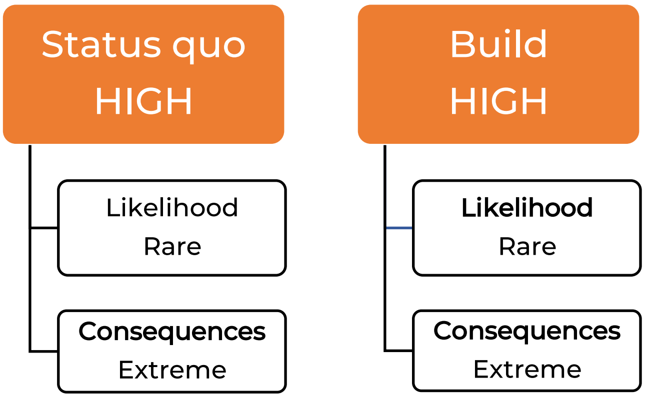
Build: should the *risk* of this overflow path being activated and flooding the town warrant action, then this riverbank could be protected. This would involve construction of a new *stopbank* on the terrace and necessary rock protection in front. However, ultimately, this would not change the *risk* rating to the bank, as the riverbed in this *reach* will continue to aggrade, and the consequences of *breach* or overtopping of any protection would still be extreme.

Consequences of overtopping:

- Damage to homes and other buildings within and to the north of the Franz Josef township.
- Inundation of SH6 to the north of the Waiho River, and the oxidation ponds.
- Injury and/or loss of life if the town is not evacuated prior to the overtopping.
- Cost of repairing and/or replacing belongings, homes, businesses, and other infrastructure.

***Risk* Rating**

Failure scenario: overtopping of the existing natural bank and floodwaters entering the town, assuming no relief from flow to the south above the SH6 bridge and with at least 4m *aggradation* in the adjacent river *reach*.



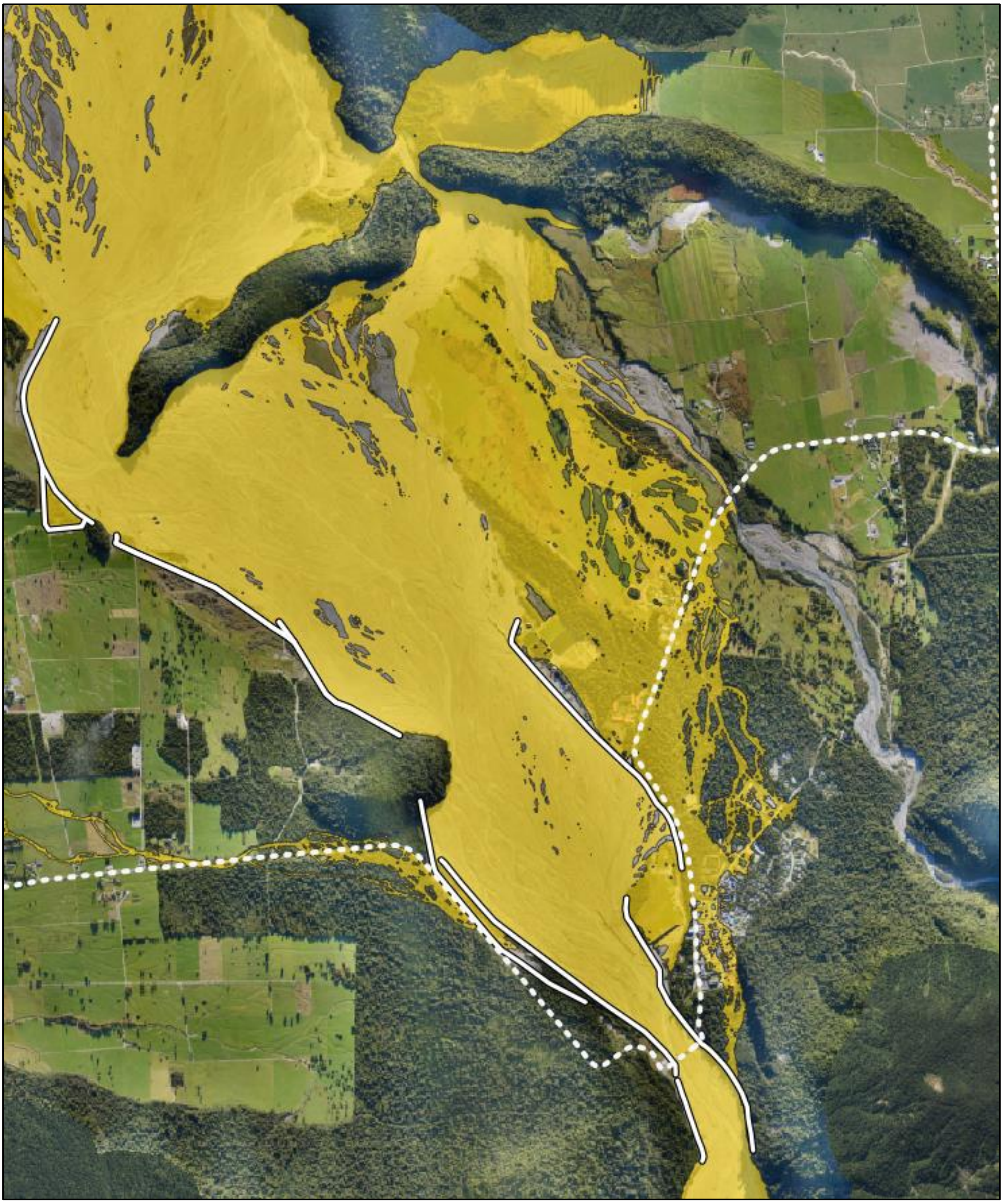
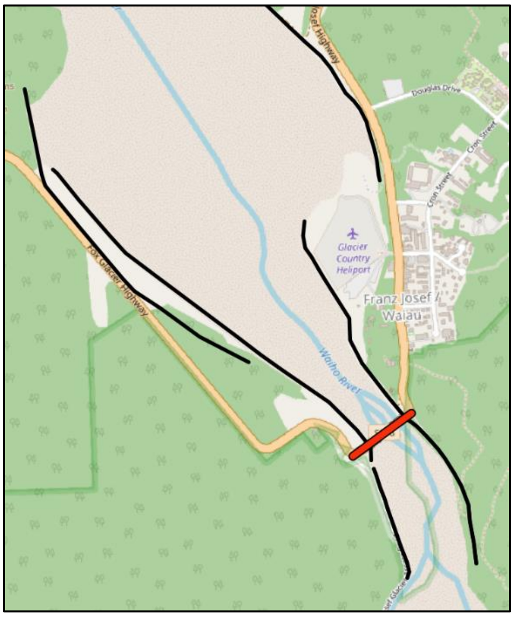


Figure 14-2 – Example *flood* extent through the Franz Josef township and downstream area from a 2,500 m^3/s flow with 4m of *aggradation* between the Callery junction and the downstream end of the Heliport *stopbank*. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.3. SH6 BRIDGE OVER THE WAIHO RIVER



The present SH6 Bailey bridge over the Waiho River provides adaptability in the response to the long term aggradational trend and short term fluctuations of the bed level, widening channel, and changing channel alignment through this *reach*. It is likely that this type of bridge will remain at the site until there is certainty on future river behaviour that is able to be addressed with a more permanent structure.

However, this bridge is vulnerable to damage. In order to protect the bridge approaches on both sides of the river, and maintain river flow under the bridge, Waka Kotahi have installed and manage rock protection works upstream of the bridge on both banks. These works include a revetment around both bridge abutments, a revetment and three groynes on the northside, and six groynes on the south side extending upstream to the Callery junction (the confluence of the Callery River with the Waiho).

Despite similar, but lower standard protection, and a testament to the power of the Waiho River, the northern approach has been severely damaged twice, in 1995 and 2019. During the March 2019 *flood*, the high flows also severely damaged the bridge and a full replacement (at the same level for expediency) was required.

In its present state, failure of this bridge due to overtopping and/or damage is likely within a 10-year period, and a *risk* analysis has been completed under the 'status quo' and 'upgrade' scenarios. The failure *likelihood* is primarily driven by an expected 2 m+ bed level *aggradation* during this period.

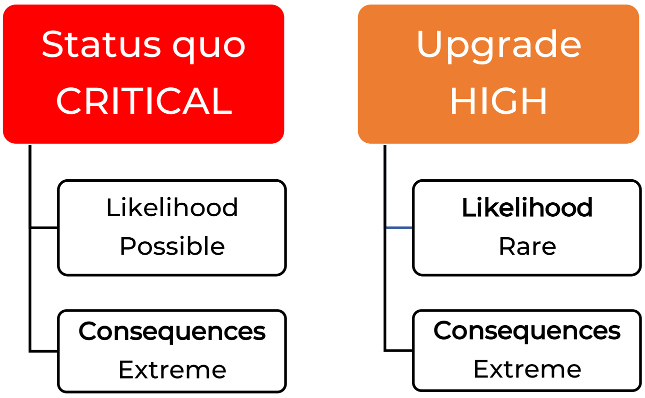
Upgrade: An upgrade of the SH6 bridge would involve lifting the bridge (and the approaches) to create more space between the riverbed and the soffit, and therefore more *capacity* for flow and the long term aggradational trend of the bed. However, ultimately, with time, this upgrade will have the same *risk* rating as the status quo option, as the riverbed will continue to aggrade. Therefore the *risk* is best managed through active monitoring, maintenance, and lifting as required.

Consequences of damage or failure:

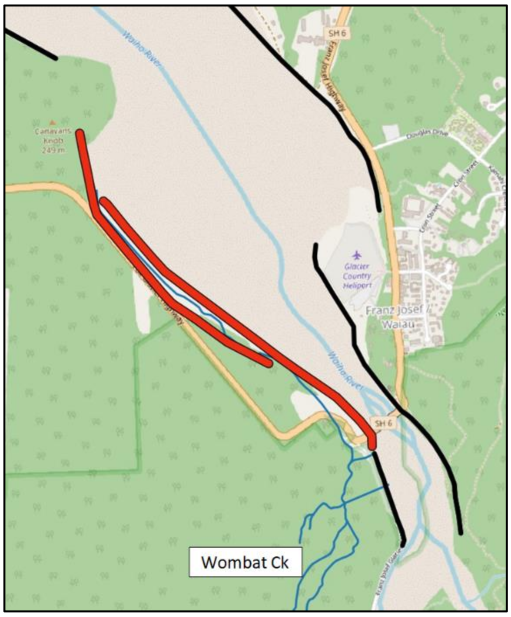
- Severance and or damage to the only through road (SH6) in Westland.
- Injury and/or loss of life if there are pedestrians or vehicles using the bridge during the time over overtopping/damage.
- Significant cost to repair, in addition to loss of revenue to community and surrounding region during repair.
- Loss of revenue to the community and region as there would likely be a reduction in tourist numbers whilst the bridge is being repaired.

Risk Rating

Failure scenario: very high flow and/or sudden landslide-dam/earthquake/*flood* induced *aggradation* resulting in overtopping and/or damage to the bridge and/or its approaches.



14.4. WAKA KOTAHI STOPBANKS – SOUTH



The Waka Kotahi stopbanks extend from the SH6 bridge to Canavan's Knob, and from Canavan's Knob back upstream, with Wombat Creek flowing between them and discharging into the Waiho River.

These banks provide immediate protection for SH6 which runs along the south side of the Waiho River between the SH6 bridge and Canavan's Knob. Importantly they also provide protection from any potential river outflows between the SH6 bridge and Canavan's Knob to most, if not all, of the southern *fan* surface, all the way to the downstream end of Waiho Flat.

Waka Kotahi maintain these stopbanks solely to ensure an appropriate level of service for SH6 users. These stopbanks and other monitoring and road closure mechanisms are used to manage road user *risk* to an appropriate level.

These stopbanks were last raised and widened in 2019/20 in response to the March 2019 *flood* event. Most of the length of the two stopbanks was lifted nominally by 1 m based on 2019 *flood* levels and LiDAR survey. However, the downstream end of the *stopbank* joining to Canavan's Knob, was widened substantially, and lifted by between 2 and 4 m in response to significant riverbed *aggradation* in that area. The lifting undertaken is expected to address the overtopping and possibly also minor riverside / *stopbank* leakage near the downstream end that was experienced in the 2019 *flood* event.

However, given the reduction in *capacity* that has already occurred since the 2019/20 upgrade as a result of *aggradation* in this upper *fan reach* over the last four years, the ongoing and likely increasing rate of *aggradation*, and the fact that these stopbanks are unlined save for fifteen rock groynes spaced at approximately 80 m intervals over most of the bank length (but also 620 m of continuous rock riprap at the upstream end), there is potential for these stopbanks to be overtopped and/or breached, resulting in significant inundation of SH6, residential buildings, other infrastructure, and farmland to the south of the river.

Upgrade: As part of the *IRG* funded Stage 1 plans, these two stopbanks will be raised a further 2 m, and widened. However, continuing to raise both these stopbanks will become untenable. The stopbanks are penned in by the river and SH6, and must allow enough space for Wombat Creek to flow between them. Therefore there is very little space to widen them, which restricts how much higher they can be raised. *Cost of upgrade: $5 M+*

Build: Realign Wombat Creek, join the two stopbanks near the downstream end and then lift only the joined riverside bank. *Cost of build: $3 M+*

Relax: Since European settlement the Waiho River has flowed at least twice to the south upstream of Canavan's Knob. The first time in 1947 when there were no protection measures in place, and the second time in 1982 when there were (WCRC, 2014). Additionally, during the March 2019 event, floodwaters leaked through these two stopbanks and also overtopped the outer bank, inundating SH6.

The relax option for the Waka Kotahi stopbanks, involves:

- Buying out and clearing the land to the south of the Waka Kotahi stopbanks and all the way to the downstream end of the Waiho Flat.
- Realigning SH6.
- Removing the Waka Kotahi stopbanks

Cost: *$100M+ (equivalent to the all-up costs of about two multi-week bridge closures)*

Consequences of failure:

- Damage and likely severance of the only through road (SH6) in Westland to the south of the Waiho River.
- Loss of life and/or injury if there are pedestrians/vehicles on the road during the *breach* and if residents and visitors in the modelled *flood* extent area are not evacuated before the *breach* occurs.
  Two *flood* extents are shown in Figure 14-3 and Figure 14-4, with breaches at the upper and lower end of the Waka Kotahi stopbanks, respectively.
- Damage and/or loss of homes, buildings, and other infrastructure.
- Damage to farmland and fencing.
- Significant cost and time to retrain the river back into its current confines, rebuild the stopbanks, repair SH6, and repair/replace belongings, homes, stock, and other infrastructure.
- Loss of revenue to the community and region as there would likely be a reduction in tourist numbers whilst the road is being repaired.

***Risk* Rating**

Failure scenario: overtopping failure leading to outflow onto the southern *floodplain* / side of the *alluvial fan*.

Status quo CRITICAL	Upgrade HIGH	Build HIGH	Relax LOW
Likelihood Likely	**Likelihood** Unlikely	**Likelihood** Unlikely	**Likelihood** Certain
Consequences Extreme	**Consequences** Extreme	**Consequence** Extreme	**Consequences** Insignificant

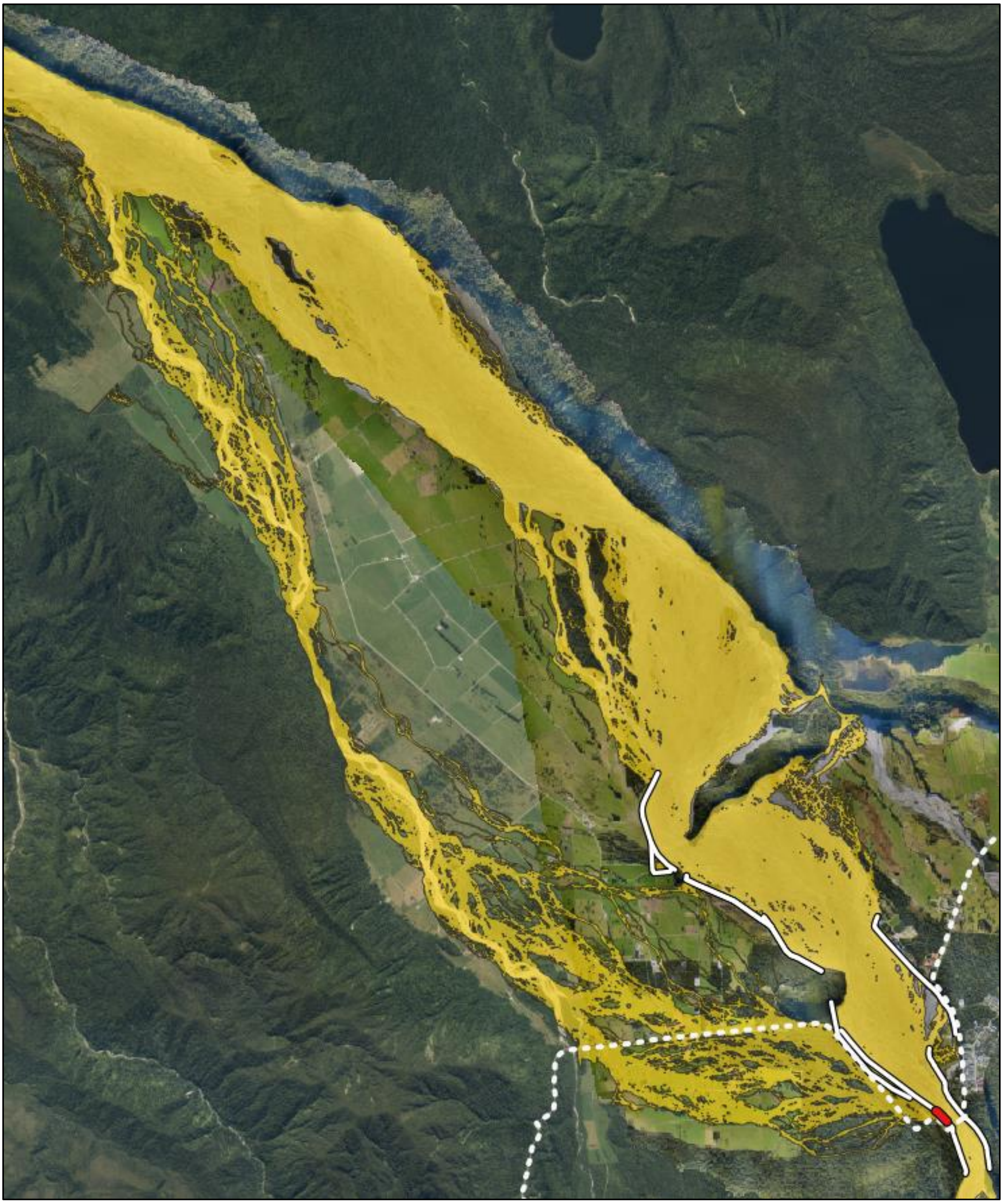


Figure 14-3 – Example of a 2,500 m³/s *flood* extent from a *breach* of the south side Waka Kotahi stopbanks, immediately downstream of the SH6 bridge using the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

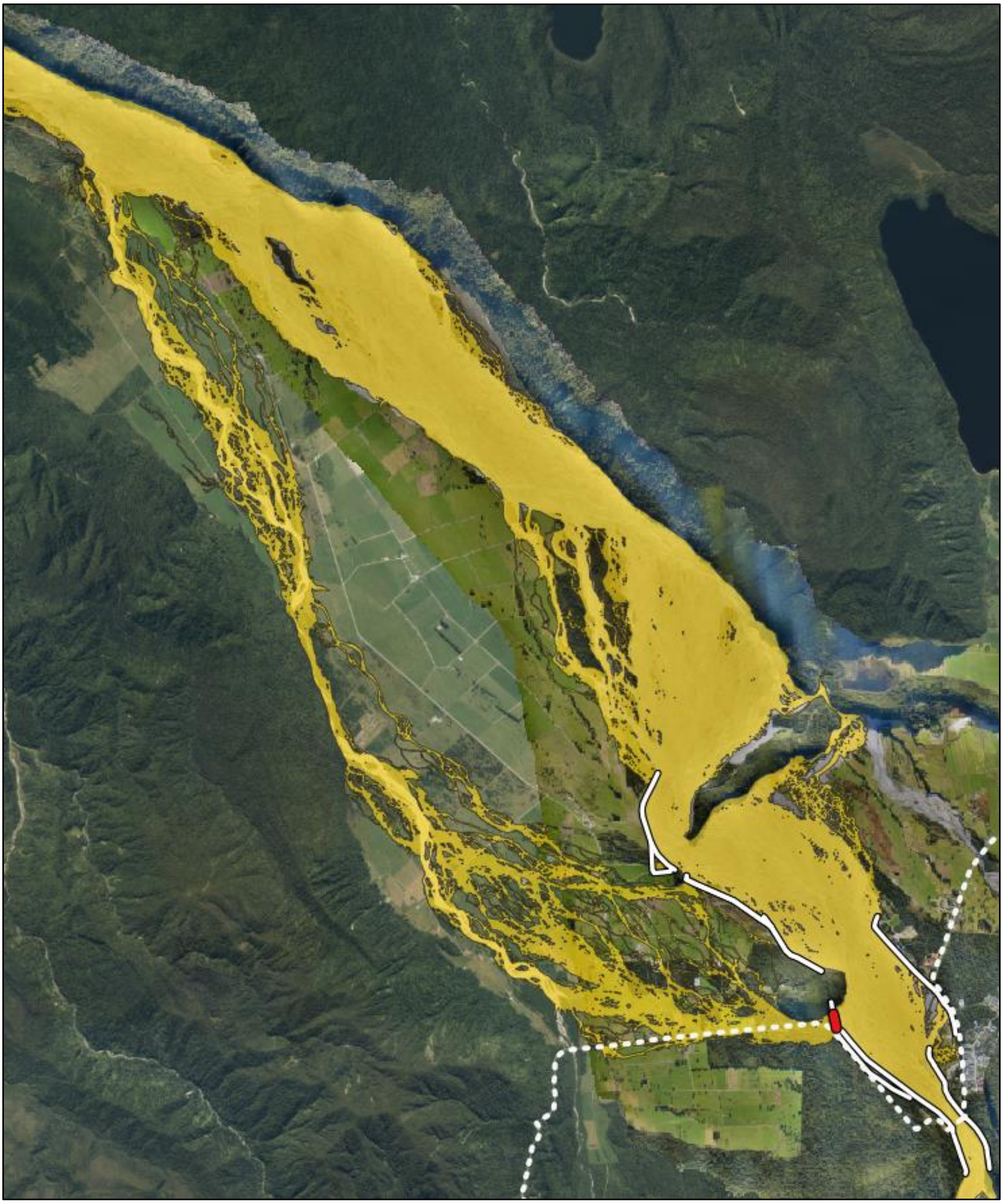
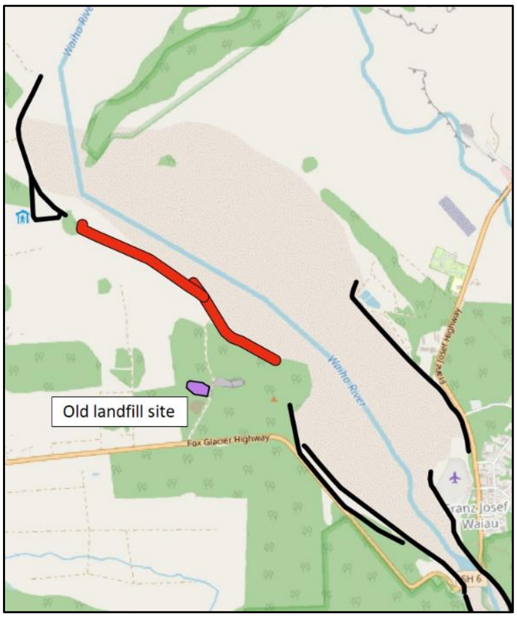


Figure 14-4 – Example of a 2,500 m³/s *flood* extent from a *breach* of the south side Waka Kotahi stopbanks just upstream of Canavan's Knob using the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.5. RUBBISH DUMP STOPBANK – SOUTH



The Rubbish Dump *stopbank* runs from the downstream side of Canavan's Knob to Rata Knoll where it ties into Milton's *stopbank*. This *stopbank* has been designed to protect the Waiho Flat farms from overflows of the Waiho River, however, in its initial design, it was unlined. Thus, with the increased channel activity, and aggrading river bed, sections have been eroded. In these locations, the repair involves rock lining. However, this does not treat the rapidly reducing *capacity* of flows this bank was designed for.

Upgrade: Raise and improve the protection (continuous rock lining) under the assumption of a relatively low standard of bank based on the affordability of the rating district.

Relax: Remove this *stopbank* and the downstream Milton's *stopbank*.

Consequences of failure:

- Damage to any roads, homes, other buildings, and farming infrastructure in the *flood* path from *breach* to Docherty Creek. An example of a *flood* path is shown in Figure 14-5.
- Injury and / or loss of life if the Waiho Flat is not evacuated in time.
- Loss of stock if they haven't been shifted out of harm's way.
- Cost and time to retrain the river, and repair and / or replace what has been damaged or destroyed.

***Risk* Rating**

Failure Scenario: breakout of the river across the Waiho Flat.

Status quo CRITICAL	Upgrade HIGH	Relax LOW
Likelihood: Almost certain	**Likelihood**: Possible	**Likelihood**: Certain
Consequences: Severe	**Consequences**: Severe	**Consequences**: Insignificant

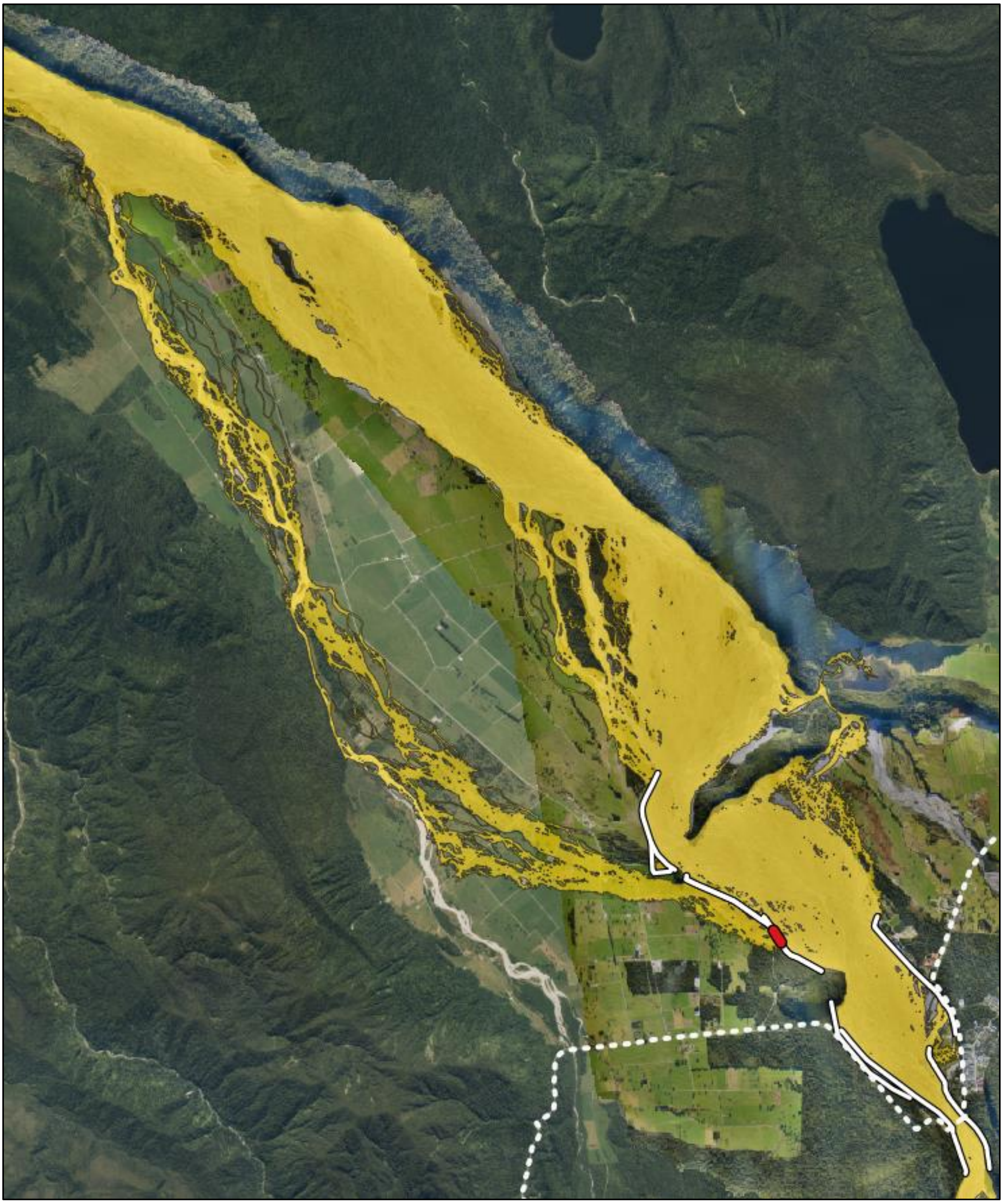


Figure 14-5 – Example of a 2,500 m^3/s *flood* extent from a *breach* of Rubbish Dump *stopbank* on the south side using the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.6. MILTON'S STOPBANK – SOUTH

The tightly confining Milton's *stopbank* extends downstream of Rata Knoll, and confines the Waiho River to an approximately 330m (at its narrowest) wide corridor against the southern end of the Waiho Loop. This corridor is the only throughway (excluding the developing *avulsion* into the Tatare) for the Waiho River to *reach* the sea, and therefore must allow (and contain) the full volume of the Waiho River when in *flood*. This is a significant ask for any *stopbank*, however even more so, when the *stopbank* must force the river to make a greater than 90 degree turn so as to protect the lower Waiho Flat.

Furthermore, in its current condition, the Milton's *stopbank* is very vulnerable to the river conditions it is exposed to:

- The lack of *toe embedment* of the rock lining provides minimal protection against the high potential for scour.
- The rock linings have not been constructed in line with industry best practice, and are therefore at *risk* of breaking open when undermined.

Upgrade: Rebuild rock protection ($1 M+)

Build: Rebuild the *stopbank* but relocate it back from the present river bed to provide more room for the river to flow through ($5 M+).

Relax: Like the Waka Kotahi stopbanks above Canavan's Knob, Milton's *stopbank* has been breached on a number of occasions which include the 1967, 1982 and 2019 floods. In these events, floodwaters spread out between the (breached) *stopbank* and Docherty Creek, inundating the lower Waiho Flat *floodplain*, as they would have done prior to the *stopbank* being built.

These breaches have occurred because the Milton's *stopbank* does not facilitate natural river channel behaviour, as described above. As a result, significant pressure from the river flow is placed upon this *stopbank*, scouring it along the toe, and increasing the chance of failure.

The relax option for Milton's *stopbank*, involves:

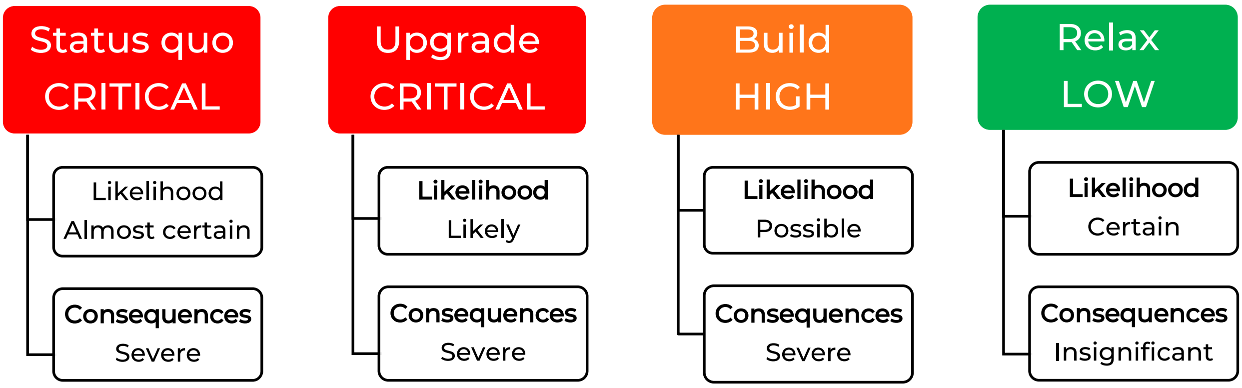
- Buying out and clearing the land to the south of Milton's *stopbank* all the way to the downstream end of the Waiho Flat.
- Removing Milton's *stopbank*.
- Cost: $30 – 50 M

Consequences of failure:

- Damage to the airstrip and any roads, homes, other buildings, and farming infrastructure in the *flood* path from the *breach* to Docherty Creek. An example of a flow path is shown in Figure 14-6.
- Injury and / or loss of life if the Waiho Flat is not evacuated in time.
- Loss of stock if they haven't been shifted out of harm's way.
- Cost and time to retrain the river, and repair and / or replace what has been damaged or destroyed.

***Risk* Rating**

Failure Scenario: catastrophic failure and breakout of the river across the Waiho Flat.



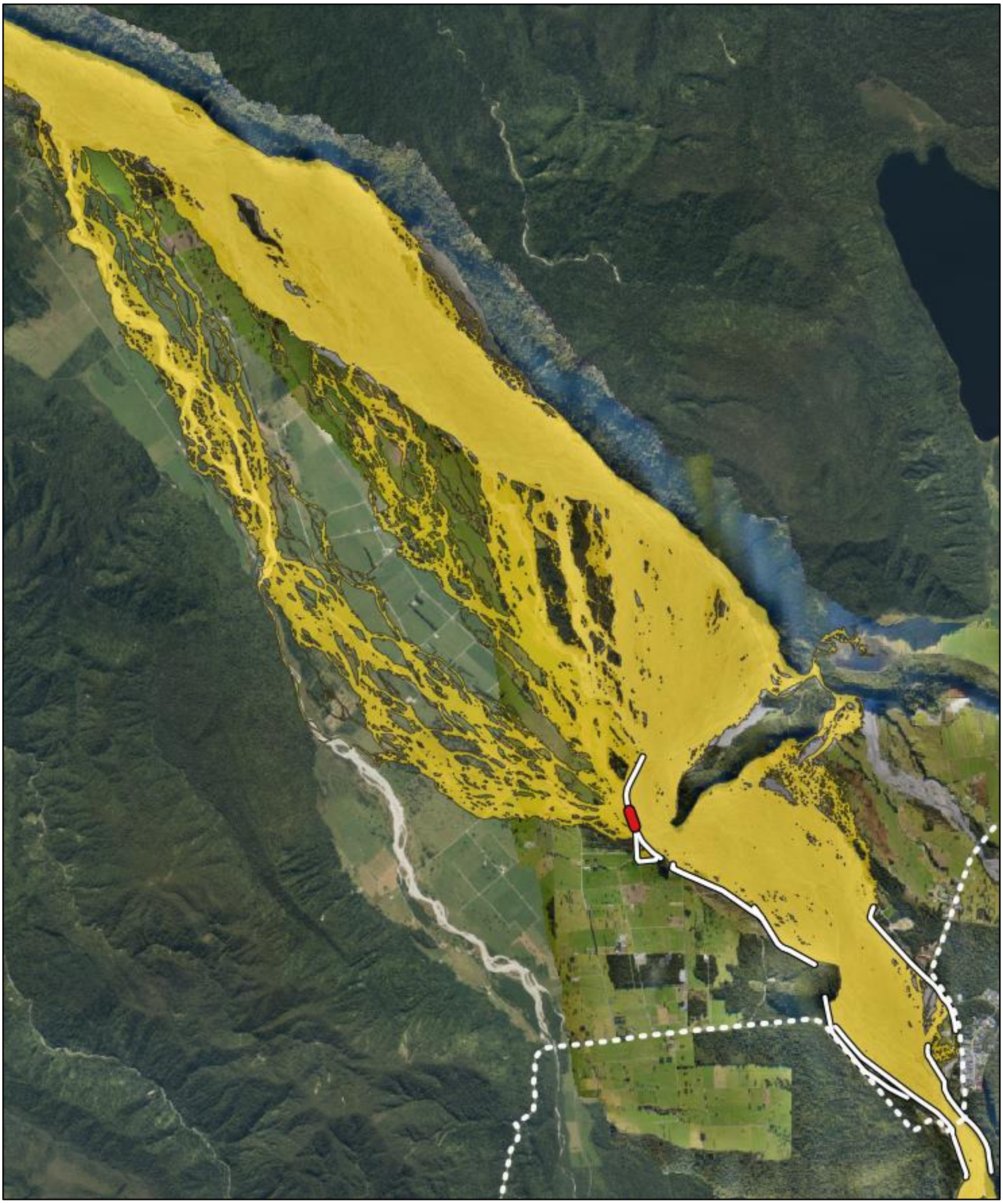


Figure 14-6 – Example of a 2,500 m^3/s *flood* extent from a *breach* (red) of Milton's *stopbank* on the south side using the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.7. DOWNSTREAM OF MILTON’S STOPBANK – SOUTH

Downstream of Milton’s *stopbank* is unprotected riverbank that is actively being eroded over time. If and when floodwaters *overtop* this bank, they erode the farmland carving out channels across it, as well as depositing sediment and gravels which reduces the quality of the pasture for stock. There are also a number of properties downstream of Milton’s *stopbank* which could be affected by floodwaters overtopping this unprotected section of riverbank. Note that increasing flow through the Tatare gorge in the Waiho Loop, due to the developing *avulsion* path from the Waiho into the Tatare upstream of the Loop, will increase the tendency of the Waiho to flow towards the southern side of its lower valley.

Build: Containment banks with some rock lining as and where required ($2 – 5 M).

Consequences of overtopping:

- Damage to any roads, homes, other buildings, and farming infrastructure in the *flood* path. An example of the *flood* extent of a 100yr *ARI flood* with no upstream breaches is shown in Figure 14-7.
- Injury and / or loss of life if the Lower Waiho Flat is not evacuated in time.
- Loss of stock if they haven’t been shifted out of harm’s way.
- Cost and time to retrain the river, and repair and / or replace what has been damaged or destroyed.

***Risk* Rating**

Failure Scenario: breakout of the river across farmland

Status quo HIGH	Build MEDIUM
Likelihood: Likely	**Likelihood**: Possible
Consequences: Moderate	**Consequences**: Moderate

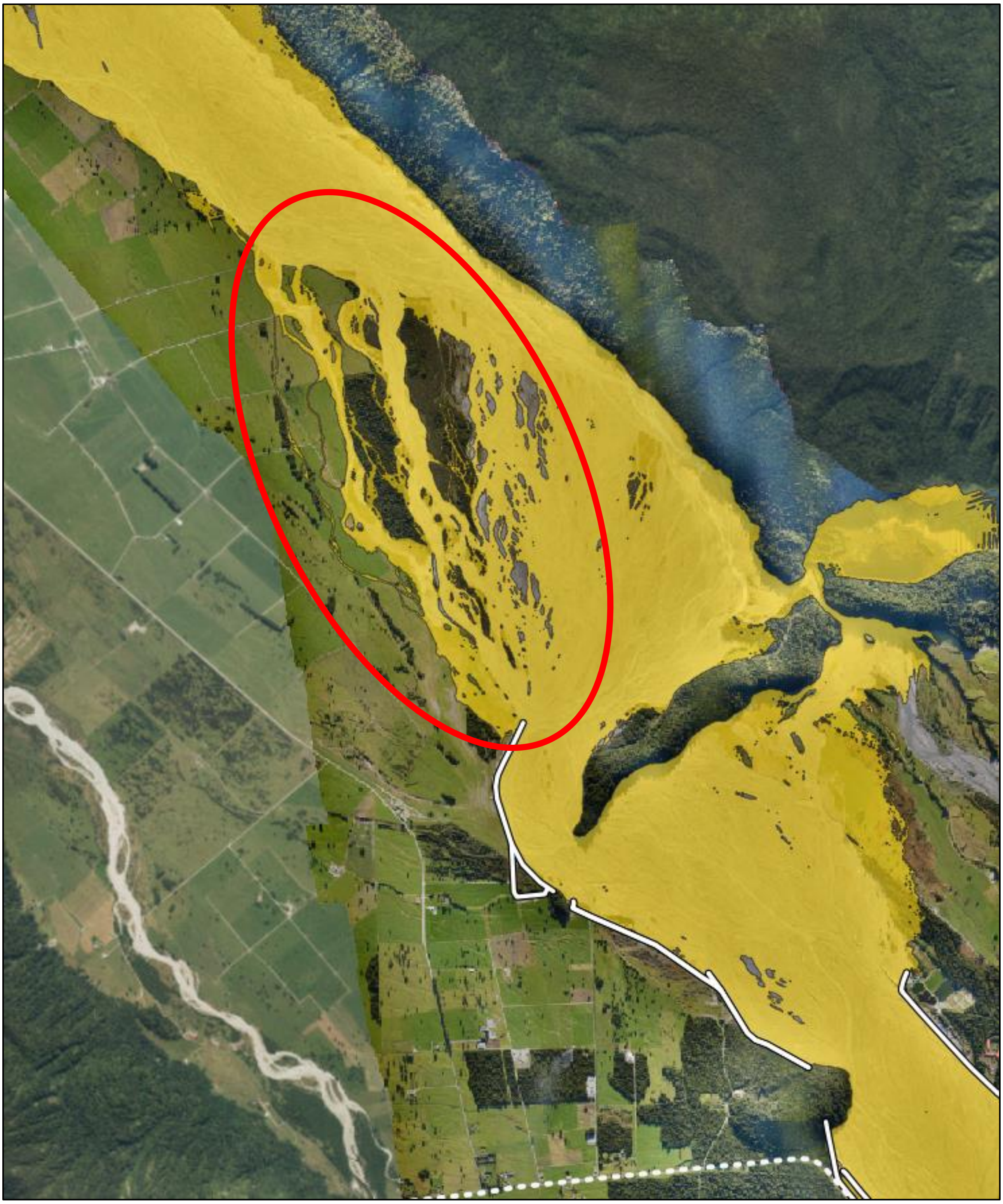
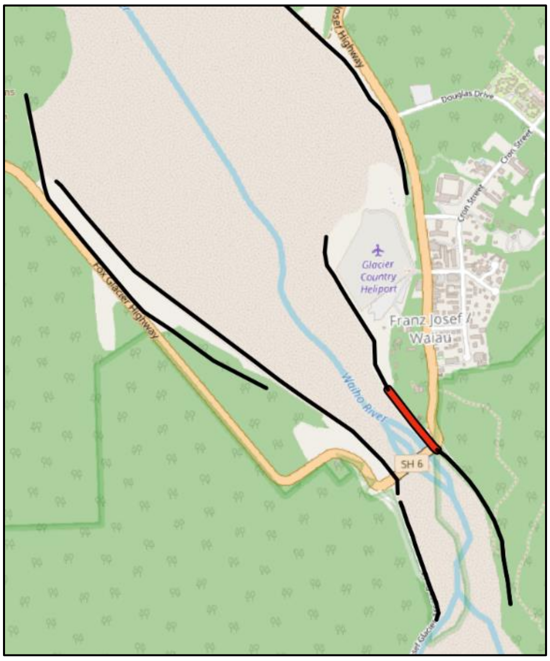


Figure 14-7 – Example of a 2,500 m^3/s *flood* extent downstream of Milton's *stopbank*, with a 100yr *ARI* flow and no upstream breaches using the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.8. CHURCH STOPBANK – NORTH



The Church *stopbank* is on the northern bank and extends from the SH6 bridge along the natural river terrace to where it ties into the Heliport *stopbank*. The top end of this *stopbank* has suffered considerable damage, though not breached, during the 1995 and 2019 *flood* events when the SH6 approach and bridge were damaged.

The following *risk* assessments assume that the *stopbank* extends downstream past the natural terrace where there are much lower ground levels and ancient channels on the landward side, on which there are at least four houses. Upstream of this, as a result of the height of the natural terrace, the *risk* is much lower.

Upgrade: This *stopbank*, along with most of the protection scheme has had plans approved to raise it to improve its design *capacity*.

Consequences of failure:

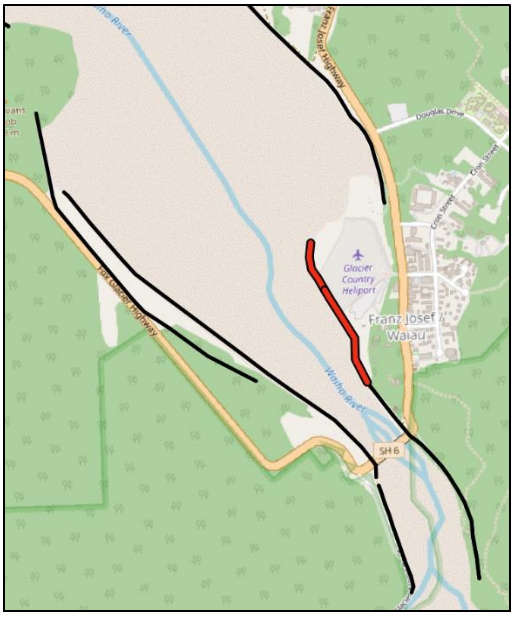
- Damage to the bridge and northern approach, and therefore possibly severance of the only through road (SH6) in Westland.
- Damage to the Heliport and any other infrastructure in its vicinity, and houses.
- SH6 and oxidation ponds inundated.
- Injury and/or loss of life if there are pedestrians or vehicles on the SH6 bridge, the road between the bridge and Franz Josef township, at the Heliport or in the adjacent houses.
- Significant cost and time to repair the approach, *stopbank*, SH6 and Heliport and other infrastructure.

***Risk* Rating**

Failure Scenario: *breach* of the *stopbank* resulting in damage to the heliport, SH6 (and potentially bridge) and part of the township (assumed).

Status quo CRITICAL	Upgrade CRITICAL
Likelihood: Likely	**Likelihood**: Possible
Consequences: Extreme	**Consequences**: Extreme

14.9. HELIPORT STOPBANK – NORTH



The Heliport *stopbank* was constructed in 1991, after in 1990 engineers decided to abandon the major northern *stopbank* (designed to protect the airstrip and hotel between 1968 and 1989) due to the ongoing *aggradation* and dynamic behaviour of the Waiho River.

In aerial imagery from 1997, the Heliport *stopbank* sticks out into the middle of the river bed with active gravels on either side of it, and the main braid running immediately beside it (Figure 3-6). In 2014, this *stopbank* was extended downstream to provide greater protection to the heliport.

Upgrade: This *stopbank*, along with most of the protection scheme has had plans approved to raise it to improve its design *capacity* – construction has actually already started.

Consequences of failure

- Catastrophic damage to the Heliport and any other infrastructure in its vicinity, houses and the downstream side of the township.
- SH6 and oxidation ponds inundated.
- Injury and/or loss of life if there are pedestrians or vehicles on the SH6 between the Waiho River and Tatare Stream, or at the Heliport.
- Significant cost and time to retrain the river back within its current confines and to repair the *stopbank*, SH6, Heliport and other infrastructure.

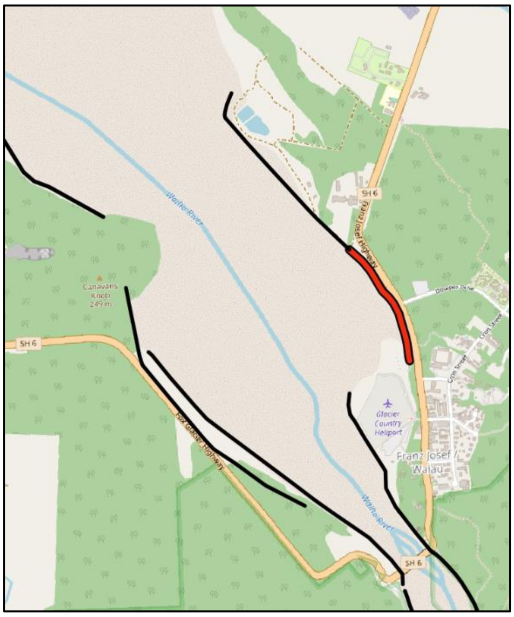
***Risk* Rating**

Failure Scenario: *breach* of the *stopbank* resulting in damage to the heliport, SH6, and part of the township.

Status quo CRITICAL	Upgrade CRITICAL
Likelihood: Likely	**Likelihood:** Possible
Consequences: Extreme	**Consequences:** Extreme

Figure 14-8 - Example of a 2,500 m³/s *flood* extent from a *breach* of the Heliport *stopbank* from the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.10. 55KPH CORNER STOPBANK – NORTH



The 55kph corner *stopbank* was constructed between 2014 and 2016, and extends from the SH6 55kph corner (the top end of the Havill *stopbank*) to just downstream of Wallace Street. Its main objective is to protect SH6 that runs parallel to it, but also serves to protect the Scenic Circle Hotel property, oxidation ponds, Top 10 Holiday Park and Kids First from flooding.

Build: Rather than continue to maintain and upgrade the 55kph corner *stopbank*, plans have been approved and construction started for a link *stopbank*, which will connect the downstream end of the Heliport *stopbank* with the upstream end of Havill's *stopbank* (Figure 14-9 - Location of the Link bank (build option) shown in red.). This new *stopbank* will effectively follow the natural fall line of the *fan*, and is therefore unlikely to experience the impact of having flow directed straight towards it. However, it will also further reduce the area of *fan* surface available to the Waiho River. Cost of this is $5 M+.

Upgrade: if the upstream Church or Heliport stopbanks *breach* or *overtop*, *flood* flows will be able to enter the Franz Josef township and get around the upstream end of the 55kph Corner *stopbank*. To prevent this the 55kph Corner *stopbank* would need to be extended upstream following the natural river bank edge.

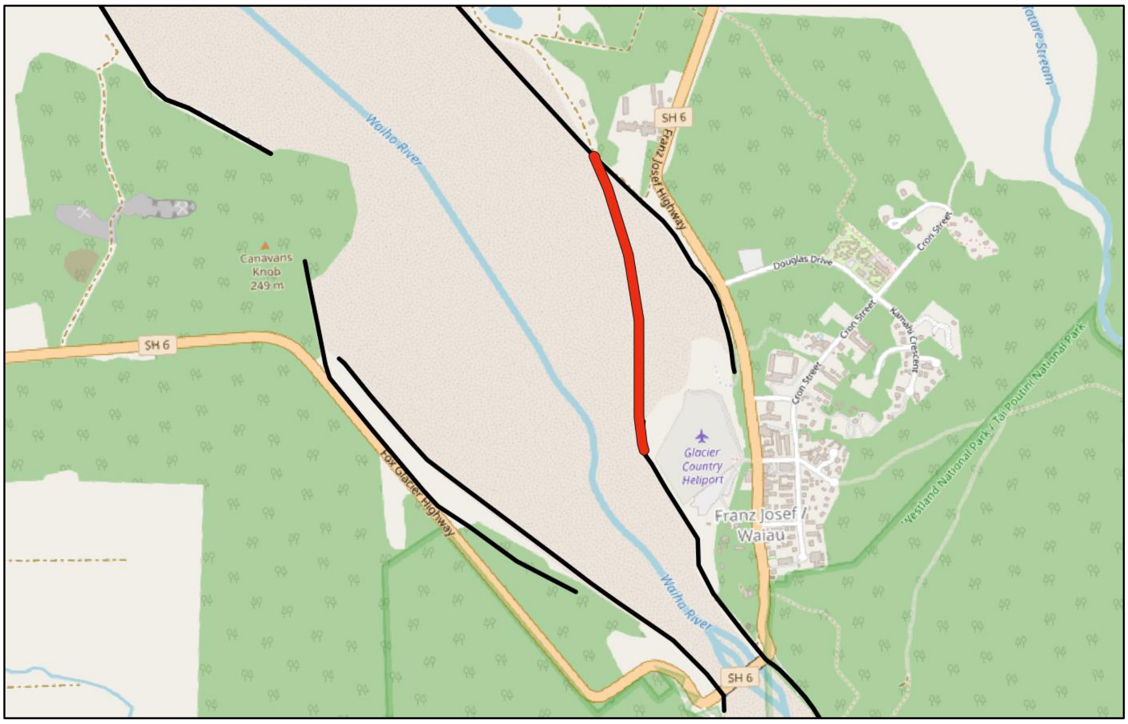


Figure 14-9 - Location of the Link bank (build option) shown in red.

Consequences of failure:

- Damage to the only through road (SH6) in Westland.
- Damage to the oxidation ponds and Scenic Circle Hotel site.
- Franz Josef Glacier school, Top 10 Holiday Park and other buildings inundated.
- Injury and / or loss of life if there are pedestrians or vehicles on the highway or at the oxidation ponds, or in the inundated buildings.
- Cost and time to retrain the river to within its current confines, repair the oxidation ponds and SH6, and replace / repair any *flood* damaged properties and buildings.
- Detrimental impact on the environment if the oxidation ponds are damaged beyond use and waste must be discharged into the Waiho River.
- Possible development of a channel into the Tatare Stream.

***Risk* Rating**

Failure Scenario: the *stopbank* breaches resulting in inundation of the SH6, Scenic Circle Hotel, Oxidation ponds, school, holiday park and other buildings and infrastructure.

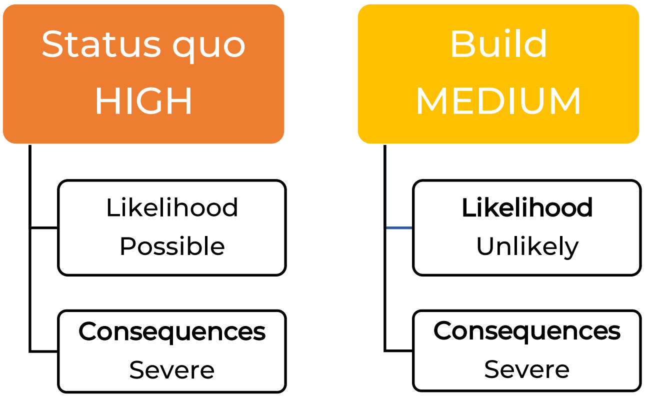
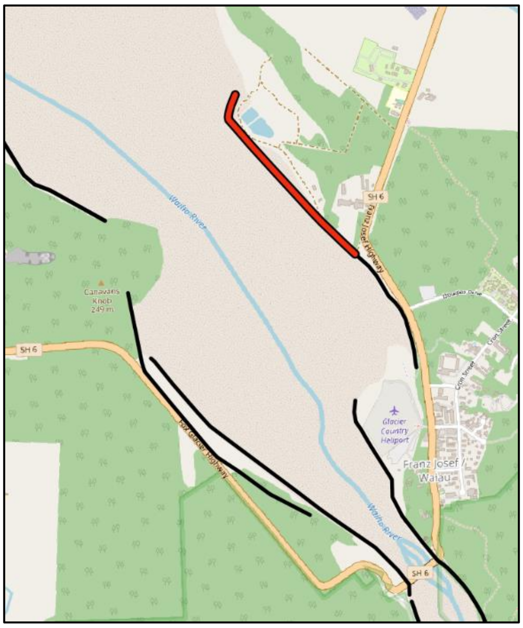


Figure 14-10 - Example of a 2,500 m^3/s *flood* extent from a *breach* of the 55kph corner NZTA *stopbank*, at the corner itself from the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.11. HAVILL'S STOPBANK – NORTH



The substantial rock lined Havill *stopbank* extends from the downstream end of the 55kph Corner *stopbank* to just below the oxidation ponds. It was built after the 2016 *flood* event breached the original (unlined) oxidation ponds access track *stopbank* and flooded the Scenic Circle Hotel and part of the Top 10 Holiday Park.

However, the depth of its toe is unknown, though believed to be inadequate for the high potential for scour in this location. Further, the ongoing *aggradation* has resulted in minimal to no *freeboard* in the section of this *stopbank* adjacent to the oxidation ponds for a 100 year *ARI* design flow.

Upgrade: The crest level of Havill's *stopbank* is raised as per planned, however, the toe is potentially still inadequate for the scour potential.

Consequences of failure:

- Destruction or damage of the oxidation ponds
- Detrimental impact on the environment if the oxidation ponds aren't able to function and biological waste must be discharged into the Waiho River.
- Significant cost and time to retrain the river back into its current confines and rebuild the *stopbank*, and to repair/replace the oxidation ponds.
- Possible development of a channel into the Tatare Stream.

***Risk* Rating**

Failure Scenario: the *stopbank* breaches or overtops during a *flood* event resulting in inundation of the oxidation ponds. This scenario does not account for the *avulsion*.

Status quo
HIGH

- Likelihood: Likely
- **Consequences**: Moderate

Upgrade
MEDIUM

- **Likelihood**: Unlikely
- **Consequences**: Moderate

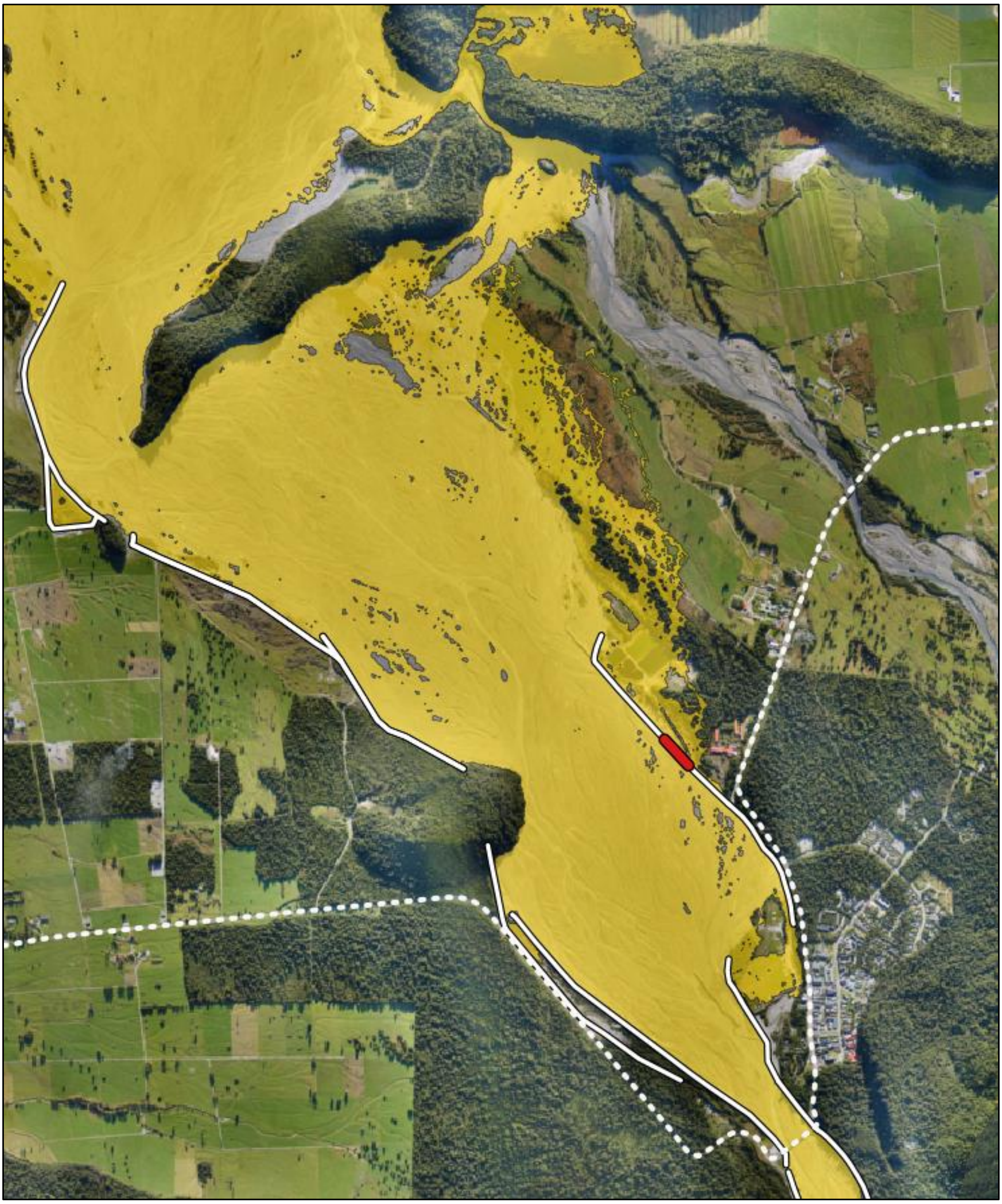
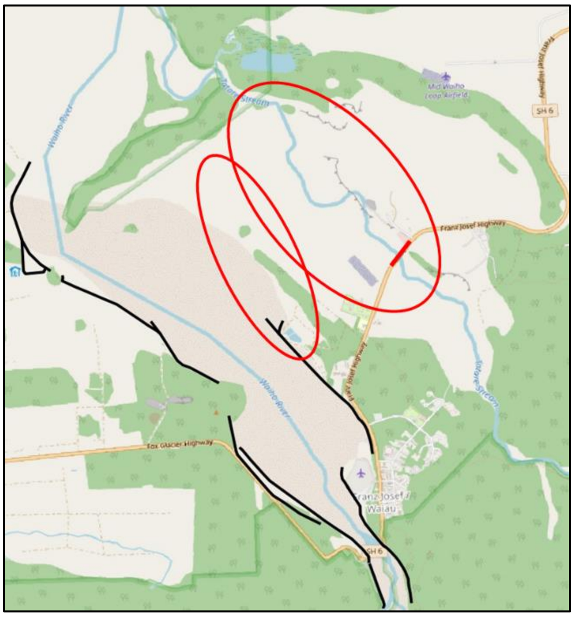


Figure 14-11 - Example of a 2,500 m^3/s *flood* extent of a *breach* of Havill's *stopbank* from the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.

14.12. AVULSION INTO THE TATARE STREAM



As the Waiho River *avulsion* into the Tatare stream continues to develop, it is likely that the Waiho River will increasingly occupy the Tatare Stream cut through the Waiho Loop into the future. However, Tatare flows are smaller than those of the Waiho, therefore the Tatare cut has naturally developed to manage smaller flows than what the additional flow of the Waiho will provide.

Therefore this additional flow will result in erosion of the cut walls and widening. However this will take considerable time, and in the foreseeable future is unlikely to create a wide enough corridor to handle the sediment and flow inputs from both rivers, particularly during a *flood* event. Thus, the cut through the Waiho Loop will continue to aggrade.

Given its smaller flow, it is unlikely that the Tatare Stream will be able to erode through the newly forming surface in the cut and upstream of the Waiho Loop. As a result of this elevated base level, the Tatare Stream bed will aggrade, infilling headwards, and be potentially significant at the SH6 bridge. The Tatare Stream itself will likely become more braided in nature with greater access to its *floodplain*, and as this infills, then its *fan* surface.

These changes in behaviour of stream and bed will have commensurate risks from flooding and erosion of its banks, which may result in loss of farmland, and settlements at lower Stoney Creek and Tatare and the existing SH6 bridge over the Tatare Stream becoming untenable.

Further, if the Waiho River cuts through the Tatare *fan* immediately downstream of the end of the Havill *stopbank*, the Tatare could aggrade much more quickly, especially with the additional input of sediment from its *fan* surface that will erode as the Waiho cuts down through it.

In addition, the developing channel between the Waiho and Tatare will continue to incise in an upstream direction, which may result in undercutting of the Havill *stopbank* and destruction of the oxidation ponds.

Build: Extra rock protection is added to the Havill *stopbank* to protect from the effects of the downstream developing *avulsion* ($15 M+).

Risk Rating

Failure scenario 1: the Tatare riverbed aggrades reducing the design *capacity* of the SH6 bridge and it is damaged or destroyed.

We have not provided a *risk* rating for this failure scenario, because this *risk* is difficult to assess due to the uncertainty of both the extent of effect and its timing. Morphological modelling is required to provide a better understanding of this *risk*, and we recommend that this be undertaken as soon as possible.

However, we have provided the *flood* extent of a 100 year *ARI* flow with no breaches anywhere in the network to show an example of an *avulsion* flow path and overland flow across the farmland (Figure 14-12).

Failure Scenario 2: the developing *avulsion* into the Tatare causes head-cutting in a single or series of events that results in undercutting and subsequent failure of the Havill *stopbank* and damage to the oxidation ponds.

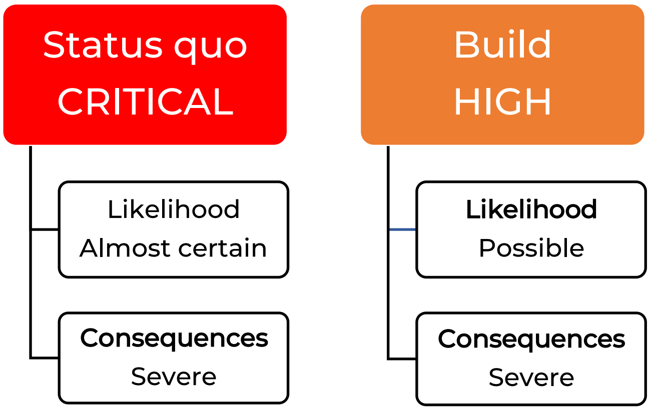


Figure 14-12 - Example of a 2,500 m^3/s *flood* extent across the *avulsion* path with a 100 year *ARI* flow and no breaches in the network from the LRS fixed bed 2D hydraulic model. The protection network is shown with the white lines, and SH6 by the dashed white line.