DAMWATCH
ENGINEERING BEYOND THE SURFACE

Dart-Rees Floodplain Adaptation - Report on 23-24 February 2022 Workshop

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Prepared for Otago Regional Council

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Executive Summary

Background

The floodplains and delta associated with the Dart and Rees Rivers at the head of Lake Wakatipu are subject to both flooding and erosion hazards which impact on the township of Glenorchy, and the wider communities of Kinloch and Greenstone through disruption of road access. The landscape scale geomorphic changes occurring in the area coupled with future climate change effects mean that these hazards are increasing over time.

The changing hazardscape is a strong influence on why and how the Otago Regional Council (ORC) and the Queenstown Lakes District Council (QLDC) are responding to these natural hazard issues. ORC are applying a Dynamic Adaptive Pathways Planning (DAPP) Approach as a framework for developing hazards adaptation pathways in this area. As part of the process of applying this approach, a floodplain adaptation workshop was held on 23-24 February 2022 which involved staff from both Councils as well as a small number of external technical experts. The workshop was intended to be a first-pass review of all possible flood mitigation and floodplain management options for the area, mainly focusing on engineering interventions (note though that this does not mean that non-engineering measures are not part of the DAPP Approach). The workshop also looked into the options put forward by the community at community workshops.

The floodplain adaptation workshop considered the flood and erosion hazard issues for three different locations as the issues are different for each location:

- Glenorchy and Lower Rees River floodplain – issue: flood hazard to residential and commercial activities;
- Kinloch Road - issue: flood hazard to access; and
- Rees Bridge and upstream right bank floodplain – Issue: flood hazard to access and to rural activities.

This report documents the proceedings and outcomes of the floodplain adaptation workshop. The conclusions presented below are outcomes from the workshop and should not be inferred to represent solely the views of the author of this report. The report is intended to inform further feedback from the community.

Glenorchy and Lower Rees River Floodplain

Due the perched nature of the Rees River, there are probably no viable long-term engineering / river management interventions to prevent flooding from the river at Glenorchy or the occurrence of an avulsion[1] event into the lagoon area. Therefore, the focus should be on preparing to manage the impacts of this inevitable event and / or mitigating those impacts or delaying the event occurrence.

In the immediate short term, this could involve:

- Flood warning improvements.
- Revision and communication of flood response procedures.
- Consideration of improvements to the existing stopbank (e.g. raising the crest profile, improving the structural quality and integrity).
- Investigation of vegetation planting on the left bank of the Rees River where flood breakouts into the lagoon area occur.

In medium or longer term, other strategies could be considered:

- Building-scale interventions (e.g. raising floor levels of existing buildings).
- Planning responses (e.g. preventing further intensification, setting a revised minimum floor level).
- Retreat of buildings in the highest-risk areas.

Planning for these possible medium or longer term strategies would need to start in the immediate short term.

It needs to be emphasised that any upgrade of the existing stopbank will be a short-term measure only. It should be communicated very clearly and carefully to the community that the purpose of the stopbank improvements is to reduce the current flooding threat to the town from the river.

ORC and QLDC will need to work together to:

- inform the community of new information on natural hazard risks;
- convey this information in an understandable way and why various flood mitigation interventions are not viable for the long-term;
- develop improved flood warning systems and updated flood response procedures;
- incorporate new flood hazard information into the planning framework; and

[1] *An avulsion is when a river channel switches location, often abruptly, along part of its course. Avulsions are characteristic of fluvial and deltaic environments, including alluvial fans and rivers with multiple channels. https://link.springer.com/referenceworkentry/10.1007/978-1-4020-4399-4_18#:~:text=An%20avulsion%20is%20when%20a,and%20rivers%20with%20multiple%20channels.*

- compile critical information to support the investigation, planning and implementation of any longer-term strategies.

Kinloch Road and Dart River Floodplain

The Kinloch Road is closed fairly frequently due to inundation by floodwaters from the Dart River overflowing the right bank and / or flood damage. The frequency of flood inundation has been increasing over time due to ongoing bed aggradation[2] and this trend is expected to continue in the future.

The road is also threatened by bank erosion on the right bank. The current westerly migration of the active channel belt along the right bank is expected to continue in the future due to the transverse slope across the riverbed. Since the 1960's, the long-term bank erosion rate has been > 10m/year in places and could be up to 50 m/year if a series of consecutive large flood events occurred.

The current reactive management approach of localised raising of the road formation and localised rock armouring of sections of the right bank are of limited benefit and not sustainable in the longer term. In the case of rock protection works, it is also expensive.

The development of any business case to improve the long-term reliability of access to Kinloch will not happen quickly due to competing higher priority works in the QLDC area. Therefore, there is a need to develop a plan for interim / emergency measures for implementation whenever road access is cut:

- An interim measure could be a temporary farm access track through Woodbine Station. This would require negotiations and an agreement with the landowner.
- An emergency access measure could be a barge / water taxi arrangement. However, this would still need to be supported by a business case.

The only longer-term solution to maintain road access to the Kinloch area which is viable would be relocation of the road onto the western hillslopes. However, this solution has several constraints such as legal and land ownership issues, and increased exposure to other hazards. It would also have high costs and a long lead time. Any permanent road relocation would need to be supported by a detailed business case by QLDC.

[2] Aggradation is a geomorphological term used to *describe the increase in land elevation, typically in a river system, due to the deposition of sediment. Aggradation occurs in areas in which the supply of sediment is greater than the amount of material that the system is able to transport. https://en.wikipedia.org/wiki/Aggradation#:~:text=Aggradation%20(or%20alluviation)%20is%20the,system%20is%20able%20to%20transport.*

Rees Bridge and Upstream Right Bank Floodplain

Widespread aggradation upstream of the Rees Bridge has not only reduced the bridge waterway capacity but created the potential for an avulsion event across the upstream right bank floodplain. Riverbed levels along the right bank are now approaching the crest of the primary stopbank in places and are higher than adjacent floodplain levels. This significantly reduces the level of service of the primary stopbank. The main impact of an avulsion event would be on road access to Paradise, Kinloch and the Routeburn Valley although it would also affect farmland and a Fish and Game Lodge near the confluence of Diamond Creek.

It is not feasible to control or prevent an avulsion event from the Rees River upstream of the bridge. However, work can be done now to manage the consequences of such an event. A better understanding of potential avulsion flow paths across the right bank floodplain needs to be obtained with the aid of 2D computational hydraulic modelling based on updated LiDAR topographic data. Planning controls need to be considered to ensure no future development occurs within these potential avulsion pathways.

One river management intervention worth exploring to lower the risk of an avulsion event on the right bank is to provide increased channel capacity with clearance of willows and other vegetation on the left bank which historically was part of the active riverbed.

Further investigation and monitoring of the Rees Bridge is required including:

- hydraulic modelling to determine a current water level / discharge rating relationship at the bridge and to understand flood patterns when the flood capacity of the bridge waterway is exceeded;
- establishing the current flood capacity of the bridge waterway and determining a critical point in terms of adequate flood capacity;
- assessing the scour risk to the bridge;
- assessing the structural stability of the bridge;
- monitoring of floodwater levels at bridge; and
- tracking shifts in the water level / discharge rating relationship at the bridge due to ongoing bed aggradation.

One urgent action than needs to be taken is to bolster the scour protection at the abutments of the existing bridge.

An emergency response plan also needs to be developed as an immediate priority to implement in case:

- the Rees Bridge is temporarily damaged; and / or
- a flood breakout and channel avulsion event occurs along the right bank upstream of the bridge.

A business case needs to be developed for the longer term by QLDC to consider longer-term options for the Rees Bridge. These options could include raising the existing bridge or constructing a new bridge. Maintaining access to Paradise, Kinloch and the Routeburn Valley during any construction works will be a significant consideration.

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1.0 Introduction

1.1 Background to Floodplain Adaptation Workshop

The Dart and Rees Rivers flow into Lake Wakatipu at the head of the lake (see Figure 1.1). The floodplains and combined delta associated with these rivers are subject to both flooding and erosion hazards which impact on the township of Glenorchy, and the wider communities of Kinloch and the Upper Rees Valley through disruption of road access.

The key flood related hazard issues affecting these locations are listed below:

- Glenorchy and Lower Rees River floodplain – flooding within parts of the Glenorchy township caused by high flows in the Rees River and / or high flood levels in Lake Wakatipu.
- Dart River floodplain and Kinloch / Greenstone Valley road access – flood inundation of floodplain causing road closures, and westwards migration of the active river channel belt towards the roadway causing bank erosion.
- Rees River Bridge – riverbed aggradation reducing the waterway flow capacity of the bridge and increasing the potential for bridge overtopping or outflanking which would also cause road closure.

There are also other associated natural hazard issues which are discussed later in this report.

In order to understand these natural hazard issues, it is necessary to consider the geomorphic processes at play in this floodplain and delta area. The environment is a dynamic, multi-hazard one characterised by actively aggrading riverbeds, actively migrating river channel belts and a prograding[3] delta shoreline. The landscape scale geomorphic changes occurring in the area coupled with future climate change effects mean that the flooding and erosion hazards are increasing over time.

The changing hazardscape affecting the Dart-Rees floodplain and delta area is a strong influence on why and how the Otago Regional Council (ORC) and the Queenstown Lakes District Council (QLDC) are responding to these natural hazard issues. ORC is applying a Dynamic Adaptive Pathways Planning (DAPP) Approach (described in Section 3) recommended by the Ministry for the Environment (MfE) as a framework for developing hazards adaptation pathways in this area (the Head of Lake Wakatipu Natural Hazards Adaptation Programme). As part of the process of applying this approach, a floodplain adaptation workshop was held on 23-24 February 2022 which involved staff from both Councils as well as a small number of external technical experts. The workshop was intended to be a first-pass review of all possible flood mitigation and floodplain management options, mainly focusing on engineering interventions (note though that this does not mean that non-engineering measures are not part of the DAPP Approach). The workshop also looked into the options put forward by the community at community workshops.

[3] The term progradation refers to the advance of a river delta further out into the receiving body of water (Lake Wakatipu in the case of the Dart Rees delta). This occurs when the volume of river-transported sediment exceeds the volume of sediment lost from the front face of the delta through subsidence, erosion and other processes.

This report documents the proceedings and outcomes of the floodplain adaptation workshop for transmission back to managers and decisionmakers in both Councils, and the local community. The report is intended to inform further feedback from the community.

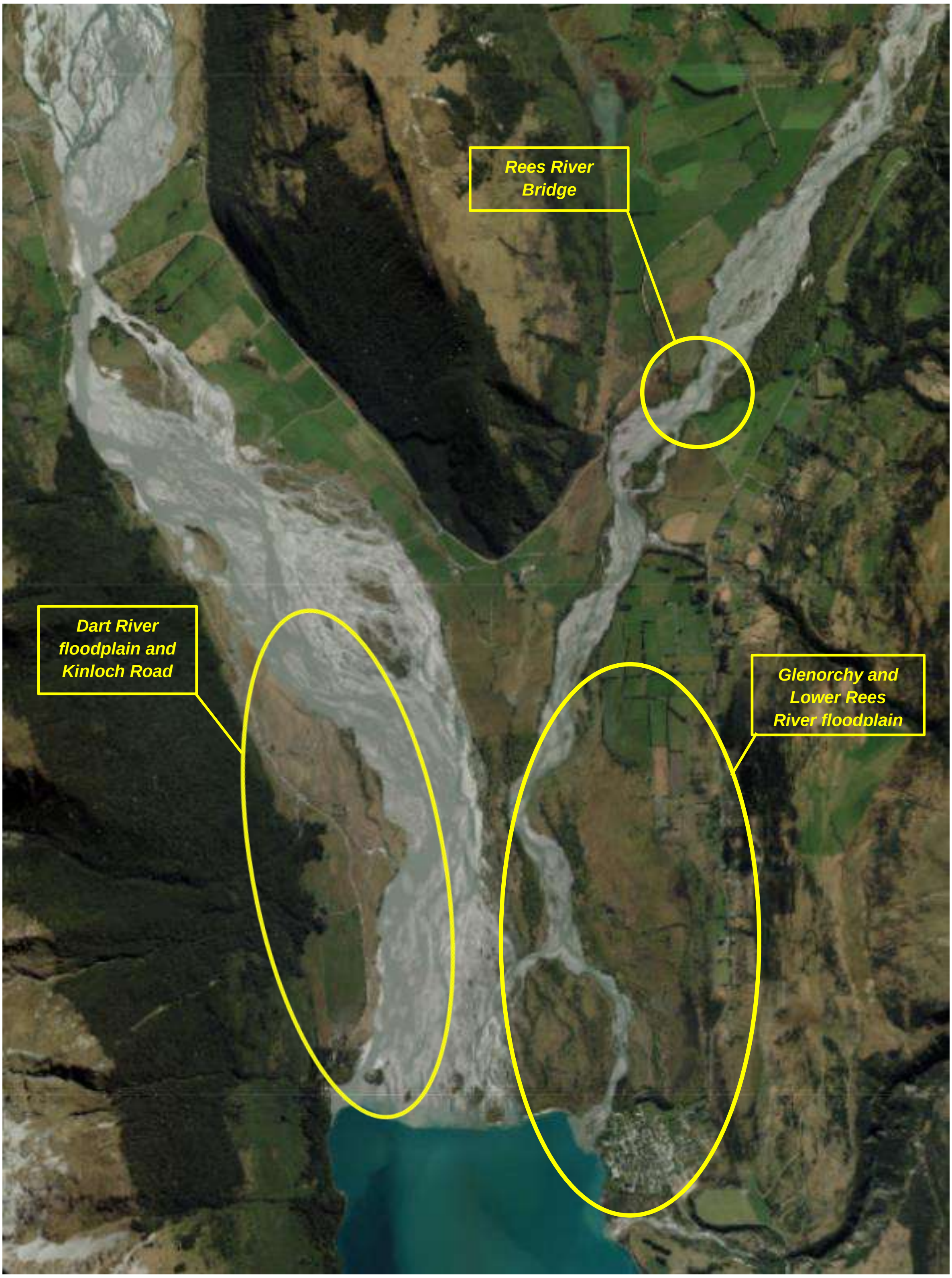

Figure 1.1: Overview of lower Dart-Rees floodplain and delta area showing key areas of interest (sourced from QLDC Spatial Data Hub)

1.2 Scope of Floodplain Adaptation Workshop and Key Questions

The broad scope of the floodplain adaptation workshop was:

- to help identify and understand which of the range of possible flood mitigation and floodplain management approaches may be feasible, environmentally acceptable and cost-effective, and;
- to identify and prioritise any next steps including filling information gaps and undertaking more detailed investigations.

The workshop posed some key questions to address:

- What does sustainable river and floodplain management look like for the Dart-Rees floodplain and delta area and what does it offer?
- What does sustainable flood protection look like and what level of protection is realistically achievable?
- What other complementary strategies are available and practical to implement in order to achieve natural hazard resilience (e.g. planning controls)?
- Can broad principles be defined for a river management strategy in this area, and what are those principles?

1.3 Project Objectives and Assessment Factors

The Head of Lake Wakatipu Natural Hazards Adaptation Programme has an objective of providing "*a framework to actively manage risks associated with natural hazards for the resilience of the area located at the Head of Lake Wakatipu, including Glenorchy and Kinloch'.*

In recognition of this, the following objectives were developed for the floodplain adaptation workshop:

a) An understanding of viable, sustainable river management approaches suitable for the floodplain / river environment of the Dart-Rees area.
b) An estimation of how long, or under what conditions these approaches might remain effective.
c) An understanding of key constraints and other factors affecting river management interventions (cost, environmental, cultural, feasibility, community acceptability etc.).
d) How these approaches might fit within the wider context of natural hazard management and adaptation (e.g. planning responses, potential retreat).
e) Specific review of risks and benefits of all options put forward by the community during engagement activities.

In assessing possible river management interventions, the following questions need to be considered:

- What are the interventions trying to achieve?
- What are the impacts?
- What are the risks?

- How much time will river management / engineered interventions provide?
- How viable are these river management / engineered interventions in the longer term given the environmental / hazard context (e.g. with continual riverbed aggradation, the geomorphic consequences of an Alpine Fault earthquake, and future climate change impacts on hydrology and flooding)?

In this context, for any river management intervention strategy to be successful:

- It must provide adequate flood protection benefits.
- The cost must be acceptable and justified.
- Adverse impacts on the environment are either avoided or minimised.
- The risks and benefits of alternative strategies / pathways must be satisfactorily communicated to other stakeholders.
- The strategy is supported and accepted by the wider community (e.g. local residents, Department of Conservation, Kāi Tahu).

1.4 Floodplain Adaptation Workshop Format and Programme

The floodplain adaptation workshop was originally planned as an in-person event but, due to the outbreak of the Omicron variant of Covid-19 in the community, it was shifted to an on-line event held over one and a half days. The workshop programme covered the following aspects:

- Setting the context and defining the problem
  - General overview of area
  - Community setting
  - QLDC and infrastructure overview
  - Overview of hazardscape for area
  - Summary of ORC's natural hazard adaptation programme
  - Geomorphic characteristics of area
  - Results of flood hazard assessment
- Describing the adaptation pathways approach, objectives and principles
  - General introduction to the approach
  - Summary of community engagement findings
  - Discussion of key questions to address
  - Discussion of objectives for adaptation
  - Discussion of principles for adaptation
  - Discussion of what a successful adaptation approach looks like
  - Discussion of assessment factors for judging success of interventions
- Considering the natural hazard challenges posed by each of the three focus areas (Rees River and Glenorchy, Dart River floodplain and Kinloch Road, and the Rees River Bridge and the upstream right bank floodplain)
  - Identification of specific threats and hazards
  - Identification of possible adaptation interventions
  - Evaluation of interventions (impacts, benefits, risks / consequences of failure, durability over time, long-term viability, regulatory / policy constraints)
  - Assessment of whether specific interventions satisfy objectives for adaptation
  - Assessment of whether specific interventions can be knitted together to provide a long-term adaptation pathway

1.5 Floodplain Adaptation Workshop Participants

The following participants were involved in the floodplain adaptation workshop:

Otago Regional Council
Dr Jean-Luc Payan (Workshop Facilitator) – Manager Natural Hazards
Tim van Woerden – Natural Hazards Analyst
Michelle Mifflin – Manager Engineering
Pam Wilson - Infrastructure Engineering Lead
Scott Liddell – River Engineer
Craig Hughes - Planning and Strategy Engineer

Queenstown Lakes District Council
Ben Greenwood - Roading Operations and Contracts Manager
Hugo De Cosse Brissac – Roading Engineer
Bill Nicoll - Resilience & Climate Action Manager
Mark Baker - Strategy & Asset Planning Manager
Alison Tomlinson - Transport Asset Manager

External Technical Experts
Professor James Brasington (Director, Waterways Centre for Freshwater Management New Zealand, University of Canterbury / Lincoln University)
Matt Gardner (Land River Sea Consulting)
Dr Grant Webby (Damwatch Engineering)

Observer
Jamie MacKenzie (University of Otago post-graduate student)

1.6 Structure of Report

The report on the floodplain adaptation workshop is structured as follows:

- Section 2 sets the scene and defines the problem.
- Section 3 outlines the adaptation pathways approach recommended by MfE.
- Section 4 considers potential flood mitigation and management approaches for the Rees River and Glenorchy.
- Section 5 considers potential flood related hazard mitigation and management approaches for the Kinloch Road and access to the Kinloch area.
- Section 6 considers potential flood related hazard mitigation and management approaches for the Rees Bridge and the upstream right bank floodplain.
- Section 7 presents a summary of the workshop outcomes and conclusions.
- Appendix A contains the workshop programme and briefing notes.
- Appendices B-E contain copies of presentations of background information contributed by different workshop participants.

2.0 Defining the Problem

2.1 Introduction

To provide some background context for the workshop participants, the floodplain adaptation workshop started with a series of presentations on different aspects by ORC and QLDC staff members and some of the external technical experts. This section provides a summary of the material presented. The slides used in each presentation are included in Appendices B-E.

2.2 Overview of Context

Figure 2.1 shows the environmental setting for the area with the floodplains for the Dart and Rees Rivers lying between the Humboldt Mountains to the west and the Richardson Mountains to the east. The Dart River Catchment extends back to the South Island Main Divide with the head of the catchment lying between the Main Divide and the head of the Rees River Catchment.

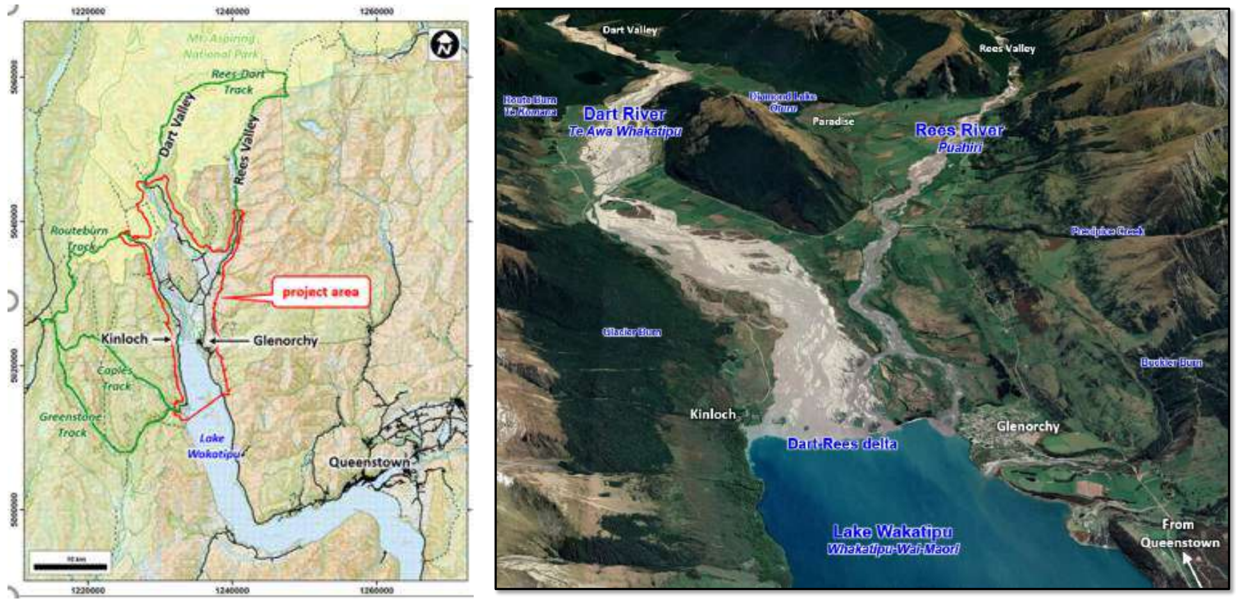

Figure 2.1: Overviews of head of Lake Wakatipu in relation to wider area

Glenorchy township is located at the head of Lake Wakatipu on the left bank floodplain of the Rees River and immediately adjacent to the shoreline delta of the Rees and Dart Rivers. The road north of Glenorchy provides access to the Dart and Rees Valleys, rural localities such as Paradise and Kinloch and the Routeburn, Caples and Greenstone Tracks. This access includes a single bridge across each river.

The area at the head of the lake is exposed to a complex range of hydrological, geomorphological and seismic related hazards. The communities in the area have been regularly impacted by natural hazard events since settlement began due to development in locations such as floodplains and alluvial fan surfaces which are prone to hazard impacts. In recent decades, these impacts have included flooding of low-lying parts of Glenorchy in November 1999 and February 2020, and frequent flooding and bank erosion affecting road access to Kinloch.

The area is also exposed to other lower-likelihood hazard sources which may have significant impacts on parts of the community. These hazard sources include debris flows, landslide dam-break induced floods, liquefaction or lateral spreading resulting from major earthquakes, and tsunamis triggered by sub-aerial or sub-aqueous landslides into Lake Wakatipu[4].

In this dynamic alpine environment, many of the natural hazard risks are not static but are subject to continual adjustment in response to geomorphic (landscape) and climatic changes. While the magnitude and timing of both types of change is uncertain, they are expected to cause increases in the severity and likelihood of natural hazard impacts[5]. This applies particularly to flooding and related hazards.

The braided channel belts, floodplains and delta of the Dart and Rees Rivers are undergoing continuous and irreversible geomorphic change over time[6]. This is evidenced by riverbed aggradation, lateral channel migration and delta advancement into the lake due to the ongoing natural process of sediment transport by water flows in these rivers.

These geomorphic changes are likely to cause an increase in the frequency and severity of future flooding impacts on the floodplains of the Dart and Rees Rivers.

2.3 Iwi Values

The area at the head of Lake Wakatipu holds significant cultural values for Kāi Tahu[7]:

> "*Whakatipu-wai-Māori holds generations of Kāi Tahu histories, the knowledge of which holds the same value for Kāi Tahu today. Kāi Tahu taoka (treasures) cover the landscape; from the ancestral mauka (mountains), large flowing awa (rivers), tūpuna roto (great inland lakes), pounamu and ara tawhito (traditional travel routes/trails).* ***These all make the area immensely significant to mana whenua.*"**

Kāi Tahu are partners with ORC.

2.4 Community Setting and Values

The total community population in the area is currently about 500. The population is mainly centred around Glenorchy with other rural settlements at Kinloch, Paradise, Greenstone, the Rees Valley and Wyuna. The main business activities are tourism and farming. Pre-Covid, daily tourist visitors peaked at more than 1000.

The population has grown rapidly since the 1980s. From census data, the population in the wider Glenorchy area grew from 270 in 2001 to 390 in 2018. The population is projected to grow to 450[8] in 2048 while average daily tourist numbers are projected in increase from 1,000 to 1,420.

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[4] Tonkin and Taylor (2021a).
[5] NIWA (2019).
[6] Wild (2013); Brasington (2021).
[7] Aukaha (2021)
[8] QLDC staff have advised that revised modelling for projected population growth in Glenorchy is to be carried out in 2022. There are several scenarios where the population growth could spike (e.g. this could be triggered by construction of a reticulated wastewater system - QLDC is actively considering investing in a wastewater treatment plant for the town).

The community values highly the lifestyle and freedom associated with the unspoilt and spectacular environment of the area as set out in a 2001 community vision statement[9]:

> "*A vibrant community where lifestyle and freedom are highly valued together with the peaceful, unspoilt rural environment and the dynamic interaction of the spectacular landscape, heritage and wilderness".*

The area has significant conservation values with the Department of Conservation (DOC) being an important stakeholder. The area forms a Gateway to Mount Aspiring National Park and Te Wāhipounamu – South West New Zealand World Heritage Area. It also provides access to the Routeburn Track (a NZ Great Walk) and to the Greenstone-Caples and Dart-Rees Tracks, and incorporates extensive DOC-managed reserves and conservation areas. The area incorporates five regionally significant wetland areas including the DOC-administered Glenorchy Lagoon and Conservation Area.

2.5 Hazardscape Review

Figure 2.2 illustrates the wide range of potential natural hazard sources impacting the area at the head of Lake Wakatipu. As noted before, these natural hazard sources are non-static and continually adjusting in response to geomorphic (landscape) and climatic changes with an adverse trend. There is also a high potential for cascading hazard scenarios in the area (e.g. the geomorphic consequences of a major earthquake).

[9] Blakely Wallace Associates (2001).

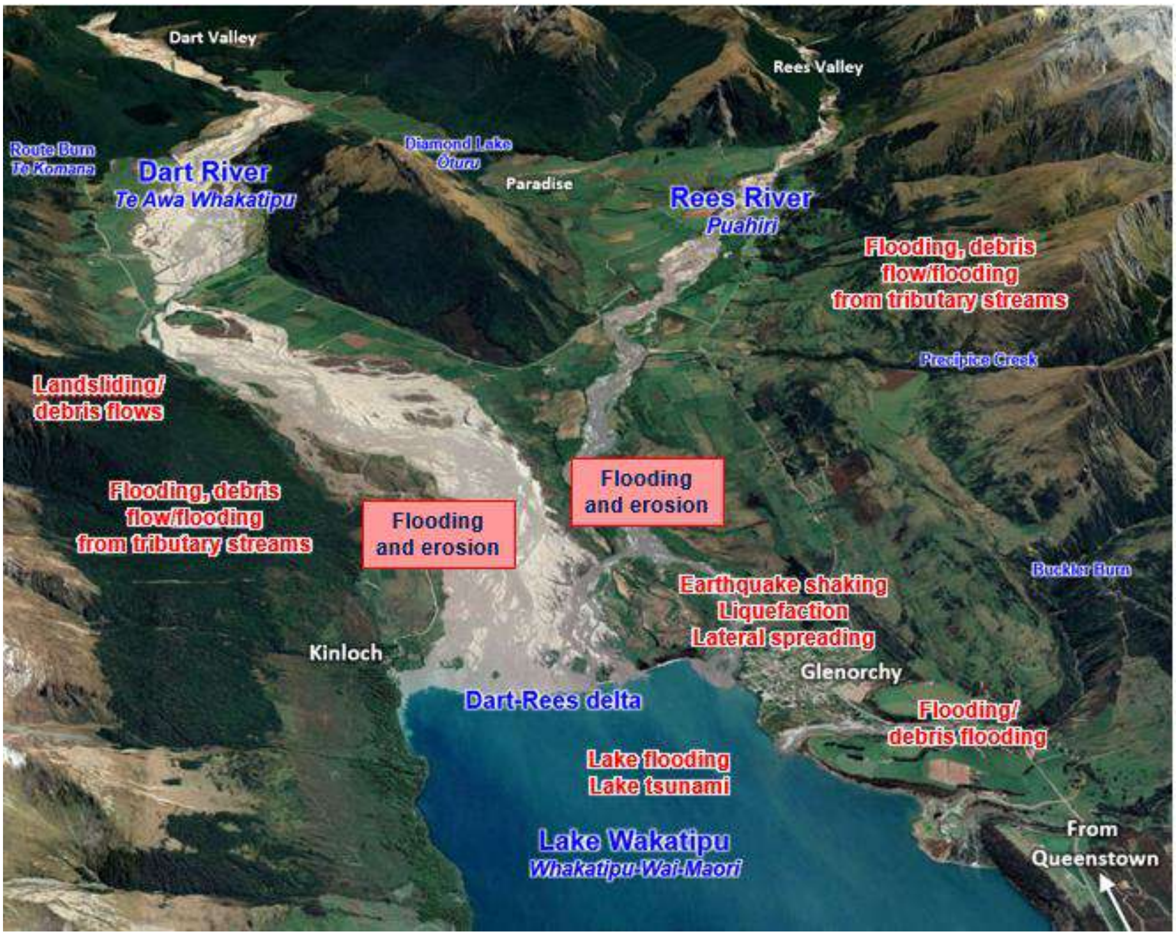


Figure 2.2: Natural hazard sources impacting on area at head of Lake Wakatipu

The main flood related hazard issues for the four floodplain focus locations are:

a) Glenorchy township
   - Increasing flood hazard due to ongoing bed aggradation in Rees River
   - Increasing flood hazard due to breakout flows into Glenorchy Lagoon and the potential for permanent channel avulsion
   - Increasing flood hazard due to climate change impacts
   - Increasing erosion hazard to existing stopbank due to the combination of ongoing riverbed aggradation and climate change impacts

b) Kinloch road access
   - Increased flood hazard to road due to ongoing bed aggradation in Dart River
   - Increased erosion hazard due to ongoing lateral channel belt migration westwards and frequency of high-velocity flows adjacent to road
   - Increasing flood and erosion hazards due to climate change impacts

c) Rees Bridge
   - Reducing bridge waterway flood capacity due to the combination of ongoing riverbed aggradation and climate change impacts
   - Increasing potential for scour and erosion damage at bridge piers and abutments due to the combination of ongoing riverbed aggradation and climate change impacts (including potential for outflanking either of the bridge abutments)

   - Increasing potential for structural damage to bridge from debris rafting and flood overtopping due to the combination of ongoing riverbed aggradation and climate change impacts

d) Right bank floodplain upstream of Rees Bridge
   - Increasing flood hazard with potential for stopbank overtopping and permanent channel avulsion due to the combination of ongoing riverbed aggradation and climate change impacts
   - Potential for cutting road access to Paradise and Kinloch
   - Potential impact on adjacent farmland

Figures 2.3-2.5 illustrate these hazard issues.

Figure 2.3: Flooding in Glenorchy in November 1999 (a combination of lake and fluvial sourced flooding)

Figure 2.4: Flooding of Kinloch Road (in the foreground) in a minor flood event in 2019 - Dart River floodplain looking upstream

Figure 2.5: Erosion protection works adjacent to Kinloch Road with evidence of recent breakout flows across road in February 2022 (note level of riverbed adjacent to right bank floodplain)

Figure 2.6: Riverbed aggradation under Rees Bridge in February 2022 (viewed looking upstream)

2.6 QLDC Perspectives

Excluding outliers, the Kinloch Road is the most expensive road in QLDC's network in terms of the cost/km length for emergency works based on data from 2016 to the present time. Recent emergency works have included raising sections of the road to try and reduce the frequency of flood inundation[11] and protection of vulnerable sections of riverbank adjacent to the road with rock armouring.

QLDC's view is that the current reactive management approach is probably not sustainable in the longer term due to funding limitations, especially with the continuing westerly migration of the active channel belt in the Dart River towards the road and the ongoing trend of riverbed aggradation. However, there is an expectation that QLDC will continue to maintain access via this road.

In the short term, QLDC are managing the Kinloch Road using two funding streams:

- LTP funding of $220,000 every second year for Rees River Bridge resilience; and
- Emergency works – when unplanned works are required outside of gravel extraction opportunities such and bank armouring or raising the road level.

[11] The Kinloch Road currently gets flooded whenever flows in the Dart River reach a threshold of about 500 m^3/s (based on the Dart at Hillocks flow gauge) whereas previously this flow threshold was (anecdotally) much higher.

The purpose of the Rees River Bridge resilience funding is to reduce gravel aggradation under the bridge. Gravel is extracted and disposed of as economically as possible, and the opportunity has been taken to raise the level of the Kinloch Road with this material. However, the volume of material which can be removed for $110,000/year is very small compared to the total volume of gravel bed material transported by the Rees River each year.

QLDC's view is that it is inevitable that the Rees Bridge will need to be raised in the near future due to the current rate of riverbed aggradation. Five years ago a Moxy dump truck could be driven under the bridge but this is now no longer possible.

The 1.4 km long Glenorchy stopbank along the left side of Lagoon Creek and the Rees River was constructed in about 2000. It has been overtopped by floodwaters a few times in recent years including in the February 2020 flood event[12]. Following a survey of the stopbank crest, QLDC recently undertook some minor scale works which included:

- the supply and placement of 1,200 tonnes of rock to protect vulnerable sections of the stopbank along the Rees River:
- the repair of some over-steep sections of the stopbank; and
- localised and minor raising of a short section of the stopbank near the golf course where the crest was low.

In addition to these works, ORC recently completed fairly substantial works to clear willows from along the banks of Lagoon Creek in order to improve the discharge capacity of the creek and to lower water levels in the lagoon under flood conditions.

2.7 Geomorphic Characteristics and Trends

While not the most catastrophic threat, flooding from rivers poses the most frequent hazard to communities at the head of Lake Wakatipu. This hazard manifests itself in several forms:

- direct flood inundation
- fast flowing floodwaters
- entrained debris and sediment
- riverbank erosion

Fluvial related hazards are expected to increase in frequency and severity in the future. There are two main drivers for this trend. Increases in average temperature due to climate change are expected to produce a 20-40% increase in winter rainfall and more intense storms by 2090 with up to a 100% increase in the mean annual flood flow[13]. Continual riverbed aggradation will result in increased bed levels and ongoing lateral channel belt migration.

Due to their proximity to the South Island Main Divide (which is subject to continuing uplift of more than 5 mm/year), the Dart and Rees Catchments experience extreme rates of erosion. The glacial legacy of over-steep catchment slopes and orographic-induced precipitation of more than 5,000 mm/year are key factors in this. The resulting unstable landscape is dominated by retreating headwater glaciers and active landslides. Occasional mass movement events can give rise to the formation of landslide dam impounded lakes with the potential for a dam-break

[12] The February 2020 flood was estimated to have been about a 1 in 15 to 1 in 20 AEP event.
[13] NIWA (2019).

flood when these dams are overtopped. The unlimited supply of sediment in the Dart and Rees Catchments means that there is more sediment available than the capacity of the two rivers to transport the sediment downstream[14]. The average annual gravel bed material load of the Dart-Rees River System into Lake Wakatipu from 1966-2007 was estimated[15] to be 300,000 m^3.

The consequences of an over-supply of sediment to the river system are that:

- there is a continual trend of bed aggradation with bed levels in many areas approaching the levels of the adjacent floodplain;
- the width of the active belt of braided channels which characterises these rivers is continually changing over time, while the belt is also migrating laterally;
- deposited sediment is constantly being reworked as channel migration occurs and the width of the active channel belt changes;
- bank erosion occurs as a result of lateral channel migration; and
- the potential for channel avulsion across adjacent floodplains increases with active channel migration and the loss of freeboard along existing banks due to bed aggradation.

Figure 2.7(a) and (b), sourced from Professor Brasington's presentation in Appendix D, show bed level changes from detailed LiDAR topographic surveys over the lower part of the Dart-Rees River System between 2011 and 2019. The graduated blue shading on the aerial image in Figure 2.7(b) indicates sediment deposition (bed raising) while the graduated red shading indicates bed degradation (bed lowering). There are substantial areas of deposition across the Lower Dart active channel belt with significant erosion and bank retreat evident along the western edge adjacent to the Kinloch Road. The overall trend in average bed level change is shown in Figure 2.7(b) with a net increase in bed levels of up to 0.2 m over most of the 3.5 km distance upstream from the delta front.

Figure 2.8, also sourced from Professor Brasington's presentation in Appendix D, shows a similar image to Figure 2.7(b) of bed level changes over Lower Rees River between 2011 and 2019. Figure 2.8 indicates that there has been extensive sediment deposition across the riverbed over the 5 km distance upstream from the delta front. Mean bed levels increased in the order of 0.2-0.3 m over the 8-year period with the larger increases occurring upstream of where the river bifurcates and the righthand branch joins the Dart River. This mean bed level trend, if it continues, would translate to an increase in bed levels of 1.25-2 m over the next 50 years.

The increase in mean bed levels on the Lower Rees River imply a significant loss of flood capacity within the active channel belt and a loss of freeboard along the existing margins with the potential for the occurrence of channel avulsion events. This is illustrated by the photograph in Figure 2.9 which shows riverbed levels approaching adjacent floodplain levels and evidence of sediment deposition from recent flood breakout flows. The flood breakout flows would have flowed overland into the Glenorchy Lagoon.

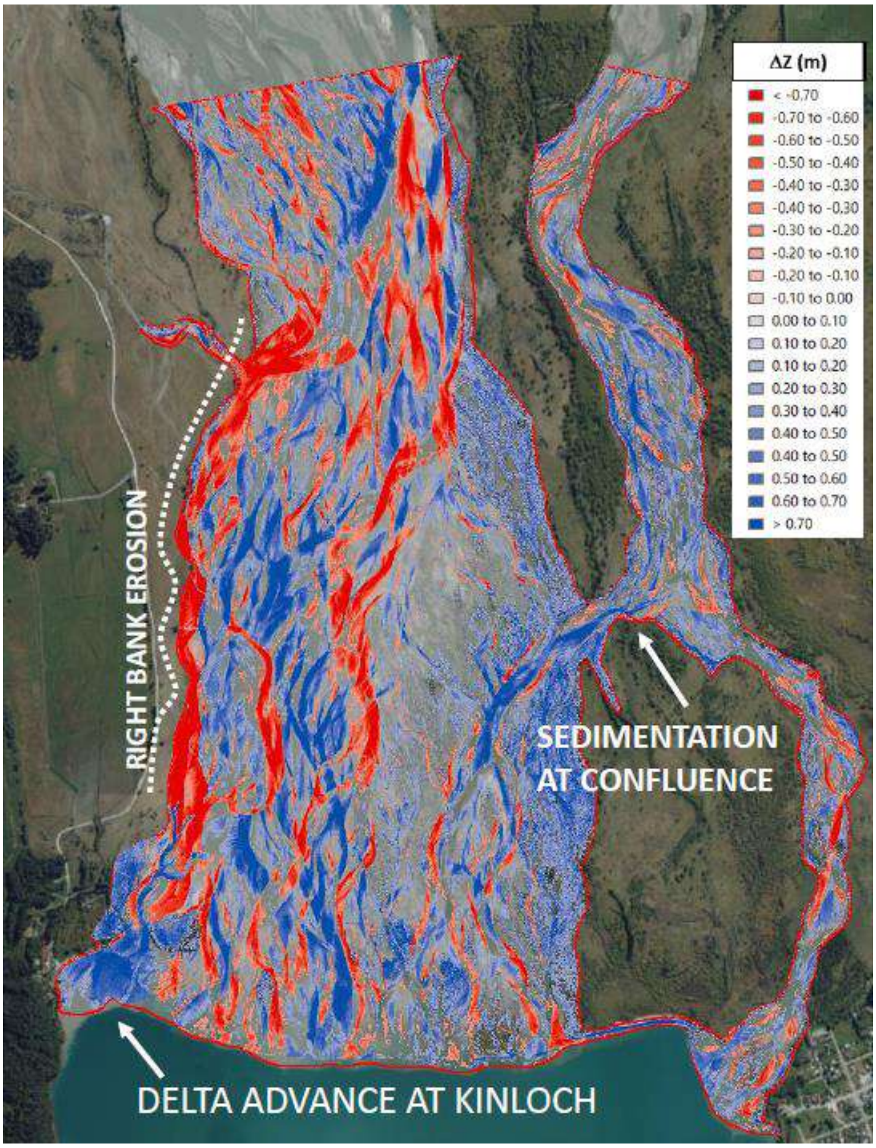
[14] The Slip Stream landslide in 2011 in the Upper Dart River Catchment had an estimated volume of 17.5 million m^3. Of this total volume, 7 million m^3 is estimated to remain in storage with about 10.5 million m^3 contributed to the sediment supply to the Dart River.
[15] Wild (2013).

A campaign of repeat high-resolution LiDAR surveys in 2009-2011 captured the evolution of a 3 km reach of the Rees River upstream of the Rees Bridge over an annual flood season. The following general observations can be made from the results of this campaign:

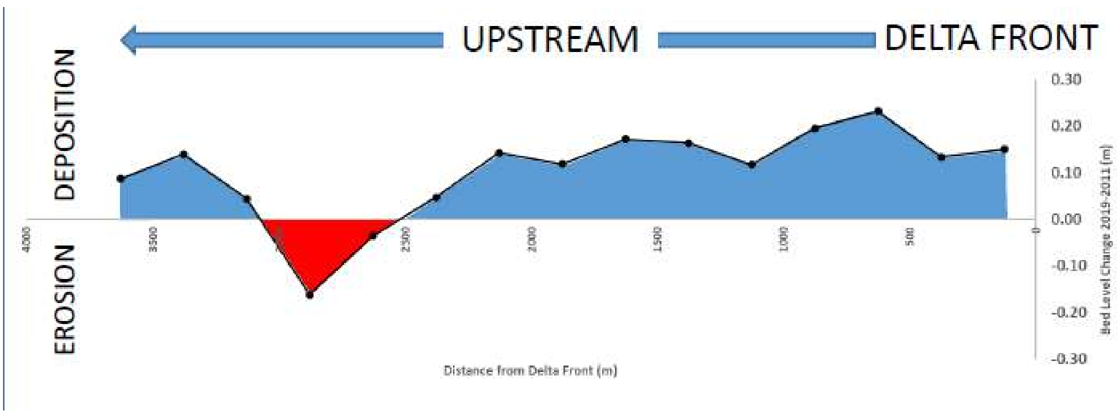
- Much of riverbed in this reach was disturbed in a single year with half of it experiencing repeated scour and fill cycles.
- Much of the riverbed in this reach was exposed to either scour or fill.
- Sediment mobilisation is episodic and related to flood events.
- The volume of sediment material mobilised in a flood is proportional to the power of that flood[16].

It should be noted that the average volume of bedload sediment material transported by flood activity in the Rees River in a single year significantly exceeds the volume of gravel material which QLDC is licensed to extract annually at the Rees Bridge.

[16] In this 2009-2011 campaign, a modest 350 m^3/s fresh in the Rees River was found to move about 30,000 m^3. This compares with the up to 20,000 m^3 volume of gravel bed material which QLDC is licensed to extract annually at the Rees Bridge to help improve the resilience of the bridge.



(a) Difference in LiDAR elevation models of riverbed between 2011 and 2019 (red indicates erosion, blue indicates aggradation)



(b) Average changes in bed level

Figure 2.7: Bed level change on Dart-Rees River System between 2011 and 2019

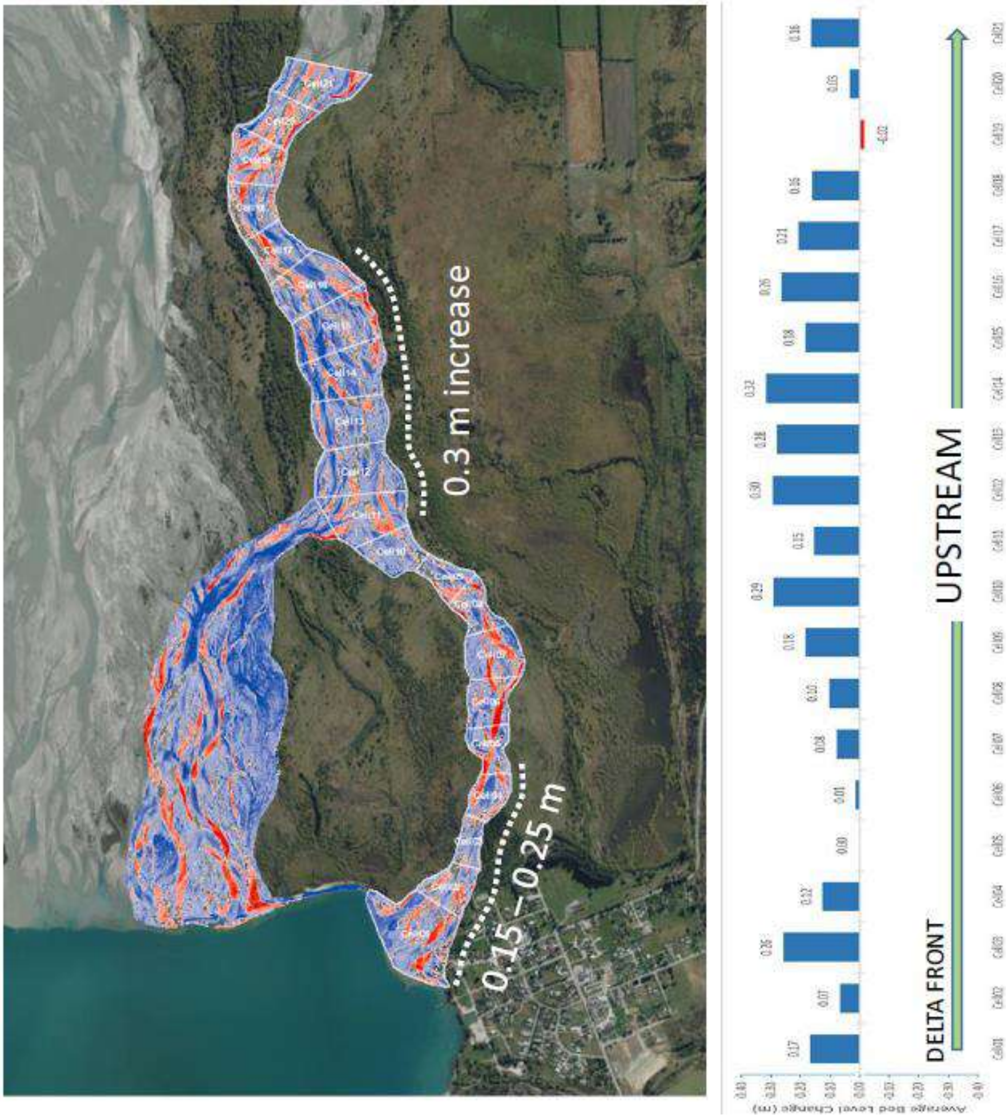


Figure 2.8: Average bed level change on Lower Rees River between 2011 and 2019 (red indicates erosion, blue indicates aggradation)

Figure 2.9: View looking downstream along the left bank of the Lower Rees River showing evidence of loss of freeboard and sediment deposition from recent flood breakout flows (photo taken on 9 February 2022 near start of bed level change map in Figure 2.8 – river flow ≈ 13 m^3/s at time of photograph)

The dynamic nature of the geomorphological behaviour of the Rees-Dart River System with an unlimited sediment supply, active expansion of the existing river corridor and sediment transport capacity limited by river flows giving rise to a continual bed aggradation trend has the following implications for existing flood hazards:

- Loss of level of service of existing stopbank protection at Glenorchy.
- Increased risk of backwater flooding along Lagoon Creek and overtopping of the stopbank at Glenorchy.
- Increased risk of severe breakout flooding and channel avulsion along the left bank of the Rees River into the Glenorchy Lagoon, along the right bank of the Rees River upstream of the Rees Bridge and along the right bank of the Dart River affecting the Kinloch Road.
- Increased risk of riparian erosion along the right bank of the Dart River affecting the Kinloch Road.
- Increased risk of abutment scour damage and structural damage due to overtopping of the Rees Bridge.

These increased risks relate to both severity and frequency.

Further information on the geomorphological characteristics and trends of the Dart-Rees River System is contained in Professor Brasington's presentation in Appendix D.

2.8 Flood Hazard Assessment

ORC recently commissioned Land River Sea Consulting to undertake a flood hazard assessment for the Dart-Rees River System using a two-dimensional (2D) computational hydraulic modelling approach. The 2D model developed for the assessment was based on a 2019 LiDAR topographic survey of the river system and covered the area shown in Figure 2.10 (reproduced from the Land River Sea Consulting report[17]). The model extended from the Rees River and Dart River Bridges down to Lake Wakatipu.

Figure 2.10: Extent of 2D computational hydraulic model of Dart-Rees River System used for flood hazard assessment

[17] Land River Sea (2022).

The model is a fixed-bed model based on the riverbed topography at the time of the 2019 LiDAR survey so that it is unable to account for scour and sediment deposition during the course of a flood which are known to occur and which will alter the riverbed bathymetry. In view of this limitation, the model predictions can only be used as an aid to understanding the inundation extent and flow depth and velocity patterns for a flood of given size. The model requires upstream boundary inputs of flood magnitudes in both the Dart and Rees Rivers, and a downstream boundary input of a fixed water level for Lake Wakatipu. The model also requires the frictional resistance of the ground surface to be defined for the riverbed area and for floodplain areas covered by different vegetation types.

The primary focus of the flood hazard assessment was on the Lower Rees River and Glenorchy area. The model was calibrated by adjusting the frictional resistance of the riverbed surface so that it correctly reproduced the flood inundation pattern in this area observed from aerial photographs of the February 2020 flood event.

Figure 2.11 (reproduced from the presentation in Appendix E) shows the flood extent estimated by the model for a 1% Annual Exceedance Probability (AEP) flood in the Dart-Rees River System with areas marked for different degrees of flood hazard depending on the magnitude of maximum flow depth and velocity. The flood hazard categories are based on those defined in Book 6 Flood Hydraulics of *Australian Rainfall and Runoff*[18] (ARR) for different degrees of hazard to people, vehicles and buildings (the hazard category definition diagram from ARR is reproduced in the presentation in Appendix E).

As noted in Section 2.4, the loss of freeboard due to widespread bed aggradation in the Lower Rees River increases the potential risk of flood breakout and channel avulsion along the left bank. Figure 2.12 (reproduced from the Land River Sea Consulting report[19]) shows one possible avulsion path towards Glenorchy Lagoon predicted by the 2D model. The flood inundation pattern and flow directions in Glenorchy resulting from this type of avulsion event for a 1% AEP flood adjusted for future climate change (and based on 2019 riverbed levels) is shown in Figure 2.13 (reproduced from the Land River Sea Consulting report[15]). This indicates the existing stopbank along Lagoon Creek and the Rees River would be overtopped with overtopping flow encroaching on the margins of the town and draining parallel to the stopbank down towards Lake Wakatipu. However, the topography of the alluvial fan surface underlaying Glenorchy prevents the floodwaters ponding in this low-lying area from flowing down the fan surface through the town directly to the lake. The stopbank overflow also spreads across the road providing access north to the Upper Rees Valley, the Routeburn Valley and Kinloch at the eastern end of the town and inundates a low-lying area there.

With floodwaters overtopping the existing stopbank at Glenorchy in this assumed flood scenario, there is also the potential for a stopbank breach to occur. In the event of this occurring, the additional floodwaters released through the breach would be contained by the natural topography of the alluvial fan surface as illustrated in Figure 2.13.

[18] Ball *et al* (2019).
[19] Land River Sea (2022).

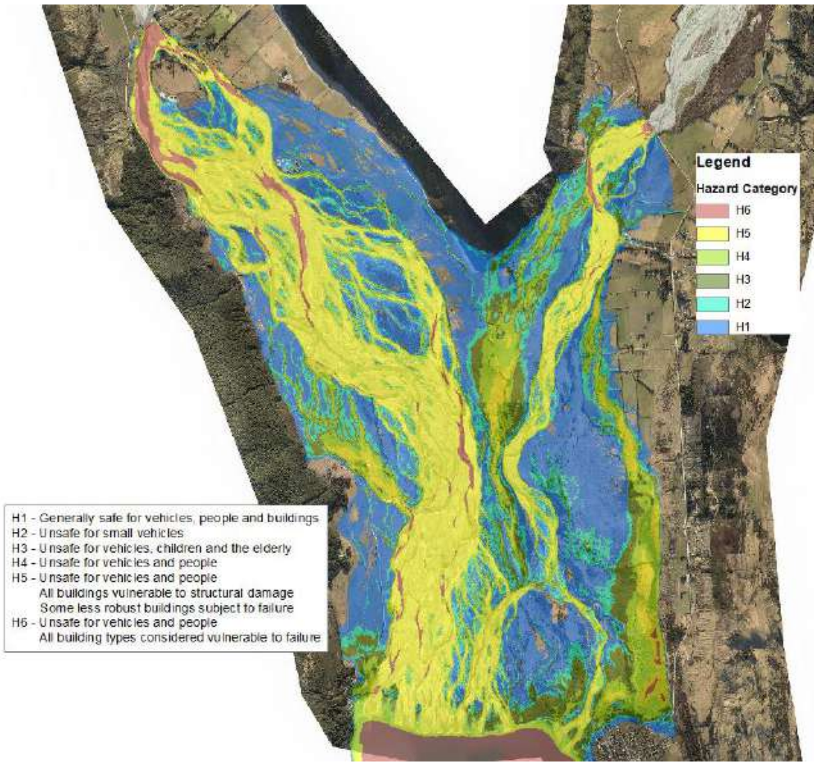


Figure 2.11: Estimated inundation extent and flood hazard categories of 1% AEP flood in Dart-Rees System

Figure 2.12: Possible channel avulsion path along left bank of Lower Rees River towards Glenorchy Lagoon

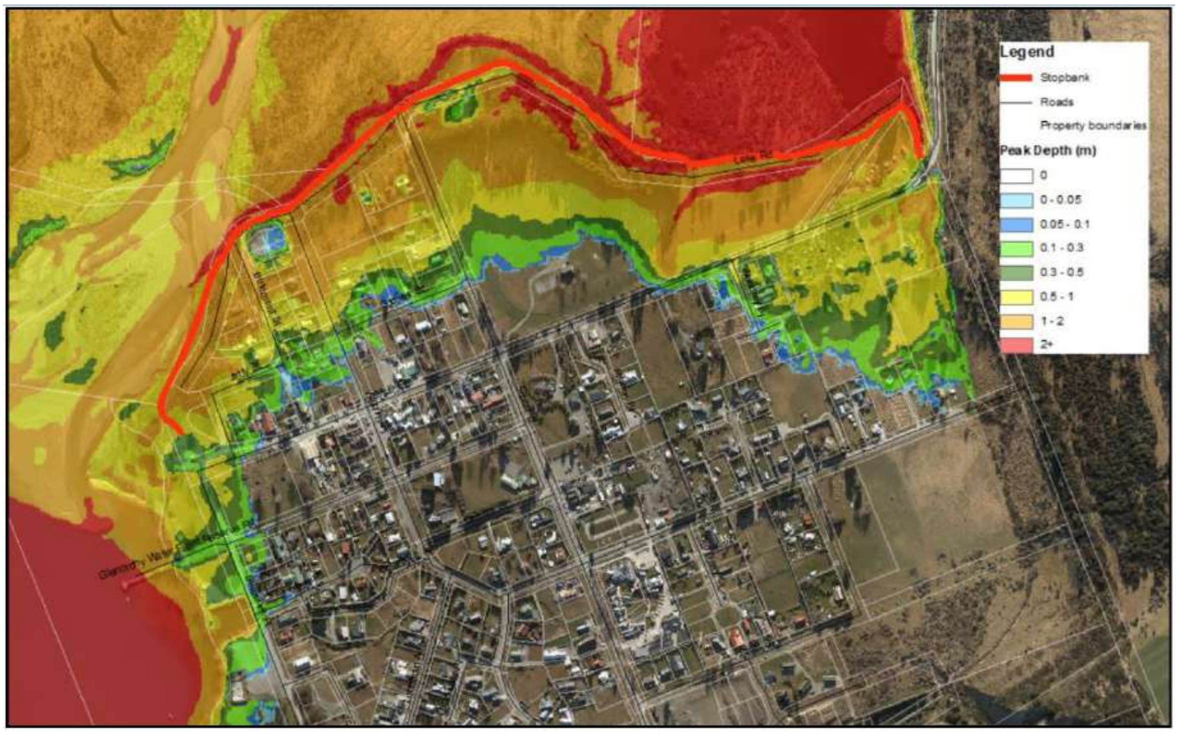


Figure 2.13: Flood inundation in Glenorchy for 1% AEP flood in Rees River adjusted for future climate change and 10% AEP lake level with flow avulsion occurring along left bank as shown in Figure 2.12

The flood inundation extents shown in Figures 2.11-2.13 reflect an assumed flood scenario for Glenorchy based on a moderately high level for Lake Wakatipu (i.e. fluvial sourced flooding from the Rees River dominates). As demonstrated by the November 1999 flood event (Figure 2.3), the potential exists for lake sourced flooding in combination with fluvial sourced flooding.

2.9 Summary of Natural Hazards Adaptation Programme

In view of the multi-hazard environment at the Head of Lake Wakatipu with the risks associated with those hazards being exacerbated over time by climate and geomorphic changes, ORC initiated an adaptation programme in July 2019 with an objective of providing "*a framework to actively manage risks associated with natural hazards for the resilience of the area located at the Head of Lake Wakatipu, including Glenorchy and Kinloch*".

It was proposed that the project would[20]:

- *Identify and evaluate potential natural hazard pathways based on the Adaptation Pathways approach recommended by MfE[21];*
- *take a more strategic and holistic approach than previous natural hazard studies;*
- *undertake a multi-hazard and climate change assessment for the area, including a review of potential hazard consequences, likelihoods and overall risks; and*

[20] ORC (2021)
[21] MfE (2017)

- *develop risk reduction / adaptation pathways over a longer-term timeframe of not less than 100 years.*

This would enable future planning to occur with more certainty in a context of ongoing change and increasing hazard risks.

The project is being led by ORC in partnership with QLDC, Kāi Tahu and other key stakeholders including the Department of Conservation (DOC) and local communities. Community engagement forms a key plank of the programme.

The programme is supported by several consultants providing specialist inputs.

3.0 Dynamic Adaptive Pathways Planning Approach

3.1 Introduction to Approach

An adaptation pathways approach to natural hazard management is a "*response strategy to anticipate and adjust to actual and expected changes in environmental conditions*". Adaptation involves "*iterative, continually evolving processes for managing change in complex systems*" (MfE, 2017). Effective adaptation means that (CCATWG, 2017) "*current and future communities are able to reduce the risks from natural hazard and climate change impacts over the medium and long term by:*

- *reducing the exposure and vulnerability of our natural, built, economic, social and cultural systems*
- *maintaining or improving the capacity of our natural, built economic, social and cultural systems to adapt*."

Figure 3.1 from MFE (2017) illustrates the ten-step decision cycle of the adaptation pathways approach based around five key questions. While the approach has been developed primarily for coastal settings where sea level rise due to climate change is a critical issue, the approach is also considered appropriate for application to the Head of Lake Wakatipu area because of the changing risk profile resulting from sediment aggradation, delta growth, and climate change.

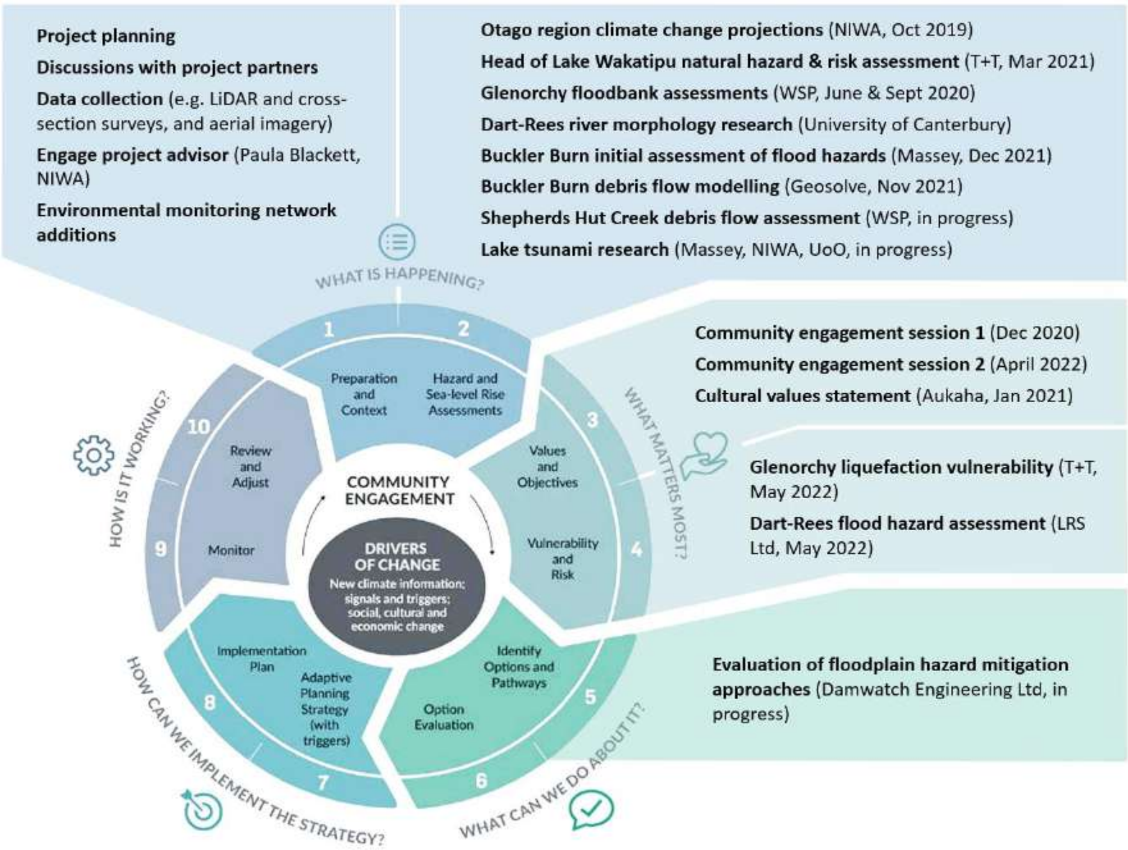


Figure 3.1: Summary of the 10-step adaptation pathways decision cycle framework (MfE, 2017) showing the main activities which have been completed for the Head of Lake Wakatipu Hazards Adaptation Project from ORC (2022)

Figure 3.2 from MfE (2017) shows an example of an adaptation pathways map. There may be a range of types of adaptation options which are available, each with advantages and disadvantages. Several alternative combinations of these options may be practical and feasible, over short-term (0-20 years), medium term (20-50 years) and long-term (50-100 years) timeframes. Aside from the 'status quo' option, there are four potential groupings of natural hazard mitigation options (MfE, 2017):

- accommodate
- protect
- retreat
- avoidance strategies

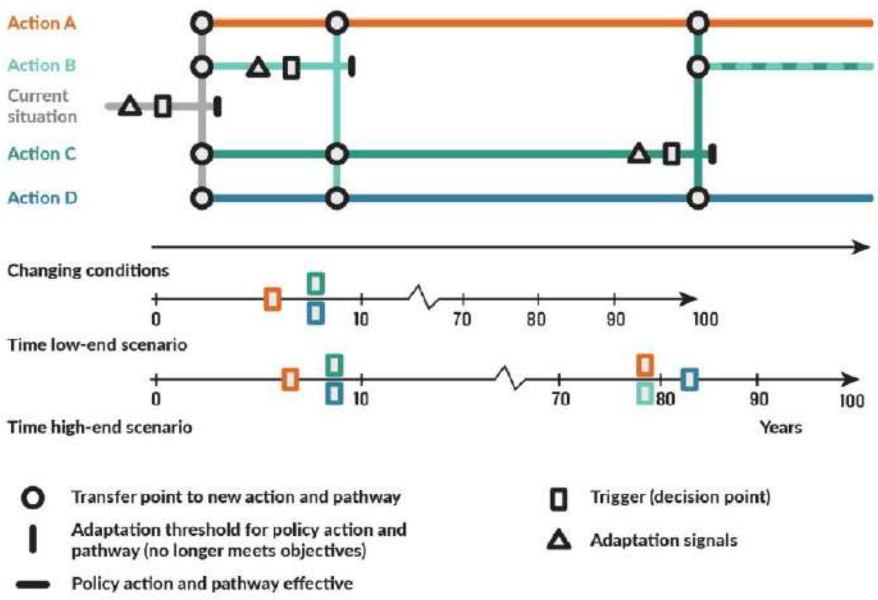


Figure 3.2: Example of an adaptation pathways map showing a series of possible adaptation options (A-D), each of which is assessed based on adaptation signals (MfE, 2017)

Adaptation pathways will evolve over time in response to changing conditions and, an effective adaptation strategy will incorporate key decision points based on triggers or thresholds.

3.2 Summary of Community Engagement Findings

ORC has embarked on a community engagement process with the support of a NIWA team to provide community input to an adaptation pathway development process, and to equip the community with the necessary knowledge to make informed decisions regarding adaptation approaches. The community engagement process is based around a series of four community engagement sessions with the titles:

a) What is happening now, and how does this affect you?

b) What could happen in the future, and what might we do?
c) How can we navigate the adaptation options?
d) What do the adaptation pathways look like, and what happens now?

The first and second of these engagement sessions were held in December 2020 and April 2021. These sessions were designed to present and discuss the natural hazard issues affecting the Head of Lake Wakatipu area, and to promote conversations about possible adaptation approaches or interventions to manage or mitigate these hazards.

During these community engagement sessions, community members suggested several possible intervention options for consideration, including structural and river management measures (see Figure 3.3):

- raising or modifying the existing Rees-Glenorchy stopbank structure;
- gravel extraction;
- channel realignments, such as diversion of Rees River flows into the Dart River;
- river control structures or plantings (e.g. groynes to mitigate channel erosion);
- bunding or new stopbanks to reduce overland flood flows into the Glenorchy Lagoon; and
- willow management or channel modification of Lagoon Creek to enhance drainage ability from the lagoon.

Community concerns were also raised about the ongoing aggradation at the Rees River Bridge, and the consequential loss of waterway flow capacity at the bridge and increased vulnerability to overtopping and debris impacts.

Access to the Kinloch and Greenstone / Caples areas via the Kinloch Road is another matter of community concern in view of the frequency of flood inundation over the road (e.g. > 10 occasions in 2019-20) and the westerly migration of the active channel belt of the Dart River towards the road, and in several areas, hard against the road. A range of potential adaptation approaches has been put forward for consideration to maintain access to these areas (see Figure 3.4), based on advice from ORC technical staff and consultants but with some community input:

- status quo (i.e. reactive repair): localised erosion protection and road raising as required to manage highest priority erosion hotspots or flooding issues.
- local realignment: realignment of sections of road from areas threatened by erosion or most highly flood-prone (but still remaining on the floodplain.
- hard engineering: installation of larger-scale erosion or flood protection structures;
- redesign: relocation of erosion or flood-prone sections of road from the floodplain to adjacent hillslopes.
- alternative transport: use of alternative transport modes (e.g. boat access).

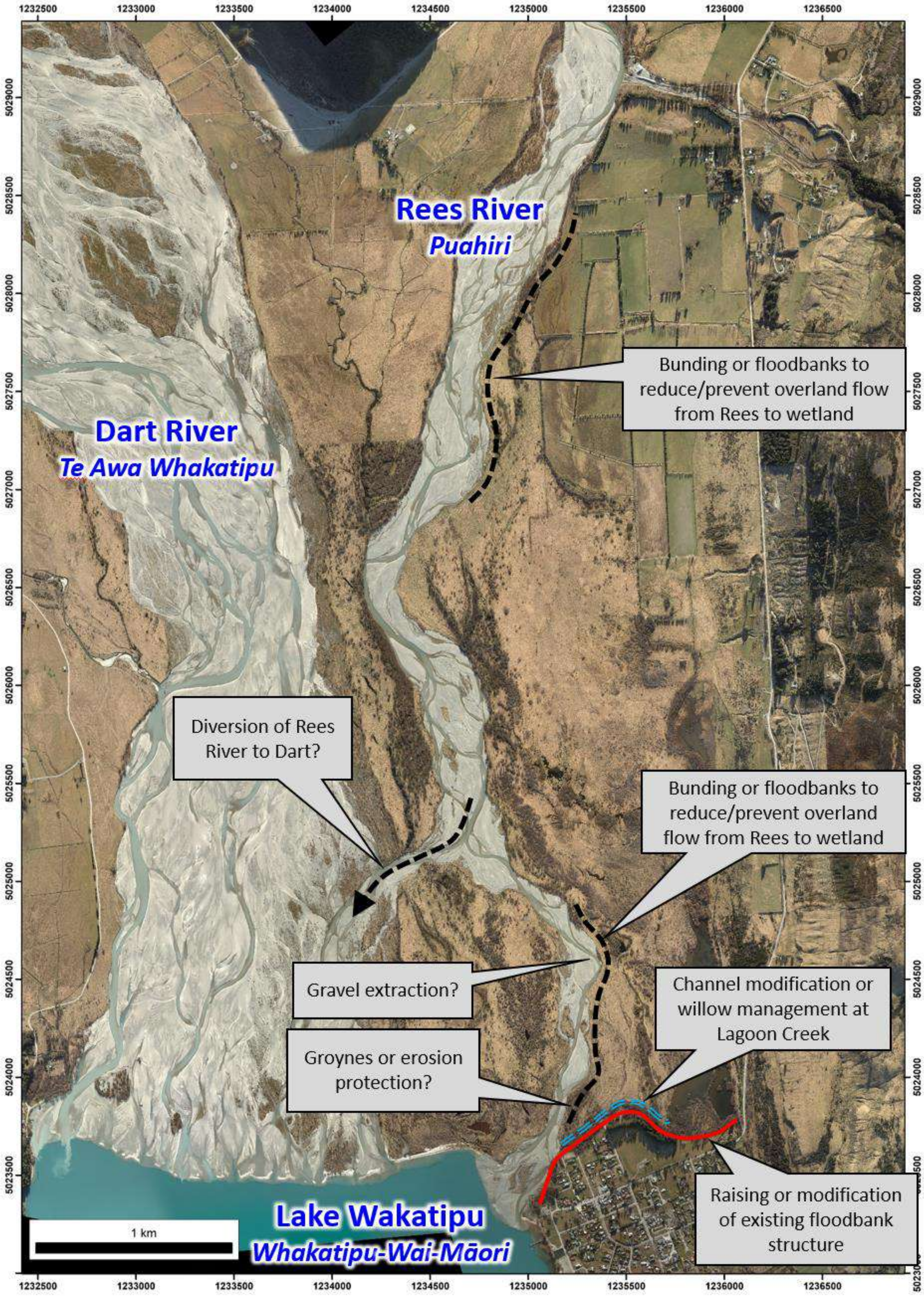


Figure 3.3: Overview of the lower Dart-Rees floodplain, showing range of potential flood mitigation options for the Rees River and Glenorchy township suggested by the local community

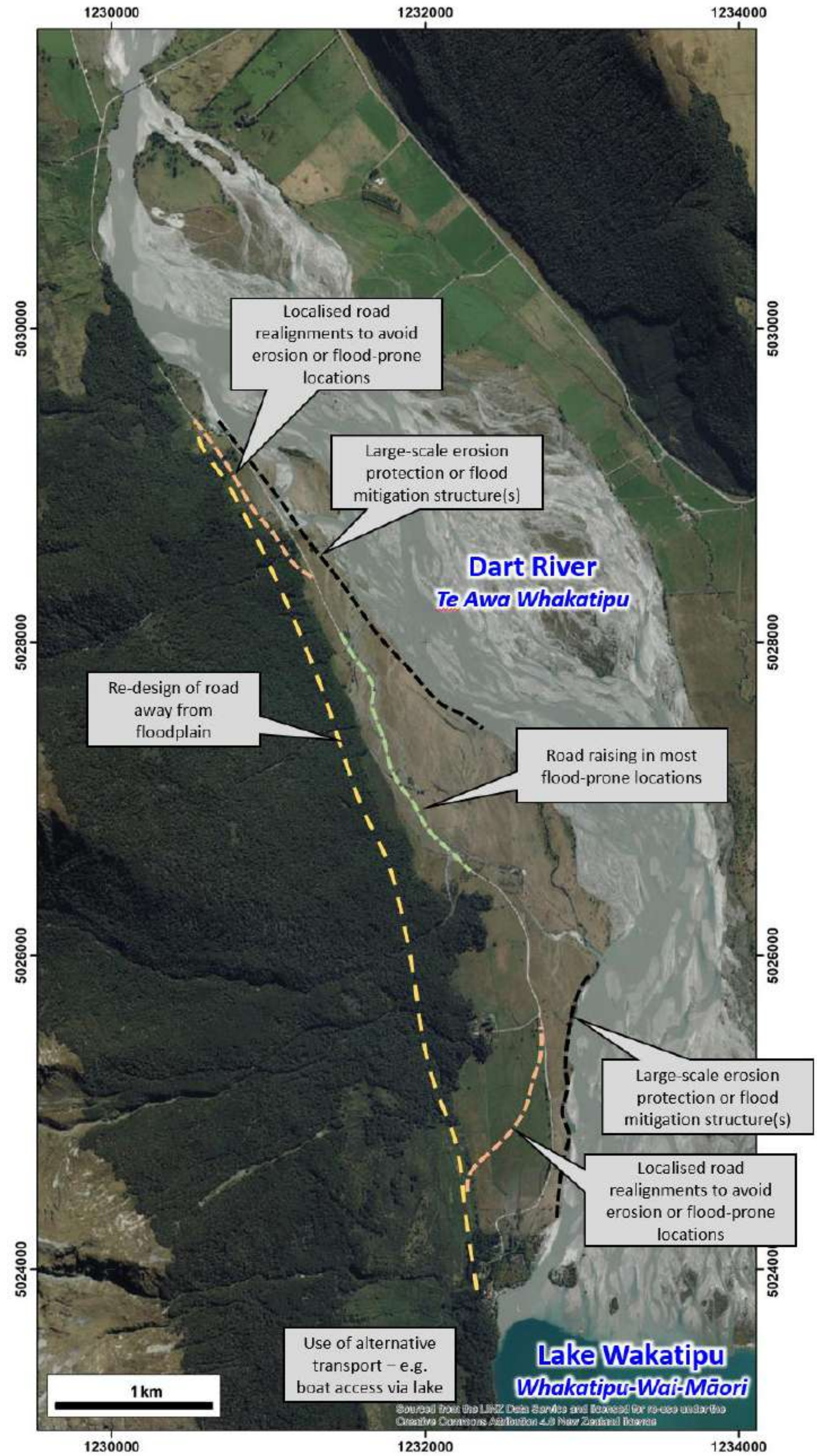


Figure 3.4: Overview of the lower Dart floodplain, showing the range of potential flood or erosion mitigation options which may be considered in order to maintain Kinloch access

3.3 Boundaries for Floodplain Adaptation Workshop

Forming an initial part of the process of applying this adaptation pathways approach, the floodplain adaptation workshop was primarily focussed on river management rather than about land-use planning controls and strategies. It also excluded responses to other hazards outside the Dart-Rees floodplain such those associated with the Buckler Burn alluvial fan or liquefaction.

3.4 Principles for Consideration in Development of Floodplain Adaptation Approach

The following principles were put forward to guide the development of adaptation pathways for the Dart-Rees floodplain area during the workshop. The principles can be grouped together under three main headings.

Natural System / Processes

- Recognition of the need to understand the underlying natural systems and processes.
- A long-term sustainable, integrated and strategic approach to floodplain risk. management, working with the natural river processes.
- Forms and levels of protection are appropriate and sympathetic to environmental amenity values.

Societal

- Widest possible benefits for community, works in with other community objectives.
- Affordable and acceptable to council, the community and direct beneficiaries.
- Sympathetic to environmental / cultural values.
- Community involvement and ownership

Political / economic

- A commitment by project partners (ORC, QLDC, DOC, Kāi Tahu) to work together.
- Adopting a precautionary approach.
- Ensuring adaptive management.
- Recognition and treatment of residual risk.
- Taking a low-regrets or even no-regrets approach to risk treatment/adaptation.
- Avoiding locking in options due to adaptation and development decisions that limit further adaptation in the future.

3.5 Workshop View of a Successful Adaptation Approach

The floodplain adaptation workshop considered that a successful floodplain adaptation approach in this context would be one:

- which has a long-term view of the situation (50+ years);
- which provides flood protection benefits;
- which has costs which are acceptable/justified;
- which considers the health of the environment and natural amenity values as key factors;

- In which the risk and benefits of alternative strategies/pathways are clearly communicated to other stakeholders;
- in which the approach is supported and acceptable to Kāi Tahu and the wider community (i.e. residents, DOC); and
- which Involves on-going monitoring of natural processes and tracking of adaptation performance.

3.6 Workshop View of Factors for Assessing Interventions

The floodplain adaptation workshop considered that the following questions need to be addressed in assessing proposed interventions as part of an adaptation approach and making a judgment on whether they are suitable and appropriate in this context:

- What are the interventions trying to achieve?
- What are the impacts?
- What are the benefits?
- What are the risks? What are the consequences of failure of specific interventions?
- How long will any river management/engineered interventions provide continued protection?
- How viable are these river management/engineered interventions in the longer-term - especially given the environmental/hazard context (e.g. ongoing riverbed aggradation, geomorphic consequences of an Alpine Fault earthquake, and climate change impacts on hydrology and flooding)?
- How are the interventions impacted by national, regional and district regulatory frameworks (e.g. National Policy Statement for Freshwater Management, the ORC Water Plan, the Resource Management Act, the District Plan etc.)?
- What on-going monitoring is required?
- What performance standards should be applied?
- What information gaps are there?

The above questions were considered during the workshop when each of the three main areas of concern on the Dart-Rees floodplain were considered. These areas are discussed in the next three section of this report.

4.0 Rees and Glenorchy Flooding

4.1 Specific Threats and Hazards

Due to the level of bed aggradation relative to the adjacent floodplain areas, the Rees River was described by Professor Brasington as "*a perched river and becoming more perched over time*" due to the unlimited supply of sediment material to feed it. This is illustrated in Figure 4.1 which shows a relative elevation model of the Dart-Rees valley floor computed by comparing valley floor levels to the average level of the adjacent riverbed. In terms of an adaptive pathways approach, the river has already reached a trigger point which largely prevents transitioning from one solution to another in such an approach.

The main hazard and threat issues for Glenorchy township were identified in Section 2.3 and Figure 2.2:

- Increasing flood hazard due to bed aggradation;
- Increasing flood hazard due to breakout flows into the Glenorchy Lagoon and the potential for permanent channel avulsion;
- Increasing flood hazard due to climate change impacts; and
- Increasing erosion hazard to existing stopbank due to the combination of ongoing riverbed aggradation and climate change impacts.

The first three flood hazards would be manifested in the occurrence of stopbank overtopping.

The erosion hazard to the stopbank could result in a stopbank breach which allow the release of floodwaters into parts of the town. A piping failure[22] of part of the existing stopbank under extreme flood conditions would also have the same effect.

As illustrated by Figure 2.13, flood inundation in Glenorchy by floodwaters originating from the Rees River (either through flood breakout into the Glenorchy Lagoon area and stopbank overtopping or a stopbank failure would mainly affect the margins of the township. However, flood inundation resulting from high lake levels in addition to fluvial sourced flooding could affect a larger part of the town (see Figure 2.3 showing the extent of flooding in the November 1999 flood event).

[22] Piping (also called "internal erosion") of an earth embankment structure takes place when water seeping through it carries soil particles away from the structure. If the seepage that discharges on the downstream side of the structure carries particles of soil (or sediment), an elongated cavity or "pipe" may be eroded backward (working upstream) toward the impounded 'reservoir' through the embankment body or foundation. When a backward-eroding pipe reaches the 'reservoir', an embankment breach can develop, forming a gap in the structure and releasing water from the 'reservoir'. Definition adapted from Unites State Association of State Dam Safety Officials, *Internal Erosion of Dams*, https://damsafety.org/dam-owners/internal-erosion-of-earth-dams.

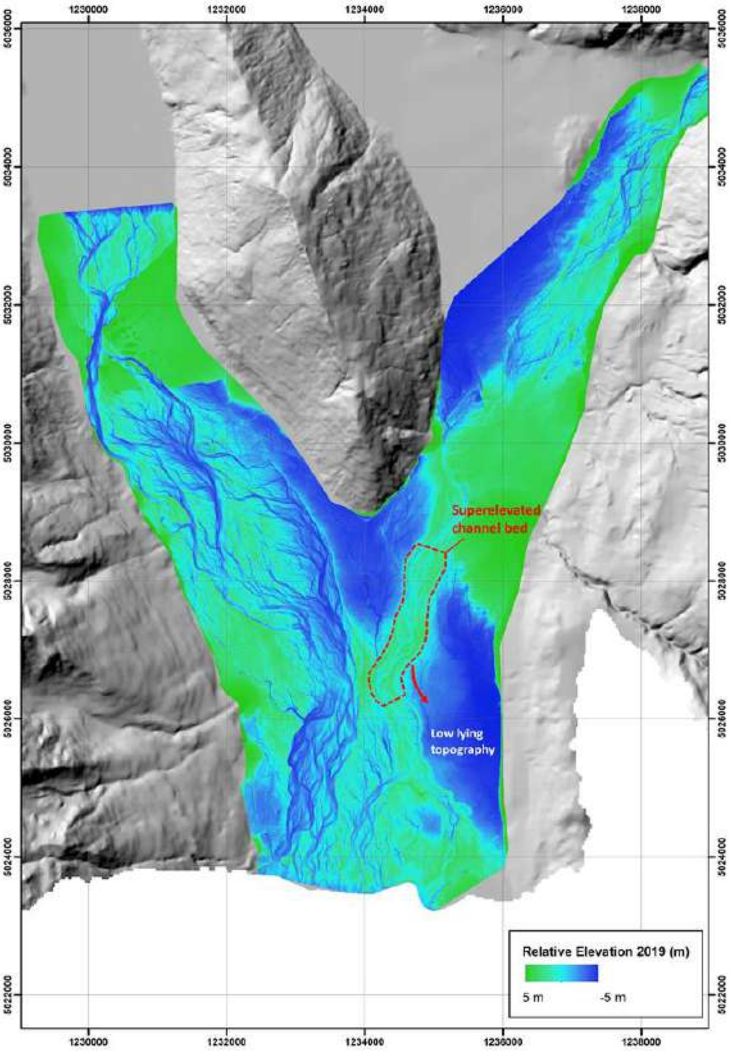


Figure 4.1: Relative elevation model of the valley floor for the Dart-Rees River System[23]

4.2 Evaluation of Community Suggestions for Intervention

Table 4.1 sets out the intervention suggestions put forward by the community for Glenorchy and provides comments on their suitability for inclusion in an adaptation pathways approach based on the information contained in Section 3.

Some of the suggested intervention options can be ruled out as ineffective or not viable. Other options are only of short-term or limited benefit and are discussed further in Section 4.3.

[23] The relative elevation model is computed by comparing valley floor elevations to average levels of the adjacent riverbed. The section of super-elevated riverbed which has been highlighted is the likely source for a potential flood breakout eastward into the lower-lying area of the wetland and Glenorchy Lagoon. The model is based on a LiDAR topographic dataset obtained in 2019.

Table 4.1: Evaluation of possible intervention options for Glenorchy suggested by community members during engagement events

Intervention	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
Raising or modifying existing stopbank structure	Intervention aims to increase level of service in short-term and provide greater scour and erosion security to existing barrier to keep floodwaters from Rees River out of Glenorchy Village. Practical short-term option but provides a false sense of long-term security and likely to result in an increased level of residual risk over time. Could be an interim measure and buy time to allow for a longer-term strategy or a strategy of raising floor levels (of existing houses) to be implemented along with new land-use planning controls.	The existing structure appears to have been constructed and maintained with a low level of engineering input (WSP, 2020a; WSP, 2020b; Tonkin and Taylor, 2021b). Any structural deficiencies will need to be remedied before the structure can be further modified. Ongoing bed aggradation will gradually reduce the level of service over time leading to an increasing fluvial hazard. Long-term bed aggradation would be exacerbated by the sediment input to the river system from a future Alpine Fault Mw 8 earthquake. Major investment in a stopbank structure makes it difficult to later retreat from the “protected” area.
Gravel extraction	Intervention would aim to lower bed levels in the Rees River in order to reduce flood levels.	Area of riverbed over which gravel extraction would be required is very extensive. Not a viable or sustainable intervention in view of the large volume of gravel material needing to be removed to lower bed levels and the large volume of sediment transported annually by the Rees River (300,000 m^3 per year from 1966-2007 into Lake Wakatipu (Wild, 2013)). Environmental impact of gravel extraction in a renowned wilderness area would be significant due to the widespread and continuous nature of the mining activity, and the problem of disposal of the extracted gravel material.
Channel realignments, such as diversion of Rees River flows into Dart River	Intervention would aim to try and divert a greater proportion of Rees River flows into the Dart River away from Glenorchy Village.	Approach would have limited effectiveness as the Rees overflow path to the Dart River is located downstream of the flow breakout points along the left bank of the Rees River. There is also no certainty over what proportion of the Rees River flow may be able to be diverted due to the braided nature of the river. Rees overflow path to the Dart River is highly dynamic and subject to continual rapid aggradation and there is no certainty that this intervention would remain permanently effective. This approach would need continuous active management to maintain some measure of diversion effectiveness (ORC currently actively monitor the overflow channel).

Intervention	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
River control structures or plantings (e.g. groynes to mitigate channel / stopbank erosion)	Intervention only aims to bolster the security of the existing stopbank by mitigating the erosion hazard to it. QLDC has recently applied some rock armouring to the most vulnerable part of the existing stopbank. Short stub groynes constructed of rock material are an alternative form of bank protection to a rock revetment type of protection (they push high flow velocities away from the bank being protected).	This intervention only provides increased erosion security to the existing stopbank, not enhanced protection from flood inundation. Other sections of the existing stopbank remain unprotected and vulnerable to attack by high flow velocities under flood conditions and as channel braids in the river shift over time. As with the existing stopbank, ongoing bed aggradation will eventually subsume groynes or other river control structures, thereby gradually reducing the level of service over time. Intervention does nothing to address the increasing flood hazard from the Rees River due to ongoing riverbed aggradation, flood breakout into the Glenorchy Lagoon and future climate change impacts.
Bunding or new structures to reduce overland flood flows into Glenorchy Lagoon	Intervention aims to block (or partially block) flood breakouts from Rees River into Glenorchy Lagoon. Glenorchy Lagoon is a Regionally Significant Wetland in the Regional Plan Water.	Blocking of flood breakouts along Rees River true left bank will cause the problem to be translocated to another point on the floodplain. This approach would require a very long structure or could be constructed as a series of partial barriers or baffles. Partial barriers/ baffles could well be washed away in an avulsion event. Intervention may provide short-term benefits for smaller floods but the level of service of any structure (or structures) would reduce over time due to ongoing bed aggradation and future climate change impacts. The Regional Plan Water has rules that limit changes affecting the functioning of a Regionally Significant Wetland. Intervention may alter wetland hydrology and therefore have potential adverse effects on lagoon ecology.
Willow management or channel modification of Lagoon Creek to enhance drainage ability from lagoon	Intervention aims to improve drainage capacity of Lagoon Creek.	This intervention would probably only have a very limited effect on lagoon flood levels. The volume of flow to be drained from the Glenorchy Lagoon in a flood breakout event is probably significantly greater than the existing discharge capacity of Lagoon Creek. Even if the discharge capacity of Lagoon Creek was doubled, this would probably only have a limited effect on flood levels in the Glenorchy Lagoon.

4.3 Evaluation of Other Possible Interventions

Table 4.2 sets out other possible intervention options for Glenorchy which were discussed during the floodplain adaptation workshop. As with the options set out in Table 4.1, comments are provided on their suitability and viability for inclusion in an adaptation pathways approach based on the information contained in Section 3.

During the workshop discussion, there were several comments made in relation to the consideration of other intervention options which are pertinent to record:

- If the benefits of any intervention are uncertain, and every large weather event is likely to "re-set" the system, then what level of cost for that intervention is acceptable needs to be carefully considered.
- There needs to be a balance between maintenance / tactical responses and major infrastructure investment for mitigating flood hazards.
- Both ORC and QLDC only have limited funds available for ongoing maintenance.
- The scope and scale of any planned river management works needs to be clearly set out in ORC's Annual Plans and Long-Term Plan, as well as clearly communicated to the community.

Table 4.2: Evaluation of other possible intervention options and strategies for Glenorchy discussed during adaptation workshop

Intervention	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
“Status quo”	The approach could possibly be adopted in a very targeted way towards a smaller number of houses as opposed to the full community now that more is known about likely flood extents and depths.	This is a hazardous approach as it ignores the reality of a (negatively) changing hazardscape affecting Glenorchy. Following this approach would need to be an informed decision at both a community and political level.
Stopbank interventions		
Retaining existing stopbank without any upgrade	The existing stopbank with its current geometry is not fit for purpose and has no defined level of service.	. There is an existing threat to life and property from floodwaters conveyed by the Rees River, which is increasing over time. The changing threat has been identified and now needs to be remedied.
Removing existing stopbank	What if the existing stopbank was not present? Based on the February 2020 flood, there would be a similar flood inundation extent in Glenorchy to what occurred in that event.	Removal of an existing structure providing some level of protection, even if that level of protection is not defined, would be a hazardous approach. The flood inundation threat is known to be increasing. The rise in floodwaters in the absence of the existing stopbank would be much faster and flooding would occur more frequently.
Local scale interventions within town		
Bunding around houses	Intervention aims to keep floodwaters away from individual houses[24].	Intervention is only suitable for isolated houses where plenty of space is available. It could have an adverse effect by diverting floodwaters towards other properties. A bund traps water if it is overtopped by an over-design flood, leaving the “protected” house within a puddle and stranding residents. Any bund is also an access constraint to the “protected” house under normal (non-flood) conditions.
Raising floor levels of existing houses	Intervention aims to raise floor levels of habitable buildings within a flood prone area to achieve a minimum level of service[24].	While the approach is feasible, it is also costly for individual houses.

[24] Clause E1.3.2 of the *New Zealand Building Code Clause E1 Surface Water* sets out a minimum performance standard for buildings with respect to floods. “**E1.3.2** *Surface water*, resulting from an event having a 2% probability of occurring annually, shall not enter *buildings* (being limited to *housing, communal residential* and *communal non-residential buildings*” (MBIE, 2020). The Building Code only applies to new building work undertaken after 1991.

Intervention	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
	The approach is feasible as has been demonstrated in Christchurch where it has been applied in low-lying areas affected by the Canterbury earthquake sequence[25]. The approach could address both lake-sourced flooding and river-sourced flooding.	If a house gets surrounded by floodwaters, residents could get stranded without warning. If houses owners make a large investment in getting a house raised, then they will likely want to stay there for a long period of time to obtain the benefit of their investment. From the flood modelling carried out for a 1 in 100 AEP flood (historic climate) in the Rees River combined with a 1 in 10 AEP flood level in Lake Wakatipu (Land River Sea, 2022), flow velocities through the inundated part of the town would likely be in the order of 0.5-1 m/s (higher across roads) with flow depths of 0.5-2.0 m. These flow depths and velocities could be potentially hazardous to people and building foundations. It is important to note that, if an avulsion event occurs into the Glenorchy Lagoon and causes the stopbank to be overtopped, the floodwaters will be carrying a lot of sediment which creates an additional hazard to buildings and properties. Effectiveness of intervention diminishes over time due to the increasing flood inundation threat . Intervention does not address the impact on utility services and roads.
Other Interventions		
Raising section of Mull St / Glenorchy-Paradise Rd at east end of town	Intervention aims to block the spread of floodwaters from the Glenorchy Lagoon area southwards across Mull St / Glenorchy-Paradise Rd. Figure 2.13 shows flood inundation extending southwards across Mull St / Glenorchy-Paradise Rd and inundating several properties in a low-lying area to the south of the road.	Raising the road level would block the spread of floodwaters into this area but could potentially create a ponding area for localised rainfall events. The number of affected properties appears small so this strategy would likely only have limited benefit.
Installation of flap-gate on culvert under Mull Street / Glenorchy-Paradise Rd at east end of town	Inundation aims to prevent the backflow of floodwaters from the Glenorchy Lagoon area southwards under Mull St / Glenorchy-Paradise Rd. The existing culvert under Mull St / Glenorchy-Paradise Rd at the east end of the town would presently allow floodwaters ponding in the Glenorchy Lagoon to backflow	

[25] https://www.ccc.govt.nz/the-council/plans-strategies-policies-and-bylaws/policies/sustainability-policies/flooding-intervention-policy

Intervention	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
	up the creek draining Bible Terrace and inundate properties to the south of the road.	
Vegetation planting in flood breakout paths to Glenorchy Lagoon area	Intervention would aim to limit the volume of overland flow to Glenorchy Lagoon. Vegetation could be planted in overland flow areas along the left bank to encourage sediment deposition and build-up of ground levels. May be an opportunity to restore the original pre-development vegetation in this area.	The effectiveness of this intervention would be reduced over time with ongoing bed aggradation in the Rees River.
Other approaches		
Flood warnings – Glenorchy Lagoon	ORC have installed level monitoring in the Glenorchy Lagoon with two alarm levels set to provide timely warning of rising flood levels.	There is currently no redundancy in the water level sensors or the communication equipment. The monitoring system needs to be made more robust (note improvements are planned in the near future). A “rate of level rise” capability needs to be explored to assess whether the monitoring system would be effective at picking up potential avulsion events from the Rees River into the lagoon area.
Flood warnings – Rees River	ORC have established a new flow gauge in the Upper Rees Valley to provide timely warning of rising flood magnitudes in the Rees River. Alert levels have not yet been defined for this gauge but will be in the near future. Civil defence authorities have been made aware of the availability of this information. ORC operates an on-call 24/7 flood monitoring / response team for responding to flood emergencies and providing support to Civil Defence authorities.	

4.4 Information Gaps and Recommended Actions

A number of information gaps were identified during the floodplain adaptation workshop discussion which require specific actions to be taken. This are grouped below under different headings.

Flood Warning / Awareness

- The level of redundancy in water level gauges and communications equipment used for flood warning purposes needs to be checked (there is currently no redundancy with the water level sensor and communications equipment installed in the Glenorchy Lagoon). The reliability of these warning systems may need to be improved with additional system redundancy.
- The flood hazard extents for Glenorchy shown on the QLDC website reflect old data based on previous flood modelling and historical flood observations. QLDC and ORC need to work together to update the flood hazard extents based on the more recent modelling work carried out by Land River Sea Consulting for ORC.
- The Emergency Management Otago flood guide for Glenorchy is still in draft form and needs to be publicly released as an operative document. The guide can be updated as the adaptation plan is developed.

Flood Forecasting

- A flood frequency model using flow data from the Rees River gauge needs to be developed as soon as practicable, and updated periodically thereafter.
- Use flood modelling to establish an approximate threshold flow value for flood breakout along the left bank of the Rees River.
- Confirm the reliability of the flood warning system including telecommunication networks and backup communication systems[27].
- Monitor when future flood breakouts occur and relate the start of these breakout events to the flows measured by the upstream Rees River gauge.

Glenorchy Lagoon and Lagoon Creek

- Undertake a channel cross-section survey of Lagoon Creek
- Undertake a computational hydraulic modelling Investigation of the interaction of Lagoon Creek and the Rees River during high flow[28].
- Could obtain bathymetric survey data for Glenorchy Lagoon – this is probably not required though as Land River Sea Consulting's 2D computational hydraulic model of the Rees River and floodplain is not very sensitive to pre flood event lagoon levels.

Robustness and Reliability of 2D Model of Rees River and Floodplain

[27] There needs to be redundancy built into the monitoring and warning systems. This was highlighted in the July 2021 flood event in the Buller River where four flood gauges failed. Note ORC uses satellite communications for collecting flood data and not the cell phone network. It also uses two sensors per flow gauge so there some redundancy built into the monitoring equipment.

[28] A coupled 1D/2D model is recommended compared to discrete 1D and 2D models to ensure that the backwater influence from the Rees River at the Rees / Lagoon Creek confluence and flow transfer between the creek and the floodplain are correctly represented.

- Uncertainty of flood inflows measured by flow gauge – ensure an adequate number of flood gaugings is undertaken at the gauge site.
- Supplement this by undertaking flood gaugings at the Rees Bridge.
- Undertake regular LiDAR / TLS[29] surveys or satellite photo analyses of the riverbed to update the Digital Elevation Model incorporated in the 2D computational hydraulic model of the Rees River and floodplain (applying corrections to the DEM for below water parts of active channel braids).
- Obtain good aerial imagery of flood extents at the peak of future large flood events.
- Collect ground observations of future large flood events (debris marks, peak flood levels).
- After future large flood events, run model simulations of each flood event with an updated riverbed profile to check model accuracy with respect to flood extents.

Glenorchy Stopbank Level of Service and Improvements

- Establish what work needs to be carried out to remedy the structural deficiencies of the existing stopbank.
- Extract long-sections of flood levels along length of stopbank from 2D model simulations of different flood scenarios to compare to the existing stopbank crest profile. Establish the current level of service of the stopbank.
- “Glass-wall” the stopbank in the 2D model and run model simulations of different breakout flow volumes to provide a better understanding of the impact of different levels of flow avulsion along the left bank of the Rees River. Use the results of these model simulations to define a range of possible stopbank improvements.
- Investigate the impact of hypothetical stopbank breach scenarios with selected stopbank improvements.

Consequences of Constructing Bunds / Bands of Heavy Vegetation on Left Bank of Rees

- Develop a delta management plan setting out how the delta will be monitored and managed in the future, i.e. how sediment aggradation will be monitored, where vegetation will be actively planted and maintained, and where vegetation will be kept clear etc.
- As part of the development of the delta management plan, explore a range of possible options for constructing partial barriers or planting dense vegetation on the left bank floodplain of the Rees River to try and limit breakout flows into the Glenorchy Lagoon from the main river.
- Undertake additional 2D model simulations for the same flood scenario to assess the effectiveness of options to limit the volume of breakout flows in the lagoon.
- Assess the implications of these options for limiting breakout flows into the lagoon on the lagoon ecology.

Building Floor Levels in Glenorchy

- QLDC to review records and determine if they already have this data.
- If not, undertake a floor level survey of residential and commercial buildings in Glenorchy.

[29] Terrestrial Laser Scanning (TLS)

- Following the floor level survey, undertake a consequence assessment using the results of the 2D model simulations to determine the number of affected properties in Glenorchy for different flood scenarios, and the magnitude to which they are affected (i.e. flood inundation depth and flow velocity).

5.0 Kinloch Road

5.1 Specific Threats and Hazards

The main hazard and threat issues for the Kinloch Road were identified in Section 2.3:

- Continual bank erosion over significant lengths of the road;
- Inundation of the road by floodwaters from the Dart River which is increasing in frequency of occurrence.
- Localised flood and debris flow events; and
- Landslides on the valley side-slopes.

Figure 3.4 shows the threat locations along the road.

As illustrated in Figure 2.7(a), the active channel belt is slowly migrating westwards such that flood flows are constantly attacking the existing bank edge requiring it to be armoured in places (refer to Figure 2.5). The westerly migration of the active channel belt is due to the transverse slope of the riverbed with bed levels higher on the east side compared to the west side. This is illustrated by three cross-sections in Figure 5.1(b) sourced from recent LiDAR data which show cross-section profiles from south-west to north-east across the riverbed and the adjacent floodplains. Figure 5.1(a) shows the location of the cross-section profiles which are aligned to coincide with the currently affected sections of the road identified in Figure 3.4.

As noted in Section 2.3, the bank erosion hazard along the right bank of the Dart River adjacent to the Kinloch Road is exacerbated by the ongoing aggradation of the riverbed.

Two areas of rock armouring protection have been applied by QLDC along the bank edge in recent years (see Figure 3.4):

- One area at the north end where the road south to Kinloch first drops off the forested valley side-slopes onto the floodplain (this is downstream of where an old river training bank – now destroyed – was located); and
- Another area nearer the village and just upstream of where the road kicks back in towards the hillside.

Other sections of the road (as marked in Figure 3.4) have been locally raised above floodplain ground levels to reduce the risk of flood inundation.

5.2 Possible Interventions

Possible interventions are shown on Figure 3.4.

The localised bank protection works and localised road raising referred to in Section 5.1 are reactive measures. Due to the scale of the aggradation problem across the Dart-Rees River System, these localised interventions are going to only have a limited lifespan, and hence effectiveness, i.e. they will only be a temporary fix.

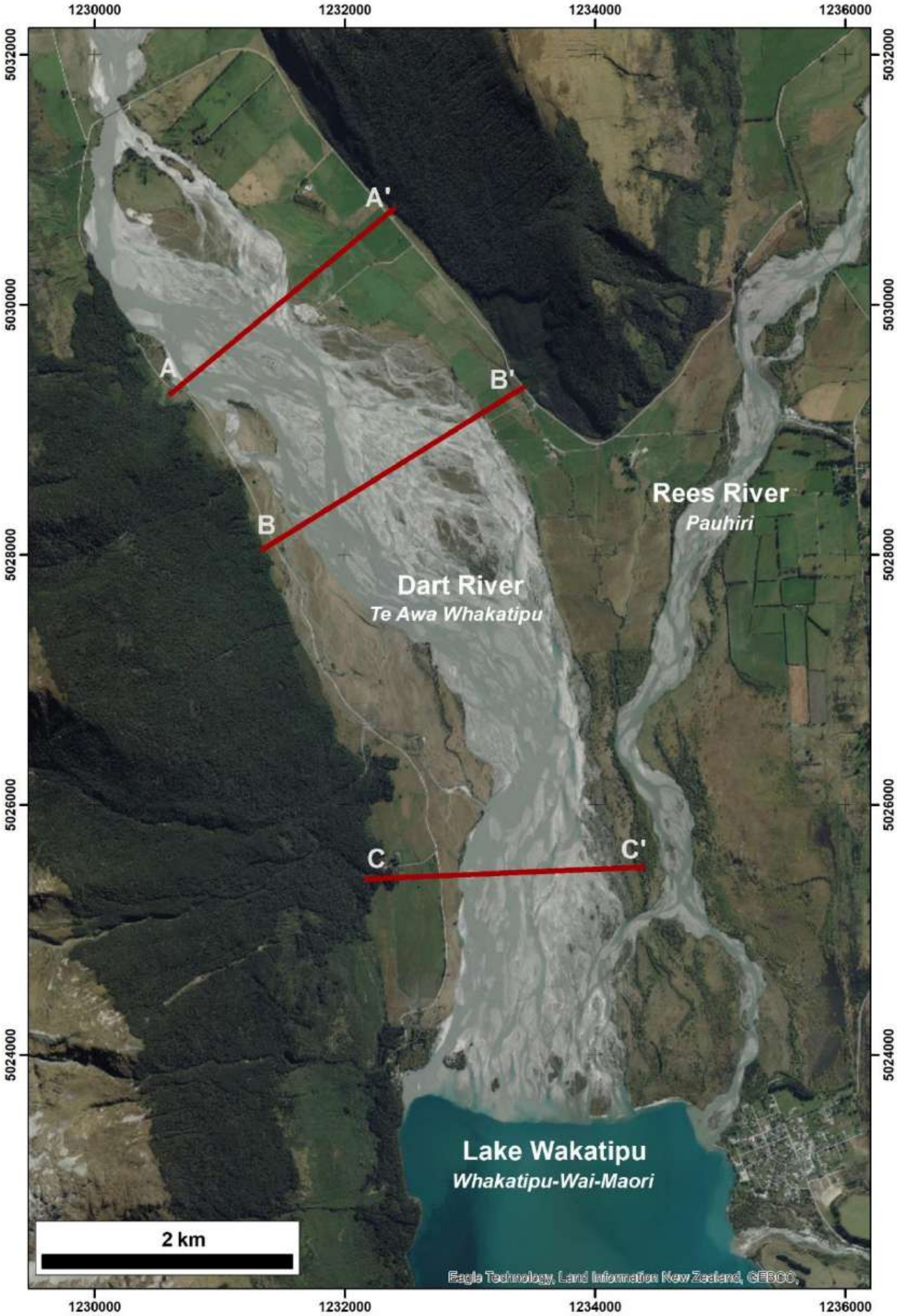
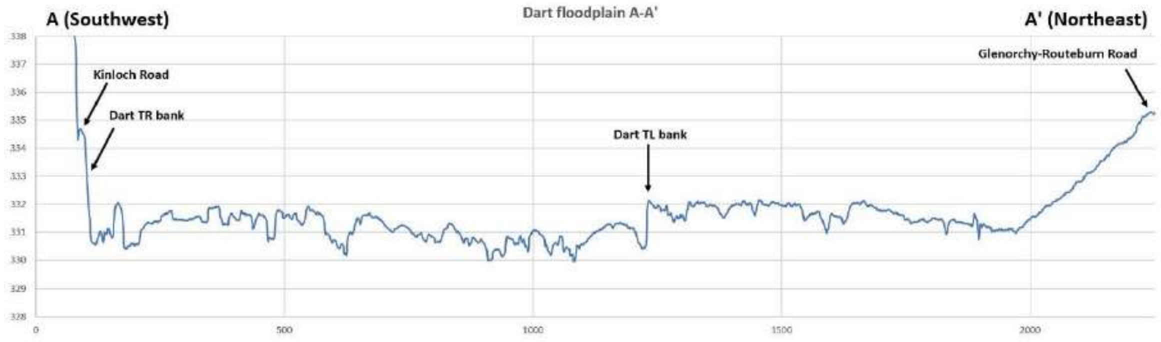
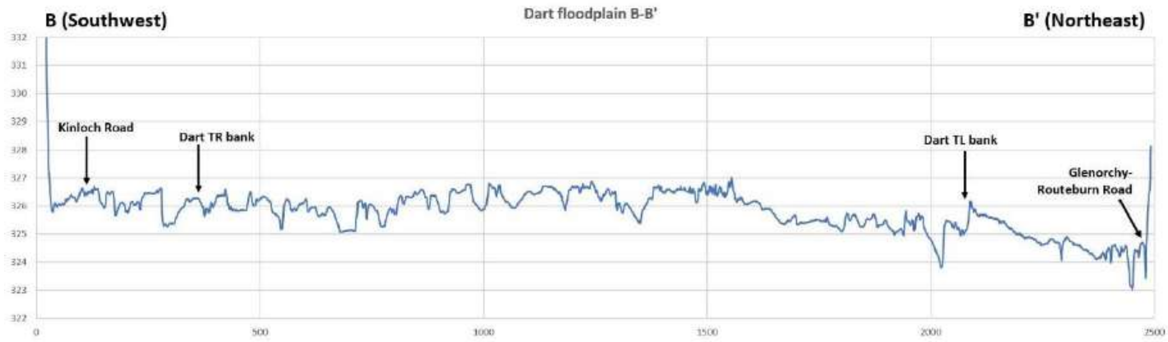


Figure 5.1(a): Location of selected Dart River cross-sections where flood flows are threatening the Kinloch Road





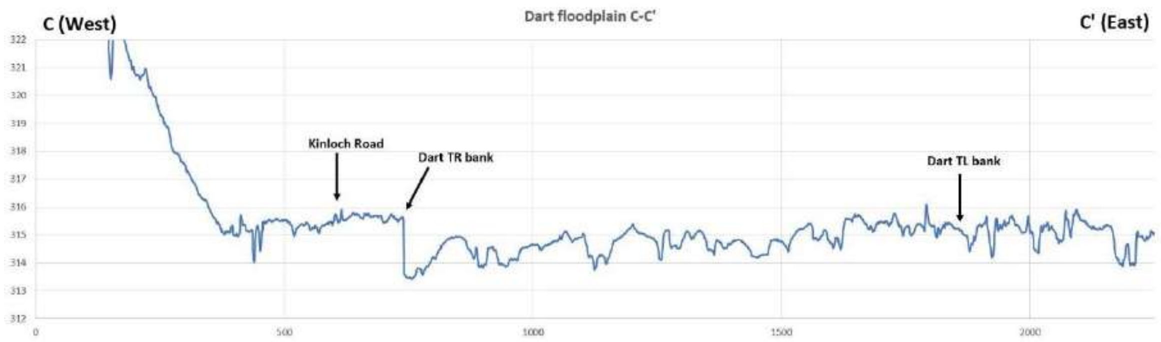


Figure 5.1(b): Profiles for selected Dart River cross-sections where flood flows are threatening the Kinloch Road

The rock that has been used for these works has been obtained from a mix of sources. Locally sourced material from the Glenorchy area has been used for ad-hoc and smaller scale repairs while the most recent works requiring a larger volume of rock have been sourced from the Queenstown area (Ben Greenwood, QLDC, pers. comm.). Rock material carted from Queenstown makes the cost of repair works quite expensive.

Another significant disadvantage of rock armouring of a bank in a braided river channel system is that the armouring tends to "suck in" braid channels and attract scour, requiring constant maintenance and often further extensions upstream and downstream beyond the original extent. Rock armouring of a bank can also be outflanked upstream and downstream.

The chance that the current east to west trajectory of the active channel belt in the Dart River will continue is very high. Rock armouring of the existing bank line may slow this trend down, but it is unlikely to have more than a 5-10 year lifespan. The next large flood could overwhelm the road.

Other intervention suggestions from the community included (see Figure 3.4):

- Large-scale erosion protection or flood mitigation structure(s);
- Re-design of the road away from the floodplain; and
- Use of alternative transport e.g. boat access across the lake.

These and other possible interventions are evaluated in Section 5.3.

5.3 Evaluation of Other Possible Interventions

Table 5.1 sets out other possible intervention options for the Kinloch Road which were discussed during the floodplain adaptation workshop. These options were evaluated for their suitability and viability. Table 5.1 also provides a summary of this evaluation with other relevant comments.

Table 5.1: Evaluation of other possible intervention options and strategies for Kinloch Road and access discussed during adaptation workshop

Intervention / Strategy	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
Large-scale erosion protection or flood mitigation structure(s)[30]	This intervention aims to arrest or slow the lateral migration of the active braid channel belt on the western side.	As noted in Section 5.2 with respect to more localised interventions of this nature, these types of structure would only have a limited lifespan due to ongoing riverbed aggradation. The approach would do nothing to address the existing flood inundation problem affecting the road which is likely to be experienced more frequently. This type of intervention is expensive. QLDC have spent $470,000 in the last five years on treating approximately 780 m of riverbank length to try and maintain access along the road. This amount is well in excess of QLDC's budget over five years for road maintenance activities and has had to be funded as emergency works.
Active river management to keep river away from road	This intervention would be aimed at separating the river from the road.	The highly dynamic nature of the braid channel pattern in the active channel belt with continual change and ongoing aggradation and channel migration makes this approach extremely challenging to implement. It would require large-scale and continuous channel modification works which would be environmentally damaging in a wilderness area. There is a high chance that such works would be ineffective in the short term due to the dynamic nature of the changing braid patterns across the riverbed. The approach would also very likely be unsustainable in the long-term due to the same dynamic behaviour of the riverbed (it is tantamount to 'fighting nature'). The cost would be very high, difficult to justify and very unlikely to be palatable to ORC, QLDC and ratepayers. The riverbed is already nearly at the level of the road in several areas and this approach does nothing to address the existing flood inundation problem.

[30] Note comparison of 1966 and 2019 right bank positions on the Dart River shows >500 m of westerly migration of the bank line in ~ 50 years. However, bank retreat is episodic and could be 20-30 m in a series of flood events, or up to 50 m in a year.

Intervention / Strategy	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
		This intervention would interfere with jetboating and other recreational activities on the Dart River. The 'keep the river away from the road' intervention would need to be fully explored in a business case developed by QLDC.
Temporary 4WD access through private land for use when existing road flooded	This strategy aims to provide an alternative temporary access route. It is an important temporary measure to investigate as a matter of urgency in order to maintain access to Kinloch most of the time and in case a section of the road nearer Kinloch is eroded away through riverbank retreat. Development of a 4WD access track could be implemented as a short-term solution in advance of the business case being drafted by QLDC for identifying a long-term solution.	The temporary access route may still not be fully passable under high flow conditions in the Dart River when the full width of the floodplain is inundated. This measure would require the cooperation of the owners of Woodbine Station (the station has recently changed ownership).
Permanent relocation of the road within the floodplain	This strategy aims to remove the road from exposure to existing flood inundation and riverbank erosion hazards. It could be a viable long-term option to maintain road access to Kinloch	This strategy would require initiating discussions with the new owners of Woodbine Station and establishing an agreement with them. Obtaining landowner agreement may take a long time and may not necessarily be achieved. This option would also need to be considered as part of a business case prepared by QLDC (the focus of the business case is not only physical access but also health and safety as people often ignore road closure signs and get stuck, requiring their rescue).
Permanent relocation of the road to the valley side-slopes	This strategy also aims to remove the road from exposure to existing flood inundation and riverbank erosion hazards. It could also be a viable long-term option to maintain road access to Kinloch. The Greenstone Road is an example of what this road could look like.	There may be legal issues with this strategy as large parts of the valley side-slopes are in the DOC estate. The environmental impact of this strategy would be more significant due to the need to clear a path through native vegetation to construct a new road. This option would lead to increased exposure to other hazards – landslides, debris flows, stream / alluvial fan flooding. This option would be more expensive than the 'permanent road relocation within the floodplain' option.
Alternatives to road access	This strategy would focus on other means of providing access to Kinloch (e.g. boat and air access).	The existing Kinloch Wharf is no longer accessible to boats due to progradation of the Dart-Rees sediment delta. There is currently no public transport funding available for a water taxi type service.

Intervention / Strategy	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
		Helicopter access is feasible but would be expensive and would require a permanent helipad at Kinloch. This option would need to be considered as part of a QLDC business case
Temporary access by boat across the lake as an emergency measure	This strategy would focus only on providing emergency access across the lake when the existing road became impassable due to flood inundation or damage. The local owner of Kinloch Lodge does operate a boat service for guests if the road is closed although this is problematic if the lodge guests have rental cars.	Delta progradation means the existing Kinloch Wharf is no longer serviceable for boat traffic. The provision of temporary access means could be required for extensive periods of time if the existing road is damaged or eroded away, or the lake remains high causing the road to stay inundated. This strategy is problematic if stranded visitors have cars (either private or rental) which they have to leave behind.

5.4 Information Gaps and Recommended Actions

The following information gaps and recommended actions were identified during the floodplain adaptation workshop discussion:

Topographic Data

- Undertake an inspection of historic aerial photographs and satellite imagery to determine detailed trends in bank line migration over time, and any hotspots[31].
- In the future, routinely obtain high-resolution satellite imagery to monitor future changes in bank lines over time.
- Obtain new LiDAR data and aerial imagery for the Lower Dart River[32].
- Analyse new LiDAR data to detect changes in bed levels and braid channel patterns.

Improved 2D Modelling

- Re-run 2D computational hydraulic model with new DEM incorporating braid channels based on 2022 LiDAR data.
- Use model simulation results to help develop possible alternative realignments of road on floodplain.
- Extract suitable information from model simulation results to support QLDC business case.

Previous Emergency Works

- Collate construction cost information on bank armouring and road raising carried out previously as emergency works to support QLDC business case.

Monitoring

- Develop a data collection plan for during and after significant flood events (Dart at the Hillocks hydrometric station flows > 1500 m^3/s).
- Obtain aerial imagery near peak of flood events.
- Fix debris marks at key locations and survey positions and levels.
- Carry out a post-event LiDAR survey of riverbed.

QLDC Business Case[33]

- Define the problem (refer Section 5.1).
- Establish who the stakeholders are.
- Identify the information needed to inform the business case.
- Start gathering the information needed to support the preparation of the business case.

[31] This work has partially been completed.
[32] Professor Brasington is planning on undertaking a repeat LiDAR survey covering this area in the 2022 calendar year.
[33] QLDC currently has a big backlog of business cases. Kinloch Road is not currently included in the QLDC Long-Term Plan. This does not preclude QLDC staff from starting work to clarify the scope of the business case and addressing data needs.

Emergency Response Plan

- Develop an immediate response plan[34] ready to implement in case the road is permanently closed before the business case is developed and considered. This includes developing a quick alternative access solution.

[34] Note that this is already in the process of being developed.

6.0 Rees Bridge and Upstream Right Bank Floodplain

6.1 Specific Threats and Hazards

The main threats to the Rees Bridge from ongoing riverbed aggradation and climate change effects were identified in Section 2.3. These include:

- Reducing bridge waterway flood capacity;
- Increasing potential for scour and erosion damage at the bridge piers and abutments; and
- Increasing potential for structural damage to the bridge from debris rafting and flood overtopping.

The bridge was originally constructed in 1958. It is currently inspected every 2 years. There was some concern about the bridge during the February 2020 flood when the freeboard under the bridge soffit was less than 0.5 m. As noted in Section 2.4, a Moxy dump truck could be driven under the bridge five years ago but this is now no longer possible due to the rise in riverbed levels from sediment aggradation.

During a site inspection prior to the floodplain adaptation workshop, it was observed that the bridge abutments appear to have no significant rock protection against scour. The left abutment is currently the most vulnerable (Figure 6.1) and there appears to be evidence of a slight amount of slumping of the approach embankment fill immediately adjacent to the structure (Figure 6.2). The right abutment appears less vulnerable with vegetation growing around and under the abutment (Figures 5.4 and 5.5). This suggests it is a long time since flood flows impinged directly on the right abutment. If flood flows are directed at an unprotected bridge abutment, there is potential for the fill in the approach embankment to be scoured out leaving the abutment undermined and flood flows outflanking the bridge structure. An immediate action should be to provide adequate rock protection to the bridge abutments, with the most urgent priority being the left abutment.

It was noted that a diffluence of braid channels exists upstream of the bridge where the main braid channel seems to pivot between left and right banks. In the 3 km long reach upstream of the bridge, there has been a mean aggradation height of about 0.3-0.35 m over the last 10 years. The highest aggradation rates in this reach are furthest upstream from the bridge. The amount of sediment deposition relative to the crest level of the existing right bank stopbank upstream of the bridge means that there exists the potential for a flood breakout onto the western floodplain. This would cause the roads to Paradise and Kinloch to be inundated. A permanent channel avulsion in this direction would sever these road connections.

Relatively small flood events in the Rees River based on measurements in the 2009-2011 field campaign (refer Section 2.5) can cause movement of 5,000-30,000 m^3 past the bridge in a single event. QLDC currently hold a resource consent to extract up to 20,000 m^3/year at the bridge but this is insignificant compared with the average volume of gravel bed material which is likely to be transported past the bridge annually. There is currently not much demand for the material and there is no desire on the part of QLDC to increase the annual take as there is no use for the material. It does not meet normal road construction specifications.

Figure 6.1: View of left abutment of Rees Bridge on upstream side from bridge

Figure 6.2: View under left abutment of Rees Bridge from upstream side of road embankment showing small amount of slumping of approach embankment fill material

Figure 6.3: View of right abutment of Rees Bridge on upstream side from bridge

Figure 6.4: View under right abutment of Rees Bridge from downstream side of road embankment

The control of sediment aggradation at the bridge is therefore not a viable solution with the volume of aggradation vastly exceeding the extraction volume on an annual basis. It is noted that there are two other active consents for gravel extraction upstream of the bridge, but the volumes taken are also small.

The main stopbank on the right bank floodplain[35] of the Rees River upstream of the Rees Bridge runs along the existing bank line seen in the aerial image in Figure 6.5. It is about 4 km long (ORC, 1999) and protects agricultural land on the floodplain as well as the roads to Paradise, Kinloch and the Routeburn Valley (the junction of the road to Kinloch and the Routeburn Valley, and the road to Paradise can be seen just to the north of the Rees Bridge in Figure 6.5). There is also evidence of a low stopbank on the left bank floodplain[36] upstream and downstream of the Rees Bridge although this is largely obscured by willow trees.

An additional secondary stopbank (Figure 6.6), which extends upstream from the Rees Bridge running parallel with the Paradise Road, can also be seen in the aerial image in Figure 6.5. It appears that this may be designed to function as a guide-bank in the event of floodwaters breaking out across the floodplain on the right bank upstream of the bridge. The guide-bank would turn flood flows back towards the bridge and force them to flow through the bridge waterway. It is noted that old paleo-channels are evident on the floodplain between the primary and secondary stopbanks in Figure 6.5 so that this area was previously part of the riverbed at some time.

Riverbed levels upstream of the bridge are now 2-3 m higher than the western floodplain and almost up to crest of the primary stopbank in places. The threat of flood breakout and even a permanent channel avulsion along the right bank with river flows bypassing the bridge is therefore very real[37]. While this type of event would impact on farmland, the primary impact would be on road access to Paradise, Kinloch and the Routeburn Valley. It could also affect a Fish and Game Lodge near Diamond Creek (at the start of the Diamond Lake track). With floodplain levels significantly lower than current riverbed levels in this area, it could be very difficult to block off river flows that had formed an avulsion path through this area.

Further upstream (out of view at the top of the aerial image in Figure 6.5), ORC maintain some rock groyne structures along the right bank which attempt to force the active channel belt over towards the left bank. The head of one of these long groyne structures (Figure 6.7) has been damaged in the past by flood activity and ORC are currently stockpiling a supply of rock to enable the damaged section to be reinstated. These structures are located too far upstream to have any influence on the behaviour of the active channel belt nearer the bridge (which will be more affected by aggradation trends across the riverbed surface). They are also only likely to remain effective in the short-term due to the level of riverbed aggradation being experienced and their low degree of submergence before being overtopped.

The scale of riverbed aggradation upstream of the Rees Bridge is such that not much can be done to mitigate the risk of a flood breakout or channel avulsion event across the right bank floodplain. The existing primary stopbank could be raised but this would increase the residual risk over time (i.e. higher impacts would result when stopbank failure in the future inevitably

[35] The main right bank stopbank upstream of the Rees Bridge was constructed by ORC in 1984 together with willow plantings adjacent to the bank (ORC, 1999).
[36] The left bank stopbank upstream of the Rees Bridge was constructed by ORC in 1996 to reduce flood overflows in that area (ORC, 1999).
[37] The main right bank stopbank required frequent regular repairs and maintenance up to 1999, including a major breach which threatened the Glenorchy-Paradise Road in January 1994 (ORC, 1999).

occurred due to the combined effects of bed aggradation and climate change) and would only buy time. This underlines the importance of understanding the location of potential channel avulsion paths across the right bank floodplain and ensuring no development or intensification occurs within those pathways in the future.

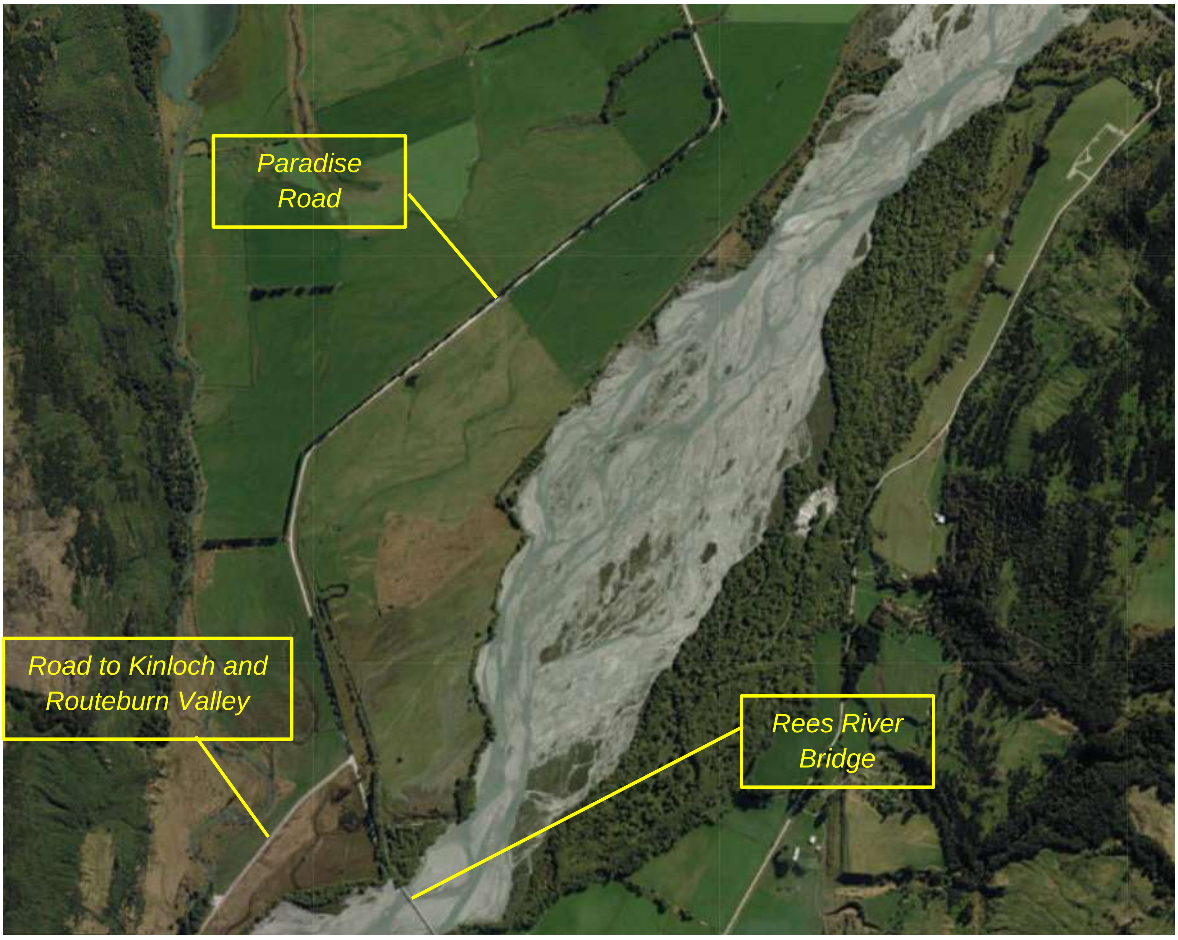


Figure 6.5: Overview of Rees River and floodplain upstream of Rees Bridge (sourced from QLDC Spatial Data Hub)

Figure 6.6: Secondary stopbank on right bank upstream of Rees Bridge which runs parallel with Paradise Road

Figure 6.7: Rock groyne structure on right bank of Rees River upstream of existing bridge (the head of the structure beyond the willow saplings in the right of the photo was damaged in a recent flood event)

It is not feasible in the long-term to either control or prevent channel avulsion from occurring somewhere across the right bank floodplain upstream of the Rees Bridge due to the unlimited supply of sediment material from the upstream catchment, the continual rapid rise in riverbed levels and the effects of future climate change. It is therefore important to be upfront in communications with local landowners and the community about:

- the threat posed by ongoing riverbed aggradation and the potential for channel avulsion to occur; and
- the increase in residual risk[38] that would result if the level of the existing primary stopbank was raised as a short-term response.

6.2 Evaluation of Possible Interventions

Figure 3.3 does not show any community suggestions for possible interventions at the Rees Bridge.

Table 6.1 sets out possible intervention options for the bridge which were considered during the floodplain adaptation workshop.

Ultimately, in view of the scale of riverbed aggradation, the bridge will need to be raised, or alternatively, replaced with a new structure. However, this is a medium to long-term solution and will require another business case to be developed by QLDC. In the interim, an ongoing programme of monitoring and investigations needs to be undertaken.

[38] Residual risk is the risk that remains after risk treatment or management has been applied to reduce the potential consequences of a hazard occurring (MfE, 2017).

Table 6.1: Evaluation of possible intervention options and strategies for Rees Bridge and upstream right bank floodplain discussed during adaptation workshop

Intervention / Strategy	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
Implement monitoring and investigations programme	Strategy aims to better quantify hazards (including changes over time), consequences and risks. Monitor riverbed aggradation over time (repeat LiDAR topographic surveys and data analysis). Use 2D computational hydraulic modelling to establish a water level / discharge rating curve at the bridge. Relate water level discharge rating data to flood frequencies. Evaluate scour risk to bridge. Evaluate structural stability of bridge including under surcharged and overtopping conditions during floods.	This strategy requires an ongoing investment in long-term active monitoring.
Install improved riprap protection of bridge abutments	Intervention aims to mitigate existing scour risk to bridge abutments. Immediate attention required as a matter of urgency (refer discussion in Section 6.1).	
Lengthen existing bridge	Strategy aims to relieve constriction of active channel belt and partially alleviate flood risk to the existing bridge. Current bridge is short relative to the width of the active channel belt upstream and downstream. Current channel belt constriction caused by bridge may accelerate gravel bed material movement past it, but may also exacerbate riverbed aggradation upstream (average bed level rise upstream was 0.3-0.35 m over 10 years to 2019). Lengthening existing bridge could assist in reducing flood levels for extreme events.	This strategy would need to consider the effects of flood breakout upstream of the bridge with flood flows bypassing the bridge. Consideration would need to be given to maintaining access across the Rees River while the bridge is being lengthened. This strategy would need to be included in QLDC's business case (noting that Waka Kotahi is a funding partner to QLDC).
Raise existing bridge	Strategy aims to alleviate current flood risk to the existing bridge. Strategy could be considered in conjunction with strategy of lengthening existing bridge. Raising the existing bridge would enable adequate freeboard to be established for design flood. Revised design flood magnitude would need to be quantified allowing for climate change effects.	The freeboard allowance for a raised bridge would need to accommodate future bed aggradation. This strategy would need to consider the effects of flood breakout upstream of the bridge with flood flows bypassing the bridge. Consideration would need to be given to maintaining access across the Rees River while the bridge is being raised.

Intervention / Strategy	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
		This strategy would need to be included in QLDC's business case (noting that Waka Kotahi is a funding partner to QLDC).
Construct new bridge	Strategy aims to alleviate current flood risk to the existing bridge and allow for futureproofing with respect to the appropriate design standards for flood magnitude and freeboard. Constructing a new bridge would enable the design flood standard with an allowance for ongoing bed aggradation and climate change effects to be achieved. Revised design flood magnitude would need to be quantified allowing for climate change effects. Consideration could also be given to making a new bridge longer than the existing to relieve the current constriction of active channel belt. Constructing a new bridge would allow the existing bridge to be used for maintaining access to Paradise, Kinloch and Routeburn Valley.	The freeboard allowance for a new bridge would need to accommodate future riverbed aggradation. This strategy would need to consider the effects of flood breakout upstream of the bridge with flood flows bypassing the bridge. Consideration could be given to a type of bridge construction that allows the bridge to be raised in the future (i.e. similar to the Waiho River Bridge at Franz Josef) to accommodate future riverbed aggradation. This strategy would need to be included in QLDC's business case (noting that Waka Kotahi is a funding partner to QLDC).
Emergency response planning	Strategy aims to have a response plan ready to implement in the event of damage to the existing bridge and / or a flood breakout / channel avulsion event on the right bank floodplain occurring before a permanent solution is implemented. Plans need to be developed for the occurrence of damage to the existing bridge and / or a flood breakout / channel avulsion event on the right bank floodplain upstream of the bridge.	
Planning controls for right bank floodplain upstream of bridge	Strategy aims to control any future development and intensification within any potential flood breakout pathways across the right bank to reduce the flood hazard to people and property.	There is a need to understand the location of potential flood breakout / channel avulsion pathways across the right bank floodplain. There is a need to compare the crest level profile along the length of the primary right bank stopbank[39] with adjacent riverbed levels. There is a need to establish a crest level profile along the length of the secondary stopbank /guide-bank running parallel with the Paradise Road.

[39] The crest level profile of the right bank stopbank was surveyed in 2020 by ORC.

Intervention / Strategy	Comments	Key Challenges for Inclusion in Adaptation Pathways Approach
		There is a need to implement planning controls to preclude further development and intensification within the area of potential flood breakout / channel avulsion pathways across the right bank floodplain.
Raise existing primary stopbank on right bank floodplain upstream of bridge	Strategy aims to improve the current level of protection against flood breakout on the right bank floodplain.	This strategy is a short-term solution only due to ongoing riverbed aggradation. It increases the residual risk to farmland and roads on right bank floodplain.
Raise existing secondary stopbank on right bank floodplain upstream of bridge	Strategy aims to improve the current level of protection against flood breakout on the right bank floodplain.	There is a need to understand the location of potential flood breakout / channel avulsion pathways across the right bank floodplain to know if this strategy would be effective, or more effective than raising level of existing primary stopbank This strategy may also only be a short-term solution due to ongoing riverbed aggradation.
Extend existing secondary stopbank on right bank floodplain further upstream	Strategy aims to improve the current level of protection against flood breakout on the right bank floodplain.	There is a need to understand the location of potential flood breakout / channel avulsion pathways across the right bank floodplain to know if this strategy would be effective, or more effective than raising level of existing primary stopbank This strategy may also only be a short-term solution due to ongoing riverbed aggradation.
Establishment of left bank flood breakout path upstream of bridge	Strategy aims to improve the current level of protection against flood breakout on the right bank floodplain with or without raising the primary or secondary stopbanks. Vegetated area on left side of Rees River upstream of bridge is lower-lying land and was previously active channel (i.e. 1966 aerial image shows this). Could remove vegetation to form a 250-300 m wide preferential breakout flow path over a 3 km distance upstream of bridge to ease pressure on right bank and reduce risk of channel avulsion occurring across right bank floodplain.	The likely effectiveness of this strategy is uncertain and needs to be investigated. Land ownership needs to be investigated. The existing Rees Bridge remains a pinch point for flood flows and this strategy does nothing to improve waterway capacity past the bridge.

6.3 Consideration of Other Monitoring and Investigation Techniques

In view of the uncertainty in the future behaviour and evolution of the Rees River upstream of the bridge, several other monitoring and investigation techniques to aid in improving the understanding of this were considered during the floodplain adaptation workshop.

One of the drawbacks of the existing 2D computational hydraulic model of Rees River is that it assumes a fixed bed based on the riverbed topography at the time of the LiDAR survey (i.e. it does not include a sediment transport component which allows for the morphology of the riverbed to change over time in response to flood activity). It is possible to develop 2D morphological models which track sediment movement and evolution of the bed morphology over time. These are good only for short-term forecasting of bed morphology change and require detailed knowledge of the prior bed topography. They diverge significantly from observed bed morphology changes over the long-term in actual case studies. Therefore, it is not considered that this technique would provide reliable or robust predictions of future riverbed evolution in this context.

Physical hydraulic modelling is another alternative technique. For the scale of the problem in this context, the size of the model would need to be very large which would make such a study very expensive. No hydraulics laboratory in New Zealand has the required capacity or the capability for a model of the size required. Even if it was practical to construct a large model, there are still likely to be scale effects (e.g. with correctly reproducing sediment transport rates). The recent physical hydraulic model projects (e.g. the Dart-Rees River System delta and the Shotover River delta) carried out in New Zealand used micro-scale models which had significant limitations to what they could represent.

Despite the limitations of 2D fixed bed computational hydraulic modelling, it is still the best approach available in conjunction with on-going observation and monitoring to assist with managing the flood hazard in the Upper Rees River. This type of model is a useful tool to help better understand what might happen in an avulsion event on the right bank floodplain upstream of the Rees Bridge as well as for visually communicating results to inform the community and decisionmakers.

One of the critical information needs to manage the flood risk associated with the Rees Bridge is to establish a water level / discharge rating relationship at the bridge site, and to monitor changes in this relationship over time in response to ongoing riverbed aggradation. The conventional approach to doing this would be to install a pressure transducer at the bridge to provide a continuous record of water levels over time and relate water level measurements to flow measurements at the upstream Rees at Invincible hydrometric station. However, there are practical difficulties with such an approach at this site as the main braid channel keeps flopping from side to side and there may be differences in water levels between braid channels. A more suitable approach would be to install a special camera system[40] at the bridge and use a Particle Image Velocimetry (PIV) technique to measure water levels and discharge at the bridge site.

[40] e.g. https://www.seba-hydrometrie.com/products.html?L=1&tx_sebaproducts_sebaproducts%5bproduct%5d=299&tx_sebaproducts_sebaproducts%5bprimarycategory%5d=3&tx_sebaproducts_sebaproducts%5bsecondarycategory%5d=&tx_sebaproducts_sebaproducts%5baction%5d=show&tx_sebaproducts_sebaproducts%5bcontroller%5d=Product&cHash=95452a37634fdd583904cc07ef1fd983

This technique is currently being used in NZ by Marlborough District Council and Horizons Regional Council.

6.4 Information Gaps and Recommended Actions

Riverbed Monitoring

- Undertake 2022 LiDAR topographic survey of riverbed and repeat surveys thereafter to monitor riverbed aggradation over time.
- Analyse LiDAR survey data to establish long-term bed aggradation trends (noting that there will be periods of slower and faster aggradation linked to flood activity and sediment pulses).
- Consider installation of a terrestrial laser scanner (TLS) on Mt Alfred to enable high frequency DEMs of the area to be obtained[41].

Existing Stopbank Crest Levels

- Use LiDAR data to establish a crest level profile for the primary right bank stopbank upstream of the Rees Bridge and compare this to adjacent riverbed levels.
- Use LiDAR data to establish a crest level profile for and the longitudinal extent of the secondary stopbank upstream of the Rees Bridge and parallel with the Paradise Road.

Computational Hydraulic Modelling

- Extend the existing 2D computational hydraulic model of Dart and Rees River System upstream to the Rees at Invincible hydrometric station with new 2022 LiDAR data.
- Carry out model simulations to establish a water level / discharge rating curve at the bridge.
- Use the model to identify flood breakout flow paths and potential avulsion pathways on the right bank floodplain upstream of the Rees Bridge.
- Use the model to investigate the establishment of preferential flood breakout flow path along the left side of the active riverbed upstream of bridge (refer further to “Upstream Floodplain Management Investigations” below).

Bridge Investigations

- Relate water level / discharge rating data at bridge to estimated flood frequencies.
- Establish current flood capacity of bridge waterway in terms of estimated flood frequencies and allowing for adequate freeboard allowance for bridge soffit.
- Determine the critical point in terms of acceptable capacity for the bridge waterway (a trigger to signal a required change in adaptation response).
- Assess the risk posed by pier and abutment scour to the bridge, including consideration of pressure scour when flood flows are surcharged on the bridge deck, or overtopping the bridge deck.

[41] TLS surveys are routinely used in the mining industry. A terrestrial laser scanner can scan over about a 6 km distance within the line of sight. The data captured could be analysed by contract or on an as required basis. Acquisition of such a scanner is currently the subject of a research proposal (Professor James Brasington, pers. comm.).

- Undertake a structural stability assessment of the bridge including for floods surcharging against bridge, and overtopping bridge.
- Determine design flood and freeboard values for either a raised bridge or a replacement bridge (design freeboard value needs to account for future riverbed aggradation).
- Consider how continued access to Paradise, Kinloch and Routeburn Roads can be maintained while the existing bridge is being raised (the existing bridge would provide this access if a new bridge is constructed).

QLDC Business Case

- Define the problem (refer to Section 6.1).
- Establish who the stakeholders are.
- Identify the information needed to inform the business case.
- Start gathering the information needed to support the preparation of the business case.

Emergency Response Plan

- Develop an immediate response plan ready to implement in case the bridge is temporarily damaged before the business case is developed and considered. This would need to consider a range of damage scenarios[42].
- Develop an immediate response plan ready to implement in case a flood breakout and channel avulsion event occurs along the right bank upstream of the bridge.

Upstream Floodplain Management Investigations

- Check land ownership details for vegetated land on left bank upstream of the Rees Bridge which was previously part of the active riverbed.
- Undertake 2D computational hydraulic modelling using the latest LiDAR data to investigate the viability of forming a controlled spillway / overland flow path across the left bank floodplain.
- Investigate removal of low vegetation over a 250-300 m wide strip to form a 3 km long controlled spillway / overland flow path across the left bank floodplain.
- Estimate costs of vegetation removal using information from similar previous work.
- Investigate revegetation of the right bank with willows as new edge protection.

Bridge Monitoring

- Use the extended 2D computational hydraulic model of the Rees River based on 2022 LiDAR data to estimate a water level / discharge rating relationship at the Rees Bridge.
- Consider installation of a PIV camera system at the Rees Bridge to help track changes in the water level / discharge rating relationship at the site over time and hence the change in flood risk.

[42] Typical damage scenarios would include scour of one of the abutments with flows partially outflanking the bridge, slumping of the bridge deck due to the occurrence of pier and / or pressure scour, lateral deformation and rotation of part of the bridge induced by flood surcharging and overtopping, and deposition of fine sediment and woody debris material on the bridge deck due to overtopping.

7.0 Summary and Conclusions

7.1 Introduction

The conclusions presented in this section are outcomes from the floodplain adaptation workshop and should not be inferred to represent solely the views of the author of this report.

7.2 Glenorchy and Lower Rees River Floodplain

Due the perched nature of the Rees River and trend of it becoming more perched over time, there are probably no viable options for engineering / river management to prevent flooding from the river at Glenorchy or the occurrence of an avulsion event into the lagoon area. Therefore, the focus should be on preparing to manage the impacts of this inevitable event and / or mitigating those impacts or delaying the event ocurrence.

In the immediate short term, this could involve:

- Flood warning improvements.
- Revision and communication of flood response procedures.
- Consideration of improvements to the existing stopbank (e.g. raising the crest profile, improving the structural quality and integrity).
- Investigation of vegetation planting on the left bank of the Rees River where flood breakouts into the lagoon area occur.

In the medium or longer term, other strategies could be considered:

- Building-scale interventions (e.g. raising floor levels of existing buildings).
- Planning responses (e.g. preventing further intensification, setting a revised minimum floor leve)l
- Retreat of buildings in the highest-risk areas.

Planning for these possible medium and longer term strategies would need to start in the immediate short term.

It needs to be emphasised that any upgrade of the existing stopbank will be a short-term measure only. It should be communicated very clearly and carefully to the community that the purpose of the stopbank improvements is to reduce the current flooding threat to the town from the river.

ORC and QLDC will need to work together to:

- inform the community of new information on natural hazard risks;
- convey this information in an understandable way and why some flood mitigation options are not viable;
- develop improved flood warning systems and updated flood response procedures;
- incorporate new flood hazard information into the planning framework; and
- compile critical information to support the investigation, planning and implementation of any longer-term options.

7.3 Kinloch Road and Dart River Floodplain

The Kinloch Road is closed relatively frequently due to inundation by floodwaters from the Dart River overflowing the right bank or flood damage. The frequency of flood inundation has been increasing over time due to ongoing bed aggradation and this trend is expected to continue in the future.

The road is also threatened by bank erosion on the right bank. The current westerly migration of the active channel belt along the right bank is expected to continue in the future due to the transverse slope across the riverbed. Since the 1960's, the long-term bank erosion rate has been > 10m/year in places and could be up to 50 m/year if a series of consecutive large flood events occurred.

The current reactive management approach for the road of localised raising of the road formation and localised rock armouring of sections of the right bank are of limited benefit and not sustainable in the longer term. In the case of rock protection works, it is also expensive.

The development of any business case for larger-scale interventions on the Kinloch Road will not happen quickly due to competing higher-priority works in the QLDC area.. Therefore, there is a need to develop a plan for interim / emergency measures for implementation whenever road access is cut:

- An interim measure could be a temporary farm access track through Woodbine Station. This would require negotiations and an agreement with the landowner. However, it needs to be pursued with some urgency.
- An emergency access measure could be a barge / water taxi arrangement. However, this would still need to be supported by a business case.

The only longer-term solutions to maintain road access which are viable would be either relocation of the road within the floodplain or relocation of the road onto the western hillslopes. The first relocation option would have significant land ownership issues. The second relocation option has several constraints such as legal and land ownership issues, and increased exposure to other hazards. It would also have higher costs and a longer lead time. Any permanent road relocation with either option would need to be supported by a detailed business case by QLDC.

7.4 Rees Bridge and Upstream Right bank Floodplain

Widespread aggradation upstream of the Rees Bridge has not only reduced the bridge waterway capacity but created the potential for an avulsion event across the upstream right bank floodplain. Riverbed levels along the right bank are now approaching the crest of the primary stopbank in places and are higher than adjacent floodplain levels. This significantly reduces the level of service of the primary stopbank. The main impact of an avulsion event would be on road access to Paradise, Kinloch and the Routeburn Valley although it would also affect farmland and a Fish and Game Lodge near the confluence of Diamond Creek.

It is not feasible to control or prevent an avulsion event from the Rees River upstream of the bridge. However, work can be done now to manage the consequences of such an event. A better understanding of potential avulsion flow paths across the right bank floodplain needs to be obtained with the aid of 2D computational hydraulic modelling based on updated LiDAR topographic data. Planning controls need to be considered to ensure no future development or intensification of development occurs within these potential avulsion pathways.

One river management intervention worth exploring to lower the risk of an avulsion event on the right bank is to provide increased channel capacity with clearance of willows and other vegetation on the left bank which historically was part of the active riverbed.

Further investigation and monitoring of the Rees Bridge is required including:

- hydraulic modelling to determine a current water level / discharge rating relationship at the bridge and to understand flood patterns when the flood capacity of the bridge waterway is exceeded;
- establishing the current flood capacity of the bridge waterway and determining a critical point in terms of adequate flood capacity;
- assessing the scour risk to the bridge;
- assessing the structural stability of the bridge;
- monitoring of floodwater levels at bridge; and
- tracking shifts in the water level / discharge rating relationship at the bridge due to ongoing bed aggradation.

One urgent action than needs to be taken is to bolster the scour protection at the abutments of the existing bridge.

An emergency response plan also needs to be developed as an immediate priority to implement in case:

- the Rees Bridge is temporarily damaged; and / or
- a flood breakout and channel avulsion event occurs along the right bank upstream of the bridge.

A business case needs to be developed for the longer term by QLDC to consider longer-term options for the Rees Bridge. These options could include raising the existing bridge or constructing a new bridge. Maintaining access to Paradise, Kinloch and the Routeburn Valley during any construction works will be a significant consideration.

8.0 References

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Appendix A

Floodplain Adaptation Workshop Programme and Briefing Notes

Dart-Rees Floodplain Hazards Adaptation Workshop (Online, 23-24 February 2022)
Finalised Programme

Participants: ORC: Jean-Luc Payan, Tim van Woerden, Michelle Mifflin, Pam Wilson, Scott Liddell, Craig Hughes
QLDC: Ben Greenwood, Hugo De Cosse Brissac, Bill Nicoll, Mark Baker, Alison Tomlinson
James Brasington (University of Canterbury)
Matt Gardner (Land River Sea Consulting)
Grant Webby (Damwatch Engineering)
Jamie MacKenzie (University of Otago – observer only)

Day / Time	Session	Contributors
Day 1 - 23rd February 2022		
0830-0845	**Welcome and Introduction**	Jean-Luc to facilitate, all
0845-0945	**Context - Part 1 (defining the problem)** - Overview - Community setting - QLDC and infrastructure overview - Hazardscape review	Jean-Luc to facilitate Tim Tim QLDC Tim
0945-1000	*Break for morning tea*	
1000-1130	**Context – Part 2 (defining the problem)** - Summary of natural hazard adaptation project - Geomorphic characteristics - Flood hazard assessment	Jean-Luc to facilitate Jean-Luc James Matt
1130-1145	*Break*	
1145-1230	**Adaptation Pathways Approach / Objectives / Principles** - Introduction to approach - Community engagement findings summary - Discussion of key questions to address - Discussion of objectives for adaptation - Workshop boundaries (what is excluded from consideration) - Discussion of principles for adaptation - Discussion of what successful adaptation approach looks like - Discussion of assessment factors for interventions	Jean-Luc to facilitate Tim Tim Jean-Luc to facilitate, all
1230-1330	*Break for lunch*	
1330- 1530	**Natural Hazard Challenge - Rees River and Glenorchy flooding** - Summarise specific threats / hazards - What specific adaptation interventions are available? - Assess each intervention against list of evaluation factors (impacts, benefits, risks / consequences of failure, durability over time,	Jean-Luc to facilitate, all

	viability in longer term, regulatory / policy constraints) - Does intervention satisfy objectives for adaptation? - Can specific interventions be knitted together to provide a long-term adaptation pathway?	
1530-1545	*Break for afternoon tea*	
1545-1645	**Natural Hazard Challenge - Rees River and Glenorchy flooding** (continuation of previous session)	Jean-Luc to facilitate, all
1645-1730	**Wrap-up for Day 1** - Summarise key points & conclusions for Rees River and Glenorchy flooding - Programme for Day 2	Jean-Luc

Day 2 – 24th February 2022		
0830-0835	**Welcome to Day 2**	Jean-Luc
0835-1000	**Natural Hazard Challenge – Dart floodplain and Kinloch Road** - Summarise specific threats / hazards - What specific adaptation interventions are available? - Assess each intervention against list of evaluation factors (impacts, benefits, risks / consequences of failure, durability over time, viability in longer term, regulatory / policy constraints) - Does intervention satisfy objectives for adaptation? - Can specific interventions be knitted together to provide a long-term adaptation pathway?	Jean-Luc to facilitate, all
1000-1015	*Break for morning tea*	
1015-1115	**Natural Hazard Challenge – Rees Bridge and Rees true right floodplain** - Summarise specific threats / hazards - What specific adaptation interventions are available? - Assess each intervention against list of evaluation factors (impacts, benefits, risks / consequences of failure, durability over time, viability in longer term, regulatory / policy constraints) - Does intervention satisfy objectives for adaptation? - Can specific interventions be knitted together to provide a long-term adaptation pathway?	Jean-Luc to facilitate, all
1115-1230	**Workshop wrap-up** - Summarise key points & conclusions for Dart	Jean-Luc

	floodplain & Kinloch Road - Summarise key points & conclusions for Rees Bridge - Where to from here? - Next steps	
1230-1330	*End/Lunch*	
1330-1430	**Time for additional discussions if needed**	

ORC – Head of Lake Wakatipu natural hazards adaptation programme

Briefing notes for Dart-Rees floodplain hazards adaptation workshop

1. Introduction and background

The Dart-Rees floodplains and delta at the head of Lake Wakatipu are subject to both flooding and erosion hazards. These hazards impact on the township of Glenorchy, and the wider rural communities of Kinloch and Greenstone through disruption of road access. ORC is utilising the Dynamic Adaptive Planning Pathways approach recommended by MfE as a framework for hazards adaptation pathways activities in this project area.

The proposed adaptation workshop is intended to be a first-pass review of all possible flood mitigation and floodplain management options. This will help to identify and understand which of these approaches may be feasible, environmentally acceptable and cost-effective, and to prioritise and justify any next steps such as more detailed investigation.

2. Natural hazards challenges at the Dart-Rees

The key natural hazard issues relating to the Dart-Rees floodplains are noted in bullet points below, and summarised in section 4 below.

- Dart floodplain and Kinloch road access – flooding of floodplain causing road closures, and westwards erosion of active river channel towards roadway.
- Lower Rees floodplain and Glenorchy – flooding within Glenorchy township caused by high flows in the Rees River, and/or high levels in Lake Wakatipu
- Rees bridge – aggradation impacting on bridge capacity

A key factor in understanding those natural hazards issues are the geomorphic processes of this floodplain environment – this is a dynamic, multi-hazard environment, characterised by actively aggrading riverbeds and a prograding delta shoreline.

3. Project scope and objectives

Preliminary notes on the project direction are summarised below, showing our thoughts on the key questions, objectives and factors which will need to be considered.

Questions

- What does sustainable river management look like for the Dart-Rees and what does it offer?
- What does sustainable flood protection look like and what level of protection is realistically achievable?
- What other complementary strategies are available to achieve natural hazard resilience (e.g. planning controls)?
- Can we define principles for an ORC river management strategy in this location?

Project Objectives

a) An understanding of viable, sustainable river management approaches, suitable for the floodplain/river environment of the Dart-Rees area.
b) An estimation of how long, or under what conditions these approaches might remain effective.
c) An understanding of key constraints/factors for river management interventions (costs, environmental, cultural, feasibility, community acceptability etc).
d) How these approaches might fit within wider content of natural hazard management and adaptation (e.g. planning responses, potential retreat)
e) Specific review of risks/benefits of all options identified by the community during engagement activities.

Intervention assessment factors

- What is intervention trying to achieve?
- What are impacts?
- What are benefits?
- What are risks?
- How much time will river management/engineered interventions provide?
- How viable are these river management/engineered interventions in the longer-term? – especially given the environmental/hazard context (e.g. ongoing riverbed aggradation, geomorphic consequences of an Alpine Fault earthquake, and climate change impacts on hydrology and flooding).

Success factors

- Provides flood protection benefits
- Costs are acceptable/justified
- Health of the environment must be a key factor.
- Risk and benefits of alternative strategies/pathways communicated to other stakeholders
- Approaches are supported and acceptable to all of wider community (e.g. residents, DOC, Kai Tahu).

4. Natural hazards overview

Rees River and Glenorchy

Glenorchy township is located at the head of Lake Wakatipu, the lower-lying locations of the residential area are exposed to flooding and have been flooded on several occasions over the period of settlement, most recently in December 1999 (Figure 7) and February 2020 (Figure 2, 3). The township area has a complex hydrological setting, where flooding may be sourced from the Rees River, Lake Wakatipu, or Buckler Burn, (or a combination of these sources).

In this dynamic environmental setting, the flood hazard for the Rees River floodplain and Glenorchy township is continually being influenced and modified by changes to geomorphology[1] (e.g.

[1] Brasington, 2020, 2021

aggradation and erosion, delta progradation) and climate[2] (hydrological changes to rainfall and river flow variables).

An existing floodbank, owned and managed by QLDC, at the northern margin of Glenorchy township provides flood protection from low-moderate flood events. This structure may be overtopped by larger events, as occurred in February 2020. Initial assessments of bank erosion and floodbank stability by WSP[3] (2020a,b) have identified several issues of concern, and the highest priority of these are planned to be addressed by QLDC. ORC, on occasion, also carries out river management works in this area such as localised gravel extraction or channel realignments, but recognises these provide only limited and short-term benefits.

In December 2019 and April 2020, ORC has undertaken community engagement activities for natural hazards adaptation with the local community[4]. These have been designed to present and discuss the natural hazard issues of the area, and to initiate conversations regarding possible adaptation approaches or interventions to manage these hazards. For management or mitigation of flood hazards at Glenorchy, community members have raised a number of possible interventions for consideration, including structural or river management approaches such as (Figure 1);

- Raising or modifying the existing Rees-Glenorchy floodbank structure
- Gravel extraction (e.g. to reduce aggradation rates)
- Channel realignments, such as diversion of Rees River flows into the Dart River.
- River control structures or plantings (e.g. groynes to mitigate channel erosion).
- Bunding or new floodbanks to reduce overland floodwater flows from the Rees River to the Glenorchy lagoon.
- Willow management or modification of Lagoon Creek to enhance drainage ability from lagoon.

A distinct but related Rees River issue has been ongoing concerns regarding aggradation of the river bed at/near the road bridge structure. This would raise the flood stage at the bridge, reducing the bridge's hydraulic capacity and making it more vulnerable to floodwater or debris impacts.

Surveyed cross sections since the mid-1980's have indicated a mean aggradation trend in these reaches of the Rees, a finding which complements many anecdotal reports from the community. LiDAR differencing analysis (e.g. Figure 5) does not currently extend as far upstream as the Rees bridge, but analysis of a recently acquired new LiDAR survey (captured mid-August 2021) may help to understand these aggradation patterns with more resolution.

Dart River and Kinloch access

The terrestrial access to the Kinloch, Greenstone and Caples areas is by way of the Kinloch Road. Sections of this road are located on the Dart River floodplain, and access is typically disrupted through flooding on multiple occasions each year (e.g. >10 times in 2019-20), and has been closed for periods of up to about a week (Figures 9 and 10). Flooding impacts appear to have increased in frequency and severity in recent years, attributed to both aggradation of the riverbed levels, and the main Dart river

[2] NIWA, 2019
[3] WSP, 2020 a, b
[4] ORC, 2021

channel being located nearer to the western side of the active riverbed and thus nearer to the roadway.

The westwards migration of the Dart River over at least the last 50 years has brought the river's active channel near to the roadway in many locations (Figure 11), and is now directly threatening the road margins in several sites (e.g. Figure 12). It is expected to become increasingly difficult to maintain road access using the current approach of reactive management to localised issues as they arise – e.g. the installation of rock armouring for erosion control.

Based on discussions with the local community, and within the ORC hazards team and project consultants, a range of potential adaptation approaches have been identified to maintain access to these areas (Figure 8).

1. **Status quo (reactive repair):** Localised erosion protection and road raising etc as required to manage highest priority erosion hotspots or flooding issues.
2. **Local realignment:** Realignment of sections of road from areas threatened by erosion or most highly flood-prone (but still remaining on floodplain).
3. **Hard engineering:** Installation of larger-scale erosion or flood protection structures.
4. **Redesign:** Relocation of erosion or flood-prone sections of road from floodplain to adjacent hillslopes.
5. **Alternative transport:** Use of alternative transport modes (e.g. boat access).

Relevant technical reports[5]

Brasington J (2020) Statement of evidence of James Brasington on behalf of the Otago Regional Council, 1 December 2020. In the matter of an application for resource consent RM191318 by Blackthorn Lodge Glenorchy Ltd.

Brasington J (2021) Fluvial hazards at the top of the lake – living with rivers on the edge. Public presentation for the Glenorchy community, 7 April 2021.

GeoSolve, 2016. Flood Protection – Kinloch Road / Dart River. Prepared for Queenstown Lakes District Council, June 2016

ORC (2010) Natural hazards at Glenorchy. May 2010.

ORC (2020) Observations on February 2020 flood event. ORC file note dated February 2020

ORC (2021) Natural hazard adaptation in the head of Lake Wakatipu. Report to council, 27 May 2021

Tonkin + Taylor (2021) Head of Lake Wakatipu Natural Hazards Assessment. Prepared for Otago Regional Council, March 2021

WSP (2020a) Glenorchy Floodbank Rees River. Memo prepared for Otago Regional Council, June 2020.

WSP (2020b) Glenorchy Rees floodbank: floodbank assessment. Prepared for Otago Regional Council, September 2020.

[5] Most of these references are already available online via the ORC website, but any others can be provided as required.

Figures

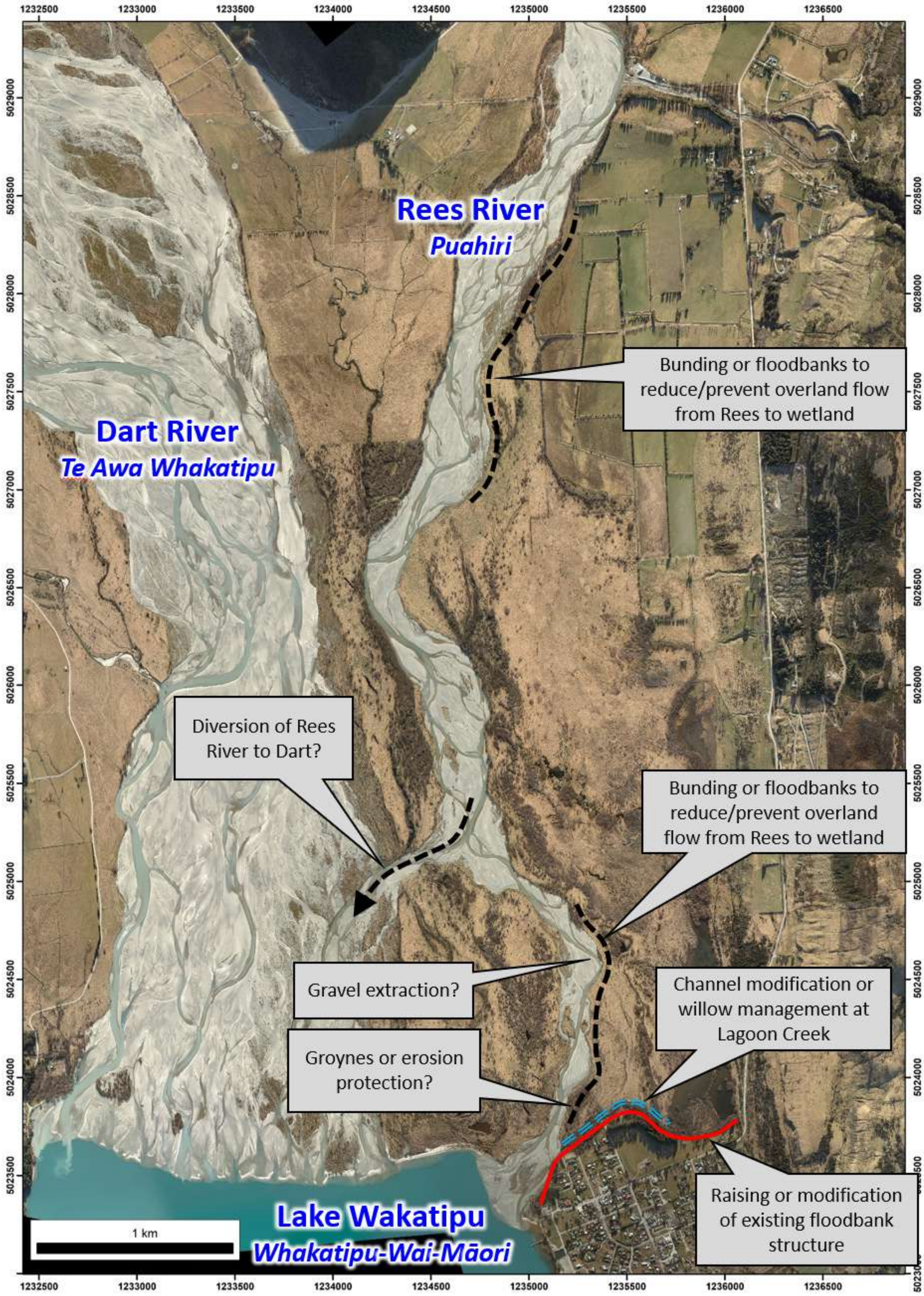
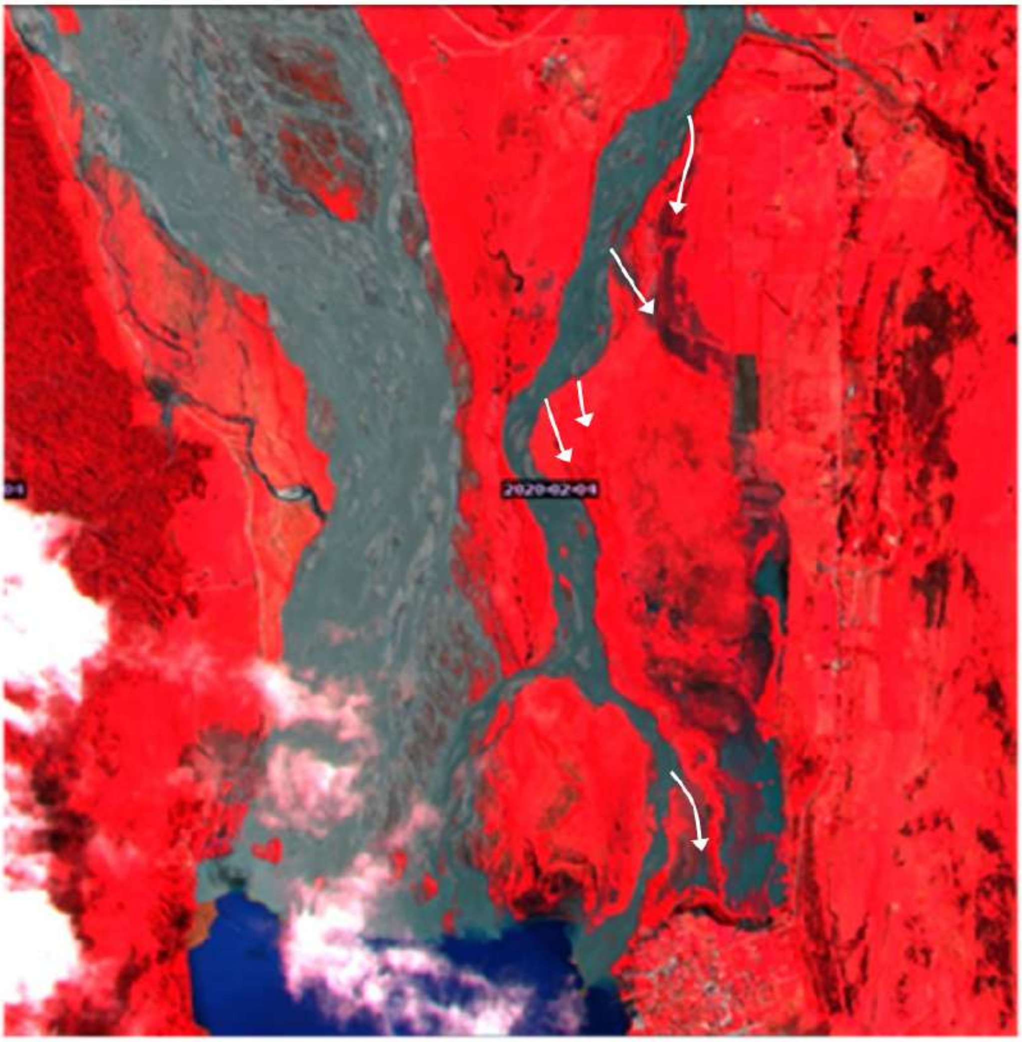


Figure 1: Overview of the lower Dart-Rees floodplain, showing the range of potential flood mitigation options for the Rees River and Glenorchy township suggested by the local community.

Figure 2: Flooding of the township in February 2020. In this event, floodwaters from the Rees River filled the Glenorchy Lagoon to the crest level of the adjacent Glenorchy floodbank and then overtopped to flow through the northwest margins of the township.

Floodwaters filled much of the Glenorchy recreation ground and golf course, before flowing along the northern/northwestern margin of the township to enter Lake Wakatipu near the lower end of Mull Street, with flooding of residential areas at the northern ends of Oban and Argyle Streets, and along much of Butement Street. Following the flood, inspections also noted increased erosion impacts to the section of the Glenorchy floodbank adjacent to the Rees River.

The key factors in this flood event are interpreted as; 1. the sustained, high flows in the Rees River, with overland flows eastwards into the wetland area, and 2. the backwater effects of elevated lake levels on flows in the lower Rees River, and on the drainage of the Glenorchy Lagoon. (Photo credit: Luke Hunter)



4 FEBRUARY 2020

Figure 3: A false colour composite image captured shortly following the Glenorchy flood event of 4th February 2020. This shows surface water coloured grey, annotated to illustrate a series of overbank flood pathways (arrowed) eastwards from the main Rees channel.

There have been several community suggestions for works (e.g. bunding/floodbanks) to reduce the impact of floodwaters taking these flow paths. (Image provided by James Brasington)

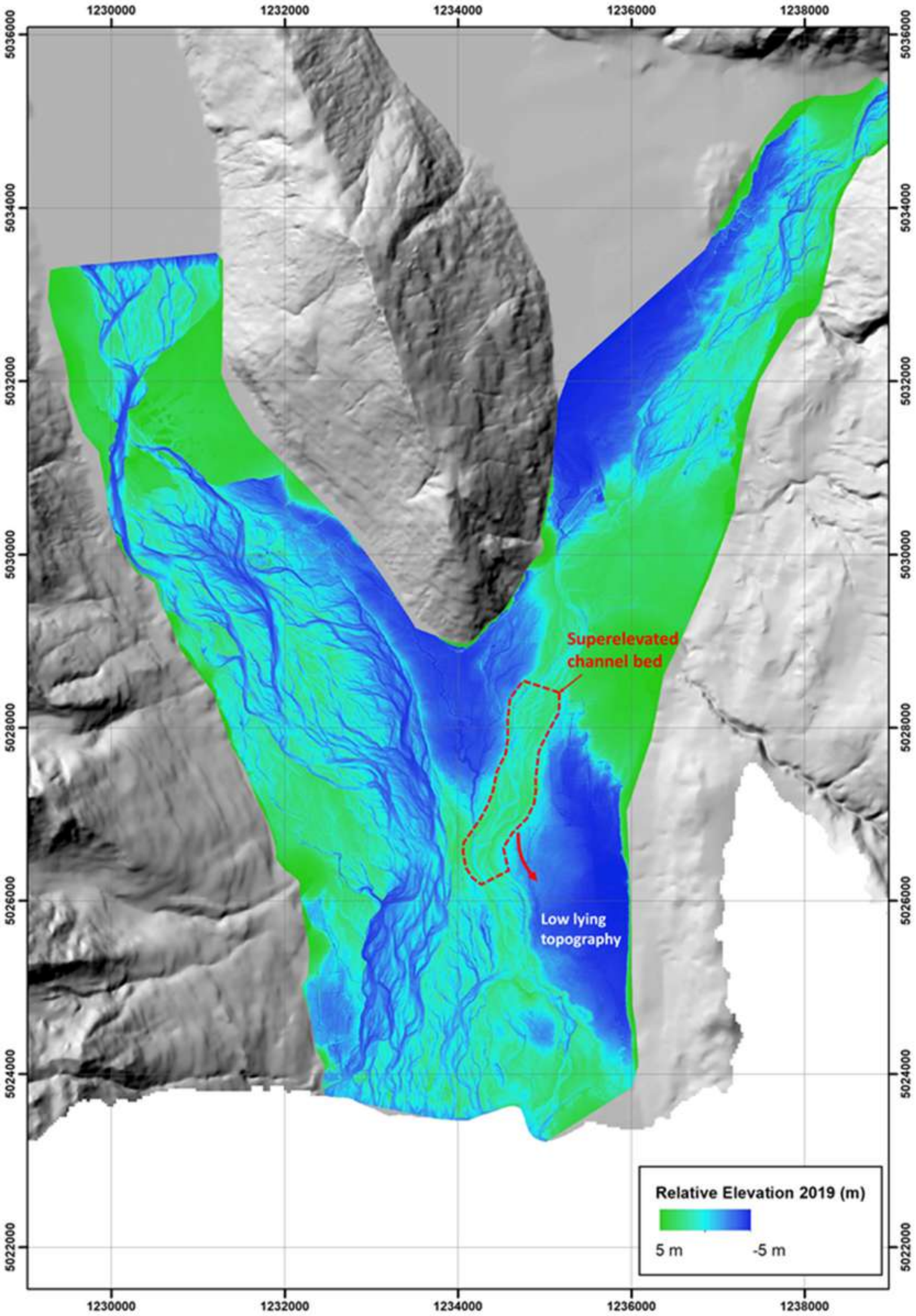


Figure 4: A relative elevation model of the Dart-Rees valley floor, comparing the valley floor elevations to the adjacent average level of the river bed. This clearly shows the section of Rees River superelevated above the valley floor, and posing a potential threat of an avulsion event. (Analysis and image by James Brasington)

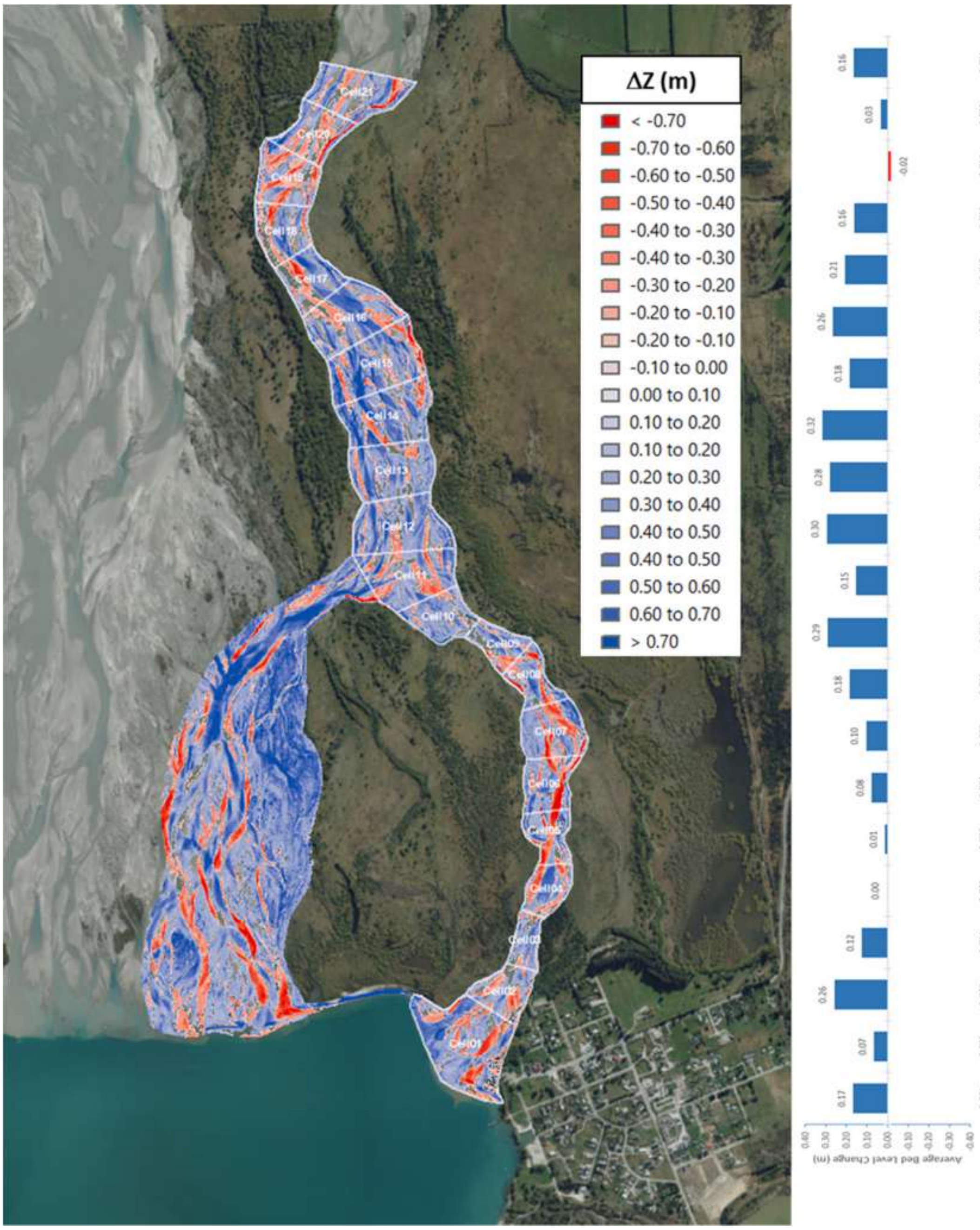


Figure 5: Map of bed level changes on the Rees River from 2011 and 2019. This shows a dominantly aggradational river system, with sedimentation (blue) outweighing erosion (red) for all reaches in the lower Rees. (Analysis and image by James Brasington)

Figure 6: Vertical aerial photograph of Glenorchy township during the January 1994 flood event.

Figure 7: Vertical aerial photograph of the lower Dart-Rees floodplain and delta, and Glenorchy township during the November 1999 flood event.

Figures: Dart floodplain and Kinloch access

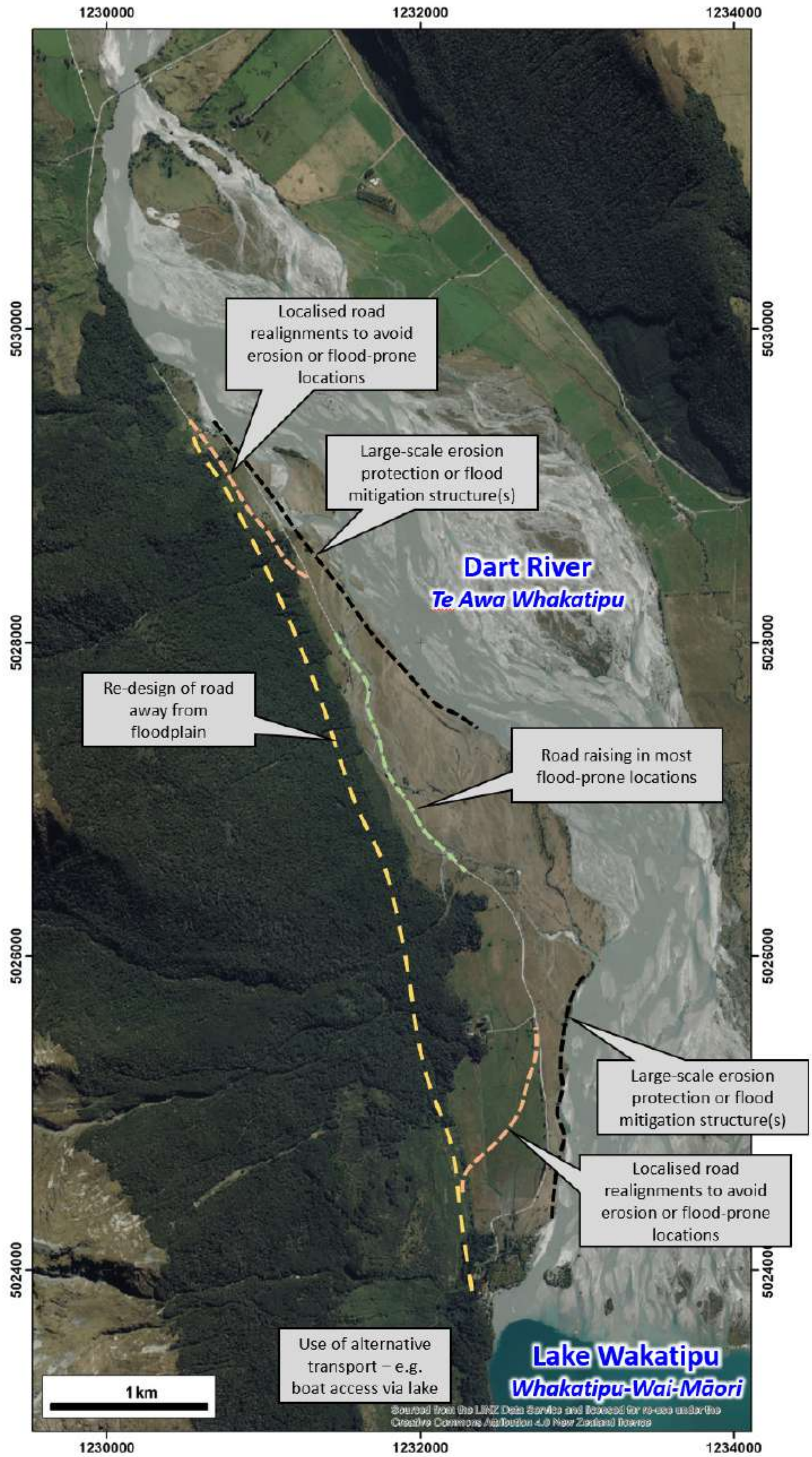


Figure 8: Overview of the lower Dart floodplain, showing the range of potential flood or erosion mitigation options which may be considered in order to maintain Kinloch access. These possible options based on suggestions provided by community.

Figure 9: Flooding of the lower Dart floodplain in a moderate 2019 flood event. This shows the Kinloch Road closed due to flooding of sections between Glacier Burn and Turner Creek.

Figure 10: Flooding of the lower Dart floodplain in the March 2019 flood event where the Dart River peaked at ~1800 cumecs. Upper photo shows the road near the delta closed due to the combination of river flooding and high lake levels. Lower photo is looking up-valley and shows flooding between Glacier Burn and Turner Creek.

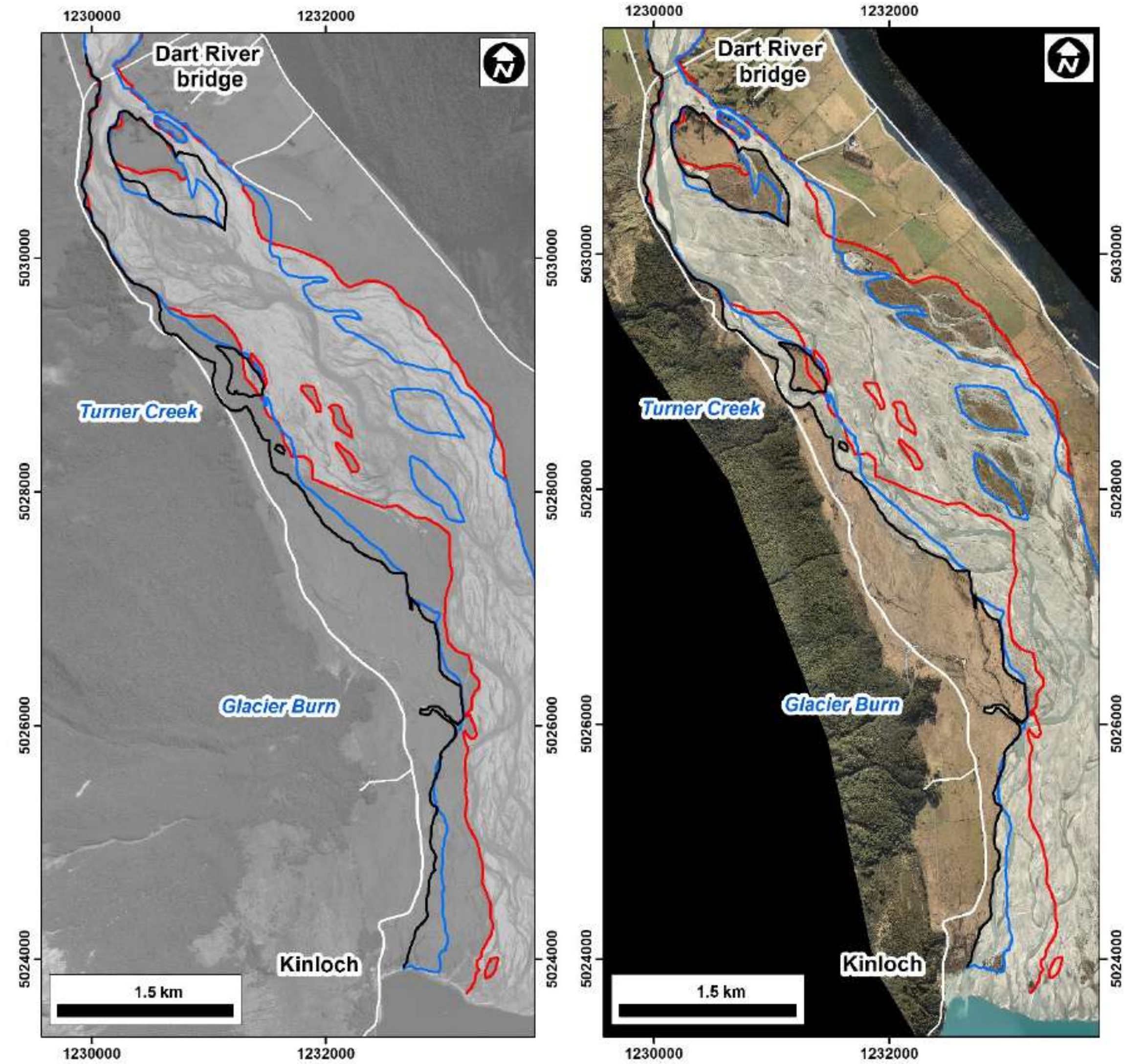


Figure 11: Comparison of aerial imagery for the lower Dart floodplain in 1966 (left) and 2019 (right). Annotation shows the river bank positions in 1966 (red), 2006 (blue) and 2019 (black), illustrating the dominant westwards migration of the active Dart River bed during this time period.

Figure 12: Aerial views (October 2020) of the Dart floodplain between Turner Creek and Kowhai Creek confluences (upper left) and between Glacier Burn and the Dart delta (lower left). Right-hand images show detail of erosion at these locations, taken February 2020 (upper right) and November 2020 (lower right).

Appendix B

ORC Presentation

HEAD OF LAKE WAKATIPU NATURAL HAZARDS ADAPTATION

Floodplain hazard mitigation approaches workshop

23-24 February 2022

Otago Regional Council | QUEENSTOWN LAKES DISTRICT COUNCIL | UC UNIVERSITY OF CANTERBURY | LANDRIVERSEA CONSULTING | DAMWATCH ENGINEERING BEYOND THE SURFACE

1

WELCOME and INTRODUCTIONS

ORC Natural Hazards	Jean-Luc Payan (Facilitator) Tim van Woerden
ORC Engineering	Michelle Mifflin Pam Wilson Scott Liddell
QLDC	Ben Greenwood Hugo De Cosse Brissac Bill Nicoll Mark Baker Alison Tomlinson
Damwatch Engineering	Grant Webby
University of Canterbury	James Brasington
Land River Sea Consulting	Matt Gardner
University of Otago	Jamie MacKenzie (observer)

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2

WORKSHOP PROGRAMME

J-L to add simplified schedule here

- Tim – overview and community 10 min
- QLDC - 30 min
- Tim – hazardscape – 20 min
- James – 30 min plus questions
- Matt - 30 min plus questions
- Jean-Luc – Summary of HOTL Adaptation project - 15 min
- Tim – Adaptation pathways intro and community engagement – 10 min
- All – discussion on adaptation principles etc – 35 min

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3

ENVIRONMENTAL SETTING

4

COMMUNITY SETTING

Total population of about 500

Centred on Glenorchy township, Also rural settlement – Kinloch, Paradise, Greenstone, Rees valley, Wyuna

Main businesses – tourism, farming

Peak of >1000 daily tourist visitors (pre-Covid).

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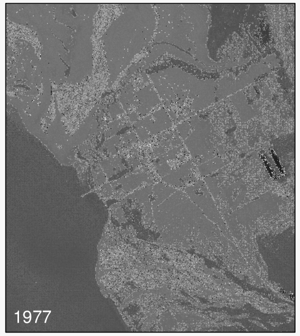
COMMUNITY SETTING

Rapid population growth since ~1980s

Resident population (census data for wider Glenorchy area)
2001: 270
2018: 450

Projected annual growth for Glenorchy township in residents, houses and visitors

	2018	2048
Residents	390	450
Total houses	230	250
Visitors (average day)	1,000	1,420



References:
NZ Census
Utility Ltd, 2018.

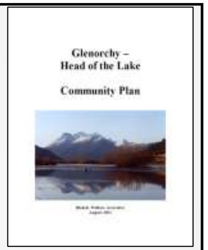
6

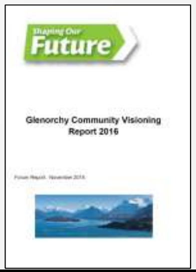
COMMUNITY SETTING

"A vibrant community where lifestyle and 'freedom' are highly valued together with the **peaceful, unspoilt rural environment** and the dynamic interaction of the **spectacular landscape, heritage and wilderness**."

Selected community vision and outcomes statements:

- The uniqueness of the area - the wilderness, scenery and quality of the landscape to be retained
- Activities to be low impact and 'fit' and respect the environment
- Flood management and repair to be visually acceptable as well as functional
- The community to be involved in decision making regarding development of the area





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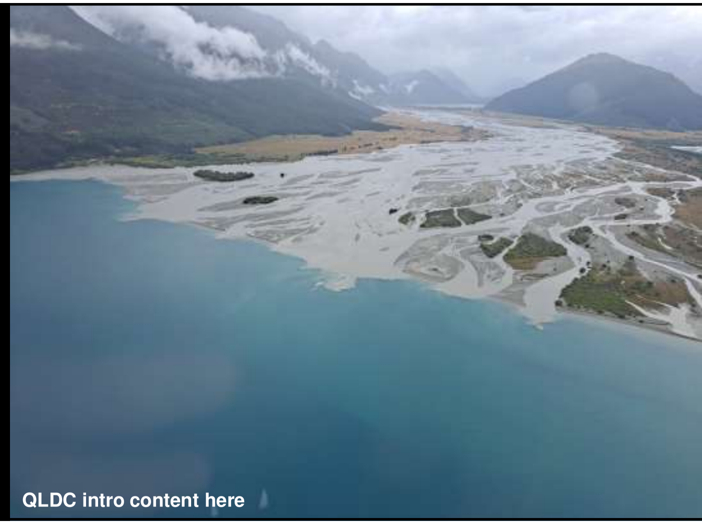
References:
Glenorchy – Head of the Lake community plan, 2001
Glenorchy community visioning report, 2016

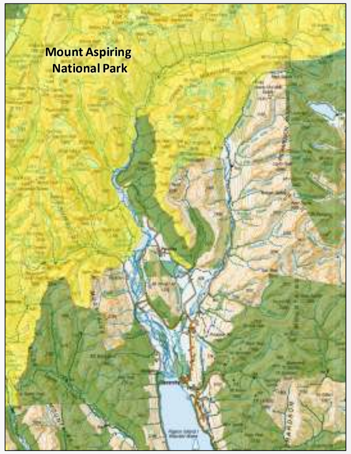
7



8

CONSERVATION

- Gateway to Mount Aspiring National Park and Te Wāhipounamu – South West New Zealand World Heritage Area
- Access to Routeburn (a NZ Great Walk, ~15,000 walkers in 2018), and many others – Greenstone-Caples, Dart-Rees.
- Extensive areas of DOC-managed reserves/conservation areas
- 5x ORC 'regionally-significant' wetland areas
- DOC conservation area and significant wetland in lower Rees and Glenorchy Lagoon.
- ORC collaborated with DOC for willow clearance at lagoon in 2020
- ORC have been providing updates to DOC throughout this project



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References:
DOC, 2011. Mount Aspiring National Park management plan.
DOC, 2016. Conservation Management Strategy - Otago.

9

IWI VALUES

"Whakatipu-wai-Māori holds generations of Kāi Tahu histories, the knowledge of which holds the same value for Kāi Tahu today. Kāi Tahu taoka (treasures) cover the landscape; from the ancestral mauka (mountains), large flowing awa (rivers), tūpuna roto (great inland lakes), pounamu and ara tawhito (traditional travel routes/trails). **These all make the area immensely significant to mana whenua.**"

Very high cultural values, to both Otago and Murihuku rūnaka.
- Widespread use and settlement
- Traditional travel routes
- Traditional resources (e.g. mahinga kai, pounamu)

Two sites designated as tōpuni (recognition of Kāi Tahu values on prominent landscape features):
- Pikirakatahi (Mount Earnslaw),
- Te Koroka (Dart/Slipstream)

- 3x high country stations returned to Ngai Tahu as part of treaty settlements (Elfin Bay, Greenstone, Routeburn).
- Several Ngai Tahu tourism businesses based in Glenorchy (Dart River Jet, kayak, horse riding, heli flights)

References:
Aukaha, 2021. Cultural values statement, Dart-Rees natural hazards project
Ngāi Tahu Ka Huru Manu Atlas (*kahuruumanu.co.nz/atlas*)
Te Rūnanga o Ngāi Tahu website (*ngaitahu.iwi.nz*)

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IWI VALUES

ORC have been providing updates to Iwi (Aukaha, Te Ao Marama) throughout this project

Aukaha has prepared a cultural values statement summarising Mana whenua associations and cultural values

Cultural values
- Mana
- Mauri
- Whakapapa
- Ki Uta ki Tai - 'from the Mountains to the Sea'
- Kaitiakitaka - 'guardianship', responsibility to provide an enhanced quality of life for future generations
- Manaakitaka
- Mahika kai
- Wai Māori and Wai Ora - protecting and enhancing the wellbeing of all bodies of water
- Maumaharataka
- Whakawhanaukataka

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References:
Aukaha, 2021. Cultural values statement, Dart-Rees natural hazards project
Ngāi Tahu Ka Huru Manu Atlas (*kahuruumanu.co.nz/atlas*)
Te Rūnanga o Ngāi Tahu website (*ngaitahu.iwi.nz*)

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HAZARDSCAPE

Wide range of potential natural hazard impacts

High potential for cascading hazards scenarios

Dynamic/ non-static hazardscape;
- Geomorphic changes
- Climate change

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HAZARDSCAPE
Glenorchy

Wide range of potential natural hazard impacts

High potential for cascading hazards scenarios

Dynamic/ non-static hazardscape;
- Geomorphic changes
- Climate change

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References:
ORC, 2010. Natural hazards at Glenorchy
T+T, 2021. Head of Lake Wakatipu natural hazards assessment

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HAZARDSCAPE
Cascading Hazards

Complex and inter-related hazards relationships,
- e.g. geomorphic consequences of a major earthquake

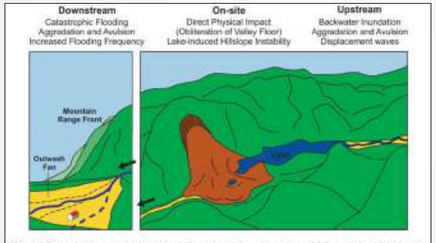
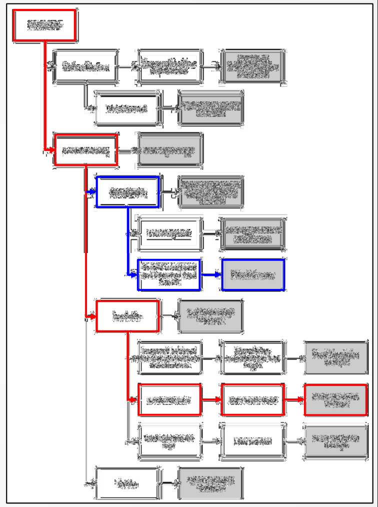


Figure 5.7: Sketch of geomorphic hazards which may result from formation and failure of a landslide dam in a mountain-foreland system (redrawn from Korup 2005a).



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References:
ORC, 2010. Natural hazards at Glenorchy
T+T, 2021. Head of Lake Wakatipu natural hazards assessment

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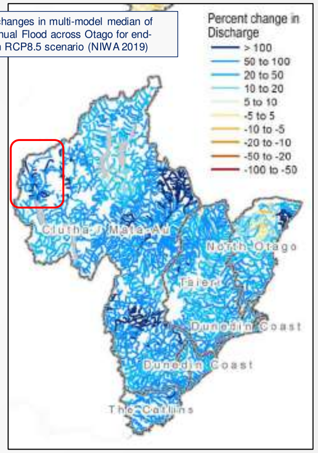
CLIMATE CHANGE

Projected increases in …
- Mean annual rainfall
- Extreme rare rainfall events
- Flood magnitudes
- Sediment transport (and aggradation rates?)
- Mean lake levels?

Dart River, 1% AEP flood
- Current climate: 2,420 cumecs peak flow
- RCP8.5 scenario: 2,900 cumecs peak flow (~20% increase)

Percent changes in multi-model median of Mean Annual Flood across Otago for end-century in RCP8.5 scenario (NIWA 2019)



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References:
NIWA, 2019. Climate change projections for the Otago Region
ORC (Mohssen), 2021. Analysis of Flood Hazards for Glenorchy

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MAIN HAZARDS ISSUES FOR FLOODPLAN HAZARD MITIGATION

1. **Glenorchy township Rees River flooding hazard**
   - Increasing flooding hazard – aggradation relative to dwellings/floodbank
   - Avulsion hazard
   - Climate changes
2. **Kinloch access**
   - Increased flooding hazard to road with riverbed aggradation
   - Continued westwards erosion of Dart River
3. **Rees Bridge**
   - Rees aggradation at bridge reducing capacity?
4. **Rees true right floodplain upstream of bridge**
   - Increasing flooding hazard – aggradation relative to floodbank?
   - Road access to Paradise
   - Flood impact to farmland



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A LONG HISTORY OF FLOODING …

Notable flood events
- 1878 – Lake Wakatipu reached 312.6m
- 1924 & '25
- 1952 – original Rees bridge washed away
- 1978

"The Rees and Dart Rivers have joined forces and become one raging torrent" (1952)

"The Dart and Rees … having converged some miles up at the foot of Mount Alfred. As far as the eye can reach this part of the country is one sheet of water" (1924)

FLOOD AT GLENORCHY, HEAD OF LAKE WAKATIPU

Otago Witness, Issue 3650, 26 February 1924, p37

References:
ORC, 1993. Known floods of Queenstown Lakes District
ORC, 1999. Queenstown Lakes District floodplain report

17

January 1994 - the 'Race Day Flood'

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November 1999

References:
ORC-QLDC, 2006. Learning to live with flooding – a flood risk management strategy for the communities of Lakes Wakatipu and Wanaka

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February 2020


Photo: QLDC


Photo: Shane Melton


Photo: Crux.org.nz


Photo: QLDC


Photo: Luke Hunter

References:
ORC file note, 2020. Notes on February 2020 flooding in Glenorchy

20

Dart floodplain 2019-2022


Dart's flooding causes chaos

21

REES RIVER FLOOD DEFENCES

Rees-Glenorchy floodbank

- Constructed in 2000, length of ~1400m
- Several assessments of structure stability in 2020-2021
- 2021 floodbank repairs near creek confluence (update from QLDC?)

Rees floodbank (true right, u/s of bridge)

- Constructed in 1984, length of ~4km

References:
WSP, 2020. Glenorchy floodbank Rees River. Memo July 2020.
WSP, 2020. Glenorchy-Rees Floodbank assessment. September 2020
T+T, 2021. Rees-Glenorchy floodbank structure failure modes assessment.

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RIVER MANAGEMENT ACTIVITIES

By ORC & QLDC

- Gravel extraction
- Channel realignments
- Groyne construction
- Rock armouring
- Floodbanking/bunding
- Debris fencing
- Willow planting
- Willow removal

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REES BRIDGE

Concerns by QLDC and community members that continued aggradation will threaten flow capacity at bridge

But potential hazard not well known;

- What is flow capacity of bridge?
- No regular monitoring of river bed levels at bridge?
- Not yet any modelling of how aggradation might impact flow capacity?

QLDC hold consent[1] for gravel extraction at bridge

- Usually extracting 10-20k m^3 annually)

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1. Consent RM20.205

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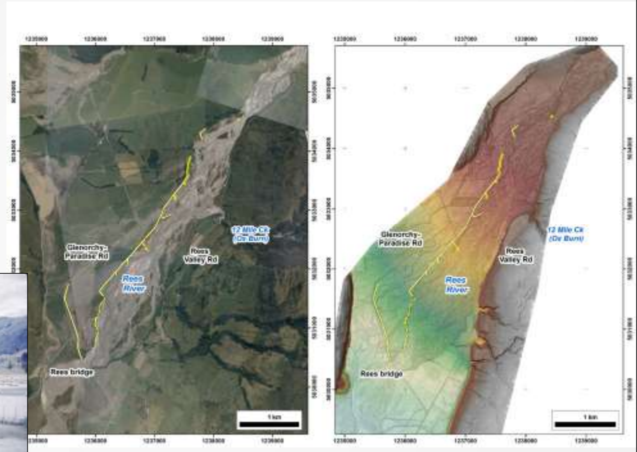
REES FLOODBANK

Concerns by residents that continued aggradation will reduce floodbank protection levels
- Potential for increased flood impacts to road and farmland

But potential hazard not well known;
- What is LOS of floodbank?
- Not yet any modelling of how aggradation might impact flow capacity?



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HEAD OF THE LAKE NATURAL HAZARDS ADAPTATION

Using the Adaptation Pathways approach to create a natural hazards adaptation strategy for the area

Aiming to develop a process for decision-making regarding the natural hazard threats in this area, in collaboration with project partners, and the local community

Key project steps to date:
- Project planning
- Develop project partner relationships
- Technical hazards investigations
- Community relationships and initial engagement sessions

Next project steps:
- Assessment of potential adaptation approaches and interventions
- Continued community engagement
- Development of initial adaptation pathways and draft adaptation strategy

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References:
ORC, 2021. Natural hazards adaptation in the head of Lake Wakatipu.

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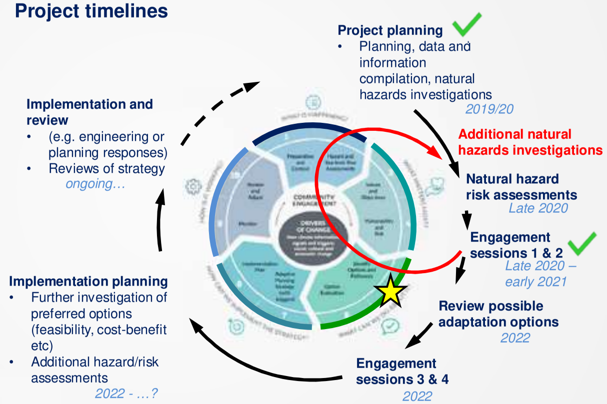
ADAPTATION PROJECT
Project timelines



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HEAD OF THE LAKE NATURAL HAZARDS ADAPTATION

- Substantial revision of Dart-Rees and Glenorchy natural hazards information in progress (2021-2022);
  - **Dart-Rees River morphology and geomorphic change assessments**
  - **Flood frequency analysis** (Dart & Rees Rivers, Lake Wakatipu)
  - **Hydraulic modelling and flood hazard assessment** (Dart-Rees, Glenorchy)
  - **Liquefaction and lateral spreading susceptibility investigation** (Glenorchy township)
  - **Buckler Burn alluvial fan hazards**
  - **Lake tsunami** (ORC support for PhD research project)

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COMMUNITY ENGAGEMENT

Four-stage engagement process

✓ 1. What is happening now, and how does this affect you? (December 2020)

✓ 2. What could happen in the future, and what might we do? (April 2021)

3. How can we navigate the adaptation options?
4. What do the adaptation pathways look like, and what happens now?

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James, Matt intro content here

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THE ADAPTATION PATHWAYS APPROACH

Adaptation: "a response strategy to anticipate and adjust to actual and expected changes in environmental conditions"

Adaptation could entail …
- tweaks and small changes to existing practices systems (i.e., incremental adaptation)
- fundamental changes and re-design (i.e., transformational adaptation)

Sequencing adaptations over time is a concept known as **adaptation pathways**
- a conceptual and analytical framework for enabling adaptation planning and decision-making in response to long-term change

References:
Ministry for the Environment, 2017). Coastal Hazards and Climate Change: Guidance for local government.

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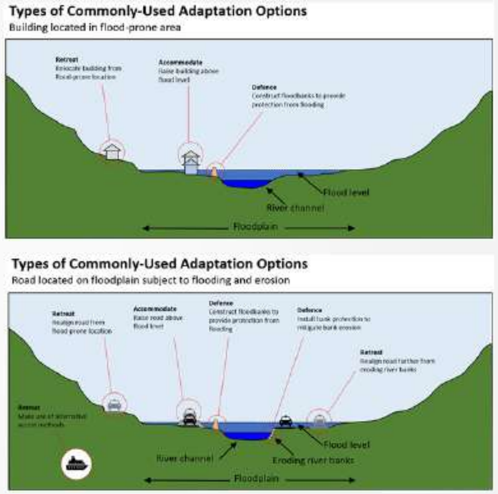
NATURAL HAZARDS ADAPTATION APPROACHES

Four groupings of natural hazard adaptation options

- Accommodate, Protect, Retreat, or Avoidance strategies
- But 'do nothing' is also an option (no systematic or proactive adaptation planning).

Combinations of these options will be required

- short term, medium term, and longer term



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ADAPTATION PATHWAYS
Signals, Triggers and Thresholds

Under what conditions does the action or option in the plan (or for the existing situation) no longer meet objectives?

Adaptation Threshold: the point at which a range of evolving conditions would become unacceptable and objectives or levels of service are no longer met (or "*what people do not want to happen*")

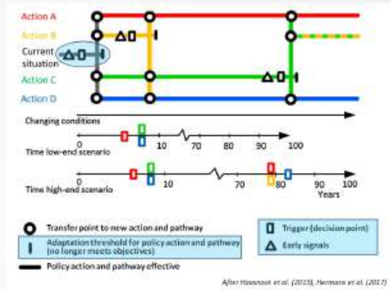
e.g. Catastrophic/repeated flooding of Glenorchy houses, sudden/complete loss of access to Kinloch?

Triggers: a decision point, when implementation of an alternative plan or pathway is required to avoid the impacts of reaching an Adaptation Threshold.

e.g. Near-miss flood events, frequency/severity of access disruptions, $ value of repair works, distress/uncertainty for residents?

Signals: indicators providing early indication of need to start re-engaging and reviewing the adaptive plan.

e.g. Channel migration/locations, aggradation and mean bed levels



References:
Ministry for the Environment, 2017). Coastal Hazards and Climate Change: Guidance for local government.

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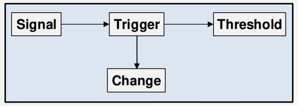
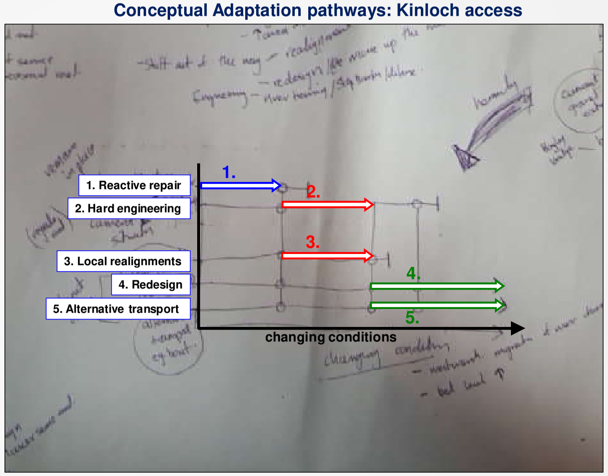


Threshold is loss of access to Kinloch (or only ad-hoc informal access possible – private boats etc)

Possible **signals/triggers** for change
- Frequency of road closures
- $ value of repair works
- Distance of active channel from road

X-axis is **changing conditions** (not time)
e.g. for Kinloch access could be
- Westwards migration of river channel
- Bed level rise

Conceptual Adaptation pathways: Kinloch access



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ADAPTATION
Examples of Adaptation Triggers

Hazards	Riverbank erodes to within X m of house(s), or other infrastructure	After X floods overtop flood protection or land use assets	The 20-year Mean Annual Flood reaches X m^3/s
Risk	Event causing >$XM damage (or insured losses)	The next catastrophic flood (define risk/impact, extent)	Levels of service for a utility or infrastructure dip below a minimum agreed level (or for X times)
Social	Measure of concern/ anxiety or wellbeing	Tolerance measure, e.g., sense of community is threatened; people start moving out or cannot move because cannot afford to	Specific societal objective is no longer met
Financial/ Economic	Insurance withdrawn or no new build insurance	Maintenance costs exceed $X pa for protection works	Bank mortgages difficult to secure
Cultural	Taonga or sites (e.g., urupa) begin to be inundated or are regularly inundated	Access to mahinga kai limited or lost	
Environmental	X% loss of wetlands/ marshes/bird numbers/ riparian habitat		
Governance/ institutional	Central government adaptation law changes	Reduction in LoS, e.g., flood control, wastewater, water supply	

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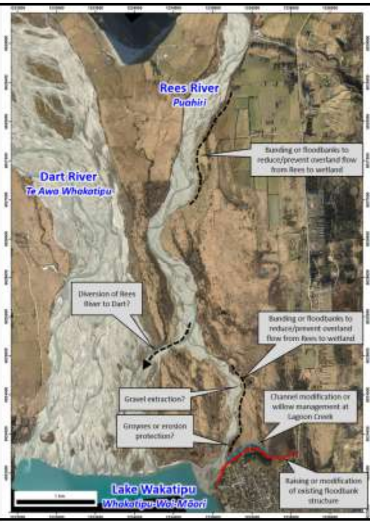
COMMUNITY ENGAGEMENT
Rees River and Glenorchy flood hazards

Potential river management or engineered interventions suggested by community members

- Raise buildings or raise land levels in the town
- Control willows at lagoon
- Gravel extraction, river channel realignments, divert Rees
- Raise the Glenorchy floodbank
- Erosion control (groynes, willow/flax plantings)
- Prevent river flows towards lagoon from lower Rees (bunding/floodbanking)

- Raise the Rees bridge, or extract gravel from underneath bridge



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References:
NIWA, 2021. Thematic analysis of notes from 8th April 2021 Glenorchy community engagement event

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References:
NIWA, 2021. Thematic analysis of notes from 8th April 2021 Glenorchy community engagement event

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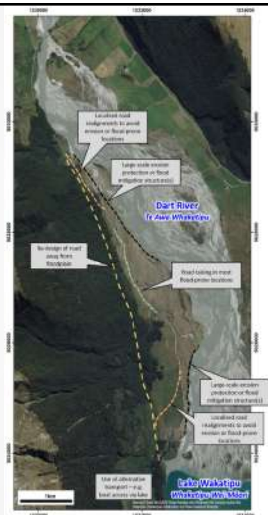
COMMUNITY ENGAGEMENT
Dart floodplain and Kinloch access

Potential river management or engineered interventions suggested by community & in ORC discussions

- Status quo ('reactive repair')
- Hard engineering structures
- Local road realignments
- Redesign (relocation from floodplain to hillslopes?)
- Alternative transport (boat access)



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KEY QUESTIONS FOR ADAPTATION AT THE DART-REES FLOODPLAIN

- What does sustainable river management look like for the Dart-Rees floodplain and what does it offer?
- What does sustainable flood protection look like and what level of protection is realistically achievable?
- What other complementary strategies are available to achieve natural hazard resilience (e.g. planning controls)?
- Can we define principles for an ORC river management strategy in this location?

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OBJECTIVES FOR ADAPTATION AT THE DART-REES

- An understanding of viable, sustainable river management approaches, suitable for the floodplain/river environment of the Dart-Rees area.
- An estimation of how long, or under what conditions these approaches might remain effective.
- An understanding of key constraints/factors for river management interventions (costs, environmental, cultural, feasibility, community acceptability etc).
- How these approaches might fit within wider content of natural hazard management and adaptation (e.g. planning responses, potential retreat)
- Specific review of risks/benefits of all options identified by the community during engagement activities.

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PRINCIPLES FOR ADAPTATION

Natural system/processes
- Recognition of the need to understand the underlying natural systems and processes
- A long-term sustainable, integrated and strategic approach to floodplain risk management, working with the natural river processes
- Appropriate forms and levels of protection, and are sympathetic to environmental amenity values

Societal
- Widest possible benefits for community, works in with other community objectives
- Affordable and acceptable to council, the community and direct beneficiaries, also environmental/cultural factors
- Community involvement and ownership

Political/economic
- A commitment by project partners (ORC, QLDC, DOC, Iwi) to work together
- Adopting a precautionary approach;
- Ensuring adaptive management;
- Recognition and treatment of residual risk
- Taking a low-regrets or even no-regrets approach to risk treatment/adaptation;
- Avoiding locking in options due to adaptation and development decisions that limit further adaptation in the future;

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WHAT DO SUCCESSFUL ADAPTATION APPROACHES LOOK LIKE?

- Has a long-term view (50-100 years)
- Provides flood protection benefits
- Costs are acceptable/justified
- Health of the environment and natural amenity values must be key factors.
- Risk and benefits of alternative strategies/pathways communicated to other stakeholders
- Approaches are supported and acceptable to all of wider community (e.g. residents, DOC, Kai Tahu).
- Involves on-going monitoring of natural processes and tracking of geomorphic changes and adaptation performance

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WHAT INTERVENTION ASSESSMENT FACTORS NEED TO BE CONSIDERED?

- What is intervention trying to achieve?
- What are impacts?
- What are benefits?
- What are risks?
- What are consequences of failure of specific interventions? (e.g. reducing level of protection through time – due to aggradation?)
- How long will river management/engineered interventions provide continued protection?
- How viable are these river management/engineered interventions in the longer-term? – especially given the environmental/hazard context (e.g. ongoing riverbed aggradation, geomorphic consequences of an Alpine Fault earthquake, and climate change impacts on hydrology and flooding).
- Regulatory frameworks (Freshwater NPS, ORC Water Plan, RMA, district Plan etc).
- What on-going monitoring is required?
- What performance standards should be applied? (what performance do community consider is acceptable?)

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CONSERVATION

References:
DOC online maps: www.doc.govt.nz/map/index.html

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Appendix C

QLDC Presentation on Kinloch Road

Kinloch Road

Impact on operations and ongoing repair costs due to flooding

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1

Context

- Dart River has been changing course over the past several years and in places flows very close to Kinloch Road
- Kinloch Road is closed relatively frequently due to surface water covering the road or flood damage

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Photo during flood 25/10/20


Photo 1 week before flood


Post flood armouring

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3

Operations approach

- Once a rainfall event which is forecast for >30mm in 24 hours begins, **monitoring** is undertaken every 4 hours between 8am-6pm in keeping with winter maintenance LoS
- If the road formation is not visible or un-trafficable the road will be **closed**
- The road will be **opened** once the road formation is clearly defined and other safety hazards (eg culverts, surface shape) are assessed and repaired
- Downer provide **communications** updates to the QLDC Comms address

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Maintenance approach

- In the short term we are managing Kinloch Road under the following two approaches

1) LTP funding of $220,000 every 2nd year for Rees River Bridge Resilience

For the 21-24 LTP, funding is in 21/22 and 23/24. The purpose of this activity is to reduce gravel aggregation under the bridge. Gravel is extracted and disposed of, ideally as economically as possible. We have been taking the opportunity to raise Kinloch Road with this gravel. Although a lesser quantum of gravel can be extracted for the budget due to a longer haul distance, there are overall synergies to Council as if this was not done, the road raising with an alternative gravel source would hit emergency works budgets. In reality the quantities of gravel we can remove for $110,000/year regardless of the disposal approach is insignificant compared to the volume of gravel that comes down the river. Ie bridge raising is likely to be inevitable in the near future. This approach only works for planned works ie securing resource for gravel extraction, notifications, season.

2) Emergency works – when unplanned works are required outside of gravel extraction opportunities such as armouring or emergency road raising

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Maintenance cost

- Context of Kinloch Road cost for emergency works Oct 2016 - now
- Excluding outliers it is Council's most expensive road /km for emergency works
- The below data does not factor in the Gravel extraction budgets, and $130k worth of Fulton Hogan work done in 2019 (this would make Kinloch Rd the most expensive despite its length)

TOP 10 ROADS BY TOTAL COST

Filtered using slicers on tab - TOP TEN ROAD EXPENDITURE

Sum of sum_cost	
Road	**Total**
GLENORCHY-QUEENSTOWN ROAD	$1,779,379.67
CROWN RANGE ROAD	$445,131.30
SKIPPERS ROAD	$437,471.73
KINLOCH ROAD	$359,792.68
CARDRONA VALLEY ROAD	$258,349.98
GLENORCHY-PARADISE ROAD	$164,282.23
THE MALL	$107,472.79
VON ROAD	$97,854.20
REES VALLEY ROAD	$92,035.55
WANAKA-MOUNT ASPIRING ROAD	$82,443.36
Grand Total	**$3,824,213.47**

TOP 10 ROADS BY COST PER KM

Filtered using slicers on tab - TOP TEN ROAD EXPENDITURE

Sum of cost_pkm	
Road	**Total**
THE MALL	$716,485.27
JOCK BOYD PLACE	$220,513.73
TOBINS TRACK(CROWN TERRACE END)	$138,345.63
KINLOCH ROAD	$40,918.08
GLENORCHY-QUEENSTOWN ROAD	$40,478.17
RIVERSIDE ROAD	$34,744.91
BENMORE PLACE	$34,565.52
SOHO STREET	$28,065.91
MONLEY LANE	$27,403.06
SKIPPERS ROAD	$26,781.25
Grand Total	**$1,308,301.54**

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Strategic approach

- We are hoping to have more idea of "where to from here" for Kinloch Rd following this workshop.. ☺

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7

Glenorchy Floodbank repairs

- Floodbank of Rees River has overtopped a few times in the recent past
- A piece of "do-minimum" works was complete by QLDC, informed by a WSP report

- This work involved:
- 1200T (about $100k supply and haul) of rock was carted to Glenorchy last year
- We had a delay approx. 6mo while WSP / ORC worked out some issues with the consent
- Works completed (about $100k more) to place the rock, repair over steepened areas and raise a small area of the stop bank near the golf course

- In addition, last year? ORC completed fairly significant works to clear the river bed of willows and this appears to have helped reduce risk by lowering the water level in the lagoon

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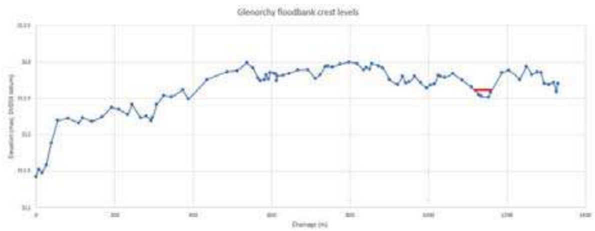
Historic survey of floodbank

- Red line = recently completed raising (indicative)



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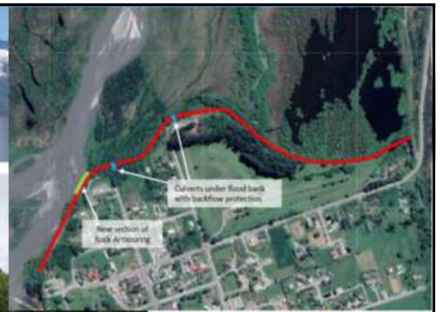

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Appendix D

Presentation by Professor James Brasington (Waterways Centre for Freshwater Management)

FLUVIAL HAZARDS AT THE TOP OF THE LAKE

LIVING WITH RIVERS ON THE EDGE

PROFESSOR JAMES BRASINGTON
Waterways Centre for Freshwater Management

FAR FROM EQUILIBRIUM

DRIVER 1: CLIMATE CHANGE

0.5-1.5 °C by 2040; 0.5-3.5 °C by 2090
20-40% increase in winter rainfall and intense storms
Up to 100% increase in mean annual flood flow

DRIVER 2: RIVER BED AGGRADATION

Build up of riverine sediment
Reduces the cross-sectional area
Reduces the gradient of the river

→ **REDUCED FLOOD CAPACITY**

REES-DART DELTA, DECEMBER 2009

FLUVIAL HAZARDS

If not the most catastrophic threat … rivers pose the **most frequent hazard** to the lakeside communities

Risks to **life, property and critical infrastructure**

- Direct inundation and swift water hazards
- Entrained debris and sediment
- Bank and stream erosion

Unlike other natural hazards … at Glenorchy we expect **fluvial hazards to increase in frequency and severity in the coming decades**

FEBRUARY 4TH 2020; c/o LUKE HUNTER

SEDIMENT: unlimited

Globally extreme rates of erosion

- **Glacial legacy > oversteepened slopes**
- **Continuing uplift > 5 mm / year**
- **Orographic precipitation > 5000 mm / year**

Unstable 'paraglacial' landscape

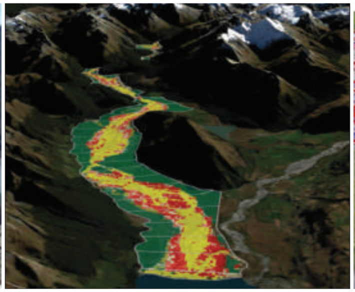
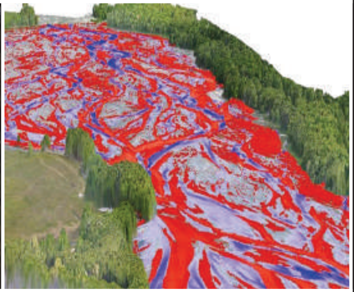
- **Catchment dominated by active landslides**
- **Retreating headwater glaciers**

***'Unlimited'* sediment availability**

- **More sediment available than the capacity of the rivers to transport it downstream**
- ***Transport limited* catchment system**

TE HORO | SLIP STREAM, MAY 2014

LINKING DRIVERS, STATES, PROCESSES … RESPONSES

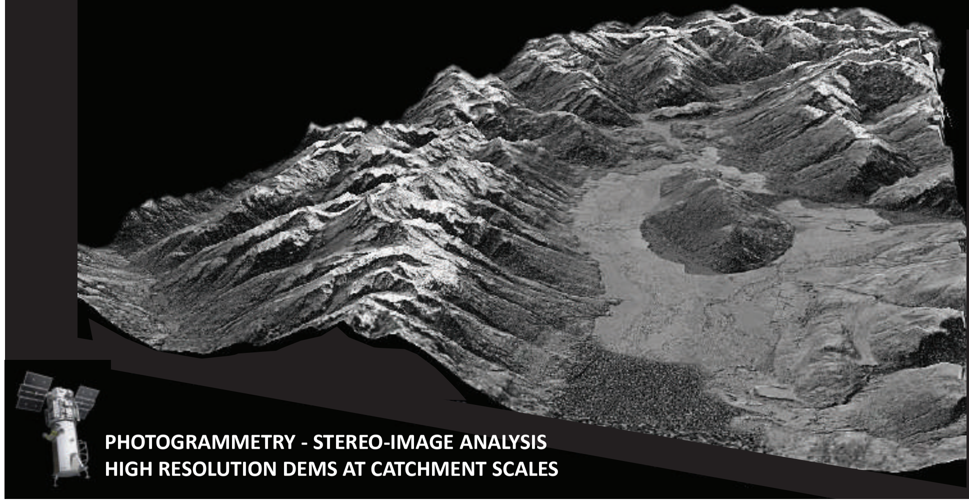




SEDIMENT DELIVERY
How much sediment is generated by erosional processes and supplied to the rivers?

STATE OF THE RIVERS
Where does the sediment go and how to the rivers respond over centennial timescales?

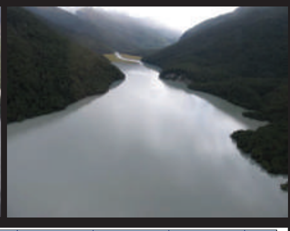
PROCESSES MECHANISMS
What controls the rate of sediment transfer through rivers and how do they adjust to floods?

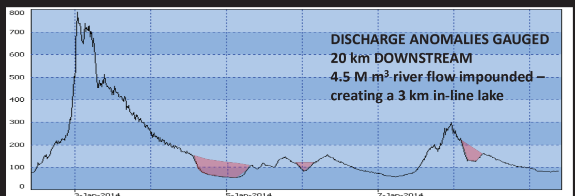
QUANTIFYING SEDIMENT DELIVERY PROCESSES



PHOTOGRAMMETRY - STEREO-IMAGE ANALYSIS
HIGH RESOLUTION DEMS AT CATCHMENT SCALES

1. MASS MOVEMENT DOMINATED CATCHMENTS

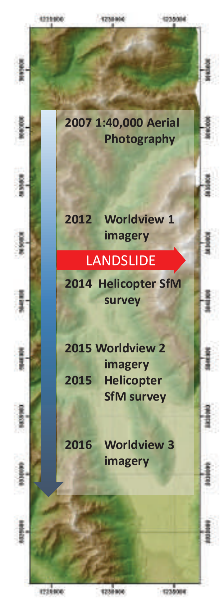


5TH JANUARY 2014 LANDSLIDE AND DEBRIS FLOWS IMPOUNDED RIVER TO CREATE A NEW INLINE LAKE

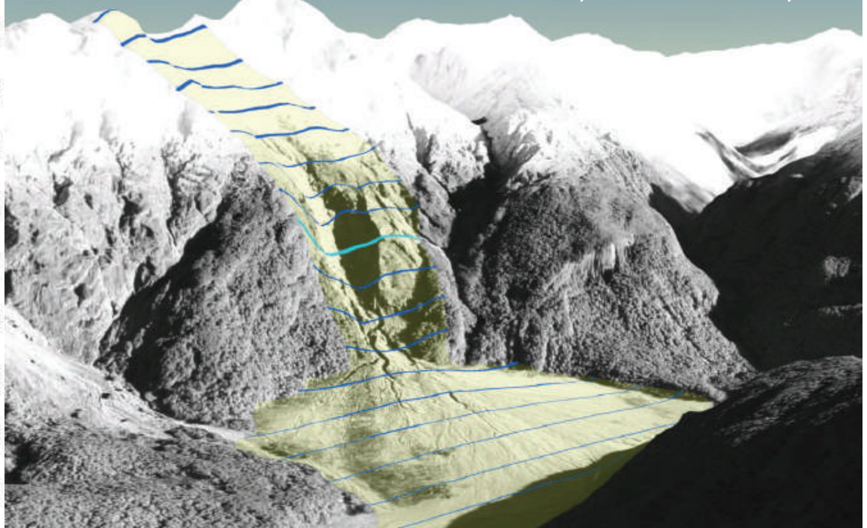
PEAK Q > 800 $m^3 s^{-1}$

INITIAL ASSESSMENT 1-2 M m^2 SEDIMENT

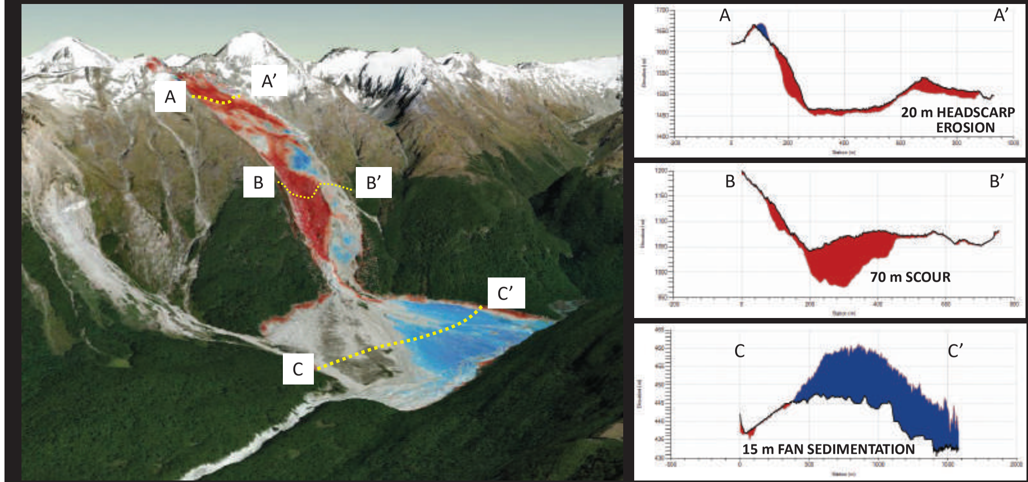
4.5 M M^3 LAKE BUT NO IMMEDIATE DAM BREAK THREAT



SLIP STREAM LANDSLIDE, UPPER DART RIVER, 2012

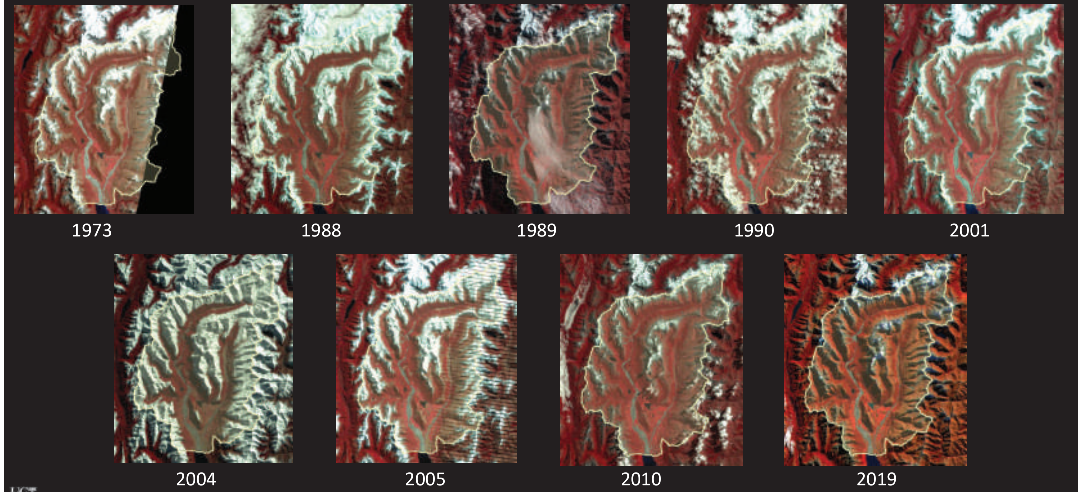


initial estimates > landslide 1-2 M m^2

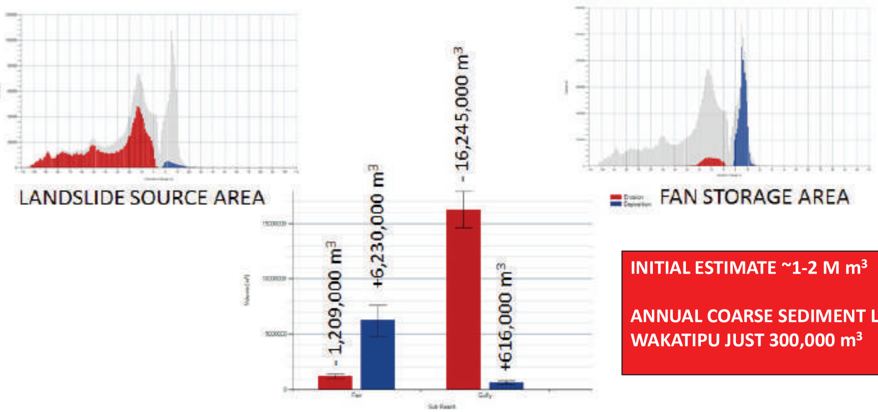


TOPOGRAPHIC CHANGE ANALYSIS: 2015-2012

2. THE STATE OF OUR RIVERS: RESTLESS!



QUANTIFYING SEDIMENT BUDGET



INITIAL ESTIMATE ~1-2 M m³

ANNUAL COARSE SEDIMENT LOAD TO WAKATIPU JUST 300,000 m³

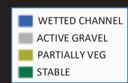
PRODUCTION – FAN STORAGE = SEDIMENT SUPPLY TO RIVER

17,454,000 – 6,846,000 = 10,608,000 m³

MAPPING THE RIVER CORRIDOR

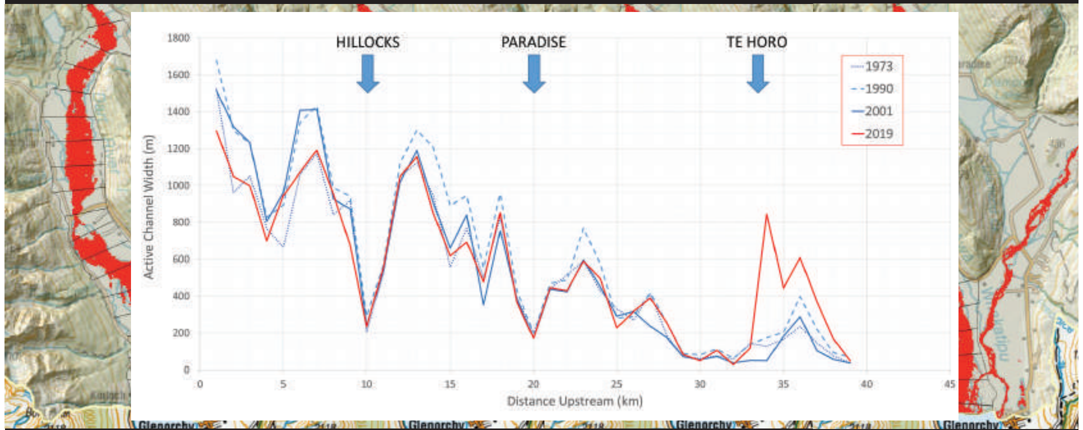
Machine Learning > classifying landcover

Visible and near infrared spectral response provides basis for landcover classification



- Wetted Areas, Exposed Gravel – Active channel bed
- Partially Vegetated – Disturbed/Stablizing channel bed
- Stable – 'Inactive' valley floor

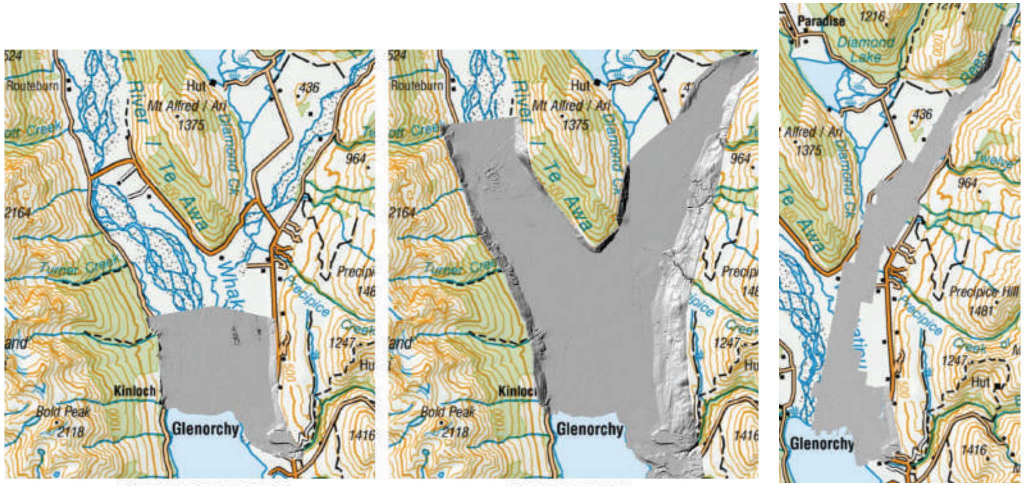
REES-DART ACTIVE CHANNEL BELT



1973 1990 2001 2019

1) Long-term migration of lower reach/delta from TL to TR

2) Expansion followed by contraction of active river corridor



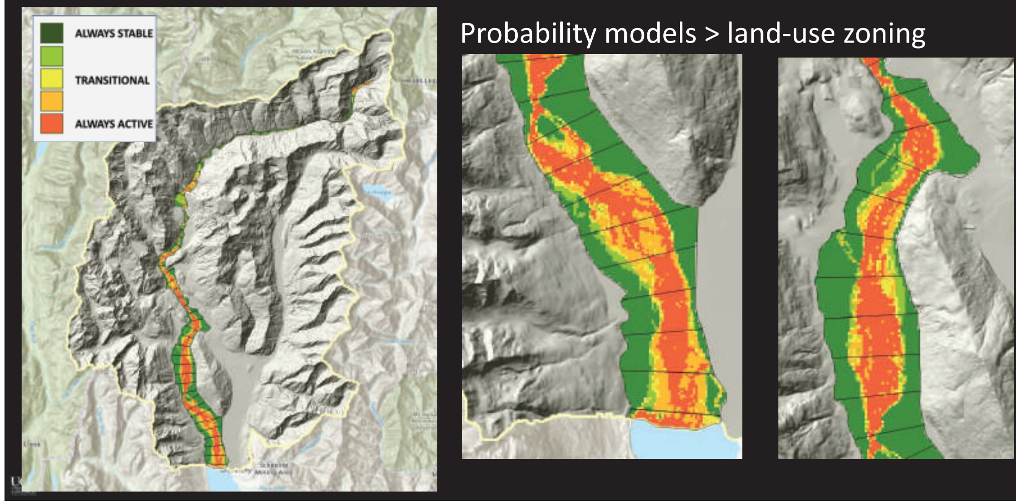
2/3 OCTOBER 2011

25 JUNE 2019

13 AUG 2021

MANAGING RIVERS … OR … RIVER CORRIDORS

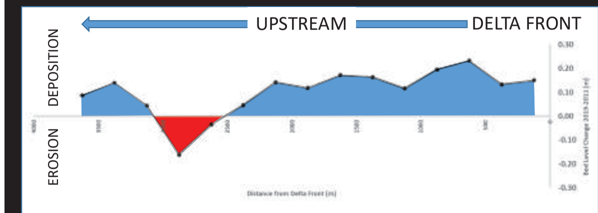
Probability models > land-use zoning

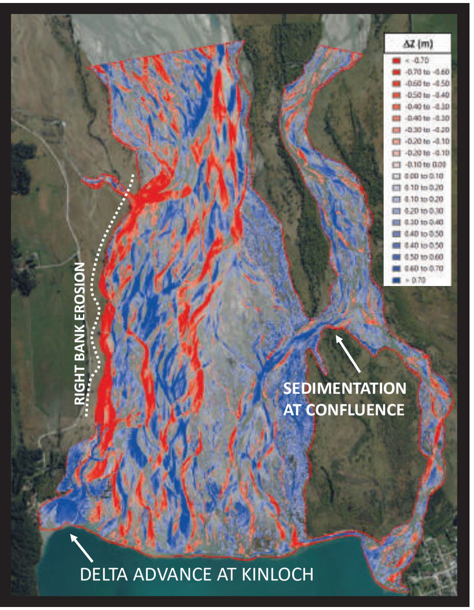


BED LEVEL CHANGE 2019 - 2011

Difference lidar elevation models surveyed in 2019 and 2011

Erosion (bed lowering) = reds
Sedimentation (bed raising) = blues





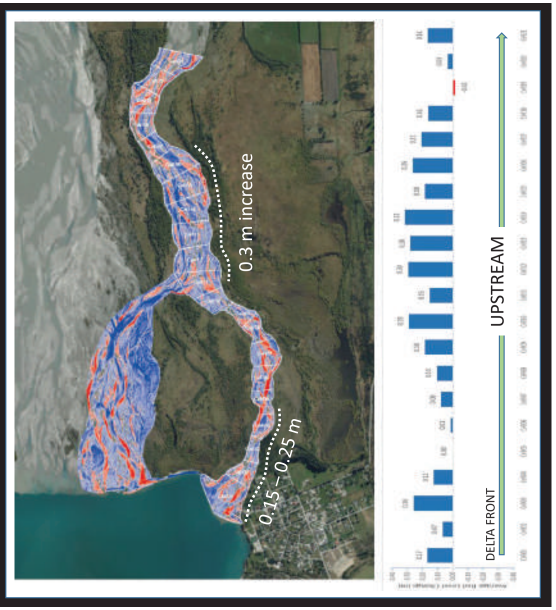
LOWER REES RIVER

Bed level change averaged over 250 m sections (cells)

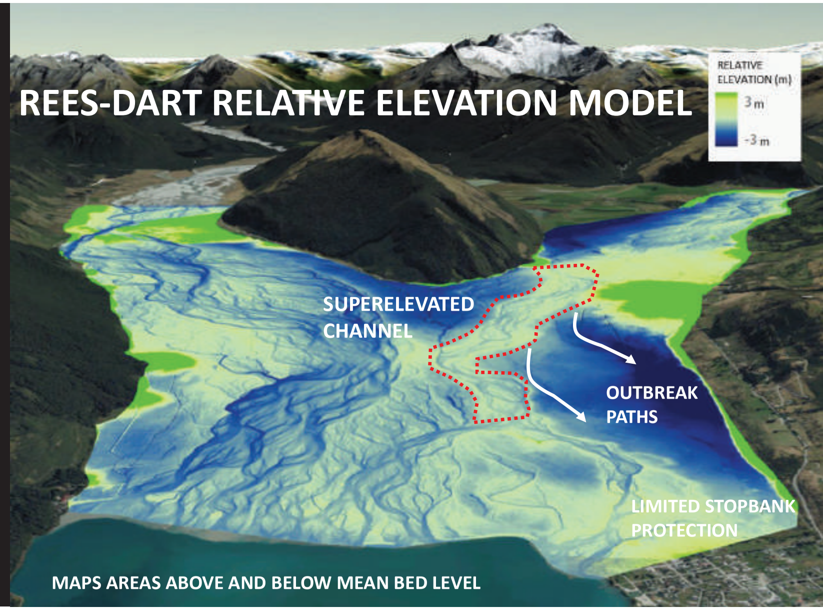
Significant and extensive sedimentation throughout lower 5 km

- 0.2 – 0.32 m increase in mean bed level in just 8 years
- > 1.25 – 2 m increase over 50 years

SIGNIFICANT LOSS OF FLOOD CAPACITY



REES-DART RELATIVE ELEVATION MODEL



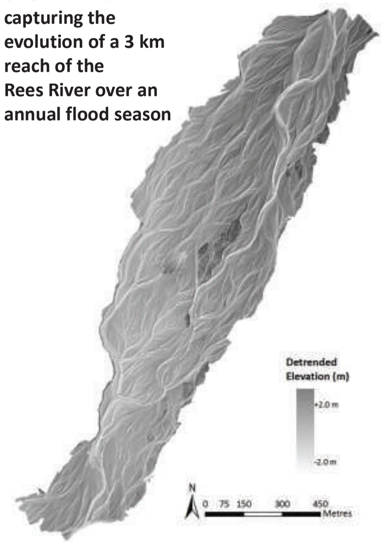
JUNE 2020

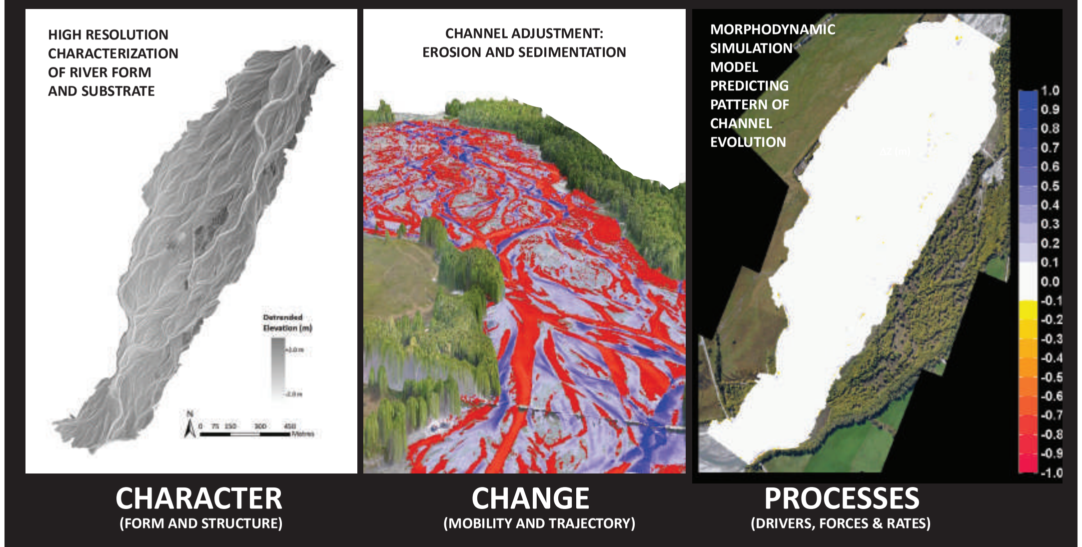
Significant loss of 'freeboard' evident along reaches of the lower Rees River

3. FORMATIVE PROCESSES

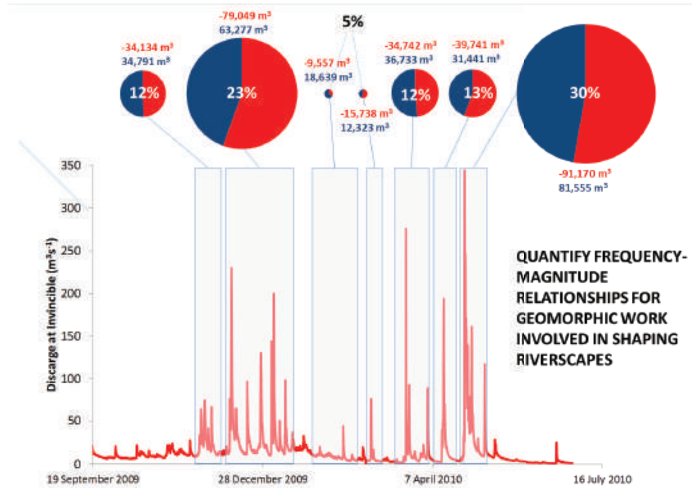
AMPHIBIOUS MOBILE TLS: REESCAN PROJECT 2009-2011

0.25 m DEMs capturing the evolution of a 3 km reach of the Rees River over an annual flood season

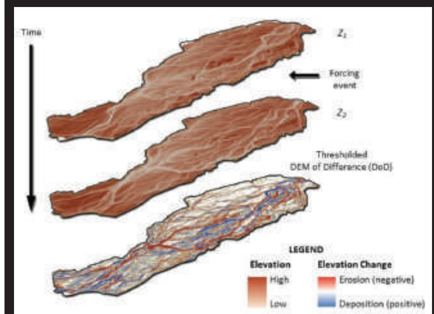




EVENT-BY-EVENT



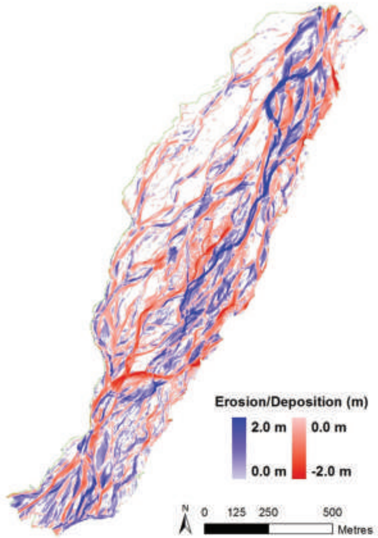
DRIVERS OF RIVER ADJUSTMENT



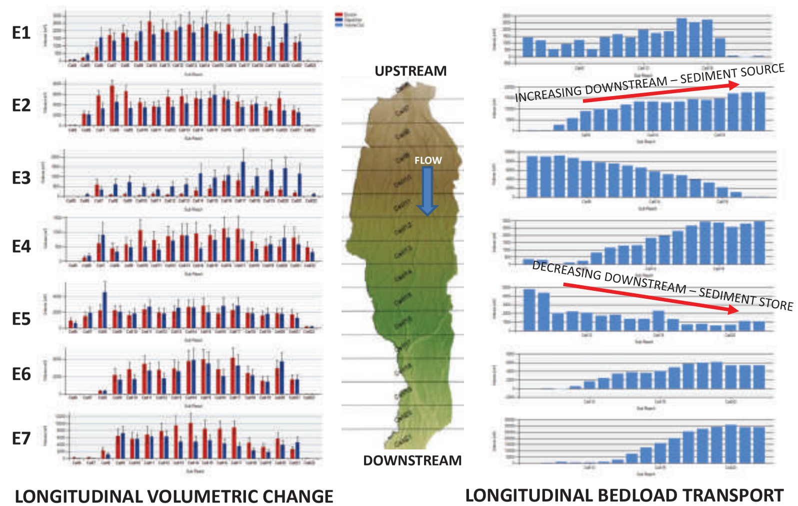
	80% C.I.
Ve (m^3)	124,442
Vd (m^3)	82,463
ΔZ (m)	-0.036
$\overline{d_e}$ (m)	-0.395
$\overline{d_d}$ (m)	0.328

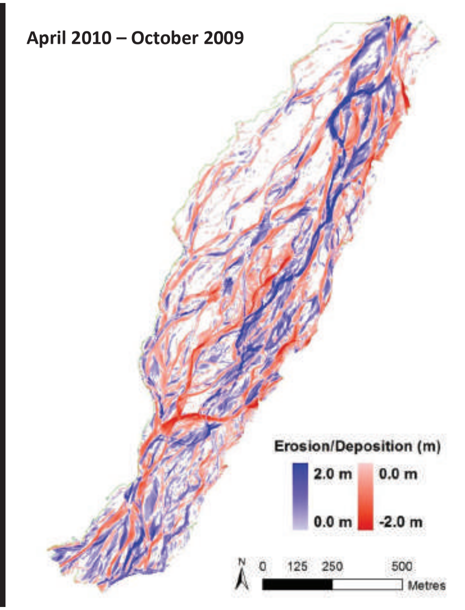
71% reach experienced scour
72% reach experienced fill

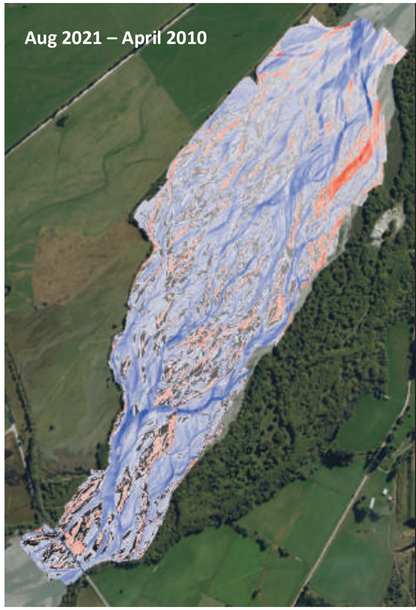
50% reach repeated scour and fill cycles
78% of the river bed mobilized/disturbed during a single year



SWITCHING BEHAVIOUR – BOTH SOURCE & SINK



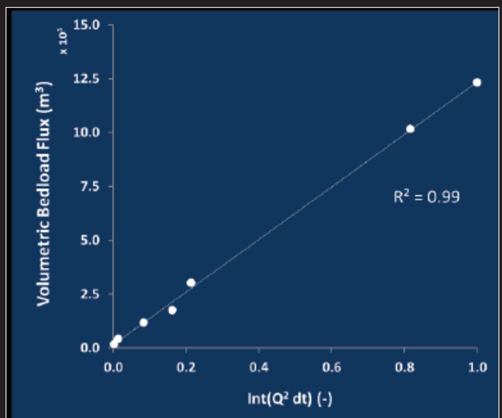




LESSONS FROM THE LANDSCAPE

1. SEDIMENT SUPPLY IS HIGH; DYNAMIC > PULSES DUE TO EXTREME EVENTS
   - Should expect variability over time, which will affect rates of downstream channel stability
2. MAKE SPACE FOR RIVERS – TREAT THE VALLEY FLOOR AND RIVER AS A CONTINUUM
   - Should expect the active river corridor to expand/contract/migrate over decadal timescales
3. SEDIMENT TRANSFER IS 'TRANSPORT LIMITED'
   - Should expect increases in storm frequency and severity to directly impact sediment transfer through the river system

CONTROLS ON SEDIMENT TRANSPORT



Rate of sediment transport increases predictability with the intensity of the driving flood

Sediment is essentially is unlimited … so …

Rate of transport is directly proportional to the power of floods

> Increases in flood frequency will lead to a direct increase in the rate of sediment transport

INCREASING FLUVIAL HAZARD?

1. RIPARIAN EROSION

Migration of the channel belt over time > periodic pressure on managed margins

Increasing sediment delivery > higher rates of anabranch migration > increased rate of lateral migration of channel belt

> KINLOCH ROAD

INCREASING FLUVIAL HAZARD?

2. LOSS OF SERVICE OF EXISTING STOPBANK PROTECTION

Elevated bed level > higher flood stages
- > Increased pressure on outer bends
- > Increased hydrostatic pressure

> overtopping

> Piping under earthen stopbanks > catastrophic breach

INCREASING FLUVIAL HAZARD?

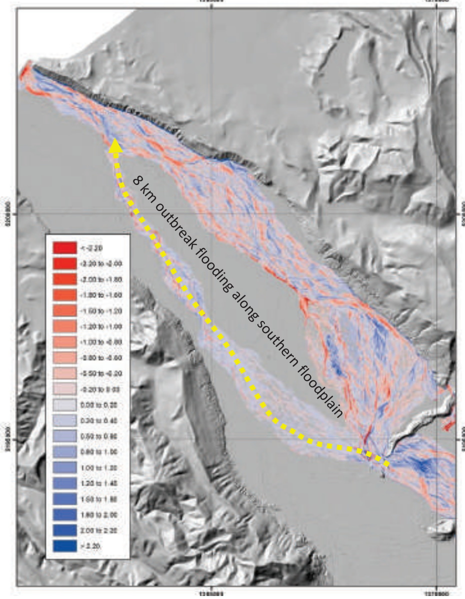
4. ELEVATED RISK OF SEVERE OUTBREAK FLOODING

Loss of freeboard upstream

Rerouting of flood flows along steeper path across the floodplain > avulsion

Catastrophic – erosional – flooding with the potential to overwhelm stopbanks

Swift water flooding through township



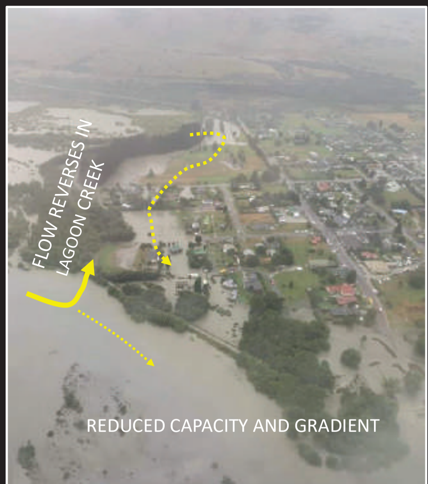
INCREASING FLUVIAL HAZARD?

3. BACKWATER FLOODING ALONG LAGOON CREEK > OVERTOPPING OF STOPBANK

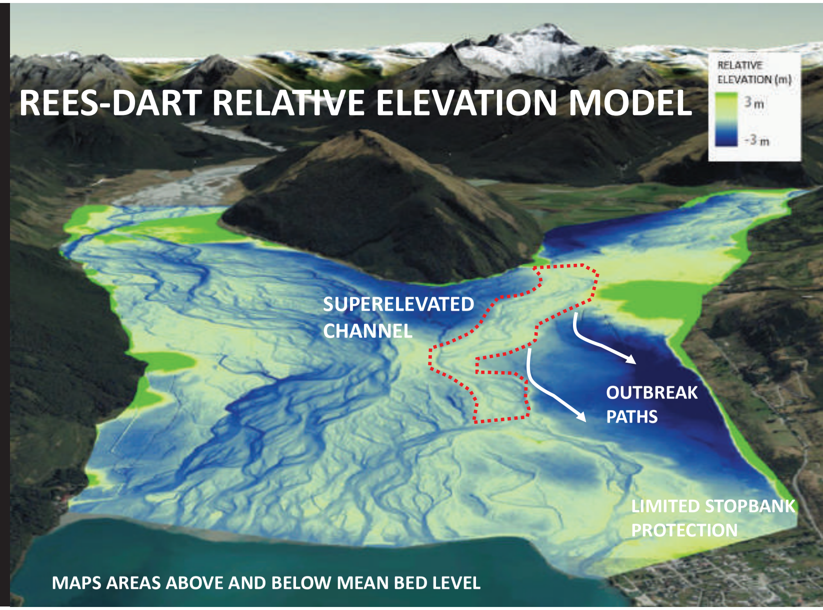
Bed aggradation > reduced cross-sectional area and reduced channel gradient

Reduces Rees mainstem flood capacity > blocks and then reverses flow along floodplain channels (Lagoon Creek)

Overtopping of stopbank at low points



BACKWATER FLOODING

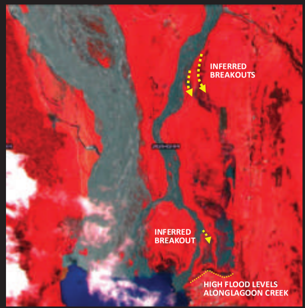


INCIPIENT AVULSION

BEFORE FLOOD

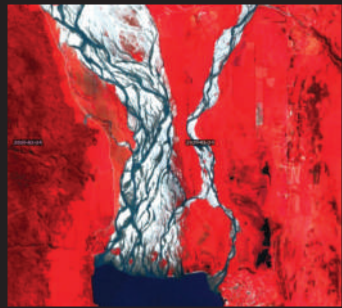
27 JANUARY 2020

FLOOD RECESSION



5 FEBRUARY 2020 (11:21 AM)

POST FLOOD



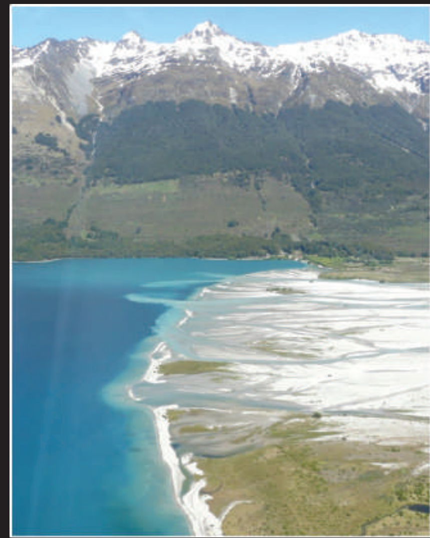
24 FEBRUARY 2020

CONCLUSIONS

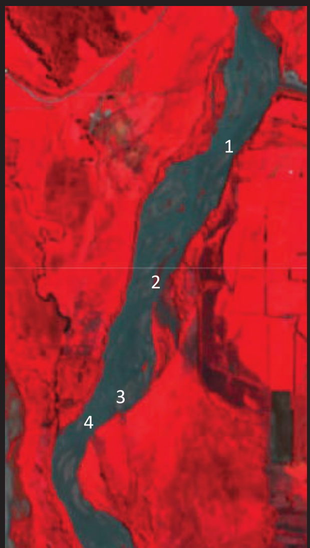
Fluvial hazards pose significant and increasing challenge for the local community into the future

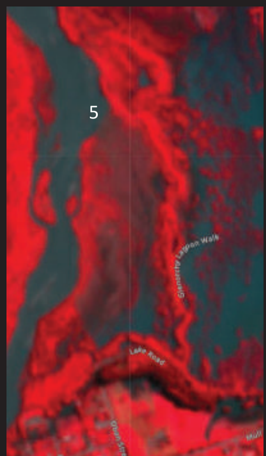
Hazard set to increase due to both climate change and long-term geomorphic evolution

Some hazards that will become increasingly hard to mitigate



FEB 2020: MULTIPLE BREACHES





Appendix E

Presentation by Matt Gardner (Land River Sea Consulting)

Rees / Dart Modelling

2021 Study

LANDRIVERSEA CONSULTING

1

Model Extent

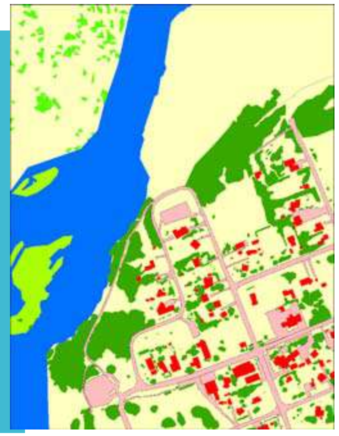
2

Model Setup

- Based on 2019 LiDAR DEM flow by LandPro
- Fixed bed model – so doesn't account for scour and aggradation – these effects need to be manually accounted for
- Main input is flow and downstream boundary level (ie Lake Level)
- Flow inputs developed by Magdy (ORC) – complex hydrology due to lack of gauging information
- Model can output – Water Level – Depth – Velocity – Shear Stress – Hazard etc to help better understand dynamic nature of the hazard
- Model is only a tool to help understand the real world – must always be interpreted in light of limitations.

3

Vegetation etc represented through roughness



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Bathymetry

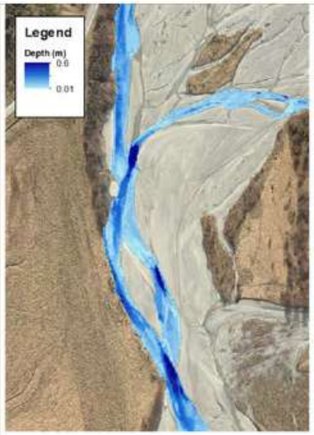


Figure 1 - Visualisation of DEM of Depth

Figure 2 - Aerial Image used for generating DEM of Depth

5

Calibration – Feb 2020 event

Model is primarily calibrated for Glenorchy flooding – not Kinloch etc – however flood extent covers full area

6

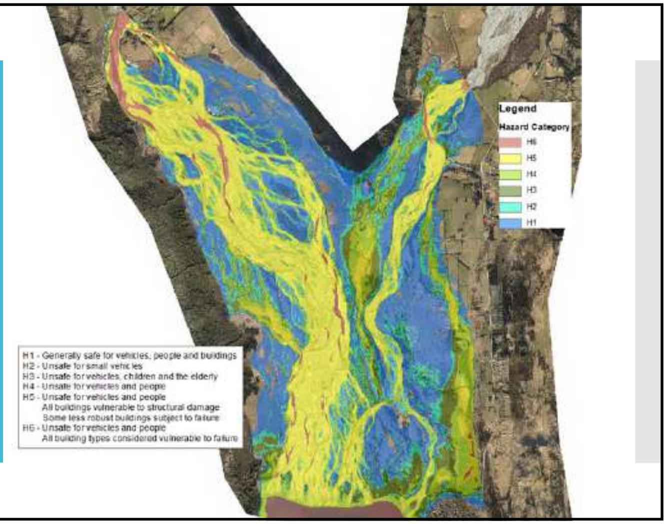
Animation (Glenorchy)

7

Animation (Full Extent)

8

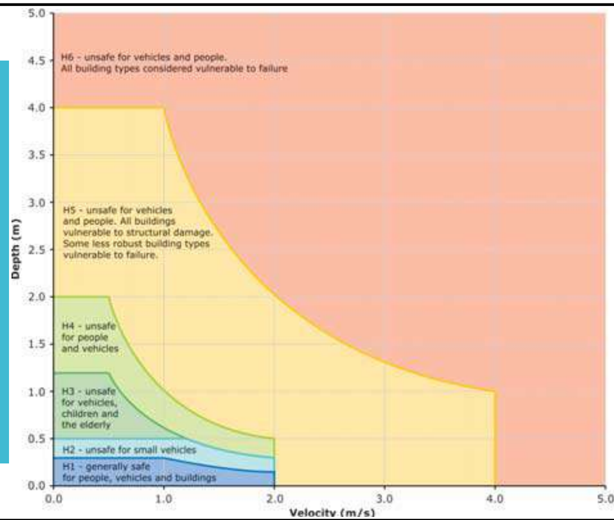
100 year ARI (1%AEP) Estimated Extent / Hazard Map



9

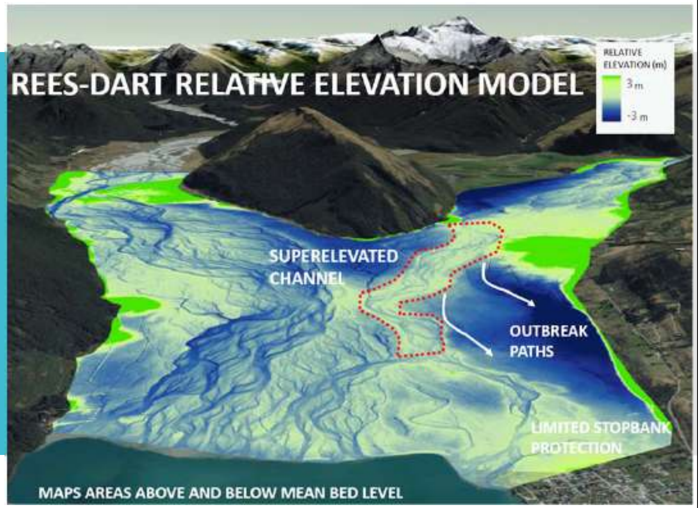
HAZARD MAP

Function of D x V



10

Modelled Avulsions / Outbreaks



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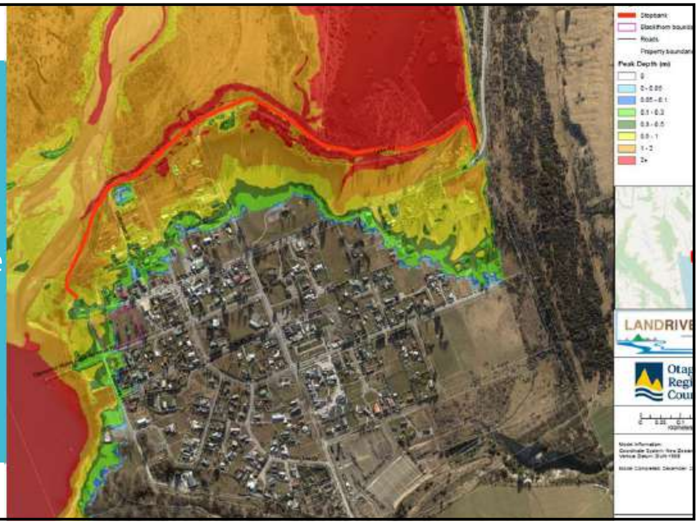
Avulsion path

12

100yrARI Future Climate Avulsion



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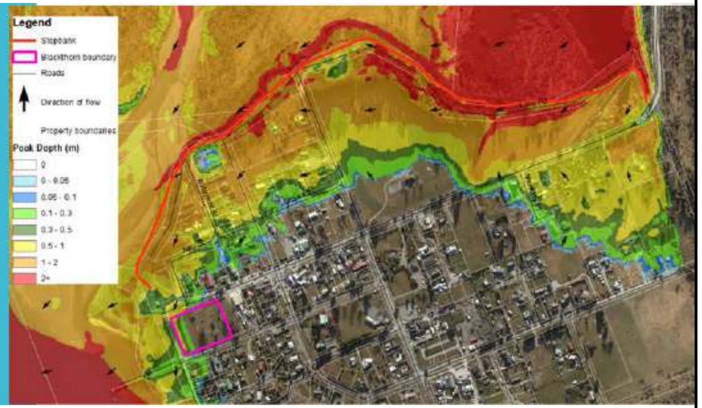
Direction of flow



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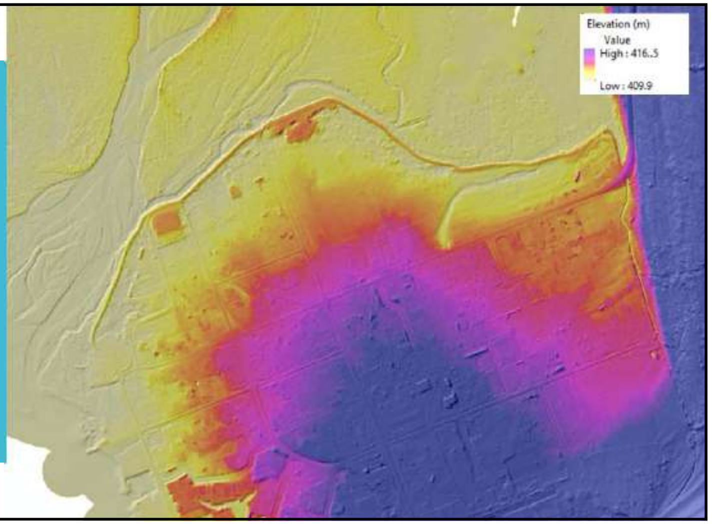
15

Sensitivity

- Roughness
- Water Levels in Lagoon (limited difference for event of size of Feb 2020 event)
- Main cause of excess water heading towards Glenorchy is likely due to diversion of flows from upstream, rather than lagoon capacity

16

Natural topography controls the flow



17

Road access issues - Dart

18

Road access issues - Rees

19

Climate Change

- Only impact on peak flow has been considered
- Impact on lake levels has not been investigated..in reality very complex as climate change likely to impact on entire long term climate cycle as well as intensity and duration of storms
- Cliamte change will have significant impact on geomorphology impacting volume of material entering the river
- This may effect level of both Dart and Rees as well as bed levels of river such as Kawarau which control the outflows from the lake and hence act as a control on lake levels.

20

Thoughts on management

- Every action has a reaction
- Models can be used to help assess wider impact on catchment
- Stopbanks can limit flood extent, but at the same time will impact on gravel transport – as well as channel more water downstream
- Models are a tool, but need expertise to interpret, especially in active gravel braided systems such as this one
- We can model removing gravel etc – however need to