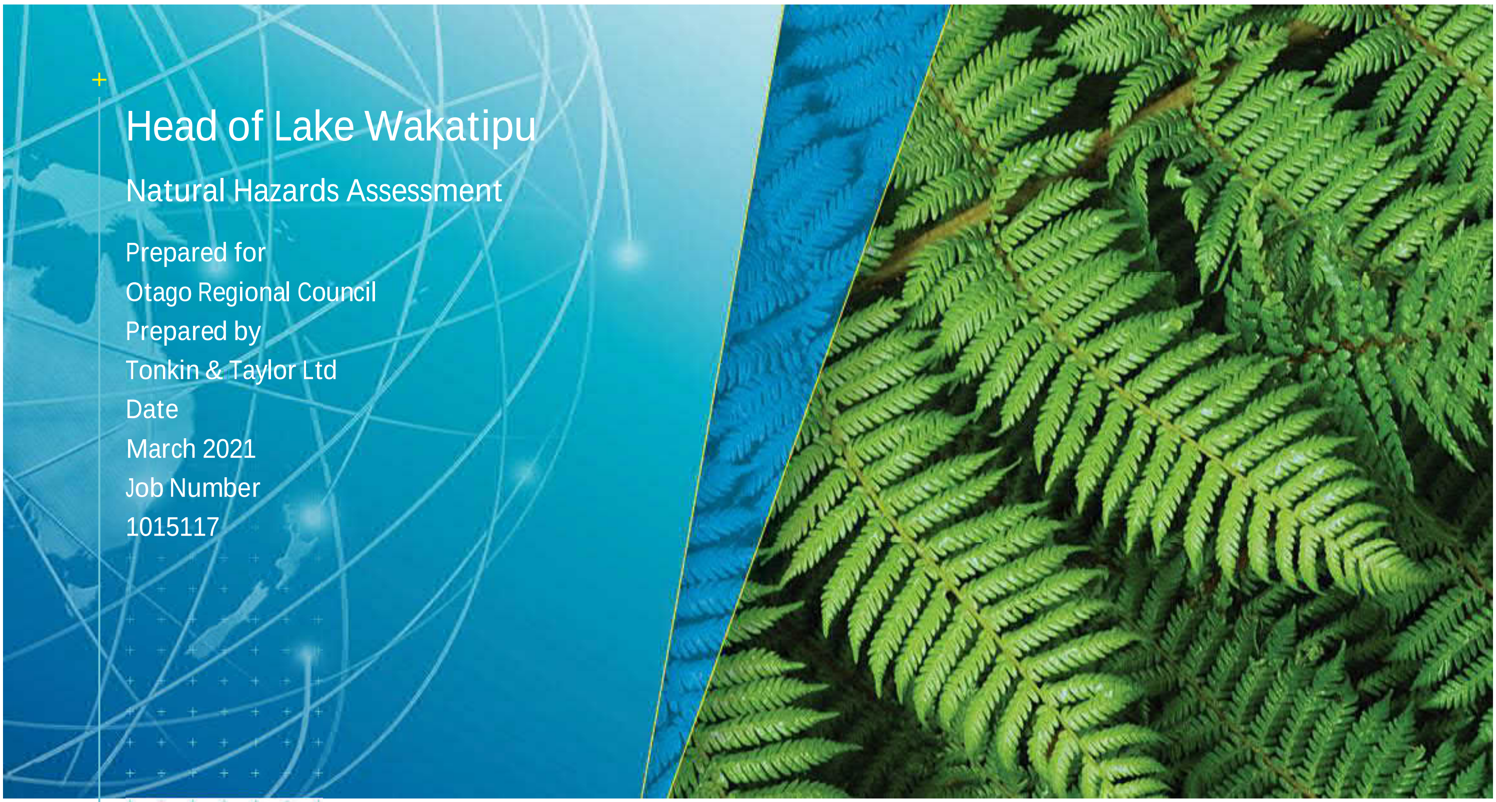
REPORT



Head of Lake Wakatipu

Natural Hazards Assessment

Prepared for
Otago Regional Council
Prepared by
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Date
March 2021
Job Number
1015117

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Document Control

Title: Head of Lake Wakatipu					
Date	Version	Description	Prepared by:	Reviewed by:	Authorised by:
27 January 2021	1	Draft Final	NWR, AJW, SVB	TB	TB
15 March 2021	2	Final	NWR, AJW, SVB	TB	NWR

Distribution:

Otago Regional Council	1
Tonkin & Taylor Ltd (FILE)	1

Table of contents

Executive summary

The Otago Regional Council (ORC), together with the Queenstown Lakes District Council (QLDC), Kāi Tahu and the Department of Conservation (DoC), is working with the local communities in an area (the Project area) at the Head of Lake Wakatipu to prepare an adaptation plan.

The information documented both in this report and through future links to a specially created web-based viewer is intended to assist with the adaptation planning process. This information provides the evidence base to inform good decisions. It must be appreciated that decisions will inevitably need to be made based on information that may be incomplete or which has considerable uncertainty. This will always be the case when dealing with a changing hazardscape.

The Head of Lake Wakatipu is a dynamic geomorphic environment which has been recently formed by, and continues to be formed by, natural processes that present a range of natural hazards. Climate change is expected to increase both the frequency and impact of the many of the natural hazards, in particular those of flooding, erosion and sedimentation arising from the Rees and Dart Rivers.

Both ORC and QLDC have been compiling information on natural hazards, and these are included as maps and are also available through the web-portal.

In addition to the information around particular hazards, the consequences of less likely events are presented, as well as cascading and coincident events. Worst case scenarios are presented. The reason for this is that preparation for possible sudden extreme events is just as important as preparing for more slower moving stresses, in adaptation planning.

Unless credible possible worst cases are clearly articulated, it is not possible to prepare for such events. This includes what could occur today, and what could occur in 50 years' time, or longer.

The purpose of the natural hazard information presented in this document is merely to inform. As this information is already publicly available this should not affect the ability of residents to obtain natural disaster insurance, nor to remove any existing human or property rights that exist within the communities.

Instead, this information is applied in a very different way from any previous assessment of natural disaster risk. Rather than presenting natural hazard risk for individual hazards probabilistically, the consequences of the multiple natural hazards are presented spatially. The Project area is mapped according to the relative uncertainty that the objectives of the community can be met. The objectives of the ORC (as articulated in the Regional Policy Statement) and the QLDC (as articulated in the Natural Hazards section of the Proposed District Plan) are also included in this map of relative uncertainty that natural hazards present to achieving the various objectives.

Together with the natural hazard maps, this risk map shows the effect of uncertainty about the nature, scale, and timing of consequences of hazard events on achieving objectives and provide a valuable insight for the community adaptation planning process.

1 Introduction

Otago Regional Council (ORC) and Queenstown Lakes District Council (QLDC) are leading a Project to develop a natural hazards adaptation strategy for the Dart-Rees area at the Head of Lake Wakatipu (the Project area).

Tonkin + Taylor (T+T) has been contracted by ORC to assess the natural hazard risks within the Project area, and so provide ORC with an improved risk understanding for the subsequent community engagement and options assessment stages of the Project.

In addition to the risk assessment covering the Project area (Part One), ORC has also engaged T+T to investigate potential site-specific natural hazard risks for a particular site in Glenorchy (Part Two). The findings from that review are summarised in a separate report dated November 2020.

This report sets out our assessment of the natural hazard risks within the Project area (Part One), as follows:

- The Project is described in Section 2
- International, National, Regional, District and Local Natural Hazard objectives are summarised in Section 3
- Section 4 describes the Natural Hazards Environment
- The Regional seismic hazard and slope-related hazards are discussed in Sections 5 and 6
- Lake and river hazards are discussed in Sections 7 and 8
- Design flood estimation and effects of climate change are discussed in Section 9
- Head of the Lake Inundation and cascading Natural Hazard scenarios are presented in Sections 10 and 11
- The effect of uncertainty on Natural Hazard Risk objectives is discussed in Section 12.

2 The Project

2.1 Project area

The Project area encompasses the lower elevations and reaches of the Dart River and Rees River valleys, extending down into the Head of Lake Wakatipu beyond Kinloch and Glenorchy as far as Greenstone Delta (West) and Shepherd's Hut Creek (East), as shown on Figure 2-1.

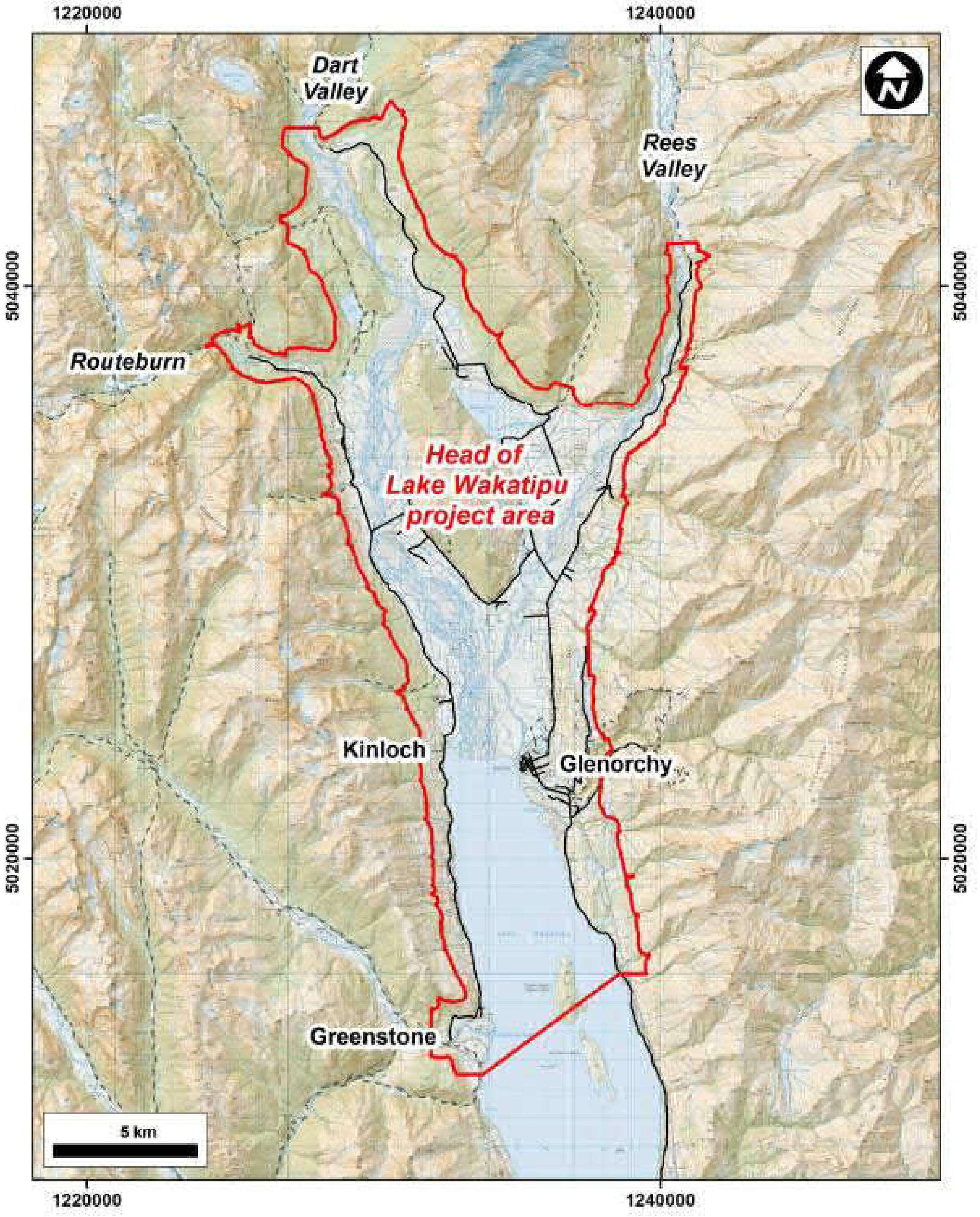

Figure 2-1: Project Area (source: ORC 2020)

2.2 Project objectives

The project, the *Head of Lake Wakatipu Natural Hazard Adaptation Strategy*, is described in the *Project Plan* dated March 2020, attached as Appendix A.

An initial project plan was developed based on a workshop held on 31 July 2019 between ORC, QLDC and DoC representatives, to discuss the issues faced by this area and to propose project objectives and approaches.

That initial project plan has subsequently gone through several iterations by a steering group, based on the subsequent discussions and feedback, working to finalise the project objectives and key tasks, deliverables, and timelines prior to formal project initiation.

The Proposed Project Objective is to "*provide a framework to actively manage risks associated with natural hazards for the resilience"* of the Project area.

Whilst a framework is important to ensure consistency of natural hazard risk management approaches, there are wider objectives, or outcomes that ORC and QLDC are seeking to achieve.

2.3 Project approach

The current project plan is structured around an *"adaptive pathways"* approach to natural hazard assessment. That approach was developed to cater for planning under conditions of uncertainty regarding the rate, timeframes, and magnitude of future changes. Adaptive pathways are being promoted by the Ministry for the Environment (MfE)[1] specifically to address the challenges associated with hazards in the coastal margins, in particular sea level rise. The dynamic environment at the Head of Lake Wakatipu has very similar uncertainties and challenges to those in the coastal environment.

The proposed approach is set out in the Project plan (Appendix A).

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[1] Climate Change. Guidance for Local Government. Ministry for the Environment, 2017

3 Objectives

3.1 International objectives

In 2014, the United Nations Human Rights Council asserted[i] that *"natural hazards are not disasters in and of themselves. Whether or not they become disasters depends on the exposure of a community, and its vulnerability and resilience, all factors that can be addressed by human (including State) action. A failure (by Governments and other actors) to take reasonable preventative action to reduce exposure and vulnerability and to enhance resilience, as well as to provide mitigation, is therefore a human rights issue".*

In 2015, New Zealand signed up to the Sendai Framework for disaster risk reduction. New Zealand has therefore agreed that, as a first priority, "*disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can then be used for risk assessment, prevention, mitigation, preparedness and response*"[2].

New Zealand has endorsed the United Nations Sustainable Development Goals (SDGs), of which SDG-13 is:

"*Strengthening resilience and adaptive capacity to climate related hazards and natural disasters"*.

3.2 National objectives

3.2.1 National Policy Statements

There is currently no national direction in the form of a National Policy Statement on Natural Hazards. However, coastal hazards are covered in the New Zealand Coastal Policy Statement, with detailed and highly directive policies about risk assessment and planning responses to identified risks from natural hazards.

The MfE Guidance on Climate Change and Coastal Hazards (2017) introduced the important concept of Dynamic Adaptive Policy Pathways. This is an area where significant development, with practical examples, is needed and the proposed engagement process for the Project area could establish a clear communication of the concept and how it can be practically applied in a non-coastal environment.

Although there is no national policy statement, there is an abundance of information at a national level on national objectives around natural hazards and natural disaster risk.

3.2.2 The Resource Management Act (RMA)

The RMA is currently the umbrella law that covers the management of natural and physical resources, including land use. The management of significant risks from natural hazards is a matter of national importance that must be considered by all those exercising functions or powers under the RMA[3].

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[2] Paragraph 23, Sendai Framework for Disaster Risk Reduction 2015-2030.

[3] Section 6 of the Resource Management Act

The definitions in the Act are fundamental to understand how it addresses natural hazards:

- The definition of natural hazard[4] refers to atmospheric, earth or water related occurrences (i.e., natural processes) that may adversely affect human life, property, or other aspects of the environment. This definition incorporates the concepts of a natural process event as a source that can result in impact. The receivers of the impact include people, property and (often overlooked by practitioners) other aspects of the environment.
- The definition of environment[5] is very broad, and when read alongside the definition of natural hazard establishes a very wide scope of matters to consider when thinking about potential adverse effects from natural hazard events.

The meaning of effect[6] is also broad, covering positive and negative dimensions, timeframes, cumulative effects and specifically incorporates risk concepts, in particular, "*any potential effect of low probability which has a high potential impact*". This definition is important in establishing the basis of a risk-based approach and the imperative to consider low probability events with high potential impacts.

ORC and QLDC have functions related to natural hazards, including addressing them in their RMA planning documents. The combined approach to developing an adaptation strategy for the Project area is an example of coordination and engagement in exercising these jointly held functions.

3.2.3 RMA replacement legislation

Following a review of the resource management system (including the RMA) in 2020 by retired Judge Tony Randerson and a review panel (MfE 2020), it is now clear that there is bipartisan support for the RMA to be repealed and replaced. This is most likely to occur quickly as recommended by the Randerson review, and most probably to begin in 2021.

Accordingly, it is important to understand the thinking around the changes to resource (including land) use and management legislation that the Randerson review has recommended to the new government, and how these could impact the objectives for the Project area.

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[4] natural hazard means any atmospheric or earth or water related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire, or flooding) the action of which adversely affects or may adversely affect human life, property, or other aspects of the environment.

[5] environment includes—
(a) ecosystems and their constituent parts, including people and communities; and
(b) all natural and physical resources; and
(c) amenity values; and
(d) the social, economic, aesthetic, and cultural conditions which affect the matters stated in paragraphs (a) to (c) or which are affected by those matters

[6] In this Act, unless the context otherwise requires, the term effect includes—
(a) any positive or adverse effect; and
(b) any temporary or permanent effect; and
(c) any past, present, or future effect; and
(d) any cumulative effect which arises over time or in combination with other effects—regardless of the scale, intensity, duration, or frequency of the effect, and also includes—
(e) any potential effect of high probability; and
(f) any potential effect of low probability which has a high potential impact.

Managing natural hazard and climate change adaptation is a key part of the review panel's recommendation to Government. The review identifies specific issues relevant to climate change and natural hazards. These include:

- Insufficient focus on addressing the effects of climate change (adaptation) and the risks from natural hazards
- Poor integration across the resource management system, and
- Capacity, capability, and funding barriers.

The panel identifies the lack of national direction, difficulties addressing contentious issues (including managed retreat), and how risk is understood as factors contributing to the lack of focus. It notes that nationally developed science, data, information, and best practice planning approaches could improve efficiency, consistency, and fairness of approaches.

The key elements of the panel's proposals are:

- A new Natural and Built Environments Act to replace the Resource Management Act
- A new Strategic Planning Act
- A new Managed Retreat and Climate Change Adaptation Act
- Fourteen Combined Plans, prepared on a regional basis, to replace over 100 existing RMA policy statements and plans: and
- More active roles for Central Government.

The key findings of the Review Panel contained in the Randerson Report are discussed further in Appendix B.

3.2.4 National Climate Change Risk Assessment

New Zealand's first National Climate Change Risk Assessment, the community engagement component of which was led by T+T, was completed and reported in the National Climate Change Risk Assessment for New Zealand: Main Report in July 2020. The Main Report is supported by three other documents (a snapshot report, a method report, and a technical report), and provides an overview of how New Zealand may be affected by climate change and identifies the most significant risks. The assessment, completed over a nine-month period, will inform a National Adaptation Plan.

The approach used to conceptualise risk in the assessment is described as follows:

> "*Climate change risk assessment requires more emphasis on consequences than on likelihood. Risk is framed using the elements of hazard, exposure, and vulnerability, with the overlap defining the risk. Risk is a function of climate hazards, the degree to which values are exposed to the hazard and their vulnerability to its effects (Ministry for the Environment, 2019).*
>
> *Risks were rated using magnitude of consequence criteria developed for this assessment. Each risk's exposure and vulnerability (sensitivity and adaptive capacity) were also rated using criteria developed for this assessment. Finally, the assessment rates the risks for decision urgency to signal the need for adaptation action, using criteria developed for this assessment*."

The emphasis here on the consequences, and the use of a more qualitative approach to assessing risk, is helpful and aligns with the flexibility that ISO 31000[7] anticipates for the means to characterise risk. There is an opportunity for ORC thought leadership to focus attention more expressly on the

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[7] ISO 31000:2018 Risk Management Guideline – defines risk as the "effect of uncertainty on objectives". Notes to the definition outline a range of means to characterise risk.

definition of risk in ISO 31000 and connect this with the approach taken in the National Climate Change Risk Assessment.

The approach was also based on guiding principles drawn from the 2019 National Disaster Resilience Strategy (Ministry of Civil Defence and Emergency Management) and adding a prosperity principle from the Treasury Living Standards Framework. The Report describes the principles as follows:

> "*The mātāpono, which are additional to the principles of Te Tiriti o Waitangi (partnership, protection, participation and potential), are:*
>
> - Manaakitanga (care and reciprocity)
> - Kaitiakitanga (intergenerational sustainability
> - Whanaungatanga (connectedness and relationships)
> - ōhanga (prosperity)
>
> Rangatiratanga (leadership and autonomy)
>
> - Kia mahi ngātahi (engagement and participation)
> - Kia āwhina (support)."

There is helpful alignment in the links to the National Disaster Resilience Strategy and Living Standards Framework, which ORC can develop and strengthen further in its adaptation strategy for the Project area.

The Main Report considers various risks across a range of domains, including Governance. Of particular relevance to the Project is the maladaptation risk (Risk G1) which, appropriately focussing on uncertainty, can be summarised as follows:

> "*Climate change adds to the uncertainties that decision-makers already face…Reliance on practices that embed processes and tools, which do not account for long-term uncertainty and change, will increase the likelihood of maladaptation across all domains*".

It outlines areas of uncertainty associated with climate change, and notes that decisions still need to be made in the face of uncertainty. It emphasises the importance of flexible and adaptive approaches to decision-making and interventions. Significant parts of this agenda are being progressed alongside the National Climate Change Risk Assessment and National Adaptation Plan processes.

3.2.5 National Civil Defence Emergency Management Strategy

The National Disaster Resilience Strategy, and the goals set for it in the Civil Defence and Emergency Management (CDEM) Plan, provides a strong context for ORC objectives. The goals emphasise the importance of community awareness and understanding and reducing risk from hazards.

The concepts of proactive risk management and building resilience in the Strategy's Vision are helpful.

The Strategy clearly identifies the RMA, and Regional and District Plans, as part of the policy context and identifies the built and natural environments as two of the key elements underpinning a resilient nation. The concepts of resilience being integrated in urban and rural design, and data enabling smart land-use are also particularly relevant.

3.3 Regional objectives

Chapter Four of the ORC Regional Policy Statement (RPS)[8] deals with "*the response and ability to be resilient to resource limitations or constraints, shock events, system disruptions, natural hazards and climate change.*"

Two key objectives are:

- Risks that natural hazards pose to Otago's communities are minimised, and
- Otago's communities are prepared for and able to adapt to the effects of climate change.

3.4 District objectives

Under its Proposed District Plan (PDP dated June 2019), QLDC has three key objectives:

- The risk to people and the built environment posed by natural hazards is managed to a level tolerable to the community
- Development on land subject to natural hazards only occurs where the risks to the community and the built environment are appropriately managed, and
- The community's awareness and understanding of the natural hazard risk in the District is continually enhanced.

3.5 Local objectives

The Glenorchy community developed a series of objectives in 2001. Subsequently, in two workshops on 11 and 12 April 2015, the objectives were refined and are summarised in the Glenorchy Community Visioning Report dated 2016. A key local community objective[9] is:

> *An environmentally sustainable, self-sufficient community*

This community objective is more of an outcome expression than is the case with the Regional and District objectives and is therefore more aligned with the outcome focus recommended for the new legislation. This in turn aligns better with ISO 31000 thinking which sees risk as not being all negative.

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[8] Partially Operative Otago Regional Policy Statement 2019: Changes as a result of appeals.

[9] The local Glenorchy community developed a series of objectives in 2001. Subsequently, in two workshops on 11 and 12 April 2015, the objectives were refined and are summarised in the Glenorchy Community Visioning Report dated 2016.

4 Hazard's environment

4.1 Natural processes

The landscape in the Project area has been created by, and is continually changing due to, natural geomorphic processes. These processes are mostly slow, but occasionally are very rapid. An understanding of how a landscape came to be is the science of geomorphology. Erosion of soil and rock, and the transport and deposition of the eroded materials by gravity and/or water, has created the existing landscape in the Project area.

Human activities have increased the rate of erosion that naturally occurred before human occupation, primarily through the removal of the forest cover on the sub-alpine areas of the catchments of the Dart and Rees Rivers. Enhanced erosion through human activity is termed "accelerated erosion". Human-induced climate change is expected to increase the rate of both erosion and deposition/aggradation.

Geomorphic processes, natural and enhanced through human activity, become natural hazards when they adversely impact the environment. The RMA definitions are useful and are discussed further in Section 4.5.2.

4.2 Natural hazards

Almost every part of New Zealand is subject to some natural hazard or another, and many are subject to several. Human settlement has become concentrated alongside rivers and coastal environments that are dynamic. This is certainly so for the Project area, which is particularly exposed to numerous natural hazards, as identified by ORC (2020):

- Floodplain, lake, and delta hazards
  - Flooding hazards
  - Lake Wakatipu flooding
  - Dart and Rees River flooding (floodplain flooding)
  - Glenorchy flooding
    - Rees River
    - Buckler Burn
    - Bible Stream
  - Other tributary streams
- Lake Wakatipu tsunami and seiche hazards
  - Delta collapse lake tsunami
  - Landslide-generated lake tsunami
  - Lake seiche
- Geomorphic floodplain and delta changes
  - Rees floodplain
  - Dart floodplain
  - Delta growth
  - Alluvial fans
    - Buckler Burn alluvial fan
    - Other alluvial fans
  - Riverbank erosion

  - Riverbed aggradation
- Slope hazards
  - Landslide, rockfalls and debris flows
  - Debris flows
- Landslide dam hazards
- Seismic hazards
  - Ground rupture
  - Ground shaking
  - Liquefaction and lateral spreading
  - Co-seismic landsliding and geomorphic multi-hazard event cascades

In setting the hazardscape in the March 2020 Project Plan (Appendix A), ORC and QLDC have categorised the above hazards as:

- River hazards
- Lake hazards
- Slope-related hazards, and
- Seismic-related hazards.

ORC and QLDC spatial information of natural hazards has been reproduced in a consistent map format, and these maps are attached as Appendix C and are also available in the web-based viewer.

ORC has then considered:

- Multi-hazard events (cascades generated by a major earthquake), and
- Climate change impacts on these events (changes in rainfall/snowfall, river flows, etc).

In describing natural hazards, it is useful to maintain the commonly used terminology adopted by the insurance industry. In addressing the issue of natural disaster risk management, it is important to understand the ability or otherwise of transferring some or all of that risk through private insurance cover, and to also understand what natural hazards (perils as referred by insurers) are covered under the current National Disaster Insurance Scheme (NDIS) managed by the Earthquake Commission (EQC). In its listing of natural hazards, the current NDIS legislation (EQC Act 1993) uses the term landslip, which is taken to be synonymous with the term landslide.

For the purposes of preparing adaptation plans, T+T considers that it is important to focus on the consequences of natural hazards, as well as understanding the proximate causes of those consequences and hence whether they are insured perils.

4.2.1 Proximate causes of natural hazards

The natural hazards listed for the Project area often cause similar types of damage because the consequences are essentially the same, or reasonably similar. The insurance industry looks at the proximate cause, namely the initial event (insured peril) that caused the resulting damage.

All the natural hazards listed by ORC in the Project area have three proximate causes, or triggers, which are:

- Earthquakes, which can cause damage to land and habitats due to, amongst other effects, shaking, liquefaction effects (including ejecta, ground subsidence and lateral spreading), tsunami (including inundation and scour), ground rupture and earthquake-induced mass movement (including landslip), and fire.

- Rainfall (including snowfall and snow melt), which can cause damage to land and habitats due to the effects of stormwater runoff (flooding) such as inundation by water and/or flood debris, erosion (and scour) of land, groundwater rise causing flooding and increased liquefaction susceptibility, and rainfall/groundwater-induced mass movement, including landslip, and snow-induced effects such as building roof collapse and avalanche. Conversely, extreme low rainfall causing drought and low river flows can also lead to social, economic, and environmental damage.
- Gravity (and time), which can cause landslips on elevated ground, including slumping of deltaic sediments (with consequential tsunami). Accordingly, it is necessary to also consider events that can occur suddenly but without a triggering seismic or rainfall event as the proximate cause.

4.2.2 Uncertainty of natural hazards

Natural hazard risk can be described as a combination of the likelihood of a natural hazard event occurring together with the consequence of the event. In this way a natural hazard event that has a low likelihood of occurrence, but which would result in a major effect or consequence, can be identified as high risk, but more concerningly is often presented as a low risk.

That process has inevitably led to too much attention being applied to the likelihood of a particular event occurring. This chance, or probability, has also led to the unhelpful description of probability as a “return period”. Rather than “return period”, a better term is “average recurrence interval”, or ARI.

The concept of probability, or likelihood, is not widely understood. There is considerable uncertainty associated with the prediction of most natural hazard events, even where there is a good historical record. Furthermore, the historical record may not be relevant for future events in dynamic environments, particularly those affected by climate change.

In addition, the probability of a natural hazard occurring over an extended time period is even more poorly understood, even amongst scientists and engineers.

In looking at adaptation strategies, T+T considers that it is much more helpful to focus on the consequences of natural hazards as it is these consequences that will need to address in adaptation strategies. This is particularly so because some low probability events potentially have such significant and widespread consequences.

4.2.3 Consequences of natural hazards

As a result of the three triggers listed in Section 4.2.1, T+T has identified three broad categories of consequences, although their severity can vary widely. The main consequences due to natural hazards (perils) in the Project area are:

- Inundation of land and habitat/ecosystems (by water and/or debris)
  - This is irrespective of whether it is from flood, landslip (including debris flows) liquefaction (including ejecta), tsunami, waves, or any other natural disaster
- Loss of land and habitat/ecosystems (from rapid erosion and scour)
  - This is irrespective of whether from flood waters, tsunami, landslip, or waves
- Movement of land and habitat/ecosystems (downslope mass movement)
  - This is irrespective of whether from fault rupture, landslip, liquefaction (including lateral spreading) or rainfall.

For residential buildings and residential land another consequence category was identified in Canterbury as a result of earthquake-related land subsidence, namely:

- Increased Vulnerability (to flooding or liquefaction as a result of earthquake-related ground subsidence), which is covered under the EQC Act and which could also occur in the Project area.

The current NDIS scheme also includes for another form of increased vulnerability, which covers additional loss or damage to residential land and buildings that is imminent as the direct result of the natural disaster that has occurred. This is colloquially referred to as Imminent Loss, or IL. This form of loss or damage to residential land and buildings is not recognised by private insurers.

4.3 Natural disasters

Natural disasters occur at the intersection of a natural hazard event with an exposed and vulnerable community or habitat/ecosystem. The Project area is restricted to areas below about the 600 m contour. This is the area where ORC has identified that natural hazard events could intersect significant parts of the built environment (including infrastructure) associated with human communities.

The typical approach to describing the risks from particular natural hazards has been to estimate their likelihood and determine the extent of consequences (typically monetary losses or human casualties). The risk then essentially becomes the probability of the loss. This has traditionally led local authorities attempting to manage frequently occurring natural hazards, and to ignore low frequency events even though the same hazard (e.g., floods having an ARI of 500 years).

Whilst this can be a useful approach for risk pricing by insurers, it is considerably less useful for establishing policies around natural disaster risk management and resilience. In part, this is because of the considerable uncertainty around both the likelihood and consequences of the less frequently occurring natural hazards. Even with “accurate” long term (say more than 30 years) river flow time series, the uncertainly around the estimation of flood flows for even a 50-year average recurrence interval event is surprisingly high. The confidence limits associated with the statistics of the data mean that the adoption of a singular value for a design flow may not be appropriate.

The uncertainty around the estimation of flood flows becomes even further complicated by climate change effects, which mean that in most places the historical record is no longer a “reliable” predictor of future flood flows, and therefore the risk. This is certainly true for the Project area. NIWA (2019) predicts that out of all of Otago, climate change will cause the greatest increase in rainfall to occur in the upper Dart and Rees River catchments, and over all seasons.

The current processes of erosion and deposition are causing significant aggradation in the lower reaches of the Dart and Rees Rivers, and as a result their confluent deltas are prograding into Lake Wakatipu. Increased rainfall is likely to accelerate these processes. This acceleration will exacerbate the already concerning situation at Glenorchy and Kinloch, where parts of the beds of the rivers are higher than the lower parts of adjacent already developed land.

The amount (depth) of rainfall is just one aspect: intensity (depth duration) of rainfall is another. It is high intensity rainfall that most frequently causes mass denudation (due to land slippage) of the hillslopes higher up the valleys. It can therefore be expected that increased erosion and mass denudation will in turn result in an increased frequency and magnitude of debris flows in the upper reaches of the rivers, and thus more sand and gravel to be transported down the river systems.

4.4 Natural disaster risk

In considering natural disaster risk, the term “risk” needs to be defined clearly.

The current definition of risk as set out in the International Standard on Risk Management - Guidelines ISO 31000:2018 is "*the effect of uncertainty on objectives*". This definition is particularly helpful for any discussion about adaptation in the Project area for natural hazard uncertainty, as it encompasses positive possibilities as well as negative ones. Traditional approaches to risk management have tended to focus on the negative, or adverse, effects of uncertainty.

Natural disaster must be considered in the context of our international, national, regional, district, and local community objectives around natural disaster risk management and resilience, set out in Section 4.5.

Natural disasters threaten not only the prosperity but potentially the existence of civil society. Natural disaster risk reduction therefore needs to be an integral part of who we are, and what we do. For some threats there is nothing we can do. For some other threats there is nothing that we should do. For the remaining threats, we need to include cost benefit information when considering options, taking a broad approach to value. Costs include environmental, social, and cultural measures as well as financial.

Although ISO 31000 outlines leading thinking and current international best practice on risk management, for the management of natural hazard risk in New Zealand the uptake of the ISO 31000 concepts and approach has been less than fulsome. Nonetheless, the concepts and approaches outlined in ISO 31000 align well with current and emerging requirements and drivers in New Zealand, and in the current and proposed future resource management legislative framework. Of particular note are:

- The focus on outcomes (as expressed in objectives)
- The concept (definition) of risk being the effect of uncertainty on objectives
- Its more flexible approach to how risk is characterised or described, that relies far more on understanding and communicating about uncertainty, than quantification
- The emphasis on a "whole of system" approach to understanding the consequences and likelihood of them occurring
- The relevance and applicability of the provisions on principles and the risk management framework to natural hazards management; and
- The opportunity to reconsider the risk management process in light of the significant changes included in ISO 31000: 2018 (which replaced the previous 2009 version).

4.5 Disaster risk reduction

The typical approaches to the management of natural disaster risk are avoidance or mitigation. These approaches can be more appropriately termed avoiding the effects of natural hazard events or defending against natural hazard events. Insurance may be an option to lessen the economic consequences of natural disasters by way of risk transfer.

Where natural disaster risk cannot be avoided or mitigated, communities are left with accepting the residual risk. This approach is termed living with natural hazards.

To enable communities to decide whether or not the residual natural risk is acceptable or tolerable, information on the consequences of natural hazards needs to be presented in a form that can be readily understood. This is also important for those providing insurance (if available).

The purpose of setting out natural hazard information in this report is therefore to present what is currently known about the various natural hazards:

- spatially where such hazards exist

- what the consequences actually look like, so that communities can make well-informed rational decisions regarding risk reduction and risk acceptance, and markets can price the risk transfer (if available).

The risk of property damage from natural hazards is something that markets can price, and about which the public can make informed choices. Individuals have both human rights and property rights that enable informed choice to flourish. The potential for loss of life, however, is different. Where lives are threatened by natural hazard events there is a general aversion by local authorities to accept even relatively low levels of assessed life risk.

Where natural hazard events threaten lives, local authorities are increasingly determining the acceptability of assessed levels of natural disaster risk. Following the second earthquake in Christchurch in 2011, Christchurch City Council adopted an Annual Individual Fatality Risk (AIFR) level of 1 in 10,000 (i.e., 1×10^{-4} probability) as a threshold to determine whether or not it is acceptable to live in a particular location, the first local authority in New Zealand to do so. The AIFR from rock fall and cliff collapse was estimated by GNS in the Port Hills, the findings from which resulted in dozens of undamaged homes being abandoned because the estimated risk to life was deemed unacceptable.

The assignment of a probability to define acceptable risk arose from work by the Food and Drug Administration (FDA) in the USA in the 1970s, in order to establish the amounts of particular substances that were safe. Safe, in the context of developing cancer by ingesting substances, was initially put at a probability of 1 in 100 million (1×10^{-8}) by the FDA in 1973, but this was changed in 1977 to be 1 in a million (1×10^{-6}). These numbers had no scientific basis but were merely considered to be “essentially zero” (Kelly, 1991).

Despite the FDA specifically advising that “essentially zero” was not to be interpreted as an acceptable level of risk, the arbitrary level of 10^{-6} has been almost universally adopted as a threshold for it. This may be a reasonable risk level for deciding whether to permit new drugs on the market, and there is a wealth of international information available on acceptable and tolerable, involuntary, and voluntary, individual, and societal risk.

Considerable caution is needed if applying the concept of AIFR to natural hazard risk tolerance. Firstly, AIFR assessments for most natural hazard events will likely have large uncertainties attached. Secondly, New Zealand is exposed to a wider range of natural hazards than most other countries, in particular Australia, England and the Netherlands where many of the limits of risk tolerance have originated. Thirdly, this approach is appropriate for large populations and data sets but less appropriate for very small populations where basic assumptions can significantly impact on the calculations, e.g., an assumption that in a small suburb/single street the average number of people living in houses is two rather than five.

Almost every part of New Zealand is vulnerable to some natural hazard, and many areas are susceptible to multiple hazards. In short, in New Zealand one may need to tolerate a theoretical level of risk from natural hazards (assuming that one can determine what the risk level is with any confidence) that other countries can avoid. This is true for the Project area.

5 Regional seismic hazard

This section provides seismic hazard information about the Project area and wider region, including:

- The location of known active faults
- Historical events
- A summary of information about shaking intensity recurrence, and
- Seismic and co-seismic damage mechanisms.

5.1 Active faults

The Project area and surrounding region lies wholly on the Pacific tectonic plate, approximately 80 km east of the Alpine Fault. There are many known active faults that can generate large levels of seismic shaking (felt intensities). The Alpine Fault is the surface expression of the transform boundary between the Pacific and Australian plates. It is a dextral reverse fault, where the Pacific Plate slips along the Australian Plate as they are forced together. Uplift at this boundary from the tectonic activity forms the Southern Alps. There are multiple crustal faults east of the Alpine Fault, near Queenstown and Wanaka that are capable of generating earthquakes larger than moment magnitude (M_w) 7, including the Cardrona-Nevis Fault System, Moonlight Fault, West-Wakatipu Fault and Pisa Fault. Earthquake magnitude is quantified on a logarithmic scale: so, a Mw 7 earthquake is approximately ten times stronger than a Mw 6 earthquake.

Seismicity in New Zealand is estimated using the National Seismic Hazard Model (NSHM) published by Stirling et al (2012). This model outlines known fault sources and their characteristics of magnitude and average recurrence of rupture. Across New Zealand, the tectonic setting and the seismicity varies. Figure 5-1 shows the individual known fault sources in and surrounding Project area and the wider region. This is from both the Stirling et al (2012) National Seismic Hazard Model dataset and Barrell (2019). There are some differences between these datasets, so to demonstrate the variability, both are presented in Table 5-1.

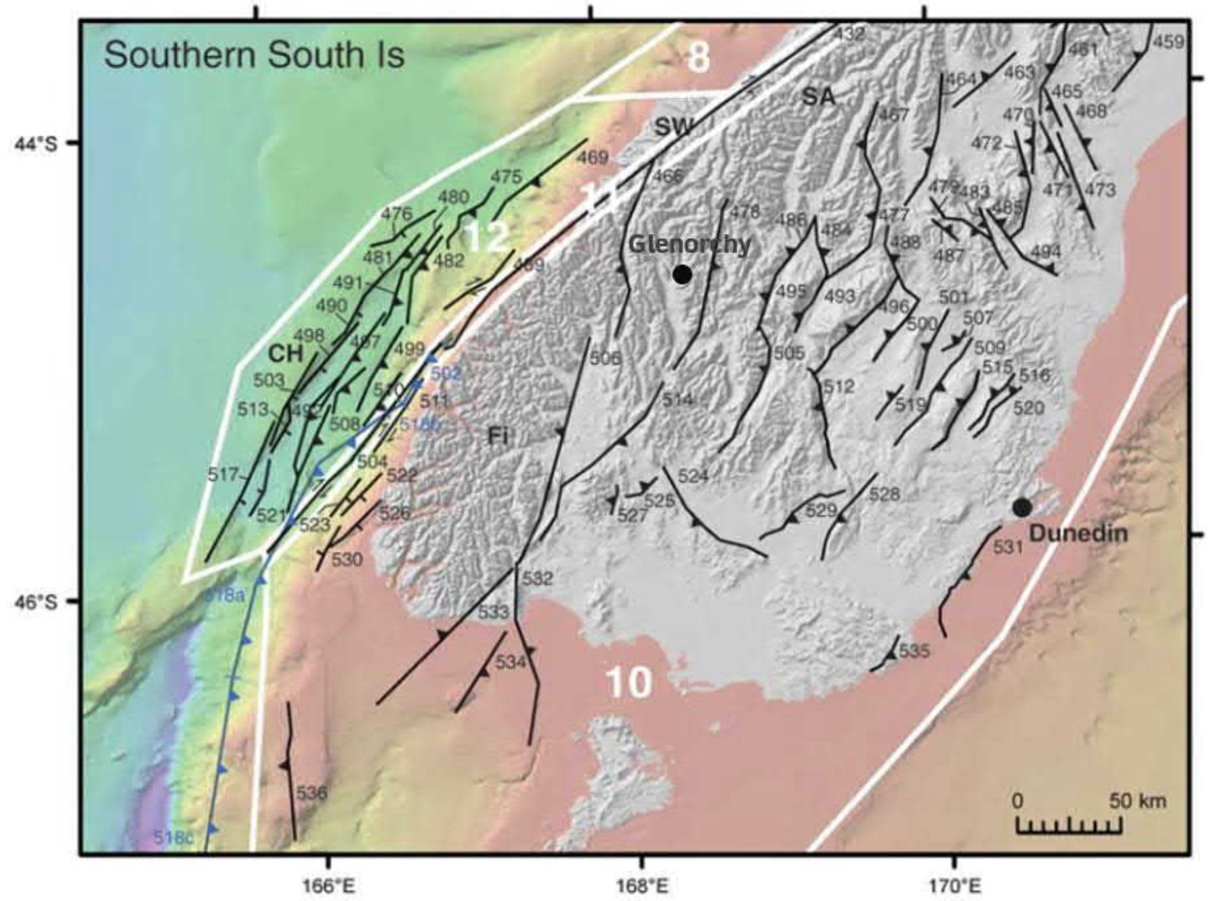


Figure 5-1: Individual known fault sources applied in the Stirling et al (2012) National Seismic Hazard Model in and surrounding the Project area.

Further to the known active faults, unknown faulting and other seismogenic (earthquake generating) sources are likely within the region. Surface expressions of past fault ruptures can be hidden by younger soil deposits. Earthquakes could be expected to occur at any location and are not limited to known faults. This was illustrated by the Canterbury Earthquake Sequence, which occurred predominantly on unknown faults. Unknown fault sources are likely to exist and some consideration is applied in Stirling et al (2012) as a distributed source model in combination with the fault source model.

Table 5-1: Selected active fault sources in the region

Fault Name	NSHM Fault number in Figure 5-1	Approximate from distance from fault to Glenorchy (km)	Estimated characteristic magnitude	Average recurrence interval (years)	
				NSHM (Stirling et al 2012)	Barrell (2019)
Alpine Fault (F2K)	432	55	8.1	250	-
Te Anau	506	45	7.7	8,000	-
West Wakatipu	-	10	-	-	20,000
Moonlight North	478	25	7.6	6,100	140,000
Moonlight South	514	45	7.6	7,000	120,000
Pisa	493	65	7.2	31,000	30,000
Hollyford	466	20	7.6	6,300	-
Milford B1	469	85	7.6	1,400	-
Cardrona	495	45	6.9	5,100	5,500
Nevis	505	45	7.5	12,000	9,000
Hokonui	524	90	7.5	9,600	-
Dunstan	496	85	7.4	7,000	7,000
Gimmerburn	501	100	7.2	5,900	7,400

5.2 Historic regional events

Historical observation records of large earthquakes in New Zealand exist back to approximately 1840. The study of the seismic hazard in the Queenstown Lakes District (ORC 2015) presents historic seismicity in the Wakatipu area, with earthquakes larger than MW 3.0 from 1942 to July 2015, reproduced here as Figure 5.2. Two earthquakes larger than MW 5.5 have been recorded over that period (labelled). The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the Head of the Lake. The Alpine Fault is approximately 55 km from Glenorchy, but is very close to the headwaters of the Dart and Rees Rivers

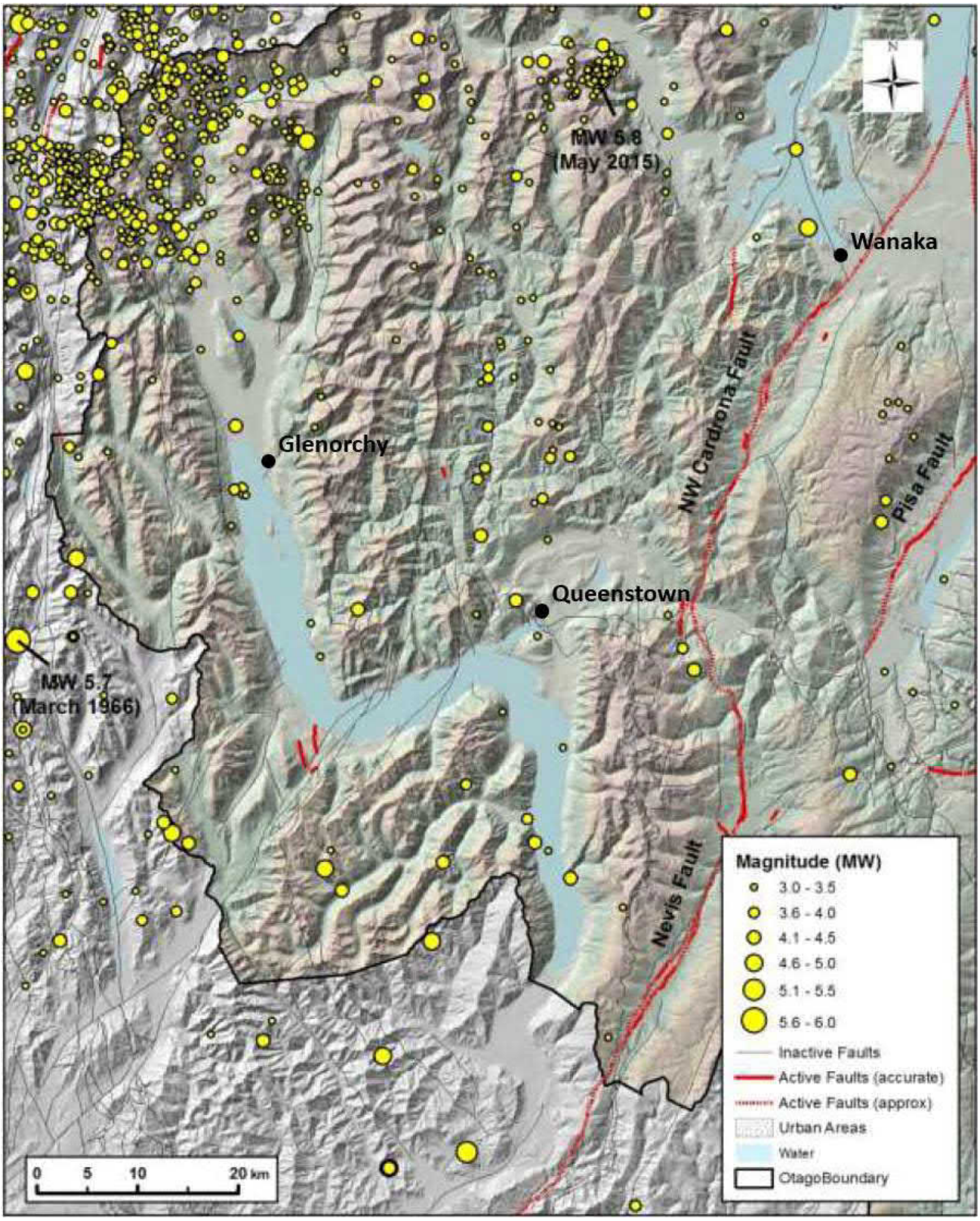


Figure 5.2: Historic seismicity in the Wakatipu area (ORC 2015, data from GeoNet accessed July 2015)

Table 5.2 summarises a selection of notable earthquakes in the QLDC region from historical records. Shaking intensity is provided in Modified Mercalli (MM) intensity scale to provide an estimate of the damage observed (Dowrick, 1996).

Table 5.2: Recorded notable earthquakes in the Queenstown Lakes District

Earthquake event	Year	Estimated epicentre from Glenorchy	Magnitude estimate (Mw)	Maximum shaking intensity (MM)	Shaking intensity (MM) in Glenorchy
Charles Sound Earthquake	10 February 1939	110 km west	7.0	6	5 to 6
Wanaka Earthquake	8 May 1943	60 km southeast	5.9	7	6
Fiordland Earthquake	24 May 1960	110 km west	6.5	6	5
Milford Sound Earthquake	4 May 1976	90 km west	6.5	6	5
Te Anau Earthquake	3 June 1988	100 km southwest	6.7	7	6 to 7
Secretary Island Earthquake	10 August 1993	120 km west	6.8	6	5 to 6
Fiordland Earthquake	21 August 2003	130 km southwest	7.2	7	5 to 6
Milford Sound Earthquake	16 October 2007	90 km southwest	6.7	6 to 7	5 to 6
Wanaka Earthquake	4 May 2015	55 km northeast	5.8	6 to 7	5 to 6
Notes	Source: Downes and Dowrick 2014, GeoNet 2018 Refer Appendix D for Modified Mercalli scale				

5.3 Head of Lake Wakatipu seismic shaking recurrence

The frequency or recurrence of earthquake shaking at a location is a function of the hazard from all faults and background (distributed) seismic sources in and surrounding the area of interest. To quantify this, a Probabilistic Seismic Hazard Analysis (PSHA) is used. Assessments using PSHA are provided in literature, standards and guidance documents for the Queenstown Lakes District and the wider Otago Region.

One site characteristic that can affect seismic shaking is the subsurface geology/geomorphology. In New Zealand, there are five subsoil classes that are typically used to characterise site amplification effects during earthquakes. These five subsoil classes and their descriptions are summarised in Table 5-3. Class A is the stiffest class with Class E the softest. These subsoil classes are defined fully in the New Zealand Structural Design Actions, Part 5, and NZS 1170.5:2004 (Standards New Zealand, 2004).

The NZTA Bridge Manual (NZTA 2016) provides an estimate Peak Ground Acceleration (PGA) for given return periods for Queenstown (the closest centre to the Project area for each of the subsoil classes in the area (Table 5-4).

As shown in Table 5-4, at the greater recurrence interval events (i.e., lower probability), the Project area and wider region is exposed to significant levels of shaking. As is shown, amplification due to the subsurface geology can significantly alter the level of shaking. However, these levels of shaking could occur at any time and could vary both spatially and with intensity, whereby the fault that produces the earthquake can significantly alter the shaking attenuation. Of note, Foster et al (2019) show the shear velocity in the Glenorchy and Kinloch areas is 200 m/s to 300 m/s, as these areas are composed of alluvial and fan gravels and sands over lake sediments aligning them with a subsoil class D/E.

Table 5-3: Subsoil classifications (NZS 1170)

Classification	Description		Shear Velocity [1.] (Vs 30, m/s)
Class A	Strong rock	Strong or extremely strong rock present at the ground surface	greater than 1,500
Class B	Rock	Less than 3 m of highly - or completely - weathered rock or soil overlying basement rock with a compressive strength of at least 1 MPa	760 to 1,500
Class C	Shallow soil sites	Limited thickness of soil overlying rock, e.g., less than 20 m of soft soil or 60 m of stiff soil	360 to 760
Class D	Deep or soft soil sites	Soil deposits that are deep and/or soft, e.g., more than 20 m of soft soil or 60 m of stiff soil	180 to 360
Class E	Very soft soil sites	Very soft soil sites, e.g., more than 10 m of very soft soil	less than 180
Note	[1.] Shear Velocity for each soil classification from NEHRP (2003)		

Table 5-4: Queenstown shaking intensity frequency based on the NZTA Bridge Manual

Frequency (ARI, years)	PGA (g)		
	Queenstown		
	Subsoil class A/B	Subsoil class C	Subsoil class D/E
100	0.15	0.20	0.16
250	0.23	0.31	0.24
500	0.31	0.41	0.32
1,000	0.40	0.53	0.42
2,500	0.55	0.74	0.58

Using the OpenSHA platform to model the seismic hazard relates the probability of exceedance versus PGA (refer Figure 5.3). This makes use of the NSHM data for both the background and fault data from GNS as of 2018, and applies the Bradley (2013) ground motion prediction equation with the Vs30 = 250 m/s. This highlights the variable probability for each ARI. However, further analysis would be required to check the sensitivity with the revision of some of the fault recurrence intervals.

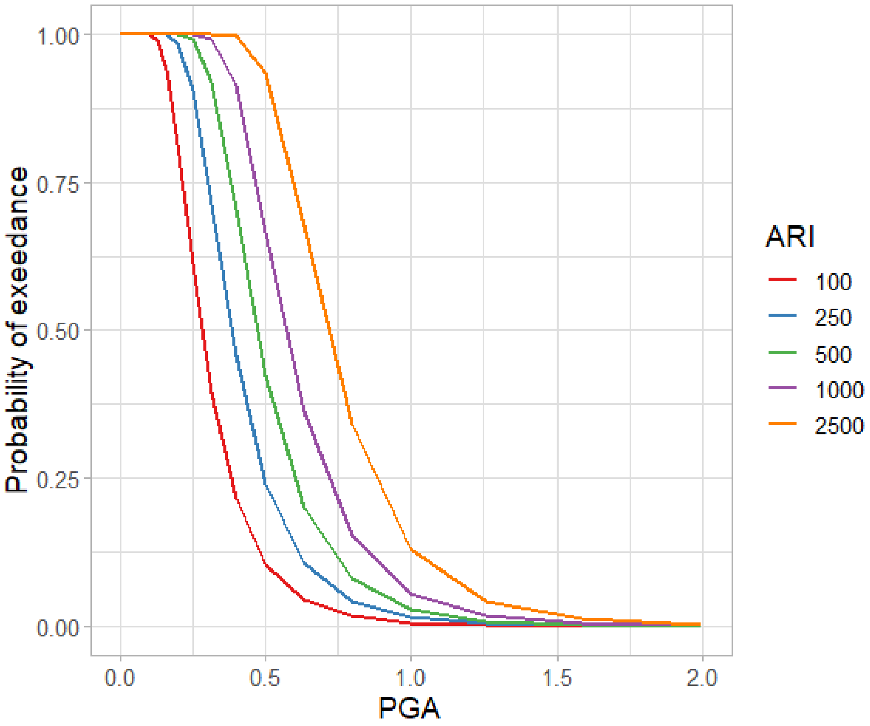


Figure 5.3: Seismic hazard exceedance probability curve

There are many challenges with assessing the shaking recurrence. The Moonlight Fault, which crosses the centre of Lake Wakatipu, provides a good example of the uncertainty regarding the assessment of the likely recurrence interval of mapped faults. This fault was previously regarded as one of the more active faults in the wider area, with an estimated recurrence interval of 6,000 to 7,000 years (Stirling et al, 2012). However, this interval was recently significantly revised to 120,000 to 140,000 years (Barrell 2019).

A feature previously considered to be associated with the Moonlight Fault is now attributed to the West Wakatipu Fault, with an estimated recurrence level of 20,000 years (Barrell 2019). Each of these faults are presented in the Figure 5-4. This demonstrates the difficulty associated with assessing seismic recurrence.

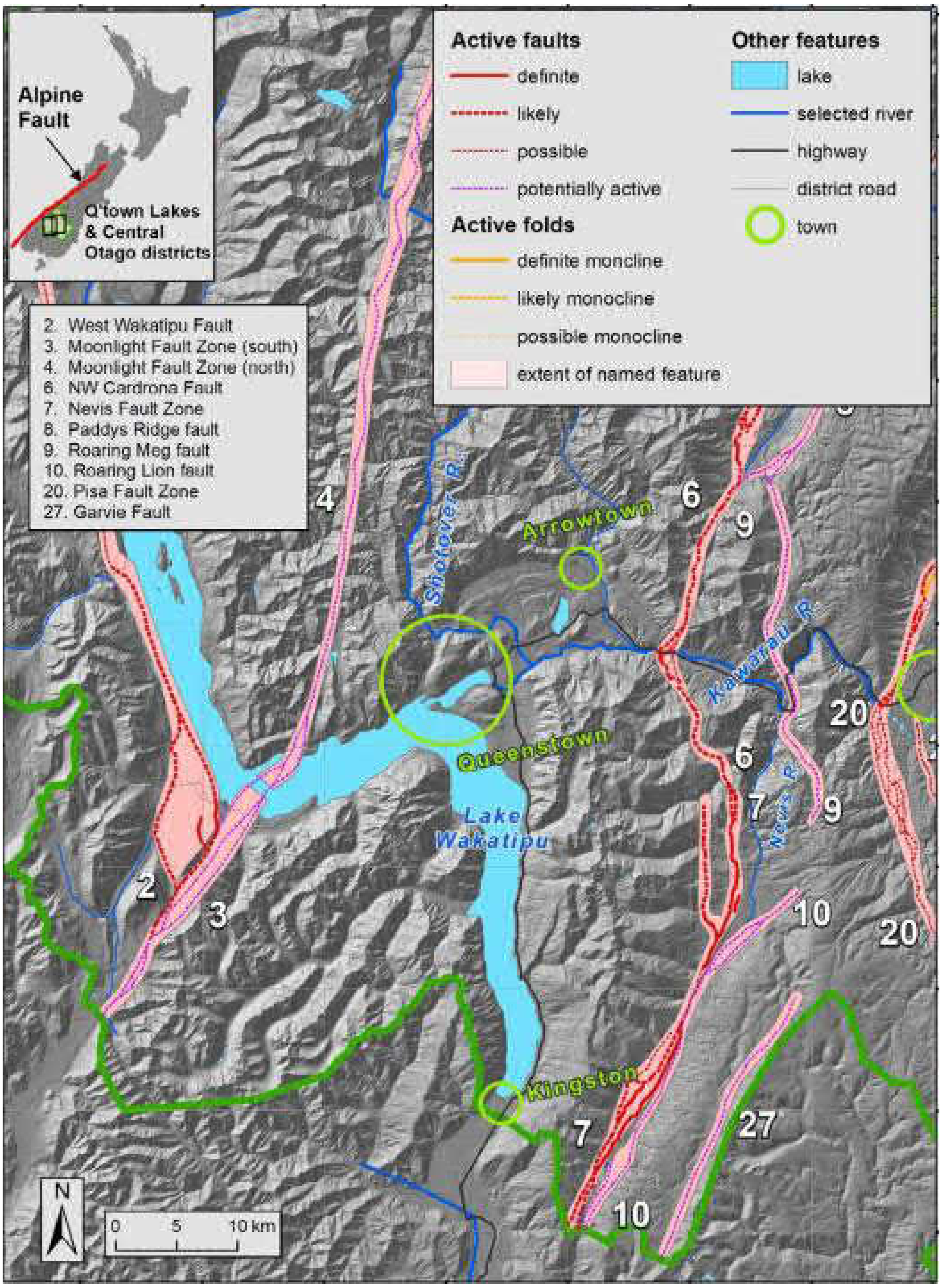


Figure 5-4: Major Faults near the Project area (Barrell 2019)

The faults in the general vicinity are estimated to cause Modified Mercalli (MM, refer Appendix D) intensities of VII and VIII (100-year ARI), and IX and VIII (2,500 year ARI) levels of seismic shaking in the Project area, as shown on Figure 5-5 and Figure 5-6.

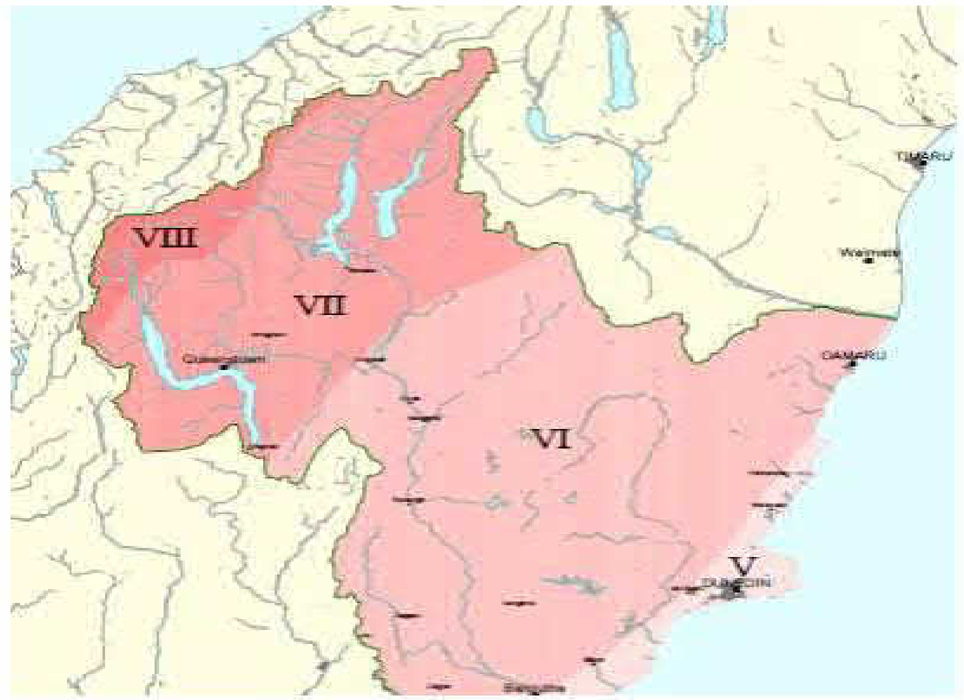


Figure 5-5: 100-year ARI MM Intensities (Murashev and Davey (2005) in ORC 2015)

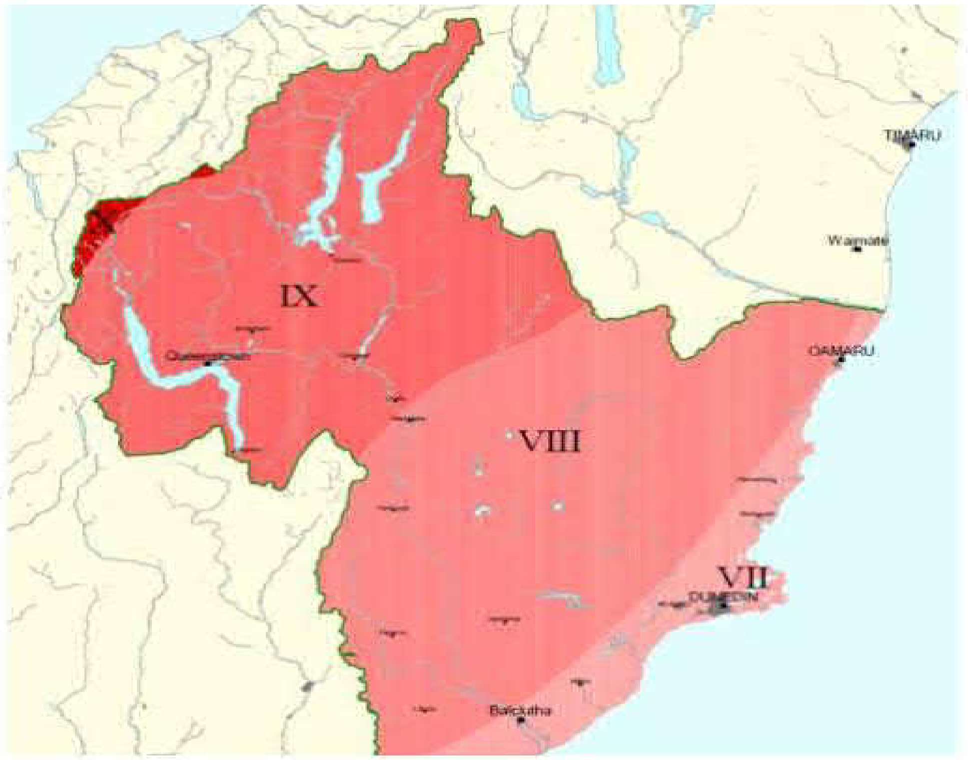


Figure 5-6: 2,500-year ARI MM Intensities (Murashev and Davey (2005) In ORC 2015)

While the national seismic hazard models can be fraught with uncertainty, the assessment of seismicity using these approaches are used to inform engineering standards, such as NZS 1170:5 and the NZTA Bridge Manual. This explains why the national seismic hazard model has background seismic points to account for the possibility of seismic events from unknown or unmapped sources.

5.4 Seismic and co-seismic damage mechanisms

Because the built environment and infrastructure are founded on and in the ground, seismic damage to these elements typically occurs as a result of ground deformation. Ground deformation can be characterised as either transient or permanent (Table 5-5, O'Rourke, 1998). Transient deformation occurs during earthquake shaking and is the direct result of the passing seismic waves, but the ground after the earthquake typically returns to its near original state (albeit that cracks will persist). Permanent ground deformation occurs when the ground shaking leaves the ground in an altered state, or if secondary effects (such as liquefaction) are triggered that can lead to significant and permanent deformations after the shaking has ceased.

Table 5-5: Seismic damage mechanisms grouped by type of ground deformation

Transient ground deformation	Permanent ground deformation
Earthquake shaking, minor cracking of the ground	Liquefaction and lateral spread Landslide Surface fault rupture Local ground subsidence Tectonic subsidence and uplift

Ground condition aspects have been broadly characterised as part of previous studies for the Queenstown Lakes District (T+T, 2013). This report focuses on the earthquake shaking, liquefaction and slope failure vulnerability, which can cause significant damage to the land and built assets. Sections 7.2.1 to 7.2.3 provide additional information about each of these seismic damage mechanisms.

Surface rupture of faults and tectonic subsidence or uplift are additional earthquake-related vulnerabilities to land and infrastructure. They may occur concurrently with other earthquake-related hazards. The occurrence of surface rupture of faults in populated areas in the Queenstown Lakes District is considered likely but is a very localised hazard (less than 100 m either side of the fault) and is therefore not considered in this assessment. The occurrence of tectonic subsidence or uplift is extremely difficult to predict and model and therefore they are also excluded from the scope of this report. It should be noted however that large scale tectonic subsidence or uplift could cause significant damage to infrastructure, in particular gravity systems vulnerable to these forms of permanent ground deformation.

5.4.1 Earthquake shaking

Earthquake shaking causes transient ground deformation, which can be damaging for both buried and on-ground infrastructure, but usually by an order of magnitude less than damage in areas where there is permanent ground displacement (O'Rourke et al, 2014). As seismic waves travel through the ground, two points located along the propagation path will experience out-of-phase motions (Opus, 2016). Those motions induce both axial and bending strains in buried infrastructure due to the forces and deformation at the pipe-soil interface. The typical pipe failure mechanism is local buckling (wrinkling of the pipe wall), which can lead to cracks in the pipe wall and leaks (O'Rourke and Liu, 1999). Other pipe failure mechanisms include tensile failures, welded joint failures and joint failures on segmented pipes.

When developing an estimate of the likely intensity of earthquake shaking at a particular site, the key considerations are the fault characteristics, fault rupture length, the distance from the fault and the subsurface ground conditions.

The subsurface ground conditions are considered for the amplification effect the ground profile can have on the seismic waves as they travel up towards the ground surface. The highest degree of amplification occurs for the softest sites, and this amplification is most significant at low levels of shaking, with the effect becoming less at higher intensities of shaking (Cousins, 2013). At high levels of shaking this effect can be reversed. However, the process is complex as it depends on the structure being affected and the component of that shaking that is considered important to the structure (shaking amplitude, frequency content or duration).

5.4.2 Liquefaction damage

When loose sandy or silty soils are subjected to strong earthquake shaking, there is a tendency for the soil particles to try to compact. If the soil is saturated with groundwater, then the water between the soil particles is unable to escape and becomes pressurised. If the shaking is sufficiently strong and long, and the soil loose enough, then it reaches a point where the water between the particles is now carrying the weight of everything above it, and the soil particles lose contact with each other. At this point, the soil behaves more like a fluid, and it temporarily loses much of its strength and stiffness. This process is called liquefaction.

Ground subsidence is a common feature associated with the occurrence of liquefaction. Liquefaction induced ground surface subsidence typically originates from either the densification and associated loss of volume of liquefiable soils or the loss of volume associated with the manifestation of liquefaction ejecta at the ground surface. The amount of ground surface subsidence is generally dependent on the density of the underlying liquefiable layers and the proximity of the liquefying layers to the ground surface.

The formation of liquefaction ejecta at the ground surface depends on a number of characteristics of the soil and geological profile. If there is a thick crust of non-liquefiable soil then liquefaction ejecta (i.e., water, sand, and silt) may not be seen on the ground surface despite the liquefaction process occurring at depth.

In areas with soils that are susceptible to liquefaction, significant damage to land, infrastructure and buildings can be caused by liquefaction-related lateral spreading in addition to the ground subsidence described and shown in Section 10.5.

6 Head of Lake Wakatipu slope-related hazards

Although the land encompassing the Project area is mostly flat to gently sloping, the land beyond and upslope of the Project area is mostly very steep. These steep hillslopes are susceptible to land slippage under both rainfall and seismic events. However, land slippage can also occur in the absence of sudden triggers due to weathering, gravity, and time. Mapped landslides in the Project area are shown on a hazard map included in Appendix C.

The roads from Queenstown to Glenorchy, and from Kinloch to Greenstone, have been constructed by cutting and filling, and these marginally stable cuts and fill slopes are particularly susceptible to land slippage. Many of the walking tracks also have sections of cutting and filling, although to a relatively minor extent.

A particularly dangerous hazard occurs where landslide debris has the potential to accumulate within narrow valleys and then flow out as a fan in what is generally termed a debris flow. The fans in the Project area, both active and inactive, are shown on a hazard map included in Appendix C.

In addition to the steep slopes, relatively gentle slopes can also slide if the soils below liquefy under high levels of shaking caused by an earthquake. Areas susceptible to liquefaction in the Project area are also shown in Appendix C.

7 Lake hazards

7.1 Flooding

The most common cause of flooding from Lake Wakatipu results from a transient imbalance between inflows and outflows to/from the lake following prolonged or consecutive heavy precipitation events in the headwaters. This leads to a gradual rise in the lake level over a period of days.

The normal water level of Lake Wakatipu is typically at about RL 310 m. Historical records show that the level typically fluctuates between about RL 310 m and RL 312 m. Higher levels result in inundation of parts of Glenorchy and Kinloch. Lower levels can have a minor effect on lake shore stability, but the rate of lake lowering, or drawdown, cannot be rapid enough to cause significant lakeshore instability on its own.

Lower lying areas of the Project area are susceptible to periodic inundation by water from either high Lake Wakatipu water levels, or from fluvial sources (in particular, the Dart and Rees Rivers, and in Glenorchy also the Buckler Burn and Bible Stream).

In November 1999, there was major flooding at the Head of the Lake which inundated low lying land and habitat in the Project area, as shown on Figure 7-1.

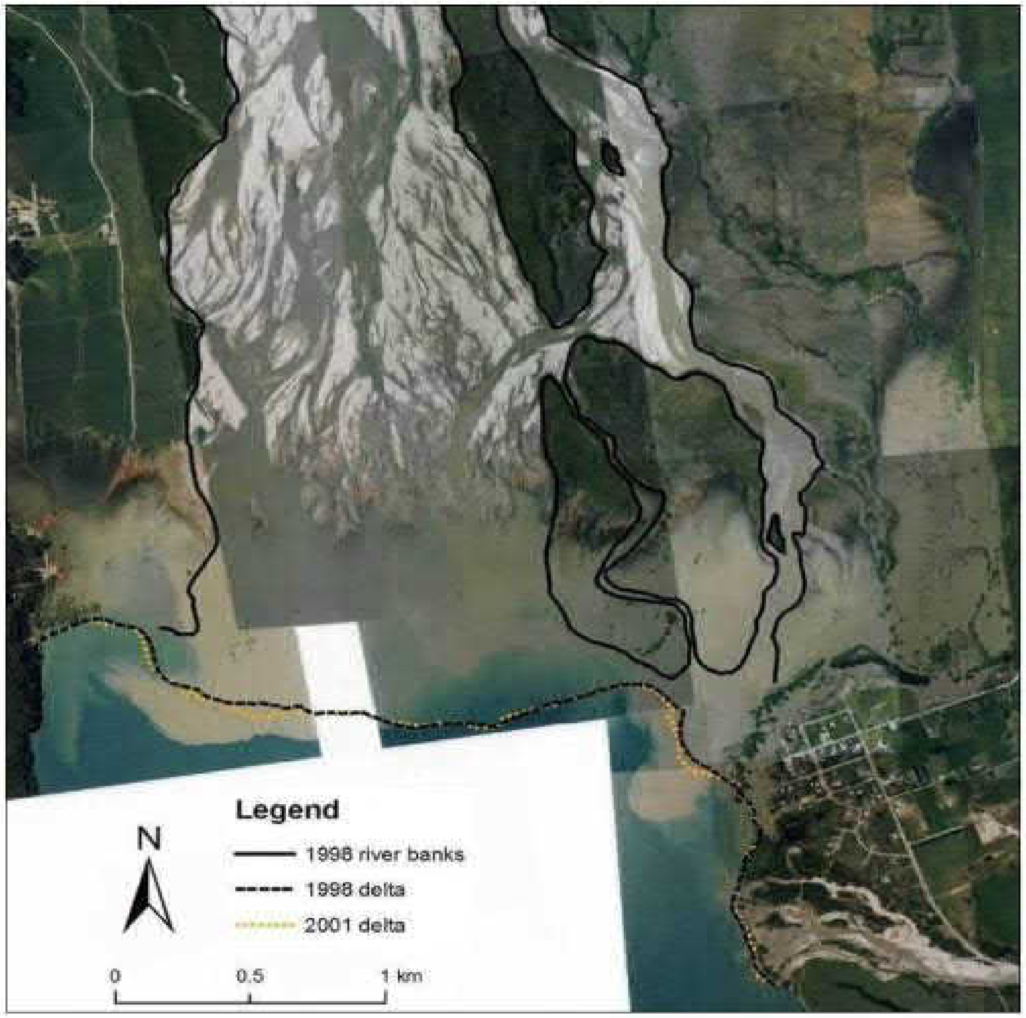


Figure 7-1: November 1999 inundation due to flood flows in the Dart and Rees Rivers (ORC)

The frequency of expected higher lake levels, as measured by average recurrence interval (ARI), is shown in Table 7.1.

Table 7.1: Lake Wakatipu levels and frequency

Frequency (ARI, years)	Lake Wakatipu level (RL m)
1	310.10
2	310.80
5	311.25
10	311.54
50	312.22
75	312.42
100	312.52
150	312.72
Source	Learning to Live with Flooding (ORC and QLDC, 2006) Glenorchy Floodplain Flood Hazard Study (URS 2007)

The highest recorded lake level is RL 312.78 m, recorded in November 1999.

A seiche is a standing wave, for instance in a lake, typically caused when strong winds and rapid changes in atmospheric pressure push water from one end of the lake to the other. ORC (2020) reports that the natural seiche of Lake Wakatipu is of small amplitude, but that a larger seiche caused by earthquake shaking could represent a hazard to the lakeside communities. For instance, a seiche triggered by an Alpine Fault rupture could lead to inundation and flooding hazard, with significant consequences for the built environment and risk to people. However, the likelihood or possible extent of this has not been investigated or assessed in detail but may be similar to tsunami.

A more extreme flood, capable of overwhelming the low-lying parts of the Project area, and in particular Glenorchy, associated with a landslide dam in the Kawarau River is an established and credible scenario (Thompson 1999). However, given the value of the wider regional assets threatened by such an event, it is reasonable to assume that every effort would be made to evacuate the dam material.

7.2 Tsunami

A tsunami may be triggered by processes that displace the deep waters of Lake Wakatipu and may result in potentially catastrophic flooding. Triggers include water displacement by land sliding, both into the lake and through the failure of submerged valley sides (i.e., the lakebed) or the collapse of the delta sediments.

A major landslide could result in extreme, transient inundation to depths of tens of metres with devastating erosive potential. Recent research by NIWA at Lake Tekapo has indicated that inundation to depths of 5 m could be expected to occur widely in such events. Land sliding is frequently associated with a triggering event, such as strong shaking in an earthquake or heavy rainfall but may also occur unexpectedly. Time and gravity alone can trigger landslides.

Tsunami may also be generated by water displaced by vertical motion on a fault traversing the lake, such as the Moonlight Fault.

8 Head of Lake Wakatipu river hazards

8.1 Flood hazard

The average recurrence intervals for flows in the main rivers in the Project area have been estimated by URS in its report to the ORC regarding the Glenorchy Floodplain Flood Hazard (URS 2007), as shown in Table 8.1.

Table 8.1: Flood peak estimates for the Dart and Rees Rivers (2007)

Frequency (ARI, years)	Dart River at Glenorchy (m^3/s)	Rees River at Glenorchy (m^3/s)	Standard Error
10	1,126	736	± 19 %
50	1,539	1,006	± 26 %
100	1,710	1,118	± 28 %
150	1,812	1,185	± 29 %
Source	Glenorchy Floodplain Flood Hazard Study (URS 2007)		

As shown in Table 8.1, URS also provides the standard errors for the Dart and Rees Rivers flood peak estimates. The standard error represents the confidence limit interval for one standard deviation of the central estimate. That is, the 100-year ARI Rees flood peak estimated by URS is in the range between 805 m^3/s and 1,430 m^3/s for one standard deviation, based on a standard error of ± 28 %. Extending this analysis, for 95 % certainty of the flood peak (which is the two standard deviation confidence limit) the 100-year ARI flood in the Rees River, based on the URS data, could be up to 1,745 m^3/s.

It is important to note that there have been 13 years additional monitoring of the Dart flow record (the basis for the Dart and Rees flood peak estimates) since the URS report. It would be appropriate to analyse the longer up-to-date record to determine more accurate flood statistics from this gauge, and to re-analyse the confidence limits for the revised statistics. In this regard flood frequency data from NIWA is more up to date, refer Table 8.2.

Table 8.2: Flood peak estimates for the Dart River (2018)

Frequency (ARI, years)	Dart River at The Hillocks (m^3/s)	Standard Error
10	1,544	± 10 %
50	1,905	± 14 %
100	2,057	± 15 %
250	2,258	± 16 %
500	2,140	± 17 %
1,000	2,561	± 18 %
Source	NZ River Flood Statistics (NIWA)	

8.2 River morphology hazard

Climate change is estimated to increase rainfall most likely in the upper Dart and Rees River catchments (NIWA 2019), which will in turn increase the amount of gravel entering the system and the size and frequency of flood events. Brasington (2020) considers that the change in the flood risk due to aggradation of the bed of the Dart and Rees Rivers, and potentially the erosive potential of the water together with the entrained material during a major flood, presents a significant threat to low lying areas of Kinloch and Glenorchy.

In the Project area, the township of Glenorchy is positioned in a highly active geomorphic setting that presents multiple and interrelated, cascading hazards.

The settlement is constructed on a sedimentary fan deposited by the Buckler Burn. Investigations by GNS Science (2009) estimate that the fan surface has been active over last few hundred years and identified historic patterns of sedimentation associated with flood and debris flows. The active channel of the Buckler Burn continues to build this fan through sediment deposition along the southern margins of the town.

The northern limits of this fan are bounded by the braided Rees and Dart rivers that carry very large quantities of sediment in frequent high flows, sourced from active landslides, fluvial erosion, and remobilization of long-term sediment stores in their upstream catchments. These rivers form a large delta at the Head of Lake Wakatipu that has been actively advancing into the lake since at least the late 19th century.

Immediately to the north of the Glenorchy township, sediments deposited by the Rees River have infilled an old inlet of Lake Wakatipu, shown on the earliest historic maps of the area. Archival photography from the Muir and Moodie catalogue shows the active braided fairway of the Rees up against the eastern (true left) valley wall as recently as 1890.

Mapping grade aerial photography of the site dates back to 1937. Comparison of this historic photography with recently acquired aerial imagery highlights the rapidity of landscape change around Glenorchy, with Figure 8-1 showing georeferenced images from 1937 and 2018.

Recent channel activity along the current eastern branch of the Rees River is overlain on each image to provide context and a consistent spatial frame of reference. This has been mapped by comparing LiDAR survey information from 2011 and 2019. From this comparison, areas of erosion are plotted in shades of red and areas of sediment deposition in shades of blue.

This analysis reveals a westward shift of this active channel belt of the Rees River. The pattern of recent activity also highlights the advance of the Rees delta since 1937. In 1937 the active braided fairway of the Rees River ran along the northern perimeter of the fan on which the town now sits, approximately parallel to the Lagoon Creek stop bank.

The advance of the Rees delta has been mapped more comprehensively from repeated aerial photography over this period by both URS (2007a) and Wild (2013). Between 1967 and 2007, Wild (2013) estimates that the Rees delta advanced by approximately 120 m. URS (2007) estimated similar rates of advance, averaging between 2 m to 3 m per year since 1937.

The southerly migration and narrowing of the active fairway of the Buckler Burn are also clearly evident in Figure 8-1. This snapshot shows only the difference between two fixed dates.

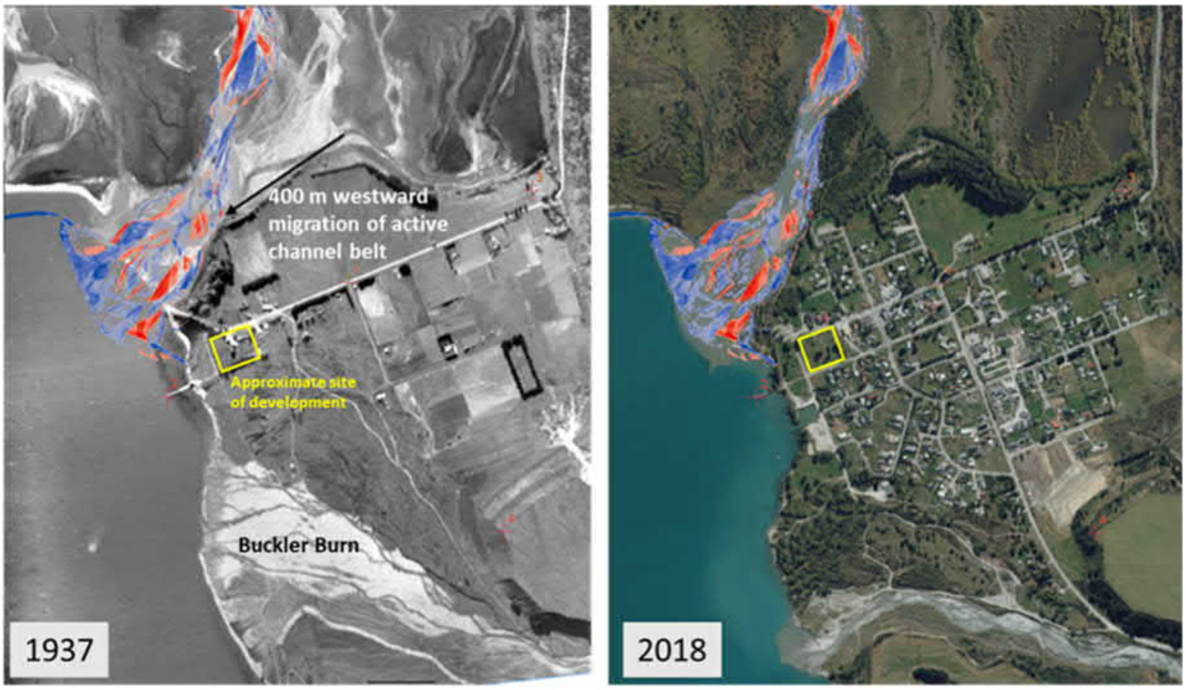


Figure 8-1: Georeferenced aerial photographs from 1937 and 2018 showing westward migration of the active fairway of the Rees along the northern perimeter of Glenorchy and southerly migration of the Buckler Burn (Brasington 2020)

Analysis of aerial photography cannot, however, reveal precise changes in the elevation of the riverbed that may promote channel instability. Recent LiDAR data indicate that the gradient of the Rees River in the lowest 4 km of the river is constant and that average level of the active channel falls at approximately 4 m per 1,000 m (a gradient of 0.004 m/m or 0.4%).

Assuming no major variation in the gradient of the river over time, the observed advance of the delta by 120 m in the last 50 years (after Wild, 2013) will have led to aggradation of the channel bed upstream, raising the average bed level of the Rees by approximately 0.5 m (i.e., estimated as 120 m x 0.004 m/m).

Aggradation of the riverbed elevates the active channel above the surrounding valley floor. This build-up promotes frequent switching of active channel into older topographic lows on the valley floor, potentially causing sudden adjustments in flow direction. These new channels then build up through sedimentation and the process of channel switching continues. This is a natural process, by which rivers with a quasi-unlimited supply of sediment, progressively infill their valleys.

Over the comparatively narrow window provided by aerial photography (1937 to present) the main active channel belt of the Rees River can be seen to have occupied and switched between flow paths that span an east-to-west belt of approximately 1.5 km. Such channel switching, or avulsion, across the valley floor is unpredictable and may be driven by the cumulative effects of progressive aggradation over multiple events rather than individual extreme events.

Forecasts of the regional impact of climate change over the coming century suggest that a warmer climate is likely to lead a higher frequency of heavy rain events and significant increases in the magnitude of the mean annual flood in both the Rees and Dart Rivers (NIWA, 2019). Warmer temperatures are also expected to increase the magnitude and frequency of high flow events in winter due to a shift in the balance of rain and snow and decreasing snowpack storage.

As sediment delivery from the Rees and Dart catchments is limited less by sediment availability and instead by the sediment transporting capacity of flood events, more frequent and higher magnitude events will drive an increase in sediment supply to the delta. The observed pattern of channel aggradation and instability is, therefore, set to intensify over the coming century due to climate change.

These effects will be accelerated significantly in the event of a major (Mw > 7) or great (Mw > 8) earthquake in this tectonically active region. Earthquake activity is likely to lead to widespread co-seismic slope failures, increasing sediment supply to rivers and streams and creating potentially hazardous landslide dams, as seen in the 2016 Kaikoura earthquake.

There are additional earthquake related hazards, notably liquefaction of the fan sediments on which parts of Glenorchy are situated and tsunami associated with land sliding into Lake Wakatipu, collapse of the delta front or by vertical movement of faults traversing the lake (e.g., the Moonlight Fault).

This brief overview illustrates the highly dynamic landscape setting for the towns of the Project area, and the township of Glenorchy in particular. This dynamism gives rise to continuously changing hazard profile for the region that is shaped by long-term and persistent trends that are inextricably related to high rates of sediment supply.

8.3 Avulsion Hazards

Advance of the Dart and Rees delta observed since at least the end of the 19th century, must be associated with a long-term increase in the mean bed level of the rivers.

This process will progressively elevate the present Rees channel above the surrounding valley floor, until it becomes unstable and breaks-out or ‘avulses’ along a shorter, steeper route, potentially reoccupying an historic paleochannel. While aggradation may also impede flows from the surrounding floodplain and contribute to backwater flooding, the threat of avulsion poses a more significant and unpredictable hazard that may result from rapid and major realignment of the principal flow of the Rees. This would have far reaching consequences that change dramatically areas at risk of flooding.

An effective and analogous illustration of this type of hazard is provided by the recent flood on the Waiho River close to Franz Josef in March 2019. In that event, long-term aggradation of the channel bed led to reduced channel capacity and elevated water levels during an event estimated to have only a 10-year ARI. Despite this relatively low magnitude event, the loss of channel capacity led to a breach in the Milton’s stop bank on the true left, close to the Waiho Loop.

The resulting outbreak (or avulsion) reoccupied a 7 km flow path along the southern floodplain of the Waiho River, with highly erosive flows inundating multiple properties and causing major damage to floodplain assets (the aerodrome and road network).

The scale of effects can be illustrated by comparing precise topographic models obtained from aerial lidar surveys commissioned by the West Coast Regional Council before this event (June 2016) and shortly after (April 2019). Analysis of the differences between the elevations in these two models enabled mapping of the distribution of erosion and deposition and the changes in the riverbed levels. This pattern is shown graphically in Figure 8-2, which clearly maps the extent of out of bank flooding along the southern floodplain.

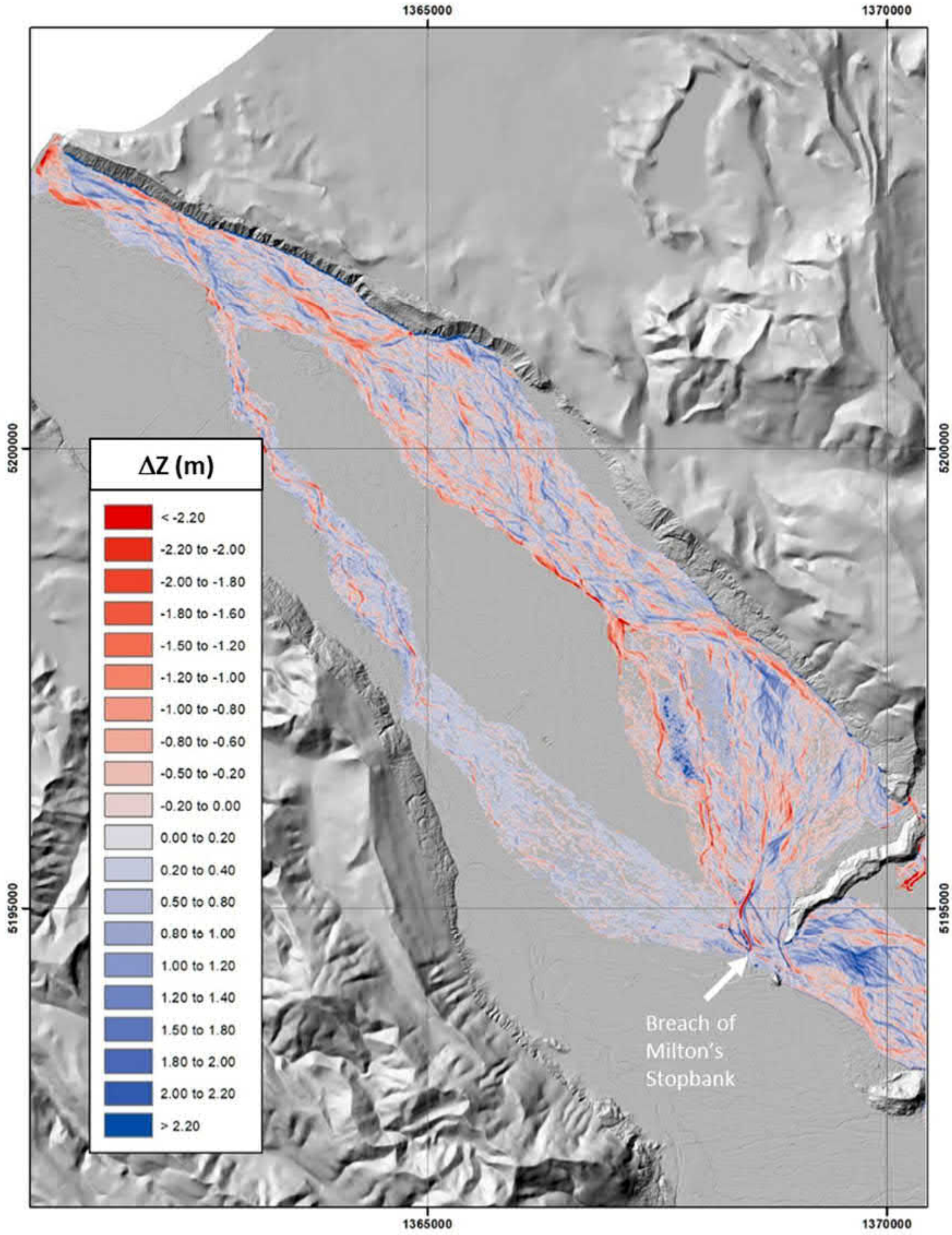


Figure 8-2: The pattern of outbreak flooding from the Waiho River in March 2019. The colour scale shows the difference in elevation between the two lidar surveys. Areas of erosion are shown as negative changes and coloured in shades of red, while areas of bed level increase or sedimentation, are shown in shades of blue

This demonstrates the capacity for avulsion to suddenly and significantly change areas at risk from flooding, with consequences that may reach far downstream of the initial outbreak. A further important insight from this example, is that the outbreak was driven not simply by a single, extreme event, but by progressive aggradation of the channel bed, a process that has been observed on the Waiho for over 70 years. This pattern of aggradation increases the sensitivity of the river to outbreak type events. In this case, the outbreak occurred for a relatively moderate event, well below the design service of the stop bank. This is a classic illustration of the mismatch between the apparent cause and consequence.

The Waiho example reinforces the importance of considering the role of sediment transport and changes in river morphology as drivers of flood risk in systems such as the Rees-Dart and Waiho Rivers.

Observations drawn from the archival analysis of aerial photography by the URS (2007a) report and Wild (2013) have shown the principal channel braid belt of the Rees River to shift periodically across a broad east-west range, extending from close to the Glenorchy Lagoon through to flows merged with the main Dart River. This pattern of avulsion is entirely consistent with the long-term trend of aggradation implied by advance of the Rees delta.

The magnitude and distribution of recent riverbed level adjustment can be quantified more precisely for the lower 4 km of the Rees by comparing airborne lidar surveys obtained by the ORC in 2011 and 2019, mirroring the approach shown in Figure 8-2.

The resulting pattern is shown in Figure 8-3, in which only elevation changes greater than a magnitude of ±0.15 m is plotted, to account conservatively for uncertainties in the accuracy of the two surveys.

From this analysis, the average longitudinal (or streamwise) change in riverbed level may be determined by integrating the observed elevation changes over 200 m intervals (Cells 0 to 21) extending upstream from the delta. The upstream extent of the analysis is limited by the area of LiDAR data captured in 2011, which was confined to the delta region.

This approach provides a robust insight into the longitudinal pattern of bed level changes, effectively averaging variations in local cross sections due the shifting morphology of individual bars. The resulting distribution vertical bed level change is shown on the inset graph in Figure 8-3. The figure clearly shows a dominant signal of aggradation along almost the entirety of the lower 4 km of the Rees. This is associated with an increase of 112,000 m^3 of sediment stored within this reach of the river over the eight-year period between surveys. This is, however, a conservative estimate of the total sediment delivered by the Rees, as a significant volume passes through the diffluence into the Dart River shown at Cell 11 on Figure 8-3 and is deposited in submerged delta topsets.

The average vertical changes provide a simpler understanding of the river response. This reveals a significant increase in bed level between Cells 9 to 18, or the reach 1.8 km to 3.6 km upstream from the delta. In this reach the average bed level has increased by between 0.25 m to 0.3 m.

There is also a clear trend of aggradation evident in the lower 800 m of the channel and the delta, where the bed level has risen by between 0.12 m to 0.26 m.

The consistent pattern of aggradation throughout the lower Rees is striking and suggests that the rate of bed level increase estimated by simply propagating the advancing delta slope upstream (i.e., 0.5 m in 50 years is potentially conservative).

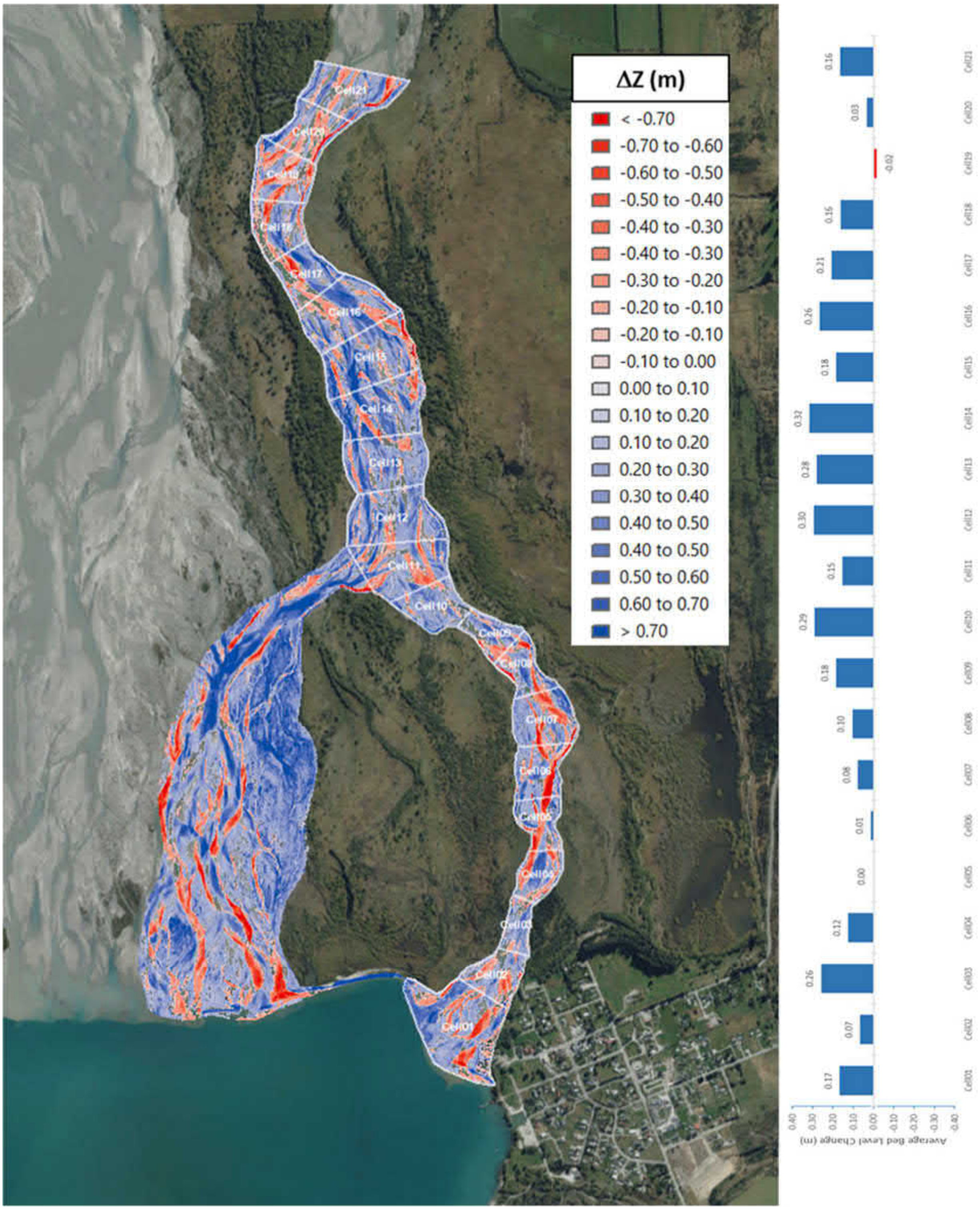


Figure 8-3: Map of bed level changes on the Rees River determined by the comparison of lidar data obtained for the ORC in 2011 and 2019. The inset graph shows the derived vertical bed level change for the 200 m cells (labelled 1 to 21) upstream from the delta. In this positive elevation changes (coloured in blue) represent increases in bed level, while negative changes (e.g., cell 19) reflect areas where the channel has, on average, degraded or incised (Brasington 2020c)

This pattern of aggradation will reduce the capacity of the channel to convey flood discharges, increasingly the probability that the channel will breakout along to steeper, lower pathway. Predicting the precise location of such outbreaks is complex, however, a useful supporting tool is provided by comparing the relative elevation of the valley floor to the local level of the active riverbed. This analysis has been computed using the 2019 LiDAR data, which covers the lower 20 km of the Rees River. The resulting 'relative elevation model' is plotted in Figure 8-4. Areas that are low relative to the adjacent active riverbed level are plotted in increasingly dark shades of blue, while those above the active bed are plotted in shades of green.

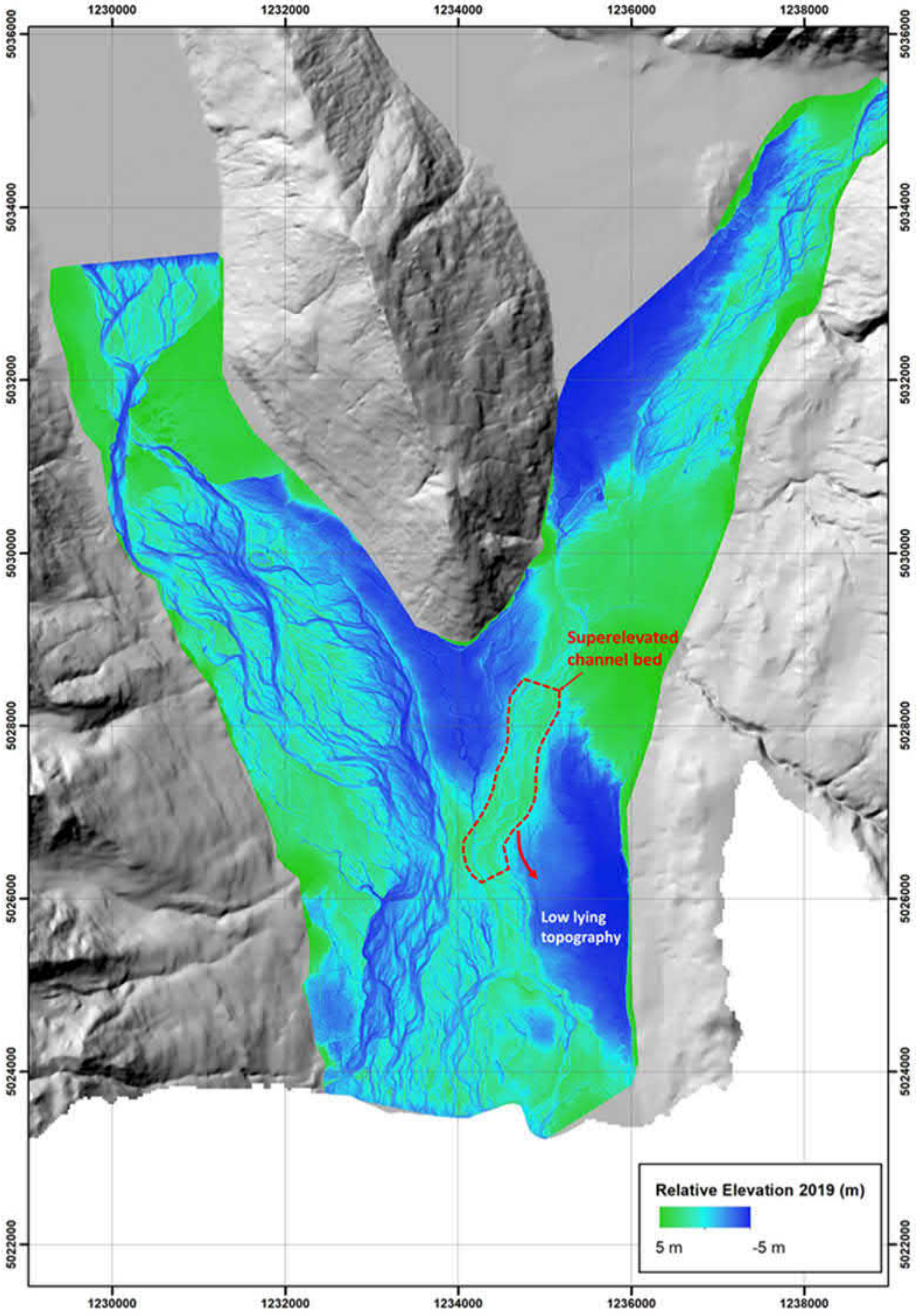


Figure 8-4: Relative elevation model of the Rees-Dart valley floor. This is computed by comparing the valley floor elevations to the adjacent average level of the riverbed. The analysis is based on a 1 m resolution lidar topographic dataset acquired in 2019 (Brasington 2020c)

This relative elevation model clearly shows the extensive low-lying topography on the eastern valley floor to the true left of the current position of the Rees and super-elevation of the riverbed, particularly through river kms 4 to 7 as highlighted on the map. In this reach, there is minimal freeboard between the channel bed and surrounding banks and continuing aggradation here poses a very tangible threat of avulsion that could route the principal flow of the Rees down towards the Glenorchy Lagoon.

This process poses a credible mechanism for a major flood hazard that would overwhelm the existing stop bank near to the Lagoon. Unlike the backwater flooding experienced on 4 February 2020, this could route a significant proportion of the Rees River along this pathway, resulting in fast moving, erosive flood waters flowing through the town.

When avulsions do occur, reorientation of flow is extremely rapid, creating hazardous flooding with little warning time to effect safe evacuation. A recent event from the Waiho River (March 2019) demonstrates the rapidity and scale of changes that accompany avulsion or breakout floods.

The outbreak flood on the Waiho occurred by breaching Milton’s stop bank, which runs along the true left (southern side) of the river close to the Waiho Loop. In this reach of the river, repeated cross-sectional surveys from 1983 to 2018 have shown the riverbed to have aggraded consistently. After an initial rise in bed level in the 1980s, the rate of aggradation over the majority of this observed record is steady, increasing by c. 1 m from 1993 to 2018. This matches broadly the rates observed in Rees River for which we have reliable data (i.e., 2011 to 2019). Projecting these observations for the Rees River over a comparable 25-year period, equates to a rise in mean bed level of + 0.5 to + 1.0 m.

The outbreak flood in the Waiho River at the end of March 2019 occurred during a relatively low magnitude event with a reconstructed frequency of 10 years ARI, which corresponds to an annual exceedance probability of 10 %. Despite the low magnitude of this driving event, the consequences were significant, resulting in a rapidly evolving and highly erosive flood extending far from the main channel belt. This flooding resulted in extensive damage due to both the erosive force of the floodwaters and the limited response time available, i.e., measured in hours, not days, weeks, or months. This process demonstrated how the cumulative effects of aggradation may progressively drive a system towards a tipping point that leads to a natural disaster triggered by an improbably low magnitude event.

Further numerical modelling would be required to evaluate the potential extent and severity of the hazard associated with an outbreak flood of this type. However, re-routing a significant proportion of a flood discharge from Rees through such a breakout is likely to affect parts of Glenorchy. The floodwaters are, moreover, likely to involve deep (greater than 1 m), fast moving (greater than 1 m/s) flows with potential to cause significant erosion along its path and to transport debris. Such a flood would pose a significant threat to infrastructure and people in the lower-lying areas of Glenorchy.

8.4 Glenorchy

Glenorchy, in particular, is located in a dynamic environment that is subject to a complex set of evolving and cascading hazards.

Advance of the Rees and Dart delta over the last century is inevitably associated with an upstream aggradation of the riverbed. The analysis of recent LiDAR data confirms this pattern and reveals average aggradation rates as high as 0.2 m to 0.4 m per decade. This long-term trend is set to intensify due to increases in the intensity and magnitude of heavy precipitation events and winter high flows driven by climate change. This will increase sediment supply to the lower reaches of the rivers and the delta.

Based on recent experience, it is clear that some parts of Glenorchy are vulnerable to flooding through direct inundation from a transient lake fluctuations and backwater flooding, driven by both high lake levels and aggradation of the riverbed. The continuing trend of riverbed aggradation increases the likelihood of future sudden and unpredictable avulsions of the principal course of the Rees.

The analysis of LiDAR data for the valley floor reveals potential breakout pathways that could route significant flood flows through low lying land to the true left of the Rees and overwhelm the existing stop bank and inundate parts of Glenorchy. This is a credible scenario and cannot be discounted without supporting evidence. Given the long-term trend of aggradation driving this hazard, any mitigation measures that may be considered would likely require a commitment to their maintenance in perpetuity and in turn, increase the potential hazard should they fail catastrophically.

Further information specifically on the Glenorchy flood hazard is provided in Appendix F.

9 Design floods

9.1 Event frequency

Frequency is often quantified by Average Recurrence Interval (ARI), or return period, e.g., 100-year ARI or 100-year return period. This is, the frequency given to an event expected to occur on average once in 100 years. This is the frequency over a very long period, during which the factors that may affect the processes remain essentially unchanged.

A frequency expressed in years is not an indication of the period between events of that frequency and magnitude. For instance, successive 100-year floods may occur at shorter intervals, even in successive years. Likewise, there may be a longer period between successive 100-year floods, greater than 100 years. It is noted that two “150 year” floods (based on URS statistics) occurred in the Dart River in March 2019 and February 2020.

A more accurate description of frequency is Annual Exceedance Probability, which is the expected probability of a flood in any year. Using this frequency descriptor, a 100-year flood has a 1 % probability of occurring in any year.

Importantly it is also possible to estimate the probability of a particular event happening over a period of time. It can be shown that the 100-year flood has a 40 % probability of occurring in a 50-year period. While a 1,000-year ARI may seem like a rare event, over a design life of 100 years this has a 10 % probability of occurrence. Similarly, the 2,500-year flood has a 4 % probability of occurring in 100 years, i.e., a 1 in 25 chance.

A forecast increase in the frequency and magnitude of heavy precipitation events due to climate change (NIWA, 2019), however, limits the accuracy of estimates determined by conventional assessment historical event probability analysis. The statistical methods used to establish such recurrence intervals assume that the driving processes are stationary, or unchanging over time.

This assumption is inconsistent with the expected effects of climate change and an increase in the frequency of flooding (and high lake levels) affecting the Head of Lake Wakatipu should be anticipated. The coincidence of elevated lake levels with high flows on the Dart and Rees Rivers will also exacerbate backwater flooding from the rivers, initiating a hazard cascade.

Risk and probability (or frequency) are often confused. Risk includes not only a measure of frequency but also consequence. An event may have a low probability but may carry significant risk because of the effects, for instance the magnitude of damage or loss of life that would be caused by the event.

9.2 Peak flow estimation

Design flood peak flows are often determined by statistical analysis of flow records. The series of annual maximum flows can be analysed to estimate the expected peak flow for a particular probability of occurrence.

Such analysis, however, has confidence limits (i.e., uncertainty bands) that depend on the length of record (as discussed in Section 8.1). It is important to recognise that an estimate of a particular flood peak (e.g., the 100-year ARI event) determined by statistical analysis may be better quantified as a range within these limits, rather than as a singular value.

9.3 Influence of climate change

In its report on climate change projections for the Otago Region, prepared for ORC, NIWA (2019) showed projected increases in both rainfall depths at various durations up to 48 hours, and in the annual number of heavy rainfall days. In its report on climate change projections for New Zealand

(MfE 2018) MfE provides data on projected increases in seasonal and annual rainfall for all regions in New Zealand. The Otago data (denoted for Queenstown) are presented in Table 9.1. These have been determined for three future time horizons to 2110, and for four projected CO_2 emissions scenarios (representative concentration pathways (RCP)) as determined by the Intergovernmental Panel on Climate Change fifth assessment (IPCC 2014), being:

- RCP 2.0 Mitigation of CO_2 emissions
- RCP 4.5 Stabilisation of CO_2 emissions
- RCP 6.0 Stabilisation of CO_2 emissions, but not so quickly
- RCP 8.5 Business as usual – no change in present global emissions.

Table 9.1: Projected changes in seasonal and annual rainfall for Wakatipu Basin

Climate scenario		Summer	Autumn	Winter	Spring	Annual
2031 to 2050	RCP 8.5	3 %	2 %	16 %	16 %	7 %
	RCP 6.0	-1 %	1 %	13 %	13 %	4 %
	RCP 4.5	3 %	1 %	13 %	13 %	6 %
	RCP 2.6	0 %	3 %	8 %	8 %	4 %
2081 to 2100	RCP 8.5	4 %	1 %	4 %	17 %	16 %
	RCP 6.0	3 %	3 %	27 %	14 %	12 %
	RCP 4.5	4 %	3 %	19 %	8 %	9 %
	RCP 2.6	5 %	5 %	10 %	7 %	7 %
2101 to 2110	RCP 8.5	3 %	-1 %	38 %	23 %	15 %
	RCP 4.5	4 %	1 %	21 %	11 %	9 %
	RCP 2.6	5 %	-1 %	6 %	5 %	4 %
Notes	Estimated for Queenstown Projected increase in rainfall compared to 1986 to 2005 climate data Source: Climate change projections for New Zealand (MfE 2018)					

From atmospheric projections based on simulations undertaken for the IPCC 5th Assessment, MfE indicated change factors between 8.6 % and 6.1 % per degree of warming for increases in rainfall depths for storm durations between 24 hours and 120 hours. The report also provides estimates for the increase in temperature in the Otago region of between 0.7 ° and 3.5 ° comparing the 1986 to 2005 climate to that expected in 2101 to 2120. These temperature increases correspond to an increase in storm rainfall, and thus perhaps flood peaks in Otago rivers, of up to between 21 % and 30 %.

Clearly, these would be very significant for potential events in the Dart and Rees Rivers and other Head of Lake Wakatipu watercourses in 100 years' time.

10 Head of Lake Wakatipu Inundation

10.1 Hazard and consequence

It is important to understand the consequences of the various natural disaster scenarios and what these looks like. This section presents the consequences rather than the hazards, i.e., the consequences of flooding (inundation) that can arise from a variety of natural hazard processes. It is the consequence that is of concern to the community in the Project area.

10.2 Inundation of Land and Habitats/Ecosystems by Water

There are four principal processes that present inundation risk that could affect the Head of Lake area:

- Direct flooding from Lake Wakatipu
- Flooding from the Dart and Rees River system
- Changes in river morphology
- Tsunami associated with both seismic and aseismic triggers.

Inundation by water originating from a landslip or fault thrust generated lake tsunami, or seiching of the lake under seismic shaking, has also been identified. Whilst these are very real possibilities, there are considerable uncertainties surrounding the likely consequences of such occurrences. However, they are also possible sources of both water inundation and potential erosion of low-lying areas adjacent to the entire lake, not just the Project area. A landslide in the Kawarau River also has the potential to cause significant inundation of land adjacent to the current lake shore, with one estimate (Thompson 1998) suggesting it could rise 30 m. Added to these uncertainties are the effects of climate change. Whist such a credible worst case has a low probability of occurrence, as the possible lake level rises become lower their probability of occurrence become greater.

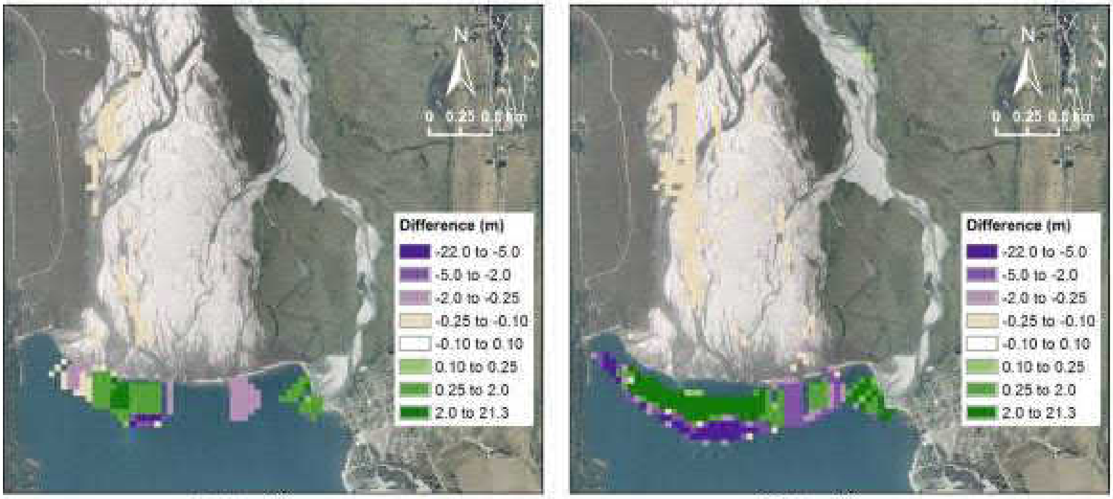
With climate change, the inundation of low-lying areas by water from elevated Lake levels and river flooding is likely to become greater than currently predicted based on historic records, further increasing "*future climate change uncertainties*".

10.3 Inundation of Land Habitats/Ecosystems by Flood Debris

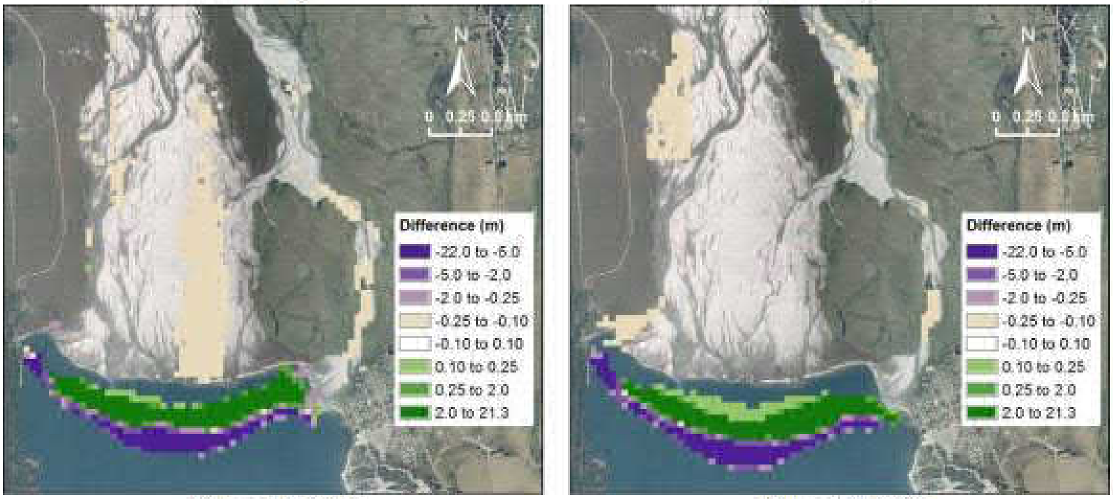
As discussed in Sections 4 and 8 the Dart-Rees delta is prograding. That is, the material transported down the Dart and Rees rivers are filling in the Head of Lake Wakatipu. What is now lake will eventually become the bed of the rivers. Current projections of the rate of this infilling of the Head of the Lake are shown in Figure 10.1.

Unless gravel is managed and stop banks maintained in perpetuity, it appears likely that significant parts of Kinloch and Glenorchy will eventually become encompassed by gravel transported by the rivers. This could be a gradual process as a result of numerous relatively small floods, but it could also occur quite rapidly during a major flood event if, for instance, the Rees River avulses from its present course into the lower lying terrain on the true left bank upstream of Glenorchy (as discussed in Section 8.3.

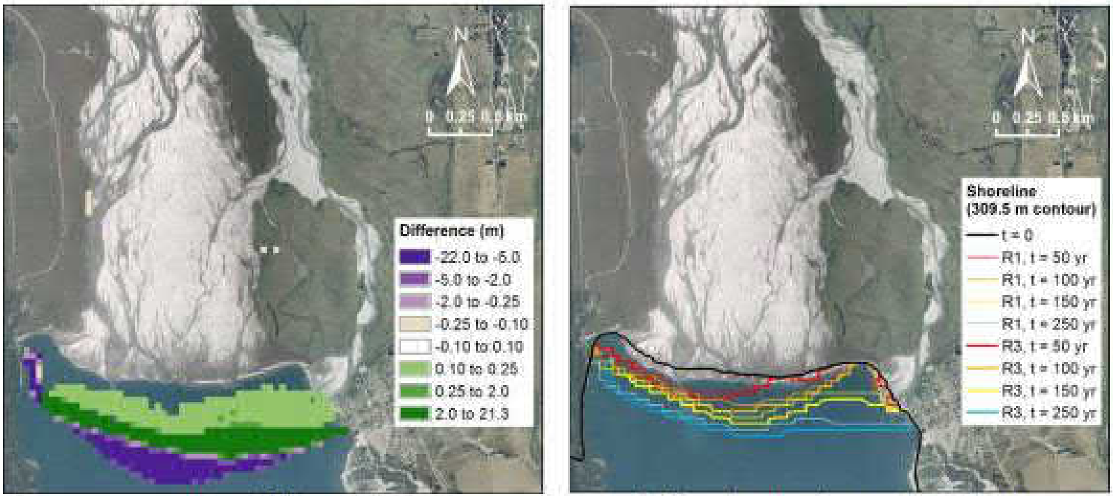
Inundation by flood debris could also occur quite rapidly following an earthquake that mobilises significant volumes of landslide debris in the Dart and Rees River catchments. Earthquake-generated landslides could also temporarily dam some of the tributaries, and even the rivers themselves. Failure of these dams would then release flood waters and debris that could inundate low lying areas as a major flood and perhaps debris flow.



(a) t = 10 years (b) t = 50 years



(c) t = 100 years (d) t = 150 years



(e) t = 250 years (f) Shoreline location: t = 0 to 250 years

Figure 10.1 Estimation of lake shoreline with time Source (Wild 2012)

10.4 Inundation of Land and Habitats/Ecosystems by Landslide Debris

There have been numerous landslides and debris flows recorded in the Dart and Rees river catchments. One of these debris flows was fatal (GNS 2019). However, these landslides are assessed to present relatively localised threats, and debris flows are very unlikely to extend down the river valleys as far as the Head of Lake Wakatipu Project area. Some of the rivers and streams discharging into the lake below the Dart and Rees Rivers delta do, however, have the potential to generate significant debris flow material as far as the lake.

Debris flows from the Buckler Burn present a credible risk to land within and below the valley mouth due to the steep terrain through which it flows and the potential to generate and mobilise large volumes of debris.

Debris flows could result from:

- High rainfall mobilising bed material together with additional debris derived from simultaneously occurring landslides on the valley sides, or
- Large landslides (triggered by earthquake shaking and/or rainfall) forming debris dams.

The potential for debris inundation over a large part of Glenorchy from a Buckler Burn debris flow must be recognised. That the recent trends have been for the debris to be deposited further to the south does not remove the fact that the much of the terrain beneath Glenorchy has originated from the Buckler Burn in the first place.

From experience in Matata and Kaikoura there is now a much better understanding of debris flows, and the limitations of modelling such events. Following the Kaikoura earthquake, large volumes of landslide debris were generated. Much of this material was retained in place until a subsequent rainfall event that remobilised the landslide debris and resulted in large debris flows and debris avalanches that inundated infrastructure downslope.

We have good recent examples of what inundation by landslip debris looks like, as shown in Figure 10.2 to Figure 10.6.

Figure 10.2 Rainfall triggered debris flow (Matata 2005)

Figure 10.3 Rainfall triggered debris flow (Matata 2005)

Figure 10.4 Rainfall triggered debris flow (Hunterville 2006)

Figure 10.5 Rainfall induced debris flow 2018 post Kaikoura Earthquake 2016 (GNS Science)

Note The earthquake-triggered landslide debris in 2016 (on the left) becomes a rainfall-triggered debris flow 15 months later in 2018 (on the right).

Figure 10.6 Rainfall induced debris flows 2018 post Kaikoura Earthquake 2016 (GNS Science)

Note the size of the debris protection wall relative to the size of the debris flow, in the left image

10.5 Inundation of Land and Habitats/Ecosystems by Liquefaction Ejecta

Inundation by sand, silt, and water as a result of liquefaction can be significant.

Prior to 2010, New Zealand had not experienced a major liquefaction event in an urban environment. With the liquefaction effects resulting from the Canterbury Earthquake Sequence (CES) from 2010 to 2011 and the Kaikoura Earthquake of 2016, there is now a much clearer understanding of liquefaction susceptibility and vulnerability, and consequential effects such as lateral spreading, flow sliding and ground surface subsidence.

The general susceptibility to liquefaction in the Queenstown Lakes District and Otago Region has been assessed by Opus (2004), T+T (2013) and GNS (2019).

T+T assessed of the liquefaction potential of the Glenorchy area as part of an assessment of the developed areas in the Queenstown Lakes District (T+T 2013).

The Dart/Rees/Buckler Burn alluvial fan is likely to comprise saturated, loose, normally consolidated silt, sand, and gravel, overlying weak lacustrine (lake) sediments. Based on the alluvial deposition environment and likely subsurface soils, it is possible that large areas of the alluvial fan upon which most of Glenorchy is situated could liquefy and slide towards the lake under strong and prolonged levels of ground shaking.

The liquefaction potential for this area was mapped as "Probably Moderate", for which T+T recommended that any proposed development be required to undertake a "*deep geotechnical investigation and reporting in accordance with DBH* (now MBIE) *guidelines and QLDC requirements, by a CPEng*".

In 2019, GNS assessed the liquefaction susceptibility for the whole of Otago. The GNS assessment mapped the much of the Project area as "*low to moderate susceptibility (B), but with some geotechnical evidence of susceptibility (B1)*". The GNS mapping, broadly consistent with the 2013 T+T assessment, is shown in Figure 10.7.

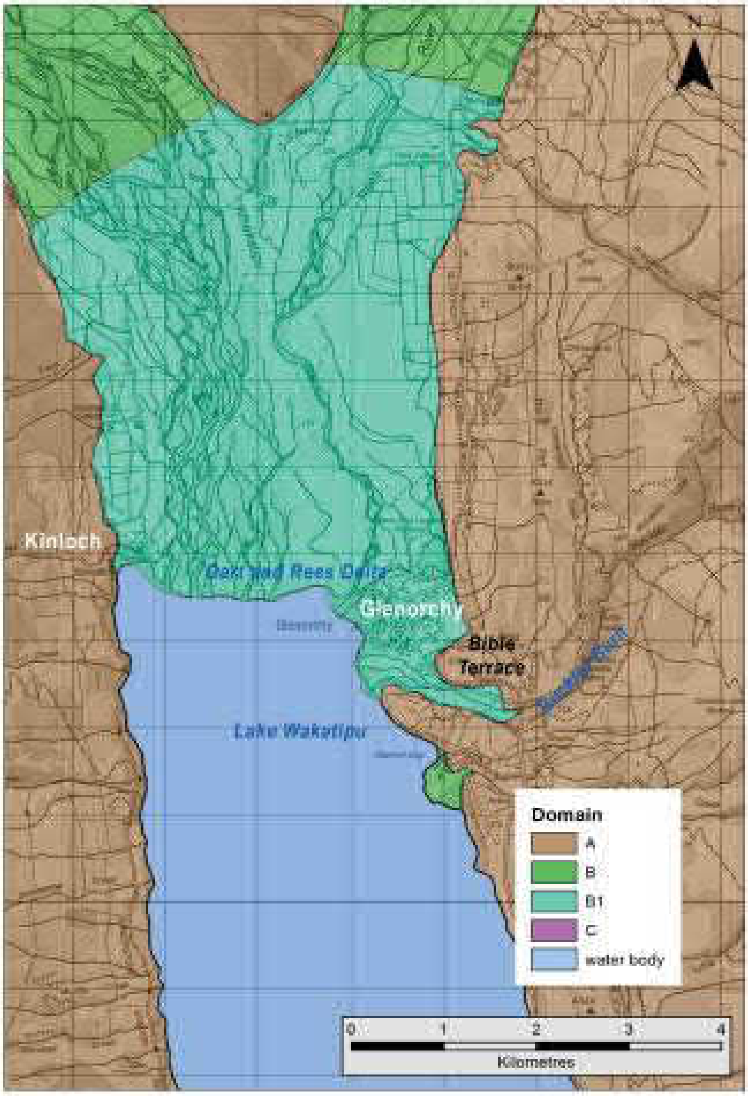


Figure 10.7 Liquefaction susceptibility in the Project area (GNS 2019)

From the Canterbury Earthquake Sequence from 2010 to 2011 there is a very good appreciation of what inundation by sand and water as a result of earthquake triggered liquefaction looks like, as shown in Figure 10.8 to Figure 10.10.

Figure 10.8 Inundation from ejected sand and water from liquefaction, Christchurch 2011 (EQC)

Figure 10.9 Inundation from ejected and water from liquefaction, Christchurch 2011

Figure 10.10 Inundation from ejection of sand from liquefaction, Christchurch 2010

It is noted that the 2019 GNS regional desktop study was for the entire Otago region, which classified the Dart and Rees delta including Glenorchy as low to moderate susceptibility. However, this regional study is at too high a level to determine accurately the liquefaction hazard for specific sites.

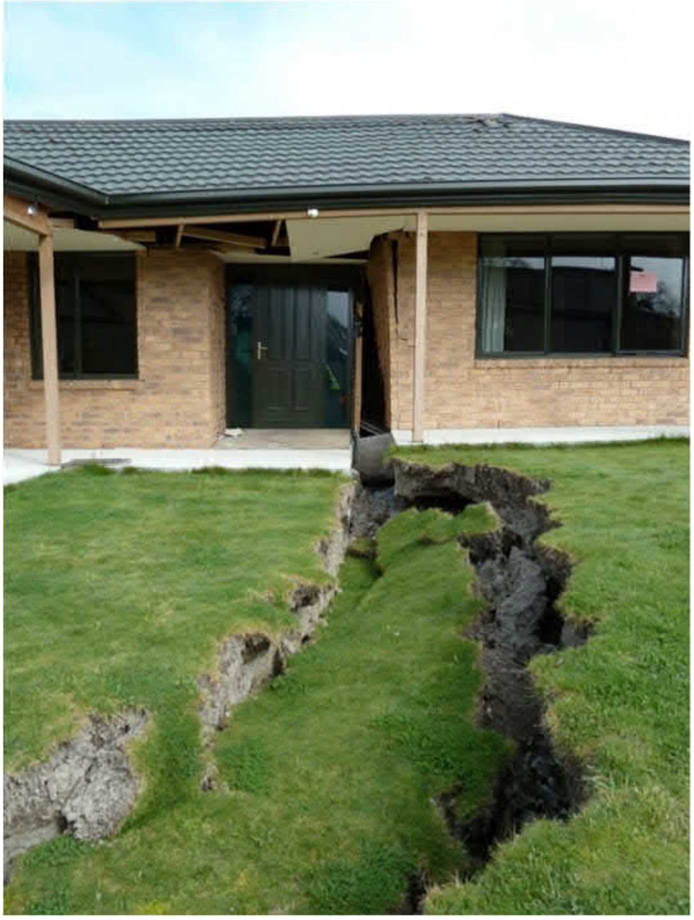
The T+T 2013 study was also high level, but more localised and detailed compared to the GNS study. The liquefaction potential for Glenorchy in the T+T study was mapped as "Probably Moderate", for which T+T recommended that any proposed development be required to undertake a "*deep geotechnical investigation and reporting in accordance with DBH* (now MBIE) *guidelines and QLDC requirements, by a CPEng*".

Thus, any actual site-specific liquefaction hazard is speculative until considerably more subsurface investigation and laboratory testing is undertaken. There are very good reasons for concern around the potential for significant liquefaction and lateral spreading effects at sites close to the lake shore or other free faces.

Liquefaction and lateral spreading hazards should also be assessed at longer return periods in support of land use decisions in resource consent applications, compared to the return periods considered under the Building Code in support of building consent applications. Until this work has been undertaken it is not possible to state that the liquefaction hazard can be practically or economically mitigated to ensure the integrity of further development and the safety of the community.

Furthermore, the GNS and T+T classifications relate to liquefaction susceptibility not consequence. The TC2 areas in Christchurch were not near major waterways and areas with large elevation differences giving rise to the potential for deep seated lateral spreading, as seen in Figure 10.11 (Kaiapoi) and Figure 10.12 (Blenheim). The lateral spreading and associated ground surface subsidence increase for larger return period levels of earthquake shaking. Hence the extent of mitigation work substantially increases in order to mitigate the hazard for larger earthquakes.

Figure 10.11 Lateral spreading, Kaiapoi



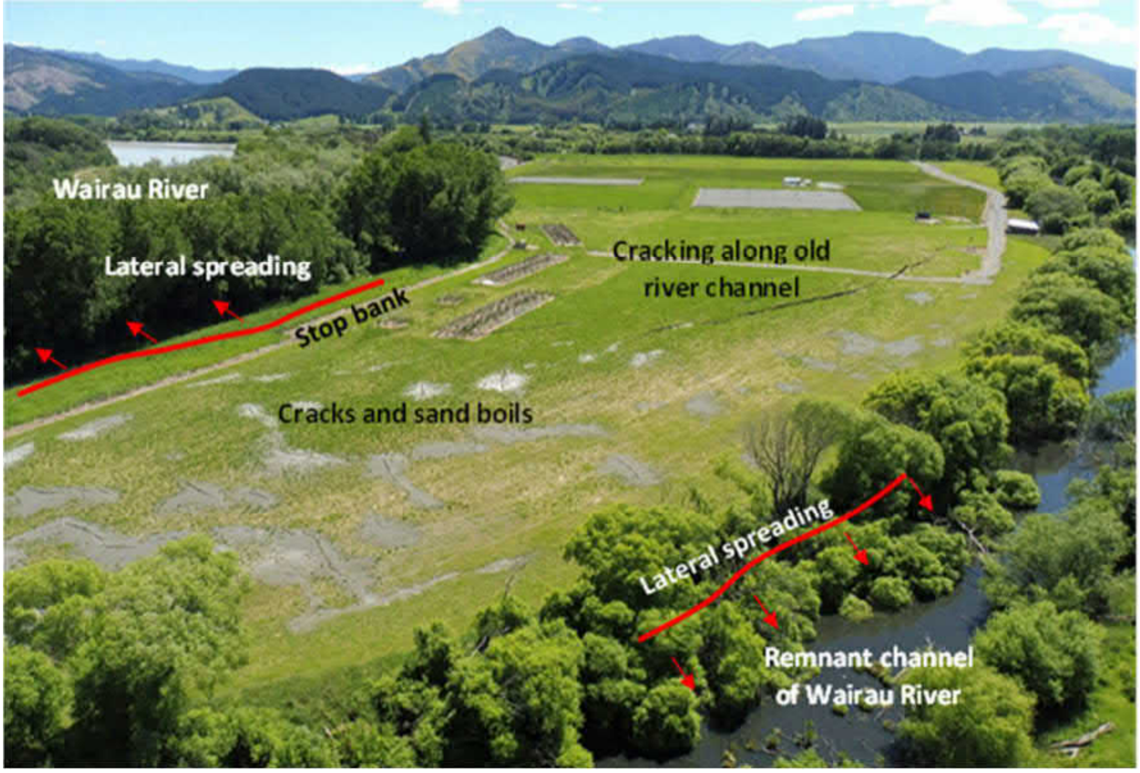


Figure 10.12 Lateral spreading, Wairau River, Blenheim

Liquefaction hazard in Glenorchy could also cause subsidence, which can also exacerbate the flood hazard.

The potential for significant lateral spreading to occur around the Head of Lake Wakatipu is because of the rapid deepening of the bed of the lake, as shown in the bathymetry (Figure 10.13)

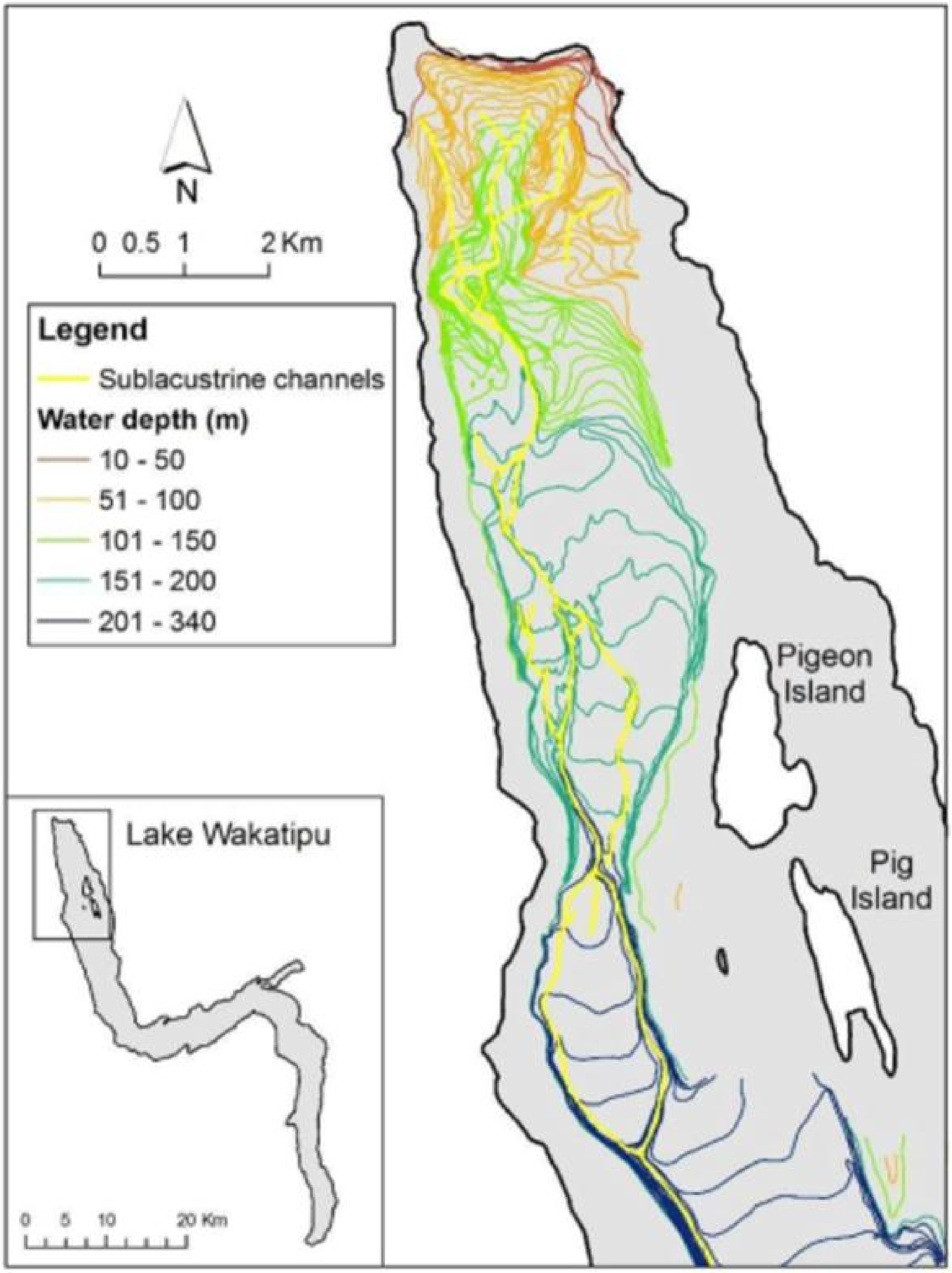


Figure 10.13 Bathymetry of the Head of Lake Wakatipu (NIWA)

10.6 Loss of Land and Habitats/Ecosystems by Erosion

Areas of past deposition by the Dart and Rees Rivers, as well as alluvial fans from rivers and streams, are being actively eroded by the Dart and Rees Rivers. A very recent example is the rapid erosion of alluvial deposits at Kinloch on the true right bank of the Dart River, as shown in Figure 10.14 and Figure 10.15.

Figure 10.14 Lower Dart River, true right bank, 8 October 2020 (J Glover)

Figure 10.15 Lower Dart River, true right bank, 15 October 2020 (J Glover)

11 Head of Lake Wakatipu Cascading Natural Disaster Scenario

The Head of the Lake Wakatipu is exposed to a range of natural hazards, which may interact to produce a cascade of events. For example:

- heavy rain may lead to an increase in lake levels
- that in turn creates backwater flooding from the Rees River
- while also triggering landslides that may lead to
  - the formation of a landslide dam
  - and riverbed aggradation that may result in a sudden avulsion of the river into a new channel.

Cascading processes can give rise to significant hazards triggered together by events that, individually, would not be considered extreme. This may result in an apparent mismatch between the cause' (i.e., the initiating hazard event) and 'consequence' (i.e., the resulting damage) that is contingent on the spatial and temporal state of the environment before the triggering event.

The likelihood of hazards resulting from cascading events may be underestimated using conventional statistical analysis that assumes individual events are independent and that their frequency does not change over time.

Some of these hazards are either exacerbated by an earthquake (Figure 11-1). Each of these can result in damage or have a subsequent cascading effect. This demonstrates the array of potential cascading events, along with the consequences that could eventuate. However, the timescale would not be immediately following the earthquake. For example, increased land sliding into the valleys triggered by a seismic event would provide sediment to be subsequently transported downstream This could be gradual under normal conditions but could be rapid following significant storm events.

A natural disaster scenario was developed for the Project area, to demonstrate the cascading nature of hazards arising from an earthquake. This is based on the hazard information presented previously in this report.

The scenario selected is an earthquake associated with the Moonlight Fault producing a fault rupture, extensive shaking across the Project area and major land sliding (Figure 11-2). Given its close proximity, a rupture along the Moonlight Fault will result in significant shaking throughout the Project area. For the purposes of this scenario, only seismic and co-seismic land sliding are considered.

11.1.1 Surface rupture

Movement and ground surface rupture along the Moonlight Fault will result in vertical offset and deformation of the land each side of the fault. The Moonlight Fault is a reverse fault meaning there will likely be a steep bank formed, similar to the 2016 Kaikoura Earthquake. The fault rupture displacement and deformation will be typically very localised, i.e., less than 100 m either side of the fault.

The Moonlight Fault crosses at the elbow of Lake Wakatipu an extends north-northeast and intersects the Glenorchy-Queenstown road. This is the only land-based connection from the Project area to Queenstown and beyond, as well as the only power supply line. A rupture of the Moonlight Fault would make this road impassable and sever power supply to Glenorchy and the rest of the District in the environs.

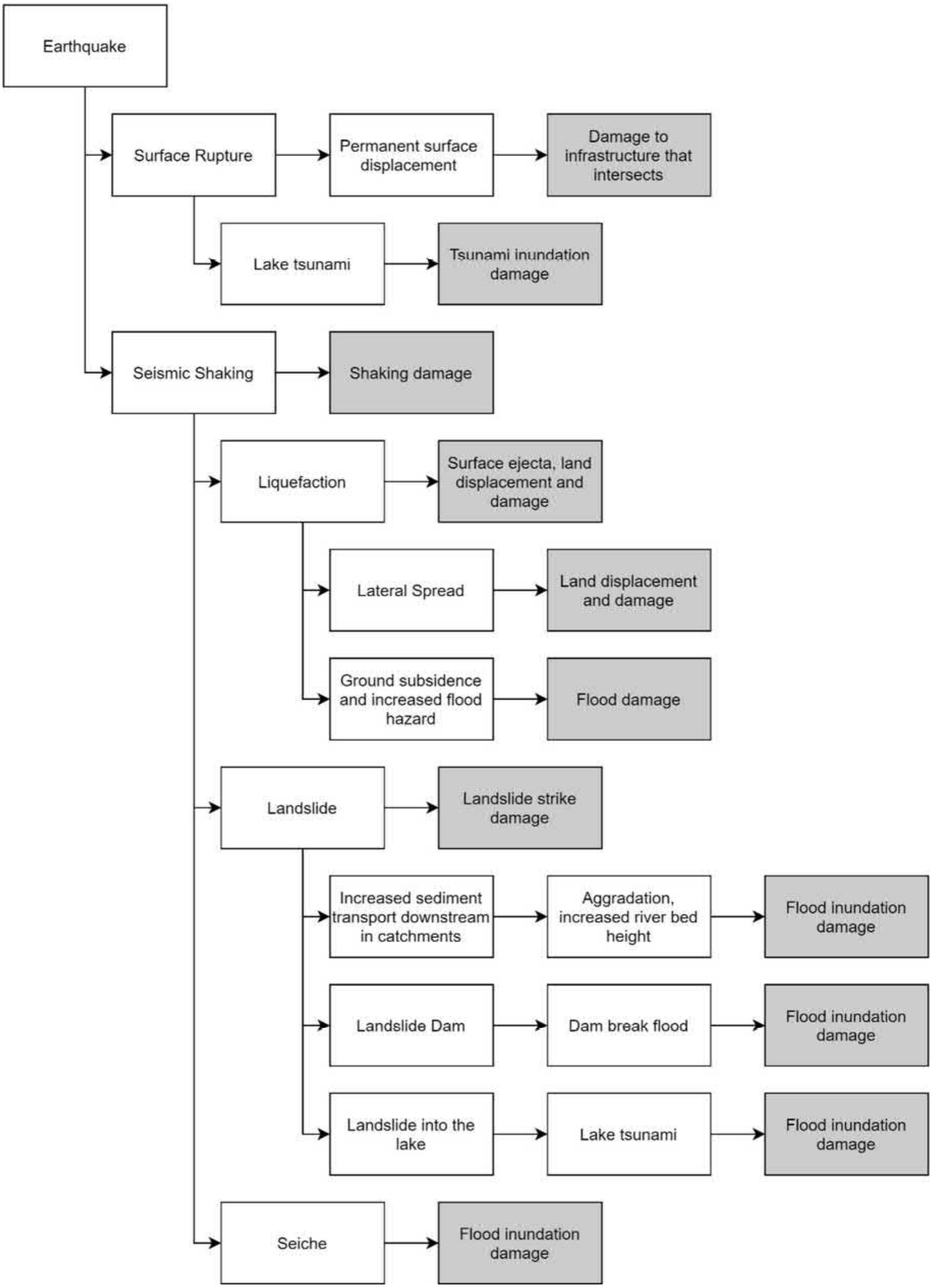


Figure 11-1 Flow diagram of hazardous phenomena resulting from an earthquake. Each branch terminates at the grey boxes which outline the damage inducing phenomena

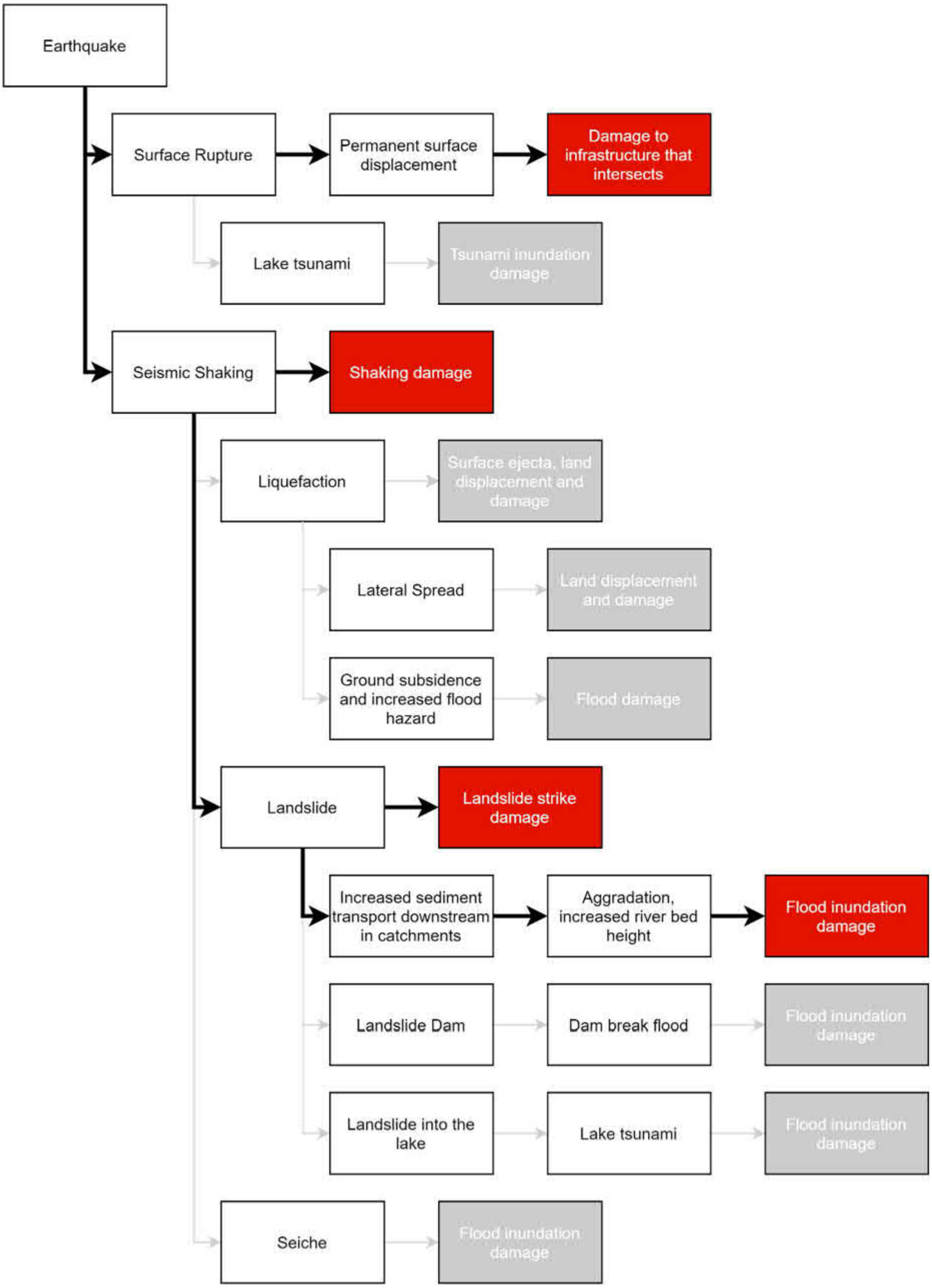


Figure 11-2 Natural disaster scenario used within this study – black arrows illustrate the sequence of the hazards scenario and red boxes represent the damage inducing phenomena

11.1.2 Seismic Shaking

Shaking from an earthquake along the Moonlight Fault has been assessed using the Bradley (2013) ground motion prediction equation to estimate the peak ground accelerations (PGA). Input parameters for the fault characteristics come from Stirling et al (2012) and the ground characteristics from Foster et al (2019). Table 11-1 presents the shaking for the Glenorchy and Kinloch for a characteristic rupture of the fault. Figure 11-3 presents the median PGA expected from a Moonlight Fault rupture.

Table 11-1 Modelled PGA from a characteristic Moonlight Fault rupture for Glenorchy and Kinloch

Centre	Modelled PGA		
	16th percentile	50th percentile	84th percentile
Glenorchy	0.19	0.31	0.48
Kinloch	0.17	0.28	0.44

Shaking of these ground accelerations is estimated to result in MMI 8-9 damage. This corresponds to damage to interior fittings, moderate structural damage on some buildings, and some breaks to buried infrastructure.

The estimated PGA from a Moonlight Fault rupture exceeds that to induce liquefaction in susceptible conditions. A PGA of 0.25g is considered to be the threshold for liquefaction. In addition, it is considered very likely the ground accelerations would exceed the typical threshold for land sliding of MMI 7, which corresponds to a PGA of 0.15g to 0.25g (Wald et al, 1999; Atkinson and Kaka 2006).

11.1.3 Landslide

Given the combination of geology and steep terrain, landslide is a prominent hazard for the region. When considering the landslide hazard, there are two components:

- the evacuation hazard, i.e., the source of the landslide
- the inundation hazard, i.e., area impacted by landslide debris runout

Given the risk of isolation from losing road access, the landslide assessment considered the evacuation and inundation susceptibility along the Glenorchy-Queenstown Road, and includes commentary around the inundation susceptibility to both Glenorchy and Kinloch.

The landslide evacuation hazard assessment applied a normalised difference approach to identify areas of different landslide evacuation susceptibility. This method has been applied in major quantitative landslide risk assessments in Whakatane, Ohope and Matata in the Bay of Plenty (T+T 2013a; T+T 2013b). This was also applied for landslide loss modelling for QLDC buried infrastructure (T+T 2017; Wild et al 2018). The approach identifies combinations of factors, such as geology and slope angle, that are most closely associated with previously mapped land sliding. A numeric value is assigned to the relative density of land sliding for a given set of conditions.

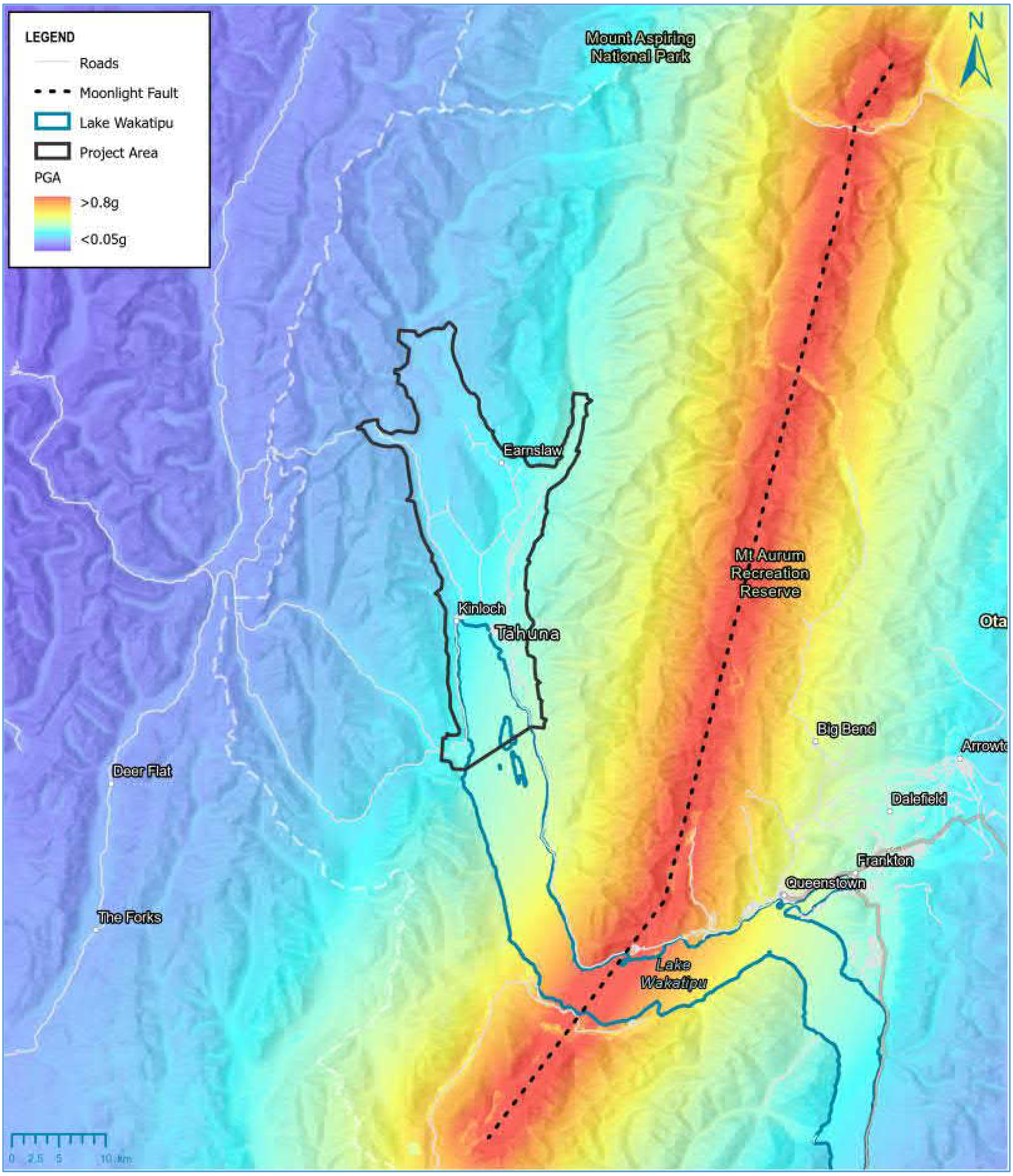


Figure 11-3 PGA map of a characteristic median rupture of the Moonlight Fault rupture. Rupture parameters are from Stirling et al. (2012) and Vs30 is from Foster et al (2019).

This normalised difference approach was applied to the Queenstown landslide layer dataset, using the 1:250,000 QMAP geology (Turnbull 2000) and 10° intervals (up to 60° and more) slope classes developed from Land Information New Zealand (LINZ) national 25 m Digital Elevation Model (DEM). Analysis of existing landslide locations, and the proportion of geology and slope that indicates landslide potential over the total area within the region, was used to produce a relative susceptibility value and extrapolated to all areas of the same geology and slope (Figure 11-4). To characterise the landslide evacuation hazard to the road, the road length is divided into a series of 50 m spaced points, and the landslide susceptibility at each is attributed (Figure 11-5). This identifies the areas of the road more susceptible of landslide evacuation and can subsequently be aggregated up to characterise the length of road within each landslide susceptible rating.

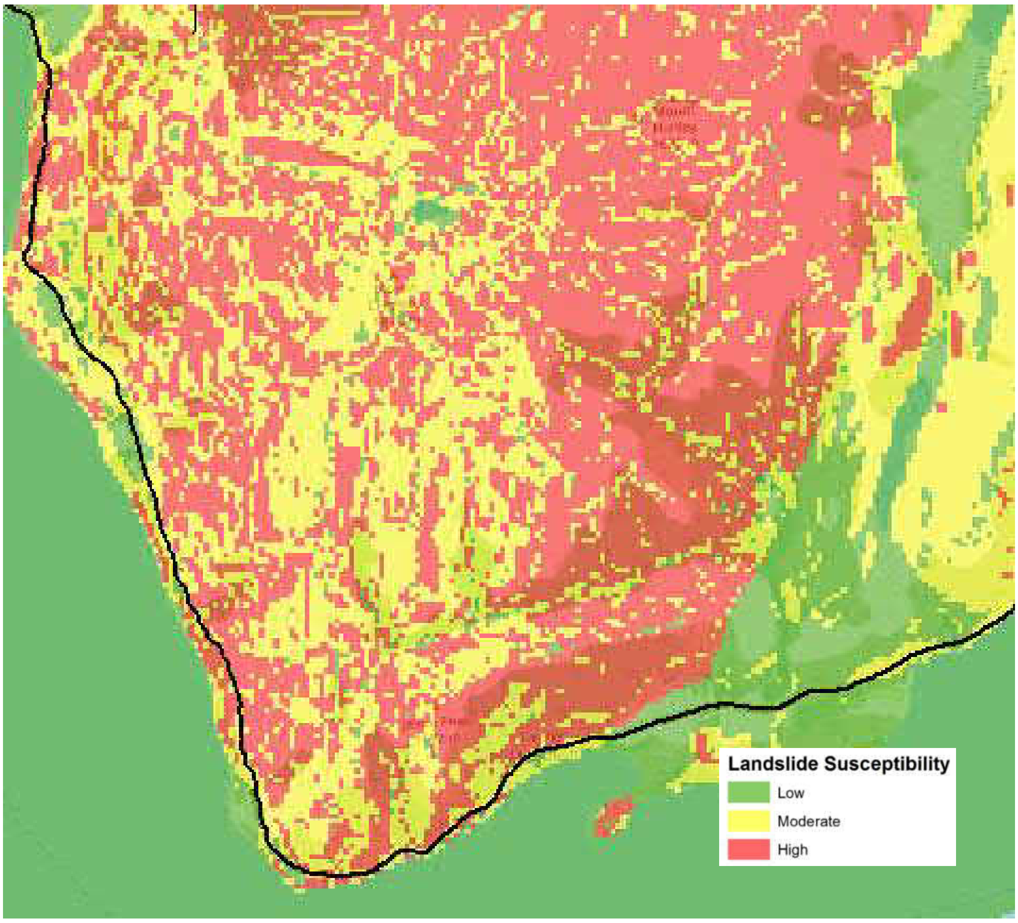


Figure 11-4 Example of the landslide evacuation susceptibility along the Glenorchy-Queenstown Road

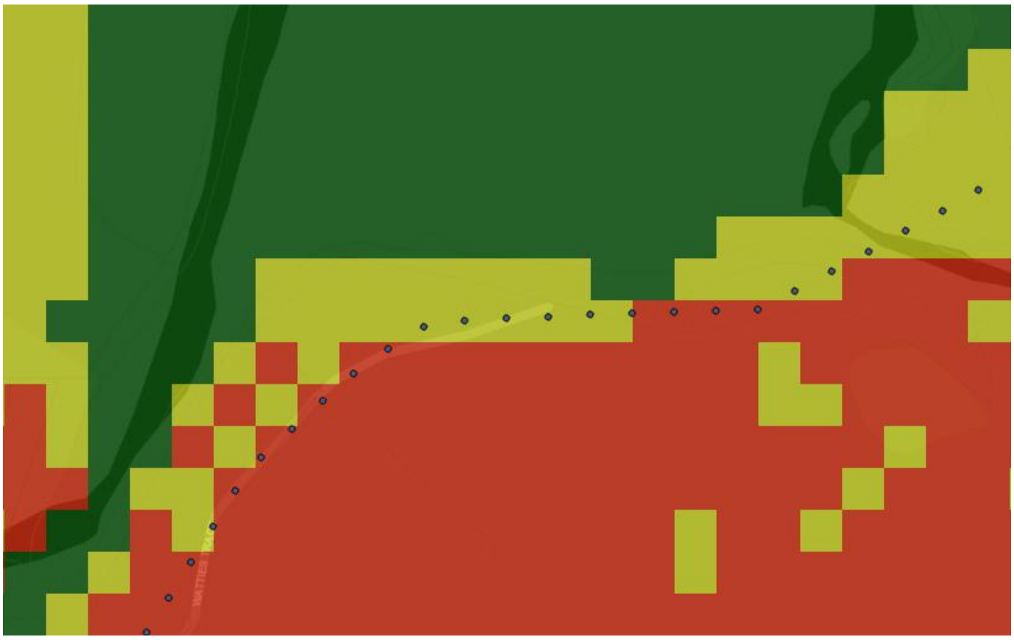


Figure 11-5 Example of landslide evacuation susceptibility assigned to 50 m interval points along the road

Landslide inundation modelling is also critical to identify above ground assets that could be impacted by runouts. The runout distance for debris generated by landslide initiation (L) is recognised as being a function of the elevation through which the debris descends (H) as well as the overall debris volume (Hunter and Fell 2003; McDougall 2014). The relationship between H and L (refer Figure 11-6) varies from 0.7 for small landslides with volumes of a few tens of cubic metres through to approximately 0.4 for large landslides with volumes of thousands or tens of thousands of cubic metres. This relationship indicates that large landslides carry more mass, and the greater potential energy drives the deposition zone further (L).

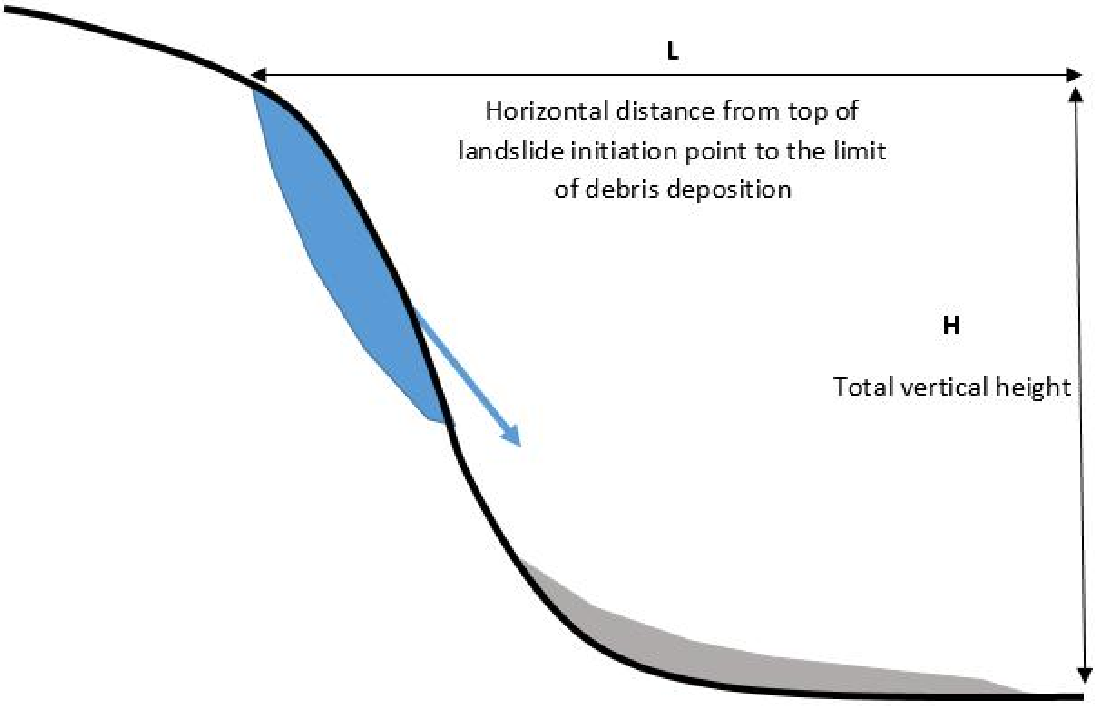


Figure 11-6 Relationship applied in this assessment between landslide evacuation and inundation

To determine if the road may be impacted by landslide inundation zones, perpendicular transects extending 400 m each way was created at 50 m intervals along the road alignment. The elevation changes and distance from the asset were determined at 50 m intervals along each transect and used to calculate the corresponding height/length ratio (H/L). H/L exceedance ratios of 0.4 and 0.7 were adopted as values to assess the sensitivity to the input parameters selected.

The points along the transect where the H/L ratio value is exceeded are identified for both exceedance values (Figure 11-7). These identify those slopes that could result in debris inundation of the road following a landslide. As for the landslide-generating slopes a susceptibility rating was assigned to the inundation zones, i.e., an inundation zone was assigned a low, medium, or high rating based on the equivalent initiation hazard rating for the slope from which the debris was generated.

Table 11-2 presents the network lengths susceptible to landslide inundation for H/L exceeding 0.7 and 0.4, respectively.

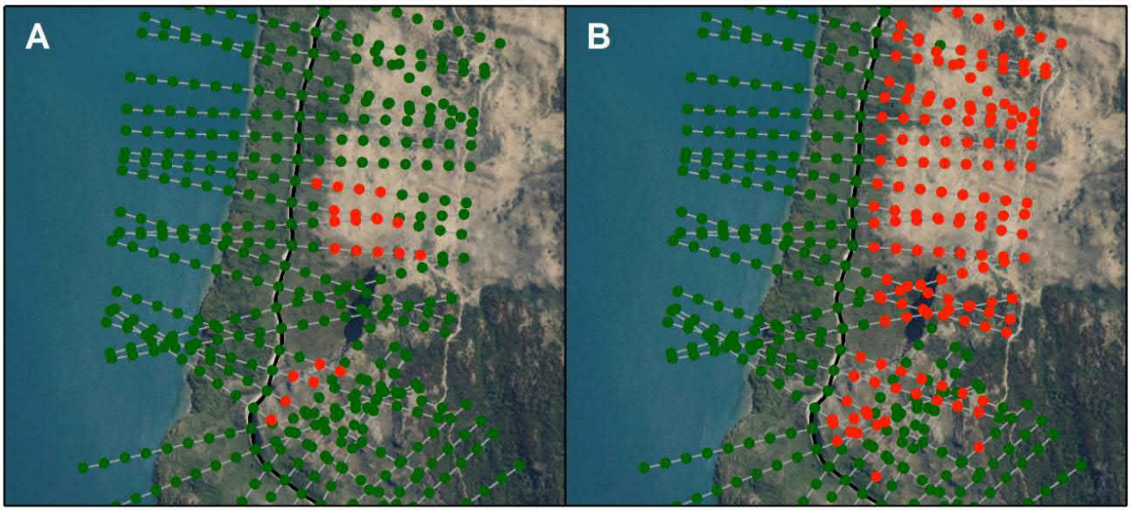


Figure 11-7 Points identified along each transect where the H/L value is exceeded for both A) 0.7; and B) 0.4

Table 11-2 Summary table for the Glenorchy-Queenstown Road landslide hazard exposure analysis

Landslide Phenomena	Proportion of road exposed			
	Very Low [1]	Low	Moderate	High
Evacuation	0%	43%	44%	13%
Inundation for H/L greater than 0.7	92%	0%	3%	5%
Inundation for H/L greater than 0.4	45%	2%	24%	28%

[1] Not identified as inundated in the landslide inundation susceptibility analysis

The profile of the slope behind Kinloch (Figure 11-8) indicates a gradient of 0.5. Given the susceptibility of the slope to fail given the geology, this demonstrates high susceptibility for inundation from large landslides above Kinloch. Further analysis should be conducted.

By comparison, the profile of the slope behind Glenorchy (Figure 11-9) demonstrates the town is between 700 m to 1 km recessed from the slope. This distance makes it less likely for landslide debris to inundate the land downslope, even from catastrophic failures of the slopes above the town.

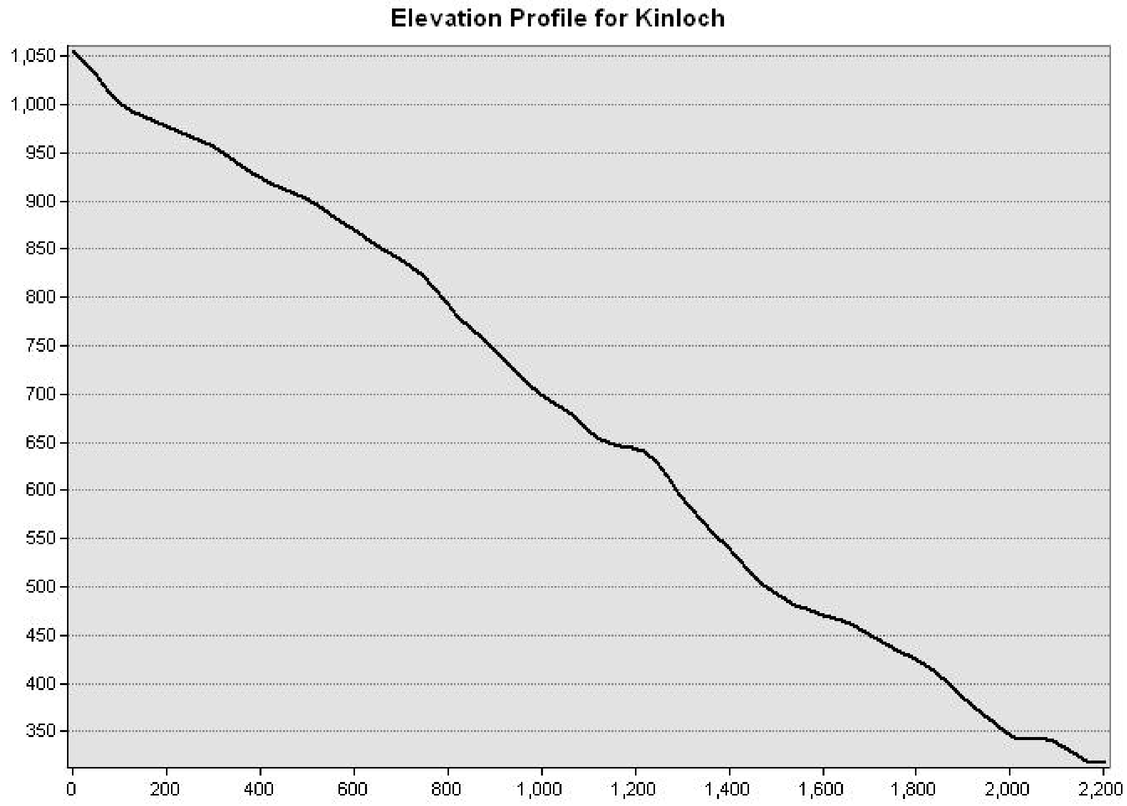


Figure 11-8 Elevation profile for Kinloch, where the town centre is located to the right

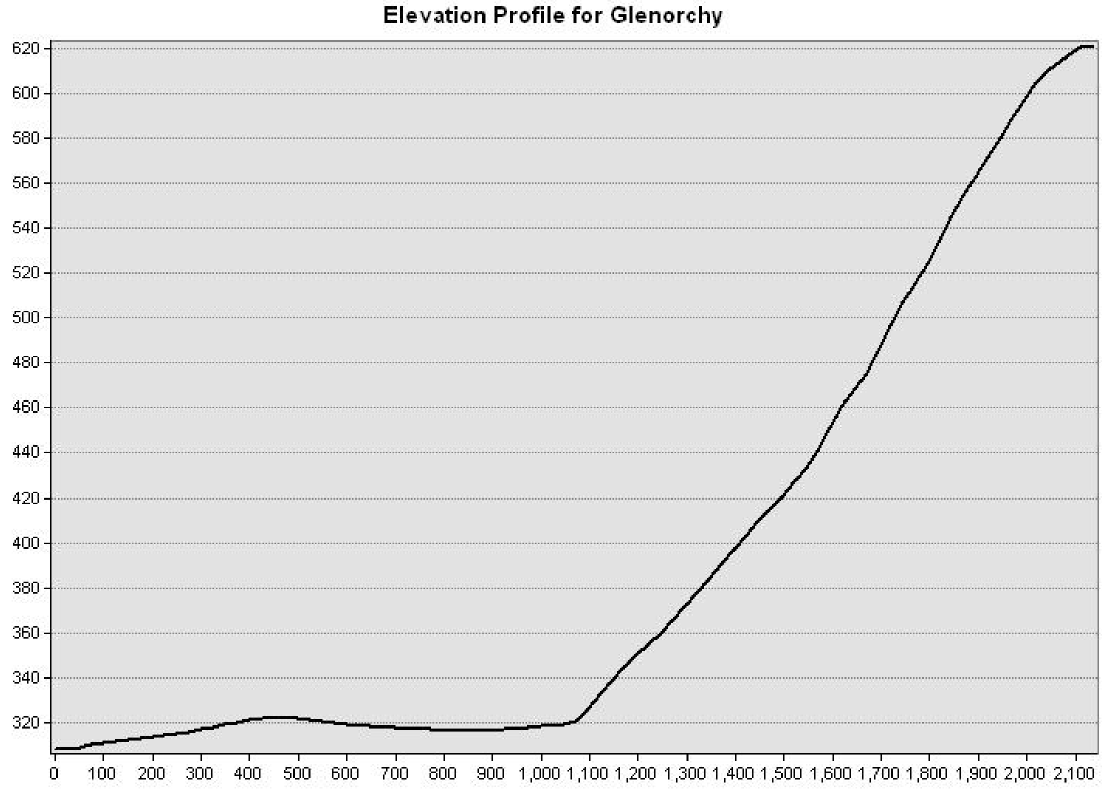


Figure 11-9 *Elevation profile for Glenorchy, where the centre of town is located to the left*

12 Natural Hazard Risk - Effect of Uncertainty on Objectives

For the Project area, the regional, district and local objectives around the management of natural hazards are set out in Section 3. These are:

- Risks that natural hazards pose to Otago's communities are minimised.
- Otago's communities are prepared for and able to adapt to the effects of climate change
- The risk to people and the built environment posed by natural hazards is managed to a level tolerable to the community
- Development on land subject to natural hazards only occurs where the risks to the community and the built environment are appropriately managed
- The community's awareness and understanding of the natural hazard risk in the District in continually enhanced.
- Glenorchy has an environmentally sustainable, self-sufficient community.

There is therefore a mix of objectives that are about outcomes, and those that are about how outcomes might be achieved. Outcome expressions are a more useful starting point.

The spatial extent of the consequences of natural hazards are set out in Section 10. Accordingly, it is now possible to see where there is a high level of uncertainty in achieving the above-mentioned objectives, and where there is a high level of certainty.

In the low-lying areas adjacent to the banks of the Dart and Rees Rivers, the land is likely to either be removed by erosion and/or covered by alluvium in the absence of interventions to defend against these natural processes. The rivers and their flood flows are both very large and dynamic and are likely to become even more so as a direct result of climate change.

The cost of defending these areas against the fluvial processes to avoid the inevitable consequences is high and would also need to be undertaken in perpetuity. The chances of success of such defences (bank protection, stop banks and gravel management) also have considerable uncertainty themselves. Within the next 200 years the Dart and Rees Rivers are likely to either erode and/or reclaim much of the low-lying alluvial land.

Many of the low-lying alluvial areas adjacent to the rivers and the lake are also susceptible to liquefaction under high levels of earthquake shaking. If this is prolonged then the land is also likely to spread towards the lake or other free faces, damaging property (including infrastructure) located on the land. The cost of defending land against the liquefaction hazard and reducing the consequences is very high, although the chances of success are considerably more assured than for flood defences. This is because, unlike flooding, the effects of liquefaction do not become greater with increased intensity of the trigger.

The very process of liquefaction itself can be mitigated through proven ground improvement techniques. However, the cost of such ground improvement is very high.

Other areas alongside the rivers and the lake are susceptible to loss of land and/or inundation by debris due to landslides, which could be generated by high intensity rainfall events or high levels of seismic shaking. In Sections 10 and 11 the consequences arising from various natural hazards scenarios have been considered, including cascading hazards following a significant seismic event.

Additional areas have been identified through this process that also present considerable uncertainty of achieving the regional, district and local objectives.

With the effects of uncertainty on objectives spatially defined, areas of land have also been identified where there is a high degree of certainty that the objectives can be achieved, at least with respect to natural hazards. These are shown in, and the map is also presented in Appendix E and is available in the ORC/QLDC web-based viewer.

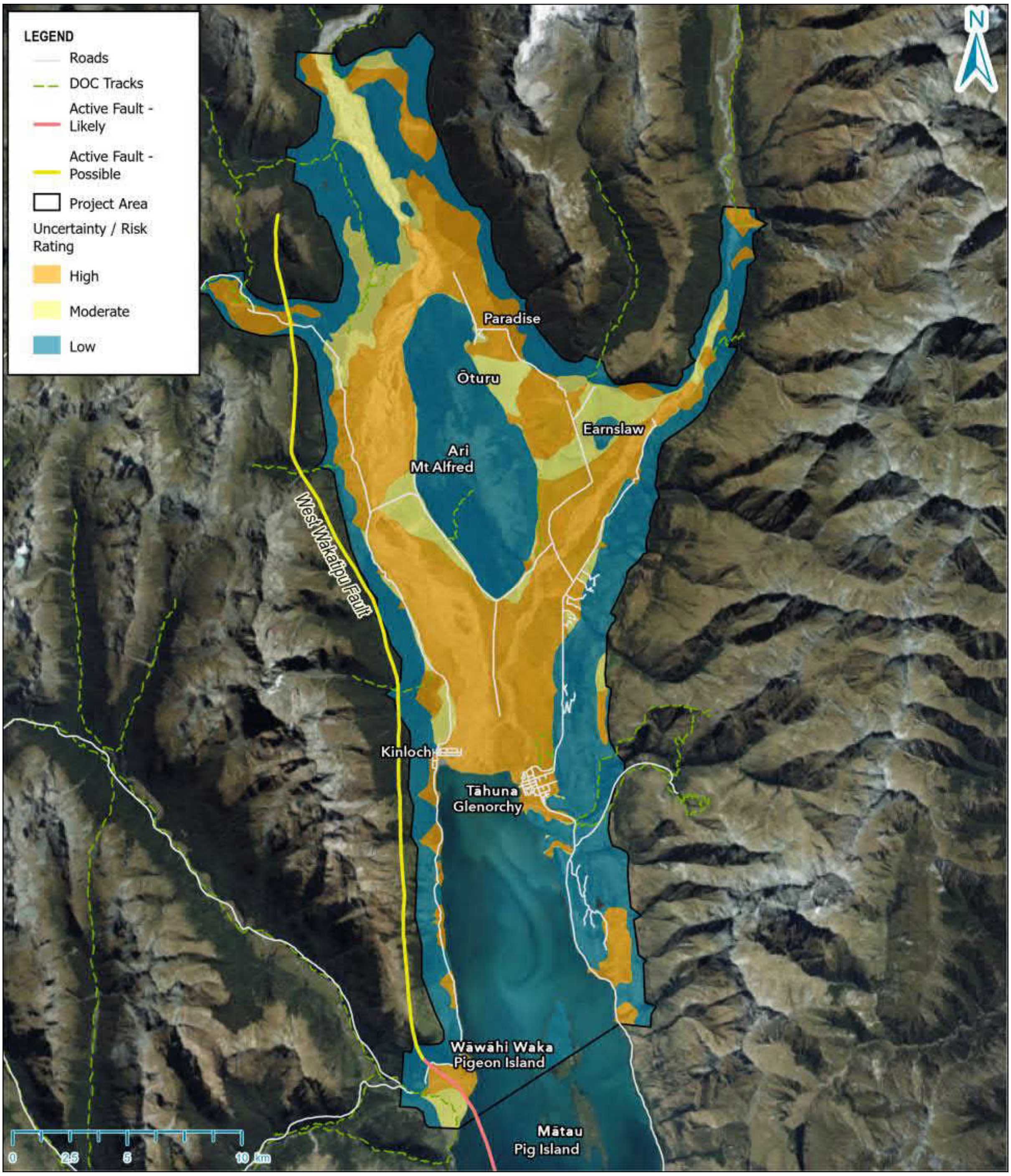


Figure 12.1: Head of Lake Wakatipu Risk Uncertainty

13 Summary

The purpose of the natural hazard information presented in this document is merely to inform. As this information is already publicly available this should not affect the ability of residents to obtain natural disaster insurance, nor to remove any existing human or property rights that exist within the communities.

Instead, this information is applied in a very different way from any previous assessment of natural disaster risk.

Rather than presenting natural hazard risk for individual hazards probabilistically, the consequences of the multiple natural hazards are presented spatially. The Project area is mapped according to the relative uncertainty that the objectives of the community can be met. The objectives of the ORC (as articulated in the Regional Policy Statement) and the QLDC (as articulated in the Natural Hazards section of the Proposed District Plan) are also included in a single map of the Project area showing the relative uncertainty that natural hazards present to achieving the various objectives.

Together with the particular natural hazard maps, the risk map shows the effect of uncertainty about the nature, scale, and timing of consequences of hazard events on achieving objectives, and therefore provides a valuable insight for the community adaptation planning process.

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15 Applicability

This report has been prepared for the exclusive use of the Otago Regional Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than the Otago Regional Council, without our prior written agreement.

We understand and agree that this report will be used by the Otago Regional Council in undertaking its regulatory functions in connection with the development of an adaptation plan for the Project area.[ii]

Tonkin & Taylor Ltd

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Appendix A: Project Plan

- Head of Lake Wakatipu Natural Hazard Adaptation Strategy, Project plan, ORC, March 2020

Appendix B: Randerson Report

- New Directions for Resource Management in New Zealand: Report of the Resource Management Review Panel, MfE, June 2020

Manging natural hazard and climate change adaptation is a key part of the recommendations of the review panel (hereafter referred to as the panel) . It identifies specific issues relevant to climate change and natural hazards. These include:

- insufficient focus on addressing the effects of climate change (adaptation) and the risks from natural hazards.
- poor integration across the resource management system; and
- capacity, capability, and funding barriers.

The panel attributes the lack of national direction, difficulties addressing contentious issues (including managed retreat) and how risk is understood as factors contributing to the lack of focus. It notes that nationally developed science, data, information, and best practice planning approaches could improve efficiency, consistency, and fairness of approaches.

The key elements of the panel's proposals are:

- a new Natural and Built Environments Act to replace the Resource Management Act.
- a new Strategic Planning Act.
- a new Managed Retreat and Climate Change Adaptation Act.
- fourteen Combined Plans, prepared on a regional basis, to replace over 100 current RMA policy statements and plans: and
- more active roles for Central Government.

Integration of environmental protection and land use planning

The panel recommends that environmental protection and land use planning continue to be integrated in a single statute – the Natural and Built Environments Act. It also recommends retaining a broad definition of the environment. Both of these elements are important to effectively manage natural hazards and climate change.

Risk reduction and resilience

The panel presents a firm view that management of natural hazards should be focussed on risk reduction and resilience, and that these should be specified as legislative outcomes.

The panel's thinking and recommendations on risk reduction and resilience are well aligned with the ORC's policies. Having noted the lack of a definition of risk in the Resource Management Act, the panel recommends the definition from the Civil Defence and Emergency Management Act be adopted. This would define risk to include reference to likelihood and consequences.

The proposal to define risk in terms of likelihood and consequences is not aligned with leading thinking on risk management. The ISO 31000 definition of risk as the effect of uncertainty on objectives (outcomes) is better aligned with the outcomes focus the panel recommends and its commentary on resilience.

Outcomes, limits, and bottom lines

The panel proposes specific text on outcomes to be included in the Natural and Built Environments Act and that there should be a positive obligation to pursue these, including through national direction, plan preparation and consenting. The specific text on natural hazards and climate change includes the following to subclauses:

- reduction of risks from natural hazards; and
- improved resilience to the effects of climate change including through adaptation.

The panel also explored concepts of targets, limits, and bottom lines, recommending specific text for a clause in the Natural and Built Environments Act on environmental limits. That clause is focussed on the natural environment domain. There is an opportunity to build on the panel's thinking on limits and bottom lines to incorporate the effects in the project area on built and natural environments as a consequence of natural hazard events and climate change.

Wellbeing, restoration, and wide view of environment

The panel uses the concept of wellbeing to introduce the importance of restoration as part of sustainable management or sustainability. It does this in the context of a wide definition of environment (incorporating people and communities as well as natural and built environments).

A specific focus on restoration provides an opportunity for ORC to consider restoration of areas such as riparian strips, wetlands in the project area that provide natural defences to the effects of natural hazards and climate change.

Implementation principles and duties

The panel is proposing a significant shift to focus effort under the Natural and Built Environments Act on resolving issues and conflicts in policy and planning processes, rather than in resource consenting processes.

The panel proposes some specific text for a clause in the Natural and Built Environments Act on implementation principles and duties. Principles about integrated management, complementing other relevant legislation and international obligation, cumulative effects and taking a precautionary approach are all helpful and relevant to ORC's policies. There is a particular opportunity for ORC to highlight the importance of international obligations such as in the Sendai Framework and other legislations (including CDEM) as relevant drivers for risk reduction.

The panel proposes that the Minister should have a duty to produce national guidance on natural hazards and climate change; and that regional and district councils should have functions on climate change adaptation and reducing risks from natural hazards.

The panel's work drew an important link between the interests of Mana Whenua and climate change adaptation and natural hazards. ORC will need to be cognisant of Mana Whenua interests that may be relevant to the proposed adaptation plan.

National direction

The importance of national direction in the panel's view is reflected in the detail of its work and reporting on the topic. The panel considers that national direction on natural hazards and climate change could cover a wide range of material, from assessment methods and priorities for risk reduction, mapping, use of nature-based solutions, adaptation of indigenous species and dynamic adaptive policy approaches. The panel also proposes a formal connection to the national adaptation plan prepared and the Climate Change Response Act.

Strategic integration and spatial planning

The panel concluded that a future resource management system should anticipate and respond to the challenges presented by climate change and natural hazards and that good decision making would require integration across a broader climate change and natural hazard legislative responses. It proposes mandatory regional spatial planning under a new Strategic Planning Act. This would be required to address climate change and natural hazards as drivers of land use change, as set out in the panel's proposed text for its Purpose clause.

The panel identified some key legislation that should be integrated under the new Act but noted that other legislation could also be included.

The panel considered the timescale for spatial planning, landing on the concept of at least 100 years. There is an opportunity here for ORC to provide some thought leadership that builds on the outcomes focus the panel is advocating to explore more enduring outcomes that could support strategic planning for timeframes well beyond 100 years. This could provide a stronger context to address low frequency natural hazard events, and also accumulating hazards such as the aggradation of the Dart and Rees riverbeds.

The panel proposes the regional spatial planning should be carried out as a joint exercise involving central government, councils, and Mana Whenua, with a strong central government input. This reflects the national interests at stake and resources that would be required.

Policy and planning framework and consenting

The most significant proposal affecting ORC is for the current array of regional policies, regional and district plans to be replaced with fourteen regional combined plans. These would regulate land and resource use to give effect to national direction and spatial strategies and allow for adaptive planning measures. A streamlined development process led by a joint committee is proposed. An audit role for the Ministry for the Environment over plans before they are notified for public comment is a novel proposal from the panel.

Assessments to support and decision-making processes on resource consent applications are also addressed by the panel. It recommends specific text for a clause in the Built and Natural Environments Act on consideration of applications. This would require regard to be given to whether and to what extent proposals contribute to outcomes, in addition to the current assessment required of effects on the environment.

The status quo biases

The panel completed some detailed analysis of the challenges associated with existing use rights and the powers of councils in relation to resource consents that have been granted. It saw significant impediments to implementing managed retreat. Significant new thinking and work will be required to address the impediments and develop the detail required to support the panel's proposals.

Given the scale of the challenges the panel proposes a new Managed Retreat and Climate Change Adaptation Act (in addition to any detailed provisions required in the Built and Natural Environments Act). It suggests that funding and compensation are "*perhaps the most significant issues*". The panel sets out a list of issues that should be addressed in the new Act. The majority of these concern funding, liability, and insurance issues.

Transition and timing

The panel is proposing a very fast transition to the new legislative regime. It recommends that work should begin as soon as possible on the preparation of the Natural and Built Environments Act, the Strategic Planning Act and the Managed Retreat and Climate Change Adaptation Act so that first two are in place by the time the Covid-19 recovery legislation expires. It recommends that work should commence immediately on data collection and analysis and that the Minister for the Environment should select one region to develop the first regional spatial strategy and combined plan. These would provide a model for other regions. The panel's expectation is that the overall transition process should be completed within 10 years of the introduction of the first two Acts.

Appendix C: Hazard Maps

- T+T, 2020
    - Seismic Faults
        - Head of the Lake
        - Wider region
    - Liquefaction Hazard
    - Landslide Hazard
    - Inundation Hazard due to Lake Level rise
        - Glenorchy
        - Kinloch
    - Flood Hazard
    - Alluvial Fans
        - Landform
        - Activity

Head of Lake Wakatipu Natural Hazards Adaptation

Seismic Faults

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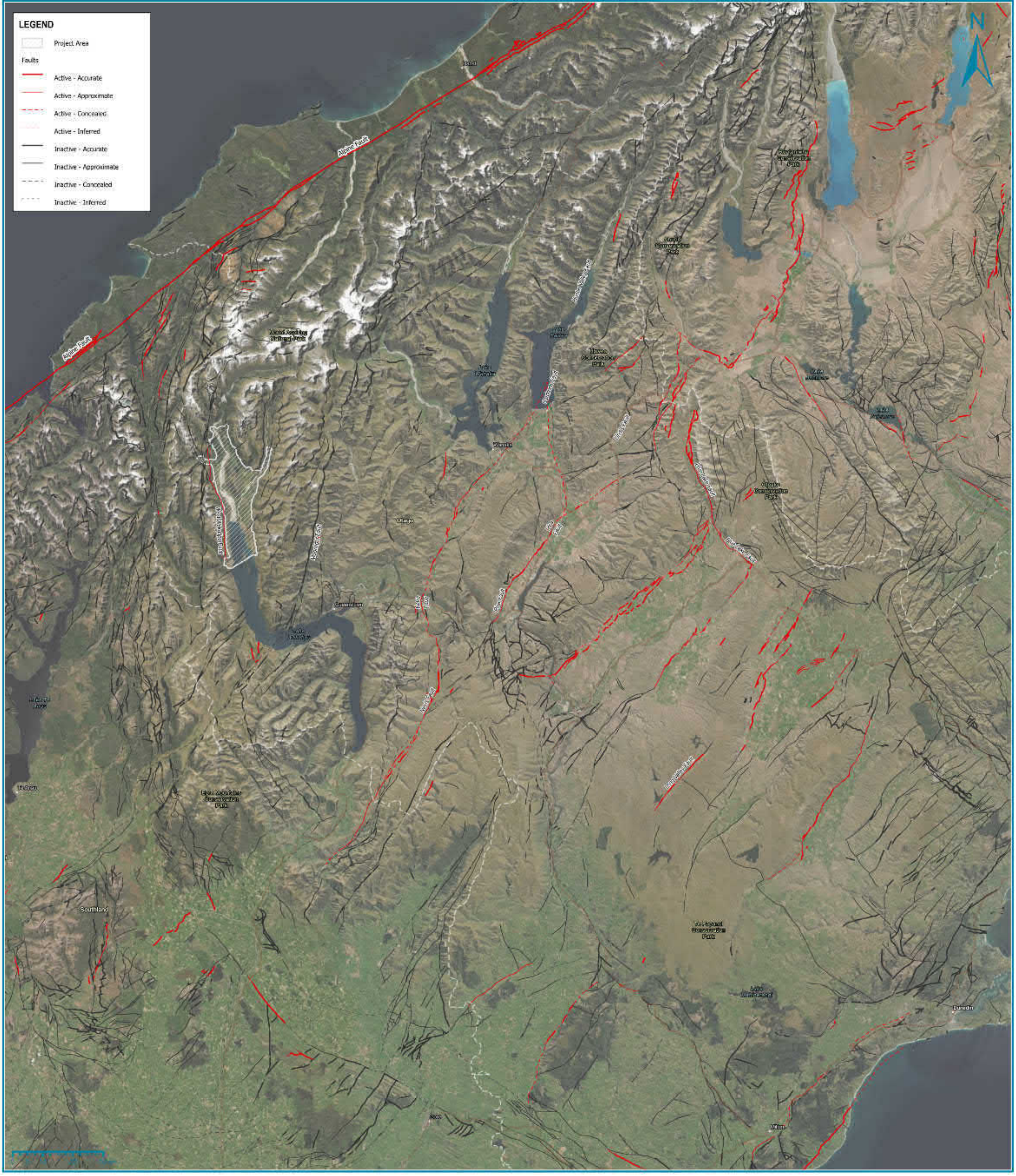
Notes: This layer shows active faults mapped at regional scale (approx. 1:250,000) in the Queenstown Lakes and Central Otago districts by GNS for the ORC (2019). It depicts the locations of active and potentially active faults at or near the ground surface.
Definite = clear evidence for the existence of an active fault or fold.
Likely = good reason to suspect the existence of an active fault or fold.
Possible = some reason to suspect the existence of an active fault or fold.
Potentially active = a known or suspected fault without identified geologically recent activity, but which could conceivably experience activity in the future.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: Fault rupture following the 2016 Kaikoura earthquake (GNS).
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Seismic Faults



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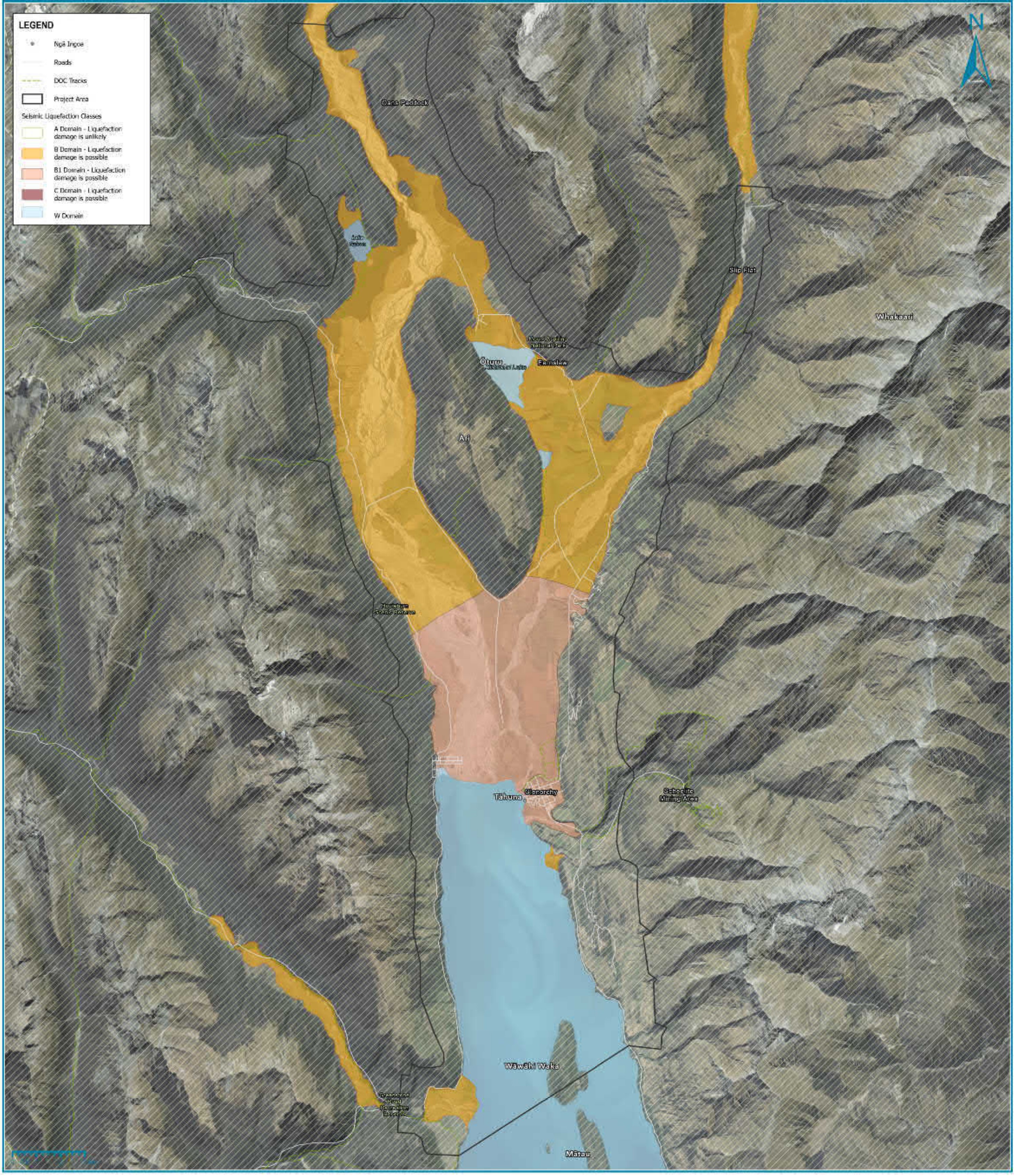
Notes: This layer shows faults mapped at a regional scale (1:250,000) by GNS.

Basemap: Earthstar Geographics, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, FAO, METI/NASA, USGS
Image: Fault rupture following the 2016 Kaikoura earthquake (GNS).
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Liquefaction Hazard



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Notes: This 2019 data set prepared by GNS for ORC identifies areas that are assessed as being underlain by sediments which may have some liquefaction susceptibility.
Domain A - Liquefaction damage is unlikely. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring.
Domain B. Liquefaction damage is possible. The ground is predominantly underlain by poorly consolidated river or stream sediments with a shallow groundwater table. There is considered to be a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain B.
Domain B1 - Liquefaction damage is possible. As for Domain B, but there is geotechnical evidence for the presence of liquefaction-susceptible materials at least in some locations in the subsurface.
Domain C - Liquefaction damage is possible. The ground is predominantly underlain by poorly consolidated marine or estuarine sediments with a shallow groundwater table. There is considered to be a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain C.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: February 2011 Liquefaction in Christchurch.
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Mapped Landslides

Notes: This layer shows mapped landslides from GNS (Turnbell 2000, Barrell et al 2009) for ORC.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: Inundation of SH1 as a result of a landslide triggered by the 2016 Kaikoura earthquake.
Map prepared November 2020 by T+T, based on data provided by ORC.

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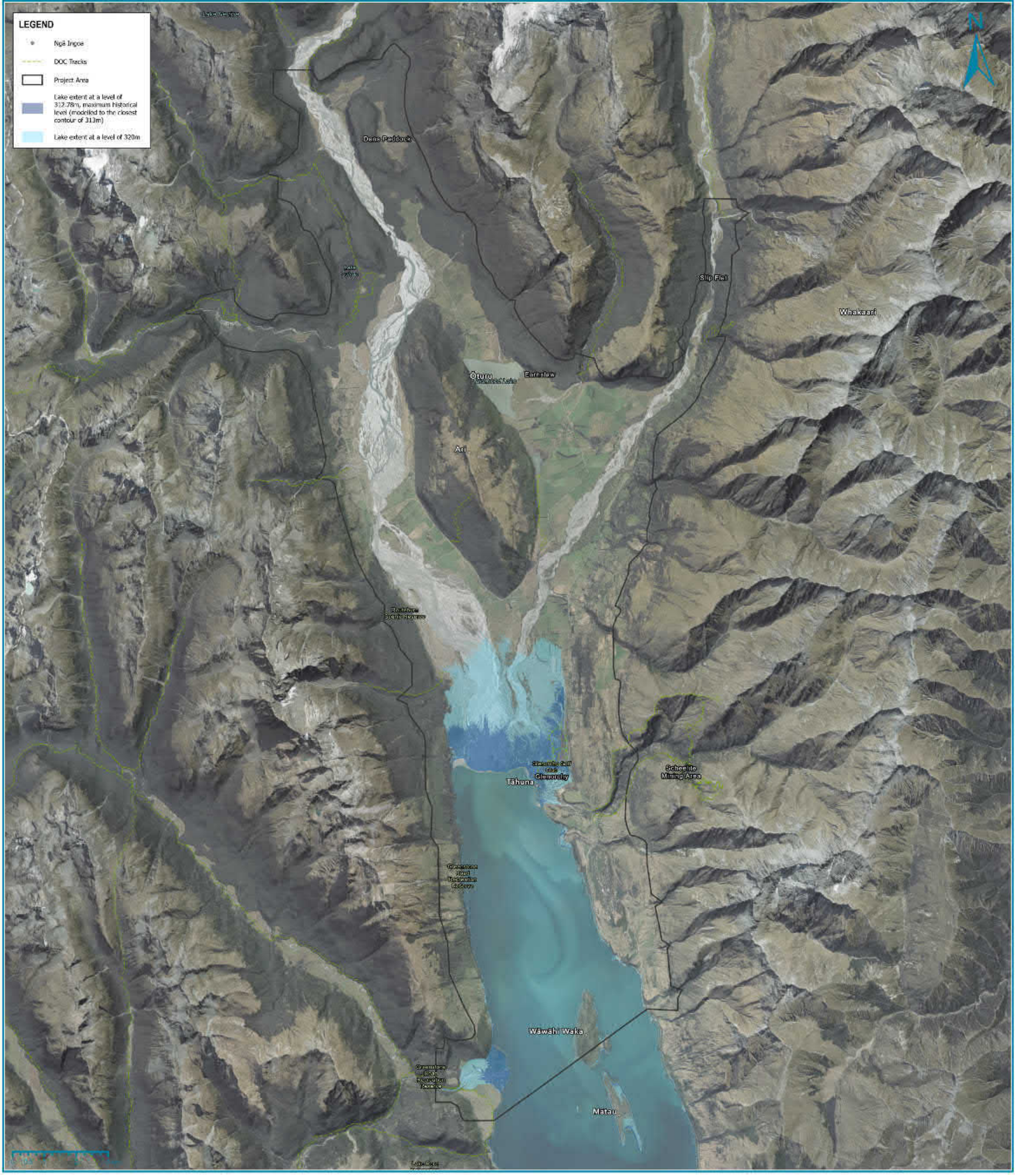
Inundation Due to Lake Level Rise



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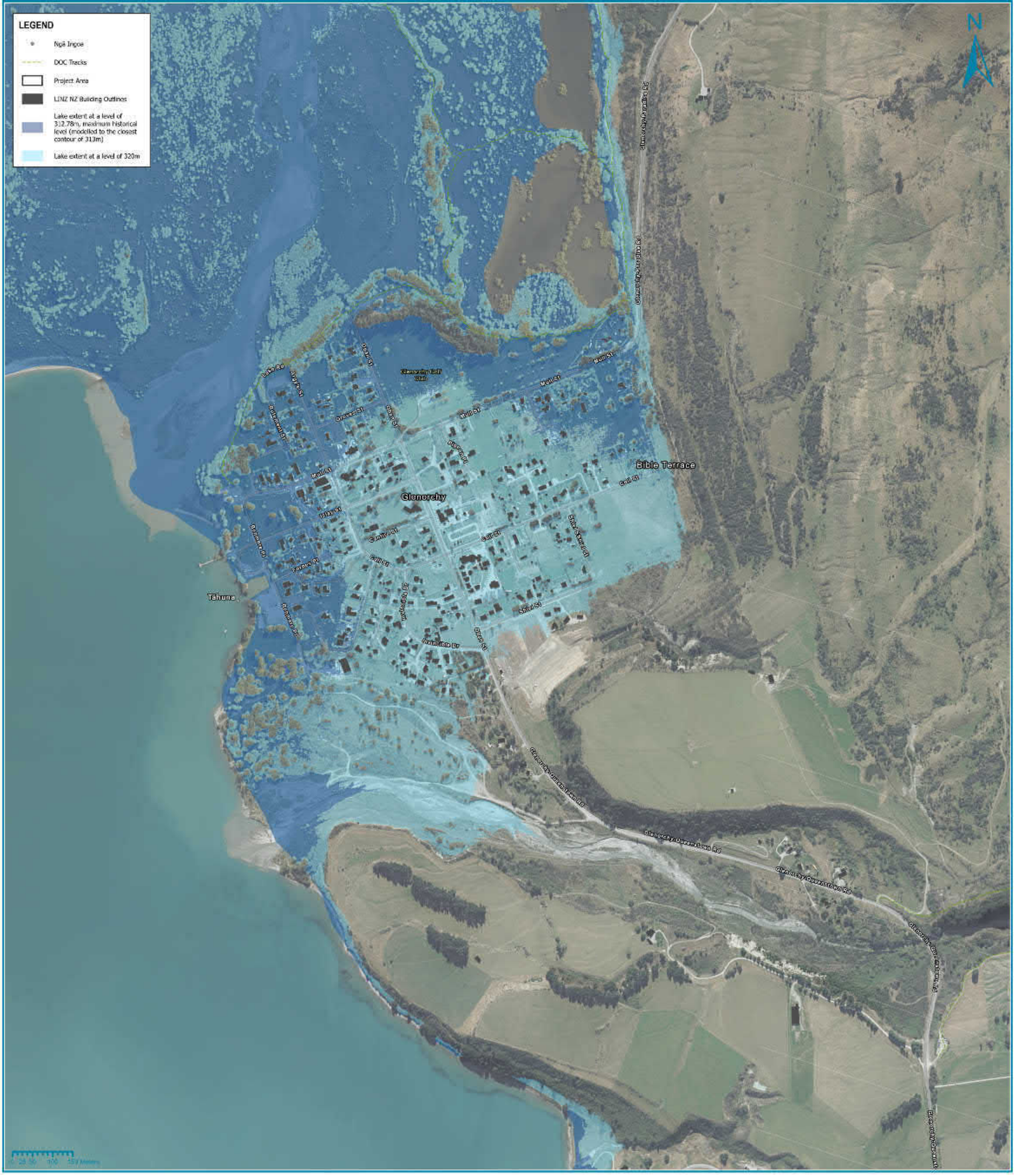
Notes: The map shows the flooded area from the historic maximum lake level. Should the Kawarau River become blocked by a landslide dam, extents show how more land could be flooded as the level rises further. The maximum case was informed by Thompson (1996) that states the inundation from a landslide blocking the Kawarau River could result in a rise in lake level of 30m (to 340m above sea level). Lesser potential lake level rises, are provided to allow comparison. These were developed using a bathtub approach using the provided DSM provided by ORC, 2019.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: November 1999 flooding of Glenorchy.
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Inundation Due to Lake Level Rise



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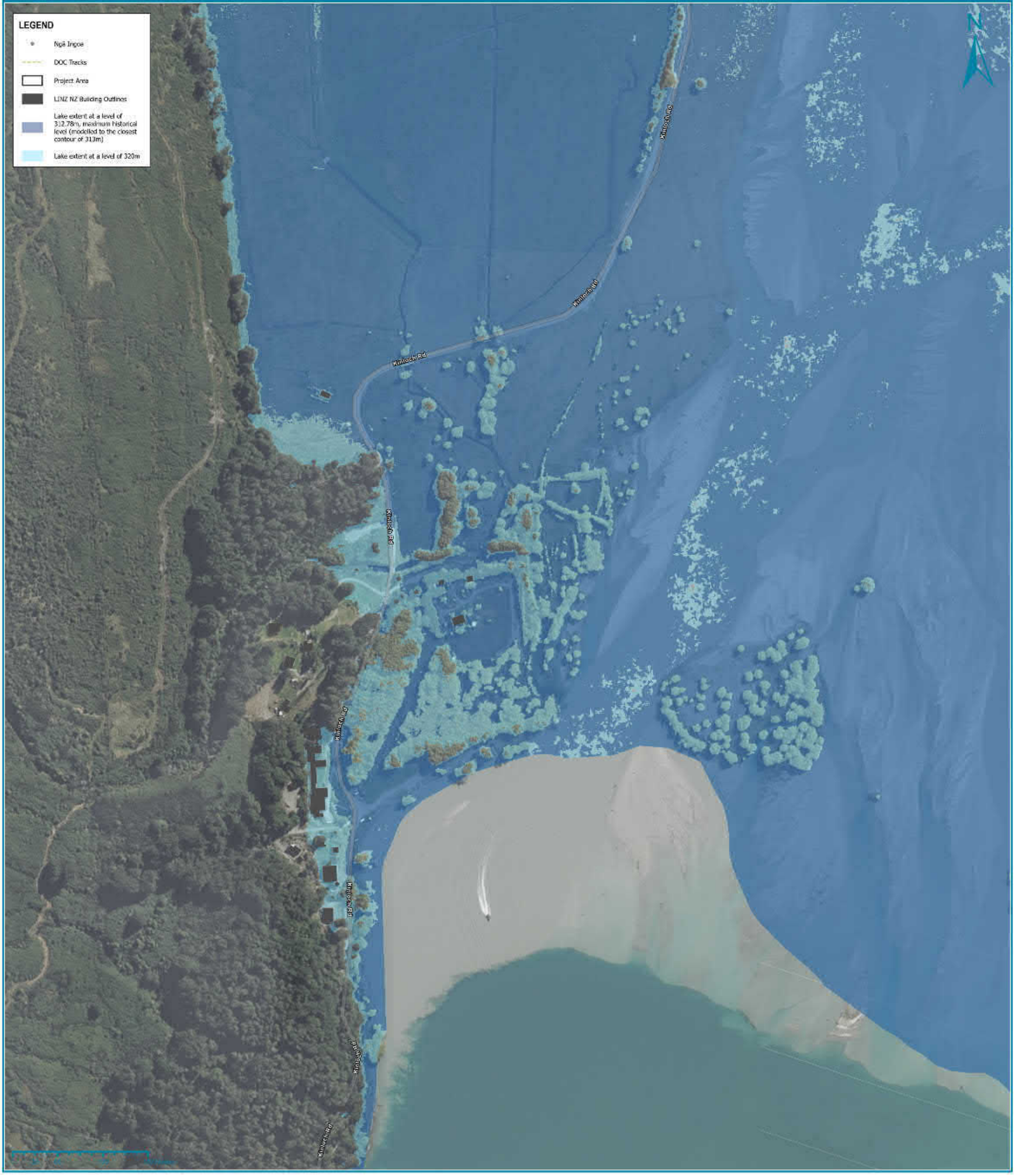
Notes: The map shows the flooded area from the historic maximum lake level. Should the Kawarau River become blocked by a landslide dam, extents show how more land could be flooded as the level rises further. The maximum case was informed by Thompson (1996) that states the inundation from a landslide blocking the Kawarau River could result in a rise in lake level of 30m (to 340m above sea level). Lesser potential lake level rises, are provided to allow comparison. These were developed using a bathtub approach using the provided DSM provided by ORC, 2019.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: November 1999 flooding of Glenorchy.
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Inundation Due to Lake Level Rise



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Notes: The map shows the flooded area from the historic maximum lake level. Should the Kawarau River become blocked by a landslide dam, extents show how more land could be flooded as the level rises further. The maximum case was informed by Thompson (1996) that states the inundation from a landslide blocking the Kawarau River could result in a rise in lake level of 30m (to 340m above sea level). Lesser potential lake level rises, are provided to allow comparison. These were developed using a bathtub approach using the provided DSM provided by ORC, 2019.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: November 1999 flooding of Glenorchy.
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Flood Hazard

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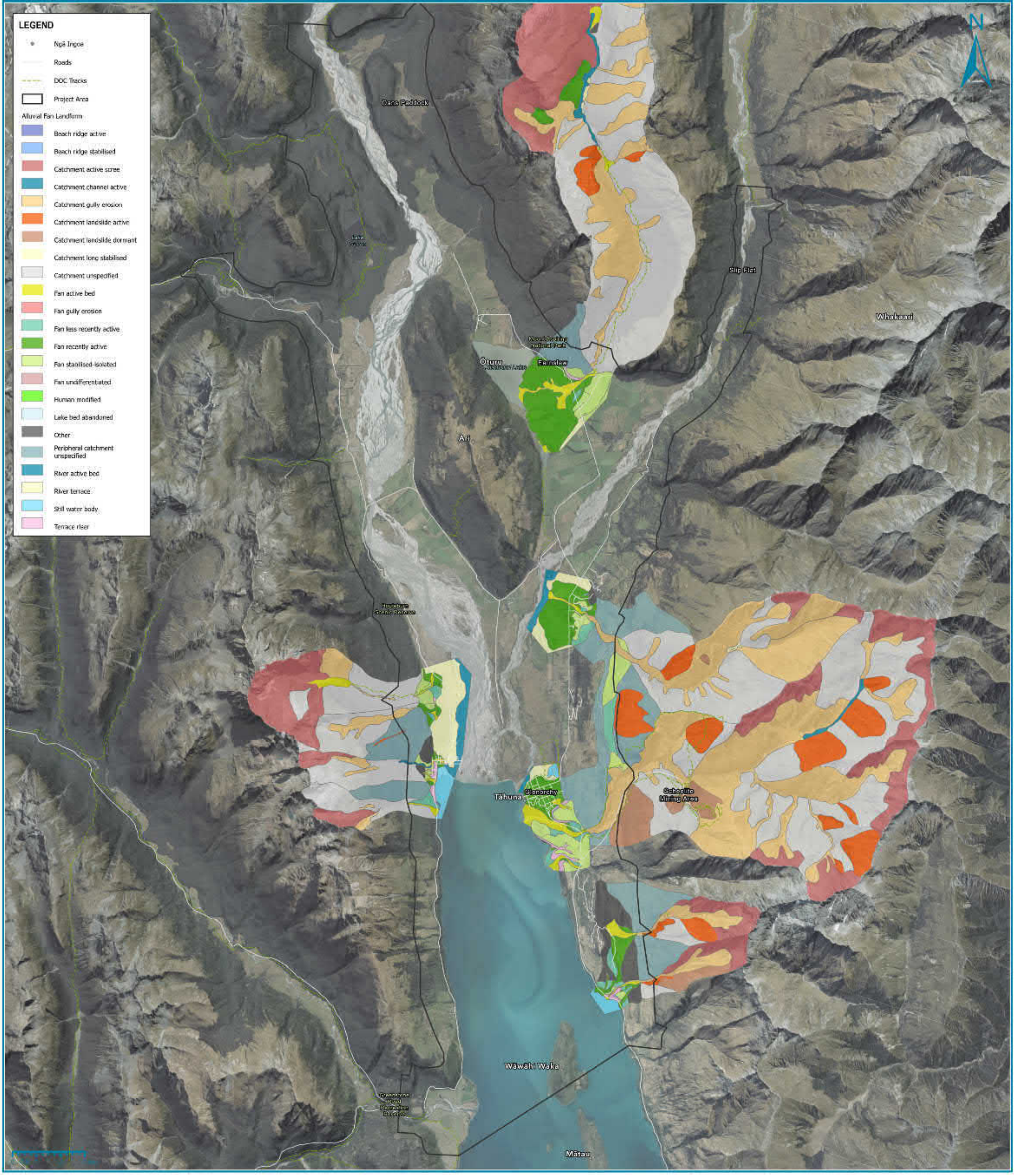
Notes: The mapped flood hazard area from the Otago Natural Hazard Database shows land which is at risk of inundation due to flood events in rivers and lakes. It does not include flooding due to overloading of the urban stormwater network. In addition, flood extents are only shown for areas where this hazard has been documented and investigated – the flood hazard area does not cover sections of some rivers and lakes where the we don't not hold sufficient information to accurately assess flood hazard.

The extent and location of flood hazard can vary considerably during each flood event, due to variations in tributary flow and sediment supply, and the changing geomorphology of the surrounding environment.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: November 1999 flooding of Glenorchy.
Map prepared November 2020 by T+T, based on data provided by ORC.

Head of Lake Wakatipu Natural Hazards Adaptation

Alluvial Fan - Landform



Notes: This layer displays alluvial fan landform channels mapped at selected locations throughout Otago, as mapped by GNS for ORC in 2009 as part of the ORC Alluvial Fans Project.
The main hazards affecting alluvial fans include inundation by floodwater, debris flow and debris flood deposits, channel migration, deposition, and erosion. The considerable buildup of sedimentation may result from alluvial fan floods. However, debris and flood flows are only intermittent and usually occur over decades or centuries.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: Alluvial fan activity near Flaxmill Creek, Makarora East.
Map prepared November 2020 by T+T, based on data provided by ORC.

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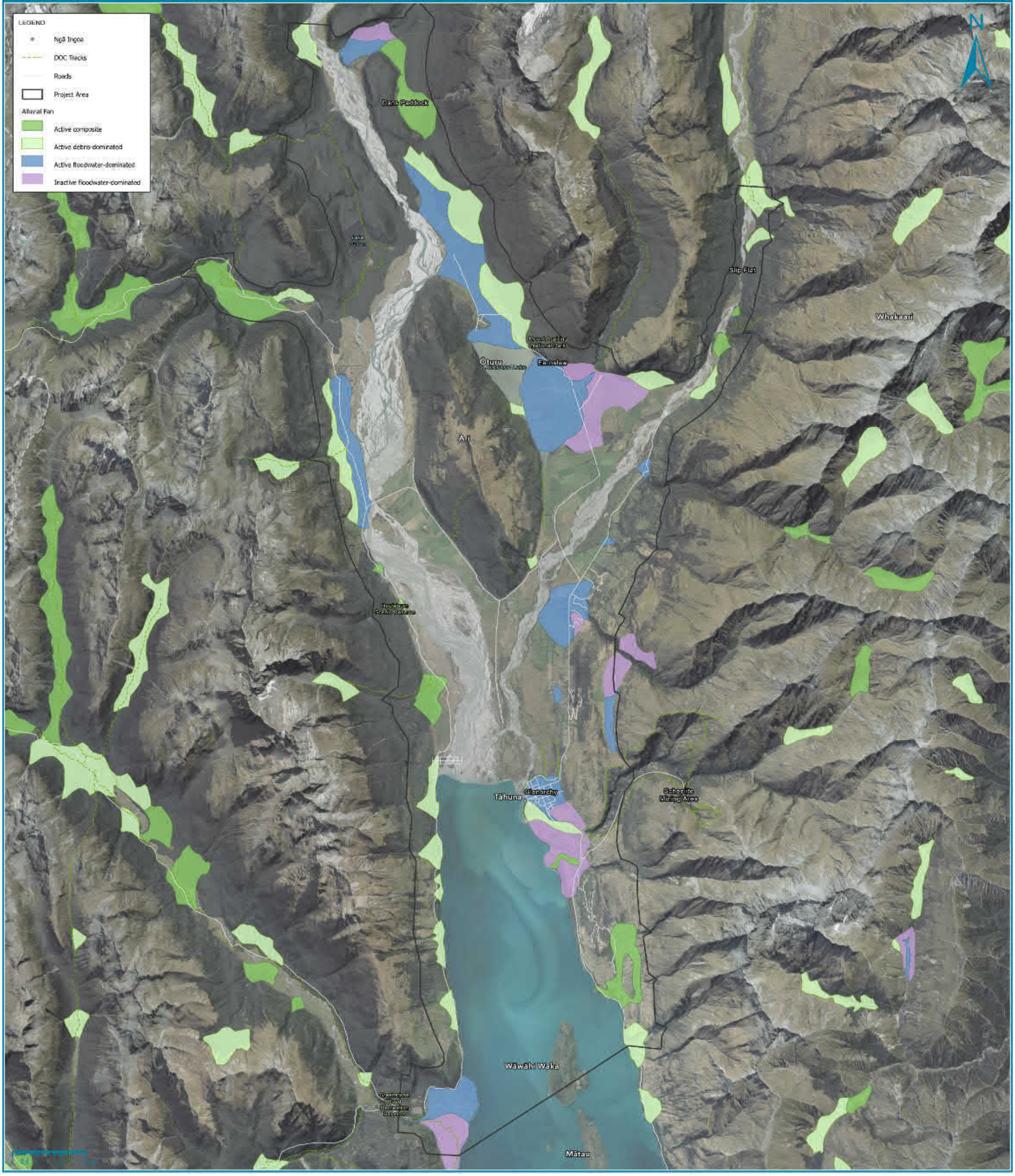
Head of Lake Wakatipu Natural Hazards Adaptation

Alluvial Fan Activity



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Notes: In this layer, alluvial fans are mapped at regional scale (1:50 000 - 1:250 000) throughout the area by Opus as part of the ORC Alluvial Fans Project (as reported by Opus, July 2007; March 2009).
The main hazards affecting alluvial fans include inundation by floodwater, debris flow and debris flood deposits, channel migration, deposition, and erosion. The considerable buildup of sedimentation may result from alluvial fan floods. However, debris and flood flows are only intermittent and usually occur over decades or centuries.

Basemap: Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, METI/NASA, USGS
Image: Alluvial fan activity near Flaxmill Creek, Makarora East.
Map prepared November 2020 by T+T, based on data provided by ORC.

Appendix D: Modified Mercalli Scale

Table D-1: Modified Mercalli Scale from Dowrick (1996)

Level	Description
MM 1	People Not felt except by a very few people under exceptionally favourable circumstances.
MM 2	People Felt by persons at rest, on upper floors or favourably placed.
MM 3	People Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.
MM 4	People Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building. Fittings Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock. Structures Walls and frames of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.
MM 5	People Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Fittings Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Hanging pictures knock against the wall. Open doors may swing. Cupboard doors secured by magnetic catches may open. Pendulum clocks stop, start, or change rate. Structures Some windows Type I cracked. A few earthenware toilet fixtures cracked.
MM 6	People Felt by all. People and animals alarmed. Many runs outside. Difficulty experienced in walking steadily. Fittings Objects fall from shelves. Pictures fall from walls. Some furniture moved on smooth floors; some unsecured free-standing fireplaces moved. Glassware and crockery broken. Very unstable furniture overturned. Small church and school bells ring. Appliances move on bench or tabletops. Filing cabinets or "easy glide" drawers may open (or shut). Structures Slight damage to Buildings Type I. Some stucco or cement plaster falls. Windows Type I broken. Damage to a few weak domestic chimneys, some may fall. Environment Trees and bushes shake or are heard to rustle. Loose material may be dislodged from sloping ground, e.g., existing slides, talus slopes, shingle slides.

Table A-1 cont.: Modified Mercalli Scale from Dowrick (1996)

Level	Description
MM 7	People General alarm. Difficulty experienced in standing. Noticed by motorcar drivers who may stop. Fittings Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. Substantial damage to fragile contents of buildings. Structures Unreinforced stone and brick walls cracked. Buildings Type I cracked with some minor masonry falls. A few instances of damage to Buildings Type II. Unbraced parapets, unbraced brick gables, and architectural ornaments fall. Roofing tiles, especially ridge tiles may be dislodged. Many unreinforced domestic chimneys damaged, often falling from roofline. A few instances of damage to brick veneers and plaster or cement-based linings. Environment Water made turbid by stirred up mud. Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings. Instances of settlement of unconsolidated or wet, or weak soils. Some fine cracks appear in sloping ground. A few instances of liquefaction (i.e., small water and sand ejections).
MM 8	People Alarm may approach panic. Steering of motorcars greatly affected. Structures Buildings Type I heavily damaged, some collapse. Buildings Type II damaged, some with partial collapse. Buildings Type III damaged in some cases. A few instances of damage to Structures Type IV. Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down. Some pre-1965 infill masonry panels damaged. A few post-1980 brick veneers damaged. Decayed timber piles of houses damaged. Houses not secured to foundations may move. Most unreinforced domestic chimneys damaged, some below roofline, many brought down. Environment Cracks appear on steep slopes and in wet ground. Small to moderate slides in roadside cuttings and unsupported excavations. Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes, etc.
MM 9	Structures Many Buildings Type I destroyed. Buildings Type II heavily damaged, some collapse. Buildings Type III damaged, some with partial collapse. Structures Type IV damaged in some cases, some with flexible frames seriously damaged. Damage or permanent distortion to some Structures Type V. Houses not secured to foundations shifted off. Brick veneers fall and expose frames. Environment Cracking of ground conspicuous. Land sliding general on steep slopes. Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, lakes, etc.
MM 10	Structures Most Buildings Type I destroyed. Many Buildings Type II destroyed. Buildings Type III heavily damaged, some collapse. Structures Type IV damaged, some with partial collapse. Structures Type V moderately damaged, but few partial collapses. A few instances of damage to Structures Type VI. Some well-built timber buildings moderately damaged (excluding damage from falling chimneys). Environment Land sliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes. Landslide dams may be formed. Liquefaction effects widespread and severe.

Table A-1 cont.: Modified Mercalli Scale from Dowrick (1996)

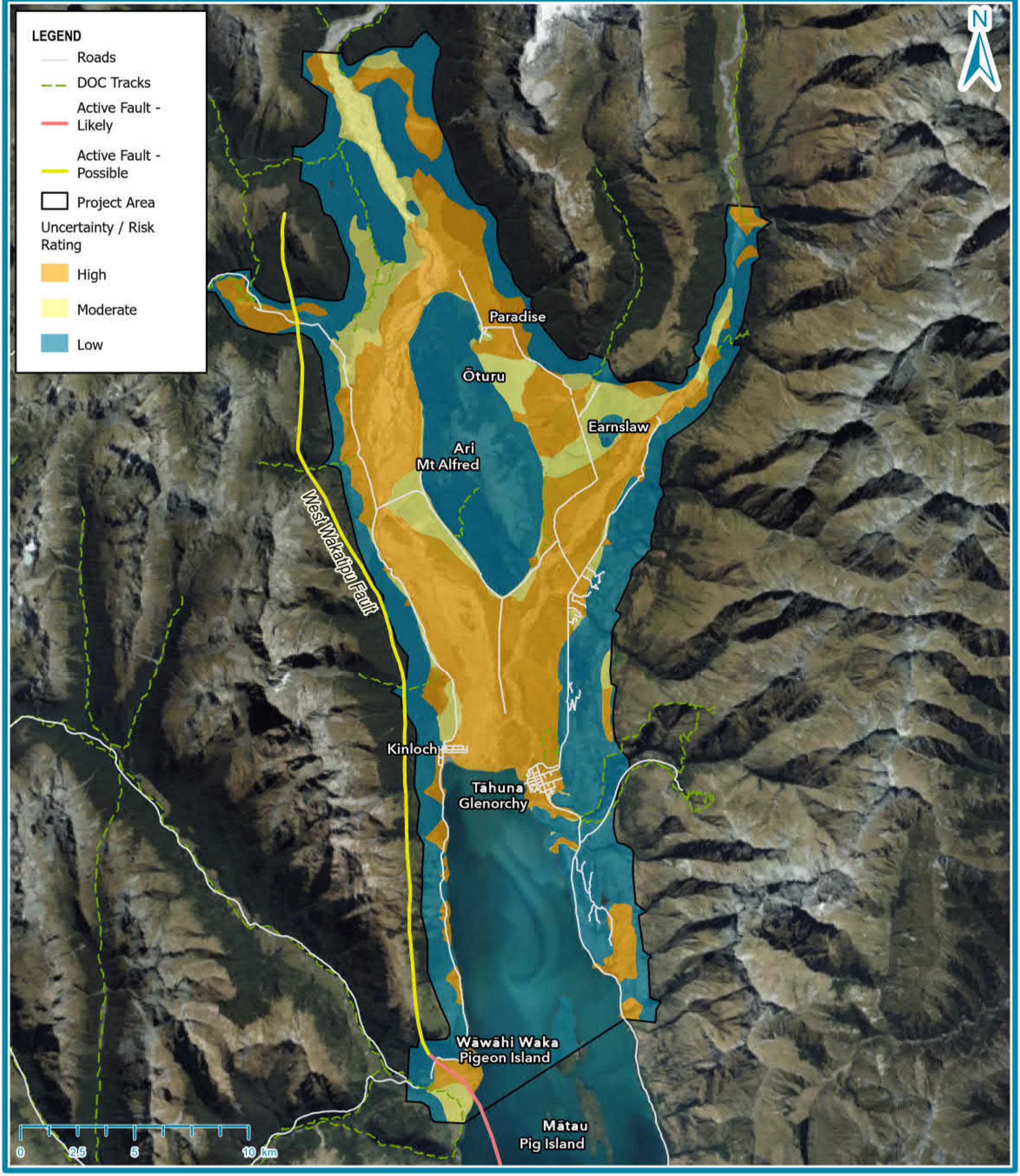
Level	Description
MM 11	Structures Most Buildings Type II destroyed. Many Buildings Type III destroyed. Structures Type IV heavily damaged, some collapse. Structures Type V damaged, some with partial collapse. Structures Type VI suffer minor damage, a few moderately damaged.
MM 12	Structures Most Buildings Type III destroyed. Structures Type IV heavily damaged, some collapse. Structures Type V damaged, some with partial collapse. Structures Type VI suffer minor damage, a few moderately damaged.

Appendix E: Risk Map

- T+T, 2021

Head of Lake Wakatipu Natural Hazards Adaptation

Natural Hazard Uncertainty And Risk Rating



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🟧 High uncertainty / risk includes areas within: Floodplain, active alluvial fans, 312m lake level rise and avulsion of the Rees River.

🟨 Moderate uncertainty / risk includes areas within: Inactive alluvial fans and areas where liquefaction is possible.

Basemap sourced from Eagle Technology, Land Information New Zealand, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, FAO, METI/NASA, USGS

Appendix F: Glenorchy

- Adapted from Evidence of Professor James Brasington to QLDC Resource Consent Hearing for proposed Blackthorn Hotel, December 2020

Glenorchy flood hazard

We know what flooding looks like in Glenorchy from documented flood events in 1999 and 2020 (refer Photos 1 and 2).

Photo 1 Flooding in Glenorchy, November 1999 (ORC)

Photo 2 Flooding in Glenorchy, February 2020 (ORC)

There are various flood protection works to reduce the extent of inundation, along the Dart and Rees Rivers as shown in Figure Appendix F.1, and in Glenorchy to protect developed land as shown in Figure Appendix F.2.

Figure Appendix F.1: Dart and Rees River active channels and flood protection works

Figure Appendix F.2: Glenorchy flood protection structures, i.e., stop banks (ORC)

Flooding from the Rees River

Flooding from the Rees River also poses a credible hazard to the township of Glenorchy.

Evaluating the risk of flooding from the Rees is subject to significant uncertainty given the absence of a river flow record and more significantly, due to the long-term and continuing aggradation of the channel bed.

Flooding affecting parts of Glenorchy are possible through three main mechanisms:

- Failure of the left bank stop bank, downstream of the Lagoon Creek confluence.
- Backwater flooding driven by high lake levels and/or aggradation of the channel bed.
- A major avulsion of the Rees River triggered by channel bed aggradation, reorientating the principal flow of the Rees towards the true left (eastern) side of the valley, and overwhelming the existing stop bank.

Stop bank Failure

The town is protected by an earthen stop bank along its northern perimeter (WSP, 2020). The lower section of this stop bank, a c. 250 m length from Lagoon Creek to the delta, lies along the true left of the current principal branch of the Rees River (refer figure 6-7).

A site inspection on 4 June 2020 revealed the main flow of the Rees hard against the stop bank and evidence of undercutting and minor slope failures along this section of the stop bank. It does not appear to be armoured. These findings have subsequently been endorsed by a recent review of the stop bank condition by WSP (2020).

The observed steepening of the flood bank could induce slumping or rotational failures that lead to a progressive breach of the stop bank during high flows. The lack of armouring is likely to lead to a rapid expansion of any breach and steep ingress of floodwaters behind the stop bank.

There are a number of properties immediately behind this section of the stop bank on Butement and Jetty Street that would be directly affected by a breach during a high flow event. The low-lying topography parallel to the river and behind the stop bank may serve to provide a conduit for flood waters, diverting them away from particular areas and into the lake.

However, further hydraulic modelling is needed to evaluate this risk robustly. This is justified as, unlike backwater flooding, a breach may generate high velocity floodwaters that pose a direct threat to life and significant erosive potential.

Backwater Flooding

Significant flooding occurred in Glenorchy on the afternoon of 4 February 2020, during a region-wide high flow event. During this event, floodwaters inundated the Glenorchy recreation ground and golf course before flowing along the northern perimeter of the town. This caused flooding of residential areas at the northern ends of Oban and Argyle Streets and along much of Butement Street, resulting in damage to a number of properties.

Floodwaters were also recorded on mobile devices. Including that, shown in video footage, and posted online (https://crux.org.nz/community/glenorchy-homes-evacuated-qtown-lake-level-critical).

The GeoSolve (2020) report and the report by PDP (2020) commissioned by the ORC, reviewed this event in connection to the likelihood of flooding affecting particular areas. Both reports conclude that elevated water levels on Lagoon Creek caused overtopping of the stop bank in the vicinity of the golf course, near to the DoC bridge and the Glenorchy-Paradise road. The GeoSolve report shows a map indicating the inundated area (refer Figure 4 of GeoSolve 2020) implying that floodwaters returned to the lake without impacting some specific areas. This is inconsistent with observations.

Overtopping this section of stop bank is an established hazard identified in the URS (2007b) flood hazard assessment. Such flooding may occur in association with either high flows from an avulsion of the Rees directing a significant flow through the lagoon or through backwater flooding along Lagoon Creek caused by elevating the level of its outfall into the Rees River/Lake.

The GeoSolve report identifies the coincidence of the flood with a high and rising lake level (RL 310.8 m rising to RL 311.3 m) to explain the chain of events leading to overtopping the stop bank. Briefly, the high lake stand elevates the flood level of the Rees, which in turn impedes the drainage of Lagoon Creek propagating a backwater effect that raises the Creek above a depression in the stop bank crest at RL 312.3 m upstream.

Drawing on the URS (2007b) flood hazard study, the GeoSolve report goes further and restates the conclusion of the URS (2007b) study, that 'flood events in the Rees and Dart Rivers will only cause a flood hazard at Glenorchy if there is a coincident high lake level'.

To consolidate this position, the report draws on a comparison between the 4 February 2020 flood and another event in March 2019, when the Dart River was recorded at an even higher discharge. In this event, the lake was at a low stage of RL 309.9 m and no flooding was observed in the town. While superficially compelling, this comparison assumes a simple and consistent correlation between flows on the Dart and Rees that is not supported by data and fails to account for significant differences in the meso-climatology of the region.

The discharge or water level of the Rees River is not currently gauged routinely. A short (approximately 20-month) record of 15-minute river flows is, however, available for the period September 2009 to March 2011, based on a rated section close to Invincible Mine.

A comparison of the overlapping 15-minute discharge records from this site and the Dart at the Hillocks is shown in Figure Appendix F.3.

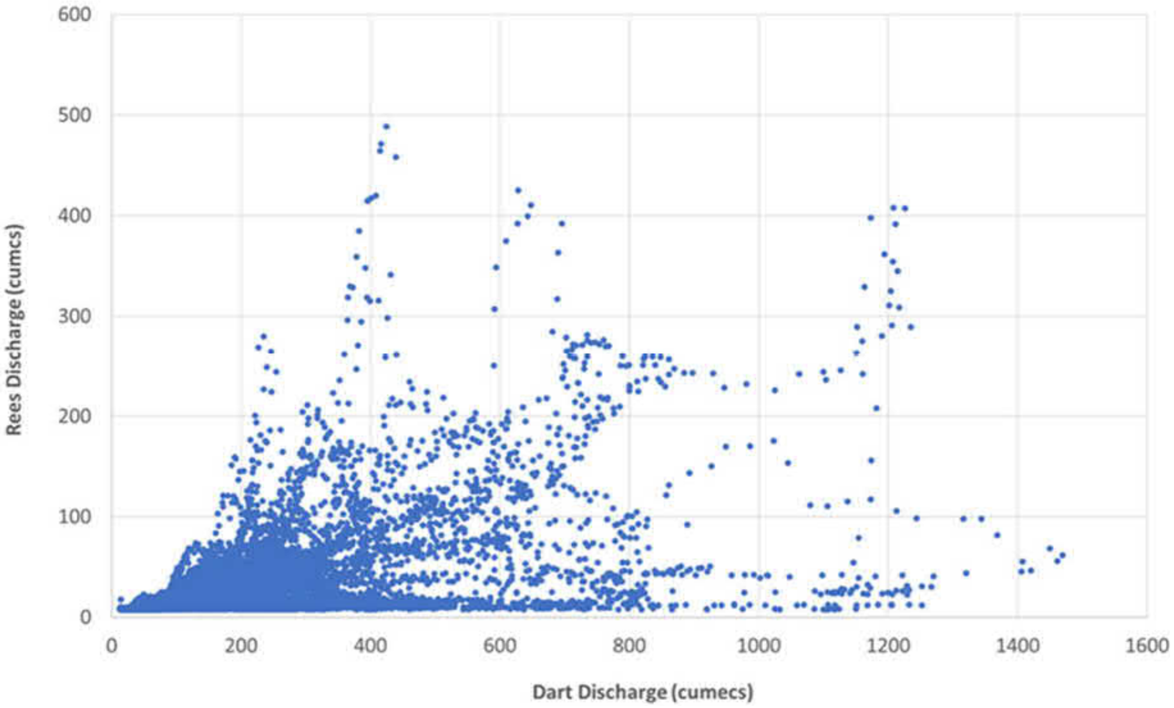

Figure Appendix F.3: Scatterplot showing the correlation between the discharge (river flow) of Dart and Rees Rivers between September 2009-March 2011 (Brasington 2020c)

This reveals significant scatter in the relationship, with high flow events in both catchments that are poorly correlated with their neighbour. This pattern reflects differences in the meteorological (synoptic) conditions that generate floods in the two catchments and renders the simple comparison of February 2020 and March 2019 events fundamentally insecure.

This observation does not however, falsify the hypothesis that flooding from Lagoon Creek is linked to the level of the lake. Nonetheless, it does raise the possibility of alternative process drivers that may also explain the observed backwater flooding.

The PDP (2020) report highlights another potential contributory cause of backwater condition, aggradation of Rees River. High rates of sediment supply to the delta have led to a progressive increase in the mean bed level of the Rees over the last century, a pattern expected only to intensify in the coming decades. Aggradation of the Rees River will reduce its flood capacity, raising the flood level for a given discharge. These elevated flows will effectively trap flows from the Lagoon, leading to a pattern of backwater flooding that is also consistent with observations on 4 February 2020.

During a visit to Glenorchy on the 4 June 2020 when the lake level was at RL 309.7 m and the Rees River in winter low flow conditions, water could be seen backing up Lagoon Creek. This pattern appears to be linked to the growth and progradation of a bar along the true left of the active channel of the Rees which was impeding drainage of Lagoon Creek and will also reduce channel capacity of the Rees during floods. Evidence of backwater conditions in Lagoon Creek at low flow is also consistent with persistent, unusually high-water levels observed in the Glenorchy Lagoon since 2017 (ORC, 2020), which appear to be independent of the level of the Lake.

These two drivers of flood risk, high lake levels and aggradation, should not be seen as mutually exclusive explanations of backwater flooding. Importantly, however, the long-term trend of aggradation creates a continuously elevating (non-stationary) baseline against which the risk of future events should be assessed.

The probability of coincident high flows on the Rees and high lake stands is also likely to increase due to the elevated frequency and magnitude of high precipitation and winter flood events (NIWA, 2019).

Despite the likelihood of continuing and increasingly frequent floods, similar and potentially more severe than that observed in February 2020, it is unlikely that such a flood generating mechanism will inundate those parts of Glenorchy above RL 313 m. There will, however, be the potential for significant flooding around the lower-lying areas as was observed in February 2020. The PDP (2020) report concludes that there is uncertainty over the depth of such flooding, but that should it exceed 1 m, it will pose a hazard to human life.

Morphology

Like Franz Josef, the bed of the lower reaches of the Rees River are aggrading and will at some stage become higher than the lower parts of the subject site at Glenorchy. On current aggradation rate the riverbed is predicted to be 0.7 m to 1.0 m higher in the next 100 years. In addition to water, the Dart and Rees Rivers have the potential to both erode and deposit significant quantities of material from and on the alluvial deposits on which Kinloch and Glenorchy are located. Brasington also considers that there is potential for the Rees River to avulse from its present course, erode its current banks (and any flood defences) and inundate the lower lying areas of Glenorchy. This is clearly plausible, and the potential for realignment of the main Rees River channel to the true left bank some distance upstream of the delta and township must be considered as realistic and a valid inundation scenario, though maybe not typically included in conventional flood risk assessments.

Flooding and Debris Flows from the Buckler Burn

Some parts of the Project area, including parts of Glenorchy are underlain by alluvial and colluvial fan sediments deposited from the Buckler Burn (GNS Science, 2009), clearly indicating historic flood and debris flow activity affecting these areas.

There is potential for catastrophic flooding from the Buckler Burn associated the formation and subsequent breaching of a landslide dam (or multiple dams) in its deeply incised catchment and from debris-laden floods driven by gravity.

For Glenorchy, GeoSolve (2020) presented numerical simulations based on the established RAMMS (Rapid Mass Movement Simulation) software. These are designed to quantify the hazards associated with a plausible range of landslide dam and debris flow scenarios. Despite evidence from sedimentary record underlying the site, the results of these simulations are used to suggest that gravity driven floods pose little risk to most of Glenorchy.

However, limited detail describing the design of the model simulations and physically anomalous simulation results (very steep, high (8 m to 10 m) depositional fronts) raise questions over the credibility of the model simulations presented.

These concerns have also been raised by Tonkin + Taylor (2020) but have not been addressed in the final GeoSolve report (2020b). Further modelling is required to address the anomalous results and to demonstrate that catastrophic debris flows do not pose a hazard to parts of Glenorchy.

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