Milford Opportunities

MILFORD OPPORTUNITIES PROJECT NATURAL HAZARD ASSESSMENT

PART B: BASIC RISK ASSESSMENT

11 JUNE 2024

CONFIDENTIAL

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Milford Opportunities

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EXECUTIVE SUMMARY

The Milford Opportunities Project aims to develop the visitor experience of the Milford Road and Milford Sound Piopiotahi located in the Te Rua-o-Te-Moko Fiordland National Park, New Zealand. The Milford Opportunities Master Plan includes the development of several key nodes, short stops, and walking/biking tracks located between Te Anau and Milford Sound Piopiotahi.

This Stage 3 phase of work follows the Stage 2 works completed by others. The objective of this Stage 3 work is to complete a natural hazard risk assessment for the MOP sites to further understand and assess the associated natural hazard risks and assess the feasibility of the MOP proposals. Stage 3, which includes this report, has been further divided into Part A (preliminary screening analysis), Part B (basic level risk analysis), and Part C (advanced risk analysis) – if deemed necessary.

This report builds on the preliminary risk assessment (WSP, 11 March 2024) and presents the results of the completed basic risk analysis (Part B). The preliminary risk assessment (Part A) highlighted 15 key nodes and short stops, and 12 walking/cycling tracks requiring further risk assessment (sites greater than or equal to Class 2). This Part B report further analyses the risks at each of these sites.

This report adopts the basic level risk analysis methodology as outlined in the GNS guidelines for completing natural hazard risk analysis on public conservation lands and waters ('GNS guidelines'). A basic level risk analysis has been completed for tsunami and landslide hazards to calculate the individual fatality risk to visitors per day (IRPD) and annual individual fatality risk (AIFR) to workers at each site. A most likely and maximum credible hazard event has been assessed for tsunami and landslides. Visitor and worker risk has been compared to existing risk tolerability criteria developed by the Department of Conservation.

TSUNAMI INDIVIDUAL RISK

Figure 1 below illustrates the calculated IRPD for visitors to nodes and short stops exposed to tsunami hazard. Due to the scale of likely landslide-induced tsunami waves in Milford Sound Piopiotahi, MOP sites in Milford Sound Piopiotahi have been grouped. Visitor risk for tsunami hazard has been determined to be 'moderate' to 'substantial' for Milford Sound Piopiotahi. This is due to the high probability of occurrence and impact of a landslide-induced tsunami in the Milford Sound Basin and prolonged visitor exposure. Landslides that cause tsunami in these environments are most likely triggered by earthquakes.

Ōtāpara Cascade Creek has been identified as a site potentially exposed to landslide-induced tsunami from Lake Gunn. For this site, tsunami risk is considered to be 'low'.

The figures presented below indicate assessed risk as a range which considers both the most likely and maximum credible event.

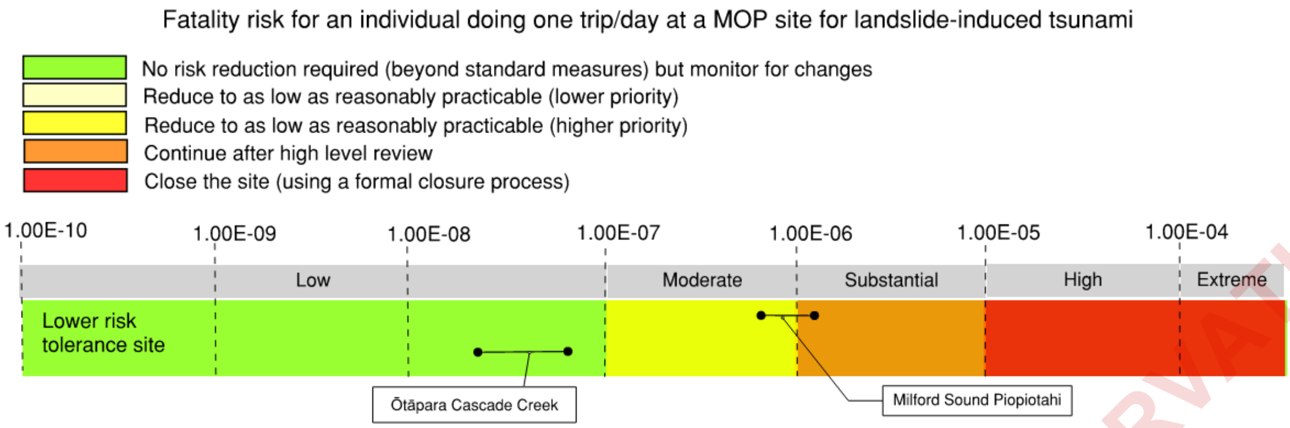

Figure 1: Calculated tsunami risk for visitors at the Milford Opportunities Project (MOP) sites. The calculated risk values are compared to the Department of Conservation (DOC) risk tolerability criteria and mitigation recommendations for lower risk tolerance sites (DOC, 2023).

For workers, AIFR for landslide-induced tsunami was estimated to be 'substantial' in Milford Sound Piopiotahi and 'low' to 'moderate' at Ōtāpara Cascade Creek. This is higher than visitor risk due to the regular exposure of workers to hazards throughout a year of working in the study area.

The Alpine Fault is potential trigger for landslide-induced tsunami in Milford Sound Piopiotahi. A 1:150-year return interval for Alpine-Fault-triggered landslide tsunami is estimated and has been used to calculate the individual risk in Milford Sound Piopiotahi. Due to the high cumulative probability of an Alpine Fault event, visitor and worker risk was estimated to be 'high'.

LANDSLIDE INDIVIDUAL RISK

Figure 2 presented below illustrates the estimated IRPD for visitors at MOP short stops and nodes exposed to landslide hazards. Visitor risk is assessed as 'substantial' to 'high' for the Freshwater Basin and Te Huakaue Knobs Flat, 'moderate' to 'high' for Ōtāpara Cascade Creek, the Divide, and Gertrude Valley, 'moderate' to 'substantial' for Countess Range Hut, and Visitor Hub, 'low' to 'substantial' for Milford Sound Lodge and Whakatipu Trails Head, and 'low' to 'moderate' for the Chasm.

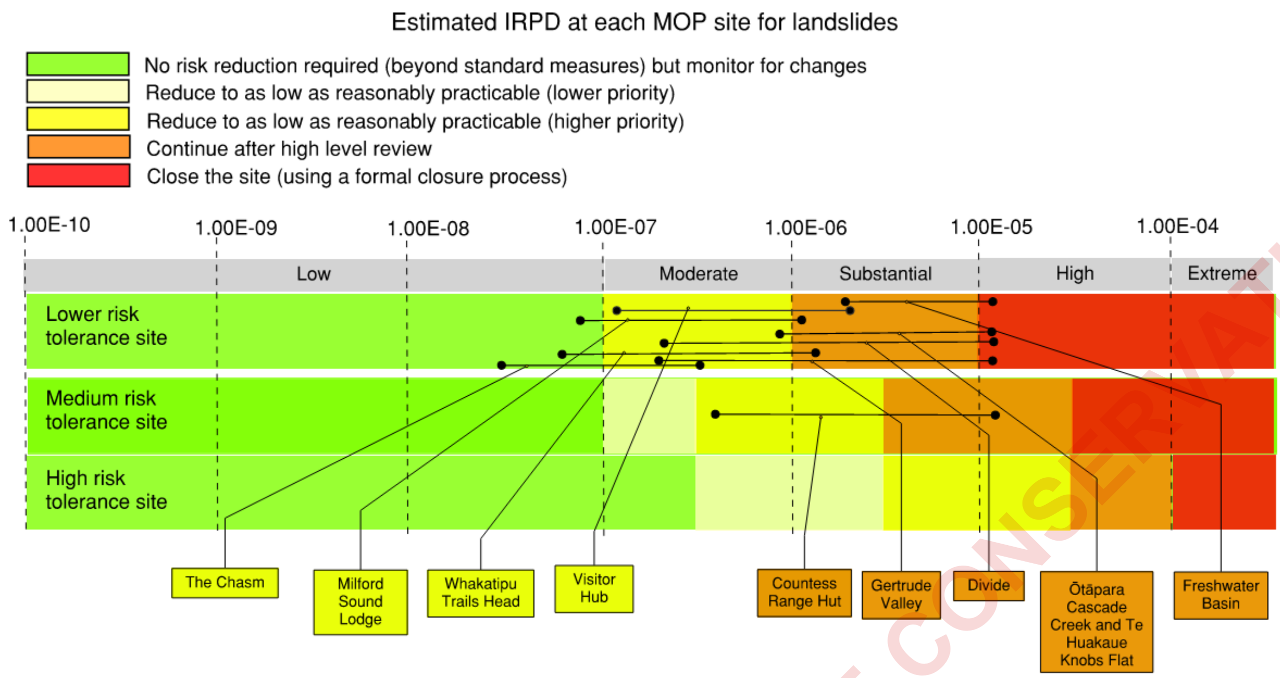

Figure 2: Calculated landslide risk for visitors at MOP sites for the most likely landslide event. The calculated risk values are compared to the DOC risk tolerability criteria and mitigation recommendations for lower, medium, and high-risk tolerance sites (DOC, 2023).

For workers, AIFR for landslides has been estimated to be 'high' for Freshwater Basin, 'moderate' to 'high' for Visitor Hub, the Divide, and Gertrude Valley, and 'moderate' to 'substantial' for Milford Sound Lodge, Little Tahiti, Countess Range Hut, Te Huakaue Knobs Flat, Ōtāpara Cascade Creek, the Chasm, and Whakatipu Trails Head.

SOCIETAL RISK

For societal risk, annual probable lives lost (APLL) and expected number of fatalities have been estimated for the most likely and maximum credible tsunami and landslide events under certain population-at-risk scenarios.

For tsunami, the most likely event considers a ~1:1000-year landslide-induced tsunami wave with a 6.3 m runup at the Cleddau Delta while the maximum credible event considers a ~1:17,000-year landslide-induced tsunami wave with a 45.9 m runup at the Cleddau Delta.

To illustrate the cumulative risk of an Alpine Fault-triggered tsunami in Milford Sound Piopiotahi, societal risk has also been calculated. This event considers a ~1:150-year landslide-induced tsunami event with a 5 m runup at the Cleddau Delta.

For the most likely (MLE), maximum credible (MCE), and Alpine Fault tsunami event in Milford Sound Piopiotahi:

- When the population at risk is 1 (estimated to be 100% of the time in Milford Sound Piopiotahi), we estimate there to be no fatalities for the Alpine Fault event, and 1 fatality for the MCE and MLE.
- When the population at risk is 50 (estimated to be 100% of the time in Milford Sound Piopiotahi), we estimate there to be 21 fatalities for the Alpine Fault event, 28 fatalities for the MLE, and 45 fatalities for the MCE.

- When the population at risk is 2000 (estimated to be 16.7% of the time in Milford Sound Piopiotahi – during daytime, high season), we estimate there to be 840 fatalities for the Alpine Fault event, 1120 fatalities for the MLE, and 1800 fatalities for the MCE.
- When the population at risk is 3000 (estimated to be 16.7% of the time in Milford Sound Piopiotahi – during daytime high season – projected numbers in 2050), we estimate there to be 1260 fatalities for the Alpine Fault event, 1680 fatalities for the MLE, and 2700 fatalities for the MCE.

For the most likely and maximum credible landslide event at each MOP site:

- When the population at risk is 1 at each site, we estimate there to be no fatalities at any site for the MLE and 1 fatality at most sites for the MCE.
- When the population at risk is 5 at each site, we estimate there to be 1 fatality at Freshwater Basin for the MLE and some fatalities (2-7) at most sites for the MCE.
- When the population at risk is 40 at each site, we estimate there to be some fatalities (2-7) at most sites for the MLE and multiple fatalities (10-40) at all sites for the MCE.

It should be noted that there are a number of scenarios that result in likely fatality from a tsunami event. It is conceivable that events smaller than the MLE may also occur.

TRACKS AND TRAILS

Tracks and trails as part of the MOP have also been assessed in terms of visitor and worker fatality risk.

For tsunami, tracks in Milford Sound Piopiotahi near the shoreline (Cleddau Delta walking tracks, Hine-te-awa Lower Bowen Falls Track) visitor and worker exposure is potentially less than at point sites; however, the risk is still considered to be 'moderate' to 'substantial'.

The Milford Sound Lodge to Tutoko River Suspension Bridge Track is likely to be impacted only by the largest tsunami events and anticipated exposure is assessed as low. Hence, tsunami risk here is considered to be 'low'.

Figure 3 presented below shows the estimated IRPD for visitors at MOP tracks exposed to landslide hazards.

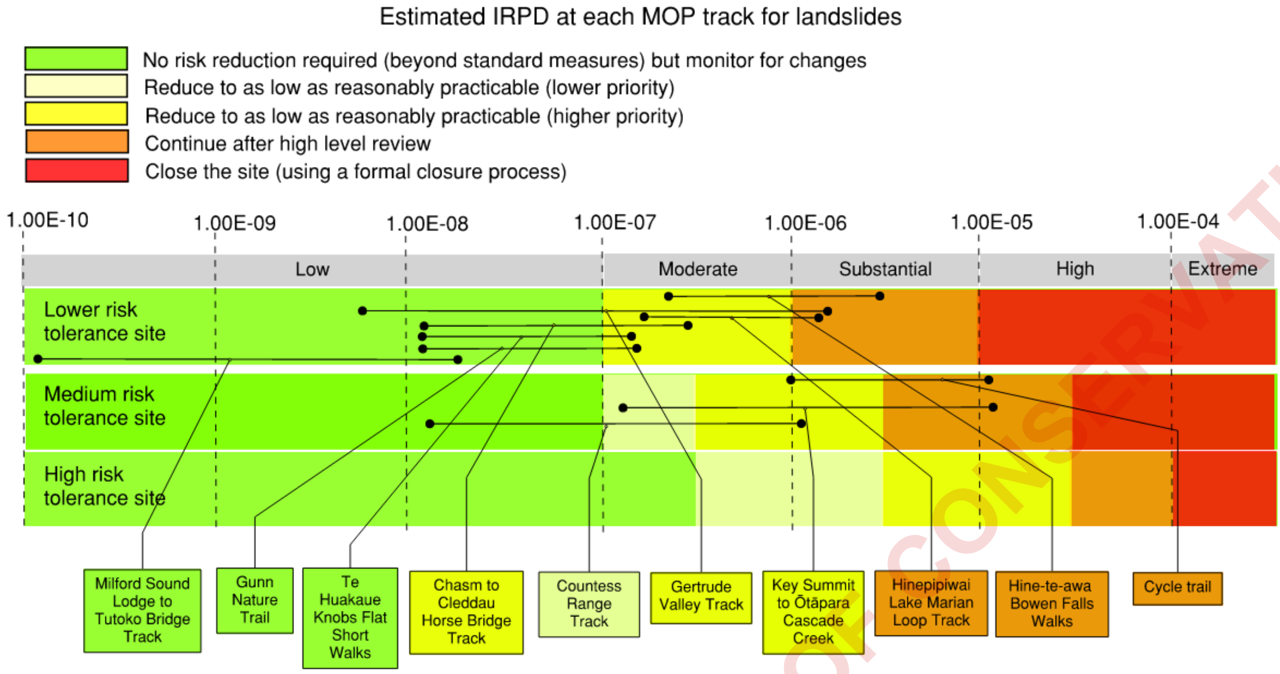

Figure 3: Calculated landslide risk for visitors at MOP walking and cycling tracks. The calculated risk values are compared to the DOC risk tolerability criteria and mitigation recommendations for lower and medium risk tolerance sites.

RISK MITIGATION

This report describes significant tsunami risk in Milford Sound Piopiotahi.

Potential tsunami risk mitigation options at sites could include clear and coordinated evacuation planning, increasing evacuation points and routes, education and early warning systems, and vertical evacuation structures. These will need to be explored and developed further through detailed design and consultation. It should be noted that quick first-wave arrival time (2 to 7 minutes) hinders evacuation, early warning systems, and vertical evacuation structures as practical mitigation options.

Potential risk mitigation at sites exposed to landslides includes education, avoidance, increasing signage, bunds, catch ditches, and the development of rockfall barriers. Design of mitigation should be informed by computational modelling of landslide hazard.

Flooding and avalanche hazards were identified at several sites in the Part A report. This report highlights that more information is required for plausible estimations of flood and avalanche risk at the MOP sites. However, in terms of the Stage 3 aims regarding feasibility, the identification of flood and avalanche hazards at the location of several MOP sites does not render the site proposals unfeasible.

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The purpose of the Milford Opportunities Project (MOP) is to develop a collaborative Master Plan for the Milford corridor and Milford Sound Piopiotahi sub-regional area to ensure:

> *"that Milford Sound Piopiotahi maintains its status as a key New Zealand visitor 'icon' and provides a 'world-class' visitor experience that is accessible, upholds the World Heritage status, national park and conservation values and adds value to Southland and New Zealand Inc."*

The Milford Opportunities Project (MOP) has engaged WSP New Zealand Limited (WSP) to undertake a natural hazard risk assessment for several key development sites located along the Milford Road in the Te Rua-o-Te-Moko Fiordland National Park, New Zealand. The purpose of the assessment is to assess the natural hazard risk at each site and determine the individual life risk posed to visitors and workers and determine if the proposals are potentially not feasible.

This natural hazard risk assessment adopts the approach as presented in the current GNS Guidelines for Natural Hazard Risk Analysis on Public Conservation Lands and Waters ('GNS Guidelines') as the basis for the assessment. The GNS Guidelines propose a multi-phase approach to assessing hazard risk including a Preliminary screening analysis, Basic risk analysis, and Advanced risk analysis.

1.2 WORKSTREAM OBJECTIVES

As part of the previous Stage 2 works Stantec and Boffa Miskell produced a report titled Hazards and Visitor Risk Review, dated March 2021. This previous report identified several natural hazards that were present along the MOP corridor that required further assessment and possible mitigation as part of the detailed design stage.

The key aim of this Stage 3 work is to build upon the previous review completed and develop the risk assessment to further refine and understand the occurrence and associated consequence of natural hazards previously identified. This will assist with establishing the technical feasibility of implementing the infrastructure proposals in the Masterplan.

The Stage 3 work, therefore, aims to further assess the footprint or occurrence of the key hazards concerning the proposed Nodes, Short stops, Tracks and Trails, and assess the individual risk of fatality in terms of temporal and spatial probability, adopting current recognised New Zealand methodologies and best practice.

The Stage 3 assessment will further assess the severity of natural hazard impacts on the MOP masterplan proposals and advise on future risk management strategies or further actions such as specific mitigation requirements where appropriate to do so.

The Stage 3 works will be reviewed by an expert technical review panel appointed by the Department of Conservation and MOP to ensure the identified critical risks are appropriately assessed and that recommendations made for future risk management or mitigation are appropriate and incorporated into the masterplan design considerations.

This natural hazard risk assessment underpins Stage 3 and builds on the analysis carried out by Stantec and Boffa Miskell in Stage 2.

The natural hazard risk assessment for Stage 3 is staged into three parts as follows:

- Part A: Preliminary screening analysis
- Part B: Basic risk analysis, and if deemed necessary,
- Part C: Advanced risk analysis (where appropriate).

This report builds on the work completed by WSP in Part A, Preliminary Screening Analysis.

Following the review of the Part A findings by the external peer review panel, the content of the Part B report was to be modified to the point where the feasibility of the Masterplan proposals could be established from a natural hazard risk to life perspective.

It was recognised that full Basic risk analysis and advanced assessments together with site-specific avalanche assessments would most likely be required for some of the sites as part of the detailed design stage but were not critical to the assessment of project feasibility (Stage 3).

As part of this stage of assessment, the proposed Masterplan sites have as part of this report now been further assessed in terms of the risks posed to life safety and societal risk that enable the feasibility of the proposals to be established.

Part C has at this stage of the assessment been assessed as "not required within the Stage 3 works".

1.3 PART A PRELIMINARY SCREENING ANALYSIS

WSP completed a preliminary risk screening analysis for nodes, short stops, and tracks in the Milford Opportunities Project (MOP) (WSP, 11 March 2024).

The Part A report identified sites exposed to landslide, tsunami, avalanche, and flooding hazards respectively.

For landslide and tsunami hazards, the report adopted the GNS Guidelines for Natural Hazard Risk Analysis (de Vilder & Massey, 2022a, 2022b, 2022c; Power & Burbidge, 2022) to estimate site hazard class at each site.

It was determined that sites identified as Class 1 did not require any further risk assessment. For sites Class 2 and above a Basic level of risk assessment was recommended. Table 1 below presents the sites identified as Class 2 or above in the preliminary screening analysis.

For avalanche and flooding hazards, further risk assessment was recommended in the Part A report. This could include Avalanche Hazard Index (AHI), Avalanche Terrain Exposure Scale (ATES), and flood modelling risk assessments. Table 2 below presents the sites where avalanche and flooding hazards were identified.

For an overview of site location please refer to Appendix A.

Table 1: Sites (nodes/short stops and tracks) classified as Site Class 2, 3 or 3a for Landslide and Tsunami hazards.

Site Class	Landslide	Tsunami
Class 2	Nodes/Short Stops: Mackay Creek DOC Campsite, Deer Flat DOC Campsite, Countess Range Hut, Te Huakaue Knobs Flat, The Divide, Whakatipu Trails Head, Gertrude Valley, The Chasm, Little Tahiti, Milford, Sound Lodge, Visitor Hub, Freshwater Basin, Cleddau Delta, Deepwater Basin Tracks: Te Huakaue Knobs Flat Short Walks, Key Summit to Ōtāpara Cascade Creek, Hinepipiwai Lake Marian Falls Loop Track, Chasm to Cleddau Horse Bridge Track, Milford Sound Lodge to Tutoko River Bridge Track, Hine-te-awa Bowen Falls – Upper Walks.	Nodes/Short Stops: Ōtāpara Cascade Creek, Little Tahiti
Class 3	Nodes/Short Stops: Ōtāpara Cascade Creek Tracks: Countess Range Track, Gertrude Valley Loop Track, Hinepipiwai Lake Marian Loop Track, Te Anau Downs to The Divide Cycle Trails	Nodes/Short Stops: Milford Sound Lodge
Class 3(a)		Nodes/Short Stops: Visitor Hub, Freshwater Basin, Cleddau Delta, Deepwater Basin

Table 2: Sites identified as being exposed to Avalanche and Flooding hazards.

Hazard	Site
Avalanche	Gertrude Valley Node 6, Gertrude Valley Loop Track, The Chasm, Chasm to Cleddau Horse Bridge Track, Hinepipiwai Lake Marian Loop Track, Countess Range Hut, Countess Range Track
Flooding	Mackay Creek DOC Campsite, Deer Flat DOC Campsite, Te Huakaue Knobs Flat, Ōtāpara Cascade Creek, Whakatipu Trails Head, Gertrude Valley, The Chasm, Little Tahiti, Milford Sound Lodge, Cleddau Delta, Deepwater Basin

1.4 TECHNICAL FEEDBACK

As part of the development and completion of the Part A Screening Assessment Report, active involvement with the Peer Review panel has enabled key sites and hazards to be refined and the approach of the Part B Risk Assessment to be tailored to suit the objectives of the Stage 3 MOP project deliverables.

The results of the Stage 2 and Part A Preliminary Screening were discussed and assessed in terms of scope for completing Basic Risk Assessments. In addition, the approach for calculating Societal Risk and reporting, particularly with respect to tsunami hazard was also discussed and explored prior to completion of the report.

This report has been reviewed by an expert panel appointed by DOC and included specialist inputs from various natural hazard experts in developing the refined risk assessment methodology.

The feedback, observations and recommendations of the technical review panel have been incorporated into the approach and report presented.

2 DATA AND INFORMATION SOURCES

To assess natural hazard risk at each site a range of datasets have been adopted and interrogated to assess hazard footprints, likelihood of occurrence and consequence.

The Part A report (WSP, 11 March 2024), outlined several data sources used in the preliminary risk screening assessment. As this report presents the subsequent stage of the risk assessment process, these previously referenced sources are still considered relevant to this analysis.

Table 3 outlines the main data sources adopted in the Part B risk assessment.

Table 3: Key data sources adopted for the basic risk assessment.

Source	Dataset	Usage
1m DEM	Southland LiDAR 1m DEM (2020-2023)	Terrain Analysis
0.75m Aerial Photos	Southland 0.75m Rural Aerial Photos (2005-2011)	Hazard Mapping
Google Earth	Google Earth imagery and terrain	3D visualisation of hazards
GNS Science	Geological Map of New Zealand	Geology, landslide inventory
NZ landslides database	NZ landslides database	Landslide inventory
Homer tunnel vehicle count	MOP hazards and visitor risk review report	Exposure
Milford Road Avalanche Atlas	Avalanche Atlas MRA	Assessment of Avalanche collection areas and run-out areas
Mieler, D., Carey, J., King, A., Hancox, G., & Taig, T. (2014). *Framework for Assessing Life Risk to Road Users from Natural Hazards: A Pilot Methodology Using the Milford Road*. GNS Science.	Milford Road natural hazard risk assessment	Landslide hazard assessment
Harris, O. (2023). Agent-based Modelling of Evacuation Scenarios for a Landslide-Generate Tsunami in Milford Sound.	Modelling of evacuation scenarios for a landslide-generated tsunami in Milford Sound	Exposure
Dykstra, J. (2012). The post-LGM evolution of Milford Sound, Fiordland, New Zealand: Timing of ice retreat, the role of mass wasting & implications for hazards	Post Last Glacial Maximum (LGM) evolution of Milford Sound and implications for hazards	Landslide and tsunami hazard assessment

Source	Dataset	Usage
Taig, T., & McSaveney, M. (2015). *Milford Sound risk from landslide-generated tsunami.*	Milford Sound tsunami risk	Tsunami hazard assessment
MRA. (2023). *Avalanche Hazard Assessment for proposal sites along the Milford Road - Milford Opportunities Group*	Avalanche hazards assessment for MOP sites	Avalanche hazard assessment
Bogie, D. (2010). *Visitor Risk Management Applied to Avalanches in New Zealand.*	Guidance on avalanche hazard assessments in New Zealand	Avalanche hazard assessment
Taig, T. (2022). *Guidelines for DOC on dealing with Natural Hazard Risk*	Guidance report	Risk assessment framework
Cox, S. (2021). *Updated assessment of rock avalanche hazard and risk at Plateau Hut, Aoraki/Mount Cook National Park.* GNS Science.	Example risk report	Landslide risk assessment

3 SETTING

3.1 SITE DESCRIPTION

As previously reported and highlighted in the MOP masterplan (Stantec, 2021), the Milford Road (State Highway 94) from Te Anau to Milford Sound Piopiotahi is a scenic journey in Te Rua-o-Te-Moko Fiordland National Park, New Zealand. The 119 km highway travels through mountainous terrain with dense beech forest and steep glacial valleys with several tourist attractions along its length.

As part of the MOP seven key 'Nodes' have been identified, these are accompanied by short stops, walking/biking tracks, accommodation locations, and viewpoints (Figure 4 and Figure 5). These sites and the surrounding area are defined as the study area for this Stage 3 report.

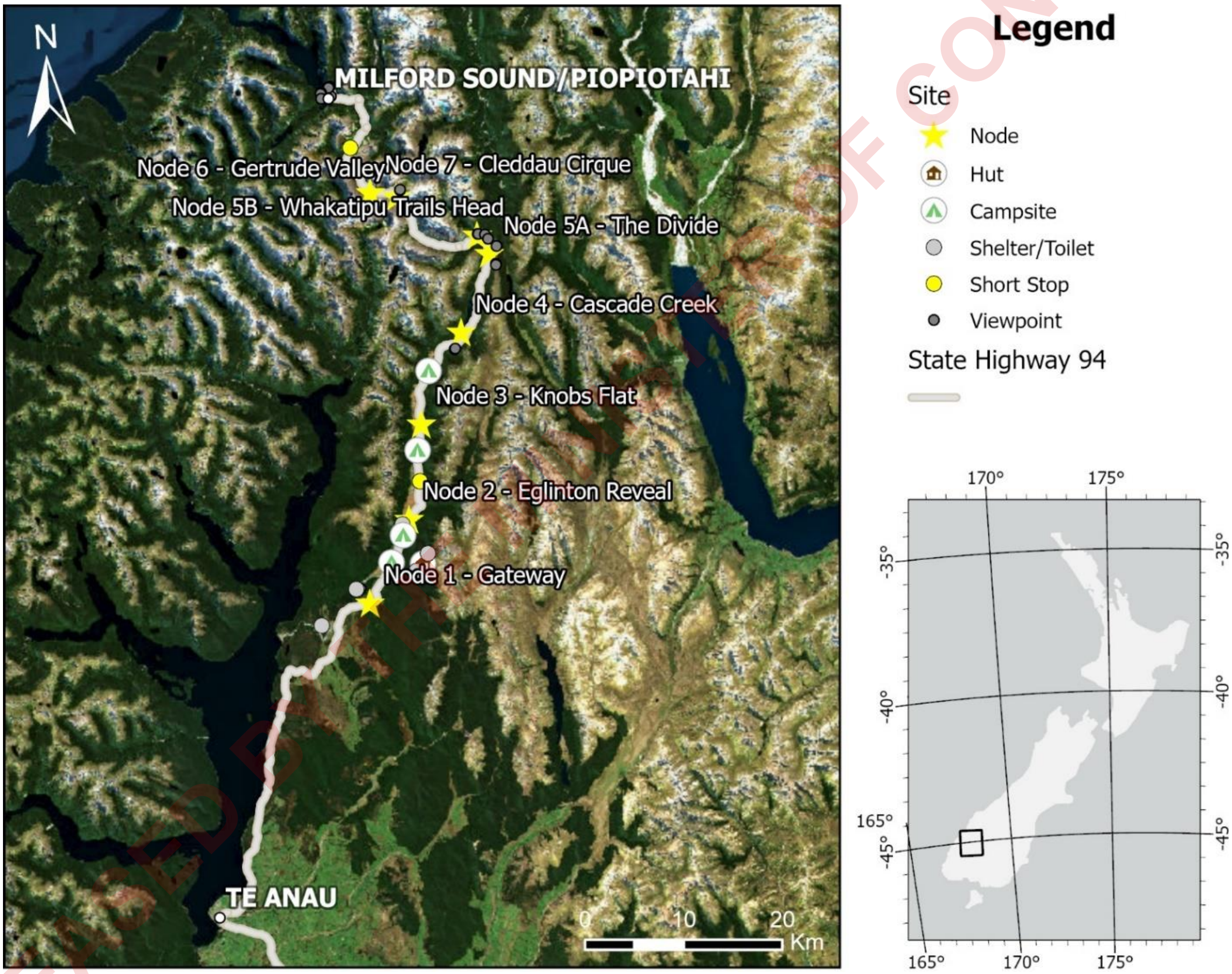

Figure 4: The Milford Road with key nodes and features of the Milford Opportunities Project labelled.

Figure 5: Milford Sound Piopiotahi sites under the MOP Master Plan (source: Stantec and Boffa Miskell).

3.2 GEOLOGICAL CONTEXT

Much of the Fiordland area is underlain by the plutonic rocks of the Median Batholith which formed due to repeated subduction along the southern margin of the ancient supercontinent Gondwana (GNS, 2010).

Fiordland separated from Gondwana in the middle to late Cretaceous and was uplifted as the Fiordland massif in the late Cenozoic. The Fiordland massif has been deeply eroded by Quaternary glaciers which have formed 'U' shaped valleys, steep mountain ranges, and deep Fiords throughout the region. Fiordland has a varied and complex present-day geology due to multiple phases of plutonism, volcanism, deformation and metamorphism, sedimentation, uplift, and glaciation.

Much of the tectonic movement in this region is associated with the Australian and Pacific plate boundary which forms the Puysegur Subduction Zone along the western margin of Fiordland (Figure 6). The associated Alpine Fault is a largely strike-slip fault that is located along this plate boundary and has been determined as being capable of producing large earthquakes above Magnitude 8.

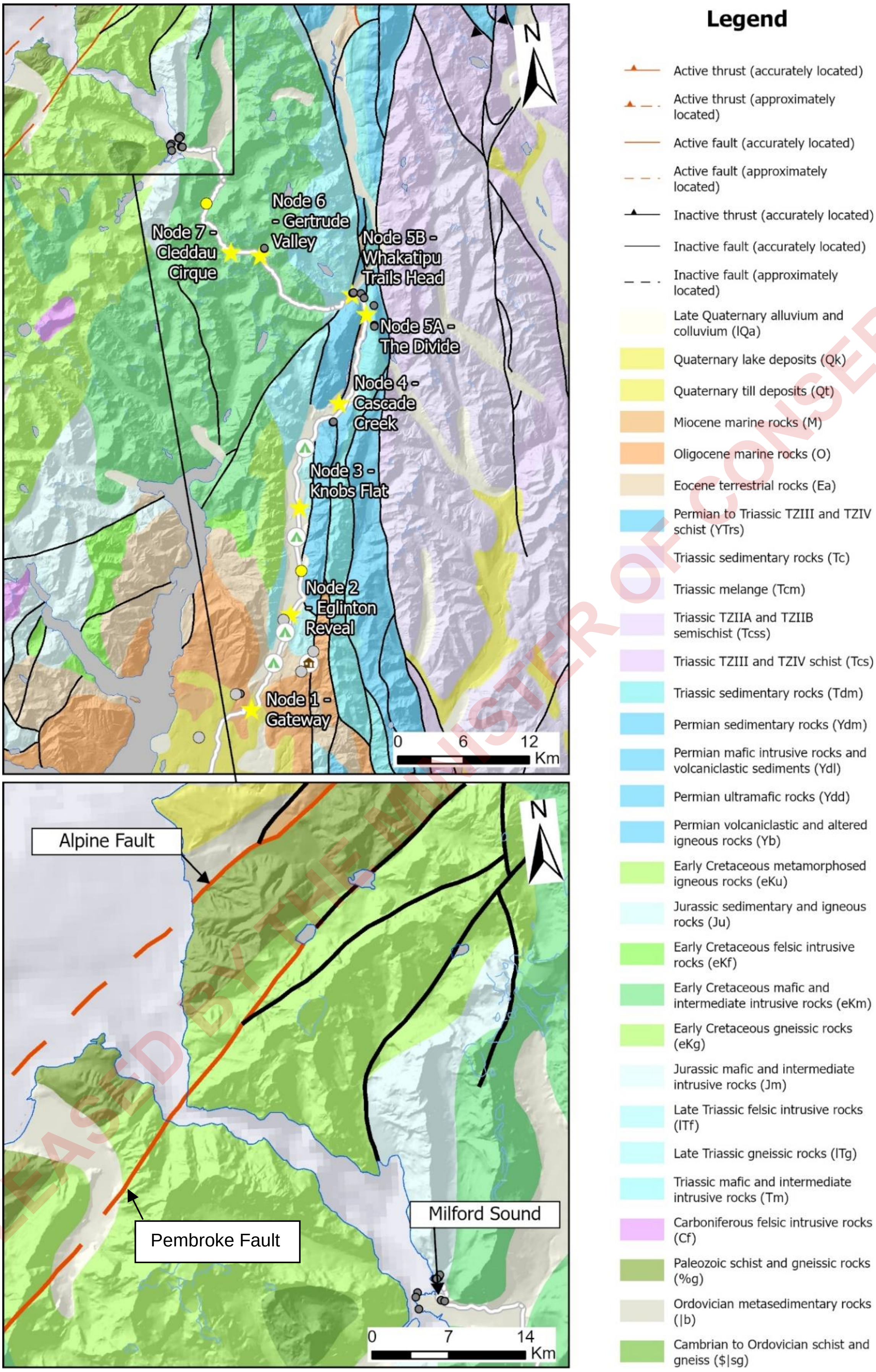

Figure 6: GNS 1:1M Geological Map of the study area with a zoomed-in inset map of Milford sound and the Alpine Fault (bottom).

3.3 NATURAL HAZARD OCCURRENCE

The Milford Road and surrounding area is well known for the occurrence of extensive, often large-scale natural hazards. These include landslides and rockfalls, tree slides, tsunami/seiche, snow avalanches, flooding/debris flows, earthquake shaking and liquefaction (Figure 7). Any of these hazards can have severe impacts on infrastructure, structures, wildlife and the environment and can pose a life risk to visitors and workers.

Many of the hazards in the study area are influenced by factors such as rock strength, geological defects, faults and seismic activity, precipitation and climate change.

3.3.1 LANDSLIDES

There have been numerous earthquakes in the Fiordland area in recent decades, ranging from infrequent large-magnitude events such as the 2009 Dusky Sound Mw 7.8 earthquake to frequent small-magnitude earthquakes distributed throughout the region.

Earthquake shaking may also trigger landslides and the size of landslide is strongly dependent upon magnitude, intensity and distance (GNS, 1997). The term 'landslide' incorporates many types of mass movement including rockfall, rock avalanche, and debris flow. The cumulative effect of a large shaking intensity earthquake may then also initiate avalanches, liquefaction effects and tsunamis or flooding.

The steep topography of the Milford area with slope angles generally steeper than 50° suggests that under high shaking intensities landslides are likely to occur.

The geology of the area also influences the potential for landslides to occur. In the Milford region, the geology is typically a hard igneous rock with limited colluvium cover. This restricts the nature of landsliding with tree sliding being the prevalent form of failure and the larger landslide or rock avalanche form of failure being driven by major discontinuities within the rock mass. The 1993 Mw 7 and 2009 Mw 7.8 earthquake resulted in only sparsely distributed small slides over the Fiordland area. Across much of Fiordland, landslides are more frequently triggered by intense periods of rainfall and snowmelt.

The study area receives an average annual rainfall of approximately 7 m with frequent intense periods of rainfall, wind, and snowfall. Precipitation and freeze/thaw cycles are known triggers for natural hazards including flooding and avalanches. Snow avalanche hazards are common along the Milford Road and tend to be prevalent at higher altitudes near the Homer Tunnel in winter months (May through to November), particularly during changeable weather fronts that deposit heavy snowfall and rain.

Figure 7: Hazards within the study area. Top left: Rock avalanche/landslide damage to Lake Howden Hut following a storm (source: Luke Bovill – Department of Conservation). Top right: Scouring of the Milford Road due to flooding (source: Dylan O'Neill/Waka Kotahi). Bottom left: The eastern portal of the Homer tunnel damaged by an avalanche (source: Conway et al. 2000). Bottom right: A damaged bridge on the Routeburn track due to flooding (source: Department of Conservation).

3.3.2 TSUNAMI

Milford Sound Piopiotahi is prone to both fault zone (seismic) initiated and landslide-induced tsunami due to its position on a low-lying area at the end of a steep Fiord within close proximity to the Alpine Fault and the Indian/Pacific plate boundary.

Tsunami wave heights are assessed using either the vertical deep-water wave amplitude (amplitude) or the vertical height of the wave above sea level at its furthest point inland (run-up).

Tsunami wave height increases as it approaches the shoreline and water becomes progressively shallower due to a wave shoaling process caused by the force from the seabed. Runup height (tsunami wave height at the shoreline with respect to bathymetry/topography) is a more useful metric when determining the extent of potential impact.

The Alpine Fault has been proven to produce large earthquakes capable of triggering landslide-induced tsunamis in Milford Sound Piopiotahi (Dykstra, 2012). The Alpine Fault is estimated to have a recurrence interval of approximately 300 years. The last Alpine fault event is estimated to have occurred in 1717 AD (AF8, 2024).

Based on the average recurrence interval it is estimated that in 2024 there is a 75% probability of an M8 Alpine Fault earthquake occurring within the next 50 years (AF8, 2024), for which there is a 44% probability of a landslide entering the Fiord (Taig & McSaveney, 2015). Therefore, the current likelihood for a landslide-induced tsunami in Milford Sound is about 1 in 150 years.

Work completed by Dykstra (2012) identified at least 18 very large post-glacial rock avalanche deposits blanketing the base of the Milford Sound fiord and a further 10 very large to giant terrestrial landslide deposits were mapped in the lower Milford Sound catchment. This work estimated tsunami maximum local run-up at the Cleddau Delta in Milford Sound to be circa 17 m. In this event, several thousand people in Milford Sound could be exposed to tsunami waves and much of the infrastructure would be at risk of total damage. Dykstra estimated the long-term life risk due to landslide-induced tsunami at Milford Sound as 0.38 deaths/year. Work completed by Taig and McSaveney (2015) estimated that for the Alpine Fault triggering a tsunami event, wave heights of 0.3-10 m and runup heights of 1.1 – 47 m can be expected at Freshwater Basin. Taig and McSaveney (2015) also established a relationship between wave amplitude and annual probability.

Submarine mass failures can also generate large displacement waves. Four submarine density flow generated-tsunami have been modelled for Milford Sound with maximum amplitudes of 0.7 – 9 m and runup heights of 0.1 – 43.2 m.

The 2021 National Tsunami Hazard Model (NTHM) for New Zealand (Power et al. 2023) identified that Milford Sound/Piopiotahi is also exposed to other sources of tsunami, namely the main Puysegur Subduction Zone and associated features. The NTHM concluded that the return interval of earthquake-generated tsunami wave amplitudes of 1-2 m at Milford Sound Piopiotahi from any fault source is approximately 100 - 200 years (Figure 8).

Lakes surrounded by steep and undulating terrain are also at risk of landslide-induced tsunami. In the study area, there are three Lakes (Lake Gunn, Lake Fergus, and Lake Marian) where the potential for landslide-induced lake tsunami may impact MOP sites. Very little work has been completed on these areas and potential wave heights and associated impacts are largely unknown.

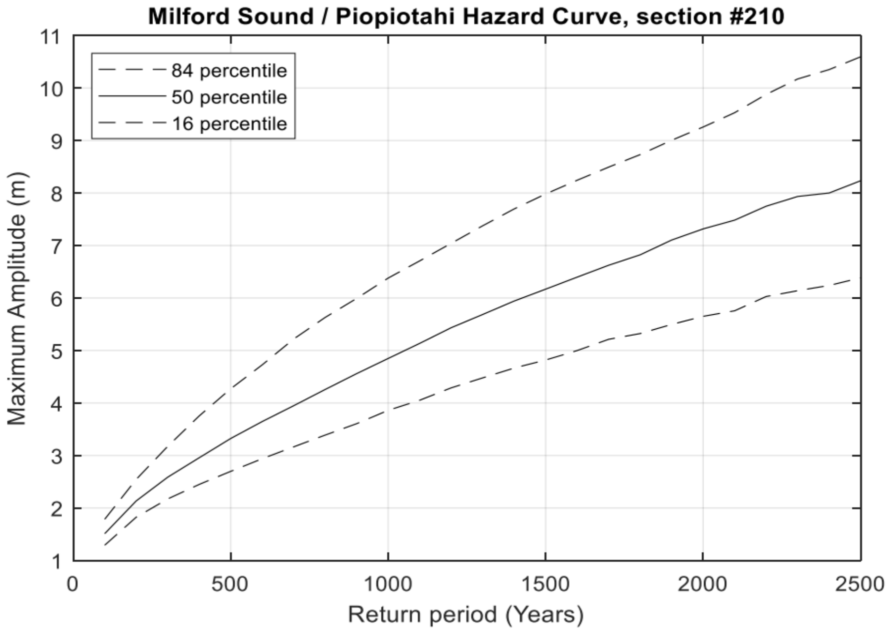

Figure 8: Return period of different earthquake-generated tsunami wave heights at Milford Sound Piopiotahi (source: GNS science 2021 National Tsunami Model).

4 STAGE 3 PART B RISK ASSESSMENT METHODOLOGY

4.1 QUALITATIVE ANALYSIS

4.1.1 SECONDARY SCREENING OF SITES

Following the submission of the Part A Preliminary Screening Analysis discussions were held with the appointed external peer review panel and MOP representatives regarding the key observations and conclusions of the report. As part of this review, the sites identified as Class 1 were confirmed as being of low-risk potential and it was accepted that no further risk assessment was deemed necessary for these sites.

The Class 1 sites therefore do not pose any unacceptable risks to the project feasibility assessment.

The identified Class 2, Class 3 and 3a sites however were assessed based on the worst-case scenario for hazard occurrence and consequence at the proposed development sites (both spot and linear sites).

For the Stage 3 Feasibility Assessment of the MOP, it was deemed necessary to first review the identified Class 2, Class 3, and Class 3(a) sites and complete a more detailed analysis of the hazard occurrence and identify any additional sites that could be re-assessed as Class 1, (i.e. those sites where only a limited footprint of a Class 2 hazard was identified or where mitigation and management practices are already in place).

This process allowed for a less sensitive review of the likely hazard class for linear and spot location sites alike and enabled a targeted approach to be adopted for those sites that exhibit a higher probability of occurrence or larger hazard footprint of Class 2, Class 3 or 3a hazard that could potentially impact the MOP proposals.

The hazard occurrence for each of the sites identified has therefore been reviewed using more detailed topographical data and satellite imagery in GIS to assess the hazard footprint and further documented reports and anecdotal information/experience in respect of the Masterplan proposal site location. A more detailed analysis of the temporal probability of exposure to refine the hazard class has then been completed.

The 1 m DEM for the Milford Road has been used to develop elevation, contour plans, hillshade models, and slope layers in ArcGIS Pro as part of the Part B assessment. Historical and recent satellite imagery together with past reports, newspaper articles and past experience has also been used to support the interpretation of hazard occurrences at each site.

Risk management procedures adopted by DOC and the MRA, including existing risk mitigation plans and policies, have also been used to interpret hazard exposure, vulnerability and management processes and procedures already in place at each site.

The results of the review are presented in Section 5.1.1

4.2 SEMI-QUANTITATIVE ANALYSIS

4.2.1 OVERVIEW

Risk can be defined as the probability and severity of an adverse effect on life, health, property, or the environment. For natural hazard risk assessment, risk is a combination of hazard likelihood, vulnerability, and exposure, where vulnerability and exposure are defined as the time spent by an individual or group of people located within a hazard-prone area and the probability of fatality if a given hazard was to occur.

A separate semi-quantitative analysis of fatality risk has been completed for tsunami and landslide (including rockfall and debris flow) hazards. The main reason for this is the different scale of impact in terms of the affected area and the number of people at risk from any particular event.

The risk analysis was intended to follow the basic level risk assessment framework as outlined in the GNS Guidelines for Natural Hazard Risk on Conservation Lands and Waters Part 3 (de Vilder & Massey, 2022b) and Part 5 (Power & Burbridge 2022). Due to the large scope and time constraints of the assessment, a simplified risk assessment approach was agreed with MOP and the peer review panel. The reader is therefore referred to the GNS guidelines for detailed methods and definitions of inputs, specifically prepared for DOC assets (de Vilder & Massey, 2022b).

Three risk metrics have been used in this assessment to quantify natural hazard risk at each site with respect to *visitors, workers, and groups* (societal risk). Risk metrics have then been compared to existing risk tolerability criteria for sites in similar risk contexts. The risk metrics and risk tolerability criteria adopted in this assessment are outlined in the following sections.

The results of the semi-quantitative analysis have then been used to discuss areas of significant risk and used to aid in the identification of potential risk mitigation strategies for further consideration of subsequent stages of the MOP.

4.2.2 RISK METRICS

This Part B report adopts the following equation to define and calculate the annual probability that a person may lose their life:

$$P_{(LOL)} = P_{(H)} \times P_{(T:H)} \times P_{(S:T)} \times V_{(D:T)}$$

where:

- $P_{(LOL)}$ is the annual probability that a person will be killed.
- $P_{(H)}$ is the annual probability of a hazardous event occurring.
- $P_{(T:H)}$ is the spatial probability of impact on the site from a hazard. For landslides, this is referred to as runout.
- $P_{(S:T)}$ is the spatio-temporal probability of the person at risk (the proportion of a year that the person is in the path of the landslide when it reaches or passes the element at risk).
- $V_{(D:T)}$ is the vulnerability or probability of loss of life if the hazard impacts the site.

This report further quantifies risk using three risk metrics:

- Annual individual fatality risk (AIFR)
  - Fatality risk experienced by an individual (probability of loss of life) over one full year of working or visiting a given study area. For this report, AIFR is only calculated for the most exposed individual, defined as being a local worker, for whom the annual exposure is much higher than for the average visitor.
- Individual risk per day per trip for visitors (IRPD)
  - Fatality risk experienced by an individual (probability of loss of life) per day or experience. The majority of visitors to Piopiotahi Milford Sound are local or international tourists who only visit once or occasionally.
- Societal risk (APLL)
  - Defined as the relationship between the frequency of occurrence of a specified hazard and the number of people in a given population being killed if the hazard were to occur.
  - For this report, Annual Probable Lives Lost (APLL) is used as the societal risk metric. This can be calculated as:

    $$\mathrm{APLL} = f \times \mathrm{N}$$

    where:
  - APLL is the annual probability that a specific number of fatalities may occur.
  - f is the annual probability of a hazardous event occurring ($P_{(H)}$). For this report, in relation to tsunami hazard at Milford Sound, we have also included consideration of the probability that the hazard reaches the element at risk ($P_{(T:H)}$) and the vulnerability of persons present at the time ($V_{(D:T)}$).
  - N is the expected number of fatalities.

    Tsunami and landslide hazards in the study area vary greatly in terms of size and potential impacts. A tsunami event in Milford Sound Piopiotahi is likely to impact significantly more individuals than a landslide occurring along a track or at a hut or short stop site. Therefore, this risk assessment considers three scenarios of exposed populations for tsunami and landslide hazards in order to assess societal risk:

    - For tsunami:
      - Probability of 1 or more people being killed by a tsunami (N≥1).
      - Probability of 50 or more people being killed by a tsunami (N≥50).
      - Probability of 2000 or more people being killed by a tsunami (N≥2000).
        - Additionally, the probability of 3000 or more people being killed by a tsunami (N≥3000) is considered to represent the forecast maximum credible scenario in 2050. This estimate is based on forecast visitor numbers supplied by MOP.
    - For landslides:
      - Probability of 1 or more people being killed by a landslide (N≥1).
      - Probability of 5 or more people being killed by a landslide (N≥5).
      - Probability of 40 or more people being killed by a landslide (N≥40)

For this assessment, the probabilities listed above have been derived from direct observations of hazards and rationalised from other similar hazard studies or comparative examples.

4.2.3 RISK TOLERABILITY CRITERIA

DOC has developed visitor-type classes which include the typical activities undertaken and the relative risk tolerance levels for each class (Table 4). These have been adopted for this study and determined for each site.

To determine risk tolerability for the average visitor and worker, the DOC risk tolerability criteria for lower and medium-risk tolerance sites respectively have been used (Table 5 and Table 6).

The majority of MOP sites have been assessed as having lower risk tolerance due to the predominant Short Stop Traveller (SST) and Day Visitor (DV) low-risk tolerance visitor groups.

Some of the walking tracks such as the Countess Range Track are targeted at the 'Backcountry Comfort Seeker' (BCC) visitor group. These sites are considered to be medium risk tolerance.

Neither DOC nor MOP have established risk tolerance thresholds for societal risk. As such the calculated societal risk values have been compared to other similar risk contexts in New Zealand.

Table 4: Overview of the DOC visitor-type classes.

Visitor Type	Definition
SST	'Short Stop Traveller' visitor group. Seeks an 'instant immersion" in nature experience, associated with a high degree of scenic value or historical interest. Expects a low-risk experience associated with safe facilities.
DV	'Day Visitor' visitor group. Seeks experiences in natural or rural settings with a sense of space and freedom. Expects an outdoor experience with a low level of risk, and safe facilities.
ON	'Overnighter' visitor group. Seeks an overnight experience in a predominantly natural setting. Expects the camping and overnight experience, and the associated activities they undertake, to be generally low risk. Includes the traditional New Zealand family holiday experience.
BCC	'Backcountry Comfort Seeker' visitor group. Seeks an outdoor experience in a backcountry environment that has low risk due to the provision of safe, comfortable facilities. For many this may be their first introduction to the New Zealand backcountry.
BCA	'Backcountry Adventurer' visitor group. The traditional New Zealand backcountry experience. This group has a higher level of backcountry skills and experience than backcountry comfort seekers. Seeks an experience that has challenge and a sense of freedom, and they accept a degree of risk and discomfort.
RS	Remoteness Seeker' visitor group. Seeks a wilderness experience with limited interaction with other parties. Seeks the challenge and complete sense of freedom that comes from prolonged contact with wild nature. Because of their high skill level and experience, they accept the higher level of risk associated with travelling through remote areas.

Table 5: Relative site risk tolerance level according to the typology and usage of the site.

Natural Hazard Risk Level	Site type
Lower Risk Tolerance Site	Promoted short walks, SST, ON, DV that are promoted day hikes, some Great Walks
Medium Risk Tolerance Site	DV, some Great Walks, Most BCC, some BCA
Higher Risk Tolerance Site	Some BCA, RS

Figure 9: DOC risk tolerability criteria thresholds for individual fatality risk per trip used in this study.

Table 6: The DOC risk tolerability criteria for sites used in this study.

Action Required	Individual one trip (lower risk tolerance site)	Individual one trip (medium risk tolerance site)	AIFR (worker)
Close the site (using a formal closure process)	>1.00E-05	>3.00E-05	>3.00E-04
Continue only after high-level review	>1.00E-06	>3.00E-06	>1.00E-04
Reduce to as low as reasonably practicable	1.00E-07 to 1.00E-06	>3.00E-07	>1.00E-05
Reduce to as low as reasonably practicable (lower priority)	n/a	>1.00E-07	>1.00E-06
Monitor situation	<1.00E-07	<1.00E-07	<1.00E-06

4.2.4 EXPOSURE

To complete the Basic Risk Analysis for this stage of the assessment the exposure at each site location has been assessed in terms of individuals (visitor and worker) and groups of people (societal).

Exposure has been informed by data supplied by MOP, assessment of the Homer Tunnel vehicle counts, and data presented in Harris (2023) and Taig & McSaveney (2015). Individual exposure bands have then been applied and assigned to each site (Table 7).

Seven societal exposure classes capturing the seasonal and daily variation in societal exposure and site usage have been identified for the study area (Table 8). These were applied to each site using average daily high and low-season visitor numbers supplied by MOP.

The Little Tahiti site, the Countess Range Hut, and some of the identified tracks currently have no exposure as they are yet to be developed/constructed. For these sites, the projected exposure if they were to be developed has been adopted. For Little Tahiti, a worker accommodation facility is currently considered a potential option. This would result in a similar level of worker exposure to the existing worker village at Cleddau Delta. No visitor exposure is assumed for this site.

For the Countess Range Hut, Milford Opportunities are considering a BCC facility with 20 bunks. For the proposed tracks, projected visitor numbers supplied by MOP have been used and assume that there will be some weekly worker exposure for maintenance. For these sites, probability of occurrence multiplied by vulnerability and/or probability that the hazards reach the exposed element can be adopted in order to estimate an appropriate building/track risk.

Table 7: Individual exposure bands for the average visitor and worker in the Milford area.

Individual Exposure Band	Visitor		Worker	
	Hours/visit	% of year	Hours/week	% of year
1	1-3 hours/visit	0.01 – 0.03	1-9 hours/week	0.59 – 5.34
2	4-7 hours/visit	0.05 – 0.08	10-24 hours/week	5.94 – 14.25
3	8-11 hours/visit	0.09 – 0.13	25-39 hours/week	14.84 – 23.15
4	12-24 hours/visit	0.14 – 0.27	40-80 hours/week	23.74 – 47.49

Table 8: Societal exposure classes for the MOP sites.

Societal exposure class	Exposure	% of year	Exposed population in Milford Sound Piopiotahi
0	Never	0	0
1	During 9am-5pm, February	2.6	3500
2	During 8pm-8am, February	3.8	200
3	During 9am-5pm, high season (October – April)	16.7	3000
4	During 8pm-8am, high season (October – April)	25.1	150
5	During 9am-5pm all year	33.3	2500
6	During 8pm-8am, all year	50	50
7	At anytime	100	50

4.2.5 TSUNAMI

4.2.5.1 HAZARD

Tsunami hazard occurrence, likelihood, and consequence have been assessed for each site identified as Class 2 or higher.

MILFORD SOUND/CLEDDAU VALLEY

Landslide-induced tsunami likely dominates tsunami risk in Milford Sound Piopiotahi and the lower Cleddau River valley where Alpine Fault earthquakes are considered to be the dominant trigger (AF8, 2024; Taig & McSaveney, 2015; Dykstra, 2012). First-wave arrival times are much less for landslide-induced tsunami than other tsunami sources.

Likelihood data from previously published studies of Milford Sound landslide-induced tsunami and Alpine Fault earthquakes have therefore been adopted for this assessment rather than 'background' far-field tsunami occurrence, for example as given in the 2021 National Tsunami Model (Power, Burbidge, & Gusman, 2023).

For this assessment published work on landslide-induced tsunami in Milford Sound (Dykstra, 2012, Taig & McSaveney, 2015), together with topographical data, has been used to estimate tsunami hazard occurrence in Milford Sound Piopiotahi.

To estimate the effects of a landslide-induced tsunami, two of the scenarios presented in Dykstra (2012) and Taig & McSaveney (2015) have been used to represent a '*most likely*' and '*maximum credible'* landslide-induced tsunami event for Milford Sound Piopiotahi (Table 9). For the 'most likely' event, we have used the median of all the scenarios presented in Dykstra (2012) and Taig & McSaveney (2015) (SM17). For the 'maximum credible' event we have adopted the scenario with the greatest wave height at the fiord shoreline at Milford Sound Piopiotahi (SM15).

As mentioned, an alpine fault-induced tsunami event has a more frequent return interval (1:150 years) than several of the scenarios presented in Dykstra (2012) and Taig & McSaveney (2015). According to the scenarios in these studies a 1:150-year landslide-induced tsunami event at Milford Sound equates to a 5 m high wave at Freshwater Basin. This alpine fault event is also considered in regard to visitor and worker risk.

OTHER SITES

In addition to landslide-induced tsunami in Milford Sound Piopiotahi, the previous Part A report highlighted the potential for landslide-induced lake tsunami initiating in Lake Marian, Lake Gunn, and Lake Fergus.

Tsunami may also be triggered by avalanches from higher altitudes, particularly surrounding Lake Marian. As previously reported, little is known about lake tsunami hazards in these areas.

Estimates for the frequency of large landslides that could trigger a significant tsunami at these lakes have therefore been based on professional judgement supported by satellite imagery and local geological, and geomorphological information. The occurrence of such significant lake tsunami is inferred to be rare.

Table 9: Estimated first arrival wave amplitudes at Freshwater Basin and Cleddau Delta for landslide deposits listed in Dykstra (2012). Source - Taig & McSaveney (2015). For landslide-induced tsunami SM17 (most likely event) and SM15 (maximum credible event).

		Wave amplitude at Freshwater Basin (m)			Runup at Cleddau Delta (m)		
		Attenuation model			Attenuation model		
Source	P(H)*/yr	3 Gorges[3]	Loenvann[2]	None[1]	3 Gorges[3]	Loenvann[2]	None[1]
Subaerial landslides with submarine deposits							
SM1	5.3×10^{-04}	4.2	2.1	8.7	18.5	8.7	41.4
SM2	9.4×10^{-04}	1.5	0.7	3.0	5.8	2.7	13.0
SM3	3.5×10^{-04}	4.7	2.4	10.7	21.0	10.1	51.9
SM4	5.9×10^{-04}	4.0	2.2	11.0	17.6	8.9	53.7
SM5	1.2×10^{-04}	7.6	4.1	21.3	35.7	18.2	110.5
SM6	1.5×10^{-03}	0.1	0.1	0.4	0.4	0.2	1.4
SM7	1.2×10^{-03}	1.3	0.7	4.7	5.0	2.7	21.0
SM8	1.4×10^{-03}	0.4	0.2	1.6	1.3	0.7	6.6
SM9	2.9×10^{-04}	4.8	2.9	21.5	21.4	12.4	111.7
SM10	1.1×10^{-03}	1.4	0.9	7.9	5.3	3.3	37.3
SM11	7.6×10^{-04}	2.0	1.3	12.6	8.1	5.1	62.5
SM12	1.3×10^{-03}	0.6	0.4	4.3	2.2	1.4	19.1
SM13	2.4×10^{-04}	5.3	3.7	42.2	24.0	16.1	232.1
SM14	6.5×10^{-04}	3.6	2.6	34.4	15.5	11.0	185.9
SM15	5.9×10^{-05}	9.7	7.0	87.2	46.9	32.7	508.6
SM16	7.1×10^{-04}	2.1	1.6	21.3	8.7	6.2	110.6
SM17	8.8×10^{-04}	1.6	1.2	18.4	6.3	4.7	94.2
SM18	1.8×10^{-04}	5.8	4.6	76.6	26.8	20.6	442.7
SM19	4.7×10^{-04}	4.4	3.6	65.6	19.5	15.5	374.0
SM20	1.1×10^{-03}	1.4	1.2	24.3	5.4	4.5	127.5
SM21	8.2×10^{-04}	1.8	1.6	38.3	7.2	6.3	209.2
SM22	1.4×10^{-03}	0.3	0.3	8.2	1.1	1.0	39.1
Granular Submarine density flows							
DF1	1.2×10^{-03}	1.3	0.7	2.7	5.2	2.4	11.6
DF2	4.1×10^{-04}	4.5	2.3	9.0	20.2	9.4	43.2
DF3	1.0×10^{-03}	1.5	0.8	5.3	5.7	3.1	24.3
DF4	1.5×10^{-03}	0.04	0.04	1.3	0.1	0.1	5.0

* P(H) is the estimated probability that the estimated wave amplitude at Freshwater Basin will be equalled or exceeded assuming the 3 Gorges attenuation model, and that the deposits have accumulated over 17,000 years.

1 No attenuation is an unrealistic model for wave propagation in Milford Sound. It calculates wave height at point of landslide impact.

2 The Loenvann attenuation model is a less conservative model which has more rapid attenuation in wave height with distance of travel, and therefore calculates lower risk.

3 The 3 Gorges attenuation model is a more conservative model with a slower rate of attenuation and therefore calculates higher risk.

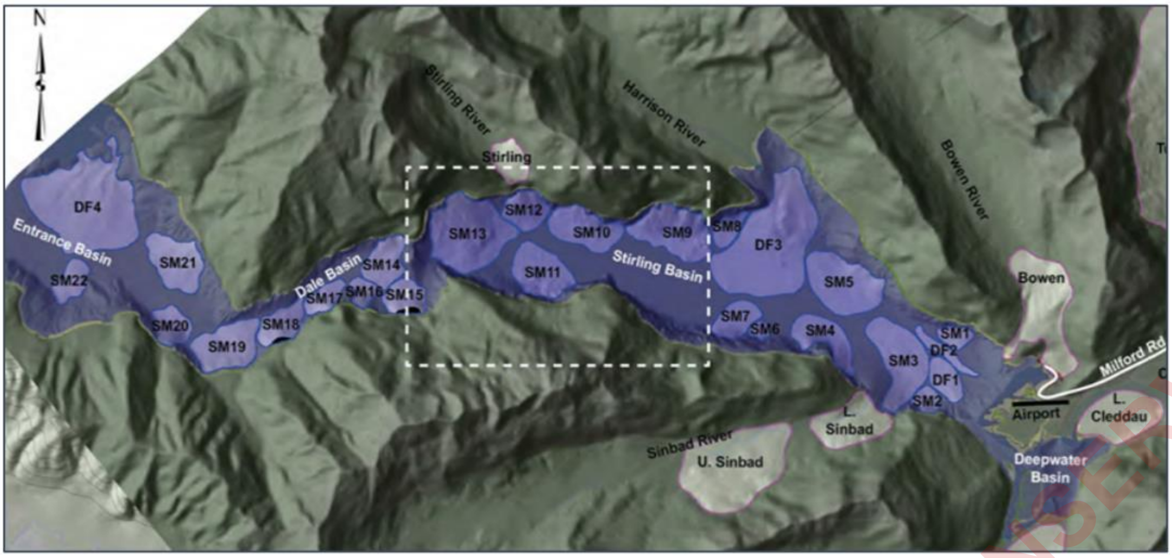

Figure 10: Historic landslide deposits (from Dykstra, 2012).

4.2.5.2 VULNERABILITY

The vulnerability (probability of fatality) of individuals to tsunami waves has been estimated for the 'most likely' (MLE) and 'maximum credible' event (MCE) at each site using professional judgement. For Milford Sound/Cleddau Valley, we estimate V=1.0 for the MCE and V=0.8 for the MLE.

4.2.5.3 EXPOSURE

Exposure to tsunami at each site used in this study is presented in Table 10 and Table 11 below. Visitor, worker, and societal risk bands relate to the values outlined in Table 7 and Table 8. As the footprint of a potential landslide-induced tsunami in Milford Sound Piopiotahi is expected to be significant, the Milford Sound Piopiotahi sites have been grouped and it has been assumed that any individual entering Milford Sound Piopiotahi (defined as west of Little Tahiti) has the potential to be exposed to tsunami. This assumption and approach were deemed reasonable given the high degree of uncertainty in estimating tsunami runup and wave dissipation by the independent peer review group.

For Ōtāpara Cascade Creek the societal risk scenarios of 1, 5, and 40 have been adopted as being an appropriate representation of the population at risk at this site.

Table 10: The exposure bands and classes for visitors and workers for each short/stop and node in the MOP for sites exposed tsunami hazard. *For sites where there is currently no exposure $P_{(H)}$ x V (Little Tahiti) has been calculated to quantify perceived risk. **visitor band taken as the most conservative assessment to include overnight stay. The exposure band for day visitors is likely to be less (Band 2 – equivalent to a 4-7 hour visit).

Area	Site	Tsunami	
		Visitor Band	Worker Band
Milford Sound Piopiotahi Sites	Cleddau Delta	4**	4
	Deepwater Basin		
	Freshwater Basin		
	Visitor Hub		
	Milford Sound Lodge		
	Little Tahiti*		

Area	Site	Tsunami	
		Visitor Band	Worker Band
Milford Road Sites	Ōtāpara Cascade Creek	4	1

Table 11: The societal exposure bands and classes for each short/stop and node in the MOP exposed to tsunami hazard. *For sites where there is currently no exposure $P_{(H)}$ x V (Little Tahiti) has been calculated to quantify perceived risk.

Area	Site	Tsunami		
		Societal Risk Band		
		N≥1	N≥50	N≥2000
Milford Sound Sites	Cleddau Delta	7	7	3
	Deepwater Basin			
	Freshwater Basin			
	Visitor Hub			
	Milford Sound Lodge			
	Little Tahiti*			
Milford Road Sites	Ōtāpara Cascade Creek	7	6 (N=5)	4 (N=40)

4.2.6 LANDSLIDES

Section 3.3.1 identified landslides, debris flow, rockfall, rock avalanche, and tree slides as potential landslide hazards in the MOP study area.

To further refine the assessment of such hazards, estimates of landslide size, runout potential, frequency, and vulnerability have been made at each site that is Class 2 or greater.

4.2.6.1 HAZARD

Areas of potential landslide occurrence have been identified at each site through the interpretation of topographical and geological layers in ArcGIS Pro. Polygons have been drawn around potential landslide hazard footprints based on local geomorphology including existing source and debris accumulation areas, changes in slope, and vegetation coverage.

For the purposes of this report, landslide volume classes have been adopted and assigned to each identified landslide hazard (Table 12). The landslide volume classes are based on landslide risk assessments in similar environments (e.g. Cox, 2021) and the range of credible landslide volumes in the study area.

For each site, a 'most likely' landslide volume and a 'maximum credible' landslide volume have been inferred.

Runout potential or the likelihood that a landslide from a potential source area reaches a site where an at-risk person may be present has been estimated for each landslide hazard. This has been based on desktop information of geological and topographical data including elevation and slope models compiled from the 1 m DEM.

A qualitative and judgemental approach was adopted to assess run-out distances or hazard impact footprints. This was further assessed against recent rockfall and landslide occurrences recorded in the region over recent years.

Landslide frequency has been estimated in recent years for the Milford Road (Mieler, Carey, King, Hancox, & Taig, 2014). This work was based on a detailed landslide inventory for the Fiordland area and estimates the frequency of different landslide volume categories for seismically triggered and non-seismically triggered events (e.g. rainfall). Landslide frequency in this report has been determined for each site of interest using available site-specific information, including Mieler et al. (2014).

Satellite imagery and elevation data were then used to inform the frequency of landsliding at each site. Each landslide hazard was assigned a frequency band (Table 12) which captures the expected range of landslide frequency within the study area. This was adjusted where anecdotal historical evidence suggested a different frequency.

4.2.6.2 VULNERABILITY

Vulnerability or chance of fatality due to landslide has been assessed as a function of landslide volume class and proximity of the landslide to the site.

Vulnerability ranges from $V_{(D:T)}$=1 (chance of fatality is 100%) to $V_{(D:T)}$ =0.6 (chance of fatality is 60%). For vulnerability, it has been assumed that anyone impacted by a landslide would be in open space (i.e. outside of a building). Vulnerability to landslides was informed using Table 7.1 in Part 4 of the GNS Guidelines (de Vilder & Massey, 2022b) and professional judgement or experience of events in the Milford and Fiordland region.

Debris flow hazards vary depending on the type of debris flow, including water content. Both debris flow and debris flood hazards have been considered in the assessment of landslide risk.

Table 12: Landslide volume class, frequency, and vulnerability used in this report.

Volume			Example	$P_{(H)}$		$V_{(D:T)}$
Class	Lower (m^3)	Upper (m^3)		Lower	Upper	
1	0	1E+02		2	4	0.6
2	1E+02	1E+03		0.5	2	0.8
3	1E+03	1E+04	Howden Hut Debris Flow	0.05	0.5	0.8
4	1E+04	1E+05		0.01	0.05	0.8
5	1E+05	1E+06	Red Slip – Milford Road	0.001	0.01	1
6	1E+06	1E+07	Lower Cleddau	0.0001	0.001	1
7	1E+08	1E+09	Lake Gunn, Bowen Falls	0.0001	0.001	1

Figure 11: The Bowen Falls and Lower Cleddau landslides in Milford Sound. Source: Dykstra (2012).

Plate 4 A very large prehistoric compound rock slide rock avalanche of ~300 Mm3 which runs-out over the Milford Road and forms a landslide dammed lake.

Figure 12: Aerial photo of the Lake Gunn landslide. Source: (Mieler, Carey, King, Hancox, & Taig, 2014).

4.2.6.3 EXPOSURE

Exposure to hazards at each site considered in this study is presented in Table 13 and Table 14 below.

Table 13: Exposure bands and classes for visitors and workers for each short/stop and node in the MOP for sites exposed landslide hazard. *For sites where there is currently no exposure $P_{(H)}$ x V (Little Tahiti and Countess Range Hut) has been calculated to quantify perceived risk.

Area	Site	Landslide	
		Visitor Band	Worker Band
Milford Sound Sites	Freshwater Basin	2	3
	Visitor Hub	4	4
	Milford Sound Lodge	4	4
	Little Tahiti*	0	4
Milford Road Sites	Mackay Creek DOC Campsite	4	3
	Countess Range Hut*	4	3
	Te Huakaue Knobs Flat	4	3
	Ōtāpara Cascade Creek	4	1
	The Divide	1	3
	Whakatipu Trails Head	1	3
	Gertrude Valley	1	3
	The Chasm	1	3

Table 14: The societal exposure bands and classes for each short/stop and node in the MOP exposed to landslide hazard. *For sites where there is currently no exposure $P_{(H)}$ x V (Little Tahiti and Countess Range Hut) has been calculated to quantify perceived risk.

Area	Site	Landslide		
		Societal Risk Band		
		N≥1	N≥5	N≥40
Milford Sound Sites	Freshwater Basin	5	5	5
	Visitor Hub	7	7	6
	Milford Sound Lodge	7	7	6
	Little Tahiti*	7	7	4
Milford Road Sites	Mackay Creek DOC Campsite	7	6	2
	Countess Range Hut*	7	4	2
	Te Huakaue Knobs Flat	7	7	7
	Ōtāpara Cascade Creek	7	6	4
	The Divide	5	6	5
	Whakatipu Trails Head	5	5	1
	Gertrude Valley	5	5	1
	The Chasm	5	5	1

4.2.7 TRACKS

For tracks, annual visitor risk has been calculated to highlight tracks where mitigation measures should be considered.

The upper annual probability of occurrence ($P_{(H)}$) and vulnerability ($V_{(D:T)}$) for the most likely tsunami and landslide event of the nearest node or short stop has been adopted for each track. Visitor risk has then been calculated by estimating the total exposure to the most likely event along each track. The typical visitor type on each track was then assessed to compare calculated visitor risk to the DOC acceptability criteria (Table 16).

For tracks, the exposure bands previously presented in the Part A analysis have been re-assessed for each hazard identified along the track course (Table 15).

Table 15: Track exposure bands for visitors exposed to hazards.

Track hazard exposure band	Exposure
1	< 10 seconds
2	10 seconds to 2 minutes
3	2 minutes to 30 minutes
4	30 minutes to 180 minutes
5	> 180 minutes

Table 16: Tracks and the typical visitor group in this assessment.

Site	Typical Visitor Group	DOC risk tolerance
Countess Range Track	BCC	Medium
Gertrude Valley Track	SST	Low
Hinepipiwai Lake Marian Loop Track	SST	Low
Te Anau Downs to the Divide Cycle Trail	BCC	Medium
Te Huakaue Knobs Flat Short Walks	SST	Low
Gunn Nature Trail	SST	Low
Key Summit to Ōtāpara Cascade Creek Track	BCC	Medium
The Chasm to Cleddau Horse Bridge Track	SST	Low
Milford Sound Lodge to Tutoko River Bridge Track	SST	Low
Hine-te-awa Lower Bowen Falls pontoon and tracks	SST	Low
Hine-te-awa Upper Bowen Falls tracks	SST	Low

4.3 FLOODING

Detailed flood modelling of the Cleddau, Eglinton, Hollyford and Tutoko River valleys has not been undertaken as part of this assessment. However, it is understood that previous studies relating to flood extents and development levels on the Cleddau Delta have been completed by others concerning the development of stop banks and flood defence works along the Cleddau River.

This previous work resulted in the raising of the existing stop banks and in identifying various protocols to manage the hazard at the delta and the Milford Sound Lodge site.

Given the existing stop bank configuration and protocols in place to manage flood hazards at Milford Sound Lodge, the Cleddau Delta, and Deepwater Basin, the flood hazard is for the purposes of this report, considered to be addressed and the risk levels are at 'low' to 'moderate' levels.

Flooding is also identified as an issue at Mackay Creek DOC Campsite, Deer Flat DOC Campsite, Te Huakaue Knobs Flat, Ōtāpara Cascade Creek, Whakatipu Trails Head, Gertrude Valley, and the Chasm. There is limited existing information on flood hazard at these sites and as such a risk assessment has not been completed.

Section 6.3 discusses potential risk mitigation measures for flooding.

4.4 AVALANCHE

As part of the initial screening analysis completed in the Part A report, several sites were identified as being potentially exposed to avalanche hazards.

The GNS methodology does not include avalanche and as such the previous Part A analysis recommended that the Part B analysis consider the possible footprint of the hazard in relation to the development proposal and consider the assigned Department of Conservation (DOC) visitor group class in order to determine the need for any further detailed assessment.

Based on the visitor group class, appropriate hazard management strategies identified by DOC can be employed to manage the perceived risk, as the hazard management strategy at each site is then aligned with the perceived risk tolerance of the typical visitor group and associated DOC hazard management guidelines (DOC, 2023).

For the Part B analysis, the occurrence and likely hazard footprints have been mapped in relation to the MOP proposals and an appropriate visitor group assessment has been completed for the proposed use at each MOP site. Based on the outcome of this assessment the need for further Avalanche Hazard Index (AHI) assessments or the need for Avalanche Terrain Exposure Scale (ATES) controls can be determined.

4.5 UNCERTAINTY

The methods for the qualitative and semi-quantitative risk analysis as discussed above include several key assumptions and estimates that affect the uncertainty of the results.

4.5.1 TSUNAMI

Tsunami frequency in Milford Sound adopts findings of previous published and unpublished reports (Dykstra, 2012; Taig & McSaveney, 2015) to estimate landslide-induced tsunami hazard potential in Milford Sound.

Each tsunami event has been treated as a potential separate tsunami event and therefore is considered to be a conservative (high) estimate of the number of tsunami events to have occurred. However, should several landslides occur during one earthquake event, there is the potential for wave heights and associated run-ups to be underestimated. Additionally, deposits may represent several landslide events and therefore the frequency of landsliding may be higher but result in smaller intensity tsunami events.

Tsunami events are assumed the inundate Milford Sound Piopiotahi, however, there may be some wave attenuation for the Visitor Hub, Milford Sound Lodge and Little Tahiti due to the elevation and distance of these sites from the main fiord body. These results are therefore considered to be relatively conservative when compared to more detailed multi-faceted model results. However, when comparing these results with other published assessments the results are considered to be a reasonable estimate.

Due to little available knowledge, the estimation of lake tsunami hazard impacts at Ōtāpara Cascade Creek Campsite is largely judgement-based. There are a multitude of factors that affect landslide-induced lake tsunami inundation potential at this site including landslide size, water depth, landslide source characteristics (i.e. slope, vegetation, geology, location), and local topography. Without a detailed analysis of these characteristics, the estimation of tsunami hazard frequency is highly uncertain.

4.5.2 LANDSLIDE

Landslide frequency and runout potential have been estimated using professional experience supported by geological/topographical data, anecdotal evidence, and visual evidence from satellite and aerial imagery. Landslide volume, frequency, and runout bands have been adopted which aim to capture the full range of landslide potential within the study area and to highlight the degree of uncertainty. Further detailed analysis of landslide runout intensity and frequency would reduce uncertainty in the values adopted.

4.5.3 RISK ASSESSMENT

Visitor, worker, and societal exposure at each of the sites in this assessment is likely to vary by the individual, time of day, season, and weather. Estimations of exposure have, where possible, attempted to incorporate these factors. We have adopted exposure bands which provide a range of relative exposure to hazards. It is uncertain where an individual or group will fit in a band and therefore relative exposure between individuals may vary greatly.

To address the uncertainties in this study, where possible previous studies have been considered and referenced. Upper and lower values for visitors and worker risk are presented which are likely to capture the spectrum of risk at each site.

5 RISK ASSESSMENT RESULTS

5.1 QUALITATIVE ANALYSIS

5.1.1 SECONDARY SCREENING OF SITES

The Deer Flat DOC Campsite was previously assessed as a Class 2 site for landslide hazard and was potentially exposed to flood hazards in the Part A report (WSP, 11 March 2024).

In discussion with MOP and DOC staff, the site had previously been impacted by flooding and was subsequently closed to facilitate the development of flood mitigation works. The management protocols now in place at the site are deemed appropriate to reduce the perceived risk to acceptable levels.

On this basis, the Deer Flat DOC campsite has been reassessed as Class 1 for flooding. No further risk assessment for this site is deemed necessary.

The Hinepipiwai Lake Marian Falls Track was previously assessed as a Class 2 Site. In discussion with MOP and DOC following completion of the Part A assessment it was indicated that Riley Consultants had been appointed by DOC to complete a Preliminary Screening Analysis of the proposed Falls track. It is understood that basic risk analysis is not being pursued for this track as part of the feasibility study. The Hinepipiwai Lake Marian Loop Track, however, was not assessed by Riley Consultants and is assessed further in Section 5.2.3 of this report.

Additionally, the Cleddau Delta and Deepwater Basin sites have been re-classified as Class 1 for landslide hazards as the probability of landsliding at each site has been further assessed as very low.

Table 17: Additional screening of sites originally assessed as Class 2 or greater.

Site	Reason
Deer Flat DOC Campsite	Applied flood mitigation measures, risk managed by DOC.
Hinepipiwai Lake Marian Falls Track	Basic risk analysis not pursued for feasibility.
Cleddau Delta and Deepwater Basin	Assessed as not exposed to landsliding

The previous Part A analysis identified the Chasm, Freshwater Basin, and Mackay Creek DOC Campsite to be sites potentially affected by flood hazards.

Detailed inspection and analysis of the hazard footprint have determined that these sites are not at risk from flood hazards but could potentially be exposed to debris flow (landslide) and would align with Class 2 for landslides.

5.2 SEMI-QUANTITATIVE RISK ASSESSMENT

For both tsunami and landslide hazards, a most likely and maximum credible event has been considered. Risk has been calculated for both events and is presented in this section as a combined value (most likely + maximum credible). For some of the input variables (e.g exposure ($P_{(S:T)}$)), it was deemed appropriate to use a lower and upper value to represent uncertainty. Hence, risk has also been assessed with a lower and upper value.

5.2.1 TSUNAMI

5.2.1.1 MILFORD SOUND PIOPIOTAHI SITES

Table 18 presented below displays the probability and vulnerability of the two landslide-induced tsunami events adopted as part of this study. The most likely event considers a ~1:1000-year landslide-induced tsunami wave with a 6.3 m runup at Cleddau Delta (Dykstra, 2012; Taig & McSaveney, 2015). The estimated temporal-spatial probability of the hazard inundating all sites in Milford Sound Piopiotahi is estimated to be 0.7 (70% chance). The estimated probability of fatality for an individual exposed to this wave is 0.8 (80% chance of fatality) (Dykstra, 2012).

The maximum credible event considers a ~1:17,000-year landslide-induced tsunami wave with a 45.9 m runup at Cleddau Delta. The estimated temporal-spatial probability of the hazard inundating all sites in Milford Sound Piopiotahi is 0.9 (90% chance). The estimated probability of fatality for an individual exposed to this wave is 99.9 (~100% chance of fatality) (Dykstra, 2012).

Table 18: Landslide-induced tsunami probability $P_{(H)}$ and vulnerability $V_{(D:T)}$ for the most likely and maximum credible events in Milford Sound Piopiotahi. Most likely and maximum event probability is based on SM17 and SM15 presented in Dykstra (2012).

Most likely event				Maximum credible event			
Runup at Cleddau Delta (m)	$P_{(H)}$	$P_{(T:H)}$	$V_{(D:T)}$	Runup at Cleddau Delta (m)	$P_{(H)}$	$P_{(T:H)}$	$V_{(D:T)}$
6.3	8.8E-04	0.7	0.8	45.9	5.9E-05	0.9	1

Table 19 presented below displays the probability and vulnerability of the AF8-induced tsunami event adopted as part of this study. This event considers a ~1:150-year landslide-induced tsunami wave with a 5 m runup at Cleddau Delta (Dykstra, 2012; Taig & McSaveney, 2015). The estimated temporal-spatial probability of the hazard inundating all sites in Milford Sound Piopiotahi is estimated to be 0.6 (60% chance). The estimated probability of fatality for an individual exposed to this wave is 0.7 (70% chance of fatality) (Dykstra, 2012).

Table 19: Landslide-induced tsunami probability $P_{(H)}$ and vulnerability $V_{(D:T)}$ for the Alpine fault-induced events in Milford Sound Piopiotahi. Runup is based on SM7, SM10, and SM20 presented in Dykstra (2012).

AF8 Scenario			
Runup at Cleddau Delta (m)	$P_{(H)}$	$P_{(T:H)}$	$V_{(D:T)}$
5	6.7E-03	0.6	0.7

INDIVIDUAL RISK (VISITOR AND WORKER)

Table 20 below presents the results of the tsunami risk assessment for visitors (IRPD) and workers (AIFR).

Risk values are a product of the hazard probability $P_{(H)}$, hazard impact probability $P_{(T:H)}$, vulnerability $V_{(D:T)}$, and the annual exposure for visitors and workers $P_{(S:T)}$.

Exposure times adopted in this assessment are provided in Table 10 and are based on current visitor and worker activity. As we have classified visitor and worker exposure in bands in this report, $P_{(S:T)}$ is given as a range with a lower and upper value. IRPD and AIFR estimates include both the 'most likely' and 'maximum credible' event to provide an overall estimate of risk.

Visitor risk for tsunami in Milford Sound Piopiotahi is estimated as 'moderate' to 'substantial'. This is largely due to the proximity to the main fiord body and shoreline and the current high levels of visitor exposure in Milford Sound Piopiotahi.

According to the DOC risk tolerability criteria, our estimates for visitor risk require a 'reduce to as low as reasonably practicable' to 'continue after high level review' approach.

For workers, risk is estimated as 'substantial' and a 'continue only after high level review' approach is recommended.

Table 20: Visitor and worker risk (IRPD) for landslide-induced tsunami in Milford Sound Piopiotahi. Exposure ($P_{(S:T)}$) has been estimated based on the current average visitor and worker in Milford Sound Piopiotahi. *Combined includes both the most likely and maximum credible events.

Visitor Risk				Worker Risk			
$P_{(S:T)}$		IRPD – combined*		$P_{(S:T)}$		AIFR – combined*	
Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
0.0014	0.0027	7.5E-07	1.5E-06	0.24	0.47	1.3E-04	2.6E-04

For the AF8-induced tsunami event, visitor and worker risk in Milford Sound Piopiotahi is estimated as 'high' (Table 21). This is largely due to the high cumulative probability of the Alpine Fault triggering a landslide that causes a tsunami (~1:150-year event).

Table 21: Visitor and worker risk (IRPD) for AF8-induced tsunami in Milford Sound Piopiotahi. Exposure ($P_{(S:T)}$) has been estimated based on the current average visitor and worker in Milford Sound Piopiotahi.

Visitor Risk				Worker Risk			
$P_{(S:T)}$		IRPD		$P_{(S:T)}$		AIFR	
Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
0.0014	0.0027	1.2E-05	2.4E-05	0.24	0.47	2.1E-03	4.2E-03

SOCIETAL RISK

Table 22 below presents the results of the calculated societal risk expressed in Annual Probable Lives Lost (APLL) for landslide-induced tsunami in Milford Sound Piopiotahi under four population-at-risk scenarios.

Frequency (f) relates to the probability of the hazard occurring and is further scaled by the probability of the hazard reaching the exposed population and the chance of fatality for people exposed to each level of hazard (most likely and maximum credible). As the exposed population increases (N) so too does the APLL and the estimated number of fatalities.

For the most likely event:

- When the population at risk is 1, we estimate there to be 1 fatality.
- When the population at risk is 50, we estimate there to be 28 fatalities.
- When the population at risk is 2000, we estimate there to be 1120 fatalities.
- When the population at risk is 3000, we estimate there to be 1680 fatalities.

For the maximum credible event:

- When the population at risk is 1, we estimate there to be 1 fatality.
- When the population at risk is 50, we estimate there to be 45 fatalities.
- When the population at risk is 2000, we estimate there to be 1800 fatalities.
- When the population at risk is 3000, we estimate there to be 2700 fatalities.

Table 22: Societal risk (APLL) for the four scenarios used in this study. The exposed population of 3000 relates to forecasted population exposure in 2050. Exposure ($P_{(S:T)}$) has been estimated based on the portion of the year that N is equalled or exceeded. For estimated fatalities, a whole number of people is provided in brackets where a decimal number is calculated.

Factor	N≥1	N≥50	N≥2000	N≥3000
f (most likely)	8.8E-04			
f (maximum credible)	5.9E-05			
$P_{(T:H)}$ (most likely)	0.7			
$P_{(T:H)}$ (maximum credible)	0.9			
$V_{(D:T)}$ (most likely)	0.8			
$V_{(D:T)}$ (maximum credible)	1			
N	1	50	2000	3000
APLL (most likely)	4.9E-04	2.5E-02	9.9E-01	1.5E+00
APLL (maximum credible)	5.3E-05	2.7E-03	1.1E-01	1.6E-01
Estimated fatalities (most likely)	0.56 (1)	28	1120	1680
Estimated fatalities (maximum credible)	0.9 (1)	45	1800	2700

Table 23 below presents the results of the calculated societal risk expressed in Annual Probable Lives Lost (APLL) for the AF8-induced tsunami in Milford Sound Piopiotahi under four population-at-risk scenarios.

For the AF8-induced tsunami event:

- When the population at risk is 1, we estimate there to be no fatalities.
- When the population at risk is 50, we estimate there to be 21 fatalities.
- When the population at risk is 2000, we estimate there to be 840 fatalities.
- When the population at risk is 3000, we estimate there to be 1260 fatalities.

Table 23: Societal risk (APLL) for the four scenarios used in this study. The exposed population of 3000 relates to forecasted population exposure in 2050. Exposure ($P_{(S:T)}$) has been estimated based on the portion of the year that N is equalled or exceeded. For estimated fatalities, a whole number of people is provided in brackets where a decimal number is calculated.

Factor	N≥1	N≥50	N≥2000	N≥3000
f	6.7E-03			
$P_{(T:H)}$	0.6			
$V_{(D:T)}$	0.7			
N	1	50	2000	3000
APLL	2.8E-03	1.4E-01	5.6E+00	8.4E+00
Estimated fatalities	0.42 (0)	21	840	1260

5.2.1.2 ŌTĀPARA CASCADE CREEK

Table 24 presented below shows the probability and vulnerability of the two landslide-induced tsunami events for Ōtāpara Cascade Creek.

There is little existing information on tsunami hazard risk at this site. This scenario considers the probability of a large enough landslide (estimated to be > volume class 4) entering Lake Gunn and triggering a tsunami wave which travels down the Lake Gunn outlet and inundates Ōtāpara Cascade Creek. This estimate is highly uncertain due to the lack of relevant information for the site and the number of variables in estimating landslide-induced tsunami impact. However, this approach is considered to be commensurate with the level of risk assessment contained in this report.

Estimates for the probability of each tsunami wave inundating the site and chance of fatality are relatively low compared to Milford Sound Piopiotahi as landsliding surrounding Lake Gunn appears to be on a much smaller scale.

The most likely event considers a ~1:1000-year landslide-induced tsunami wave triggered in Lake Gunn. The estimated temporal-spatial probability of the hazard inundating Ōtāpara Cascade Creek is 0.1 (10% chance). The estimated probability of fatality for an individual exposed to this event is 0.1 (10% chance of fatality).

The maximum credible event considers a ~1:10,000-year landslide-induced tsunami wave. The estimated temporal-spatial probability of the hazard inundating Ōtāpara Cascade Creek is 0.5 (50% chance). The estimated probability of fatality for an individual exposed to this wave is 0.4 (40% chance of fatality).

Table 24: Landslide-induced tsunami probability $P_{(H)}$ and vulnerability $V_{(D:T)}$ for the most likely and maximum credible events at Ōtāpara Cascade Creek.

Most likely			Maximum credible		
$P_{(H)}$	$P_{(T:H)}$	$V_{(D:T)}$	$P_{(H)}$	$P_{(T:H)}$	$V_{(D:T)}$
1.0E-03	0.1	0.1	1.0E-04	0.5	0.4

INDIVIDUAL RISK

Table 25 shows the results of the tsunami risk assessment for visitors (IRPD) and workers (AIFR).

Visitor risk for tsunami in Ōtāpara Cascade Creek is estimated as 'low' and a 'continue to monitor' approach is recommended.

Worker risk for tsunami in Ōtāpara Cascade Creek is estimated as 'low' to 'moderate' and a 'reduce to as low as reasonably practicable (lower priority)' approach is recommended.

Table 25: Visitor (IRPD) and worker risk (AIFR) for landslide-induced tsunami in Ōtāpara Cascade Creek. Exposure ($P_{(S:T)}$) has been estimated based on the average visitor and worker in Ōtāpara Cascade Creek. *Combined includes both the most likely and maximum credible events.

Visitor Risk				Worker Risk			
$P_{(S:T)}$		IRPD – combined*		$P_{(S:T)}$		AIFR – combined*	
Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
0.0014	0.0027	4.1E-08	8.2E-08	0.01	0.05	1.8E-07	1.6E-06

SOCIETAL RISK

Table 26 presents societal risk expressed in Annual Probable Lives Lost (APLL) for landslide-induced tsunami in Ōtāpara Cascade Creek under three population-at-risk scenarios.

For the most likely event:

- When the population at risk is 1, 5, or 40 we estimate there to be no fatalities.

For the maximum credible event:

- When the population at risk is 1, we estimate there to be no fatalities.
- When the population at risk is 5, we estimate there to be 5 fatalities.
- When the population at risk is 40, we estimate there to be 8 fatalities.

Table 26: Societal risk (APLL) for the four scenarios used in this study. Exposure ($P_{(S:T)}$) has been estimated based on the portion of the year that N is equalled or exceeded. For estimated fatalities, a whole number of people is provided in brackets where a decimal number is calculated.

Factor	N≥1	N≥5	N≥40
f (most likely)	1.0E-03		
f (maximum credible)	1.0E-04		
$P_{(T:H)}$ (most likely)	0.1		
$P_{(T:H)}$ (maximum credible)	0.5		
$V_{(D:T)}$ (most likely)	0.1		
$V_{(D:T)}$ (maximum credible)	0.4		
N	1	5	40
APLL (most likely)	1.0E-05	5.0E-05	4.0E-04
APLL (maximum credible)	2.0E-05	1.0E-04	8.0E-04
Estimated fatalities (most likely)	0.01 (0)	0.05 (0)	0.4 (0)
Estimated fatalities (maximum credible)	0.2 (0)	1	8

5.2.2 LANDSLIDES

Table 27 describes landslide hazard at each site in terms of estimated volume, runout potential ($P_{(T:H)}$), vulnerability ($V_{(D:T)}$), and probability ($P_{(H)}$). As we have classified landslide probability as a range in this report, $P_{(H)}$ is given with a lower and upper value.

The 'most likely' landslide event considers smaller failures with less consequence than the 'maximum credible' landslide event at each site.

These findings below assume that individuals are not in buildings and do not account for existing mitigation. This approach is deemed to be conservative, however, risk mitigation options at several of these sites should be explored and evaluated.

Table 27: Landslide probability $P_{(H)}$, runout ($P_{(T:H)}$), and vulnerability $V_{(D:T)}$ for the most likely and maximum credible events at each MOP site.

Site	Primary landslide type	Most likely event					Maximum credible event				
		Volume class	$P_{(T:H)}$	$V_{(D:T)}$	$P_{(H)}$		Volume class	$P_{(T:H)}$	$V_{(D:T)}$	$P_{(H)}$	
					Lower	Upper				Lower	Upper
Freshwater Basin	Landslide	3	0.2	0.8	5.0E-02	1.0E-01	7	1	1	1.0E-04	1.0E-03
Visitor Hub	Landslide	3	0.1	0.8	1.0E-03	1.0E-02	6	0.5	1	1.0E-04	1.0E-03
Milford Sound Lodge	Landslide	3	0.02	0.8	1.0E-03	1.0E-02	7	0.5	1	1.0E-04	1.0E-03
Little Tahiti	Landslide/treeslide	3	0	0.8	1.0E-03	1.0E-02	6	0.25	1	1.0E-04	1.0E-03
Countess Range Hut	Rockfall	2	0.01	0.8	5.0E-02	5.0E-01	6	1	1	1.0E-04	1.0E-03
Te Huakaue Knobs Flat	Debris Flow	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
Ōtāpara Cascade Creek	Debris Flow	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
The Divide	Landslide	3	0.1	0.8	5.0E-02	5.0E-01	6	0.75	1	1.0E-04	1.0E-03
Whakatipu Trails Head	Landslide	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
Gertrude Valley	Rockfall	2	0.1	0.8	5.0E-02	5.0E-01	6	1	1	1.0E-04	1.0E-03
The Chasm	Landslide	3	0.1	0.8	5.0E-03	2.0E-02	6	0.75	1	1.0E-04	1.0E-03

5.2.2.1 INDIVIDUAL RISK

Table 28 presents the results of the landslide risk assessment for visitors (IRPD) and workers (AIFR) at MOP sites.

Risk values are a product of the hazard probability $P_{(H)}$, runout $P_{(T:H)}$, vulnerability $V_{(D:T)}$, and the annual exposure for visitors and workers $P_{(S:T)}$.

Exposure times adopted in this assessment are provided in Table 10 and are based on current visitor and worker activity. IRPD and AIFR estimates include both the 'most likely' and 'maximum credible' events to provide an overall estimate of risk.

Table 28: DOC risk levels and mitigation for workers at each site exposed to landslide hazards.

Site	P(S:T)		IRPD – combined*		P(S:T)		AIFR – combined*	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Freshwater Basin	0.0005	0.0008	3.7E-06	1.4E-05	0.15	0.23	1.2E-03	3.9E-03
Visitor Hub	0.0014	0.0027	1.8E-07	3.6E-06	0.24	0.47	3.1E-05	6.2E-04
Milford Sound Lodge	0.0014	0.0027	9.0E-08	1.8E-06	0.24	0.47	1.6E-05	3.1E-04
Little Tahiti	0.0000	0.0000	0.0E+00	0.0E+00	0.24	0.47	5.9E-06	1.2E-04
Countess Range Hut	0.0014	0.0027	1.0E-07	2.1E-06	0.01	0.05	3.0E-06	2.7E-04
Te Huakaue Knobs Flat	0.0014	0.0027	6.8E-07	1.4E-05	0.01	0.05	5.2E-06	2.5E-04
Ōtāpara Cascade Creek	0.0014	0.0027	1.2E-06	1.3E-05	0.01	0.05	5.2E-06	2.5E-04
The Divide	0.0001	0.0003	1.2E-06	1.3E-05	0.01	0.05	2.4E-05	2.2E-03
Whakatipu Trails Head	0.0001	0.0003	4.7E-07	1.4E-05	0.01	0.05	5.2E-06	2.5E-04
Gertrude Valley	0.0001	0.0003	1.0E-07	1.6E-06	0.01	0.05	2.4E-05	2.2E-03
The Chasm	0.0001	0.0003	4.7E-07	1.4E-05	0.01	0.05	2.8E-06	1.3E-04

Table 29 and Table 30 below present a summary of the estimated DOC risk level and mitigation approach for MOP sites exposed to landslide hazards.

Table 29: DOC risk levels and mitigation for visitors at each MOP site exposed to landslide hazards.

DOC Risk level	DOC Mitigation	Site(s)
Low - Moderate	No risk reduction required but monitor for changes - Reduce to as low as reasonably practicable	— The Chasm
Low - Substantial	No risk reduction required but monitor for changes - Continue only after high level review	— Milford Sound Lodge — Whakatipu Trails Head
Moderate - Substantial	Reduce to as low as reasonably practicable - Continue only after high level review	— Visitor Hub — Countess Range Hut
Moderate - High	Reduce to as low as reasonably practicable - Close the site	— Ōtāpara Cascade Creek, — The Divide — Gertrude Valley
Substantial - High	Continue only after high level review - Close the site	— Freshwater Basin — Te Huakaue Knobs Flat

Table 30: DOC risk levels and mitigation for workers at each site exposed to landslide hazards.

DOC Risk level	DOC Mitigation	Site(s)
Moderate - Substantial	Reduce to as low as reasonably practicable - Continue only after high level review	— Little Tahiti — Countess Range Hut — Te Huakaue Knobs Flat — Ōtāpara Cascade Creek — The Chasm — Whakatipu Trails Head
Moderate - High	Reduce to as low as reasonably practicable - Close the site	— Visitor Hub — Milford Sound Lodge — The Divide — Gertrude Valley
High	Continue only after high level review - Close the site	— Freshwater Basin

5.2.2.2 SOCIETAL RISK

Table 31 presents societal risk expressed in Annual Probable Lives Lost (APLL) at each MOP site for the most likely and maximum credible landslide event under three population-at-risk scenarios.

For the most likely event:

- When the population at risk is 1 at each site, we estimate there to be no fatalities at any site.
- When the population at risk is 5 at each site, we estimate there to be 1 fatality at Freshwater Basin.
- When the population at risk is 40 at each site, we estimate there to be some fatalities (2-7) at Freshwater Basin, Visitor Hub, Te Huakaue Knobs Flat, Ōtāpata Cascade Creek, the Divide, Whakatipu Trails Head, Gertrude Valley, and the Chasm

For the maximum credible event:

- When the population at risk is 1 at each site, we estimate there to be 1 fatality at every site except Little Tahiti. This is due to the distance of the Little Tahiti site from a potential maximum credible source.
- When the population at risk is 5 at each site, we estimate there to be some fatalities (2-7) at every site except Little Tahiti.
- When the population at risk is 40 at each site, we estimate there to be multiple fatalities (10-40) at all sites.

Table 31: Societal risk (APLL) for the three scenarios used in this study. Exposure ($P_{(S:T)}$) has been estimated based on the portion of the year that N is equalled or exceeded. For estimated fatalities, a whole number of people is provided in brackets where a decimal number is calculated.

	Site	N=>1			N=>5			N=>40		
		P(S:T)	APLL	Estimated fatalities	P(S:T)	APLL	Estimated fatalities	P(S:T)	APLL	Estimated fatalities
Most likely landslide	Freshwater Basin	0.3	1.6E-02	0.16 (0)	0.3	8.0E-02	0.8 (1)	0.33	6.4E-01	6.4 (6)
	Visitor Hub	1.0	8.0E-04	0.08 (0)	1.0	4.0E-03	0.4 (0)	0.50	3.2E-02	3.2 (3)
	Milford Sound Lodge	1.0	1.6E-04	0.016 (0)	1.0	8.0E-04	0.08 (0)	0.50	6.4E-03	0.64 (1)
	Little Tahiti	1.0	0.0E+00	0	1.0	0.0E+00	0	0.25	0.0E+00	0
	Countess Range Hut	1.0	4.0E-03	0.008 (0)	0.3	2.0E-02	0.04 (0)	0.04	1.6E-01	0.32 (0)
	Te Huakaue Knobs Flat	1.0	4.0E-03	0.08 (0)	1.0	2.0E-02	0.4 (0)	1.00	1.6E-01	3.2 (3)
	Ōtāpara Cascade Creek	1.0	4.0E-03	0.08 (0)	0.5	2.0E-02	0.4 (0)	0.50	1.6E-01	3.2 (3)
	The Divide	0.3	4.0E-02	0.08 (0)	0.3	2.0E-01	0.4 (0)	0.29	1.6E+00	3.2 (3)
	Whakatipu Trails Head	0.3	4.0E-03	0.08 (0)	0.3	2.0E-02	0.4 (0)	0.03	1.6E-01	3.2 (3)
	Gertrude Valley	0.3	4.0E-02	0.08 (0)	0.3	2.0E-01	0.4 (0)	0.03	1.6E+00	3.2 (3)
	The Chasm	0.3	1.6E-03	0.08 (0)	0.3	8.0E-03	0.4 (0)	0.17	6.4E-02	3.2 (3)
Maximum credible landslide	Site	N=>1			N=>5			N=>40		
		P(S:T)	APLL	Estimated fatalities	P(S:T)	APLL	Estimated fatalities	P(S:T)	APLL	Estimated fatalities
	Freshwater Basin	0.3	3.3E-04	1	0.3	1.7E-03	5	0.33	1.3E-02	40
	Visitor Hub	1.0	5.0E-04	0.5 (1)	1.0	2.5E-03	2.5 (3)	0.50	2.0E-02	20
	Milford Sound Lodge	1.0	5.0E-04	0.5 (1)	1.0	2.5E-03	2.5 (3)	0.50	2.0E-02	20
	Little Tahiti	1.0	2.5E-04	0.25 (0)	1.0	1.3E-03	1.25 (1)	0.25	1.0E-02	10
	Countess Range Hut	1.0	1.0E-03	1	0.3	1.3E-03	5	0.04	4.0E-02	40
	Te Huakaue Knobs Flat	1.0	7.5E-04	0.75 (1)	1.0	3.8E-03	3.75 (4)	1.00	3.0E-02	30
	Ōtāpara Cascade Creek	1.0	7.5E-04	0.75 (1)	0.5	1.9E-03	3.75 (4)	0.50	3.0E-02	30
	The Divide	0.3	2.5E-04	0.75 (1)	0.3	1.3E-03	3.75 (4)	0.29	1.0E-02	30
	Whakatipu Trails Head	0.3	2.5E-04	0.75 (1)	0.3	1.3E-03	3.75 (4)	0.03	1.0E-02	30
	Gertrude Valley	0.3	3.3E-04	1	0.3	1.7E-03	5	0.03	1.3E-02	40
	The Chasm	0.3	2.5E-04	0.75 (1)	0.3	1.3E-03	3.75 (4)	0.17	1.0E-02	30

5.2.3 *TRACKS*

5.2.3.1 TSUNAMI

For tracks in the Milford Sound near the shoreline (Cleddau Delta walking tracks, Hine-te-awa Lower Bowen Falls Track) visitor and worker exposure to tsunami is likely to be less than at point sites, however, the risk is still considered to be 'moderate' to 'substantial'.

The Milford Sound Lodge to Tutoko River Suspension Bridge Track is likely to only be impacted by the largest tsunami events and exposure is low. Hence, we consider tsunami risk here to be 'low' to 'moderate'.

5.2.3.2 LANDSLIDE

Visitors and workers on walking and cycling tracks in the MOP are exposed to landslide risk.

Table 32 describes landslide hazard at each track in terms of estimated volume, runout potential ($P_{(T:H)}$), vulnerability ($V_{(D:T)}$), and probability ($P_{(H)}$). As we have classified landslide probability as a range in this report, $P_{(H)}$ is given with a lower and upper value.

The 'most likely' landslide event considers smaller failures with less consequence than the 'maximum credible' landslide event at each site.

The findings below do not account for existing mitigation. This is deemed to be conservative, however, risk mitigation options at several of these tracks should be explored and evaluated.

Table 32: Estimated most likely and maximum credible landslide events at each track.

Site	Most likely event					Maximum credible event				
	Volume class	$P_{(T:H)}$	$V_{(D:T)}$	$P_{(H)}$		Volume class	$P_{(T:H)}$	$V_{(D:T)}$	$P_{(H)}$	
				Lower	Upper				Lower	Upper
Countess Range Track	2	0.01	0.8	5.0E-02	5.0E-01	6	1	1	1.0E-04	1.0E-03
Gertrude Valley Track	2	0.1	0.8	5.0E-02	5.0E-01	6	1	1	1.0E-04	1.0E-03
Hinepipiwai Lake Marian Loop Track	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
Te Anau Downs to the Divide Cycle Trail	3	0.1	0.8	5.0E-02	5.0E-01	6	0.75	1	1.0E-04	1.0E-03
Te Huakaue Knobs Flat Short Walks	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
Gunn Nature Trail	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
Key Summit to Ōtāpara Cascade Creek Track	3	0.1	0.8	1.0E-02	5.0E-02	6	0.75	1	1.0E-04	1.0E-03
The Chasm to Cleddau Horse Bridge Track	3	0.1	0.8	5.0E-03	2.0E-02	6	0.75	1	1.0E-04	1.0E-03
Milford Sound Lodge to Tutoko River Bridge Track	3	0.02	0.8	1.0E-03	1.0E-02	7	0.5	1	1.0E-04	1.0E-03
Hine-te-awa Lower Bowen Falls pontoon and tracks	3	0.2	0.8	5.0E-02	1.0E-01	7	1	1	1.0E-04	1.0E-03
Hine-te-awa Upper Bowen Falls tracks	3	0.2	0.8	5.0E-02	1.0E-01	7	1	1	1.0E-04	1.0E-03

Table 33 below presents the estimated IRPD and AIFR for tracks in the MOP.

Visitor risk (IRPD) is assessed as:

- 'moderate' to 'substantial' for the Gertrude Valley Track, Hinepipiwai Lake Marian Loop Track, Te Anau Downs to the Divide cycle trail, and the Hine-te-awa Bowen Falls Tracks,
- 'low' to 'moderate' for the Countess Range Track, Te Huakaue Knobs Flat Short Walks, Gunn Nature Trail, Key Summit to Ōtāpara Cascade Creek Track, and the Chasm to Cleddau Horse Bridge Track,
- 'low' for Milford Sound Lodge to Tutoko River Bridge Track.

Worker risk (AIFR) is assessed as:

- 'moderate' to 'high' for the Te Anau Downs to the Divide cycle trail and the Hine-te-awa Bowen Falls Tracks,
- 'moderate' for Countess Range Track, Key Summit to Ōtāpara Cascade Creek Track, and Chasm to Cleddau Horse Bridge Track,
- 'low' to 'moderate' for the Gertrude Valley Track, Te Huakaue Knobs Flat Short Walks, and Gunn Nature Trail.

Table 33: Visitor (IRPD) and worker risk (AIFR) for landslides on tracks in the MOP. *Exposure ($P_{(S:T)}$) to each landslide event has been estimated for each entire track. *Combined includes both the most likely and maximum credible events.

Site	P(S:T) – total*		IRPD – combined*		P(S:T) -total*		AIFR – combined*	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Countess Range Track	5.7E-05	3.4E-04	2.9E-08	1.7E-06	3.0E-03	1.8E-02	1.5E-06	8.9E-05
Gertrude Valley Track	2.3E-06	5.7E-05	9.4E-09	2.3E-06	1.2E-04	3.0E-03	4.9E-07	1.2E-04
Hinepipiwai Lake Marian Loop Track	3.4E-04	3.4E-04	3.0E-07	1.6E-06	1.8E-02	1.8E-02	1.6E-05	8.5E-05
Te Anau Downs to the Divide Cycle Trail	3.4E-04	3.4E-04	1.4E-06	1.4E-05	1.8E-02	1.8E-02	7.3E-05	7.3E-04
Te Huakaue Knobs Flat Short Walks	2.3E-06	5.7E-05	2.0E-09	2.7E-07	1.2E-04	3.0E-03	1.0E-07	1.4E-05
Gunn Nature Trail	2.3E-06	5.7E-05	2.0E-09	2.7E-07	1.2E-04	3.0E-03	1.0E-07	1.4E-05
Key Summit to Ōtāpara Cascade Creek Track	5.7E-05	3.4E-04	5.0E-08	1.6E-06	3.0E-03	1.8E-02	2.6E-06	8.5E-05
The Chasm to Cleddau Horse Bridge Track	5.7E-05	3.4E-04	2.7E-08	8.0E-07	3.0E-03	1.8E-02	1.4E-06	4.2E-05
Milford Sound Lodge to Tutoko River Bridge Track	2.3E-06	5.7E-05	1.5E-10	3.8E-08	1.2E-04	3.0E-03	7.8E-09	2.0E-06
Hine-te-awa Lower Bowen Falls pontoon and tracks	5.7E-05	3.4E-04	4.6E-07	5.8E-06	3.0E-03	1.8E-02	2.4E-05	3.0E-04
Hine-te-awa Upper Bowen Falls tracks	5.7E-05	3.4E-04	4.6E-07	5.8E-06	3.0E-03	1.8E-02	2.4E-05	3.0E-04

6 RISK MITIGATION

6.1 TSUNAMI

The tsunami risk assessment presented in this report has concluded that risk mitigation should be considered at the Milford Sound Piopiotahi sites (Cleddau Delta, Deepwater Basin, Freshwater Basin, Visitor Hub, Milford Sound Lodge, and Little Tahiti).

There are several strategies and approaches to managing tsunami risk, these generally align to either 'soft' (e.g. evacuation, education, and early warning systems) or 'hard' (e.g. engineered protection structures, vertical evacuation structures) measures.

Mitigation measures are typically refined through detailed design and incorporate both hard and soft measures. It is recommended that the MOP proposals be reviewed in light of this assessment and further discussions and refinement of the proposals be made in line with the following observations.

6.1.1 'SOFT' RISK MITIGATION MEASURES

A formal evacuation plan based on further tsunami modelling from a variety of sources would potentially reduce the life risk at the MOP sites in Milford Sound, Piopiotahi.

This would be a logical first step and could be implemented promptly. However, Harris (2023) noted that this is unlikely to be effective for the vast majority of landslide-induced tsunami due to the 2–7-minute arrival time of tsunami waves at the shore in Milford Sound.

Harris (2023) calculated that 0.1% to 5.2% of people under the existing evacuation plan would be safely evacuated to evacuation points (Figure 13) during the longest wave arrival time scenario. The major factors in successful evacuation were the evacuees' speed of travel and origin locations, and high population exposure resulting in congestion. This study recommended focusing efforts on education (increasing signage) and relocating accommodation away from the Cleddau Delta to further mitigate the risk.

The feasibility of upgrading existing and developing further evacuation points could be investigated and may help to increase evacuation effectiveness when coupled with increased education. Any evacuation route should be wide, clearly sign-posted, direct, and easily accessible. It should be noted that evacuation routes and points are also subject to natural hazard risk which should be considered when determining locations.

The Freshwater Basin Ferry Terminal is a point of high risk. An additional evacuation point east of the terminal building 50 m up the slope could reduce risk (Figure 13). This would require the construction of a track and elevated platform designed to accommodate high pedestrian numbers and sufficient holding space.

The lookout track east of the Visitor Hub serves as the evacuation point for the nearby accommodation facilities. Congestion has been noted as a concern for this route. This track could be upgraded to be more conducive to efficient evacuation.

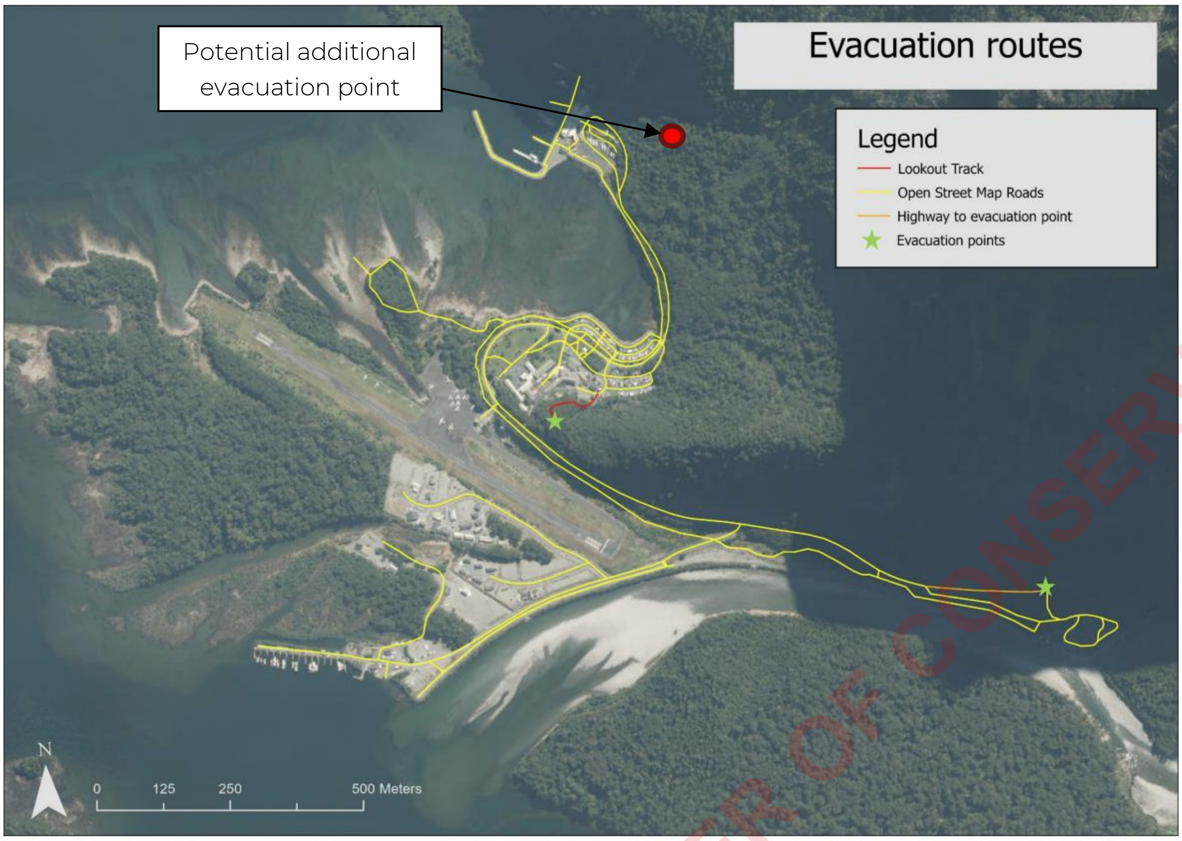

Figure 6. The available routes for evacuee agents to use.

Figure 13: Current evacuation points and routes in Milford Sound modelled in the Harris (2023) study with annotation from WSP denoting an additional evacuation point. Source: Harris (2023).

Early warning systems that are commonly used throughout the world are unlikely to be effective in the Milford Sound context as local source tsunamis have such limited time between formation and impact. It is unlikely that officials would be able to issue any warnings before the waves arrive onshore. Educating the public about evacuating as soon as long or strong ground shaking is felt is therefore likely to be more effective. However, detailed tsunami modelling could consider the relative impact of far-field tsunami such as a subduction zone earthquake, for which early warning systems may be practical. Modelling of tsunami wave occurrence is however not straightforward and is likely to be complicated further by building locations, variations in geomorphology along the fiord and tidal considerations. Modelling is also likely to be subject to multiple variations in opinion and peer review.

Shaking from an Alpine Fault rupture further afield may take several minutes to reach Milford Sound and trigger a landslide. Mitigation measures could consider an early warning system for distant Alpine Fault rupture and earthquakes.

It should be noted that any increase in public understanding of tsunami risk and evacuation procedures is likely to lower life risk in Milford Sound through increasing evacuation effectiveness. Visitors may also choose to spend less time in Milford Sound or avoid the low-lying areas around the delta thus reducing exposure. Increased signage and implementing evacuation briefings could also be explored as part of the visitor experiences.

6.1.2 'HARD' RISK MITIGATION MEASURES

Vertical evacuation structures for tsunamis such as those constructed in the United States and Japan may contribute to the lowering of tsunami risk in Milford Sound. This is most likely to be effective at the Visitor Centre where the roofs of the existing three-storey buildings could be retrofitted as evacuation points. Vertical evacuation structures could also be considered at Freshwater Basin, Deepwater Basin, and the Cleddau Delta, however, would need to be significantly higher than the current buildings to mitigate the risk from the potential tsunami waves which have a potential wave amplitude up to ~10 m (Taig & McSaveney, 2015).

Entrained debris within tsunami waves (rocks, trees, boats, cars etc) are likely to place extreme demands on any vertical evacuation structures. The structural integrity of the existing buildings in Milford Sound Piopiotahi and any proposed vertical evacuation structure would need to be considered in evaluating the ability to survive the impact of tsunami waves.

Any vertical evacuation structures should consider ample evacuation routes and structure floor space to increase evacuation effectiveness. Furthermore, the short arrival time of landslide-induced tsunami waves should be considered when determining the effectiveness of vertical evacuation structures.

Seawalls and Dykes are considered to be unrealistic in the Milford Sound Piopiotahi context due to the size of the structures required being in stark contrast to the natural setting. This type of heavy infrastructure is not considered to be in keeping with the intent of any redevelopment at Milford Sound.

The first tsunami vertical structure in the United States: Ocosta Elementary School, Westport, Washington. The building is designed to withstand an earthquake and has a flat roof over the gym to accommodate up to 1,000 students and community members from a resulting tsunami. Source: Pete Eckert, Eckert & Eckert Photography
Download Image

Figure 14: A school building with a rooftop vertical evacuation structure for tsunami in Washington, USA.

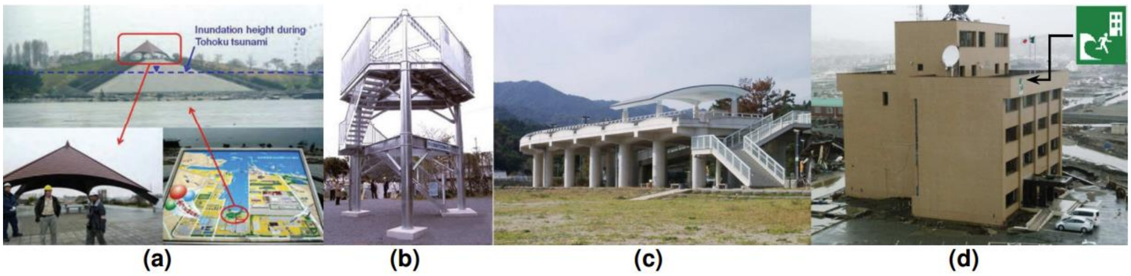

Fig. 4 – Tsunami evacuation structures (FEMA P-646, 2012): (a) soil berm at Sendai, Japan; (b) Life-Saving Tower; (c) Minamisanriku, Japan; and (d) Kesennuma Port, Japan

Figure 15: A range of tsunami vertical evacuation structures in Japan.

Any development at Little Tahiti should consider tsunami risk. Little Tahiti is located on a low-lying flood plain and is at least 300 m away from any notable increase in elevation. Vertical evacuation structures on top of any new buildings may be an appropriate risk treatment at this site.

6.2 LANDSLIDE

The landslide risk assessment completed herein has identified that risk mitigation should be considered at all sites except Cleddau Delta and Deepwater Basin.

The MOP sites are exposed to several different types of landslide hazards including rockfall/rock avalanche, treeslides, and debris flow/flood. Mitigation options usually depend on the type and scale of the hazard that is being addressed while feasibility will depend on site characteristics/conditions and financial controls. As with tsunami, the most effective mitigation strategy for landslides is considered to be through reducing exposure through education, increased signage, and avoidance of hazard-prone areas.

In the first instance, a detailed understanding of landslide susceptibility at each site is required to assess which mitigation options would be effective. Computational modelling of landslide source areas and runout zones would be required in order to understand the hazard footprint and likely impact forces. This can then inform mitigation strategies and highlight areas of key risk.

Detailed design can consider the hazard footprint and associated impact forces and can then either adopt avoidance or reduction measures to reduce the risk levels. This could be a relocation of a track position to avoid a rockfall site or elevating a bridge crossing to avoid a debris flow channel.

Risk mitigation for rockfall/rock avalanche may include source area treatment (risk feature removal, encapsulation or removal) or point protection through the development of catch fences, bunds drainage ditches or overflow channels. Increased barriers/signage (Figure 16) also reduce risk.

For smaller-scale rockfall hazards at MOP sites, these mitigation options may be appropriate. For larger rockfall and rock avalanches, bunds and earthworks may be appropriate engineering solutions, however, avoidance of hazard-prone areas where possible should be prioritised.

Rockfall and rock avalanche could be a potential hazard anywhere in the study area, however, the Gertrude Valley, Whakatipu Trails Head, and the Countess Range Hut are assessed as sites that may have a high risk of these landslide types. Avoidance of areas near steep and fractured rock faces, talus deposits, and active rock avalanche fans should be prioritised at these sites. Bunding and catch fences may be appropriate in some areas to isolate hazard zones (Figure 17). Slope modelling and site investigations should inform any engineered solution at these sites once detailed designs have been developed.

Treeslides are also likely to occur anywhere in the study area but are generally prevalent on steep, heavily vegetated slopes with shallow soil/bedrock contact. Freshwater Basin, Visitor Hub, and Milford Sound Lodge are highlighted as sites where there are frequent treeslides. Treeslides are difficult to mitigate due to the uncertainty of occurrence and scale of these hazards. Avoidance of areas at the bottom of steep vegetated slopes such as the area north of the Freshwater Basin ferry terminal and north of the Milford Road at Milford Sound Lodge are considered the most likely solutions that would reduce risk. The development of hard-engineered solutions for these hazards are generally associated with high costs, extensive source area risk reduction work (removal) and ongoing high maintenance costs.

Figure 16: Examples of rockfall and landslide mitigation. Left: A rockfall catch fence in Kaikoura. Source: Geofabrics. Right: A rockfall bund along a road. Source: NZGS

Debris flow hazards can be mitigated in a similar manner to rockfall and flood hazards depending on how fluid-like the flow is likely to be. For debris-dominated flows, bunding and catch fences may be appropriate. For fluid-dominated flows which are likely at Te Huakaue Knobs Flat and Ōtāpara Cascade Creek, mitigation could include upgrading and extending the existing stop banks. This should be informed by debris flow and flood modelling in the surrounding catchments. Site closure during extreme weather events will minimise the risk also.

Figure 17: The rockfall bund and catch fence at Loop 2 on the Milford Road.

6.3 FLOODING

Additional site-specific flood modelling is recommended for Mackay Creek DOC Campsite, Te Huakaue Knobs Flat, Ōtāpara Cascade Creek, Whakatipu Trails Head, Gertrude Valley, The Chasm, Little Tahiti, Milford Sound Lodge, Cleddau Delta, and Deepwater Basin. Flood modelling should inform detailed design aspects of the proposed structures, such as floor slab levels, drainage considerations and further mitigation if required. Flood mitigation can include but is not limited to:

- Hazard information – signage
- Avoidance of flood-prone areas for any new developments
- Bridging watercourses
- Flood modelling
- Site closure
- Stop banks and levees
- Rock armouring
- Gravel removal/re-routing of river channel

6.4 AVALANCHE

The following sites are identified as predominantly Day Visitor (DV) sites exposed to avalanche hazards; Gertrude Valley Node 6, Gertrude Valley Loop Track, The Chasm, Chasm to Cleddau Horse Bridge Track. For these sites, the following risk mitigation measures are recommended:

- Avalanche path mapping and avalanche hazard index (AHI)
- Move tracks out of avalanche paths if possible.
- Applying outcomes of AHI scores:
- Signs at paths
- Temporary closures
- Active control Information at track ends, huts, visitor centres, website and publications
- Avalanche hazard advisories where practical.

The proposed Countess Range Hut and Track are currently classified as Back Country Comfort-Seeker (BCC) sites exposed to avalanche hazards. For the Countess Range Hut and Track, the following risk mitigation measures are recommended:

- Avalanche assessment (AHI) and path mapping of hut sites and proposed track.
- Do not build huts, track endpoints, or car parks in avalanche paths.
- Where tracks need to cross avalanche paths look for ways to minimise the length of track in avalanche path.
- Where structures are needed in avalanche paths to minimise other risks, the encounter probability over the life of the structure and the costs versus benefits of permanent versus temporary/seasonal structures needs to be considered.
- Provide information to users if low risk.

If these sites are developed for lower-skilled and risk tolerance visitors, additional and ongoing avalanche management needs to be considered.

Whilst it is understood that known avalanche hazards along the Milford Road are limited to areas west of the divide (MRA, 2023), proposals including the Countess Range track and hut development are located above the tree line in areas that are prone to heavy snowfall. Avalanche paths are not known to impact the Countess Range proposals however further assessment and consideration of this hazard is considered prudent in developing mitigation measures akin to those adopted for the Routeburn Track, namely the completion of an AHI together with the implementation of appropriate control measures.

In the Part A report two additional sites on the Milford Road (Homer Tunnel and Cleddau Cirque) were identified as having avalanche risk. Avalanche risk at these sites is managed by the MRA.

In terms of the Stage 3 aims regarding feasibility, the identification of avalanche hazards at the location of several MOP sites does not render the site proposals unfeasible.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

— This risk assessment has confirmed that the greatest natural hazard risk facing MOP is the risk of landslide-induced tsunami impacting Milford Sound Piopiotahi and associated infrastructure.

— The risks posed by other natural hazards (landslides, treeslides, avalanches, flooding) can be managed using existing DOC management strategies.

— The most likely trigger for a large, rapid landslide into Milford Sound Piopiotahi is a large, nearby earthquake such as AF8, which has an estimated 75% probability of occurring within the next 50 years and an increasing likelihood as time passes (cumulative probability).

— A large, rapid landslide into Milford Sound Piopiotahi triggered by an AF8 earthquake could generate a tsunami wave ≥ 5m high at the shoreline, arriving within a few minutes after the trigger event.

— Such an event has the potential to cause a large number of deaths. Our estimates for number of fatalities from a landslide-induced tsunami in Milford Sound Piopiotahi for the different population at-risk scenarios are as follows:

  — When the population at risk is 1, we estimate there to be 1 fatality.

  — When the population at risk is 50 (assumed to represent the low season exposure in Milford Sound Piopiotahi), we estimate there to be 21-45 fatalities.

  — When the population at risk is 2000 (assumed to represent the high season exposure in Milford Sound Piopiotahi), we estimate there to be 840-1800 fatalities.

  — When the population at risk is 3000 (assumed to represent the forecasted high season exposure in Milford Sound Piopiotahi in 2050), we estimate there to be 1260-2700 fatalities.

— Potential tsunami risk mitigation options at sites could include:

  — Clear and coordinated evacuation planning.

  — Increasing evacuation points and routes.

  — Education.

  — Early warning systems.

  — Vertical evacuation structures.

These will need to be explored and developed further through detailed design and consultation.

7.2 RECOMMENDATIONS

This report has presented a natural hazard risk assessment for MOP nodes, short stops and walking/cycling tracks. Several assumptions have been made that could be refined by further work. To further understand the hazard risk in the study area and reduce the uncertainty around the results presented in this report we recommend the following:

- Detailed hazard analysis including computational modelling for sites where there is a 'moderate' level of risk or above.
  - This could include landslide-induced and offshore tsunami modelling in Milford Sound Piopiotahi and landslide runout modelling for MOP sites.
  - This will help to focus mitigation efforts.
- Further hazard analysis for sites where there is a flooding or avalanche risk.
  - This could include flood modelling in the Cleddau, Tutoko, and Eglinton River valleys and avalanche path mapping at Gertrude Valley Node 6, Gertrude Valley Loop Track, The Chasm, Chasm to Cleddau Horse Bridge Track, Hinepipiwai Lake Marian Loop Track, Countess Range Hut, and Countess Range Track.
- Refining individual exposure for further analysis and reducing exposure where there is 'substantial' risk.
- Undertake a risk tolerance assessment for societal risk to determine overall risk tolerability and risk tolerance thresholds.
  - This will involve assessment of the known risk against timeframes and climate change implications, consequences, life safety risk after risk reduction measures, stakeholders (who bear the consequences of the risk or risk mitigation measures), and engagement/perceptions of the risk and risk tolerance.
- Consider risk mitigation measures for tsunami hazard in Milford Sound Piopiotahi and landslide hazards at nodes, short stops, and tracks.

8 LIMITATIONS

This report ('Report') has been prepared by WSP New Zealand Limited ('WSP') exclusively for the Milford Opportunities Project (MOP) ('Client') in relation to a natural hazard risk assessment of the MOP sites ('Purpose') and in accordance with the revised reverse brief agreed with the MOP and the project instruction ('Agreement') dated November 2023. The findings in this Report are based on and are subject to the assumptions specified in the Report. WSP accepts no liability whatsoever for any use or reliance on this Report, in whole or in part, for any purpose other than the Purpose or for any use or reliance on this Report by any third party.

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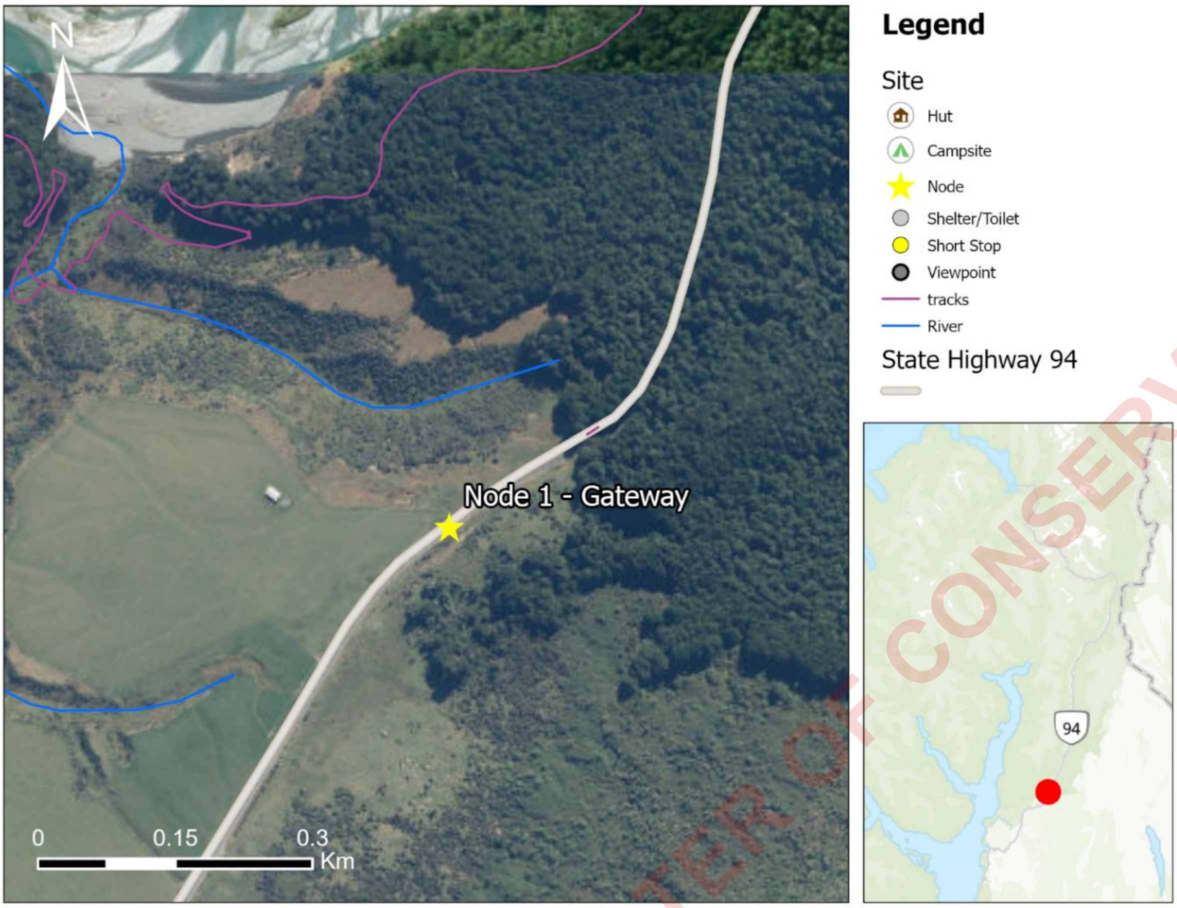
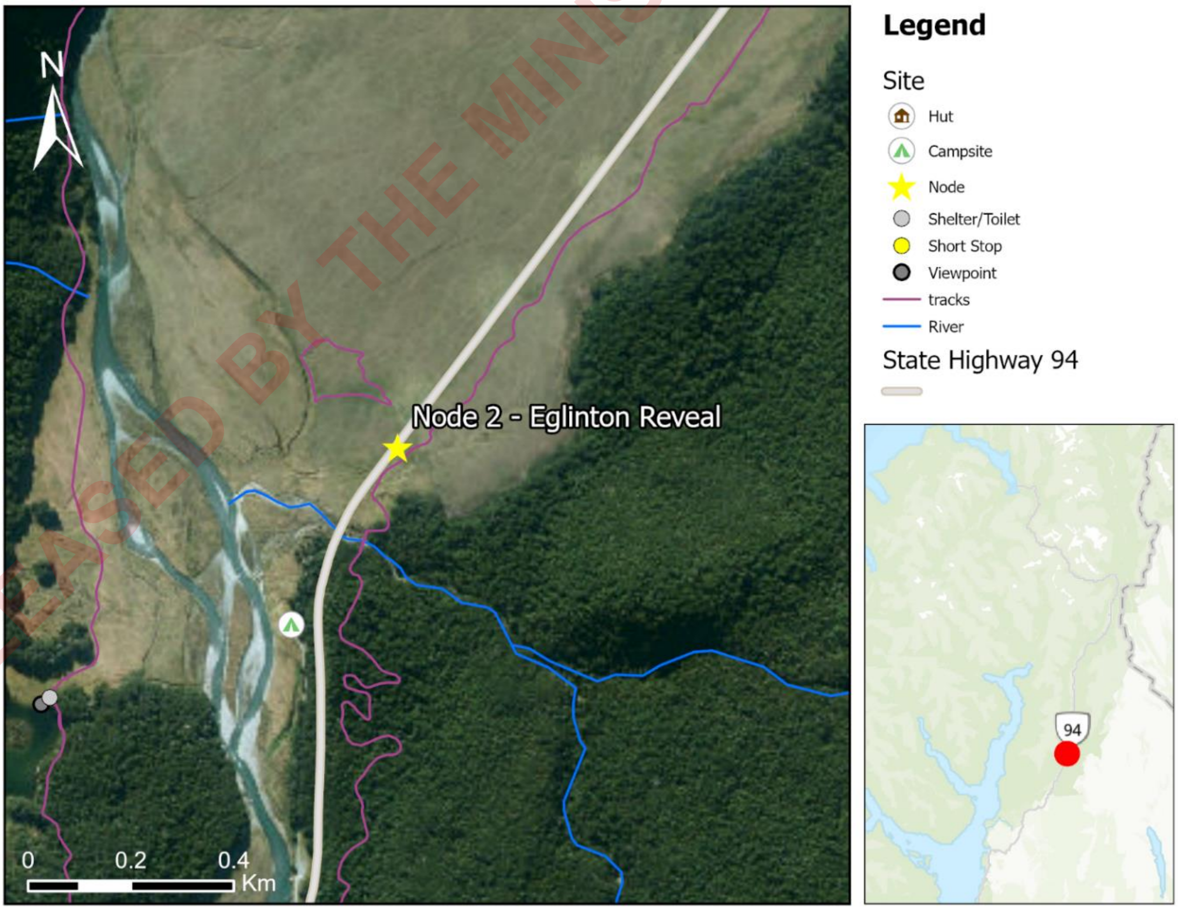
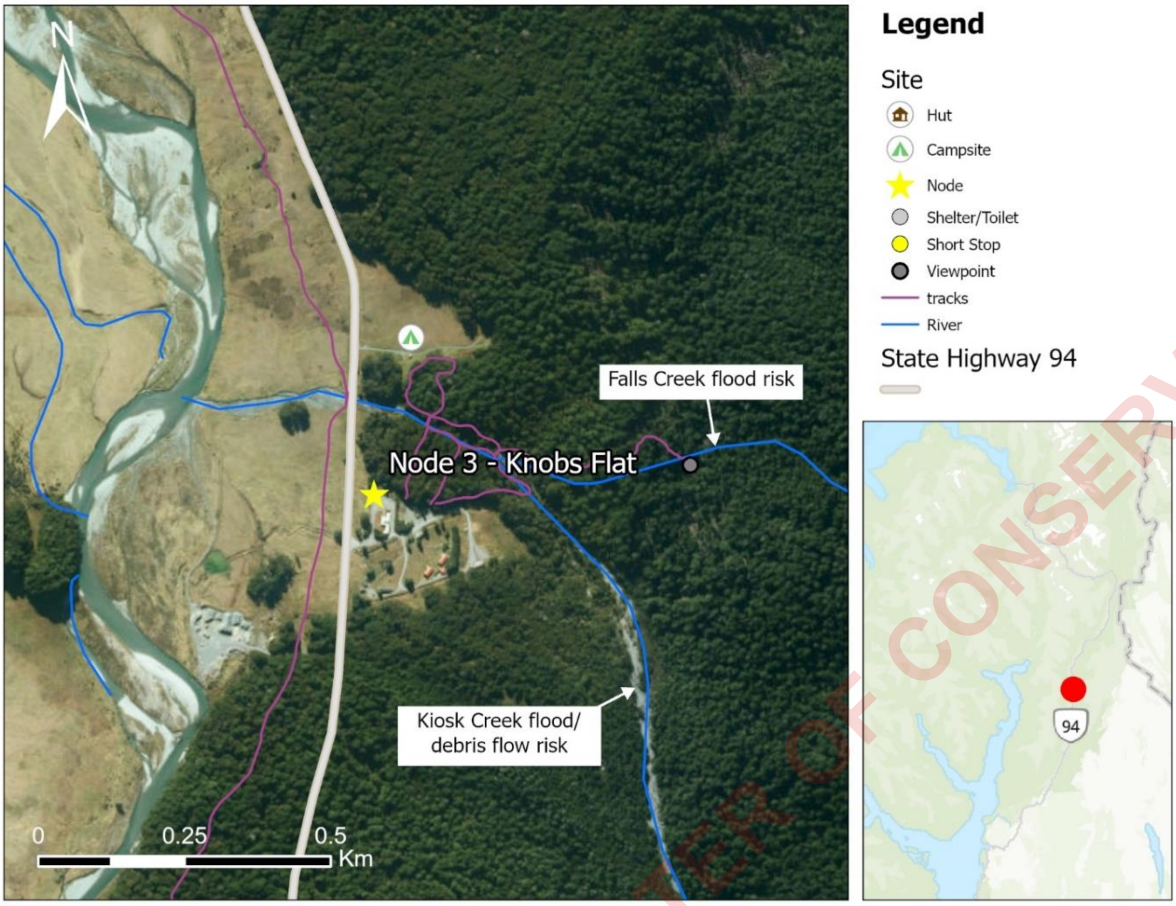
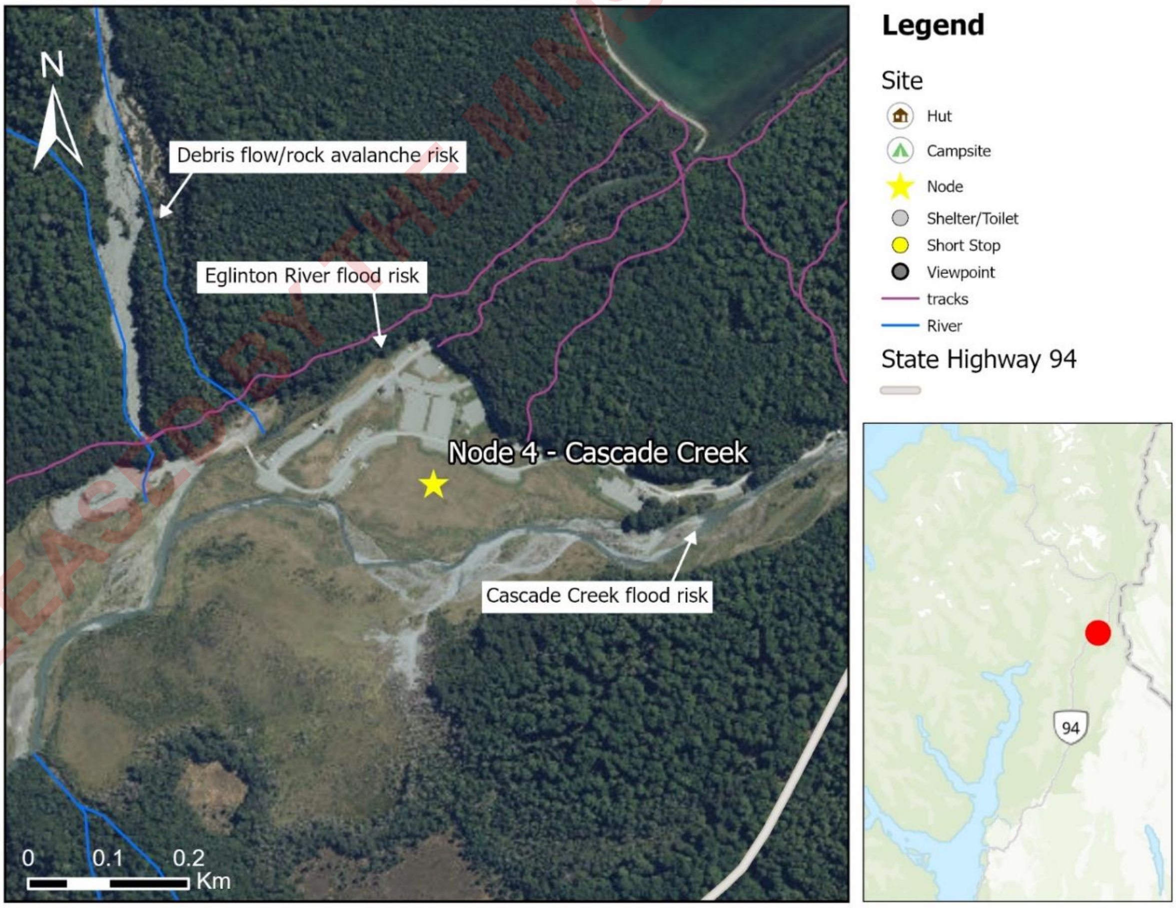
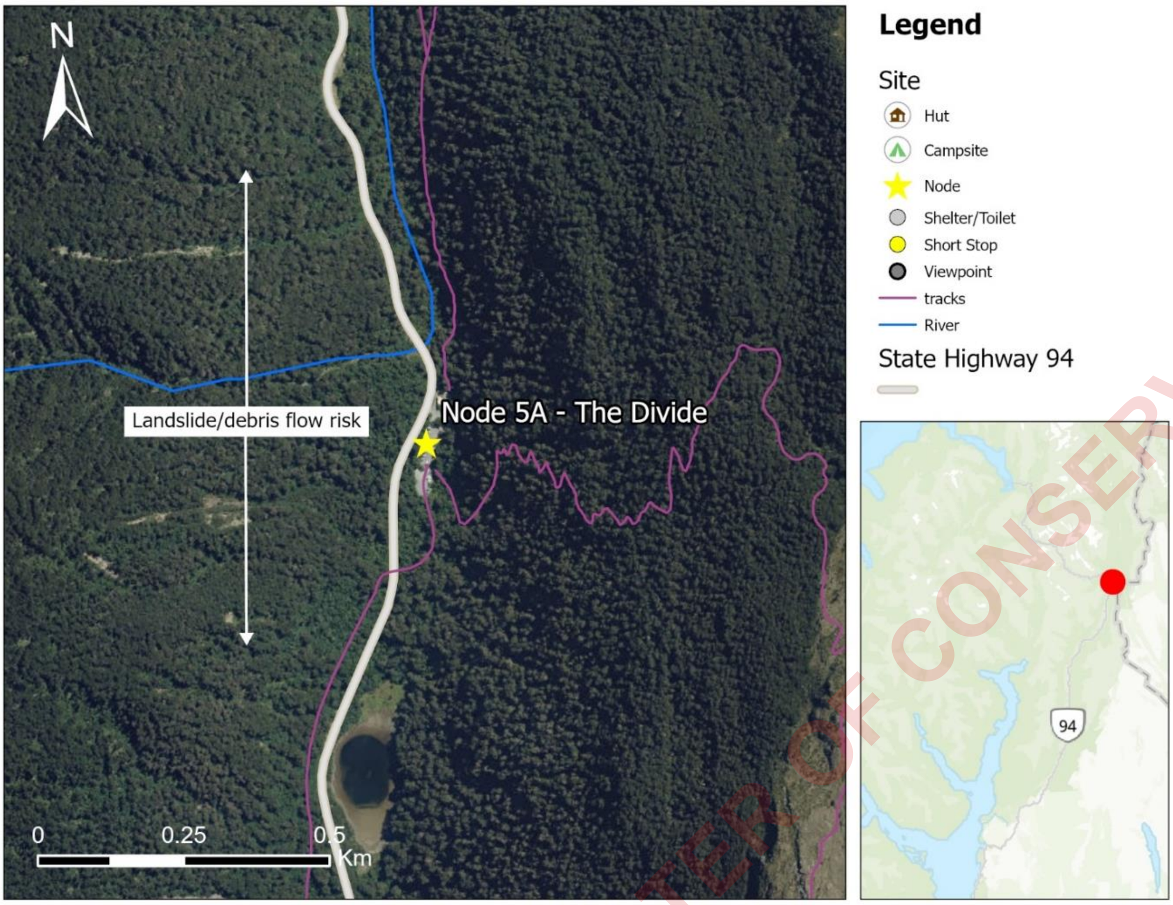
APPENDIX A – NODE SITE MAPS


N
Node 1 - Gateway
0
0.15
0.3
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94

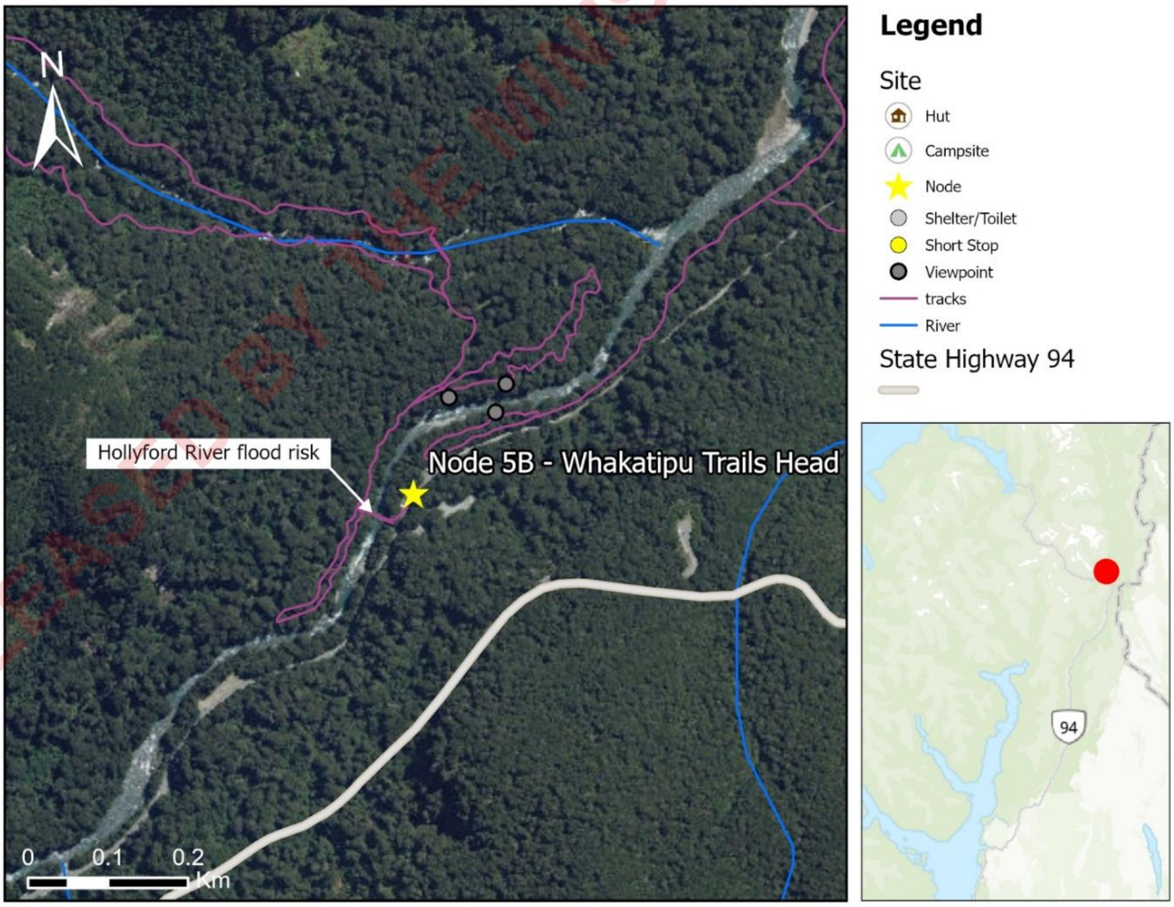

N
Node 2 - Eglinton Reveal
0
0.2
0.4
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94


N
Falls Creek flood risk
Node 3 - Knobs Flat
Kiosk Creek flood/
debris flow risk
0
0.25
0.5
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94

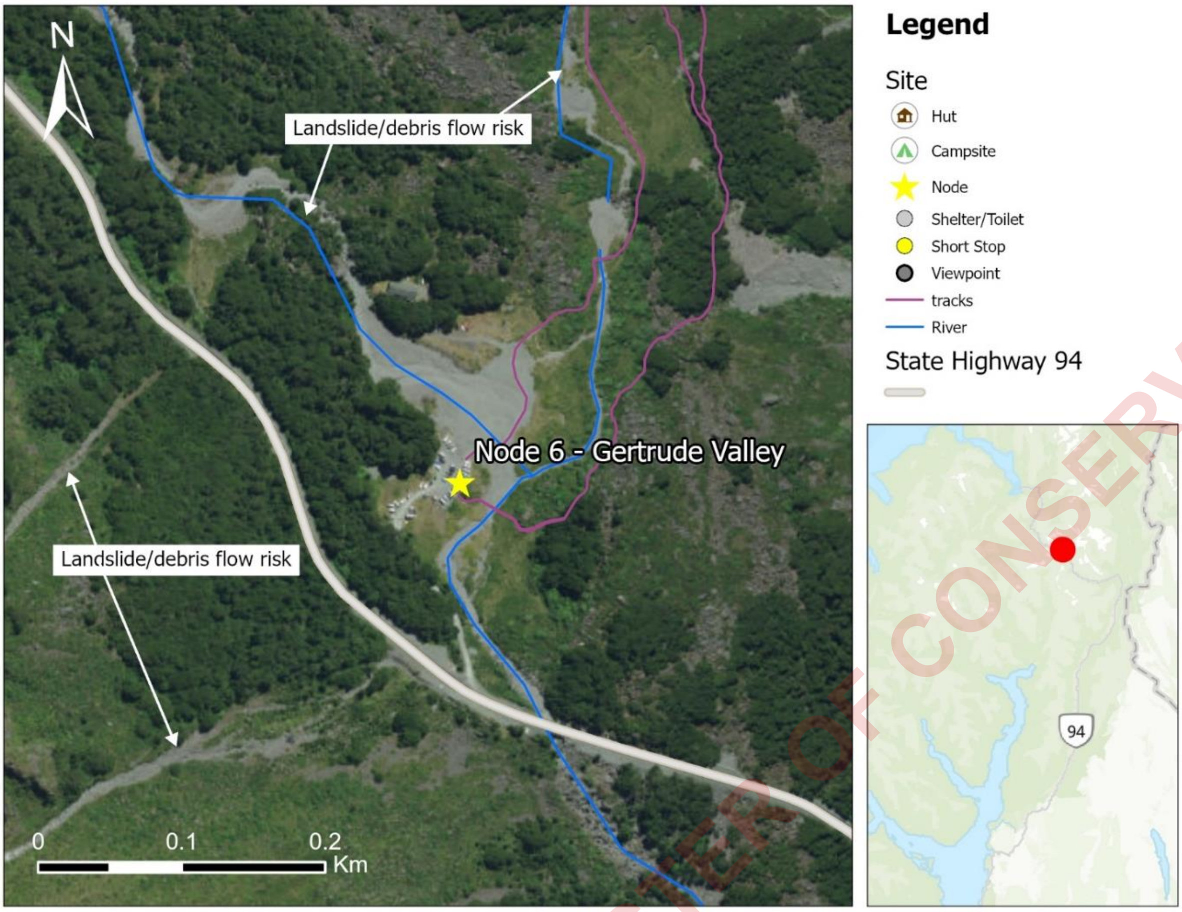

N
Debris flow/rock avalanche risk
Eglinton River flood risk
Node 4 - Cascade Creek
Cascade Creek flood risk
0
0.1
0.2
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94

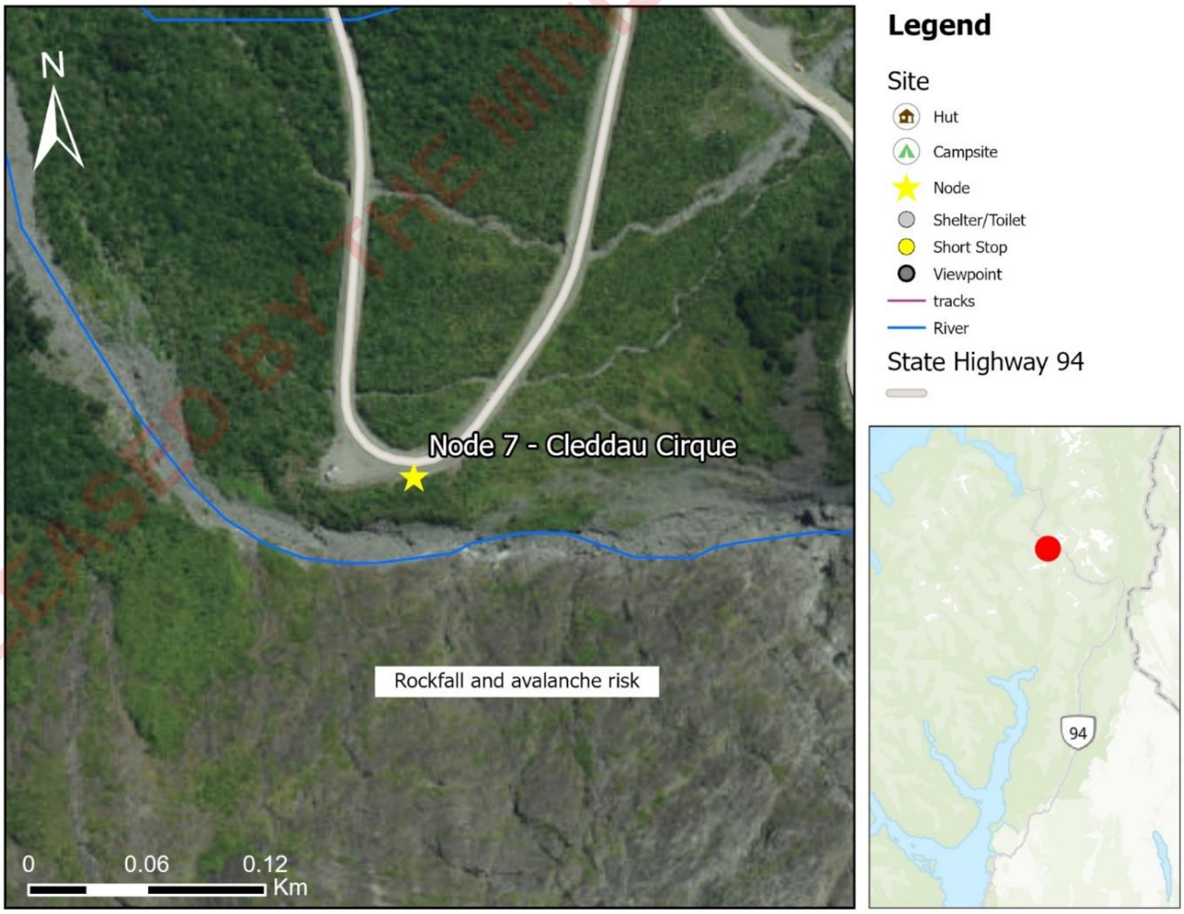


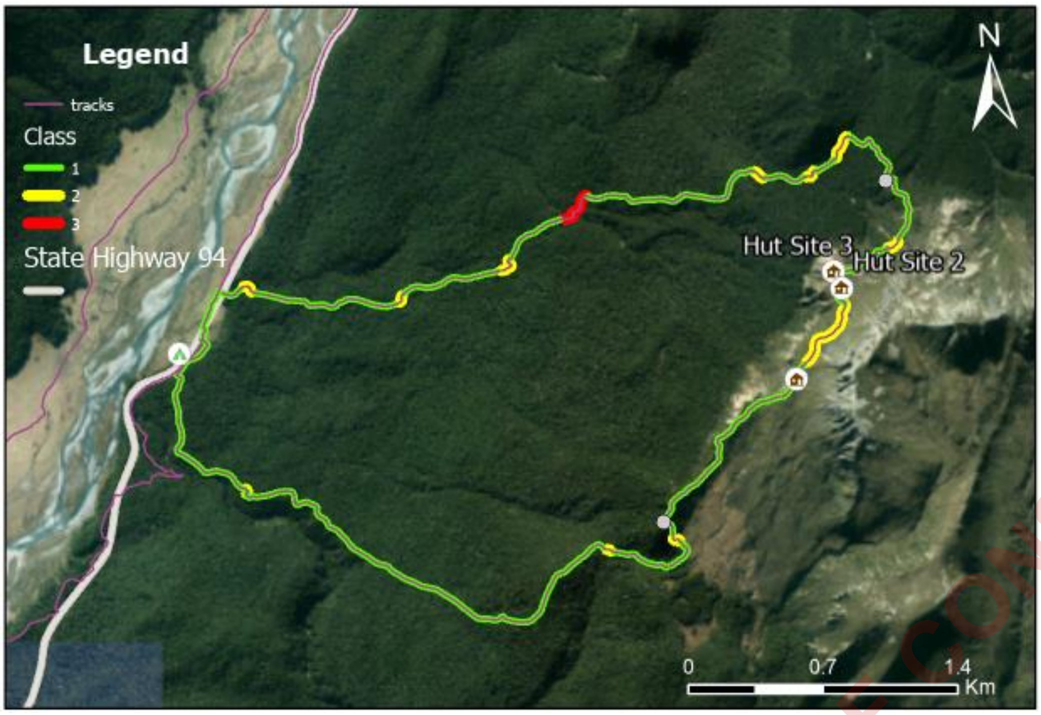
N
Landslide/debris flow risk
Node 5A - The Divide
0
0.25
0.5
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94



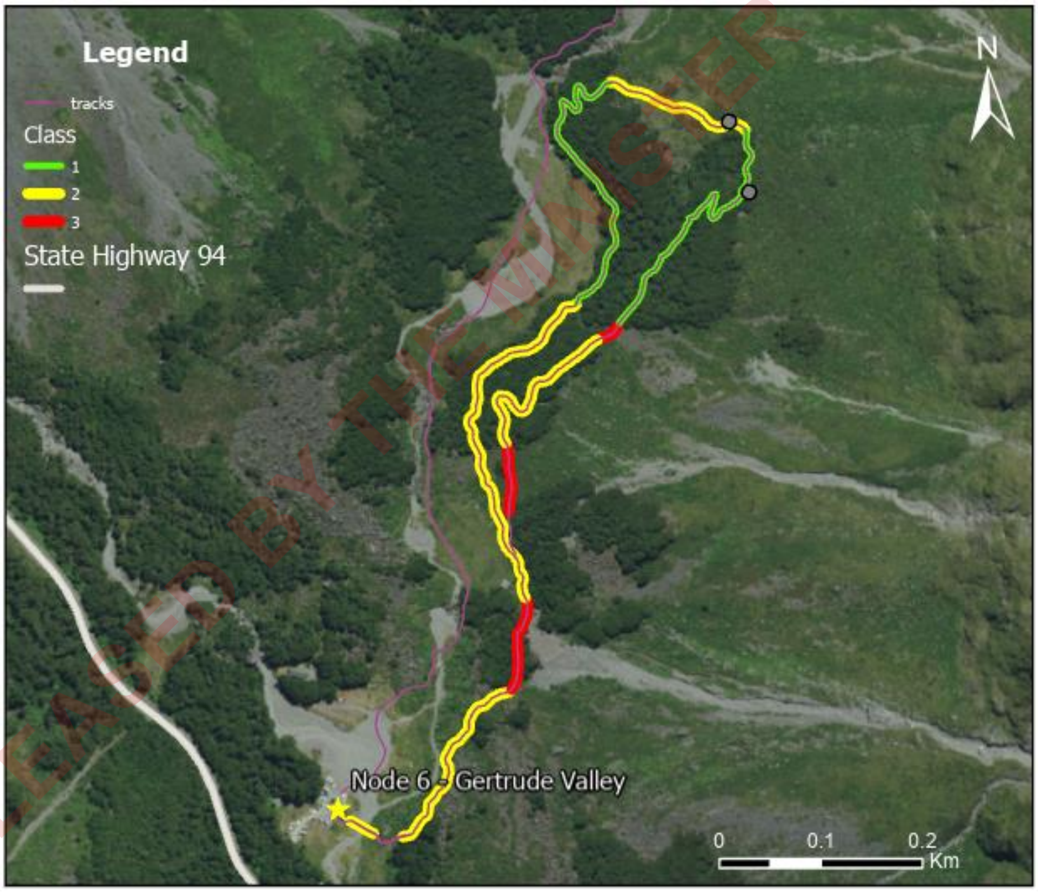
N
Hollyford River flood risk
Node 5B - Whakatipu Trails Head
0
0.1
0.2
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94


N
Landslide/debris flow risk
Node 6 - Gertrude Valley
Landslide/debris flow risk
0
0.1
0.2
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94

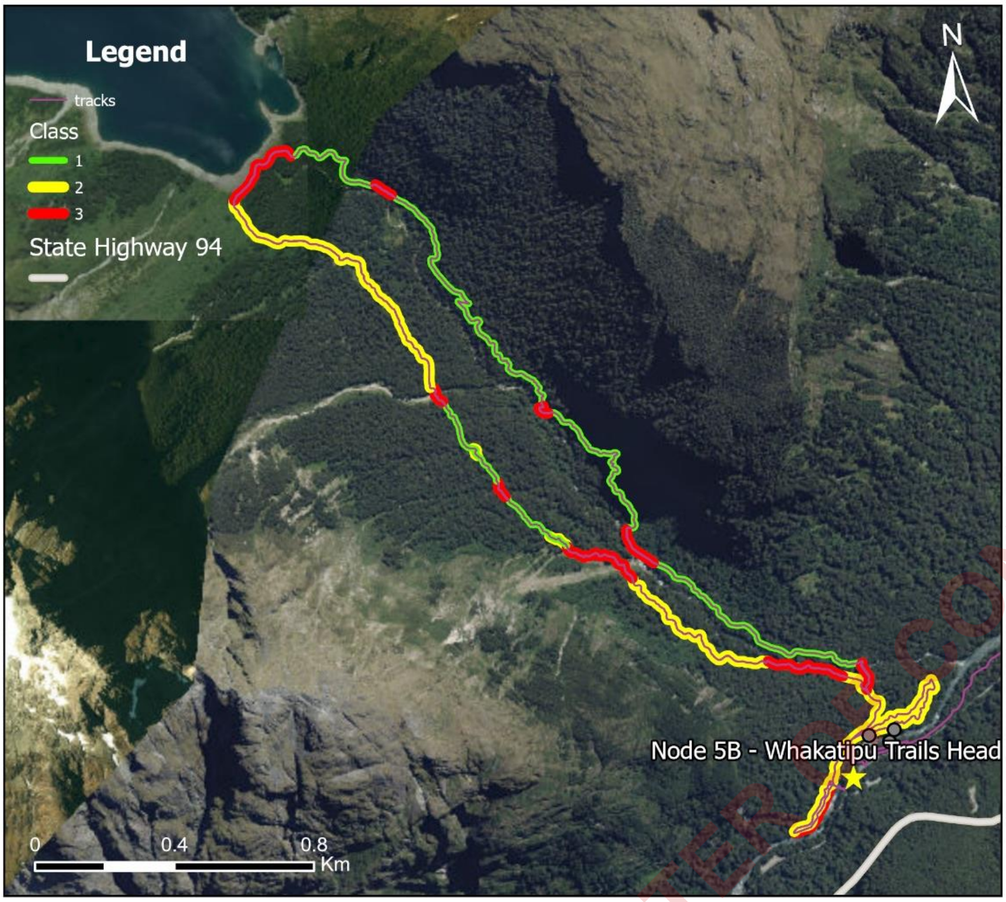

N
Node 7 - Cleddau Cirque
Rockfall and avalanche risk
0
0.06
0.12
Km
Legend
Site
Hut
Campsite
Node
Shelter/Toilet
Short Stop
Viewpoint
tracks
River
State Highway 94
94



Plan of the Countess Range Track with sections marked with Preliminary Assessed hazard Class.



The proposed Gertrude Valley Loop Track and associated viewpoints.



The Lake Marian Loop Track highlighted with preliminary hazard Classes for natural hazard risk.