Otago Regional Council

Roxburgh Debris Flow and Debris Flood Study

Hydrogeomorphic Modelling and Quantitative Risk Assessment Report

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Hydrogeomorphic Modelling and Quantitative Risk Assessment Report

Otago Regional Council

WSP New Zealand Limited
Wellington
L9 Majestic Centre
100 Willis Street
Wellington 6011, New Zealand
+64 4 471 7000
wsp.com/nz

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	NAME	DATE	SIGNATURE
Prepared by:	Harley Porter *Geohazards Analyst*	30/01/2026	
	Sophie Hill *Engineering Geologist*	30/01/2026	
Reviewed by:	Doug Mason *Principal Engineering Geologist*	30/01/2026	
	Tim McMorran *Technical Director – Engineering Geology*	30/01/2026	
Approved by:	Richard Woods *Service Line Leader – Risk & Resilience* *Project Director*	30/01/2026	

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GLOSSARY

Hydrogeomorphic hazard	A natural hazard arising from the interaction of hydrological processes (such as rainfall, runoff, flooding) and geomorphic processes (such as erosion, sediment transport, and mass movement).
Exposure	The situation of people, infrastructure, housing, production capacities, and other tangible human assets located in hazard-prone areas. It refers to what is at risk of being affected by a hazard.
Vulnerability	The conditions determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of an individual, community, assets, or systems to the impacts of hazards.
Risk	The potential for loss or damage when a hazard interacts with exposure and vulnerability.
Resilience	The ability of a system, community, or society exposed to hazards to resist, absorb, adapt to, and recover from their effects in a timely and efficient manner, while preserving essential structures and functions.
Mitigation	The lessening or minimizing of the adverse impacts of hazards and related disasters through structural measures (e.g. retaining walls, drainage) and non-structural measures (e.g. land-use planning, building codes).
Climate change	A long-term shift in global or regional climate patterns, primarily driven by human activities that increase greenhouse gas concentrations in the atmosphere.
RCP (Representative Concentration Pathway)	Representative Concentration Pathways are greenhouse gas concentration trajectories adopted by the IPCC for climate modelling and research.

EXECUTIVE SUMMARY

The Roxburgh area in Central Otago, New Zealand, is exposed to destructive flows of water and sediment from adjacent hillside catchments. These hydrogeomorphic hazards (also known as debris flows or debris floods) are triggered by high-intensity rainfall events and have a history of causing damage and disruption to the built environment in the town. The Otago Regional Council (ORC) requires detailed hazard and risk assessment of 13 catchments in Roxburgh to inform potential spatial planning, mitigation/adaptation options, and to understand the potential runouts of hydrogeomorphic events (Figure 1).

As part of this programme, WSP New Zealand Limited (WSP) has been engaged by ORC to complete hydrogeomorphic hazard modelling and risk assessment for 13 alluvial fans that lie adjacent to the Clutha River along the base of the Old Man Range in Roxburgh. The study has been carried out in stages, and this report presents the hydrogeomorphic modelling and the findings of the risk assessment for the 13 catchments.

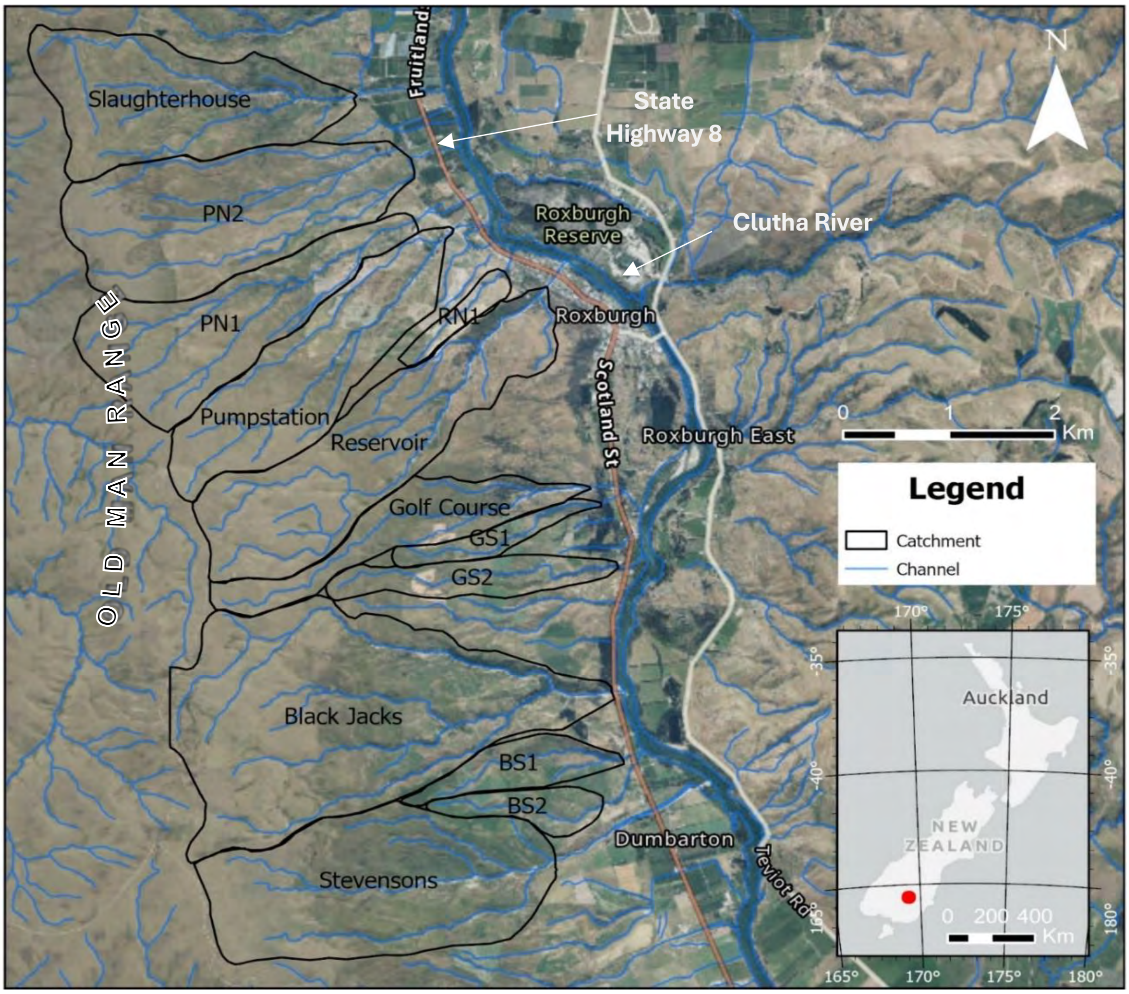


Figure 1: A map of the 13 catchments covered in this study.

HYDROGEOMORPHIC HAZARD ASSESSMENT AND MODELLING

This study assessed hydrogeomorphic hazards in Roxburgh, focusing on debris flows (sediment dominated) and debris floods (fluid dominated). Available geomorphic evidence indicates that the more fluid-dominated debris floods have been the dominant fan-forming process historically and the modelling has therefore been undertaken to represent this hazard type. Hydrogeomorphic hazard assessment consisted of the development of a historical debris flood inventory, geomorphological and hydrological assessments, frequency-magnitude assessment and interpretations, and numerical hydrogeomorphic modelling of debris flood runout from the 13 catchments and inundation over the alluvial fans. High likelihood (i.e. low impact), median likelihood, and low likelihood (maximum credible impact) scenarios were modelled for each of the 13 catchments. The modelling considered a Representative Concentration Pathway (RCP) 8.5 climate scenario as a worst-case scenario, where climate change is likely to increase the intensity, duration, and frequency of rainfall events in Roxburgh.

The catchments assessed in this study are generally steep, pasture or tussock covered, and actively eroding, with significant debris source material for future debris flood events. Apart from the urban area of Roxburgh township, the alluvial fans in the study area have largely been developed for horticulture and agriculture.

Several catchments and their alluvial fans in the study area have been impacted from historical debris floods and debris flows, affecting lifeline infrastructure, properties, and buildings. These events have led to infrastructure outages, particularly on State Highway (SH8) and water and electricity services, as well as damage to residential properties. The most widely documented event was the 2017 debris flood events which inundated several of the alluvial fans in this study with water and debris resulting in damage to property, buildings, and lifeline infrastructure. Culverts along SH8 have historically impeded debris floods, causing inundation upstream and laterally from the culvert location in the channels. Upgrades to several culverts were made following debris floods in November 2017 to enhance capacity and resilience.

QUALITATIVE RISK ASSESSMENT

The hydrogeomorphic hazard assessment results are used to inform a qualitative risk assessment for each catchment. This risk assessment uses the requirements of the proposed Otago Regional Policy Statement (RPS) APP6 risk assessment framework. The APP6 framework requires the assessment of qualitative risk level using the descriptors Acceptable, Tolerable, and Significant, based on relative hazard likelihood and consequences (Table 1). The purpose of the qualitative assessment is to screen the catchments and identify which fans may be exposed to significant risk from debris flood inundation, so that these can be assessed in more detail in a quantitative risk assessment (Table 2).

Table 1: The APP6 qualitative risk assessment matrix used in this study.

Likelihood	**Consequences**				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	Green	Yellow	Yellow	Red (hatched)	Red (hatched)
Likely	Green	Green	Yellow	Yellow	Red (hatched)
Possible	Green	Green	Yellow	Yellow	Red (hatched)
Unlikely	Green	Green	Green	Green	Yellow (hatched)
Rare	Green	Green	Green	Green	Yellow (hatched)
Green, Acceptable *Risk*: Yellow, Tolerable *Risk*: Red, Significant *Risk*, Hatching: *Quantitative assessment required*					

A **significant risk** level for debris floods is assessed for PN2, PN1, GS2, BS2, Stevensons, Slaughterhouse, and GS1. For these catchments further quantitative risk assessment is required.

A **tolerable risk** level, but with a consequence level of 5 (i.e. catastrophic) for debris floods, is assessed for Pumpstation, BS1, and Reservoir. For these catchments further quantitative risk assessment is also required.

The remaining catchments Golf Course, RN1, and Black Jacks have **acceptable** or **tolerable risk** levels without catastrophic consequences, though continued monitoring and consideration of mitigation strategies is advised. Future development of alluvial fans will increase exposure and potential consequences, requiring reassessment of qualitative risk if infrastructure and lifelines are developed. In consultation with ORC, the Golf Course and RN1 catchments were also assessed quantitatively.

Table 2: Qualitative risk assessment for each catchment in this study.

Catchment	Highest Assessed Risk	Quantitative Risk Assessment Required
PN1	Significant	**Yes**
GS2	Significant	**Yes**
BS2	Significant	**Yes**
Stevensons	Significant	**Yes**
PN2	Significant	**Yes**
Slaughterhouse	Significant	**Yes**
GS1	Significant	**Yes**
Pumpstation	Tolerable with a catastrophic consequence	**Yes**
BS1	Tolerable with a catastrophic consequence	**Yes**
Reservoir	Tolerable with a catastrophic consequence	**Yes**
Golf Course	Tolerable	No*
RN1	Acceptable	No*
Black Jacks	Acceptable	No
*ORC would like to understand the spatial quantitative risk of Golf Course and RN1 for future planning; and therefore, these catchments are also assessed quantitatively.		

QUANTITATIVE RISK ASSESSMENT

Quantitative risk assessment was completed for 12 catchments in this study outlined in Table 2. Annual risk for people (annual individual fatality risk - AIFR) and buildings (annual property risk – APR) was calculated spatially on each alluvial fan following the guidelines developed by AGS for landslide risk assessments (AGS, 2007). These guidelines consider factors such as the likelihood of the hazard occurring and the vulnerability of exposed elements to determine the annual probability of an exposed element being impacted. This assessment was completed for 1 by 1 m grid cells and risk value rasters were produced for each alluvial fan.

Spatial analysis indicates that typically areas within 200–300 m of main channels and downslope of SH8 are the most vulnerable, with risk decreasing with distance and elevation from the main channel.

Calculated AIFR values were also compared to established risk tolerability criteria outlined in Table 3 below. This table is based on tolerability criteria from the Otago RPS APP6 risk assessment framework.

Table 3: The risk tolerability criteria used in this assessment for existing and new development (ORC, 2021).

Risk Category	Annual Risk - Existing Development	Annual Risk - New Development
Acceptable	$< 1x10^{-5}$	$< 1x10^{-6}$
Tolerable	$1x10^{-4}$ to $1x10^{-5}$	$1x10^{-5}$ to $1x10^{-6}$
Significant	$> 1x10^{-4}$	$> 1x10^{-5}$

For AIFR, significant risk areas range from 5–83% of total fan area for existing development and increase to 16–100% under new development criteria (Figure 1 and Figure 3). BS2 exhibits the highest risk (83% existing development, 100% new development). Stevensons and Golf Course also show elevated risk levels (39% and 32% respectively). GS2 rises from 21% (existing) to 68% (new), indicating widespread risk. GS1 and RN1 have the lowest significant risk proportions for existing development (9% and 5% respectively).

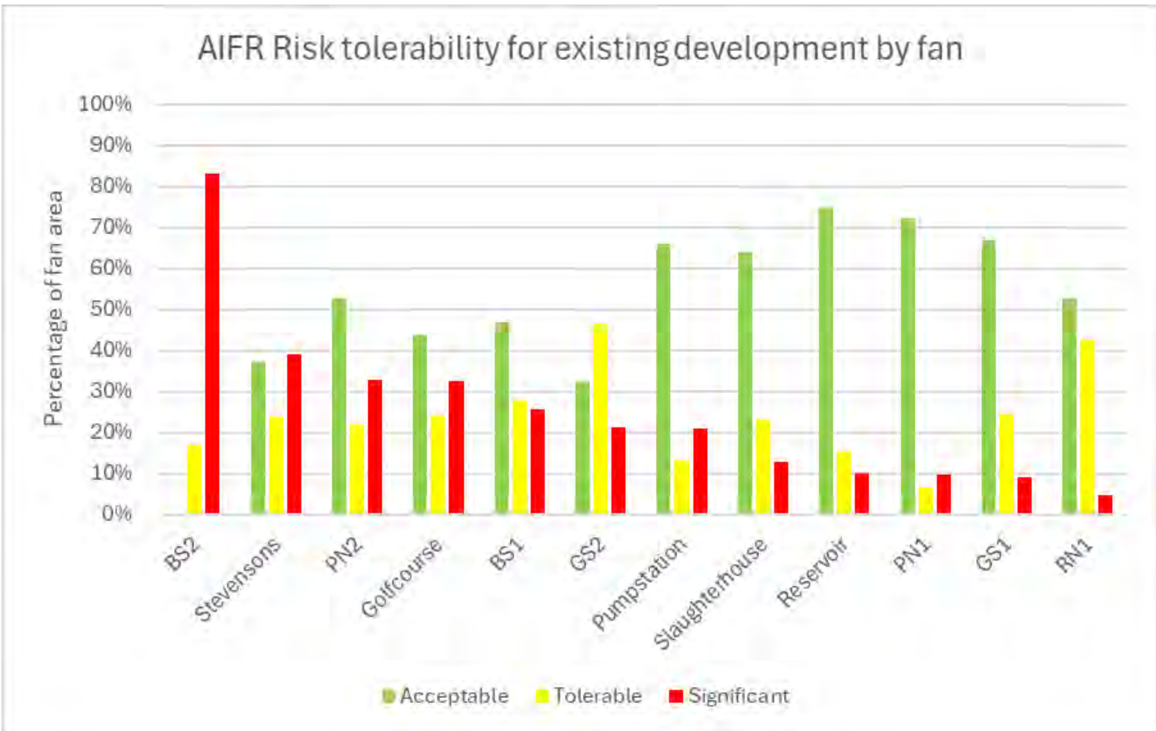


Figure 2: Percentage of each fan in each risk tolerability class for AIFR and existing development.

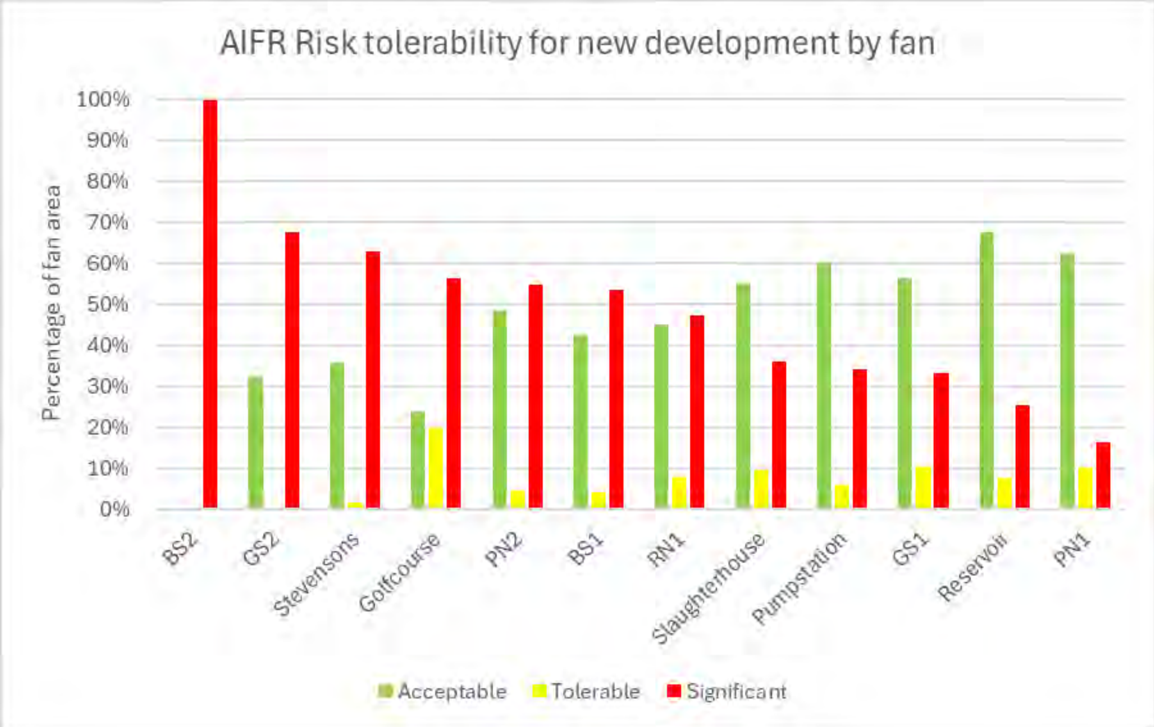


Figure 3: Percentage of each fan in each risk tolerability class for AIFR and new development.

RISK MITIGATION STRATEGIES

A range of structural, non-structural, and planning-based mitigation strategies have been identified to manage debris flood risk in Roxburgh.

Structural measures such as debris flood barriers, diversion channels, and reinforced culverts are particularly relevant given Roxburgh's steep terrain and sediment dynamics. Their feasibility depends on site-specific constraints including land access and hydrological design.

Non-structural approaches, including early warning systems, community education, and regular maintenance, are highly feasible and cost-effective, especially in a small, well-connected community like Roxburgh.

Land use planning tools, such as zoning restrictions and the preservation of natural buffers, offer long-term resilience but require strong policy support and community engagement.

Together, these strategies provide a comprehensive framework for reducing debris flood risk across the catchments assessed in this study.

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The Otago Regional Council (ORC) has engaged WSP New Zealand Limited (WSP) to undertake a detailed hydrogeomorphic hazard and risk assessment for the township of Roxburgh and its vicinity in Central Otago, New Zealand. The assessment includes hydrogeomorphic modelling for 13 catchments near Roxburgh and the estimation of potential impacts on the built environment and exposed populations. This assessment will inform potential spatial planning and outline physical mitigation/adaptation options.

This study will firstly undertake hydrogeomorphic modelling in the 13 catchments of interest followed by a qualitative risk assessment which will be used as a screening tool to assess which catchments, due to significant risk, may require further quantitative risk assessment. Quantitative risk assessment will be completed for catchments deemed to have significant hydrogeomorphic hazard risk or those highlighted by ORC as critical to future planning.

This report presents the methodology and findings of the hydrogeomorphic modelling and risk assessment. It builds on work completed in a gap analysis phase completed by WSP (see Appendix A).

1.2 SCOPE OF WORK

The primary objective of this study is to carry out a detailed hydrogeomorphic hazard and risk assessment for 13 catchments near the township of Roxburgh.

The scope of work for this assessment includes the following:

1 Desk study of available information (Data collation and gap analysis).

1 Geomorphic characterisation of the catchments and hydrological analysis of stream flows.

2 Hazard mapping and hydrogeomorphic hazard modelling of potential inundation extent.

3 Qualitative risk assessment.

4 Quantitative risk assessment.

This report describes the results of steps 2 to 5 above. A previous report presents the results of the literature review and gap analysis (Appendix A).

1.3 HAZARD DEFINITION

Hydrogeomorphic hazards refer to slope processes involving water and sediment that can have severe and wide-ranging impacts on both the human and natural environment. These processes can include landslides, which are rapid movements of large masses of earth and rock. Hydrogeomorphic hazards such as debris floods and debris flows are a type of landslide that impact alluvial fans (Figure 4).

Alluvial fans are typically cone-shaped deposits of sediment that form on the margins of mountainous areas and valley floors. These landforms are created through sediment transport and deposition, often driven by flash floods, hydrogeomorphic hazards, and seasonal rainfall or snowmelt. Key characteristics of alluvial fans include their fan-like shape and gentle slope compared to upstream areas. Alluvial fans are prone to natural hazards such as flooding, hydrogeomorphic hazards, and landslides, making them areas of concern for communities and planners.

Hydrogeomorphic hazards range from fluid-dominated floods which typically occur on gentler slopes to sediment-dominated debris flows and debris avalanches which occur on steeper slopes (Figure 4). Figure 4 was developed to describe the range of hydrogeomorphic processes in Canada; therefore, geomorphic factor ranges (typical sediment concentration, slope gradient, and water content) may not reflect those of hydrogeomorphic hazards in New Zealand.

High-intensity rainfall events are the dominant trigger for hydrogeomorphic hazards where heavy rainfall can saturate the soil, leading to erosion, landslides, and debris flows. Also, rapid snowmelt in alpine areas can increase water flow, triggering floods. Other potential triggers for hydrogeomorphic hazards include volcanic eruptions, earthquakes, and outburst floods from glaciers or landslide dams (Kaitna et al., 2024).

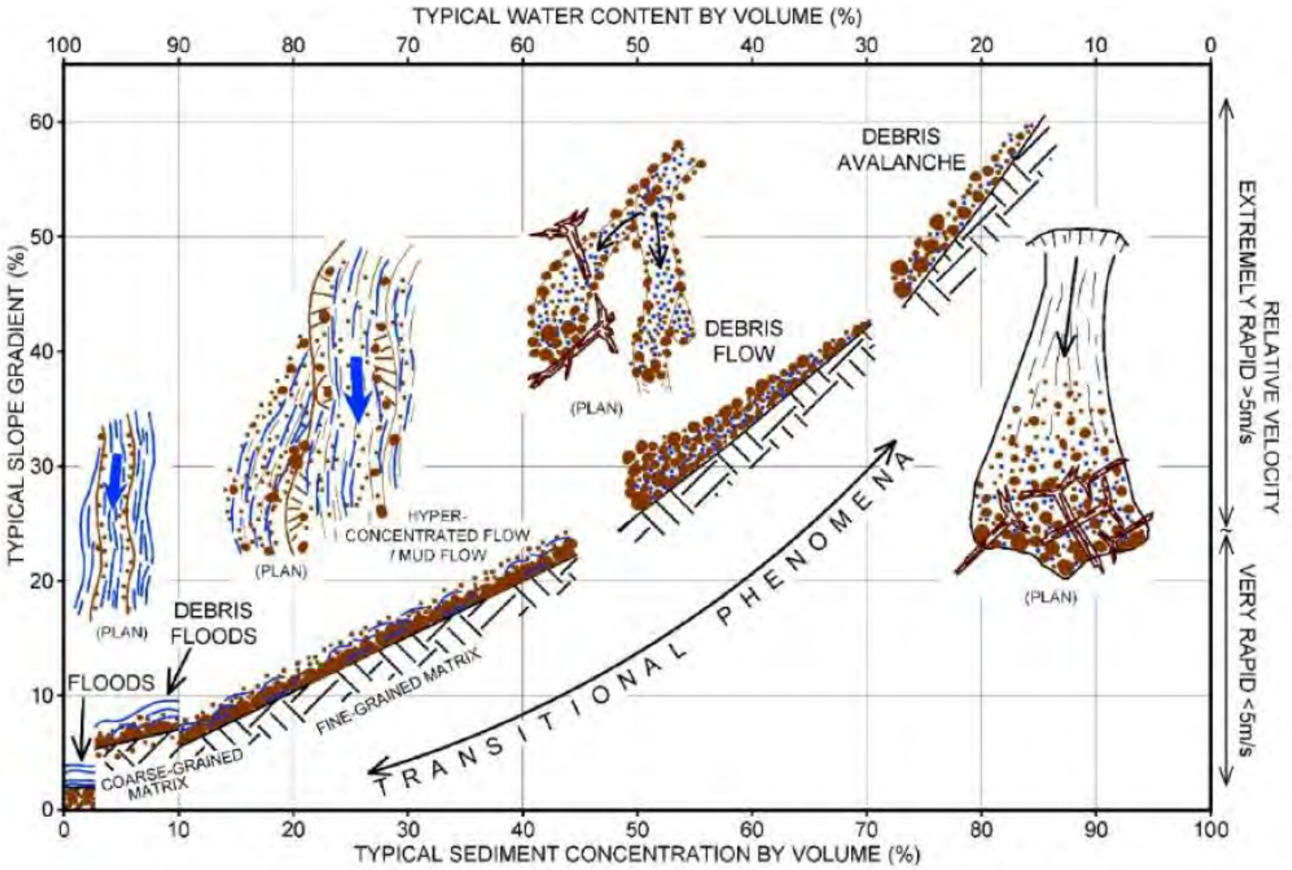


Figure 4: The main types of hydrogeomorphic hazards by typical slope angles and sediment concentration (BGC Engineering Inc, 2020).

Hydrogeomorphic hazards can result in loss of life and injury due to their sudden and unpredictable nature as well as extensive damage to property and infrastructure. Additionally, these events can lead to environmental degradation, including soil erosion, loss of vegetation, and alterations in river courses, which can have long-term ecological consequences.

Hydrogeomorphic hazards typically occur in gullies and creeks of steep mountain catchments and vary due to sediment concentration and water content (BGC Engineering Inc, 2020). The mechanisms behind hazard initiation can vary, ranging from channel runoff that erodes sediment along the flow path to slope failures that transform into fluid-like landslides.

1.3.1 DEBRIS FLOOD

Debris floods typically contain more water than other hydrogeomorphic hazards and gradually deposit sediment along their course. In June 2020, Cougar Creek in Canmore, Alberta, experienced a significant debris flood event triggered by intense rainfall (Figure 5) (Church & Jakob, 2020; Camire & Esarte, 2018). The heavy rains caused a rapid increase in water flow, which mobilised large amounts of debris resulting in substantial erosion, sediment deposition, and damage to homes, businesses, and transportation routes.

The Cougar Creek debris flood occurred in a similar geomorphic context to Roxburgh and the Teviot Valley and serves as an example of potential debris flood characteristics. Cougar Creek is situated in the Front Range of the Canadian Rockies, characterised by steep slopes and a complex geological structure. The region has undergone phases of glaciation and de-glaciation, which have shaped the landscape and contributed to the accumulation of loose debris which were mobilised during the 2013 event.

Figure 5: The 2013 Cougar Creek debris flood event in Alberta, Canada on (a) 19 and (b) 20 June 2013. (c) The channel of Cougar Creek after the debris floods downstream of location (a) and (b) (Church & Jakob, 2020).

1.3.2 DEBRIS FLOW

Debris flows typically have a greater sediment concentration than debris floods and are capable of transporting large boulders. In May 2005, the coastal community of Matata in the Bay of Plenty, New Zealand, experienced a devastating debris flow event triggered by intense rainfall (McSaveney et al., 2005). The heavy rain caused debris flows and avalanches on the steep slopes surrounding the town, which then flowed down stream valleys, carrying rocks, trees, and sediment (Figure 6). The debris flows inundated the town, destroying homes, severing major transport links, and causing over NZ$20 million in damage (Tonkin and Taylor, 2006). Remarkably, there were no fatalities or serious injuries.

Figure 6: The 2005 debris flow in Matata, New Zealand (McSaveney et al., 2005). Left: The boulder-laden debris flow deposit on the fan at Awatarariki Stream. Right: Debris flows are known for their ability to transport huge boulders as part of their mix of water, sand, gravel, cobbles, and boulders such as this boulder of bedded siltstone in the bed of Awatarariki Stream.

The 2005 Matatā debris flow demonstrates how intense rainfall in steep, sediment-rich catchments can trigger destructive events, mobilising large volumes of debris and damaging infrastructure. Similar geomorphic and climatic conditions exist in Roxburgh and the Teviot Valley suggesting a comparable susceptibility to high-energy debris flows under extreme rainfall scenarios.

1.3.3 HYDROGEOMORPHIC EVENTS IN THE TEVIOT VALLEY

The Roxburgh area has experienced several notable hydrogeomorphic hazard events that have impacted developed alluvial fans. Heavy rainfall has triggered debris floods and debris flows in the area, causing significant damage to infrastructure and property. The region has also seen flooding incidents due to rapid snowmelt and intense rainstorms, impacting local communities.

Debris flood and flows have occurred historically in the Roxburgh area, with recorded events in 1938, 1978, 1993, 2017, and frequent smaller localised events. The 1978 event affected a wide area, causing flooding and channel avulsion in multiple creeks. Reservoir Creek in northern Roxburgh aggraded and sent boulder debris through residential properties, prompting the construction of a 180m long concrete-lined chute, designed to rapidly convey flood waters and sediment down the alluvial fan surface to the Clutha River.

Given the history of events and prominent alluvial fan landforms, the Roxburgh area has a recognised hydrogeomorphic hazard (Woods, 2011) and active alluvial fan landforms have been identified (OPUS, 2009; Mackey, 2021).

The most notable event in recent years are the 2017 events. On 26 November 2017, Roxburgh, Central Otago, experienced severe thunderstorms with high-intensity, short-duration rainfall, leading to significant debris flows and debris floods in several stream catchments. The rainfall, ranging from 40 to 100 mm within an hour, caused extensive damage, including overwhelmed culverts, damaged aerial pipelines, road blockages, and inundation of property.

The economic costs associated with hydrogeomorphic hazards are substantial, encompassing the expenses related to recovery, rebuilding, and implementing preventive measures to mitigate future risks. Overall, the impacts of these hazards underscore the importance of effective management and preparedness strategies to protect communities and ecosystems. This report analyses hydrogeomorphic hazards in Roxburgh, Central Otago and completes qualitative and quantitative risk assessment to support appropriate risk management including land use planning.

1.4 STUDY AREA

The study area is located between Coal Creek Flat and Dumbarton in the Teviot Valley, Central Otago. It includes 13 stream catchments along the eastern side of the Old Man Range and their alluvial fans (Figure 7). These streams all flow into the Clutha River, which truncates several of the alluvial fans in this study. The catchments in the study area generally comprise exposed rocky ridgelines, incised stream valleys and are dominated by tussock grasslands with isolated areas of native bush. Generally, the larger catchments in the study area are associated with named streams (i.e. Slaughterhouse Creek, Pumpstation Creek, Reservoir Creek, Golf Course Creek, Black Jacks Creek, and Stevensons Creek) while the smaller catchments have been assigned brief names (i.e. PN2, PN1, RN1, GS1, GS2, BS1, BS2). The alluvial fans in the study area have mostly been developed with orchards and pastoral land but do include built up areas including the main township of Roxburgh. Infrastructure including State Highway 8 (SH8), local roads, and utilities have also been established on many of the fans.

Over the past 20 years, several reports have analysed hydrogemorphic hazards in Roxburgh. The 2009 Otago Alluvial Fans Project assessed alluvial fans, highlighting the development of coalesced fan complexes along the Old Man Range, prone to significant debris transport during high intensity rainfall events (OPUS, 2009). Woods (2011) focused on Reservoir Creek, noting modifications including a concrete channel following recurrent hydrogeomorphic events. DAMWATCH (2017) evaluated the impact of the 2017 events on the Clutha River, finding slight increases in flood risk due to sediment deposition. Dellow et al. (2018) assessed the 2017 events, including trigger analysis and volume estimates. Golder (2019a) and Golder (2019b) provided hazard assessments and mitigation recommendations, stressing the need for site-specific measures and reducing surface water runoff to manage hydrogeomorphic hazard risks.

A detailed summary of previous reporting is provided in Appendix A.

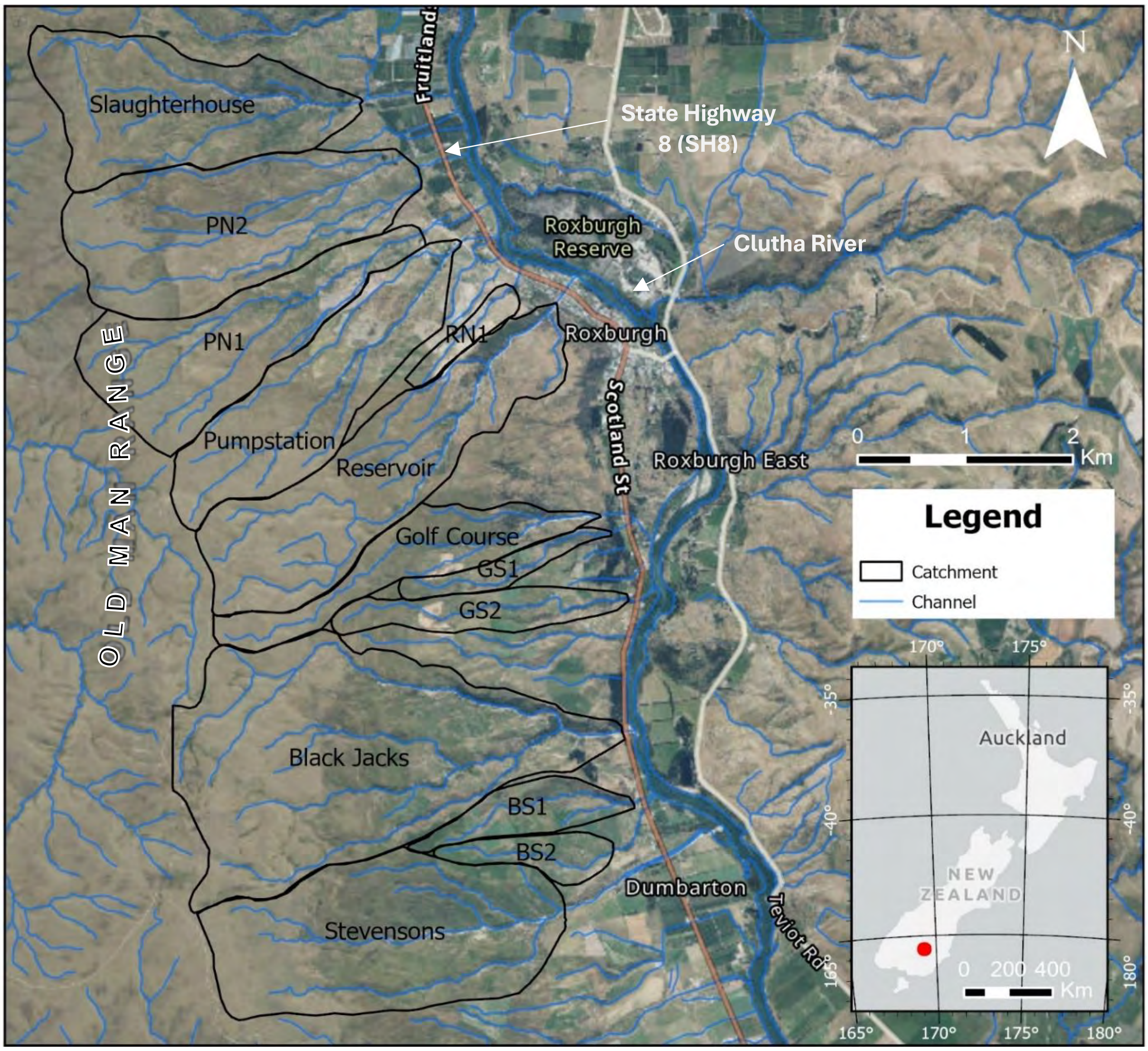


Figure 7: The 13 catchments assessed in this study.

1.5 METHODOLOGY

Previous reporting has established that Roxburgh is prone to frequent and repeated hydrogeomorphic hazards. Further risk assessment is required to quantify risk to people and the built environment, inform planning decisions, and focus risk mitigation efforts. This report presents the methodology and results for the hydrogeomorphic modelling and risk assessment for Roxburgh which includes (Figure 8):

- Review of historical hydrogeomorphic hazard activity in each catchment
- Geomorphological assessment of the alluvial fans to assess the extent of each fan and the volume of debris that has been deposited on the post glacial river terraces of the Clutha River.
- Review of available subsurface geological records to confirm the presence of hydrogeomorphic hazard deposits.
- Review of LiDAR terrain data and aerial imagery (including records of numerous helicopter flyovers completed by the WSP team) to identify key geological information within the catchments above the alluvial fans, including: geomorphic features on the hillslopes within the

catchment, the location and extent of recent and historic landslides, the geomorphic characteristics of the channel in each part of the catchments including reaches where erosion or deposition processes occur, and geomorphic evidence of previous hydrogeomorphic hazards and their deposits.

- Confirm hydrological characteristics of each catchment including hydrological return period relationships, including predicted effects of climate change.
- Assess hydrogeomorphic hazard input volumes for a range of return periods for each catchment based on the historical landslide magnitudes and relative erodibility of the channel throughout each catchment.
- Conduct debris flow modelling using RAMMS software for multiple hydrogeomorphic hazard magnitudes to estimate the inundation of the alluvial fan in each case.
- Complete a qualitative risk assessment using the ORC Regional Policy Statement (RPS) methodology for natural hazard risk assessment (APP6). It is noted that this is a proposed RPS and there are likely to be minor updates to the APP6 approach once it is finalised.
- Complete a quantitative risk assessment of ‘significant risk’ catchments following the AGS (2007) methodology.
- The approach aligns with a basic quantitative risk analysis (Level D) in accordance with de Vilder et al., (2024) landslide planning guidance. The quantitative risk assessment calculates annual individual fatality risk (AIFR) and Annual Property Risk (APR).

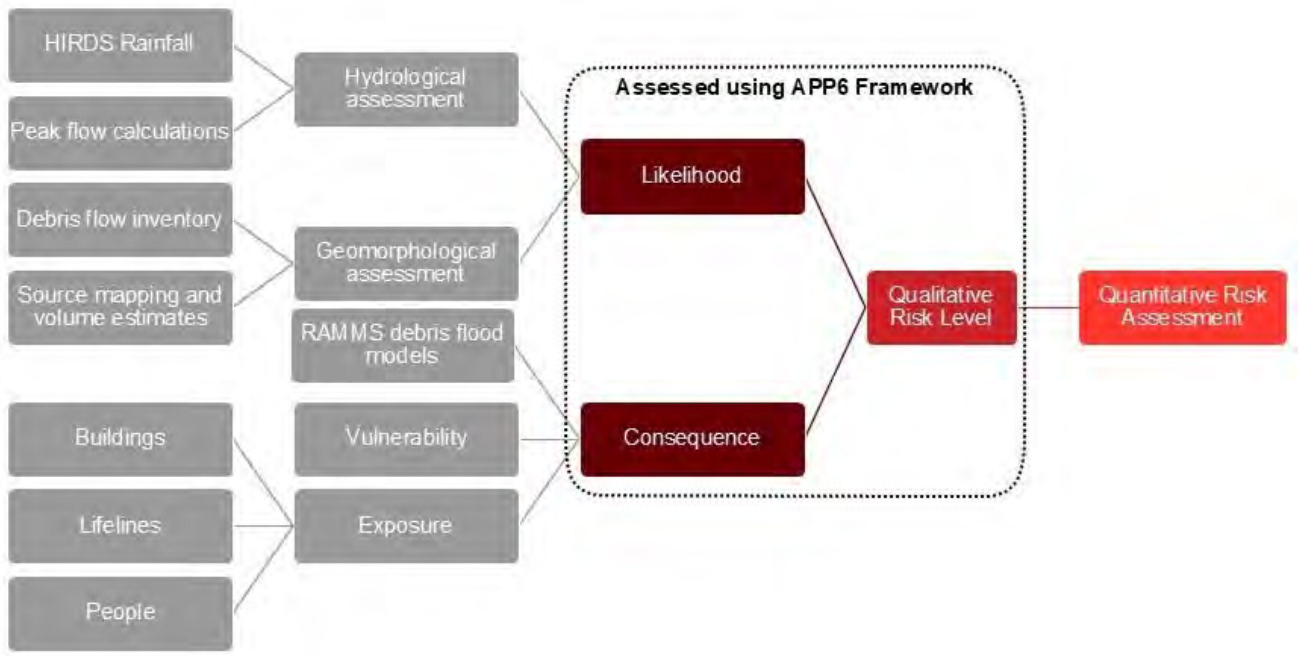


Figure 8: Methodological process for hydrogeomorphic modelling and risk assessment of catchments in Roxburgh.

1.5.1 RISK ASSESSMENT

The APP6 methodology for natural hazard risk assessment is used as the qualitative risk assessment framework in this study (ORC, 2021). This framework assigns a qualitative risk level (acceptable, tolerable, or significant risk) based on hazard likelihood and assessed consequences for three hazard event sizes representing a high likelihood event, a median likelihood event, and a maximum credible event.

The APP6 methodology includes a four-step process to determine natural hazard risk:

1. Determine the likelihood of the three hazard scenarios using the best available information and with consideration of the effect of climate change.
   a. Climate change assessment should use the Shared Socio-Economic Pathway (SSP) scenarios or representative concentration pathways (RCP) scenarios provided in the National Adaptation Plan (Ministry for the Environment, 2022).
2. Determine the consequence of each hazard scenario on buildings, lifelines, and people using an ORC-developed consequence schema and the descriptors insignificant, minor, moderate, major, and catastrophic.
3. Assess the natural hazard risk level of each hazard scenario using the descriptors acceptable, tolerable, and significant risk representing increasing risk levels.
4. Undertake a quantitative risk assessment for natural hazard scenarios deemed to present a significant level of risk or a tolerable risk with catastrophic consequences.

Quantitative risk assessment considers the numerical aspects of risk such as the probability of the scenario occurring. The quantitative risk assessment in this report focusses on risk to people and buildings, calculating Annual Individual Fatality Risk (AIFR) and Annual Property Risk (APR) for each catchment. This assessment follows established guidelines (AGS, 2007; ORC, 2021).

Detailed methodology for the qualitative and quantitative risk assessments are provided in Section 2 and Section 4 respectively.

2 HYDROGEOMORPHIC MODELLING

2.1 INTRODUCTION

Previous reports have highlighted the potential for hydrogeomorphic hazards including debris flows and debris floods within the study area (Dellow et al, 2018; Golder, 2019a; Golder, 2019b; Mackey, 2021; Opus, 2009; Woods, 2011; WSP, 2021; WSP, 2024). Historical hydrogeomorphic events have inundated Roxburgh township causing damage to the built environment including residential property and critical infrastructure. Previous reporting focused on documenting and analysing historical hazard events and qualitatively assessing future hazard potential. Further detailed hydrogeomorphic hazard assessment was recommended as part of risk mitigation measures (Golder, 2019a; Golder, 2019b).

This section presents the hydrogeomorphic modelling completed in each catchment in the study area to estimate the probable spatial occurrence of hydrogeomorphic hazards. A broad understanding of hazard potential informed modelling and included:

- Historical hydrogeomorphic event inventory and analysis.
- Geomorphological assessment
  - Overview of geology and terrain.
  - Catchment characteristics including terrain analysis and source potential.
  - Geomorphological mapping of each catchment.
  - Site walkovers and geotechnical investigations.
- Hydrological assessment
  - Analysis of key hydrogeomorphic triggers; rainfall and stream flow in catchments with consideration of climate change.
- Frequency and magnitude analysis of hydromorphic hazard events.

Hydrogeomorphic modelling has been undertaken using RAMMS (Rapid Mass Movement Simulation) (RAMMS, n.d.). RAMMS is a three-dimensional numerical simulation software package designed for simulating the runout behaviour of natural hazards such as avalanches, debris flows, and rockfalls. RAMMS-DF (Debris Flow) simulates debris flows' release, movement, and deposition. It is used for hazard mapping, evaluating mitigation measures, and risk assessment.

Table 4 lists the key datasets used for this phase of this assessment. Digital elevation models derived from LiDAR, aerial photography, geological and topographical maps, and previous reporting were used as key inputs for the historical hydrogeomorphic hazard event inventory and geomorphological assessment. The hydrological assessment used LiDAR, rainfall data, land cover and soil drainage information. These layers were combined and analysed in ArcGIS Pro. Further detail on how these datasets were analysed using specific programme tools is provided in the following sections and in the appendices.

Table 4: Datasets used for the hydrogeomorphic modelling phase of this assessment.

Source	Dataset(s)	Usage
ORC	2024 1 m DEM and Orthophotography	Geomorphological and hydrological assessment
	2022 1 m DEM and Orthophotography	Geomorphological assessment – catchment characterisation, terrain analysis, and geomorphological mapping.
	2019 1 m DEM and Orthophotography	
	2017 Orthophotography	
LINZ	Otago 0.1 m Urban Aerial Photos (2023-2024)	
	Otago 0.3 m Rural Aerial Photos (2019-2021)	
	Otago 0.1m Urban Aerial Photos (2018)	
	Otago 0.75m Rural Aerial Photos (2004-2011)	
Retrolens	Historical Aerial Imagery (1945-1985)	
GNS	1:250k Geological Map of New Zealand	
	New Zealand Landslide Database	
NIWA	High Intensity Rainfall Design System (HIRDS)	Analysis of key hydrogeomorphic triggers and hydrological assessment
LRIS	Land Cover Database (LCDB) v5.0	Geomorphological assessment – catchment characterisation, terrain analysis, and geomorphological mapping. Hydrological assessment
	Soil Drainage Classification	Hydrological assessment
Other	Previous studies and reports including journal papers, previous consultancy reports, and photographs.	Various

2.2 HISTORICAL HYDROGEOMORPHIC HAZARD INVENTORY

To understand the nature of hydrogeomorphic hazards in Roxburgh we have compiled a hydrogeomorphic hazard inventory that captures information on the location, trigger, intensity, and impacts of historical events. Information on historical hydrogeomorphic hazard events was sourced from previous reports, anecdotal information, and photos supplied by contractors or from WSP's records.

2.2.1 SUMMARY

There have been seven documented high-intensity rainfall events that have triggered hydrogeomorphic hazards in Roxburgh (Table 5). Of these events only the November 2017 events have been recorded in detail (Dellow et al., 2018). This section provides an overview of each event.

Table 5: Summary of all known hydrogeomorphic events in Roxburgh.

Date	Catchment(s)	Trigger	References
8 November 1938	Slaughterhouse	Rainfall. Intensity not known.	Mackey. (2021). The soil conservation and rivers control council (1957).
13 October 1978	Reservoir, Stevensons	116 mm rain in 24 hours	Woods, 2011; Dellow et al. 2018; Otago Catchment Board, 1980; Golder, 2019a
Mid-March 1983	Reservoir, Stevensons	Rainfall. Intensity not known.	Otago Catchment Board. (1983).
Late December 1993	Slaughterhouse	Rainfall. Pomahaka at Moa Flat recorded a peak hourly rainfall of 12.5 mm on 30 December.	Brenstrum, 1994; Dellow et al. 2018
26 November 2017	Black Jacks, Golf Course, Reservoir, Pumpstation, Stevensons, RN1	Rainfall. 40-100 mm rainfall in 1 hour.	Dellow et al. 2018; Golder, 2019a
Late January 2018	Black Jacks, Golf Course	Rainfall (Ex tropical cyclone Fehi). Pomahaka at Moa Flat recorded a peak hourly rainfall of 23.5 mm on 18 January.	Dellow et al. 2018
November 2018	Black Jacks, Golf Course	Rainfall. Clutha at Teviot Valley Station recorded a peak hourly rainfall of 8.5 mm on 19/20 November.	Anecdotal evidence from Trevor Crossan, ORC Roxburgh

2.2.2 8 NOVEMBER 1938

On 8 November 1938, a high-intensity, short-duration rainfall event caused thousands of tons of boulders and silt to be deposited on flatter slopes occupied by orchards (The Soil Conservation and Rivers Control Council., 1957). A boulder weighing at least 20 tons was transported by the deluge and left on top of a gully bank.

The consequences included orchards being buried under boulders and silt, blockage and washout of irrigation races, and several chains of the Milton-Queenstown Highway being covered in silt. The private damage to orchards was estimated at £4,720, repairs to the creek at £350, and damage to the highway at £50.

2.2.3 13 OCTOBER 1978

Hydrogeomorphic hazards in the Reservoir and Stevensons catchments were triggered by 116 mm of rain in 24 hours, blocking SH8 and piling up around residential properties, causing damage to buildings (Woods, 2011).

Debris transported onto the lower Reservoir catchment fan was mainly from streambank erosion near the water supply intake at 250m elevation (Dellow et al., 2018).

Above this point, there was some slipping and bank erosion, but it was less extensive than in the lower reaches. This is typical of this catchment, where the lower channel is filled with blocking alluvium, transported downstream during major floods (Otago Catchment Board, 1980).

A concrete channel, proposed in 1980, was constructed through Roxburgh at the Reservoir catchment from the fan-head to the Clutha River, designed to pass small to medium-sized flows.

At Stevensons Creek, channel incision and bank erosion were observed, with boulder-sized debris deposited below the fan apex (Golder, 2019a). Levees were constructed along the channel above and below the SH8 crossing to minimize further bank erosion and potential avulsion.

Figure 9: Photographs showing damage to a shed and extent of debris deposits at Reservoir Creek October 1978

2.2.4 MID-MARCH 1983

A debris slide occurred in the middle of Stevensons catchment, damming the creek (Otago Catchment Board, 1983). The dam subsequently breached, releasing a large flow of debris that entered a shed, causing damage to machinery and vehicles. A total of 1.3 meters of material was recorded inside the shed.

2.2.5 LATE DECEMBER 1993

A large boulder from Slaughterhouse Creek was transported down the catchment and blocked SH8 for a short time.

2.2.6 26 NOVEMBER 2017

On the afternoon of 26 November 2017, thunderstorms with lightning strikes and high-intensity, short-duration rainfall occurred over Roxburgh, Central Otago (Dellow et al., 2018). A thunderstorm cell centred over Roxburgh delivered 40 to 100 mm of rainfall between 4:00 pm and 5:00 pm, causing debris floods and flows in four stream catchments to the west of Roxburgh. Dellow et al (2018) estimated likely event volumes for the catchments affected (Table 6).

Table 6: Estimated event volumes in four Roxburgh catchments as a result of the 2017 rainfall event. From Dellow et al (2018).

Catchment	Minimum Volume (m^3)	Maximum Volume (m^3)	Probable volume (m^3)
Black Jacks Creek	15,000	262,500	120,000
Golf Course Creek	1000	2000	1500
Reservoir Creek	30,000	350,000	160,000
Pump Station Creek	1000	2000	1500

Table 7: Rainfall at each catchment during the 2017 event. From Dellow et al (2018).

	Duration	
Location	60 min (est)	3 hour
Black Jacks Creek	100	152
Golf Course Creek	80	104
Reservoir Creek	60	81
Pump Station Creek	40	59

Golder, (2019a) estimated the average return interval (ARI) for the 2017 events based on rainfall data and relative size of events (Table 8).

Table 8: Estimated volumes and ARI of the 2017 debris flows and debris floods.

Catchment	Volume (m^3)	Rainfall	ARI
Pumpstation	1,500 (Dellow et al., 2018)	40 mm rain in 1 hour/59 mm in 3 hours	100 (Golder, 2019a)
Reservoir	160,000 (Dellow et al., 2018)	60 mm rain in 1 hour/81 mm in 3 hours	>500 (Golder, 2019a)
Golf Course	1,500 (Dellow et al., 2018)	80 mm rain in 1 hour/104 mm in 3 hours	>500 (Golder, 2019a)
Black Jacks	120,000 (Dellow et al., 2018)	100 mm rain in 1 hour/ 152 mm in 3 hours	>500 (Golder, 2019a)

2.2.6.1 STEVENSONS CREEK

At Stevensons Creek, aggradation of sediment occurred within the channel, but the hazard remained within the existing channel bed (Golder, 2019a).

This catchment probably received a similar amount of rainfall to Black Jacks Creek (<2 km away).

2.2.6.2 BLACK JACKS CREEK

The event was characterized by streambank erosion rather than ground saturation, resulting in vegetation loss and sediment entrainment. Rainfall in this catchment was estimated to be 100 mm in 1 hour (Dellow et al., 2018). The damage included an overwhelmed culvert at SH8, with the road being buried by 1-2 meters over a length of 50-70 meters.

Figure 10: Left: Debris flood deposit in Black Jacks Creek upstream of SH8 November 2017. Right: Debris flood deposit on SH8 from Black Jacks catchment. The surface of the road has been exposed by the excavator.

Figure 11: The new culvert at Black Jacks Creek SH8 crossing following the 2017 event.

2.2.6.3 GOLF COURSE CREEK

A debris flood in Golf Course Creek primarily caused by streambank erosion, deposited small boulders (less than 0.5 m) and silt over the catchment fan. The event was triggered by 80 mm of rain in 1 hour, which exceeded the capacity of the culverts below SH8. Debris from the event blocked culverts under SH8 and caused the debris to spread across a rugby field, golf course, and stream margins.

The estimated volume of debris was approximately 1,500 m³ (Dellow et al., 2018); however, based on available imagery this is likely to be a significant underestimate of the actual volume of debris that inundated the fan, based on the aerial extent and thickness of inundation. Similarly, estimation of total debris volumes using empirical relationships of peak water discharge to debris discharge also show large variability and potentially significantly larger volumes of debris inundation (Appendix D).

Figure 12: Top left and top right: The 2017 debris flood at SH8 crossing of Golf Course Creek. Bottom left and bottom right: The new culvert at Golf Course Creek pictured in 2023.

2.2.6.4 RN1 – EDINBURGH STREET

Figure 13: Photos of the Edinburgh Street culvert along SH8 following a debris flood.

2.2.6.5 RESERVOIR CREEK

The Reservoir Creek debris flood was similar in size and volume to those at Black Jacks Creek. The catchment experienced 81 mm of rainfall in three hours, with most of it falling within one hour. These powerful debris flows stripped vegetation and moved large boulders (up to 2 m). Vegetation loss was mainly confined to the stream channel, suggesting streambank erosion as a key source. The short-duration rainfall led to rapid water accumulation, scouring the stream bed and entraining sediment in the debris flood. The debris flood was estimated to be 160,000 m^3 in volume (Dellow et al., 2018).

The concrete channel constructed following the 1978 event performed well, although the debris flood event likely exceeded its design capacity. The channel contained all large debris, but water and fine-grained sediments exited the channel, flowing down SH8 and local roads, affecting several properties and the local school. Some buildings experienced water damage, with silt deposits up to 7 cm. This event caused minor damage compared to the 1978 event.

Figure 14: 2017 Reservoir Creek debris flood inundation in Roxburgh.

2.2.6.6 PUMPSTATION CREEK

Pumpstation Creek experienced debris floods with boulders up to 0.5 meters in size, triggered by 40 mm of rainfall in one hour. The debris flood exited the channel at a farm bridge and a culvert under SH8, spreading debris across the fan and around a house. The estimated debris volume was approximately 1,500 m^3 (Dellow et al., 2018); however, based on the extent of debris in this catchment (c. 20,000 m^2) and assuming an average depth of debris inundation of c. 1 m the true volume of debris inundation is more likely to have been around 20,000 m^3 at this fan. Similarly, estimation of total debris volumes using empirical relationships of peak water discharge to debris discharge also yield larger volumes of debris inundation, albeit with significant variability (Appendix D). A landslide above the fan-head showed movement and was suggested to be monitored at the time (Dellow et al., 2018). The event destroyed a small farm bridge, blocked the culvert beneath SH8, and deposited debris on the road and around at least one house. There was minor damage to the cladding on a farm shed.

Figure 15: SH8 culvert damage at Pumpstation Creek as a result of the 2017 debris flood.

2.2.7 LATE JANUARY 2018

Cyclone Fehi in early 2018 triggered debris floods in two Roxburgh catchments which impacted SH8 crossings (Golder, 2019a). At Golf Course Creek the culverts were blocked by debris, and gravel to cobble-sized debris was deposited on the highway. Remobilised debris in the Black Jacks stream bed led to further accumulation at the SH8 road alignment. The debris floods in November 2017 stripped vegetation, which allowed the January 2018 rainfall to further scour the stream bed. This subsequent rainfall moved smaller gravel clasts (up to 200 mm) compared to the larger boulders (up to 2 m) transported in November 2017.

2.2.8 NOVEMBER 2018

A rainstorm event in November 2018 overwhelmed SH8 crossings at Golf Course Creek and Black Jacks Creek, depositing debris across SH8. Debris aggradation occurred at the lower section of the Reservoir Creek concrete channel but was limited by the use of heavy machinery, which kept the toe of the fan at the confluence with the Clutha River clear (anecdotal evidence from Trevor Crossan, ORC Roxburgh).

2.2.9 HISTORICAL RAINFALL TRIGGER INTENSITY

Debris floods in Roxburgh have been triggered by various rainfall intensity events. On 13 October 1978, 116 mm of rain in 24 hours impacted the Reservoir and Stevensons catchments. On 26 November 2017, 40-100 mm of rainfall in one hour triggered debris floods in multiple catchments. Debris floods transported over 100,000 m³ of material in Black Jacks and Reservoir catchments in this event, triggered by at least 60 mm of rainfall in an hour. Smaller debris floods, less than 10,000 m³ of material, occurred in Golf Course Creek and Pumpstation Creek, triggered by at least 40 mm of rainfall in the same event. These were recorded at the time as significant events for the area with widespread inundation and impacts.

Localised debris floods have also occurred in the area at lower rainfall intensities; however, the magnitude of these events is unclear. In Late December 1993 12.5 mm of peak hourly rainfall triggered a debris floods in the Slaughterhouse catchment. In 2018 two events with peak hourly rainfalls of 23.5 mm and 8.5 mm remobilised debris from the 2017 event in Black Jacks and Golf Course.

2.3 GEOMORPHOLOGICAL ASSESSMENT

2.3.1 GEOLOGY AND TERRAIN

The 13 catchments in the study area are located on the eastern flank of the Old Man Range west of the Clutha River, Central Otago. The Old Man Range comprises an anticlinal ridge in underlying Triassic Caples Terrane (TZIII) schist described as well-foliated psammitic and pelitic schist with minor greenschist and metachert (Turnbull, 2000). Widespread large landslides in the area have accumulated a thick mantle of debris from eroding bedrock which is a source material for recent debris floods. Alluvial fans at the base of catchments have built out onto old river terraces along the Clutha River. River terraces proximal to Roxburgh have been dated as middle to late Pleistocene while overlying alluvial fans have been dated as Holocene (Heron, 2020).

We assume that debris floods started to deposit material onto fans following retreat of glaciers in the head of the Clutha River catchment. Denton et al. (2021) suggests this may have occurred 18,000 years ago due to indications of a poleward shift of the austral westerlies (movement of the midlatitude westerly winds in the Southern Hemisphere towards the poles) in glacial moraines.

To the north of Roxburgh township, Slaughterhouse Creek, PN2, PN1, Pumpstation Creek drain the slopes of the Old Man Range to the northeast (Figure 16). Alluvial fans in this area are extensive and primarily comprise orchards and productive agricultural land. Building and infrastructure development increases towards the Pumpstation Creek alluvial fan which includes the proposed Quail Haven subdivision.

At the northern end of Roxburgh township, the alluvial fans of RN1 and Reservoir Creek have been developed with primarily low-density single-storey residential buildings and servicing infrastructure.

South of the Roxburgh township, Golf Course Creek, GS1, GS2, Black Jacks Creek, BS1, BS2, and Stevensons Creek drain the slopes of the Old Man Range to the east towards the Clutha River. The alluvial fans of these catchments are largely undeveloped with large areas of orchard and agricultural land with minor developments such as the Roxburgh Golf Course. With the exception of Stevensons Creek, alluvial fans in this area are comparably small and restricted by the Clutha River which runs close to areas of bedrock along the base of the Old Man Range.

Typically, the lower catchments (generally <600-750 m elevation) in the study area are dominated by pastoral farming, while the upper catchments (generally >600-750 m elevation) comprise extensive areas of alpine tussock grassland. Other vegetation within the catchment areas is minimal and is limited to small areas of pine forest and regenerating native bush in sheltered gullies.

Figure 16: Alluvial fans of the catchments north of Roxburgh township with the Clutha River in the centre of the photo.

Figure 17: Alluvial fans of the catchments in Roxburgh township with the Clutha River at the bottom of the photo.

Figure 18: Aerial photographs of three of the catchments to the south of Roxburgh township; Golf Course (left), Black Jacks (middle), and Stevensons (right) catchments.

2.3.2 CATCHMENT CHARACTERISTICS

Each catchment and fan in the study has been assessed in terms of its geomorphological characteristics. Catchment extents were provided by ORC and have not been modified. Fan extents were mapped in ArcGIS Pro using a hillshade layer from the 2024 1m DEM. Features such as the fan apex and toe were identified in the DEM and imagery by changes in vegetation, slope, and curvature. The Alluvial Fans Project mapping was used as an additional resource to inform fan mapping by overlaying the geomorphological maps from this project with the more recent DEM and imagery (OPUS, 2009). Catchment maps including geomorphic mapping of debris flood sources and alluvial fan extents are provided in Appendix B.

This work builds on a large programme of work done by Golder in 2019 (Golder, 2019a) and routine inspection work by WSP for NZTA. The Golder (2019a) assessment included several days of field mapping of the Pumpstation, Reservoir, Golf Course, Black Jacks, and Stevensons catchments by an experienced engineering geologist and a helicopter flyover of the entire catchments of those fans. Additional geotechnical investigations and site walkovers were completed by WSP in November 2025 in the study area to support the geomorphological assessment.

2.3.2.1 HAZARD CHARACTERISATION

MELTON RATIO

Previous reports have indicated that Melton and Relief Ratios are useful preliminary indicators for characterising which hydrogeomorphic hazard is likely to occur (Wilford et al., 2004; Jakob, et al., 2020; Golder, 2019a). As described in Section 1.3, hydrogeomorphic hazards can be fluid-dominated floods and debris floods to sediment-dominated debris flows and debris avalanches. Typically, a greater melton ratio indicates that debris flows are more likely; however, catchments producing various hydrogeomorphic hazards are not uncommon (Figure 19).

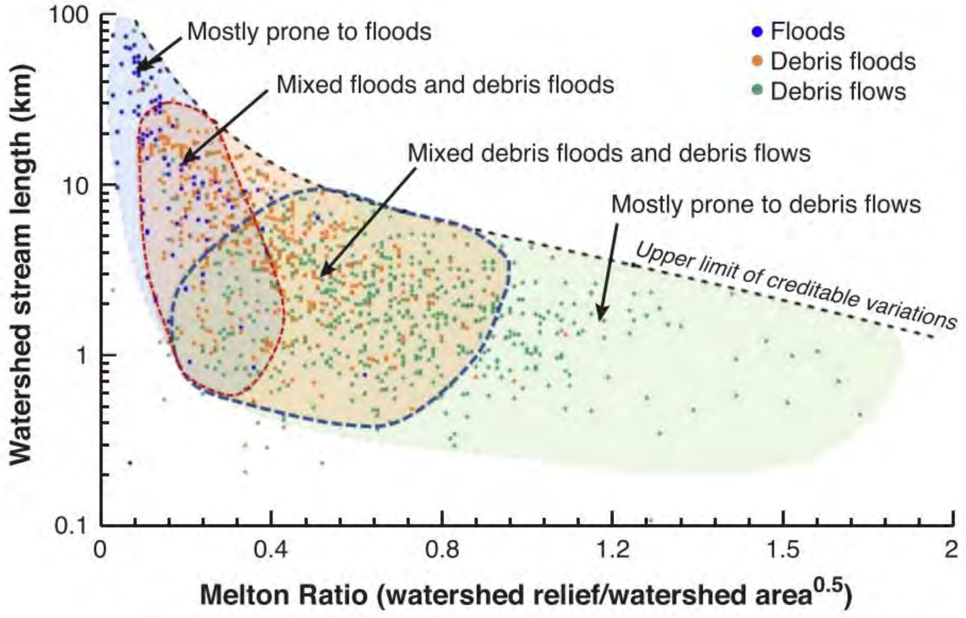


Figure 19: Characterisation of hydrogeomorphic hazards due to Melton Ratio and catchment length using data from fans in Alberta and British Columbia, Cananda (Church & Jakob, 2020).

Melton and Relief Ratios have been calculated for each catchment using the below equations and Table 9:

$$Melton\ Ratio = \frac{Catchment\ Relief}{\sqrt{Catchment\ area}} \qquad Relief\ Ratio = \frac{Catchment\ relief}{Catchment\ length}$$

Table 9: Class boundaries for hydrogeomorphic processes (Wilford et al., 2004).

Variable	**Hydrogeomorphic process class boundaries**		
	Flood	Debris Flood	Debris Flow
Melton ratio and length	< 0.3	0.3 – 0.6 When Melton ratio > 0.6, catchment length ≥ 2.7 km	Melton ratio > 0.6 and catchment length < 2.7 km
Relief ratio and length	< 0.15	0.15 – 0.35 Relief ratio > 0.35 then catchment length > 2.7 km	> 0.35 and catchment length < 2.7 km

Wilford et al. (2004) also differentiated hydrogeomorphic hazard type by sediment concentration and deposition:

- Debris flow deposits: 70-90% sediment, deposited in marginal levees and/or terminal lobes.
- Debris floods: 20-40% sediment, deposited as fans, bars, sheets, or splays.
- Flood deposits: less than 20% sediment.

Catchment relief ratios in the study area range between 0.21-0.29 while Melton ratios range between 0.43-0.78 (Table 10). Based on the derived catchment geometry, debris floods are indicated to be the dominant hazard type in the majority of the catchments.

Table 10: Topographical characteristics of each catchment in the study with dominant hazard type identified.

Catchment	Area (km^2)	Length (km)	Relief (km)	Relief Ratio	Melton Ratio	Dominant Hazard Type
Slaughterhouse	2.93	2.58	0.783	0.30	0.46	Debris Flood
PN2	3.58	3.16	0.846	0.27	0.45	Debris Flood
PN1	2.60	3.34	0.797	0.24	0.49	Debris Flood
Pumpstation	2.68	3.80	0.862	0.23	0.53	Debris Flood
RN1	0.28	1.71	0.372	0.22	0.70	Debris Flood/ Debris Flow
Reservoir	3.52	5.13	0.904	0.18	0.48	Debris Flood
Golf Course	1.44	3.77	0.886	0.24	0.74	Debris Flood
GS1	0.41	2.27	0.499	0.22	0.78	Debris Flood/Debris Flow
GS2	0.84	3.12	0.704	0.23	0.77	Debris Flood
Black Jacks	6.33	4.30	1.093	0.25	0.43	Debris Flood
BS1	0.71	1.98	0.57	0.29	0.68	Debris Flood/Debris Flow
BS2	0.50	2.00	0.473	0.24	0.67	Debris Flood/Debris Flow
Stevensons	4.11	3.34	0.949	0.28	0.47	Debris Flood

GEOLOGICAL EVIDENCE FOR HYDROGEOMORPHIC HAZARD TYPE

Previous hydrogeomorphic hazard events in Roxburgh have predominately been described as debris flows (e.g. Dellow et al., 2018; Mackey, 2021; WSP, 2024) with Golder (2019a) describing events as debris flows/debris floods.

Melton ratios calculated for this study indicate that hydrogeomorphic hazards in Roxburgh are dominated by debris floods. While melton ratios are useful indicators of hydrogeomorphic hazard type, field data can provide physical evidence of hydrogeomorphic hazard type. Hydrogeomorphic deposits on alluvial fans allow for geologists to identify stratigraphy and classify hydrogeomorphic hazards (Figure 20). Debris flows are known for their ability to transport large boulders (>1 m in diameter) and to deposit sediment as they lose energy, while debris floods have higher water content and deposit sediment more gradually along their path. Debris floods can also transport large boulders in high-energy flows and are typically preserved in the geological record as matrix-supported units with cemented pebbles, cobbles, and boulders (Church & Jakob, 2020).

In Roxburgh, photos taken during and immediately following the 2017 events, generally indicate high-energy debris flood characteristics dominated by water transporting large boulders with less than 40% sediment (Figure 21). While deposits suggest a range of hydrogeomorphic hazards have occurred in Roxburgh (Figure 22). Exposed stratigraphy in stream channels indicate alternating events between matrix-dominated debris floods and coarse gained pebble and cobble-dominated deposits suggesting high-energy debris floods or debris flows. Deposits include marginal levees, terminal lobes, fans, and bars which indicate both debris floods and debris flows (Wilford et al., 2004). We infer that hydrogeomorphic events in Roxburgh are dominated by high energy debris floods (as shown in Figure 21) with infrequent debris flows. This is consistent with the Melton ratio calculated for each catchment.

Figure 20: Typical debris flood stratigraphy from Cougar Creek, Alberta, Canada (Church & Jakob, 2020). Unit 1 is described as a matrix-supported outbreak flood deposit with little stone imbrication while Units 2 and 4 are high-energy debris flood deposits. Unit 3 is interpreted as a basal density flow (part of flow in contact with the ground) of Unit 2.

Figure 21: 2017 Debris flood events in Roxburgh. A and B) Black Jacks Creek during active debris flood in 2017. C and D). Debris flood deposits in Reservoir Creek shortly following the 2017 event.

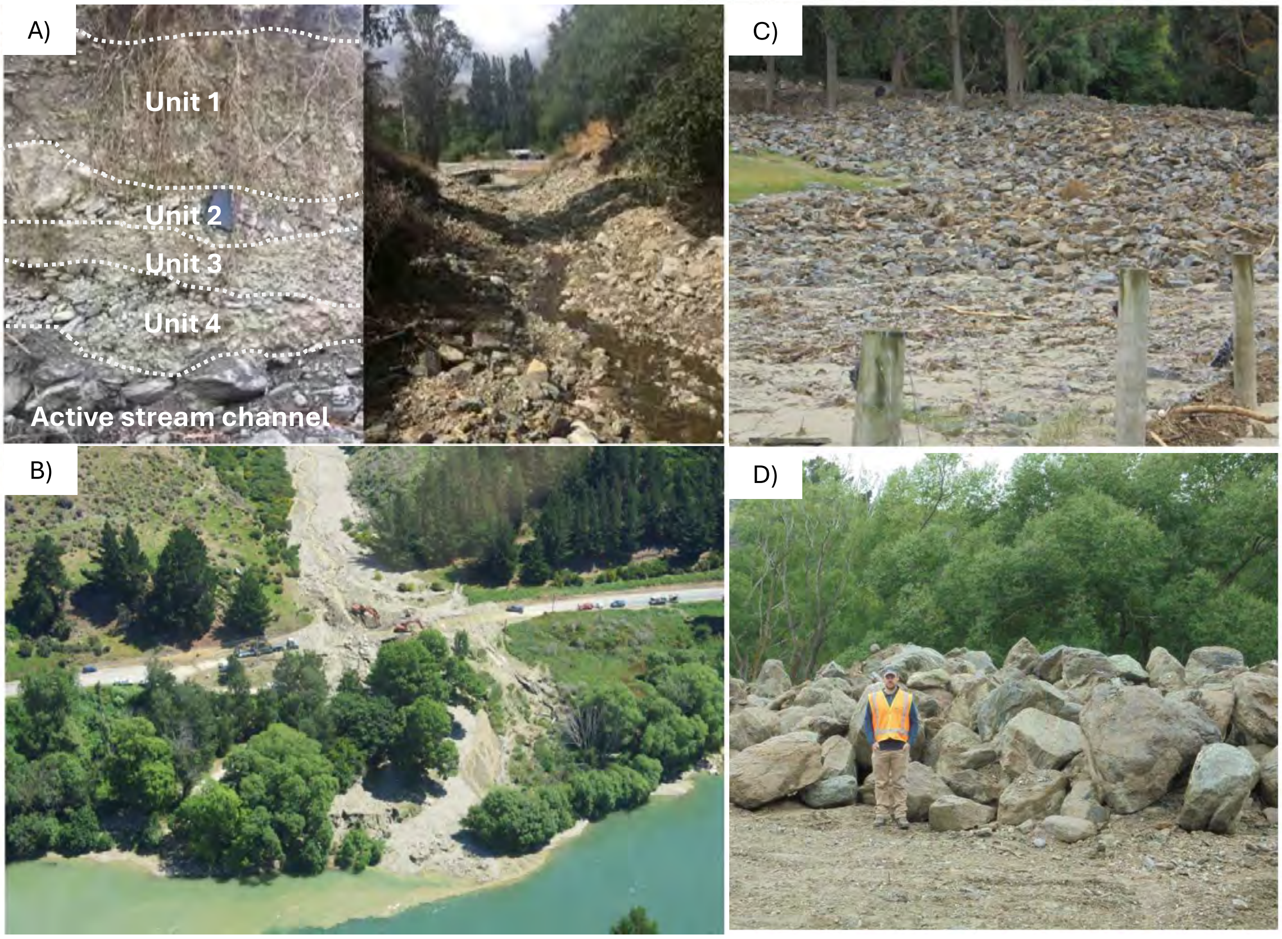


Figure 22: Debris flood and debris flow deposits in Roxburgh. A) Sequence of debris deposition in Pumphouse Creek upstream of SH8 (Golder, 2019a). Units vary between finer grained deposits with some pebbles (Units 1 and 3) to coarse gained pebble-dominated deposits (Units 2 and 4). B & D) Debris deposition on Black Jacks alluvial fan following the 2017 event (Dellow et al., 2018). C) Boulder field at Golf Course Creek following the 2017 event (Dellow et al., 2018).

2.3.2.2 DEBRIS SOURCES

Debris flood source area potential in each catchment including landslides, rockfall, and channel erodibility was assessed using geological and topographical maps, aerial imagery, and photographs. Geomorphological mapping of each catchment was undertaken to identify potential source areas for future events. For the purposes of this assessment, we have classified source types as either streambank erosion, landslides, or entrained debris in the channel.

Geomorphological evidence from LIDAR and aerial imagery was used to identify debris source areas. Streambank erosion was evident from eroded and undercut banks, exposed rock, and sediment deposits. Landslides were identified by disrupted terrain, scarps, and displaced material. Entrained debris in channels was identified by the accumulations of rocks, soil, and vegetation, at times forming natural dams or altering the stream's flow path.

STREAMBANK EROSION

Streambank erosion refers to the removal of soil, rocks, and vegetation from the banks of streams and rivers due to hydraulic forces from debris floods and gravitational forces acting on the streambank, leading to the destabilisation and collapse of the bank. Heavy rainfall, rapid snowmelt, or other hydrological events can accelerate this process, resulting in sudden and substantial additions of material to debris floods. The incorporation of streambank material alters the dynamics of debris floods, affecting their speed, travel distance, and deposition patterns. Several catchments in the study area exhibit signs of recent erosion including exposed soil and rock, stripped vegetation, scarps, and over steepened slopes (Figure 23).

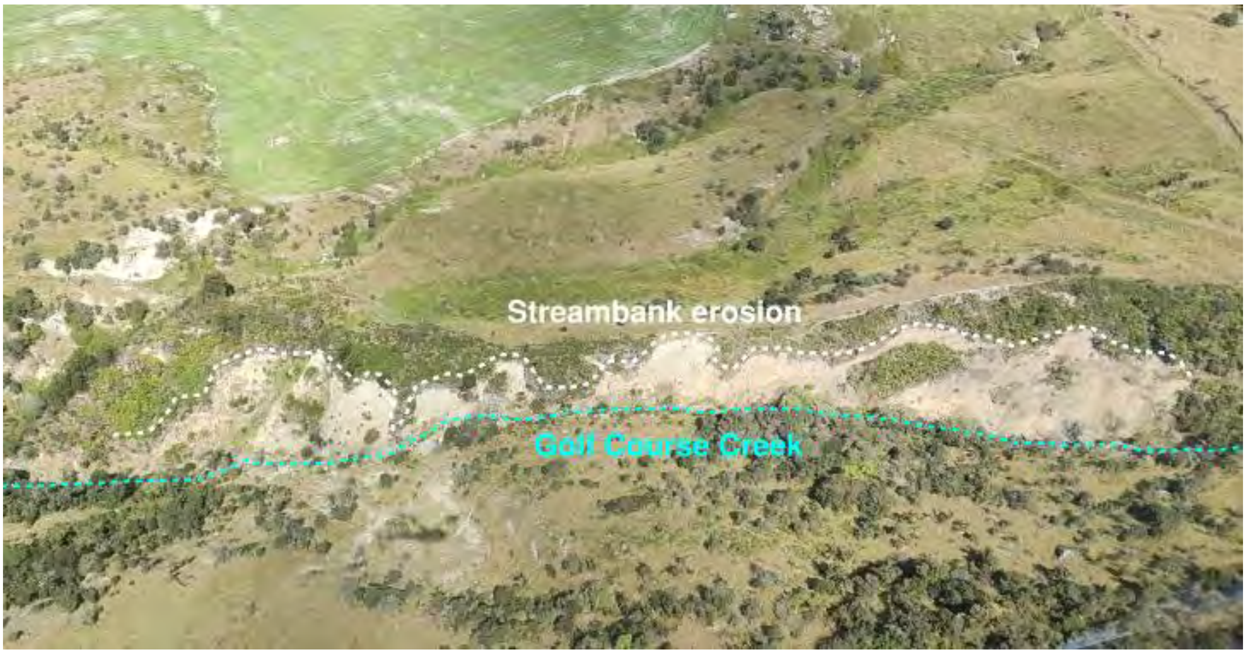


Figure 23: Recent streambank erosion in Golf Course Creek.

LANDSLIDES

Landslides are a significant source of material for debris floods. A landslide involves the movement of a mass of rock, debris, or earth down a slope under the influence of gravity. This movement can contribute a substantial amount of loose material to debris floods. Landslides encompass a variety of movements including falls, topples, slides (translational and rotational), large-scale creeps, and flows. Complex movements combine multiple types, such as a slide transitioning into a flow. While debris floods are considered to be fast-moving, fluid-like landslides, other landslides can deposit debris into a flow altering flow dynamics, magnitude, and runout.

There is evidence of recent and frequent landslides in the study area including rotational and translational slides and rockfalls (Figure 24). Additionally, the study area is known to be susceptible to widespread slow creeping landslides which can be observed in the landscape (Figure 25). Slow creeping landslide features are much larger than typically surficial landslides observed in the aerial imagery and photographs. These types of landslides are typical of schist landscapes in Central Otago and are thought to be less likely to contribute to debris floods due to much slower rate of movement and relatively intact rock material. For the purposes of this study, we refer to these features as deformed slopes, and large-scale creeping landslides.

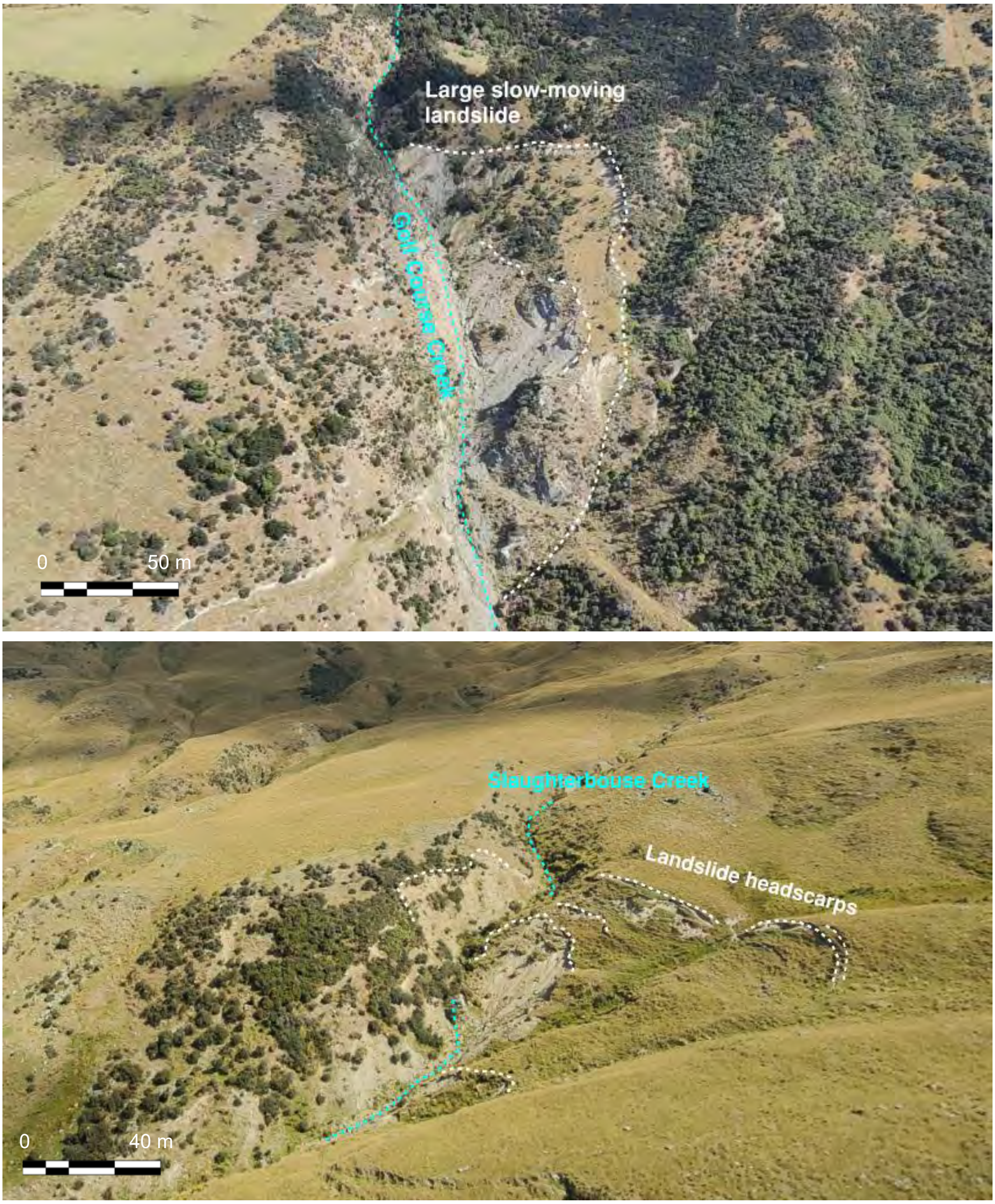


Figure 24: Different landslides identified in the study area acting as potential sources for future debris floods.

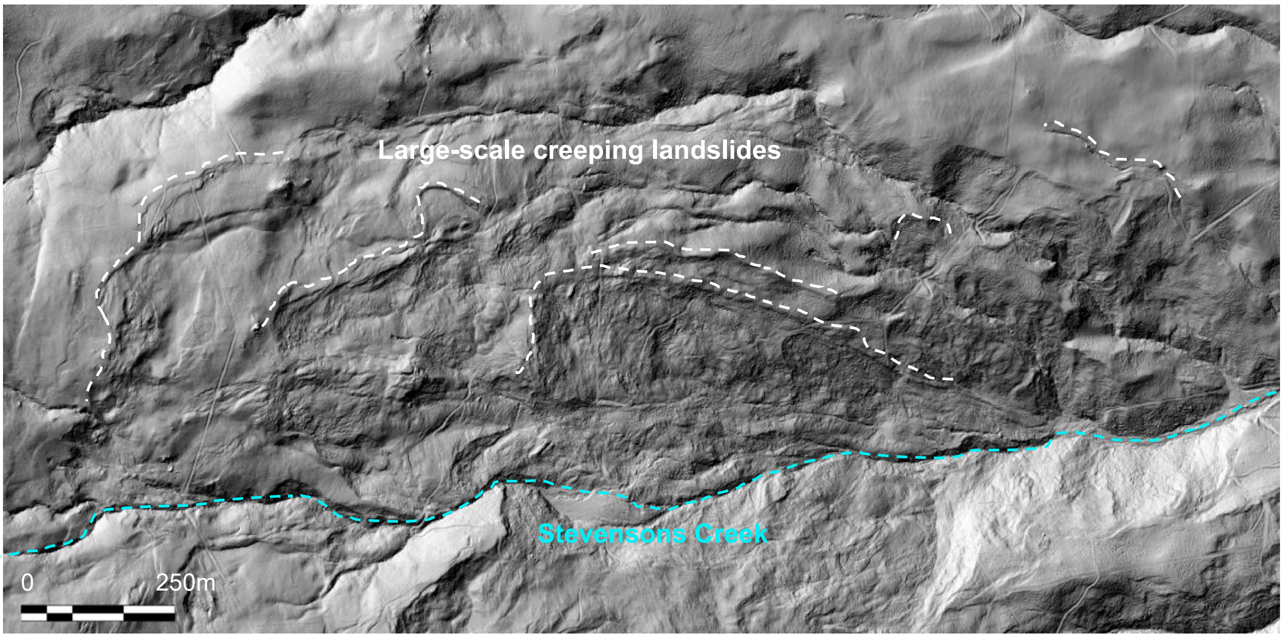


Figure 25: Evidence of larger scale creeping landslides in a hillshade generated from the 1m DEM.

ENTRAINED DEBRIS

Entrained debris in the channel refers to channel floor material that can be readily mobilized and incorporated into a debris flood. This process significantly increases the volume and complexity of the debris flood. Previous debris floods and erosion processes have also deposited significant material within the channel margins of catchments in the study area. These deposits are also potential source material for subsequent debris flood events (Figure 26).

Figure 26: Debris in the Black Jacks Creek channel following the 2017 debris flood event. Deposited material is a key source for future debris flood events.

2.3.2.3 GEOMORPHOLOGICAL MAPPING

The three source types described above have been mapped within the study area using the 2024 ortho imagery and LiDAR supplied by ORC. Table 11 presents a summary of the geomorphic mapping of potential debris flood source areas in each catchment. Figure 27 presents this information normalised by catchment area (adjusted to account for the size of each catchment, to enable comparison of the catchments). The named catchments in this study (Golf Course, Stevensons, Reservoir, Slaughterhouse, Pumpstation, and Black Jacks) have a greater proportion of more recently active and smaller scale source types (entrained debris, landslides, and streambank erosion) compared to the other catchments. This is also generally the case for larger scale slope creep or deformed slopes identified in the mapping. Typically, the named catchments display more active morphology, indicated by bare soil and rock slopes/channels, changes in slope, headscarps, and landslide deposits than the other catchments. This observation is consistent with recorded debris flood events.

Individual catchment summaries and maps are provided in Appendix B. Mapping was undertaken at the 1:1000 scale, where typically only features > 20 m^2 were mapped.

Table 11: Summary of geomorphic mapping for debris flood source areas of each catchment.

Catchment	Catchment area (km^2)	Streambank erosion (m^2)	Entrained debris (m^2)	Landslide (m^2)	Deformed slope (m^2)
Slaughterhouse	2.93	17,069	11,797	17,097	375,649
PN2	3.58	1,220	2,459	6,145	45,483
PN1	2.60	1,020	5,796	17,336	5,645
Pumpstation	2.68	6,707	14,266	7,432	54,477
RN1	0.28	201	975	-	-
Reservoir	3.52	30,093	25,819	4260	240,033
Golf Course	1.44	11,668	15,370	16,444	65,701
GS1	0.41	76	2,093	-	-
GS2	0.84	-	1,640	-	-
Black Jacks	6.33	16,065	23,056	11,897	292,581
BS1	0.71	1,335	888	226	19,842
BS2	0.50	1,098	1,546	1,240	30,281
Stevensons	4.11	26,166	38,442	54,162	733,878

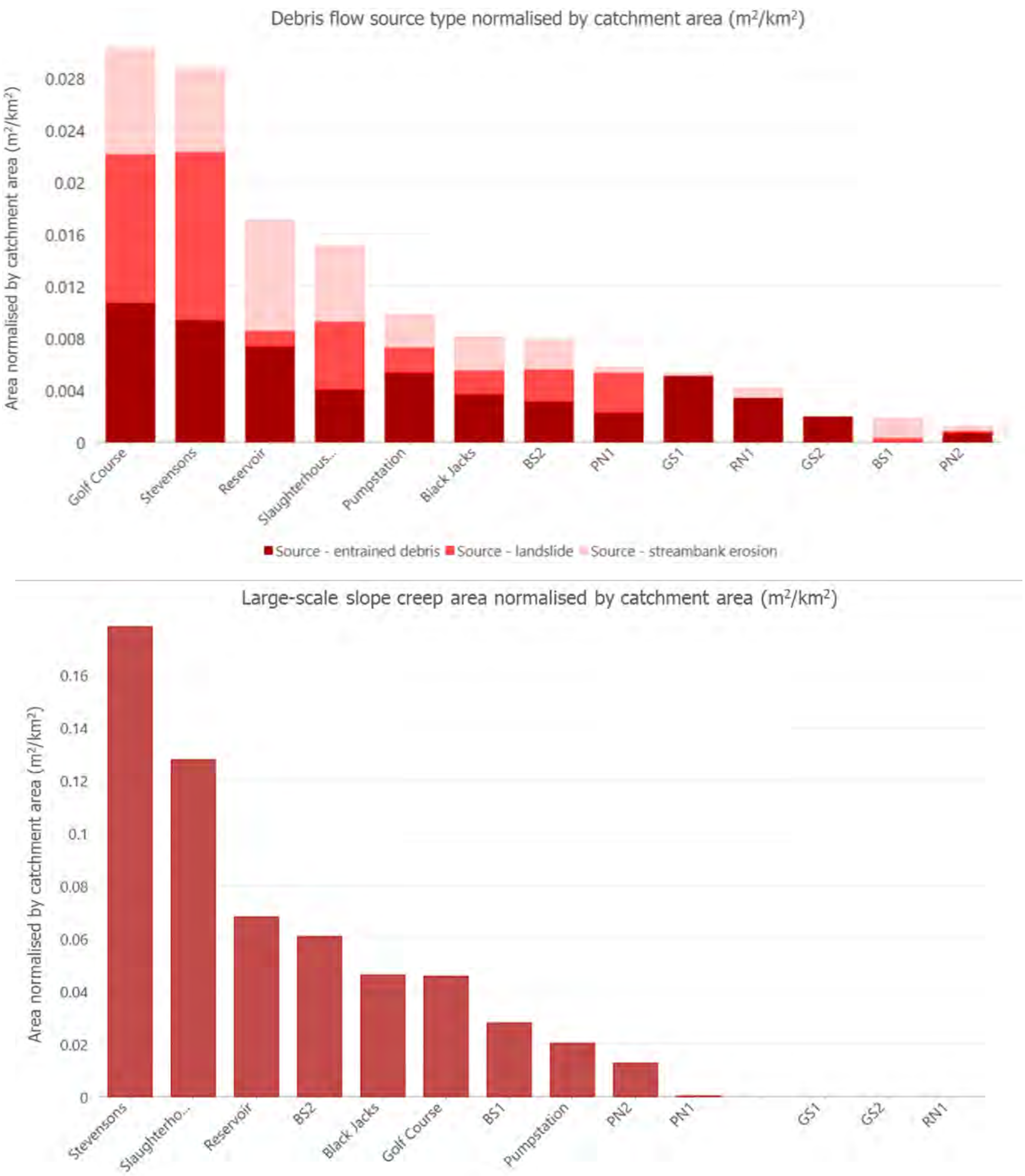


Figure 27: Mapped source area totals in each catchment normalised by catchment area (m^2/km^2). Top: Recently active and generally smaller scale debris flood source areas in each catchment. Bottom: Larger scale deformed slopes or slope creep in each catchment.

2.3.3 GEOTECHNICAL INVESTIGATIONS SUMMARY

In November 2025, eight test pits were excavated across two alluvial fans near Roxburgh, Central Otago, to validate debris flood modelling and risk assessments. Six pits (TP01–TP06) were located on Stevensons Fan in Dumbarton, while two (TP07–TP08) were on Pumpstation Fan near Roxburgh township. Excavations ranged from 4–7 m in depth and revealed predominantly unsorted silty and sandy gravels with cobbles and boulders, indicative of high-energy debris flow and debris flood deposition. Occasional thin silt and sand layers, some containing rootlets, suggest intermittent low-energy flood events or paleosols. A thick gravelly silt unit was encountered at depth in several pits, particularly near the Clutha River, consistent with older, lower-energy alluvial deposits.

Groundwater was only encountered in TP08, and was observed at 4 m depth.

The stratigraphy reflects active fan aggradation in a post-glacial environment, dominated by Holocene debris flow and flood deposits overlying older Pleistocene alluvium. Variability in grainsize and sorting supports episodic high-energy deposition interspersed with quieter periods. Anecdotal and historical borehole data indicate deeper sequences of lignite-bearing sediments and schist bedrock at significant depth (> 20 m). Overall, the findings align with regional geological history, where Quaternary glacial and fluvial processes shaped terraces with alluvial fans forming following glacier retreat.

A detailed summary of this work including maps and test pit logs is provided in Appendix I.

2.4 HYDROLOGICAL ASSESSMENT OF CATCHMENTS

The purpose of this assessment is to evaluate the peak flows from each catchment using HEC-HMS modelling (SCS method) as this is a key input for the hydrogeomorphic modelling. As part of this assessment, it was necessary to update the peak flow data for the five catchments within the study area based on the previous assessment carried out by Golder (2019a). In addition, the assessment now includes an evaluation of seven additional catchments. Trigger frequency was analysed as part of this assessment including the effect of climate change scenarios on rainfall intensity and duration. Detailed methodology is provided in Appendix C.

2.4.1 HYDROLOGY

2.4.1.1 RAINFALL

The rainfall hyetographs used in this assessment were generated using the asymmetric hyperbolic tangent distribution methodology described in HIRDS version 4 (NIWA, 2018). For the 100-year and 250-year ARI events, total rainfall depths were obtained directly from the HIRDSv4 depth–duration–frequency (DDF) dataset, while depths for the 500-year, 1,000-year, and 2,500-year ARI events were extrapolated from the same dataset (refer to Figure 40).

The resulting hyetographs for each ARI event are presented in Figure 28. These profiles are based on the East of South Island region, confirming that the adopted temporal distributions are representative of rainfall behaviour in a climatically and geographically relevant setting.

The rainfall depths are summarised in Table 12, and the derived hyetographs were subsequently used to generate hydrographs that formed inputs to the RAMMS modelling and the associated risk assessment.

During the hydrological assessment it became apparent that PN2 has two main channels which coalesce on the upper alluvial fan. Debris floods could occur in either channel and hence, we have split PN2 into PN2 north (northern-most main channel) and PN2 south (southern-most channel).

Table 12: Rainfall data used for the model.

Rainfall Event	Rainfall Depth (mm)
100yr ARI, climate change RCP 8.5, 1hr duration	49.5
250yr ARI, climate change RCP 8.5, 1hr duration	62
500yr ARI, climate change RCP 8.5, 1hr duration	84
1000yr ARI, climate change RCP 8.5, 1hr duration	105
2500yr ARI, climate change RCP 8.5, 1hr duration	140

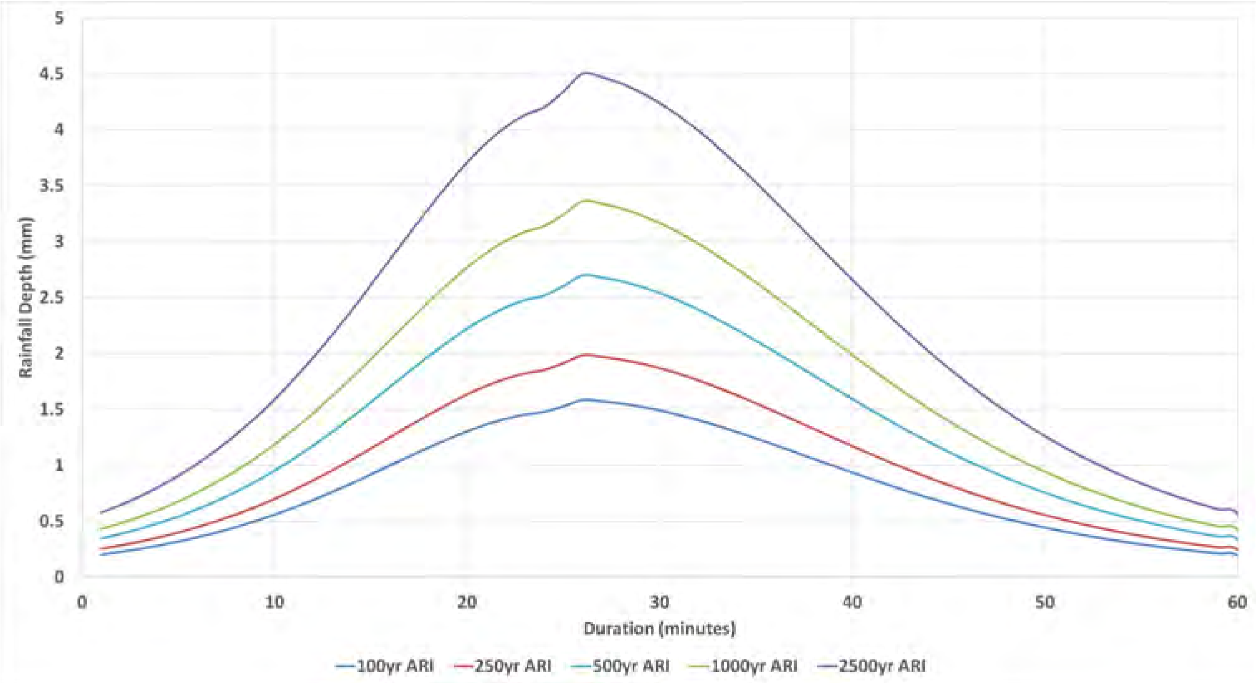


Figure 28: Rainfall depth for each ARI of interest in the hydrological assessment.

2.4.1.2 PEAK FLOW

Catchment delineation and assessment were not performed. The catchments used in this assessment were provided by the client and have not been reassessed, adjusted, or modified. Table 13 presents the parameters and inputs used in the HEC-HMS model setup. The soil storage parameter and initial abstraction values were set to default settings in the HEC-HMS model.

Table 13: Catchments summary and input data for the HEC-HMS modelling.

Catchment	**ID**	**Area (ha)**	**CN weighted**	**Time of Concentration (ToC) (minutes)**	**Lag time**	**Initial Abstraction (I_a)**
Black Jacks	1	633.49	67	26.79	17.86	24.84
BS1	2	70.77	61	12.81	8.53	32.48
BS2	3	49.81	61	11.68	7.78	32.48
Golf Course (GLF)	4	143.79	66	21.04	14.025	26.73
GS1	5	40.65	60	13.04	8.69	33.28
GS2	6	84.42	63	16.75	11.164	29.40
PN1	7	259.58	65	17.94	11.96	27.88
PN2-North	8	231.7	63	17.21	11.47	29.98
PN2-South	9	128.7	63	17.21	11.47	29.98
Pumpstation (PPS)	10	268.26	66	19.65	13.1	26.60

Catchment	ID	Area (ha)	CN weighted	Time of Concentration (ToC) (minutes)	Lag time	Initial Abstraction (I_a)
Reservoir (RSV)	11	351.98	67	26.84	17.89	24.94
RN1	12	28.462	61	8.33	6.67[1]	32.48
Slaughterhouse (SLH)	13	293.1	63	15.21	10.143	29.76
Stevensons (STV)	14	411.48	65	16.78	11.19	27.57

[1] Since the time of concentration for catchment RN1 was less than 10 minutes, a lag time of 6.67 minutes (2/3 of 10 minutes) was applied.

The results generated from HEC-HMS modelling for each catchment are in Table 14 below:

Table 14: Peak flow (m^3/s) for each catchment in the study area.

Peak Flow / Catchment	Q100 (m^3/s)	Q250 (m^3/s)	Q500 (m^3/s)	Q1000 (m^3/s)	Q2500 (m^3/s)
Black Jacks	12.5	25.4	55.7	89.8	156.9
BS1	0.8	2.1	5.4	9.4	17.6
BS2	0.6	1.5	3.9	6.7	12.6
Golf Course (GLF)	2.8	5.8	13.1	21.4	37.8
GS1	0.4	1.1	2.9	5.1	9.7
GS2	1.2	2.8	6.9	11.6	21.3
PN1	4.7	10.7	23.6	38.8	69.2
PN2-North	3.3	7.7	18.7	31.7	57.9
PN2-South	1.8	4.3	10.4	17.6	32.2
Pumpstation (PPS)	5.3	11.2	25.1	40.9	72.1
Reservoir (RSV)	6.9	14.1	30.9	49.9	87.1
RN1	0.3	0.9	2.3	4	7.4
Slaughterhouse (SLH)	4.3	10.1	24.6	41.5	75.9
Stevensons (STV)	7.7	16.6	38.1	62.8	112

2.5 FREQUENCY-MAGNITUDE OF DEBRIS FLOOD EVENTS

2.5.1 VOLUME AND LIKELIHOOD

The review of historical data revealed limited information to develop detailed frequency-magnitude relationships for the study area. This study estimates three debris flood magnitudes (high likelihood, median likelihood, and maximum credible event) for each catchment based on the geomorphic mapping of source areas (as outlined in Section 2.3.2.2 and Section 2.3.2.3). These magnitudes are informed by the debris flood inventory, global examples, and hydrological and geomorphological assessments. The mapping identified three potential source areas: entrained debris in the channel, streambank erosion, and landslides. However, the mapping does not provide a volume without estimating factors such as the depth of erosion or the likelihood that a source will be entrained in a flow or flow. For this study, we have developed a specific framework for calculating likely debris flood volume based on mapping of potential sources. This section outlines the results of our approach and compares calculated volumes to historical events to assess frequency. The detailed methodology applied in this assessment is provided in Appendix D.

Table 16 presents the volume estimates for the high likelihood, median, and maximum credible debris flood event for each catchment in the study area. Volumes are calculated using Equation 1 and the variables described in Appendix D. A lower, upper, and median volume has been calculated for each event. The median volume for each event (i.e. median volume for the high likelihood, median likelihood, and maximum credible events) is used as an input to the hydrogeomorphic modelling in RAMMS and has been rounded to the nearest 1,000 m^3.

For the high likelihood event, we have calculated debris flood volumes for the larger named catchments in the study area between 35,000 to 100,000 m^3 with smaller catchments < 10,000 m^3. The 2017 events have records for debris flood events in the study area exceeding 100,000 m^3 (Black Jacks and Reservoir). These two debris floods were triggered by at least 60 mm of rainfall in an hour. Smaller debris floods (<10,000 m^3) in Golf Course Creek and Pumpstation Creek were triggered by at least 40 mm of rainfall in an hour in the same event. Therefore, we estimate that the amount of rainfall required to trigger high likelihood events is 40-60 mm in 1 hour. This is equivalent to a 1:50 to 1:150-year rainfall event for the study area under a Representative Concentration Pathway (RCP) 8.5 scenario until 2100 (Figure 40). An RCP8.5 scenario is a high-emissions pathway of greenhouse gas emissions in climate models and represents a conservative scenario for rainfall in Roxburgh.

For the median likelihood event, we have calculated debris flood volumes for larger named catchments in the study area between 80,000 to 210,000 m^3 with smaller catchments < 80,000 m^3. Historical debris flood events in the study area greater than 100,000 m^3 have been triggered by 60-100 mm of rainfall in 1 hour (2017 Black Jacks and Reservoir). This is equivalent to a ~1:200 to 1:800-year rainfall event for the study area under a RCP8.5 scenario until 2100 (Figure 40).

For the maximum credible event, we have calculated debris flood volumes for larger named catchments in the study area in the 150,000 to 430,000 m^3 range. Smaller catchments are generally in the 30,000 to 150,000 m^3 range. There is no historical evidence for events greater than 200,000 m^3; however, the geomorphology of some of the catchments suggest that there is enough source material to produce debris flood volumes of this magnitude with sufficient rainfall. These maximum credible events could have occurred prior to human settlement. The amount of rainfall required to trigger events of this magnitude is uncertain; however, for the purposes of this assessment we estimate that at least >140 mm of rainfall in 1 hour is reasonable. This is equivalent to a >1:2500-year rainfall event for the study area under a RCP8.5 scenario until 2100 (HIRDS).

Table 15: Assessed trigger intensity and indicative frequency for each debris flood event size in this assessment.

Event	Trigger (based on 2017 events)	Indicative Frequency
High Likelihood	40-60 mm of rainfall in 1 hour	50 – 150 years
Median Likelihood	60-100 mm of rainfall in 1 hour	200 – 800 years
Maximum Credible	>140 mm of rainfall in 1 hour	>2,500 years

Table 16: Estimated volumes for each debris flood event using Equation 1.

Catchment	High likelihood event volume (m^3)			Median likelihood event volume (m^3)			Maximum Credible event volume (m^3)		
	Total volume		Median Volume	Total volume		Median Volume	Total volume		Median Volume
	Lower	Upper		Lower	Upper		Lower	Upper	
Black Jacks	37,504	152,436	95,000	75,008	333,363	204,000	150,016	666,726	408,000
BS1	2,778	11,406	7,000	5,555	24,955	15,000	11,111	49,910	31,000
BS2	7,881	32,236	20,000	15,762	70,534	43,000	31,524	141,069	86,000
Golf Course	18,348	74,537	46,000	36,697	163,013	100,000	73,394	326,025	200,000
GS1	2,456	9,998	6,000	4,912	21,895	13,000	9,824	43,789	27,000
GS2	5,081	20,735	13,000	10,163	45,359	28,000	20,325	90,718	56,000
PN1	3,222	13,109	8,000	6,445	28,666	18,000	12,890	57,332	35,000
PN2-North	8,121	33,153	21,000	16,242	72,514	44,000	32,483	145,028	89,000
PN2-South	5,717	23,338	15,000	11,433	51,046	31,000	22,867	102,093	62,000
Pumpstation	14,577	59,192	37,000	29,154	129,446	79,000	58,307	258,891	159,000
Reservoir	28,048	113,971	71,000	56,097	249,250	153,000	112,193	498,500	305,000
RN1	2,880	11,724	7,000	5,761	25,643	16,000	11,522	51,286	31,000
Slaughterhouse	17,419	70,917	44,000	34,838	155,097	95,000	69,675	310,193	190,000
Stevensons	39,156	159,330	99,000	78,311	348,452	213,000	156,623	696,904	427,000

2.5.2 COMPARISON OF VOLUME ESTIMATES

In Roxburgh, sediment deposited by debris flood has built significant fans onto old river terraces. The total volume of material on each fan is a useful indicator of yearly accumulation and is compared in this section to our calculated volume estimates to validate volume estimates.

The majority of the alluvial fans in the study area are truncated by the Clutha River or coalesce; therefore, the true extents and volumes of those fans are not known. It is likely that a significant proportion of material has been lost to the Clutha River and is not preserved on these fans.

The alluvial fans for PN1, PN2, Slaughterhouse, and Stevensons are extensive with little truncation from the Clutha River or other fans. It is more likely that the majority of material deposited has been preserved on these fans. Therefore, we only compare calculated volumes to total fan volume and yearly accumulation for these fans.

In theory, well-formed and uninterrupted alluvial fans are most similar to circular half cones in geometry and hence we have calculated fan volume using the below equation:

$$V = (\pi r^2 \frac{h}{3})/2$$

Where:

- r = radius of the fan measured from the fan apex to the fan outlet.
- h = the maximum height of material on each fan informed by generating elevation profiles in ArcGIS Pro along each fan using the 2024 1m DEM as the elevation surface. The maximum height of material on each fan was taken to be the difference between the highest point on each elevation profile and lowest point at the margin of the fan. We acknowledge this has not been validated by ground investigations.

In reality, streams do not produce alluvial fans with geometries of perfect half cones; therefore, there is some uncertainty is this simple volume calculation; however, we judge it to be sufficient for a comparison. To reduce uncertainty, we only calculate the volume and yearly accumulation for fans that are the most similar to a half cone in geometry.

We assume that debris floods and flows started to deposit material onto fans following retreat of glaciers in the head of the Clutha River catchment. Denton et al. (2021) suggests this may have occurred 18,000 years ago due to indications of a poleward shift of the austral westerlies (movement of the midlatitude westerly winds in the Southern Hemisphere towards the poles) in glacial moraines. Therefore, we estimate the average yearly accumulation on each fan by dividing total fan volume by 18,000. There is uncertainty adopting any estimate for retreat of the glaciers. Estimates for glacial retreat are uncertain due to climate variability, incomplete historical data, and complex interactions between glaciers and their environment (Huss et al., 2014; Zemp, et al., 2019). Additionally, local factors and human impacts contribute to the unpredictability of glacier dynamics.

The average yearly accumulation of debris on each fan since glaciation is presented in Table 17. These values have been multiplied by the average return period of each event considered in this study (1:100, 1:500, and 1:2500 for the high likelihood, median likelihood, and maximum credible events) for comparison to the volumes estimated for those events. These return periods are thought to best represent the return period of each event size and most closely correlate to the return periods in Table 15. For example, the average accumulation value was multiplied by 100 for the 1:100 year event to extrapolate an average yearly accumulation out to 100 years.

The comparison for the high likelihood, median likelihood, and maximum credible event volumes is presented in Figure 29, Figure 30, and Figure 31. This comparison was only completed for four fans that are not significantly truncated by the Clutha River; Slaughterhouse, PN2, PN1, and Stevensons. For PN2 we have combined the calculated volumes for the northern and southern portions of the fan for the purposes of this comparison.

For the median likelihood event, this comparison appears to work reasonably well for catchments with fans that are not truncated by the Clutha River. For the high likelihood event, our estimate appears to be greater than the average yearly accumulation estimate.

For the maximum credible event, our estimate is lower than the volume calculated using the average yearly accumulation estimate. While there is some discrepancy between volume estimates at the lower and upper bound of credible events, this comparison yields results that are within an order of magnitude. We expect this discrepancy arises because the average yearly accumulation represents a long-term mean over centuries of deposition, whereas the high-likelihood and maximum credible events are individual occurrences of specific magnitudes, likely falling on either side of the mean event size.

Table 17: Average yearly debris accumulation on each alluvial fan in Roxburgh post-glaciation.

Catchment	Maximum height of material on fan (m)	Fan Radius (m)	Total volume of material on fan (m^3)	Average yearly accumulation since glaciation (m^3/yr)
Slaughterhouse	13	763	3,960,690	220
PN2	15	421	1,391,342	77
PN1	10	356	663,252	37
Stevensons	18	840	6,646,752	369

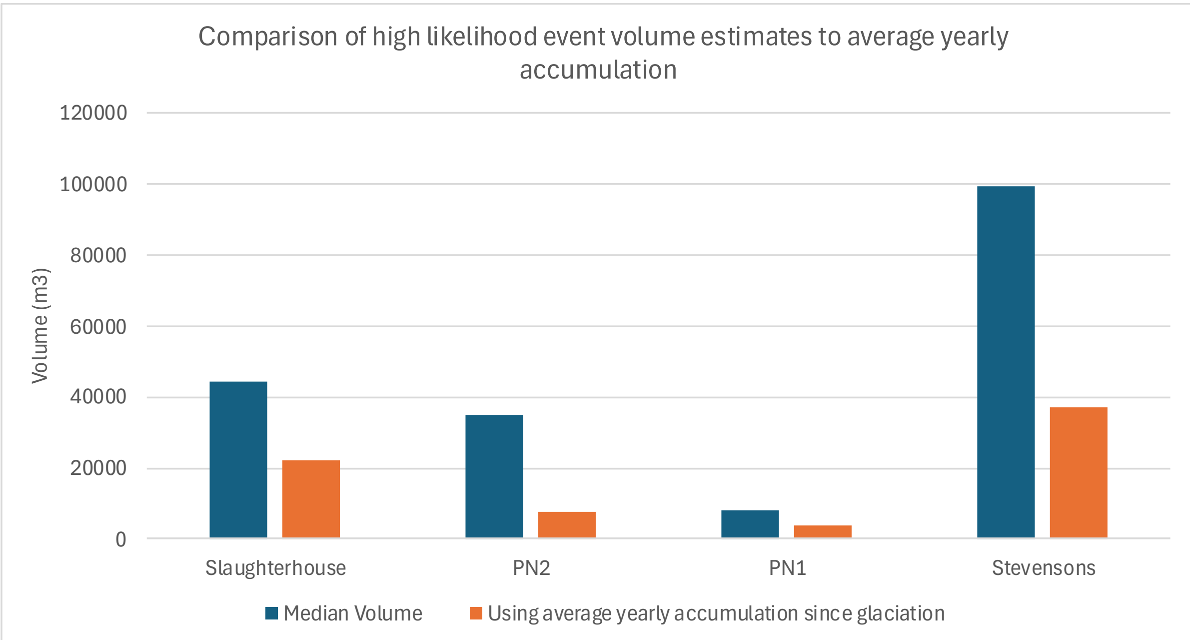


Figure 29: Comparison of the high likelihood volume estimate to volume calculated using the average yearly accumulation since glaciation.

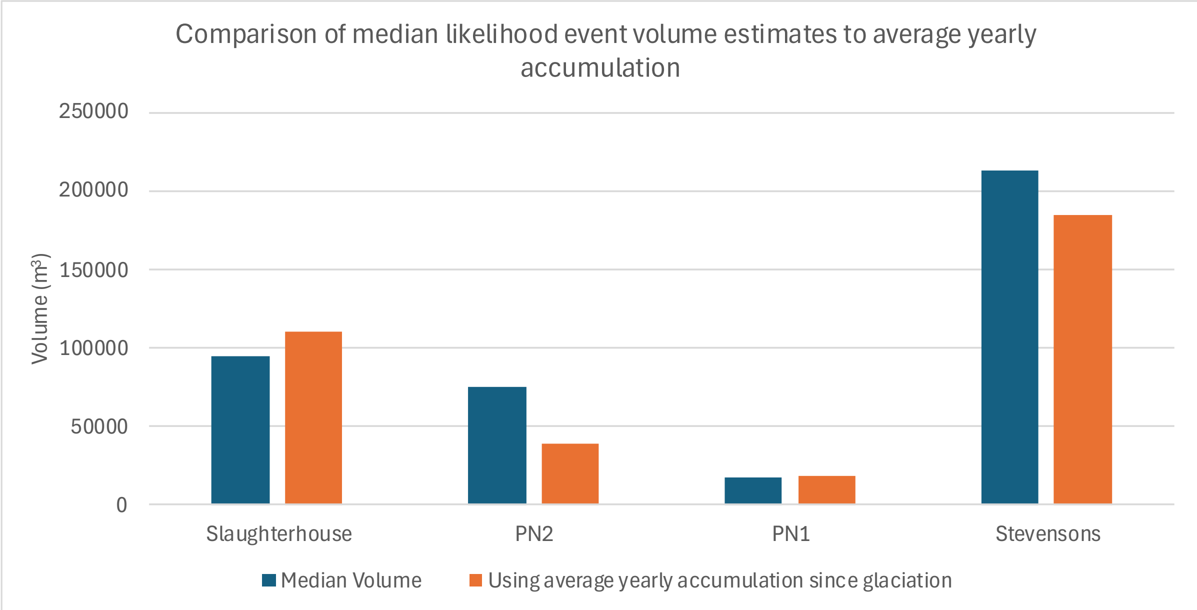


Figure 30: Comparison of the median volume estimate to volume calculated using the average yearly accumulation since glaciation.

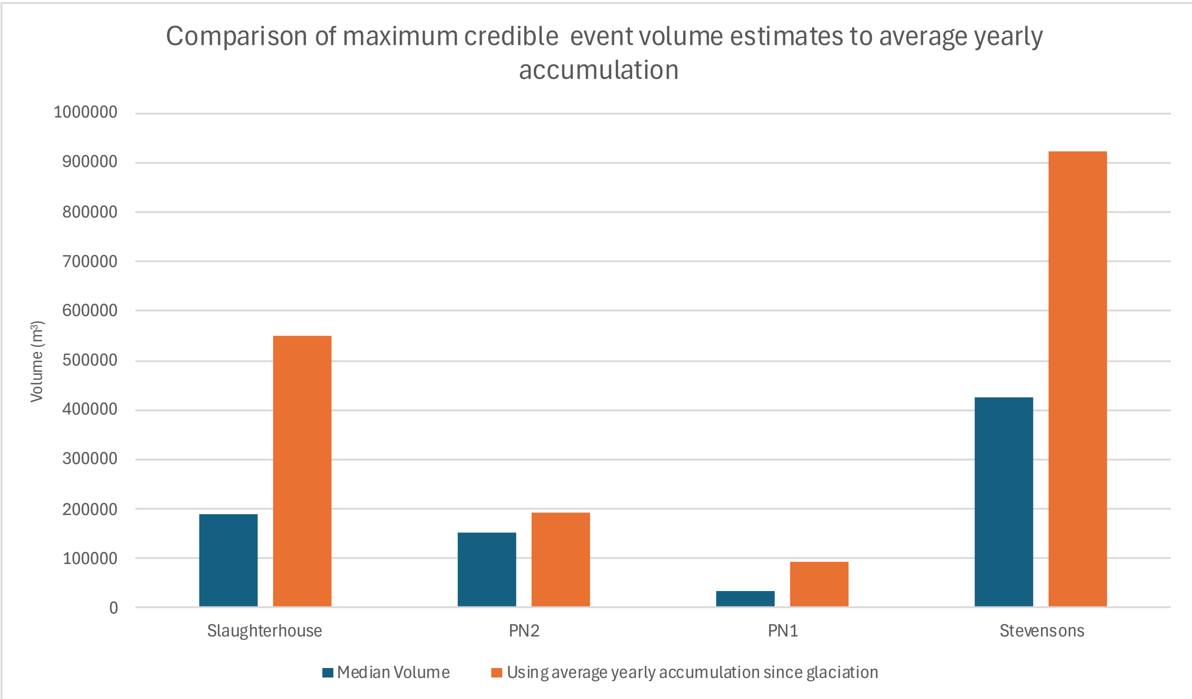


Figure 31: Comparison of the maximum credible volume estimate to volume calculated using the average yearly accumulation since glaciation.

2.6 RAMMS DEBRIS FLOOD SIMULATION

2.6.1 RAMMS SOFTWARE

RAMMS (Rapid Mass Movement Simulation) is a numerical modelling software developed by the WSL Institute for Snow and Avalanche Research, designed to simulate natural hazard processes. RAMMS Debris Flow (RAMMS-DF, Version 1.8.27) uses a single-phase model to simulate the mass movement of debris flow type processes on a three-dimensional (3D) terrain. The software allows for a wide range of input parameters used to refine the model and simulate different types of flow behaviour. During the simulation, RAMMS-DF calculates the progressive downslope movement by use of depth-average equations which model the debris flow dynamics.

The purpose of the RAMMS-DF modelling was to assess the potential debris flood hazard for further risk assessment, on the alluvial fans below each of the thirteen (13) catchments within the Roxburgh study area; this includes Black Jacks, BS1, BS2, Golf Course (GLF), GS1, GS2, PN1, PN2 (North and South), Pumpstation, Reservoir, RN1, Slaughterhouse and Stevensons. Based on the geomorphological assessment carried out for each catchment, the most dominant hazard for the alluvial fan below each catchment was classified as a debris flood (fluid dominated), as opposed to a debris flow (solid dominated), refer to Section 2.3.2. The modelled inputs outlined in Appendix E are defined based upon flow behaviour consistent with a debris flood event.

The RAMMS debris flood models generated for this assessment incorporate the volumes estimates described in Section 2.5 and the hydrology of each catchment (Section 2.4), specifically the peak flow of the main channels.

RAMMS-DF is widely accepted for the simulation of a debris flood events used by researchers and practitioners around the world. Model parameters have been adjusted to align with the flow behaviours' of a debris flood. It is important to calibrate and adjust the modelled input parameters used to define a debris flood event to reflect field observations from previous events. Calibration and sensitivity testing of RAMMS outputs was undertaken to validate the model assumptions.

The methodology used in the RAMMS modelling for this assessment including input parameters, calibration, limitations, and outputs are provided in Appendix E. Mapped outputs of the debris flood assessment are provided in Appendix F.

3 QUALITATIVE RISK ASSESSMENT

3.1 INTRODUCTION

Historical debris floods have caused damage to the built environment in Roxburgh including critical infrastructure, services, and residential and commercial property. There is a need to assess the relative risk level of catchments to focus further assessment and mitigation.

Qualitative assessment of debris flood risks on each alluvial fan in the study area is used to determine relative risk level and tolerability. The APP6 methodology for natural hazard risk assessment (ORC, 2021) is used as the framework for this risk assessment. This framework uses the following relationship:

$$Risk = Hazard\ Likelihood\ \times Consequence$$

A qualitative risk assessment using this framework will be completed for the three scenarios for each catchment described previously: a high likelihood event, median event, and maximum credible event Table 16. This assessment will use the output maps of debris flood inundation modelled for the three scenarios for each catchment (the hazard extent), geospatial layers of exposed assets and people (exposure), and vulnerability functions used in comparable studies to assess hazard likelihood, consequence, and risk. The input datasets used in this phase are summarised in Table 18.

Table 18: Datasets used for the qualitative risk assessment.

Source	Dataset	Usage
ORC	2021 Regional Policy Statement – APP6 framework	Qualitative risk assessment framework
AGS	AGS Landslide Risk Management Guidelines 2007	
WSP	Phase 3: Hydrogeomorphic Modelling – debris flood extents and intensities	Hazard likelihood and consequence assessment
LINZ	NZ Building Polygons	Consequence assessment
	NZ Road Centrelines 1:50k	
	NZ Bridge Centrelines 1:50k	
CODC	Heritage Buildings shapefile	
	Water Supply Points	
	Stormwater Pipes	
	Stormwater Points	
	Wastewater Pipes	
Transpower	Structures 1:50k	
GNS	Residential building dataset (Scheele et al., 2021). Used as the population dataset in this assessment. Landslide Planning Guidance (de Vilder et al., 2024)	

Source	Dataset	Usage
Other	Previous studies and reports including journal papers, previous consultancy reports, and photographs.	Qualitative risk assessment framework and consequence assessment

3.2 HAZARD LIKELIHOOD

We estimated a debris flood volume for a high likelihood, median likelihood, and maximum credible event in each catchment in Phase 3 (Table 16). Discussion of the frequency or likelihood of each event size is in Section 2.5.1 and outlined in Table 15. For the qualitative risk assessment, we use the qualitative descriptors of likelihood and indicative frequencies outlined in Table 19. Based on relative debris flood volume, peak flow, and rainfall:

— The high likelihood debris flood event in each catchment is assessed as a 'likely' event.

— The median debris flood event in each catchment is assessed as a 'possible' event.

— The maximum credible debris flood event in each catchment is assessed as a 'rare' event.

Table 19: The hazard likelihood descriptors and indicative frequency schema used for this assessment (ORC, 2021).

Likelihood	Indicative frequency
Almost certain	Up to once every 50 years (2% AEP)
Likely	Once every 51 – 100 years (2 – 1% AEP)
Possible	Once every 101 – 1,000 years (1 – 0.11% AEP)
Unlikely	Once every 1,001 – 2,500 years (0.1 – 0.04% AEP)
Rare	2,501 years plus (<0.04% AEP)

3.3 CONSEQUENCE

We have assessed the consequences of each debris flood event using Table 20 as outlined in APP6 (ORC, 2021) and through consideration of the following:

— the nature and scale of activities in the area,

— individual and community vulnerability and resilience,

— impacts on individual and community health and safety,

— impacts on social, cultural and economic well-being,

— impacts on infrastructure and property, including access and services,

— available and viable risk reduction and hazard mitigation measures,

— lifeline utilities, essential and emergency services, and their co-dependence,

— implications for civil defence agencies and emergency services,

— the changing natural hazard environment,

— cumulative effects including multiple and cascading hazards, where present, and

— factors that may exacerbate a natural hazard event including the effects of climate change.

For the purposes of this assessment, we use the numbers 1-5 to represent relative consequence levels aligned with Table 20. For example, an insignificant consequence is represented as a 1.

Inundation extents produced from the RAMMS modelling have been used to determine the exposure of each asset to hazard intensity in GIS. Maps of RAMMS outputs and exposed assets (buildings and lifelines) are provided in Appendix F. Maps showing the spatial distribution of risk are included in the quantitative risk assessment phase of this study.

Table 20: The consequence matrix used in this assessment from APP6 (ORC, 2021).

Severity of Impact	Built				Health & Safety
	Social/Cultural	*Buildings*	Critical *Buildings*	Lifelines	
Catastrophic **(V)**	≥25% of *buildings* of social/cultural significance within hazard impact area have functionality compromised	≥50% of *buildings* within hazard impact area have functionality compromised	≥25% of critical facilities within hazard impact area have functionality compromised	Out of service for > 1 month (affecting ≥20% of the town/city population) OR suburbs out of service for > 6 months (affecting < 20% of the town/city population)	> 10 dead and/or > 1001 injured
Major **(IV)**	11-24% of *buildings* of social/cultural significance within hazard impact area have functionality compromised	21-49% of *buildings* within hazard impact area have functionality compromised	11-24% of *buildings* within hazard impact area have functionality compromised	Out of service for 1 week – 1 month (affecting ≥20% of the town/city population) OR suburbs out of service for 6 weeks to 6 months (affecting < 20% of the town/city population)	1 – 10 dead and/or 101 – 1000 injured
Moderate **(III)**	6-10% of *buildings* of social/cultural significance within hazard impact area have functionality compromised	11-20% of *buildings* within hazard impact area have functionality compromised	6-10% of *buildings* within hazard impact area have functionality compromised	Out of service for 1 day to 1 week (affecting ≥20% of the town/city population) OR suburbs out of service for 1 week to 6 weeks (affecting < 20% of the town/city population)	11 – 100 injured
Minor **(II)**	1-5% of *buildings* of social/cultural significance within hazard impact area have functionality compromised	2-10% of *buildings* within hazard impact area have functionality compromised	1-5% of *buildings* within hazard impact area have functionality compromised	Out of service for 2 hours to 1 day (affecting ≥20% of the town/city population) OR suburbs out of service for 1 day to 1 week (affecting < 20% of the town/city population	10 injured
Insignificant **(I)**	No *buildings* of social/cultural significance within hazard impact area have functionality compromised	< 1% of *buildings* within hazard impact area have functionality compromised	No damage within hazard impact area, fully functional	Out of service for up to 2 hours (affecting ≥20% of the town/city population) OR suburbs out of service for up to 1 day (affecting < 20% of the town/city population	No dead No injured
When assessing consequences within this matrix, the final level of impact is assessed on the 'first past the post' principle, in that the consequence with the highest severity of impact applies. For example, if a *natural hazard* event resulted in moderate severity of impact across all of the categories, with the exception of critical *buildings* which had a 'major' severity of impact, the major impact is what the proposal would be assessed on. If a *natural hazard* event resulted in all of the consequences being at the same level (for example, all of the consequences are rated moderate), then the level of consequence is considered to be moderate.					

3.3.1 VULNERABILITY

3.3.1.1 BUILDINGS

Physical vulnerability models for buildings quantify the relationship between debris flood intensity and the resulting damage (consequence). For the purposes of this qualitative risk assessment, we derive a binary vulnerability function based on the APP6 framework wording and incorporating ORC feedback for defining building functionality post event.

Building consequence has been determined for buildings within the hazard impact area that have their functionality compromised. The hazard impact area is defined as the extent of inundation in each scenario, and a building is considered to have its functionality compromised when it cannot be used for its intended purpose immediately after an event. This may include the following:

- If the building has sustained significant damage.
- If the building is Red/Yellow stickered under the Building Act.
- If key utilities are not operative (e.g. water supply, wastewater, power).
- If safe access/egress is not possible.

We assume that any debris flood inundation above the floor level of a building will mean that the building cannot be used for its intended purpose immediately following an event; and therefore, is classified as functionality compromised. Minimum floor levels for new buildings in Roxburgh must consider CODC plan rules and ensure adequate clearance from the ground to prevent moisture ingress and flooding. Minimum floor levels differ dependent on planning zone and exposure to flooding. For this assessment, we assume an average floor level of 0.3 m across the study area. Buildings exposed to more than 0.3 m of inundation in our assessment are considered to be functionality compromised. This was selected as a reasonable and conservative average value and is commensurate with the scale of this assessment.

GNS completed statistical analysis for different landslide intensity types (e.g. debris velocity, debris height, kinetic energy) to determine which landslide intensity best correlates with loss for buildings (GNS, 2018; Beca, 2020). For debris floods this was found to be debris height against the building (m), and hence for building vulnerability we only consider debris height (presented as debris depth in the RAMMS model outputs).

For this qualitative assessment we have only considered existing buildings in Roxburgh on the alluvial fans and within the modelled extent of debris flood inundation. Further quantitative risk assessment will assess property risk at any point on each alluvial fan irrespective of existing development. The types of buildings assessed include:

- Social/cultural buildings: places of worship, museums, art galleries, Marae, educational facilities, and heritage buildings.
- Critical buildings: schools, healthcare/medical facilities, fire/police facilities, and civil defence facilities (i.e. buildings with post-disaster function). According to local CDEM, key buildings with post-debris flood event functions are:
  - Roxburgh Service Centre on Scotland Street. This building is understood to be earthquake strengthened, and has Starlink, VHF radio, generator, etc., and two meeting areas for an ICP and public space.
  - Roxburgh Area School gymnasium. This building is also understood to be resilient to natural hazards.
  - Miller's Flat Hall (an alternative to Roxburgh buildings) approximately 10kms away.

3.3.1.2 PEOPLE

The assessment of vulnerability to persons is subjective and there is little published information. Generally, the following statements apply to human vulnerability to debris floods (adapted from AGS (2007):

- The velocity of the debris flood has a major effect on vulnerability.
- Persons who are near the source of a debris flood are likely to experience a high velocity impact and will have a high vulnerability and persons who are near the limit of the travel (or run out) of the debris flood will experience low velocity impact by only part of the debris flood mass and will have a lower vulnerability.
- Persons who are in buildings which collapse totally have high vulnerability.
- Persons who are in buildings are less vulnerable than those in the open unless the building collapses.
- Persons in vehicles are less vulnerable than those in the open. Their vulnerability depends on the volume and velocity of the debris flood. Experience in Hong Kong (Finlay et al., 1999) indicates that rapid landslides of only a few hundred cubic metres are likely to result in death of the occupants of the vehicle.

The APP6 methodology classifies health and safety consequences in terms of number of injuries and deaths as a result of an event (ORC, 2021). There have been several international hydrogeomorphic events (mostly debris flows) that have resulted in casualties (Table 21).

Table 21: A summary of hydrogeomorphic events that have resulted in casualties.

Event	Number of victims	References
1998 Sarno, Italy Volcaniclastic debris flow	160 fatalities	Zanchetta et al (2004); Haugen & Kaynia (2008)
2010 Zhouqu, China debris flow	1765 fatalities	Hu et al (2012); Zhang & Matsushima (2018)
2011 Taiwan debris flow	70 fatalities	Lo et al (2012)
2005 Austria debris flow	1 fatality	Fuchs et al (2007)
2011 South Korea debris flows	16 fatalities	Kang & Kim (2016); Jeong et al (2015)

The 1998 Sarno volcanic-clastic debris flows in southern Italy were triggered by 30 hours of continuous rainfall generating a series of debris flows resulting in over 150 fatalities (Zanchetta et al., 2004). The primary causes of fatalities were due to building collapse and burial due to significant debris inundation.

The debris flow event in Zhouqu, Gansu Province, China, on August 7, 2010, destroyed 4,321 houses and resulted in 1,765 fatalities (Hu et al., 2012; Zhang & Matsushima, 2018). This event was triggered by intense rainfall, which formed a flash flood entraining debris as it moved downstream. It also created a dammed lake which inundated the main urban area of Zhouqu for a month due to repeated landslide dam failures. Event fatalities were primarily due to the rapid and destructive nature of the debris flow, which led to immediate destruction and building collapse trapping victims in their homes or buried under debris. The 2011 Taiwan debris flow event was triggered by Typhoon Morakot and caused 70 fatalities. Similarly to the Zhouqu and Sarno events, fatalities were most due to building collapse or burial.

While there are several studies that analyse the above events, most focus on the physical vulnerability of buildings rather than for people (e.g. Hu et al., 2012; Zhang & Matsushima, 2018). These events resulted in debris flow inundation of up to several metres in depth which was sufficient to destroy buildings and cause widespread fatalities. It remains uncertain at which depths of inundation a building will be destroyed or a person outside a building will be killed.

For this study, we use an existing vulnerability function for people from the literature and relate it to inundation depth. Finlay et al (1999) developed a vulnerability function for people exposed to different debris intensity cases (Table 22). We have assumed a level of inundation and consequence that relates to each case. There is little evidence linking fatality likelihood to inundation depth, so we have relied on expert elicitation to derive inundation depths. The following statements have informed our estimates:

- We assume that 1 m of inundation is enough to bury the average person in open space. This is consistent with values used in similar studies in the Otago Region (e.g. Gorge Road – Beca (2020) and AGS (2007).
- We assume that 0.5 m of inundation is enough to inundate a building and potentially cause harm to an individual inside that building, while 1 m of inundation is enough to trigger building collapse and potentially kill an individual inside that building.
  - A previous debris flow risk assessment in Auckland adopted a value of 0.5 m to indicate loss of life for people inside buildings (GHD, 2024). This value is for a different risk context than Roxburgh and is assessed as a conservative value for loss of life. The Auckland assessment was based on urban catchments with higher population densities, different building typologies, and limited flow paths, whereas the Roxburgh context involves rural catchments with lower exposure, different structural vulnerability, and broader fan geometries.
  - GNS (2018) indicates that 1 m of inundation is enough to enter a building through windows or doors and may cause harm to an individual inside the building.

Debris flood velocity is known to have an effect on the vulnerability of people to debris floods (AGS, 2007). For people inside buildings, GNS (2018) estimated vulnerability to landslide velocity. For people inside buildings, we also consider the velocity of the flow (m/s), for which we assign a vulnerability value from GNS (2018) and a consequence to each case. Where there is a difference between the consequence derived from the depth or velocity layer, we use the maximum assessed consequence.

Table 22: The vulnerability function for people used in this risk assessment.

Case	Inundation depth (m)	Vulnerability (Finlay et al 1999)	Velocity (m/s)	Vulnerability (GNS, 2018)	Consequence
Person in open space					
If not buried	0 - 0.2	0.1	N/A	N/A	Uninjured
Struck by debris	0.2 - 1	0.5	N/A	N/A	Injury
Buried by debris	>1	1	N/A	N/A	Death
Person Inside Building					
If the debris strikes the building only	< 0.5	0.05	< 0.05	0	Uninjured
Inundated building with debris but person is not buried and escape possible	0.5-1	0.2	0.05 - 0.5	0.2	Injury
Inundated building with debris but person is not buried	0.5-1	0.2	0.5 – 5	0.6	Injury
Building collapse or building inundated with debris	1-3	1	>5	1	Death

For population we use a population dataset developed by GNS Science for risk assessments in New Zealand (Scheele et al., 2021). This dataset includes information on the number of people in each building in Roxburgh which are defined by polygons. In New Zealand, the average person spends 68.9% of the year at home indoors which is equivalent to 17 hours a day (Khajehzadeh & Vale, 2016). This estimate incorporates daily variation during the week and at weekends. We assume the average person may spend an additional 3 hours indoors daily (averaged over week and weekend) elsewhere. Therefore, we assume that 80% of people in Roxburgh are inside buildings at the time of each event. This is equivalent to a daytime scenario where the majority of people are located inside residential homes or workplaces or a night-time scenario where the majority of people are also at home.

Therefore, we also assume that 20% of people in Roxburgh are located outside at the time of the event. The building polygon and population layer was used to define the spatial distribution of both people inside and outside buildings. The distribution of people on the fan and whether they are inside or outside at any time is variable. To reflect this, we randomly selected 20% of the population dataset to be the location of where people are outside.

3.3.1.3 LIFELINES

The APP6 methodology defines severity of impact for lifelines using qualitatively assessed service outage times and affected population (ORC, 2021). Debris flood vulnerability functions and relationships for lifelines are not as well established in the literature as for buildings and people particularly in regard to outage times and affected populations. International studies for lifeline vulnerability to hydrogeomorphic hazards have highlighted:

- Power lines are highly vulnerable to all magnitudes of debris flow (Glade, 2003).
- Road vulnerability increases for larger landslide volumes and intensities:
  - Jaiswal et al (2011) provided vulnerability estimates for landslides of varying volumes (Table 23).

Table 23: Jaiswal et al. (2011) vulnerability classes for roads.

Magnitude class	**100 to 1,000 m^3**	**1,000 to 10,000 m^3**	**10,000 to 100,000 m^3**
Road vulnerability	0.2 - 0.4	0.4 - 0.8	0.8 - 1.0

  - Nieto et al (2021) developed fragility curves for road embankments, showing a higher probability of embankment sliding and headcut erosion with increasing inundation debris flow depths (Figure 32).

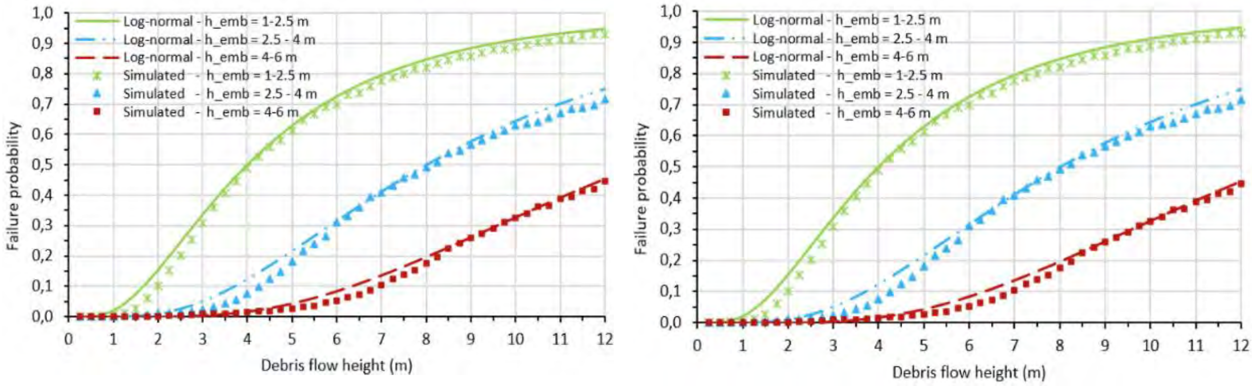


Figure 32: Failure probability of road embankments (left) and probability of headcut erosion (right) with debris flow height.

- Winter et al. (2020) found that the probability of road destruction increases significantly with larger landslide volumes:
  - For landslide volumes > 10,000 m^3 there is a 40% chance the road is completely destroyed,
  - For landslide volumes > 100,000 m^3 there is a 70% chance the road is completely destroyed,
  - For landslide volumes > 1,000,000 m^3 the road is completely destroyed.
- FEMA (2013) estimates minimal damage to buried or exposed water pipelines during floods, but significant damage to small, closed water treatment plants (WTPs) at increasing flood depths, with major electrical equipment requiring cleanup and repair when flood levels exceed ground level.
  - FEMA (2013) estimates 1.2 m of flood depth as functionality threshold for small closed WTPs. Cleanup, repair of small motors, buried conduits, and transformers required when flood level exceeds ground level. Clean and repair of major electrical equipment initiated when flood level exceeds (0.9 m).

For the purposes of this report, we assess service outages and affected population for each scenario using expert elicitation informed by the literature discussed above, modelled debris flood depths, the hydrogeomorphic hazard inventory, and our experience of remedial works following debris floods and other related hazards. We have overlain inundation extents and shapefiles of lifelines in GIS to assess where significant inundation of lifeline assets occurs.

For lifelines we have assessed transport (roads, bridges), telecommunications (towers, chorus fibre cable), water supply (treatment facility, pipes, and storage), wastewater (treatment, pipes, and storage), and electricity (power stations, lines, power poles, and substations).

The following factors and general assumptions were considered when determining service outage times and affected population:

- Depth, and extent of inundation.
  - Infrastructure receiving < 0.5 m of inundation is unlikely to be damaged; however, service outages in the order of hours to days may be required depending on extent.
  - Infrastructure receiving > 0.5 m of inundation may require repair and service outages in the order of days to weeks may be required depending on extent.
  - Infrastructure receiving > 1.0 m or culvert receiving > 4 m of inundation may require repair/replacement and service outages in the order of weeks to months may be required depending on extent.
    - For culverts exposed to this level of inundation it is also assumed that attached infrastructure (e.g. pipelines and cables) are likely to be damaged.

- Location of inundation
  - Debris flood impacts that are within the Roxburgh township (urban area) are assumed to affect ≥20% of the population.

3.3.2 CONSEQUENCE TABLES

Table 24, Table 25, and Table 26 present the assessed consequence level (1-5) for each catchment and debris flood event. Where a consequence level of 5 relates to a catastrophic consequence. A maximum consequence level across built environment and health and safety consequences is provided and used as the consequence input to the qualitative risk assessment outlined in the following section. Maps of each debris flood scenario are provided in Appendix F and detailed tabulated inputs for consequence level assessment are provided in Appendix G. There are no social/cultural buildings or critical buildings compromised in any of the events.

Table 24: Assessed consequence for the high likelihood debris flood event in each catchment.

Catchment	High Likelihood Event					
	Built Environment				Health and Safety	Maximum Consequence Level
	Social/Cultural	Buildings	Critical Buildings	Lifelines		
Slaughterhouse	1	1	1	2	1	2
PN2	1	4	1	2	1	4
PN1	1	5	1	2	1	5
Pumpstation	1	4	1	2	2	4
RN1	1	1	1	2	1	1
Reservoir	1	2	1	3	1	3
Golf Course	1	1	1	2	1	2
GS1	1	1	1	2	1	2
GS2	1	4	1	1	1	4
Black Jacks	1	1	1	1	1	1
BS1	1	4	1	1	1	4
BS2	1	4	1	1	1	4
Stevensons	1	4	1	1	1	4

Table 25: Assessed consequence for the median likelihood debris flood event in each catchment.

Catchment	Median Likelihood Event					
	Built Environment				Health and Safety	Maximum Consequence Level
	Social/Cultural	Buildings	Critical Buildings	Lifelines		
Slaughterhouse	1	5	1	4	2	5
PN2	1	5	1	1	2	5
PN1	1	5	1	4	1	5
Pumpstation	1	4	1	4	4	4
RN1	1	1	1	1	1	1
Reservoir	1	4	1	4	2	4
Golf Course	1	1	1	4	1	4
GS1	1	5	1	2	1	5
GS2	1	5	1	2	2	5
Black Jacks	1	1	1	2	1	2
BS1	1	4	1	1	1	4
BS2	1	5	1	2	2	5
Stevensons	1	5	1	2	1	5

Table 26: Assessed consequence for the maximum credible debris flood event in each catchment.

Catchment	Maximum Credible Event					
	Built Environment				Health and Safety	Maximum Consequence Level
	Social/Cultural	Buildings	Critical Buildings	Lifelines		
Slaughterhouse	1	5	1	4	4	5
PN2	1	5	1	1	4	5
PN1	1	5	1	4	1	5
Pumpstation	1	5	1	4	4	5
RN1	1	3	1	1	2	3
Reservoir	1	5	1	5	4	5
Golf Course	1	1	1	4	1	4
GS1	1	5	1	2	1	5
GS2	1	5	1	2	1	5
Black Jacks	1	1	1	2	1	2
BS1	1	5	1	1	1	5
BS2	1	5	1	2	2	5
Stevensons	1	5	1	4	4	5

3.4 QUALITATIVE RISK

For each debris flood event we have qualitatively assessed the risk based on the assessed likelihood and consequence of each event. Risk level and tolerability has been assessed based on Table 27 as outlined in APP6 (ORC, 2021). Qualitative risk level in APP6 uses the descriptors acceptable, tolerable, and significant, where a significant risk level requires further quantitative risk assessment. The highest risk level of any event for each catchment will be used to identify whether further quantitative risk assessment is required. Quantitative risk assessment will be undertaken for people and buildings.

Table 27: The APP6 risk table (ORC, 2021).

Likelihood	**Consequences**				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain					
Likely					
Possible					
Unlikely					
Rare					
Green, Acceptable *Risk*: Yellow, Tolerable *Risk*: Red, Significant *Risk*, Hatching: *Quantitative assessment required*					

Table 28 outlines the assessed qualitative risk level for each catchment in this study based on the APP6 framework. This illustrates that:

- **A significant risk level** for debris floods is assessed for PN2, PN1, GS2, BS2, Stevensons, Slaughterhouse, and GS1 and further quantitative risk assessment is required.
  - A consequence level of 5 (catastrophic) is indicated in the high likelihood event for PN1 and in the median likelihood event for PN2, GS2, BS2, Stevensons, Slaughterhouse, and GS1 due to the proportion of buildings assessed as compromised.
- **A tolerable risk level with a consequence level of 5** for debris floods is assessed for Pumpstation, BS1, and Reservoir. For these catchments further quantitative risk assessment is also required.
  - A consequence level of 5 is indicated in the maximum credible event for these catchments. For Pumpstation and BS1 this consequence level is due to the proportion of buildings assessed as compromised.
  - For Reservoir, the SH8 bridge crossing is likely to be structurally compromised during the maximum credible event due to significant inundation and may require repair/replacement. This is estimated to be out of service for > 1 month and is likely to affect > 20 % of the population in Roxburgh.
  - A consequence level of 5 is also assessed for buildings for Reservoir.
- **A tolerable risk level with a consequence level <4** for debris floods is assessed for Golf Course. For this catchment further quantitative risk assessment is not required under the APP6 criteria; however:
  - Debris flood modelling has indicated the potential for significant inundation on areas of the fan and major levels of consequence due to impacts to lifelines.

- A consequence level of less than 4 is largely due to limited development on the fan in the areas of modelled inundation extent. If these areas are developed in the future, this consequence level may change.
  - This catchment has been highlighted by ORC as critical for future planning and development in Roxburgh; therefore, quantitative assessment will be carried out to help inform future growth and land use planning decisions.
- **An acceptable risk level** for debris floods is assessed for RN1 and Black Jacks. For these catchments further quantitative risk assessment is not required.
  - For RN1, In the median and maximum credible events, there are some buildings compromised and injuries. While quantitative risk assessment is not required under APP6 for this catchment, particular attention and assessment is recommended for any future decision making.
    - This catchment has been highlighted by ORC as critical for future planning and development in Roxburgh; and therefore, will also be assessed quantitatively.
  - For Black Jacks, there is significant inundation in the modelled debris flood scenario; however, there are no exposed buildings or people on the fan, so consequences are insignificant expect for minor consequences noted to infrastructure. For all RAMMS scenarios, the majority of the fan is inundated with more intense inundation occurring easter of SH8. If this fan is developed, then the qualitative risk level presented in this report is likely to be different.

Table 28: Assessed qualitative risk level for each catchment. Colour coding aligns with Table 27 and the consequence level is noted for each event.

Catchment	High Likelihood Event	Median Likelihood Event	Maximum Credible Event	Highest Assessed Risk	Quantitative Risk Assessment Required
PN1	5	5	5	5	Yes
GS2	4	5	5	5	Yes
BS2	4	5	5	5	Yes
Stevensons	4	5	5	5	Yes
PN2	4	5	5	5	Yes
Slaughterhouse	2	5	5	5	Yes
GS1	2	5	5	5	Yes
Pumpstation	4	4	5	5	Yes
BS1	4	4	5	5	Yes
Reservoir	3	4	5	5	Yes
Golf course*	2	4	4	4	No*
RN1*	1	1	3	3	No*
Blackjacks	1	2	2	2	No
*ORC would like to understand the spatial quantitative risk of Golf course and RN1 for future planning and as such these catchments will be considered in the next phase.					

4 QUANTITATIVE RISK ASSESSMENT

4.1 INTRODUCTION

The qualitative risk assessment presented in this report has highlighted there are several catchments in Roxburgh with sufficient debris flood risk to support further quantitative risk assessment.

Quantitative risk assessment considers the numerical aspects of debris flood risk such as the probability of the scenario occurring (Figure 33). Risk is assessed for people (annual individual fatality risk, AIFR) and property (annual property risk, APR) for three debris flood scenarios for each catchment (including a maximum credible event). Risk tolerability and mitigation recommendations are also discussed.

This section summarises the methodology and results of the quantitative risk assessment completed for these catchments. The methodology used in this study follows the approach in the Australian Geomechanics Society Landslide Risk Management Guideline (AGS, 2007), and aligns with a Level D assessment under the New Zealand Landslide Planning Guidance (de Vilder et al., 2024) and the ORC Regional Policy Statement – APP6 (ORC, 2021).

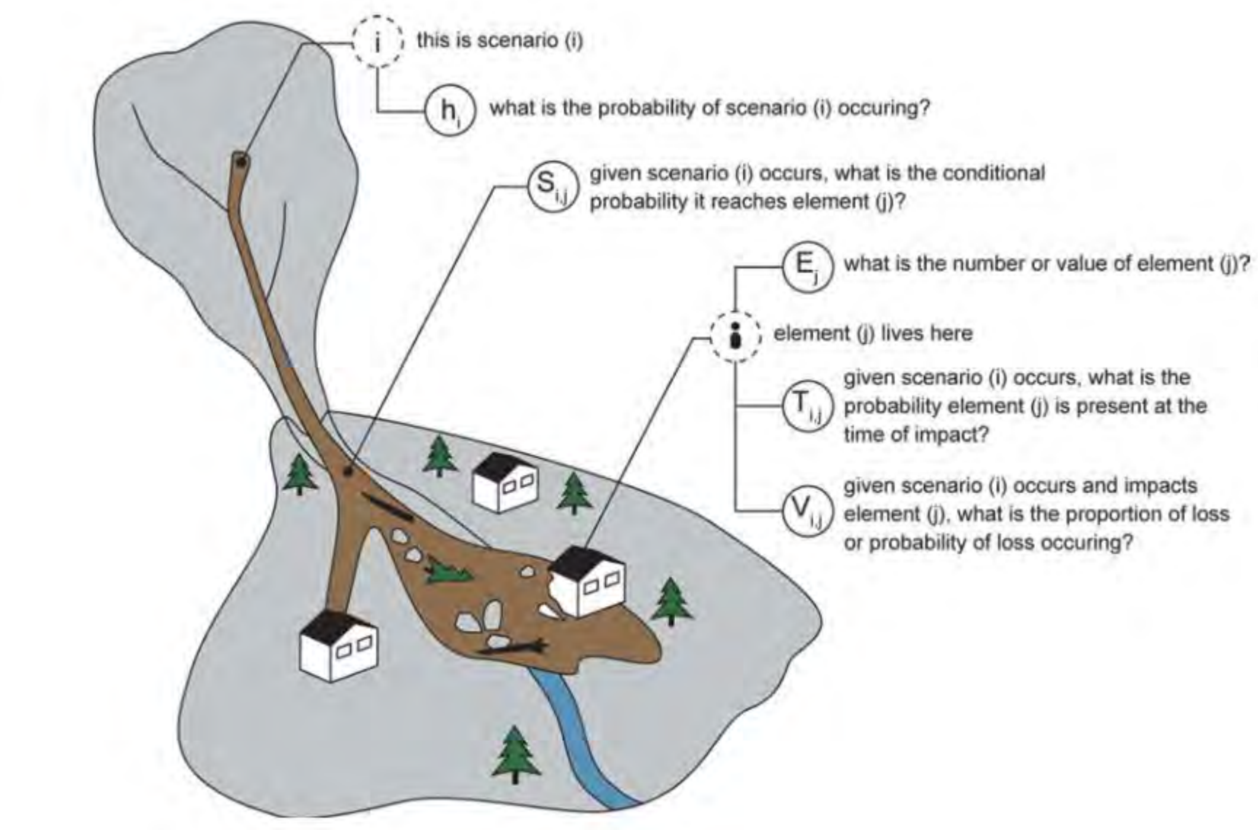


Figure 33: An illustration of quantitative risk inputs for debris floods (from Jakob, et al., 2022).

4.2 ANNUAL INDIVIDUAL FATALITY RISK

4.2.1 INTRODUCTION

A quantitative assessment of the annual individual fatality risk (AIFR) posed by debris flood scenarios has been carried out for the study area. AIFR is the probability that an individual most at risk is killed in any one year as a result of a debris flood occurring. AIFR is calculated using the below equation:

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

Where:

- $P_{(H)}$ is the annual probability of a hazard occurring.
- $P_{(S:H)}$ is the spatial probability of impact of the hazard in a specific location potentially occupied by the person most at risk.
- $P_{(T:S)}$ is the temporal spatial probability that the person most at risk is present.
- $V_{(D:T)}$ is the vulnerability, or probability of death of the person most at risk, in the event of an interaction with the hazard.

Risk assessment requires estimation of likelihoods, consequences, and risks, considering both spatial and temporal factors. These factors are often associated with significant uncertainties, and judgement is often required to estimate the nature and size of potential hazards and their impacts as part of the risk assessment process.

In this study, input uncertainty has been accommodated by considering a range of likely values that may occur. We have calculated an average, minimum, and maximum value for each factor in the AIFR equation, for each alluvial fan. The average AIFR value from this range was compared to tolerability criteria. This value is determined by averaging the input probabilities.

To spatially illustrate the calculated AIFR results, a 1 m by 1m grid or fishnet was generated for each alluvial fan in this assessment. Input variables and an AIFR value were calculated for each cell based on the methodology described in the following sections.

4.2.2 DEBRIS FLOOD PROBABILITY - $P_{(H)}$

Section 2.5 describes a frequency-magnitude relationship for future debris floods including an assessment of source potential, trigger frequency, and climate change for catchments in Roxburgh. Debris flood volumes were calculated for high likelihood, median likelihood, and maximum credible events based on source mapping and dataset analysis. As part of this assessment, the frequency and return period of each event size was estimated based on historical records, geomorphic evidence, and rainfall data. Rainfall data was based on a Representative Concentration Pathways - RCP8.5 climate scenario for the study area sourced from the High Intensity Rainfall Design System (HIRDS) (NIWA, 2023). An RCP8.5 scenario is a high-emissions pathway of greenhouse gas emissions in climate models and represents a conservative scenario for rainfall in Roxburgh.

In this quantitative risk assessment, we also consider the return period of rainfall events under a present-day scenario (no climate change) using HIRDS data. Historical rainfall data is used to represent present-day rainfall. The unrounded average return period of each rainfall event over present-day and RCP8.5 (Table 29) is used as the debris flood probability in the risk assessment. Rounded values are also provided in Table 29 in brackets and are used in the discussion below.

For the high likelihood event, we have calculated debris flood volumes between 20,000 m^3 and 100,000 m^3 and estimate an average return period of 300 years under present day rainfall and 100 years under RCP8.5 rainfall:

- Historical debris floods in the study area have been triggered by at least 40 mm of rainfall in an hour, while debris floods exceeding 100,000 m^3 have been triggered by at least 60 mm of rainfall in an hour (2017 debris flood events) (Dellow et al., 2018). Therefore, we assume that debris floods of this size are likely to be triggered by 40-60 mm of rainfall in 1 hour.
  - According to HIRDS rainfall data for the study area, this rainfall event occurs every 120 to 450 years under a present-day rainfall scenario (no climate change) and 50 to 170 years under an RCP8.5 climate scenario.

For the median likelihood event, we have calculated debris flood volumes between 43,000 and 213,000 m^3 and estimate an average return period of 1,400 years under present day rainfall and 500 years under RCP8.5 rainfall:

- Historical debris floods in the study area greater than 100,000 m^3 have been triggered by 60-100 mm of rainfall in 1 hour (Dellow et al., 2018).
  - According to HIRDS rainfall data for the study area, this rainfall event occurs every 450 to 2,300 years under a present-day rainfall scenario (no climate change) and 170 to 850 years under an RCP8.5 climate scenario.

For the maximum credible event, we have calculated debris flood volumes between 86,000 and 427,000 m^3 and estimate an average return period of 12,000 years under present day rainfall and 10,000 years under RCP8.5 rainfall:

- There is no historical evidence for events greater than 200,000 m^3; however, some catchments have notable source material including landslides, incised and eroded stream banks, and entrained debris in the channel suggesting debris flood volumes of this magnitude could potentially occur with sufficient rainfall.
- These maximum credible events could have occurred prior to human settlement.
- The amount of rainfall required to trigger events of this magnitude is uncertain; however, for the purposes of this assessment we estimate that at least 140 mm of rainfall in 1 hour is reasonable for the lower bound.
  - According to HIRDS rainfall data for the study area, this rainfall event occurs at least every 6,900 years under a present-day rainfall scenario (no climate change) and 2,400 years under an RCP8.5 climate scenario.
  - The upper bound of this event is determined to be the estimate for the retreat of glaciers from the head of the Clutha catchment following the last glacial maximum (LGM) (18,000 years - Denton, et al., 2021). During the LGM peak, glaciofluvial pulses built extensive alluvial terraces throughout the study area. As glaciers retreated, the Clutha incised these terraces, creating accommodation space for subsequent debris-flow and flood deposition on the LGM terrace surfaces.

This report adopts the average return period and annual probability values for each event size listed in Table 29.

Table 29: Assessed triggers and return periods for the three event sizes assessed with consideration of climate change.

Event	Trigger	Return Period (years)			
		Present day		RCP8.5 scenario	
		Range (rounded)	Average (rounded)	Range (rounded)	Average (rounded)
High Likelihood	40-60 mm of rainfall in 1 hour	123 – 453 (120 – 450)	288 (300)	48 – 170 (50 – 170)	109 (100)
Median Likelihood	60-100 mm of rainfall in 1 hour	453 – 2,339 (450 – 2,300)	1,396 (1,400)	170 – 847 (170 – 850)	509 (500)
Maximum Credible	>140 mm of rainfall in 1 hour	6,893 – 18,000[1] (6,900 – 18,000[1])	12,447 (12,000)	2,438 – 18,000[1] (2,400 – 18,000[1])	10,219 (10,000)

[1] The estimate for the retreat of glaciers from the area and the start of fan building (Denton, et al., 2021).

4.2.3 SPATIAL PROBABILITY ($P_{(S:H)}$)

The spatial probability that each debris flood event reaches the most at-risk person was assessed using debris flood modelling software RAMMS (Rapid Mass Movement Simulation). Historical debris flood events, geomorphic mapping of potential debris flood sources, and hydrological analysis of each catchment informed RAMMS model inputs. Details of the RAMMS debris flood modelling methodology and adopted parameters are provided in Section 2.6.

For each RAMMS debris flood event, a spatial probability of impact ($P_{(S:H)}$) was assigned to each 1 m grid cell. Cells inundated in each event were assigned a $P_{(S:H)}$ of 1 for that event, while those outside of the inundation extent were assigned a $P_{(S:H)}$ of 0. For this assessment, the centroid of each cell was used to define whether it was within the inundation extent or outside of it.

4.2.4 TEMPORAL SPATIAL PROBABILITY ($P_{(T:S)}$)

Temporal spatial probability or exposure in this AIFR assessment refers to the amount of time the most at-risk person spends in a hazard-prone area and includes consideration of self-evacuation and any forewarning given an event. The alluvial fans in this assessment are either located in low density residential or rural zones. For each zone, we have considered the proportion of the year an individual is likely to spend outside and inside (Table 30).

In New Zealand, the average person spends 68.9% of the year at home indoors which is equivalent to 17 hours a day (Khajehzadeh & Vale, 2016). This estimate incorporates daily variation during the week and at weekends. For residential areas we assume that 70% of the time the individual most at risk is inside and that person spends 1 hour a day outside at home which is equivalent to 4% of the year. The remainder of time this person spends at their workplace or elsewhere. For rural areas we assume that individuals spend a greater amount of time at home as generally people in these areas live on farms or orchards where they also work. For rural areas we assume that the person most-at risk spends 75% of the time inside and 10% of the time outside.

This differs from the qualitative component of the assessment, where an additional three hours of time spent indoors was assumed based on the referenced statistic, to account for time spent indoors at locations other than the primary residence. This assumption was considered conservative and appropriate for the qualitative stage, which was intended to capture exposure across the entire fan at a broad screening level.

For the quantitative stage, this variable has been revised to reflect the increased spatial resolution of the assessment, which is undertaken on a 1 × 1 m grid scale. At this scale, the exposure assessment requires greater specificity to avoid over-conservatism and to better represent realistic patterns of occupancy. Accordingly, a more detailed treatment of indoor time has been adopted, incorporating land-use zoning, likely patterns of self-evacuation, and spatial variability in receptor presence. The referenced study has been retained as a baseline statistic but has been supplemented with site-specific considerations to ensure the variable is appropriate for the refined quantitative analysis.

Table 30: Exposure assumptions for the different zones on the alluvial fans in this study.

Zone	Proportion of year spent outside	Proportion of year spent inside	Alluvial fans
Residential	0.04	0.7	Pumpstation, RN1, Reservoir
Rural	0.1	0.75	Slaughterhouse, PN2, PN1, Golf course, GS1, GS2, Black Jacks, BS1, BS2, Stevensons

Probability of self-evacuation was assessed for each scenario using the relative velocity of each debris flood and considers whether an individual is inside or outside at the time of the event (Table 31). We assume the probability of self-evacuation is less for faster moving debris flood events and for people inside buildings. When a person is outside the opportunity to see or hear the debris flood and evade is more likely (Taig et al., 2015). Further, larger events are generally associated with high velocities and hence forewarning is likely to be less. For each event magnitude the temporal spatial probability was calculated for each grid cell by multiplying the values in Table 30 by the probability of not evacuating.

For example, a grid cell on Pumpstation alluvial fan is estimated to be occupied by a person outside 4% of the time (0.04). For the high likelihood event there is a 60-80% chance of self-evacuation (which is the same as a 20-40% chance of not evacuating) for this person as they are outside and can potentially avoid the oncoming debris flood. The product of these numbers is 0.008-0.016 which would be assigned as the lower and upper bound for temporal spatial probability for a person outside during the high likelihood event for that grid cell.

Evacuation procedures facilitated by Civil Defence and Emergency Management were not considered in this assessment.

Table 31: Probability of self-evacuation for each debris flood scenario.

Case	High Likelihood Debris Flood	Median Likelihood Debris Flood	Maximum Credible Debris Flood
People inside buildings	0.5 - 0.7	0.3 - 0.5	0.1 - 0.3
People outside	0.6 - 0.8	0.4 - 0.6	0.2 – 0.4

4.2.5 VULNERABILITY

The vulnerability of people to debris floods and existing vulnerability functions is discussed in Section 3.3.1.2. For this quantitative risk assessment, we apply the vulnerability function outlined in Table 22.

Vulnerability is intrinsically related to exposure in that the location of people or assets determines the intensity of hazard experienced. In this assessment we do not consider the specific location of people or buildings, rather, we calculate a vulnerability for each 1 m grid cell for a hypothetical person either inside or outside a building. The intensity of debris flood inundation in each grid cell is determined using the debris flood models developed in this report. The vulnerability function is based on two existing studies; Finlay et al. (1999) and GNS (2018). For people inside buildings, we use the more conservative (i.e. higher) vulnerability value from either study, determined using the inundation depths and velocities derived from the RAMMS outputs. For people located outside buildings, GNS (2018) does not provide vulnerability values, so we rely solely on the values from Finlay et al. (1999).

4.3 ANNUAL PROPERTY RISK

4.3.1 INTRODUCTION

We have calculated Annual Property Risk (APR) for each alluvial fan in this quantitative risk assessment using the below equation:

$$APR = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(B)}$$

Where:

- APR is the annual probability of building damage.
- $P_{(H)}$ is the annual probability of a hazard occurring. This value is the same for APR and AIFR and hence for discussion of this parameter the reader is referred to Section 4.2.
- $P_{(S:H)}$ is the spatial probability of impact of the hazard in a specific location occupied by a property. For the purposes of this assessment, we apply the same methodology as for AIFR outlined in Section 4.2.3.
- $P_{(T:S)}$ is the temporal spatial probability. For houses and other buildings, $P_{(T:S)}$ = 1.0 (i.e. the house or building is always present) and hence is not discussed further in this section.
- $V_{(B)}$ is the vulnerability of the property or building to the spatial impact (or expected proportion of property value lost in the event of being impacted by the hazard), typically termed the damage ratio.

The APR assessment does not consider specific locations of buildings or building types, rather it considers the possibility for buildings to be present in any location on each alluvial fan. The property value variable E in the AGS equation (AGS, 2007) is not considered in this assessment as this study is intended for land use planning. This approach enables the relative comparison of risk levels within the land use planning context, ensuring that the analysis remains independent of specific property constructions, which may frequently change.

To spatially illustrate APR, a 1 m by 1m grid or fishnet was generated for each alluvial fan in this assessment. Input variables and an APR value were calculated for each cell based on the methodology described in the following sections.

4.3.2 VULNERABILITY

This assessment does not consider existing buildings in Roxburgh and instead calculates APR for areas of the fan to provide ORC with risk outputs for future planning rules. A vulnerability value was assigned to each 1 m grid cell based on the debris flood RAMMS models. To calculate vulnerability, we used an existing damage state (DS) function for buildings exposed to certain thicknesses of debris from landslides (Wolter et al., 2024) (Table 32 and Figure 34). This vulnerability function is based on typical residential dwellings in New Zealand consisting of mostly light timber-framed structures on concrete slab or pile foundations. This means that vulnerability in this assessment is expressed as the extent to which a building located within each grid cell is damaged in each event (e.g. a vulnerability of 1 is equal to 100% damage).

The building vulnerability values ($V_{(B)}$) were derived using a simplified linear approximation of the damage-ratio trend shown in Figure 34. The fitted line in Figure 34 can be approximately expressed as:

$$V_{(B)} = 0.222 * Inundation\ Depth - 0.1242$$

Our analysis calculates building vulnerability using the simplified equation:

$$V_{(B)} = \min(1, 0.2 * Inundation\ Depth)$$

This simplified relationship avoids negative damage ratios at lower inundation depths, is easier to apply consistently across the model, and provides results that remain within the published vulnerability ranges (Table 32).

This assessment does not consider the construction characteristics of a building.

GNS completed statistical analysis for different landslide intensity types (e.g. debris velocity, debris height, kinetic energy) to determine which landslide intensity best correlates with loss for buildings (GNS, 2018; Beca, 2020). For debris flows this was found to be debris height against the building (m), and hence for building vulnerability we only consider debris height (depth).

Table 32: The damage state matrix developed by Wolter et al (2024).

Damage State (DS)	Damage Classification	Description	Damage Ratio (DR)	Maximum Debris Height (m) (linear)
DS0	None: No Damage	Damage is outside the building footprint	0	0
DS1	Insignificant: Minor non-structural damage	Superficial (non-structural) inundation or <10% of building footprint is under-cut	0-0.2	0.1-1.5
DS2	Light: Non-structural damage only	Moderate (non-structural) inundation or <20% of building footprint is under-cut	0.2-0.4	1.5-2.4
DS3	Moderate: Reparable structural damage	Structural damage or house is displaced	0.4-0.6	2.4-3.25
DS4	Severe: Irreparable structural damage	Key structural elements (e.g. columns/beams) fail	0.6-0.8	3.25-4.2
DS5	Critical: Structural integrity fails	Impact-induced collapse or >50% of building is under-cut	0.8-1.0	>4.2

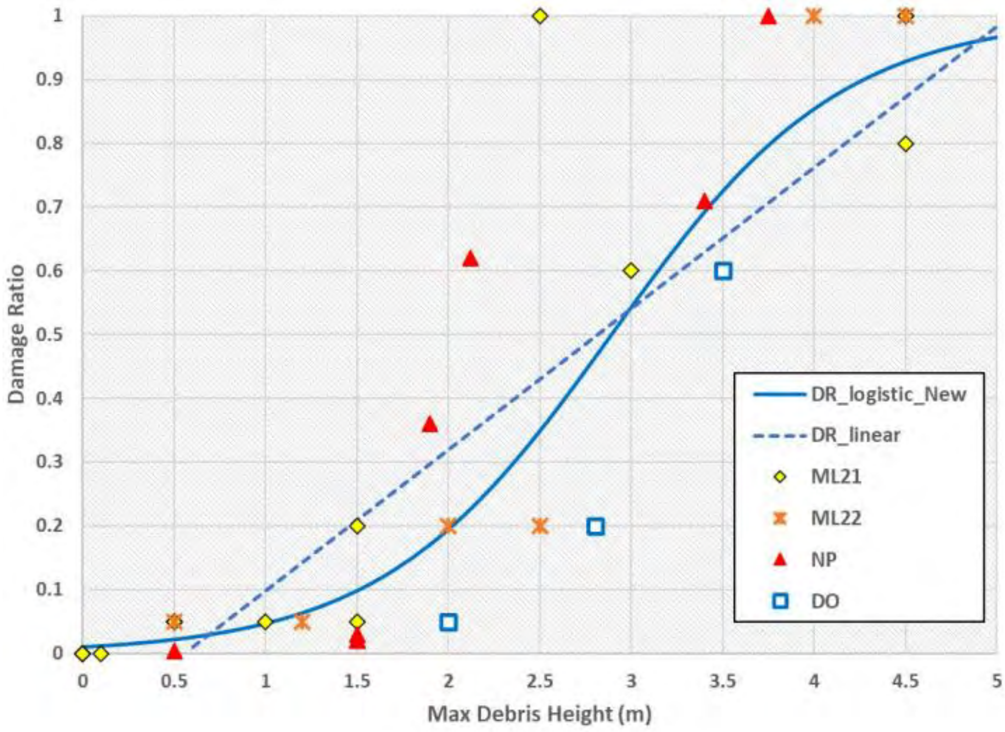


Figure 34: The damage function for buildings used in this assessment (Wolter et al., 2024).

4.4 RESULTS SUMMARY

The 1 m by 1 m grid for each alluvial fan is used to present AIFR and APR for each alluvial fan in this quantitative risk assessment. This included the following steps completed in GIS:

1. Firstly, a spatial probability of impact (run out) and vulnerability value were calculated for each cell for each debris flood event magnitude based on the RAMMS outputs (high likelihood, median likelihood, and maximum credible).
2. This value was then multiplied by the remaining risk variables to calculate AIFR and APR in each cell for each event magnitude.
3. Finally, AIFR and APR risk values for the high likelihood, median likelihood, and maximum credible event were summed to calculate a total AIFR and APR value for each 1 m cell. This was completed separately for AIFR and APR.
4. This was then converted into raster layers and symbolised according to the risk bands outlined in Table 33 below.

For the above process, the average of each risk input value was used.

AIFR and APR for the present day scenario has also been compared to existing tolerability criteria and categorised as either acceptable, tolerable, or significant in accordance with the APP6 of the proposed Otago Regional Council Regional Policy Statement (RPS) (ORC, 2021) and the AGS Guidelines for Landslide Risk Management (AGS, 2007). Table 34 outlines the risk tolerability criteria used in this assessment for existing and new development.

Table 33: Risk bands used to symbolise the AIFR and APR maps.

Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

Table 34: The risk tolerability criteria used in this assessment for AIFR and APR for existing and new development under a present-day climate change scenario.

Risk Category	AIFR and APR - Existing Development Scenario	AIFR and APR - New Development Scenario
Acceptable	$< 1x10^{-5}$	$< 1x10^{-6}$
Tolerable	$1x10^{-4}$ to $1x10^{-5}$	$1x10^{-5}$ to $1x10^{-6}$
Significant	$> 1x10^{-4}$	$> 1x10^{-5}$

AIFR and APR maps are provided in Appendix H. Figure 35 and Figure 36 show the percentage of each fan classified as acceptable, tolerable, or significant risk for AIFR for existing and new development under a present-day climate change scenario. Figure 39 and Figure 38 present this information for APR.

For AIFR, fans in this assessment have 5-83% of their total fan area classed as significant risk for existing development, which increases to 16-100% using the tolerability criteria for new development. BS2 stands out with 83% of its fan classed as significant risk for existing development and 100% for new development. Stevensons and Golf Course also have notably high areas of significant risk with 39% and 32% of total fan area within this class for existing development. GS2 has a relatively modest significant risk proportion for existing development (21%); however, using the tolerability criteria for new development this increases to 68% of total fan area indicating consistently high-risk values across the fan. GS1 and RN1 have the lowest proportion of significant risk with 9% and 5% for existing development.

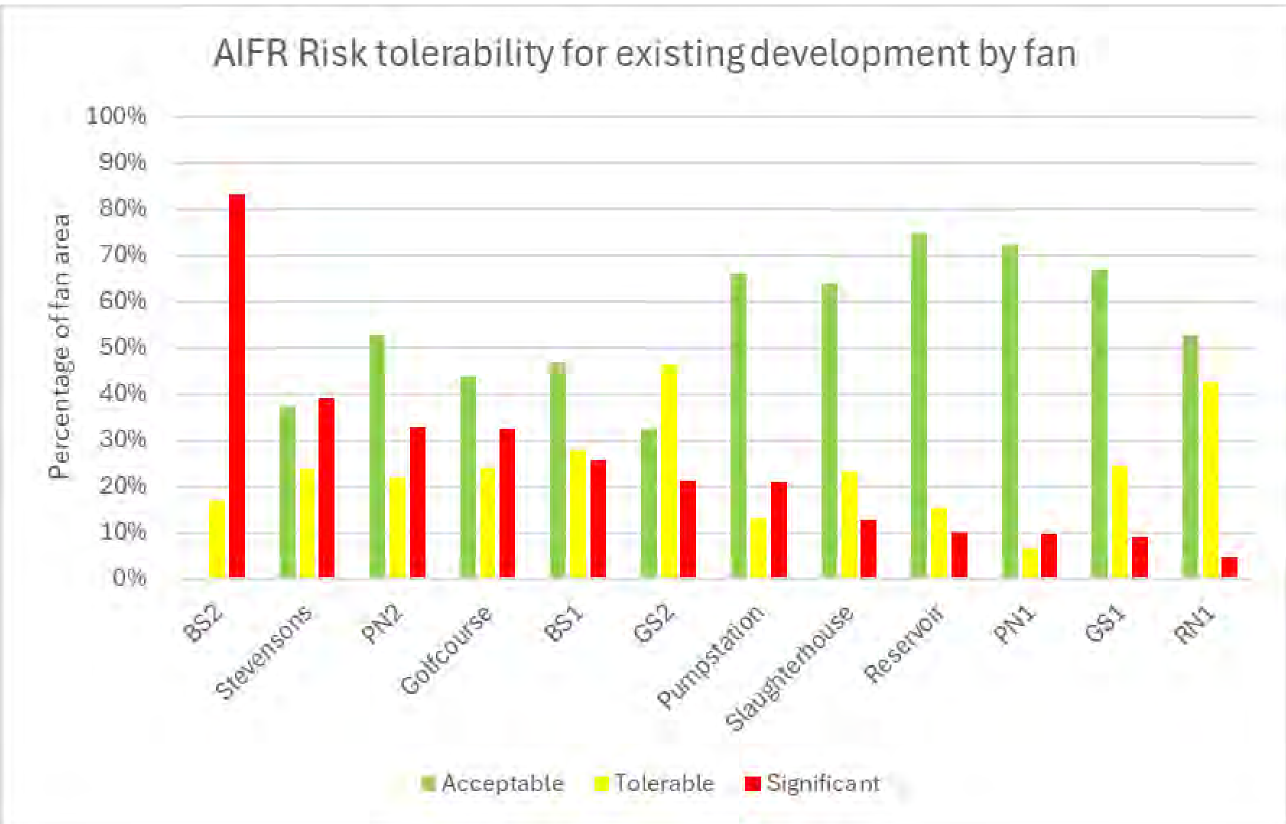


Figure 35: The percentage of each fan within each AIFR risk tolerability class for existing development.

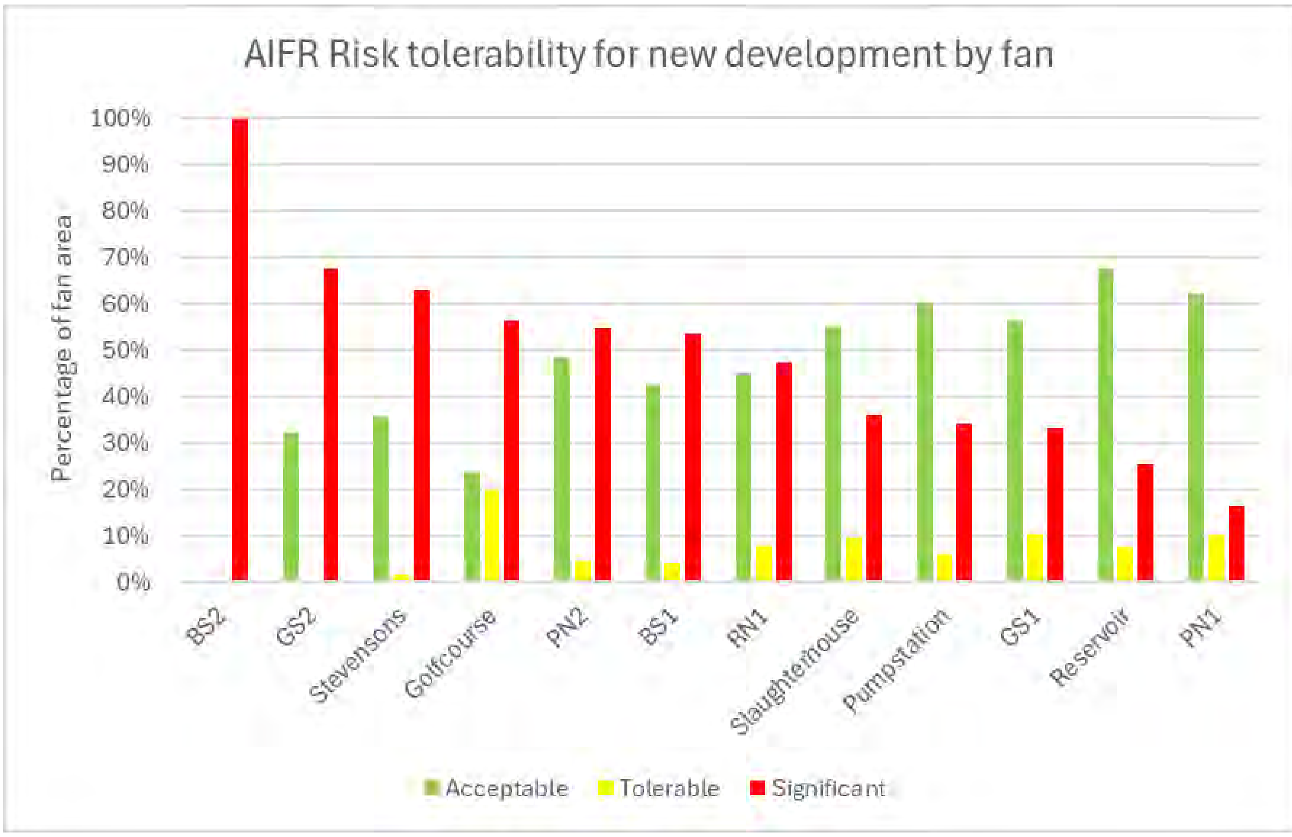


Figure 36: The percentage of each fan within each AIFR risk tolerability class for new development.

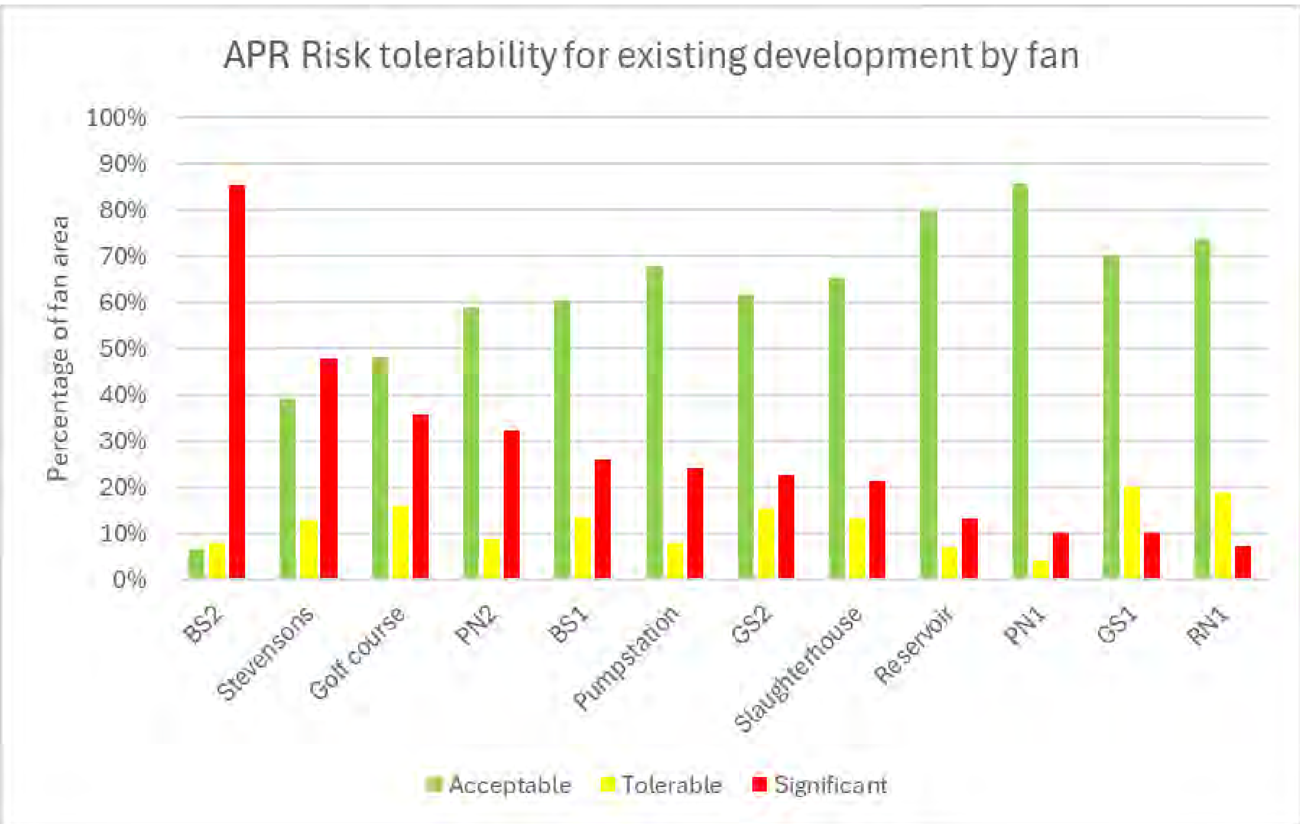


Figure 37: The percentage of each fan within each APR risk tolerability class for existing development.

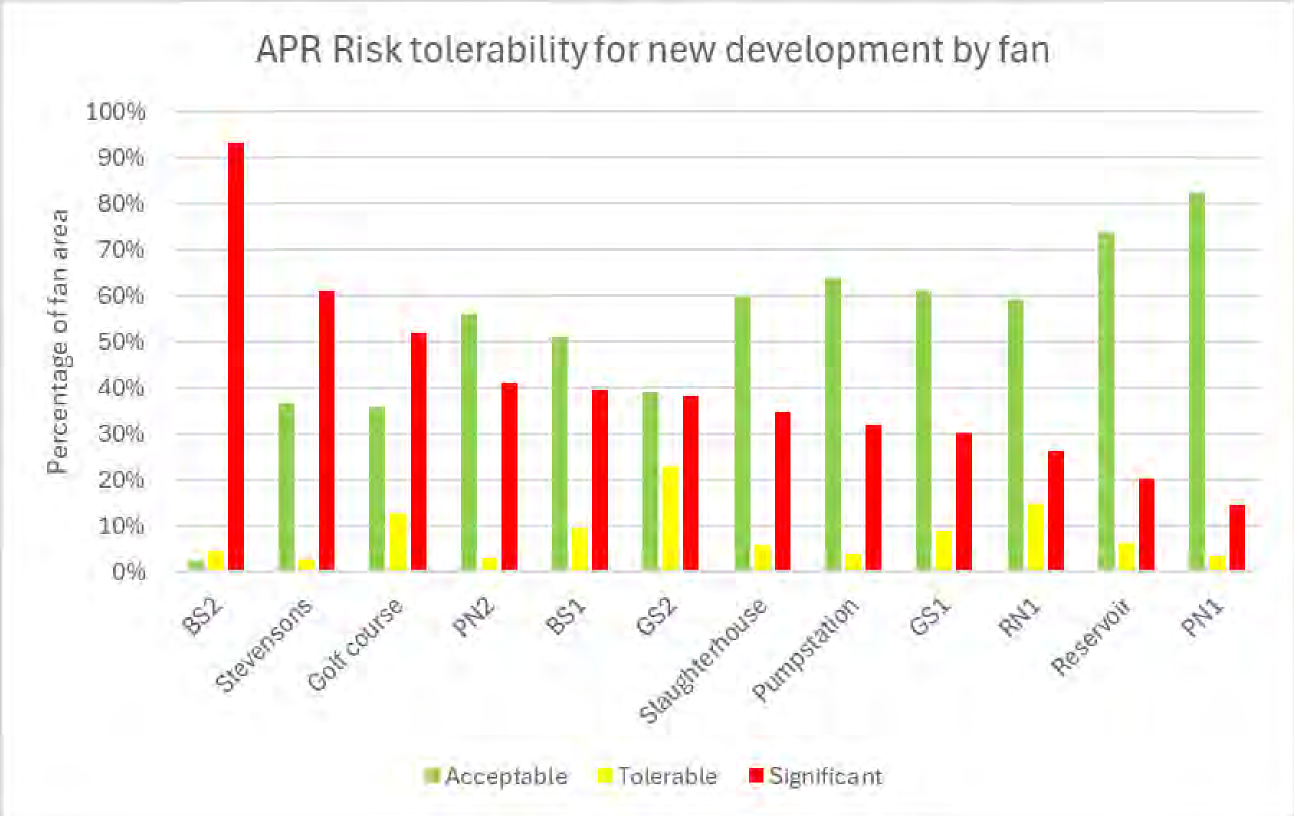


Figure 38: The percentage of each fan within each APR risk tolerability class for new development.

4.4.1 SLAUGHTERHOUSE

Slaughterhouse, the northernmost catchment in this study, has a reasonably large alluvial fan compared to others in this study and has variable risk values across the fan for AIFR and APR (as shown in Appendix H). Areas of higher risk are typically located within approximately 100-300 m of the main channel and are concentrated around the SH8 crossing. The spatial distribution and extent of AIFR and APR is similar; however, higher AIFR risk values can be observed further away from the main channel, particularly to the north.

4.4.2 PN2 AND PN1

PN2, north of Roxburgh township, has consistently high areas of significant risk compared to other fans in this study. Spatially, AIFR and APR is higher for areas on the fan west of SH8, than areas east of SH8, on the lower fan. This is largely due to the topography of the fan and main channel. Debris flood modelling indicates that an almost ~90° bend in both the northern and southern channels on the upper fan forces debris to exit the main channel and inundate the areas of the fan upslope of SH8. Much of the inundation in the modelling is concentrated in these areas rather than being contained within the main channel.

Interestingly, the main channel of PN1 has a similar bend on the upper fan; however, only minor inundation occurs outside of the main channel at this point. This is likely due to the comparatively low volume of source material mapped for PN1 in the geomorphological assessment phase of this study. This results in consistently lower AIFR and APR values than PN1. Spatially, areas of higher risk are generally confined to areas within 50 m of the main channel, with risk decreasing with distance from the channel.

4.4.3 PUMPSTATION

Higher risk areas for AIFR and APR for Pumpstation generally include; the channel margins and the area of the fan downslope and east of SH8.

Lower risk areas are typically on the upper fan outside of the main channel.

This is likely due to the fact that the culvert at SH8 is assumed to be blocked during each scenario which causes the debris flood inundation to disperse across the lower fan downslope of SH8.

4.4.4 RN1

Compared to other alluvial fans in this study, RN1 has relatively modest risk, particularly for existing development. Areas of elevated AIFR and APR include the channel margins, along SH8 at the culvert, and isolated areas on the lower fan. For AIFR, these areas are slightly enlarged. Edinburgh Street and the local topography appears to provide protection to areas of the upper fan to the east which are generally lower risk than the rest of the fan.

4.4.5 RESERVOIR

Reservoir has a relatively large alluvial fan compared to others in this study and has notable exposure as the main fan within Roxburgh township. For AIFR areas of elevated risk include the channel margins, the southern side of SH8 at the bridge, and isolated areas on the lower fan. For APR, areas of elevated risk are not as extensive south of SH8 into Tweed Street Reserve and laterally along SH8. On the lower fan (downslope of SH8), higher risk areas are generally contained between Tweed Street and Leitholm Place with isolated areas of elevated risk outside of these areas.

4.4.6 GOLF COURSE, GS1, AND GS2

Golf course, south of Roxburgh township has consistently high areas of significant risk for AIFR (as shown in Figure 34 and Figure 35). Golf course and GS1 have main channels that coalesce on their alluvial fans; however, the majority of debris flood risk is thought to relate to debris floods in Golf course catchment. AIFR and APR are high for large areas of the Golf course alluvial fan east of SH8 including the Roxburgh Golf course itself. The existing settlement west of SH8 has lower levels of risk than the lower fan; however, there are isolated areas of elevated risk.

GS1 generally has lower debris flood risk than other fans in this study with 56% of total fan area classed as acceptable for AIFR for new development. Areas of lower risk include the upper fan outside of the main channel, and the existing properties just south of the golf course.

GS2, just south of GS1, has a relatively small alluvial fan which is restricted by the Clutha River and surrounding topography. This fan stands out in terms of AIFR for existing development with a notable proportion of its fan classed as significant risk. Higher risk areas include the channel margins and surrounding the SH8 crossing, while lower risk areas are generally, >50 m from the main channel.

4.4.7 STEVENSONS, BS1, AND BS2

Stevensons has a high proportion of the fan area in the higher risk zones for AIFR and APR compared to other fans in this study. AIFR and APR varies spatially on the fan as shown in Appendix H, where:

- Risk is generally higher within approximately 200-300 m of the main channel and particularly on the fan area east of SH8.
- Lower risk areas typically include those >300 m from the main channel, particularly to the south, and isolated areas of elevated land such as stopbanks and river terraces.

In terms of APR for Stevensons, the above spatial distribution of risk is generally the same with slight differences.

To the north of the Stevensons alluvial fan, BS1, and BS2, are small, confined fans with notable proportions of higher risk areas compared to other fans in this study (as shown in Figure 34 and Figure 35). Spatially, the majority of the alluvial fan area for BS2 is classed as within higher risk bands. BS1 has less of its fan within those higher risk bands with areas on the margins of the fan assessed as lower risk.

5 RISK MITIGATION

This report does not analyse or discuss detailed risk mitigation; rather, it provides only a high-level overview of potential approaches that could be considered. The strategies outlined in this section are indicative and require further detailed investigation, planning, and critically, engagement with local communities and stakeholders. Effective mitigation for debris flood hazards is a complex process that extends beyond technical solutions, and future work should focus on collaborative development of practical, locally informed measures that support resilience and long-term adaptation.

5.1 OVERVIEW OF MITIGATION APPROACHES

Debris floods pose significant hazards to life, property, and infrastructure, particularly in alluvial fan environments where sediment-laden flows can rapidly inundate large areas. Effective risk mitigation can include a combination of structural, non-structural, and planning-based approaches:

- **Structural Mitigation**:
  - Debris flood barriers, check dams, and retention basins to intercept and slow debris.
    - These may be practical in upper catchments where debris floods initiate and near fan apexes. Roxburgh's steep terrain and sediment dynamics may make these interventions effective. However, feasibility depends on channel geometry relative to the debris volume to be retained, as well as land access, environmental impact assessments, long-term maintenance (including practicality of removing debris following an event), and financial considerations (both for construction and ongoing maintenance).
  - Diversion channels to redirect flows away from vulnerable areas.
    - These may be applicable in flatter fan areas such as PN2 and Pumpstation, where flows threaten infrastructure like SH8. Feasibility may be limited however, and channel or bund dimensions, land availability and hydrological design constraints must be considered.
  - Reinforced culverts and bridges could be designed to withstand debris flood impact and prevent blockages. However, culverts designed to convey debris floods are typically large, particularly when compared to the equivalent clear water flood capacity.
    - Critical in catchments like Pumpstation and Golf course, where culvert blockage is a known risk. Upgrading such infrastructure may be feasible and align with existing transport planning, though it requires significant capital investment and inter-agency coordination.
- **Non-Structural Measures**:
  - Early warning systems using rainfall and stream flow sensors.
    - Potentially feasible and relevant, especially given existing hydrological monitoring networks in Otago. These systems can be expanded to include debris flood-specific alerts, enhancing community safety.
    - Key challenges for successful implementation include localised trigger events (thunderstorms that only impact few catchments) and rapid onset debris flood hazard.
  - Community education and evacuation planning.
    - Roxburgh's small population allows for targeted outreach and effective planning. These measures are low-cost and practical, with strong potential for reducing risk.

    - Regular maintenance of channels and infrastructure.
        - Channel maintenance to maintain channel capacity is important across all catchments, particularly Reservoir and Pumpstation. Such maintenance requires consistent funding and coordination between local and regional authorities.
- **Land Use and Planning:**
    - Zoning restrictions in high-risk areas.
        - Zoning is effective in preventing new development in significant risk zones. Feasibility is moderate to high, though implementation may face resistance from landowners and require robust policy frameworks.
        - Managed retreat or planned relocation can be an effective strategy for reducing exposure in areas of highest risk with existing development. However, it remains socially and politically challenging and is not well supported under current policy frameworks
    - Elevated construction and use of flood-resistant materials.
        - May be feasible for new developments in tolerable risk zones. Retrofitting existing structures may be more challenging but could be considered for critical infrastructure.
    - Preservation of natural buffers such as vegetation and terraces.
        - Preservation of natural buffers such as vegetation and terraces is likely feasible and environmentally beneficial. Maintaining vegetation and terraces can reduce flow velocity and sediment transport, especially in GS1 and Slaughterhouse catchments.
    - The proposed RPS has specific policies for managing risk for both new activities and existing development within the Otago region.
- **Long-term adaptation and resilience:**
    - This includes promoting community and household-level preparedness and response planning.
        - Building adaptive capacity including allocating budgets and resources to help communities prepare for and respond effectively to debris flood events is critical.
    - Ensure that debris flood hazard and risk information is integrated into both current and future development decisions.
    - Embed local knowledge and mana whenua values into planning processes.
    - Promote collaboration and partnerships among agencies, local communities, and mana whenua creating a more coordinated and inclusive approach to risk reduction.

It is important to note that the potential risk mitigation strategies discussed above would not achieve a complete reduction of risk and there will always be a degree of residual risk.

6 UNCERTAINTY

There is intrinsic uncertainty in the assessment of life and property risk and the results presented in this report. Output uncertainty is an outcome of the underlying uncertainties of the various inputs in this assessment including the geomorphological and hydrological assessment of catchments, frequency-magnitude debris flood event assessment, RAMMS modelling, and qualitative risk assessment approach. Model limitations and uncertainties have been noted throughout this report and in the appendices. This section summarises the main limitations and uncertainties. It is important to note that the risk assessment results presented in Section 4 should be considered in conjunction with the uncertainties outlined in this section and where mentioned elsewhere in the report and appendices.

6.1 GEOMORPHOLOGICAL ASSESSMENT OF CATCHMENTS

There is limited historical and geological evidence on debris flood events in the study area. In this report, we have made assumptions and interpretations on the geomorphology of catchments based on previous reporting, terrain analysis (e.g. Melton ratios), and geomorphological mapping.

The current debris flood risk assessment project for Roxburgh has utilised the results of previous field investigations, and specific additional field investigations. The WSP project team has relevant local experience of the Roxburgh environment, gained from (a) previous projects, including field mapping of the Roxburgh catchments during the previous Golder (2019) debris flood assessment and hydrogeomorphic assessment of debris floods for specific areas, (b) routine (at least annual) inspections of the various road infrastructure along the entire project area, and (c) emergency event response to debris flood and other natural hazard events.

The Golder (2019) debris flood assessment included several days of field mapping of the Pumpstation, Reservoir, Golf Course, Black Jacks, and Stevensons catchments by experienced engineering geologists and a helicopter flyover of the entire catchments of those fans. The field mapping yielded substantial observational data that has been incorporated in the current study. The focus of the field mapping was to observe outcrops and geomorphic features from the catchments and fans that characterise debris flood (or flow) behaviour on each fan, with a particular emphasis on evidence of the 2017 event. No sub-surface investigations were completed and the field mapping concentrated on the five named catchments.

An Alexandra-based WSP team completes routine inspections of the state highway roading infrastructure, including the Roxburgh area, for NZTA. This team completes regular road-based inspections of bridges and culverts, particularly after heavy rainfall events and collects observations of flood damage or stream erosion or aggradation to assist with the local road maintenance programme. Annual helicopter flyovers of the fans and catchments are completed as part of this programme.

We believe that this level of field investigation is appropriate for the current debris flood assessment, given the detailed LiDAR terrain data and aerial imagery provided by ORC for this study (which was not available for the 2019 Golder assessment). The high-quality LiDAR-based DTM allows analysis of catchment and fan geomorphology to a level of detail that would have required lengthy field mapping, particularly given the large area of the fans and catchments in this study.

6.1.1 GEOMORPHIC MAPPING AND CONSIDERATION OF FURTHER FIELD WORK

The geomorphological mapping for this study was completed in GIS using publicly available topographical and geological information and LiDAR captured for this study. While it consists of the best currently available information, the geomorphological mapping undertaken in this assessment is subject to human mapping bias, input dataset uncertainty, and limitations due to the constraints of this study. Geomorphic mapping was undertaken at a scale appropriate to a catchment-wide debris flood hazard assessment and was focused on identifying recently active and dominant contributors to debris-flow initiation. The mapping therefore prioritised features most likely to influence current and future debris flood behaviour, rather than exhaustively cataloguing all geomorphic evidence of relict and prehistoric landsliding within each catchment.

Source areas were identified based on observable geomorphic indicators at the adopted mapping scale, including breaks in slope, channel heads, confined gully systems, and landforms exhibiting surface expression consistent with recent mass movement or debris flood activity. Areas of broader slope deformation outside of discrete source features were mapped where visible; however, it is recognised that subtle or small-scale landslide features may not be captured.

Accordingly, the maps presented in Appendix B should be interpreted as representing the dominant and recently active debris flood source areas, rather than a comprehensive inventory of all landsliding features. This limitation is inherent to the scale and scope of the assessment and has been considered in the interpretation of results.

Additional field surveys, stereophotographic analysis, remote sensing, and automated classification geospatial techniques (e.g. geomorphons) could be considered to refine and help reduce uncertainty in the desktop-based geomorphological mapping.

Test pitting was completed on two representative fans to inform subsurface characterisation. No direct investigations were undertaken on the remaining fans, and their characterisation therefore relies on geomorphic mapping, remote data, and extrapolation from investigated areas. This results in elevated uncertainty for the un-investigated fans, which has been managed through conservative assumptions. Further field investigations would reduce uncertainty if refinement of the assessment is required; additional intrusive site investigations such as targeted borehole drilling and test pitting would refine the geological models at particular fans, allowing improved calibration of the debris flood inundation scenarios.

6.2 HYDROLOGICAL ASSESSMENT

The hydrological assessment undertaken in this study used the **SCS Curve Number method within HEC-HMS** to estimate runoff volumes and peak flows for debris flood scenarios. While this approach is appropriate for rural, ungauged catchments with limited observed flow data, several assumptions and input constraints introduce uncertainty into the runoff estimation. These uncertainties are summarised below:

- **Catchment Boundaries**:
  Catchment extents were provided by Otago Regional Council and adopted without modification. Any inaccuracies in the initial delineation may influence contributing area estimates and runoff volumes.
- **Discharge Point Assumptions**:
  The location and characteristics of discharge points were not verified. It was assumed for modelling purposes that each catchment drains independently via a culvert or defined outlet point. This simplification may not reflect actual hydrological connectivity between catchments or the influence of downstream infrastructure (e.g. SH8 culverts).
- **SCS Curve Number Parameters**:
  Curve Numbers (CNs) were assigned based on land use, soil type, and hydrological soil group

classifications obtained from national datasets (e.g. LCDB v5.0 and LRIS). These datasets were not ground-truthed; therefore, do not account for potential localised variation in infiltration capacity or vegetation cover.

- **Initial Abstraction and Loss Parameters**:
  Standard SCS assumptions were applied for initial abstraction and soil moisture conditions, as no catchment-specific rainfall-runoff calibration data was available. Antecedent moisture conditions were not explicitly modelled, which can influence peak flow estimates—particularly under high-intensity, short-duration rainfall events.

- **Rainfall Input Data**:
  Design rainfall intensities were obtained from NIWA's High Intensity Rainfall Design System (HIRDS v4). While HIRDS provides robust regional estimates, extrapolation of rainfall depths to high-frequency events (e.g. <1-hour durations) can introduce uncertainty in mountainous terrain where orographic enhancement or storm cell concentration may occur.

  The Roxburgh area is situated within a complex topographic setting, where surrounding ranges and valley orientations can significantly influence local rainfall patterns through orographic enhancement. This process occurs when moist air masses are forced to rise over elevated terrain, leading to increased condensation and precipitation. As a result, rainfall intensities in Roxburgh may be locally amplified compared to broader regional estimates.

  This introduces a degree of uncertainty when applying rainfall intensity data from HIRDS, which is based on interpolated climate data and may not fully capture fine-scale orographic effects specific to Roxburgh's catchments. While HIRDS provides valuable baseline information for design rainfall estimates, its spatial resolution and reliance on regional climate models mean that actual rainfall intensities for Roxburgh may be underestimated.

- **Model Calibration and Validation**:
  The HEC-HMS model was not calibrated against observed flow data due to a lack of streamflow gauges in the study area. As such, the model outputs represent uncalibrated estimates of hydrological response, introducing uncertainty in the peak flow and runoff volumes provided as inputs to the RAMMS debris flood modelling.

Overall, the use of the SCS method within HEC-HMS is considered suitable for this level of assessment, particularly in the context of informing qualitative risk classification and RAMMS scenario definition. However, further refinement—such as local calibration, improved soil parameter validation, and event-based hydrograph verification—would be beneficial if the results are to inform detailed design.

6.3 CLIMATE CHANGE

In this assessment the RAMMS models are based on rainfall depths for 1:100, 1:500, and 1:2,500 rainfall events under an RCP8.5 climate scenario. Rainfall and peak flow have been modelled using the RCP 8.5 climate scenario with rainfall data from HIRDS (NIWA, 2023). This is a worst-case climate scenario for Roxburgh with increase in rainfall intensity and peak flow in the catchments assessed in this study. This is a conservative scenario and represents the upper bound of hydrological input variables. The selection of this scenario aligns with GNS landslide planning guidance for Level C and Level D analyses and is appropriate for the purposes of this risk assessment (de Vilder et al., 2024). We have conducted climate change sensitivity testing on our model, with the results presented in Appendix E. Debris flood inundation and extent was not found to increase significantly between the RCP8.5 scenario used in this report and a present day climate scenario when all other variables were kept the same.

6.4 FREQUENCY-MAGNITUDE OF DEBRIS FLOOD EVENTS

As noted, there is limited historical and geological evidence to produce a detailed frequency-magnitude assessment. Our frequency-magnitude assessment for each catchment is based on the geomorphological mapping and informed using the historical event inventory collated for this study.

For some catchments, there are no records of previous events and average event frequencies from catchments where we have historical event records for (e.g. Reservoir) are adopted. This study-wide approach is also adopted for the selection of factor values such as entrainment factor and assumed depths of erosion.

Event frequencies and factor values may differ from those presented in this study with future debris flood events or with individual assessment of factor values for each catchment.

6.5 RAMMS MODELLING

Debris flood modelling was undertaken in this study using RAMMS software and inputs from geomorphological and hydrological assessments. Several assumptions and input constraints in the RAMMS modelling that affect uncertainty are summarised below:

- **Topographic Resolution**:

  RAMMS-DF simulations used a 1 m resolution DEM, which extended processing times. Lower resolutions (> 1 m) were insufficient for defining topographic features.

- **Calibration Event**:

  The 2017 Reservoir Creek event was used to refine model parameters. A summary of this calibration is presented in Appendix E. Model parameters and details were adjusted as a result of this calibration. Due to time constraints and limited calibration data, this single event was applied to all catchments.

- **Consistency of Parameters**:

  Modelled input parameters were consistent across all catchments, reflecting similar geomorphological characteristics.

- **Debris Flood Assumptions**:

  The model assumes parameters specific to debris flood events, not accounting for debris flood impacts.

- **Peak Flow Rates**:

  Hydrological assessments assumed clear-water flood events. Debris floods, which include water, mud, and rocks, may have higher peak flow rates. No bulking factor was applied. Accurate bulking factors require detailed data on sediment volume, type, and mobilisation potential. In the absence of such data, applying generic or assumed bulking factors could introduce significant uncertainty and reduce the reliability of the model outputs. Further, the model was intended for preliminary hazard screening rather than detailed design.

- **Channel features**:

  The main drainage channels intersect SH8. The DEM does not incorporate culverts, other than at Reservoir Creek. Therefore, the RAMMS models assume minor debris block the culvert inlets, leading to overtopping onto SH8.

- **Localised features affecting debris runout**:

  The RAMMS model uses a bare earth DEM, which excludes buildings, services, and vegetation. Therefore, the debris flood runout inundation does not take into account the presence of localised features such as houses, fences, vegetation etc. that would affect the true inundation distribution in a real debris flood event.

- **Clutha River**:

  RAMMS-DF model inputs do not include the depth or competence of the Clutha River; and therefore, the effects of the river on the debris flood distribution are not accounted for.

Overall, the use of RAMMS and the assumptions outlined in this report are considered suitable for this level of risk assessment. However, further refinement such as additional model calibration, considering debris flow (rather than debris flood) parameters and bulking factors, and alteration of the underlying DEM and model parameters to include culverts and above-ground features (buildings, services etc) would be beneficial if the results are to inform detailed design.

6.6 RISK ASSESSMENT

6.6.1 DEBRIS FLOOD HAZARD

We use the RAMMS models to define the hazard layer used in the risk assessment. The specific limitations of these models are outlined in Section 6.5. However, further limitations in regard to the risk assessment include the sensitivity of the model to changes in input variables (volume and peak flow), the maximum credible scenario credibility for some catchments, and areas outside of modelled debris extent.

Firstly, the models appear to be sensitive to changes in volume for which there is reasonable uncertainty for the calculated volumes in this assessment. However, the RAMMS models do not appear to be as sensitive to changes in peak flow. For some smaller and less active catchments in the study area there is not as much geomorphic evidence for a maximum credible event as others and such the assessment of this event size for some catchments may be conservative. For the purposes of the qualitative risk assessment, where possible, we have maintained relative conservatism to not exclude catchments from the quantitative risk assessment phase.

We also only assess exposure for existing buildings, development, population, and lifelines. Further assessment could consider potential development on the alluvial fans aligning with local and regional planning rules. This would provide ORC with potential future exposure under urban intensification.

Debris flood models produced in RAMMS were used to inform the spatial probability and vulnerability assessment in the quantitative risk assessment. The RAMMS models used the LiDAR surface elevation data as an input and debris flood extents generally follow the paths of least resistance on each alluvial fan (i.e. lowest elevation cells in the LiDAR). Existing channels on alluvial fans are filled with debris first. Debris spillage from the main channel does occur in some scenarios and generally the spatial probability of inundation decreases with lateral distance from the channel. Historically, SH8 bridges and culverts on the alluvial fans have impeded flow and caused debris spillage initiating along the road alignment and dispersing downslope. However, there are also instances where debris spillage outside of the channel margins has occurred upslope of the SH8 crossing near the fan apex (2017 Golf Course). It is possible that inundation could occur on the fan outside of the RAMMS models extents; and therefore, calculated risk values for these areas may be higher than presented in this report.

6.6.2 DEBRIS FLOOD PROBABILITY

Any estimate for the probability or recurrence of hazards is uncertain and relies on historical information and field observations. For this assessment, there is limited historical information, particularly for larger debris flood magnitudes. We have estimated debris flood return period based on the 2017 debris flood events and rainfall data from HIRDS (NIWA, 2023). The limitations of this assessment include:

- A single debris flood event does not provide long-term averages for debris flood probability.

    - Future event records could be incorporated into similar assessments and would reduce the uncertainty of hazard return period and magnitude.
- This assessment does not consider other trigger sources (e.g. earthquake induced landslides within the catchments prior to heavy rainfall).
- Long-term rainfall return period estimates are uncertain, particularly given climate change.
    - In this assessment, we have used an average return period of rainfall incorporating present-day rain (rainfall return period based on historical averages) and RCP 8.5 rain (worst-case climate scenario) to account for uncertainty.

In this report, we use the historical event inventory to inform hazard likelihood. There is a reasonable amount of uncertainty in this assessment, due to the limited number of historical events our estimates are based on. The incorporation of future debris flood events and historical debris flood events in settings similar to Roxburgh could be used to reduce uncertainty.

6.6.3 QUALITATIVE CONSEQUENCE CRITERIA

Impacts to lifelines in this assessment are assessed qualitatively and do not consider asset criticality, lifeline interdependency, or prioritisation of asset restoration following an event. Further assessment of lifeline impact during debris flood events could be undertaken in consultation with local lifeline operators and Civil Defence and Emergency Management (CDEM).

6.6.4 TEMPORAL SPATIAL PROBABILITY

In the qualitative and quantitative risk assessment, we estimate the time a person spends in a hazard prone area using national averages and local knowledge. These are averages and the overall temporal spatial probability may vary for individuals and for the Roxburgh area. Further, the distribution of population in Roxburgh during severe rainfall events, seasonal variations of population due to tourists, and evacuation procedures facilitated by Civil Defence and Emergency Management were not explicitly considered in the assessment. Due to the typically rapid response of catchments in Roxburgh to rainfall, it is unlikely that there will be enough warning for formal evacuation procedures to take place. We have incorporated self-evacuations into this assessment which are more likely to take place.

6.6.5 SPATIAL DISTRIBUTION OF RISK

Risk assessments inherently involve uncertainty due to the variability and limitations in the input data. In this report, we have acknowledged these uncertainties and, where feasible, incorporated a range of input values to reflect the plausible bounds of risk. However, the primary results presented thus far have been based on average input values, which provide a central estimate but may not fully capture the spectrum of possible outcomes.

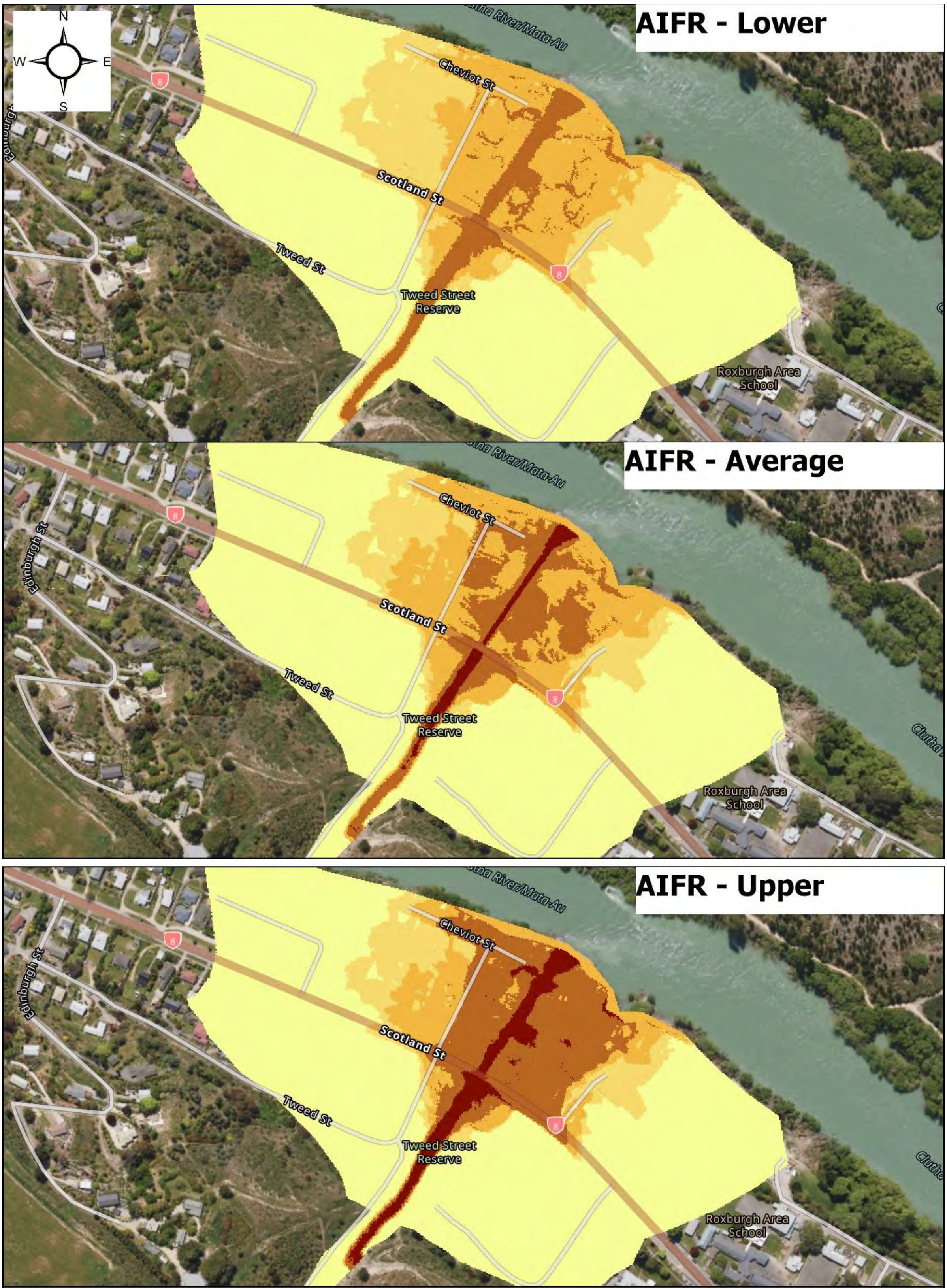
To better illustrate the uncertainty in quantitative risk, this section compares the spatial distribution of AIFR across three scenarios lower-bound, average, and upper-bound input values for a present-day event on the Reservoir alluvial fan.

Figure 39 presents three spatial maps showing AIFR values under each input scenario:

Lower Risk Inputs: These represent fewer conservative estimates, such as lower event frequency and exposure. Under this scenario, areas of significant risk are generally confined to the main channel, where flow concentration and depositional processes are most active. Peripheral zones show minimal risk, suggesting that under optimistic assumptions, the hazard footprint is relatively contained.

Average Risk Inputs: This scenario reflects the average values of the input parameters. The spatial extent of significant AIFR values expands slightly beyond the main channel, indicating that even under typical conditions, risk is not strictly limited to the primary flow path. This highlights the importance of considering adjacent areas in land-use planning and emergency preparedness.

Upper Risk Inputs: These incorporate more conservative assumptions such as higher event frequency and exposure. The result is a marked increase in the spatial extent of significant risk, with elevated AIFR values extending into zones classed as ‘tolerable’ in the lower and average AIFR scenarios. This scenario underscores the potential for broader impact under worst-case conditions and reinforces the need for robust contingency planning.



Colour	Risk Value	AIFR Risk Tolerability - Existing Development	AIFR Risk Tolerability - New Development
	<1E-06	Acceptable	Acceptable
	1E-06 to 1E-05		Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

Figure 39: Present day lower, average, and upper AIFR for Reservoir.

6.6.6 MAXIMUM CREDIBLE EVENT

The assessed AIFR and APR values reflect the combined contribution of a spectrum of credible events, spanning low-probability/high-consequence scenarios through to higher-frequency, lower-magnitude events. While the maximum credible event represents the largest potential consequence and is therefore an important component of the hazard characterisation, it does not dominate the calculated risk metrics.

This outcome reflects the comparatively low probability of occurrence assigned to the maximum credible event. Although such an event contributes to the upper tail of the consequence distribution, its weighting in the overall risk calculation is limited by its low frequency. Consequently, the aggregated AIFR and APR values are influenced by smaller-magnitude events with higher likelihoods, including high-likelihood and median events, which collectively contribute a greater proportion of the expected annual risk.

Uncertainty associated with parameters underpinning the maximum credible event is acknowledged. However, given the relatively low contribution of this event to the total risk metrics, uncertainties in its characterisation do not materially skew the calculated AIFR and APR. Instead, the resulting risk values are relatively robust and reflect a balance between event consequence and likelihood across the full range of assessed scenarios. This reduces sensitivity to assumptions associated with any single extreme event and provides confidence that the reported risk metrics are not unduly driven by worst-case, low-probability conditions.

Accordingly, the maximum credible event remains relevant for understanding potential worst-case impacts and emergency planning considerations, but it does not disproportionately control the quantitative risk outcomes presented in this assessment.

7 CONCLUSIONS

This report presents the hydrogeomorphic modelling and risk assessment for 13 catchments along the Old Man Range in Roxburgh, Central Otago. This work included an overview of historical hydrogeomorphic events in the study area, a geomorphological and hydrological assessment, a frequency-magnitude assessment of events, scenario modelling, and risk assessment. The risk assessment was undertaken according to APP6 for high likelihood, median likelihood, and maximum credible debris flood events determining both qualitative and quantitative risk for people and buildings. We conclude the following:

7.1 DEBRIS FLOOD HAZARD

- Roxburgh is a township that has been historically impacted by debris flood and debris flow events.
  - Impacts have included inundation of lifeline infrastructure, property, and buildings, resulting in service outages to roads (particularly SH8) at stream crossings and damage to exposed water and electricity lines.
  - Culverts along SH8 have impeded debris flood flow causing lateral inundation outside of the channel.
  - In November 2017 several debris floods occurred which prompted upgrades to several culverts to increase capacity and resilience during future events.
- The catchments assessed in this study are generally steep, pasture- and tussock-covered, and actively eroding with significant debris source material identified in several catchments.
  - Alluvial fans in the study area have mostly been developed into horticultural and agricultural uses except for the urban areas in Roxburgh. Alluvial fans have built out onto river terraces and are truncated by the Clutha River which transports away debris deposited during debris flood events.

7.2 QUALITATIVE RISK ASSESSMENT

- A significant risk level for debris floods is assessed for PN2, PN1, GS2, BS2, Stevensons, Slaughterhouse, and GS1. For these catchments further quantitative risk assessment is required.
- A tolerable risk level, but with a consequence level of 5 (i.e. catastrophic) for debris floods, is assessed for Pumpstation, BS1, and Reservoir. For these catchments further quantitative risk assessment is also required.
- The remaining catchments Golf Course, RN1, and Black Jacks have acceptable or tolerable risk levels without catastrophic consequences, though continued monitoring and consideration of mitigation strategies is advised.
- Future development of the alluvial fans of these catchments will increase exposure and potentially consequence. Reassessment of qualitative risk should be undertaken if alluvial fans are to be developed with infrastructure and lifelines.
- Climate change was considered through the incorporation of the RCP8.5 climate change scenario in modelling inputs.

7.3 QUANTITATIVE RISK ASSESSMENT

This assessment has identified several catchments within the Roxburgh area where debris flood risk is considered significant, for both existing and new development. Using established risk tolerability criteria, catchments such as Stevensons, BS2, PN2, Golf course, GS2, BS1, and Pumpstation on average exceed the threshold for significant risk based on both Annual Individual Fatality Risk (AIFR).

Spatial analysis reveals that areas within close proximity to main channels – typically within 200–300 m – are most vulnerable, with risk decreasing with distance and elevation. Notably, Stevensons exhibits the highest average AIFR, and PN2 the highest average APR, with significant proportions of both fans showing areas of elevated risk. Other fans such as Slaughterhouse, Reservoir, and PN1 present tolerable risk for existing development but significant risk for new development, highlighting the importance of future land use planning.

It is important to note that risk shown in this report is based on the average of risk inputs adopted and that more conservative (higher bound) or less conservative (lower bound) risk input values may result in a different spatial representation of risk as illustrated in Section 6.6.5.

7.4 EFFECT OF CLIMATE CHANGE ON RISK LEVELS

Debris flood risk is thought to increase under the RCP8.5 climate change scenario. Projected increases in high-intensity rainfall events under this scenario lead to more frequent debris flood of varying magnitudes within the study catchments. Consequently, the probability of debris flood occurrence and associated risk is higher in the RCP8.5 scenario than the present-day scenario, and this effect is reflected in the risk maps presented in this report.

7.5 RISK MITIGATION

The spatial variability of risk across each fan, as illustrated in Appendix H, underscores the need for site-specific mitigation strategies. These should be informed by both the average risk values and the geomorphological characteristics of each catchment.

This study has highlighted a range of potential structural, non-structural, and planning-based mitigation strategies to manage debris flood risk in Roxburgh. Structural measures such as debris flood barriers, diversion channels, and reinforced culverts may be practical given the area's steep terrain and sediment dynamics, though their feasibility depends on site-specific constraints like land access and hydrological design. Non-structural approaches—including early warning systems, community education, and regular maintenance—are likely feasible and cost-effective, especially in a small, well-connected community like Roxburgh. Land use planning tools, such as zoning restrictions and the preservation of natural buffers, offer long-term resilience but require strong policy support and community engagement. Together, these strategies provide a comprehensive framework for reducing debris flood risk across the catchments assessed in this study.

8 LIMITATIONS

This report ('Report') has been prepared by WSP New Zealand Limited ('WSP') exclusively for Otago Regional Council ('Client') in relation to Roxburgh debris flow risk assessment ('Purpose') and in accordance with the Short Form Agreement with the Client dated 25 November 2024 ('Agreement'). The findings in this Report are based on and are subject to the assumptions specified in the Report and Request for Proposal (RFP) dated 4 October 2024. 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.

In preparing this Report, WSP has relied upon data, surveys, analyses, designs, plans and other information ('Client Data') provided by or on behalf of the Client. Except as otherwise stated in this Report, WSP has not verified the accuracy or completeness of the Client Data. To the extent that the statements, opinions, facts, information, conclusions and/or recommendations in this Report are based in whole or part on the Client Data, those conclusions are contingent upon the accuracy and completeness of the Client Data. WSP will not be liable for any incorrect conclusions or findings in the Report should any Client Data be incorrect or have been concealed, withheld, misrepresented or otherwise not fully disclosed to WSP.

APPENDIX A – BACKGROUND INFORMATION

GAP ANALYSIS REPORT

Otago Regional Council

ORC DEBRIS FLOW MODELLING

PHASE 2: GAP ANALYSIS REPORT

18 FEBRUARY 2025 CONFIDENTIAL

ORC DEBRIS FLOW MODELLING

PHASE 2: GAP ANALYSIS REPORT

Otago Regional Council

WSP
Christchurch
12 Moorhouse Avenue
Addington
Christchurch 8011, New Zealand
+64 3 363 5400
wsp.com/nz

REV	DATE	DETAILS
A	18 February 2025	Final for Client Issue

	NAME	DATE	SIGNATURE
Prepared by:	Harley Porter	17 February 2025	
Reviewed by:	Doug Mason	17 February 2025	
Approved by:	Richard Woods	17 February 2025	

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1 INTRODUCTION

1.1 PROJECT BACKGROUND

The Otago Regional Council (ORC) has engaged WSP New Zealand Limited (WSP) to undertake a detailed debris flow hazard and risk assessment in Roxburgh, Central Otago. This assessment will inform potential spatial planning and outline physical mitigation/adaptation options. The assessment will include debris flow modelling in 13 catchments to the west of the Clutha River (Figure 1) and estimation of potential impacts on the built environment and exposed populations.

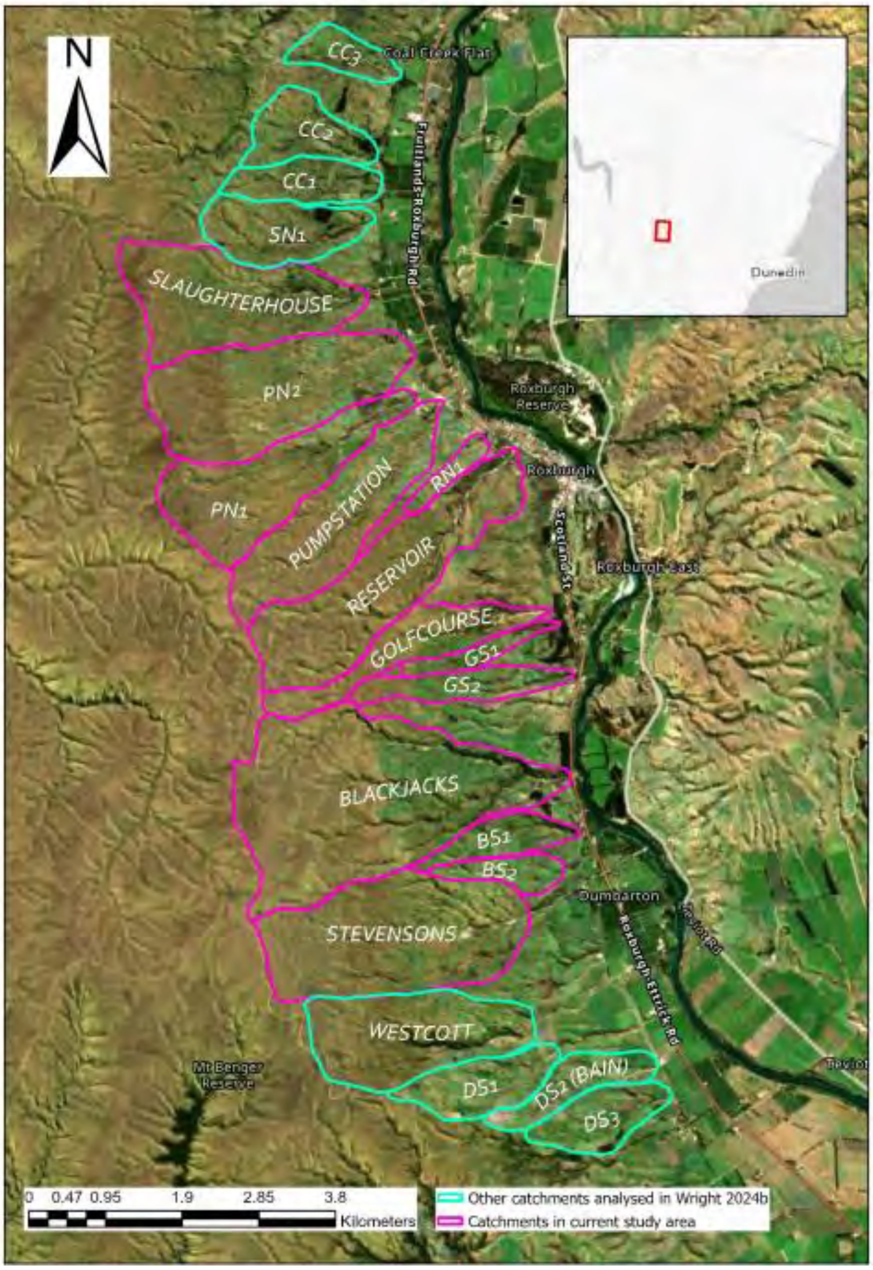

Figure 1: The 13 debris flow catchments to be assessed in this study in Pink. Other catchments analysed in previous studies outlined in green. Figure from ORC Request for Proposal (RFP) dated 05/09/24.

1.2 SCOPE AND PURPOSE

The objective of this study is to assess and map the hazards and risks posed by debris flows in the Roxburgh area of Central Otago. The project will be delivered in six key phases with internal and external peer review throughout (Figure 2).

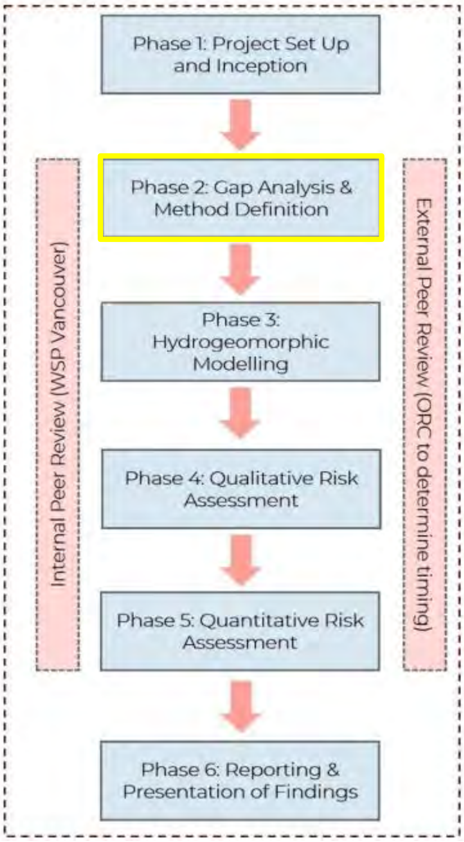

Figure 2: High-level project structure with current phase highlighted in yellow.

This report has been prepared as part of Phase 2 and presents an overview of the proposed methodology for this study and the findings from a gap analysis of available information. This will inform the hydrogeomorphic modelling and risk assessment phases of the project.

2 METHODOLOGY

2.1 GAP ANALYSIS AND METHOD DEFINITION

The objective of this phase is to identify available input datasets for debris flow modelling and risk assessment in the study area and assess any gaps. A gap analysis workshop was held with ORC and WSP at the outset of the project in January 2025 to discuss the datasets already collated and identify areas where ORC could assist in filling the remaining gaps.

This gap analysis report presents an overview of that process including potential gaps in the input datasets required to complete the hydrogeomorphic modelling and risk assessment work.

2.1.1 PREVIOUS REPORTS

As part of this phase of the project WSP has reviewed several previous debris flow reports in the study area. These will provide key input data and background material to our project. The previous reports reviewed to date are:

- The Soil Conservation and Rivers Control Council. (1957). Floods in New Zealand 1920-53.
- Otago Catchment Board. (1980). Proposal for works at Reservoir Creek, Roxburgh.
- Otago Catchment Board. (1983). Disaster Damage Roxburgh Area: March 1983.
- Opus. (2004). Geotechnical & Hydrological Assessment Report. Dunedin: Opus International Consultants Ltd.
- Barrell et al. (2009). Otago Alluvial Fans Project Supplementary maps and information on fans in selected areas of Otago.
- Opus. (2009). Otago Alluvial Fans Project. ORC report.
- Woods. (2011). Otago Alluvial Fans High Hazard Fan Investigation. ORC report.
- DAMWATCH. (2017). Preliminary Assessment of Flood and Erosion Hazards in Clutha River.
- Dellow et al. (2018). Hazard and risk assessment of the Roxburgh debris flow of 26th November 2017. GNS report.
- Golder. (2019a). Management and Reduction of Debris Flow Risk in Roxburgh, Otago.
- Golder. (2019b). Management and Reduction of Debris Flow Risk in Roxburgh, Otago.
- Mackey. (2021). Managing ongoing debris flow risk in Roxburgh, Otago.
- WSP. (2021). Quail Haven Stage 2: Geotechnical Assessment.
- WSP. (2024). Quail Haven - Stage 2 Pump Station Creek Debris Flow Field Assessment.
- GeoSolve. (2024). Quail Haven Stage 2 Debris Flow Risk Review 3768 Fruitlands - Roxburgh Road, Roxburgh.
- WSP. (2024). Pump Station Creek Debris Flow Field Assessment.

2.2 HYDROGEOMORPHIC MODELLING

Hydrogeomorphic modelling will estimate debris flow hazard potential in the 13 catchment areas and their alluvial fans. This phase will include the following steps:

- Catchment characterisation and geomorphological assessment:
  - Assess inputs required, including development of a suitable DEM for debris flow modelling.
  - Review historical debris flows in the area, and assess all recorded previous events, informed by previous projects, geological and historical records, and aerial imagery.
  - Characterise alluvial fans to estimate long-term deposition rates on Clutha River terraces over the past 10,000+ years.
  - Analyse aerial imagery and helicopter flyover records to identify geological features and evidence of debris flows.
  - Conduct field mapping with helicopter flyovers to gather data from previously unvisited catchments.
  - Define the hydrogeomorphic characteristics of each catchment, the potential volume of contributing landslides and channel erodibility, the geometry of the alluvial fans (depositional areas) and any existing mitigation structures.
- Debris flow modelling and likelihood assessment:
  - Determine hydrological parameters including flow/return period relationships and climate change implications using CMIP-6 datasets.
  - Estimate debris flow volumes for various return periods, considering historical landslide data and channel erodibility.
  - Conduct debris flow modelling using RAMMS software to estimate the extent of debris flow inundation in each catchment along with the inundation depth and velocity characteristics for each modelled scenario. This will include a sensitivity analysis of at least one catchment to determine the most appropriate input parameters, calibrated using past debris flow event/s.

2.2.1 RAMMS SOFTWARE OVERVIEW

RAMMS (Rapid Mass Movement Simulation) is a three-dimensional numerical simulation software package designed for simulating the runout behaviour of natural hazards such as avalanches, debris flows, and rockfalls. RAMMS-DF (Debris Flow) simulates debris flows' release, movement, and deposition. It is used for hazard mapping, evaluating mitigation measures, and risk assessment.

Debris flow characteristics are defined in RAMMS using the following parameters:

- Frictional Parameter, Mu (μ) – Dry-Coulomb type friction parameter representing the basal shear friction.
- Frictional Parameter, Xi (ξ) – Viscous-turbulent friction parameter relating to the turbulent behaviour of the flow.
- Internal Pressure Parameter, Lambda (ƛ) – 'Earth' pressure parameter used to control the ability of a flow to spread by resistance to internal strain.
- Flow Density (ρ) – Bulk density of the debris flow including fluid and solid components.

RAMMS-DF offers two primary initiating methods for debris flow simulations:

1. Block release
   - Suitable for small unchanneled debris flows. This method involves specifying a release area with a given initial depth, which is then released as a block. This approach is useful for simulating sudden releases of debris.
2. Input Hydrograph
   - More appropriate for channelised debris flows. This method uses an input hydrograph to specify the discharge as a function of time, allowing for a more dynamic and continuous flow simulation.

2.3 QUALITATIVE RISK ASSESSMENT

Following completion of the catchment characterisation, geomorphological assessment, and debris flow modelling WSP will complete a qualitative risk assessment using the ORC Regional Policy Statement (RPS) methodology for natural hazard risk assessment (APP6) (ORC, 2021). This phase will include:

1. Selection of risk descriptors
   - Develop qualitative natural hazard risk descriptions for the 'Built' and 'Health and Safety' consequences as detailed in Table 7 of APP6. To assess the consequences of the natural hazard scenarios, WSP will review available information and data for considerations 1-11 in Step 2 of the APP6 framework.
2. Debris flow likelihood
   - Determine the likelihood of three debris flow scenarios for each catchment representing a high likelihood event, median likelihood event, and the maximum credible event with consideration of climate change.
     - Desktop review of the latest downscaled NIWA/MfE CMIP-6 models.
3. Estimate impacts of modelled debris flow
   - Assess the severity of impacts on the built environment including social/cultural buildings, residential buildings, critical buildings, and lifelines.
   - Lifelines considered in this assessment are transportation (roads and bridges), electricity, water supply, wastewater, and telecommunications.
   - Assess the vulnerability of local infrastructure including interdependencies.
   - Assess potential casualties for each debris flow event using population data and existing vulnerability models.
4. Determine the relative risk level of each event and agree with ORC which catchments are classed as 'significant risk' in accordance with APP6 and require further quantitative risk assessment.

2.4 QUANTITATIVE RISK ASSESSMENT

Complete a quantitative risk assessment of catchments identified as having ‘significant risk’ for debris flow following the AGS 2007 methodology (AGS, 2007). The approach will align with a basic quantitative risk analysis in accordance with de Vilder et al (2024) Level D planning guidance. The quantitative risk assessment will calculate annual individual fatality risk (AIFR) and Annual Property Risk (APR). Critical to this analysis will be determining the vulnerability of individuals, structures and other infrastructure to inundation depth and velocity from debris flow. WSP will rely on published empirical information relating to vulnerability to assist with this assessment. Previous assessments will be used to summarize assumptions and calculate risk metrics efficiently.

The inherent uncertainty in natural hazard risk assessments will be articulated and demonstrated, especially for potential future land use.

2.4.1 ANNUAL INDIVIDUAL FATALITY RISK (AIFR)

AIFR assesses the probability that an individual most at risk is killed by debris flow in any one year. It considers:

- Annual probability of debris flow occurring.
- Spatial probability of debris flow traversing the location of the person most at risk.
- Temporal spatial probability, including the time the person is present and potential evacuation warnings.
- Vulnerability or probability of death in the event of interaction with the hazard.

Input uncertainty is addressed by considering a range of likely values, and providing a range, minimum, and maximum for each risk area.

An average AIFR for each area is determined by averaging the input probabilities.

2.4.2 ANNUAL PROPERTY RISK (APR)

APR assesses the annual probability of total property loss due to debris flow, assuming development according to the current planning zone. It considers:

- Annual probability of debris flow occurring.
- Spatial probability of debris flow impacting the property, considering travel distance and direction.
- Temporal spatial probability.
- Vulnerability of the property to spatial impact.

APR uses the annual and spatial probability parameters from the AIFR assessment.

3 GAP ANALYSIS FINDINGS

Table 1 provides an overview of the input datasets required for the analysis and the gaps identified by WSP in this intial phase of the project. The key gaps identified during this analysis are as follows:

1 Limited data on frequency/magnitude of debris flow hazards

After an initial review of previous reports, it is apparent that there is limited quantitative data available on previous events in each catchment. A detailed historical record is a key part of determining a frequency/magnitude relationship of debris flows.

Determining trigger (i.e. rainfall, seismic) intervals are another important factor in developing frequency/magnitude relationships. There is a lack of data quantifying what rainfall is required (i.e. intensity-depth-duration) to trigger debris flows of different magnitudes largely due to few events in recent years. However, this can be addressed by a literature review of published rainfall intensity-duration thresholds elsewhere (e.g. Italy, Taiwan and China) and compare to any recorded rainfall from debris flow events in Roxburgh.

1 2024 LiDAR 1 m DEM correction

It is understood that the 2024 LiDAR 1 m DEM supplied by ORC has not yet been hydrologically corrected at SH8 crossings of debris flow channels. This will affect the results of the debris flow modelling and is a key gap to be filled before any modelling can be completed. ORC have arranged for the surveyor to correct the DEM for the Reservoir Creek crossing only. A methodology for other stream crossings in the assessment will need to be determined.

2 Geospatial information on existing mitigation structures, culverts, and engineered channels away from SH8.

WSP has a good understanding of these structures along SH8; however, data on any structures along channels or roads separate from the state highway network would be useful.

3 Electricity distribution geospatial data/asset information

Electricity distribution geospatial data in Roxburgh would contribute to the risk assessment and determining outages during modelled debris flow events. It is noted that the distribution company in Central Otago is Aurora Energy.

4 Roxburgh infrastructure interdependencies.

It would be helpful to understand whether there are any local nuances in the critical infrastructure network in Roxburgh including any specific or non-standard interdependencies.

Table 1: Overview of potential gaps and issues for each phase and item in the assessment with key gaps in bold.

Phase	Item	Description	Dataset(s)	Potential Gaps/Issues
Hydrogeomorphic Modelling	Catchment characterisation	Geomorphological characterisation of catchments including main channel assessment and fan morphology. Also current and historic land use, vegetation type, and changes in vegetation.	— 2019, 2022, and 2024 LiDAR — 2017 Ortho Imagery — Recent and historic imagery (LINZ, retrolens). — GNS NZ Geological Map. — NZ Geotechnical Database — LRIS soil classification and LCDBv5. — Previous reports (Section 2.1.1).	— **2024 LiDAR hydrological conditioning for SH8 bridges and culverts.** — Digitisation/collation of previous inspection notes and photos. — Lack of subsurface geological data in the area will limit the geomorphological assessment of the debris fans.
	Hydrology	Hydrological assessment of catchments including calculating baseline flow, clear-water peak flows, and hydraulic capacity of existing infrastructure.	— NZTA RAMM database. — Previous reports (Section 2.1.1).	— **Geospatial information on existing mitigation structures, culverts, and engineered channels away from SH8.** — Digitisation of existing culverts and structures along SH8.
Risk Assessment	Hazard Frequency	Develop a hazard/frequency relationship for catchments.	— Hazard inventory collated from previous records and reports. — 2019, 2022, and 2024 LiDAR — Recent and historic imagery (LINZ, retrolens). — Trigger data (rainfall, seismic etc) — Previous reports (Section 2.1.1).	— **Limited historical data may influence the uncertainty of estimates, and particularly for considering climate change effects**.
	Buildings (including Social/Cultural and critical)	Buildings potentially exposed to debris flow hazards. This includes social/cultural and critical buildings as defined in APP6 (ORC, 2019).	— LINZ NZ Building outlines — GNS residential building dataset. — GNS vulnerability/fragility functions for buildings to hazards. — CODC Heritage Buildings	— Incomplete/outdated datasets. — Garages and other appurtenant structures are included in the datasets which may affect occupancy assumptions for assessment. This could be addressed once hazard extents have been derived by targeted GIS- and field-based truthing of the building datasets within the debris flow inundation areas.

Phase	Item	Description	Dataset(s)	Potential Gaps/Issues
				— Future planning zones are important for consideration of temporal changes in risk exposure.
	Lifelines	Exposed critical infrastructure including electricity, water supply, wastewater, transport, and telecommunications.	— LINZ NZ Road Centrelines 1:50k — LINZ NZ Bridge Centrelines 1:50k — Transpower Structures 1:50k. — CODC water asset shapefiles. — Vulnerability/impact models for lifelines.	— **Electricity distribution asset shapefiles (Aurora Energy).** — Telecommunications datasets. — **Roxburgh interdependencies.**
	People	Population data for Roxburgh.	— StatsNZ census data. — Vulnerability model for people. AGS (2007)	

4 CONCLUSIONS

- This report presents an overview of the proposed methodology and GAP analysis results as part of a debris flow risk assessment at Roxburgh for ORC.
- Initial gaps identified by WSP include:
    - An initial review of previous reports reveals that there is limited available data on past events in each catchment. A detailed historical record is crucial for establishing a frequency/magnitude relationship for debris flows. This will be a large focus for the initial characterisation of the catchments and training of the debris flow modelling. Further, there is little information on triggers for debris flows in Roxburgh.
    - The 2024 LiDAR 1 m DEM provided by ORC lacks hydrological corrections at SH8 debris flow channel crossings, which is essential for accurate debris flow modelling. ORC is coordinating with their surveyor to address this.
    - WSP has a solid grasp of mitigation structures along SH8, but additional data on other channels or roads would be useful.
    - Geospatial data from Aurora Energy on electricity distribution in Roxburgh is crucial for infrastructure risk assessment and outage predictions during debris flow events.
    - Understanding any unique interdependencies in Roxburgh's critical infrastructure network would be beneficial for the risk assessment.
- The effects of uncertainties need to be incorporated into the risk assessment and articulated in the results, e.g. the limited information on hazard frequency-magnitude relationships for the catchments, or uncertainty in the future use of land in areas susceptible to debris flow inundation.
- WSP will continue to work with ORC to fill gaps identified in this report through the subsequent phases of the project.

5 LIMITATIONS

This report ('Report') has been prepared by WSP New Zealand Limited ('WSP') exclusively for Otago Regional Council ('Client') in relation to the Phase 2 Gap Analysis and Method Definition ('Purpose') and in accordance with the Short Form Agreement for Consultant Engagement signed by Richard Saunders (Client) on 28 November 2024 and Richard Woods (WSP) 25 November 2024 ('Agreement'). The findings in this Report are based on and are subject to the assumptions specified in the Report and WSP's response to the Request for Proposal dated 04 October 2024. 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.

In preparing this Report, WSP has relied upon data, surveys, analyses, designs, plans and other information ('Client Data') provided by or on behalf of the Client. Except as otherwise stated in this Report, WSP has not verified the accuracy or completeness of the Client Data. To the extent that the statements, opinions, facts, information, conclusions and/or recommendations in this Report are based in whole or part on the Client Data, those conclusions are contingent upon the accuracy and completeness of the Client Data. WSP will not be liable for any incorrect conclusions or findings in the Report should any Client Data be incorrect or have been concealed, withheld, misrepresented or otherwise not fully disclosed to WSP.

6 REFERENCES

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de Vilder, S., Buxton, R., Allan, S., & Glassey, P. (2024). *Landslide planning guidance: reducing landslide risk through land-use planning.* Lower Hutt: GNS Science.

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PREVIOUS REPORTING

There have been several previous reports analysing debris flood and debris flow hazard in Roxburgh and the surrounding area over the last 20 years. These are briefly summarised below.

OTAGO ALLUVIAL FANS PROJECT

The 2009 Otago Alluvial Fans Project completed qualitative assessments of alluvial fans and associated hazards in Otago. This assessment included detailed hazard descriptions, mapping, annotated photos, and mitigation recommendations for eight catchments in Roxburgh (Opus, 2009; Barrell et al., 2009). This assessment concluded:

- Coalesced alluvial fan complexes have developed all along the base of the Old Man Range, from Roxburgh northwards. They are formed by a series of streams which appear small and insignificant under normal flow conditions; however, during floods they are capable of carrying significant volumes of debris including large boulders.
- The catchments slope between 7° and 20°, rising from 160 m at the valley floor to over 1,000 m on the Old Man Range. Vegetation includes tussock, matagouri, and briar. Landsliding has affected large areas, with debris including large schist blocks dislodged by streams during floods and deposited on the fans. Stream avulsion occurs during high-intensity rainfall events, and downstream erosion by the Clutha River helps maintain fan gradient and channel flow. The fan complex is classified as active, composite debris and floodwater dominated.
- Sheet floods occurred during storms in the 1970s and early 1980s, leading to engineering mitigation works such as enlarging stream channels and removing willow trees to reduce flooding risk. No reference to which catchments were modified is provided in Barrel et al (2009).

Woods (2011) completed a qualitative assessment of high-hazard alluvial fans in Otago, which included Reservoir Creek. The assessment featured annotated photos, historical imagery, GIS maps, and detailed descriptions of debris flood events, notably the 1978 event in Reservoir Creek. This assessment concluded:

- Reservoir Creek has deposited an alluvial fan onto older river terraces formed by the Clutha River. The Clutha River actively removes sediment and debris at the toe of the fan. This fan has been extensively modified by urban development and is bisected by State Highway 8 across the mid-fan.
- The upper catchment is dominated by small bushes and alpine tussocks, with no large forest areas. The slopes are covered by large-scale mass-movement features and highly weathered colluvial deposits actively eroded by the creek. The creek bed consists of unconsolidated debris deposits from adjacent slopes, deposited during debris-flow events, with the channel incising into these deposits afterward.
- The well-defined channel efficiently transfers debris and flood flows to the alluvial fan. Active slope instability is mainly due to over-saturation during storm events, causing slides and rock falls, as observed in October 1978.
- The channel within the fan area has been extensively modified by excavation and construction of concrete-lined channels to efficiently transfer debris floods to the Clutha River, preventing them from spreading into residential areas. These modifications were carried out by the Otago Catchment Board in 1980 and 1981, with further improvements after storm damage in 1983.
- The Reservoir Creek alluvial fan has experienced recurrent debris-flow events, notably in October 1978, impacting residential properties. Hazards associated with Reservoir Creek include high-velocity debris and debris-flood flows, channel avulsion, bank erosion, and floodwater sheet-flow inundation.

DAMWATCH. (2017). ASSESSMENT OF FLOOD AND EROSION HAZARDS IN THE CLUTHA RIVER

Following a significant debris flood event in several of the Roxburgh catchments in 2017 (see Section 2.2), DAMWATCH (2017) analysed the debris flood events and residual flood hazard levels for the Clutha River, supported by river bathymetry, cross-sections, and hydraulic modelling. This assessment concluded:

- The sediment lobes deposited in the Clutha River by Reservoir Creek and Black Jacks Creek due to the 26 November 2017 rainstorm event are the only ones that have significantly affected the water level profile along the river at these locations. This has caused the existing flood hazard to be increased slightly due to slightly elevated flood levels.
- The water surface profile past the confluence of an unnamed creek (that passes through the golf course), and the Clutha River indicates that minimal sediment deposition has occurred in the Clutha River from this unnamed creek due to the 26 November rainstorm.
- Other minor sediment lobes deposited in the Clutha River upstream of Reservoir Creek do not visually appear to project out very far into the main river, and in fact project less than the sediment deltas of other tributary creeks that were not affected to the same extent by the 26 November 2017 rainstorm event.
- Flood flows will gradually erode the sediment deposits over time, causing the increased flood and bank erosion hazards to slowly return to pre-26 November 2017 levels.

DELLOW ET AL. (2018). HAZARD AND RISK ASSESSMENT OF THE ROXBURGH DEBRIS FLOWS OF 26TH NOVEMBER 2017

Dellow et al. (2018) completed a hazard and risk assessment of the debris flows that occurred in Roxburgh following the high-intensity rainfall event in 2017. This report concluded:

- Thunderstorms with lightning and high-intensity rainfall occurred over Roxburgh on 26 November 2017, delivering 40-100 mm of rain in an hour and triggering debris flows in four stream catchments west of Roxburgh (Pumpstation, Reservoir, Golf Course, and Black Jacks).
- The debris flow in Reservoir Creek exceeded the channel capacity, causing silt and flood damage.
- Other creeks lack specific mitigation measures and were affected by blocked culverts and road blockages.
- January 2018 rainfall during cyclone Fehi remobilised debris in Black Jacks Creek, causing further accumulation.
- Debris flows are likely to reoccur due to remaining sediment and lack of vegetation.
- Engineering works, vegetation re-establishment, and education are recommended to mitigate debris flow hazard. Extreme rainfall intensity is the best indicator of potential debris flows.

GOLDER. (2019). MANAGEMENT AND REDUCTION OF DEBRIS FLOW RISK IN ROXBURGH, OTAGO

Golder (2019a) conducted a preliminary hazard assessment for five Roxburgh catchments, including field evaluations, catchment characterisation, potential channel sediment volumes, average return interval (ARI) estimations for debris flow events, and analysis of SH8 overtopping during significant rain events (Table 35). Golder (2019b) provided recommendations to mitigate debris flow hazards, such as increasing SH8 culvert capacity, regular channel excavation, armouring, constructing deflection and training levees, monitoring catchments, and conducting further risk assessments. These reports concluded:

- Two large debris flow events occurred in 1978 and 2017, linked to localized high-intensity rainfall. Damaging debris flow events affect Roxburgh every few decades.
- Increased erosion following 2017 debris flow events along creek banks from 600-700 m elevation downstream to debris fan areas, mostly due to shallow slope instabilities. Similar erosion increase occurred after the 1978 event, lasting a few years before the exposed sediment and landslide scarps became re-vegetated.
- Sediment for future debris flow/flood events is readily available in all catchments.
- Current SH8 crossings at Pumpstation Creek, Golf Course Creek, and Black Jacks Creek are not designed for peak flow events.
- Significant floods can reduce channel capacity, leading to avulsion and potential damage to dwellings, commercial buildings, and infrastructure.
- Reservoir Creek, Pumpstation Creek, and Golf Course Creek pose high life risks to adjacent dwellings, especially Reservoir Creek with a high probability of impacting multiple dwellings during avulsion events.
- Recommendations for mitigation to reduce debris flow hazard include:
  - Increasing culvert capacity will improve functionality during floods and small debris flow events but will not fully mitigate sediment aggradation and channel avulsion.
  - Effective risk reduction requires detailed assessment and design of a combination of site-specific mitigation measures.
  - Reducing surface water runoff in catchments will help decrease sediment erosion and the risk of debris flows/floods. Options include limiting grazing and encouraging widespread afforestation of unstable or erosion-prone hillslopes.
  - Conduct a detailed debris flow hazard and risk assessment, including cost-benefit analysis and hazard zonation, before the detailed design stage.
  - Regularly monitor slope instabilities at Pumpstation Creek and Golf Course Creek and regularly monitor creek channels for aggradation and changes in morphology.
  - Highway patrol crews should monitor creeks during adverse weather and implement preventative closures as needed.
  - Verify clear-water peak flow estimations by monitoring flows in at least one relevant creek before designing mitigation measures.
  - Consider an early-warning system using rainfall data and radar tracking to predict debris flows/floods and alert authorities.
  - Survey SH8 crossings for detailed hydraulic capacity assessment before designing mitigation measures.

It is noted in the table caption that the sediment volumes in Table 35 are based on estimated yield rates of each catchment, not including entrainment due to bank erosion and/or slope failure. This is different from our assessment which calculates debris flood volume considering other sources including bank erosion and slope failure and hence we have not compared these numbers.

Table 35: Overview of catchment information from Golder (2019a) study. Sediment volumes are presented based on estimated yield rates of each catchment, not including entrainment due to bank erosion and/or slope failure.

Creek	Channel characteristics	Estimated available channel sediment volume (m^3)	Type of crossing at SH8 (capacity m^3/s)
Pumpstation Creek	920 - 600 m asl: No evidence of recent erosion. 600 - 190 m asl: Slope instabilities, bank erosion, scour. 190 - 140 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 140 - 80 m asl: Debris fan, deposition of debris, bank erosion, scour.	18,000	Arched culvert (3.00)
Reservoir Creek	980 - 600 m asl: No evidence of recent erosion. 600 - 280 m asl: Slope instabilities, bank erosion, scour. 280 - 120 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 120 - 105 m asl: Debris fan, deposition of debris, bank erosion, scour. 105 - 85 m asl: Concrete channel. 85 - 78 m asl: Deposition of debris.	50,000	Trapezoidal concrete channel/bridge (266)
Golf Course Creek	980 - 650 m asl: No evidence of recent erosion. 650 - 220 m asl: Slope instabilities, bank erosion, scour, active landslide area at 330 – 220 m asl. 220 - 140 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 140 - 75 m asl: Debris fan, deposition of debris bank erosion, scour.	20,000	One circular culvert and one boxed culvert (1.18)
Black Jacks Creek	1,120 - 700 m asl: No evidence of recent erosion. 700 - 245 m asl: Slope instabilities, bank erosion, scour. 245 - 100 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 100 - 74 m asl: Debris fan, deposition of debris, bank erosion, scour.	24,000	Bridge (26)

Creek	Channel characteristics	Estimated available channel sediment volume (m^3)	Type of crossing at SH8 (capacity m^3/s)
Stevensons Creek	1,050 - 800 m asl: No evidence of recent erosion. 800 - 330 m asl: Slope instabilities, bank erosion, scour. 330 - 140 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 140 - 74 m asl: Debris fan, deposition of debris, bank erosion, scour, lateral levees from about 135 m asl.	33,000	Bridge (71)

QUAIL HAVEN SUBDIVISION HAZARD ASSESSMENTS

The Quail Haven Subdivision is exposed to debris floods from the Pumpstation catchment. Opus, 2004) conducted a geotechnical and hydrological assessment for the Quail Haven subdivision area and summarised the area's geological and hydrological characteristics. Further analysis of the area was completed by WSP in 2021 and 2024 which included a debris flood geotechnical assessment, catchment characterization, geological descriptions, and identification of likely breakout locations for debris flood events (WSP, 2024; WSP, 2021).

The WSP (2021) report included a summary of previous work, performed geotechnical analyses, and conducted a qualitative debris flood risk assessment for the Stage 2 subdivision area. The debris flood risk assessment estimated the likelihood, consequences, and risk of three scenarios using the methodology outlined in APP6 of the 2021 Otago Regional Council Policy Statement (ORC, 2021) (Table 36).

Table 36: The results of the debris flood risk assessment for Quail Haven subdivision (Pumpstation catchment) (WSP, 2021).

Risk Item	Likelihood	Consequence	Risk
Large debris colliding with houses (e.g., boulders)	Possible (once every 101 - 1000 years) e.g., 1 - 0.11% AEP	Moderate	Tolerable
Inundation of property with water and silt	Possible (once every 101 - 1000 years) e.g., 1 - 0.11% AEP	Major	Significant
Flood Inundation at the Farm Bridge	Possible (once every 101 - 1000 years) e.g., 1 - 0.11% AEP	Major	Significant

The WSP (2024) assessment involved HEC-RAS modelling for a channel profile of the Pumpstation catchment based on available 1 m LiDAR. The assessment concluded that future debris flood events from the Pumpstation catchment could likely inundate the subdivision, primarily due to potential blockages at the SH8 culvert. This study concluded:

- Multiple debris floods have contributed to the Pumpstation Creek fan, with an average recurrence of about 20 years for debris and hyper-concentrated flows that can overwhelm roads and damage infrastructure.
- Debris floods and hyper-concentrated flows from up-catchment can transition rapidly to hyper-concentrated and/or water flow types, suggesting high channel-overbank connectivity.
- Debris floods are unlikely to impact subdivision, but hyper-concentrated flows can be expected within 100-year timeframes, posing a hazard to on-fan development. The subdivision area north of the stream is at greater risk of inundation than the area south of the stream.
- Contemporary channel geometry is highly altered by debris management, with periodic sediment removal. The channel section between the bridge and ford has greater capacity and promotes sedimentation, reducing debris flood risk to the subdivision.
- Mitigation strategies that concentrate flows may adversely affect energy relationships downstream or upstream. Mitigation strategies that diffuse energy, such as channel setbacks, are recommended.
- Elevating foundations and reinforcing building walls can reduce residual risk. Routine monitoring and post-event reviews are recommended to ensure risks do not increase.

— Periodic clearance and maintenance activities should continue to keep the stream within its prescribed channel. Regular inspection is recommended to maintain flow regimes and prevent impacts on the State Highway culvert.

MACKEY. (2021). MANAGING ONGOING DEBRIS FLOW RISK IN ROXBURGH OTAGO

Mackey (2021) summarised the November 2017 debris floods and the implications of this event on future debris floods and mitigation strategies. This report concluded:

— The 2017 debris floods were primarily triggered by high flows scouring the channel bed, rather than discrete landslides, due to common topographic controls across the catchments.

— Since 2017, landslides have activated adjacent to deeply scoured channels, showing a strong connection between channel and hillslope processes.

— The Otago Regional Council (ORC) and other agencies have conducted remedial work, expert assessments, and ongoing monitoring of the channels.

This data is being used to explore various risk mitigation options.

APPENDIX B – GEOMORPHIC SUMMARIES AND MAPS

OVERVIEW

This section summarises the geomorphic characteristics of each catchment in the study area. Catchment maps including geomorphic mapping of debris flood sources and alluvial fan extents are provided. The 1 m LiDAR supplied by ORC was used to estimate the approximate elevation of features. A previous report (Golder, 2019a) completed geomorphic characterisation for Pumpstation, Reservoir, Golf Course, Black Jacks, and Stevensons catchments. For detailed geomorphic characterisation of these catchments the reader is referred to the Golder (2019a) report.

SLAUGHTERHOUSE

The Slaughterhouse Creek catchment, the northern-most catchment in this study, is located approximately 3 km north of Roxburgh township. The alluvial fan forms an extensive semi-circular cone and has deposited material onto an old Clutha River terrace; however, the active channel of the Clutha does not truncate the active fan. The alluvial fan has been developed with orchards and horticultural land with few residential and commercial buildings.

Above the fan apex (> 200 m elevation) the catchment is used as agricultural land featuring grassland for grazing and tussock land with small patches of native bush. The catchment has two main channels (north and southern branch) with smaller tributaries and gullies contributing to each. The middle catchment (200- 550 m elevation) is characterised by a steep and incised main channel, stream bank erosion, and landslides, with significant accumulated debris visible from aerial photographs (Map 1 - Appendix B). Entrained debris is present over the length of the stream bed below 550 m elevation and is concentrated in the middle catchment. This includes schist boulders and cobbles and is a potential source for future debris flood events. In some areas there is significant streambank erosion and landslides, particularly along the northern branch. Further, there are several areas with evidence of large-scale deformed slopes likely due to slow-moving and deep-seated landslides.

The upper catchment (>550 m elevation) is mostly tussock land and exposed schist outcrops. The main channels in this area are less steep and there are little signs of active erosion.

PN1 AND PN2

The PN1 and PN2 catchments, directly south of Slaughterhouse, are elongated catchments draining the north-eastern slopes of the Old Man Range. The alluvial fans for these catchments are currently used as orchards and horticultural land with few residential and commercial buildings.

The catchments are characterised by agricultural land, tussocks, and small isolated areas of native bush. There is very little visible debris entrained in the main channels of these two catchments and only small, isolated areas with evidence of recent streambank erosion and landslides (Map 2 - Appendix B). There is evidence for larger-scale deformed slopes, particularly in PN2 which could contribute material to future debris floods. Further, PN2 has two main channels that coalesce at the alluvial fan apex. These channels appear to have been redirected away from productive land.

PUMPSTATION

The Pumpstation Creek catchment and alluvial fan is located north of Roxburgh township with a catchment area of 2.68 km². The catchment has two channels where only the main creek channel to the South has shown recent debris flood or flow activities (Golder, 2019a).

The alluvial fan has a channel running along the true right slope, crossing SH8 through a culvert, and widening before reaching the Clutha River, with gradients flattening to about 5-6 degrees. The fan area has steep, shallow soils and significant human disturbance, particularly in the south due to earthworks (WSP, 2024). Surface deposits include skeletal soils with scattered boulders, and the adjacent farm block has less disturbed topography with closely grazed grass. The fan has been partially developed with residential buildings and properties particularly along SH8 and includes a water treatment plant.

From approximately 160 m elevation at the fan apex to the upper catchment (> 600 m elevation) the catchment is dominated by debris deposition, with a wider channel and visible scour and incision, and active landslides. The main channel contains boulders, cobbles, and gravel, and vegetation including shrubs and small trees. In this section there are multiple potential debris sources and significant debris deposited in the channel that could be remobilised during a future event (Appendix A).

The upper catchment features tussock grass terrain and a narrow creek channel with visible schist bedrock and vegetated tributaries, with no recent visible erosion. There are limited debris sources in the upper catchment, and it is unlikely that material from this section will contribute to future debris floods.

RN1

The RN1 catchment has an alluvial fan at the northern margin of Roxburgh township with the main channel crossing under SH8 parallel to Edinburgh Street. The alluvial fan has been developed with residential buildings and servicing infrastructure.

The catchment is relatively small (0.3 km^2) and is used as agricultural land. The main channel appears to be recently undisturbed and is vegetated with grass and small shrubs will only small sections of entrained debris closer to the fan apex. There appears to be frequent rockfall occurring in the catchment from schist outcrops; however, there are only small, isolated areas of recent or active streambank erosion. While this assessment highlights there is limited source material within this catchment, in 2017 this catchment had a debris flood event (described in Section 2.2.6), suggesting there is a potential for future debris flood risk.

RESERVOIR

The Reservoir Creek catchment is a steep, 10.4 km² area with small bushes and alpine tussocks, featuring a well-incised creek channel that actively erodes weathered colluvial deposits and efficiently transfers debris and flood flows to the alluvial fan. The creek has formed a semicircular alluvial fan on old Clutha River terraces, with concrete-lined sections directing debris floods away from residential areas, modified in the early 1980s and further improved after storm damage in 1983. The alluvial fan has been developed as a residential area with infrastructure, community buildings, and the Roxburgh Area School.

The middle catchment (280 - 700 m elevation) is characterised by steep slopes, exposed bedrock, with common soil slips, slumping, shallow and deeper-seated potentially relict landslides. In places there is significant scour and incision into older deposits which are diverted by natural barriers and farm access tracks.

The upper catchment (> 700 m elevation) features tussock grass terrain with a narrow creek channel and visible schist bedrock, showing few erosional features. Mapped geomorphic features in this area of the catchment are minimal with a few small landslides and deeper-seated landslides identified in the LiDAR.

GOLF COURSE

Golf Course Creek drains the east-facing slopes of the Old Man Range, with its main channel crossing both the old and current SH8 before passing through a local golf course and reaching the Clutha River. The alluvial fan has a channel 3-5 m wide, crossing SH8 through culverts, and reaching the Clutha River, with recent debris deposition and levees channelising the creek. North of the main channel and to the west of SH8 there is a small residential development on the fan while the rest of the fan is mostly comprised of the golf course.

The middle catchment (180 – 650 m) is characterised by steep slopes with exposed bedrock, undercut slopes, active soil slips, landslides, and bank erosion. In some sections there is significant scour, incision, and bank erosion with boulders up to 2 m in diameter identified in the channel (Golder, 2019a). There is a large landslide (~10,000 m^2) in this section of the catchment which likely mobilised following the 2017 rainfall event.

The upper catchment (> 650 m elevation) features tussock grass terrain with an incised channel up to 15 m deep, containing boulders and cobbles.

GS1 AND GS2

The GS1 and GS2 catchments are directly south of the Golf Course Creek catchment. The main channel of the GS1 catchment joins the Golf Course main channel on the alluvial fan at approximately 100 m elevation. The alluvial fan for GS1 includes the southern extent of the golf course and a small residential development along SH8. The GS2 alluvial fan is 400 m south of GS1 and has been developed as an orchard with servicing infrastructure and buildings.

The catchments are primarily used as agricultural land with tussocks, and small isolated areas of native bush. The main channels appear to be recently undisturbed and are vegetated with grass and small shrubs will very little evidence for entrained debris in the channel, recent streambank erosion, or landslides.

BLACK JACKS

Black Jacks Creek drains the east-facing slopes of the Old Man Range, with its main channel on the fan fed by two central tributaries and one south branch. The alluvial fan has a creek bed 10-15 m wide, incised up to 5-6 m into older deposits, and crosses SH8 before reaching the Clutha River. There is no current residential or commercial development on the fan.

Golder (2019a) divided Black Jacks Creek into several sections across its South Branch, Central Tributaries, and North Branch:

- The South Branch features tussock grass and schist bedrock outcrops, with channels incised up to 10-15 m and slopes steeper than 10-15 degrees.
- The Central Tributaries have gently sloping terrain with channels less than 5 m wide, showing soil slips and erosion.
- The North Branch includes tussock grass, schist bedrock outcrops, and channels up to 5-10 m wide, with increased bank erosion and soil slips.

Typically, the north branch displays more evidence than other branches for potential debris sources with numerous scarps, incision, and erosion. Additionally, several deeper-seated landslides have been mapped along the north branch.

The upper catchment (>750 m elevation) shows little signs of active erosion and is dominated by tussock and exposed schist.

BS1 AND BS2

The BS1 and BS2 catchments are relatively small catchments directly north of Stevensons catchment. The alluvial fans have been primarily developed as orchards and horticultural land with servicing infrastructure and buildings.

The catchments are primarily used as agricultural land with tussocks, and small isolated areas of native bush. The main channels appear to be recently undisturbed and are vegetated with grass and small shrubs will very little evidence for entrained debris in the channel, recent streambank erosion, or landslides. There is evidence for areas of deformed slopes indicated by steep headscarp areas and slumped land in the LiDAR.

STEVENSONS

Stevensons Creek drains the east-facing slopes of the Old Man Range, and includes two northern tributaries and one southern branch, which joins the main channel at approximately 230 m elevation. The alluvial fan extends over pasture and horticultural land, crosses SH8, and eventually reaches the Clutha River. The alluvial fan has an 8-degree slope, with a channel incised 1-2 m into older deposits with levees built to protect farmland and recent debris removal to increase capacity.

The South Branch features tussock grass and schist bedrock outcrops, with channels incised up to 20 m and slopes steeper than 10-15 degrees, showing soil slips and slumping (Golder, 2019a).

The North Branch has gently eastward-dipping topography with channels 2-5 m wide, showing no noticeable erosion in the upper sections but increased rockfall and debris deposition in steeper sections.

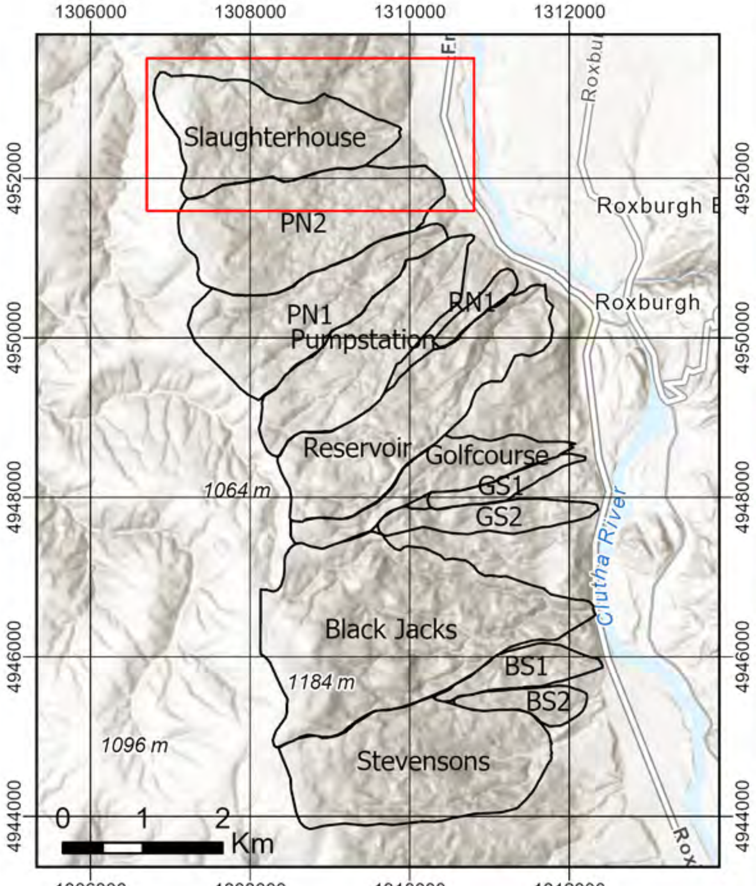
There is a large landslide (~25,000 m^2) to the north of the northern branch with a head scarp at approximately 550 m elevation. This appears to have developed since the 2017 intense rainfall event.

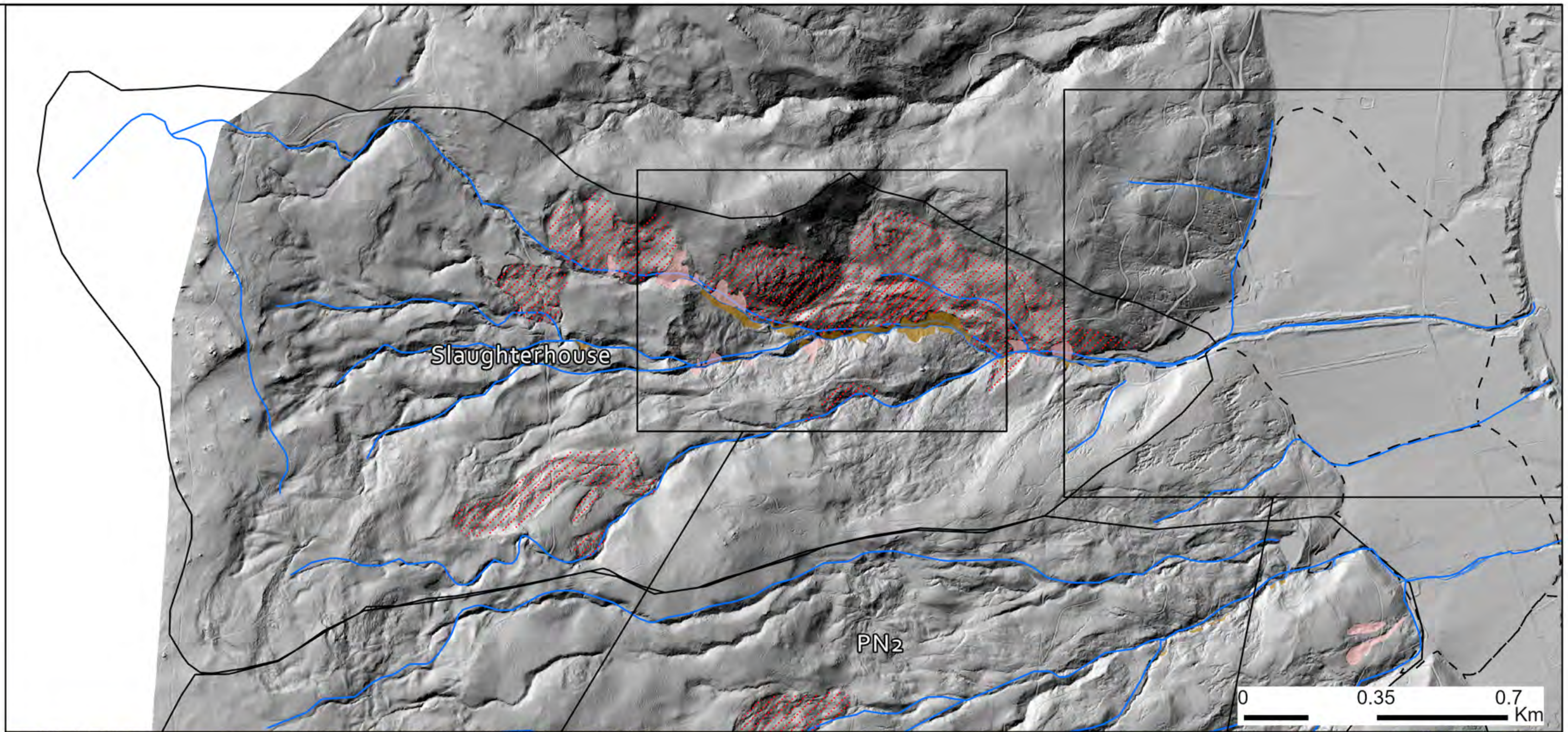
GEOMORPHOLOGICAL MAPS

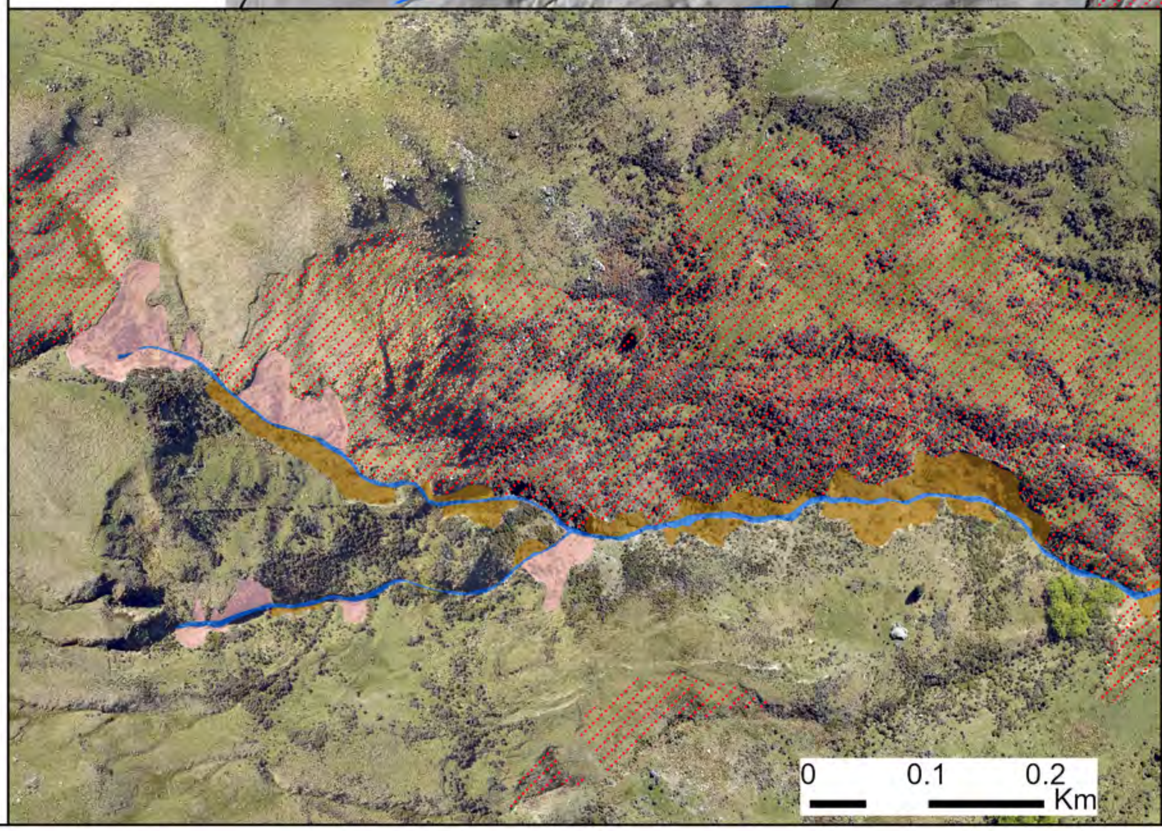
Slaughterhouse Creek

Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Alluvial Fan
- Catchment
- Channel







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wsp

Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - Slaughterhouse Creek

Map 1 of 10

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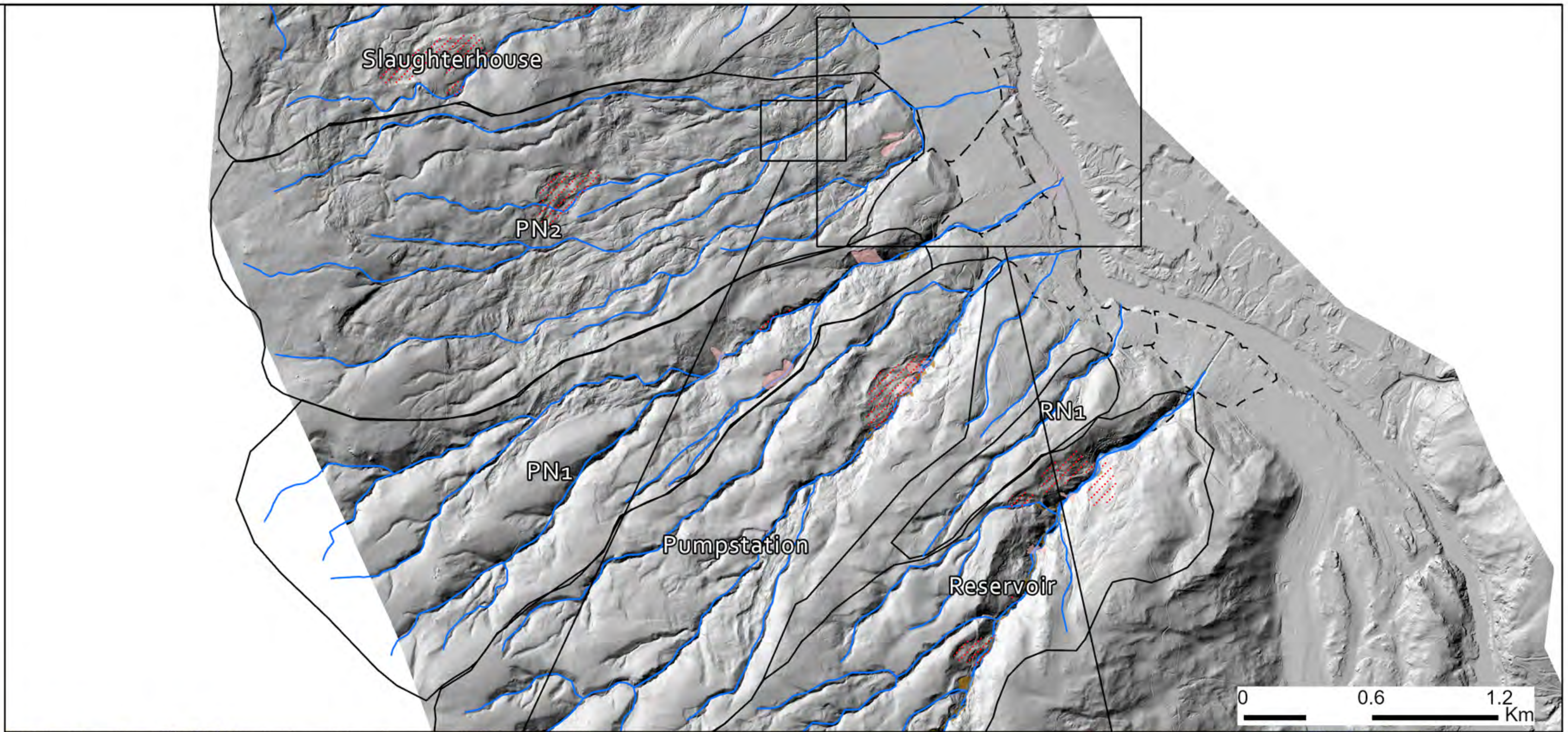
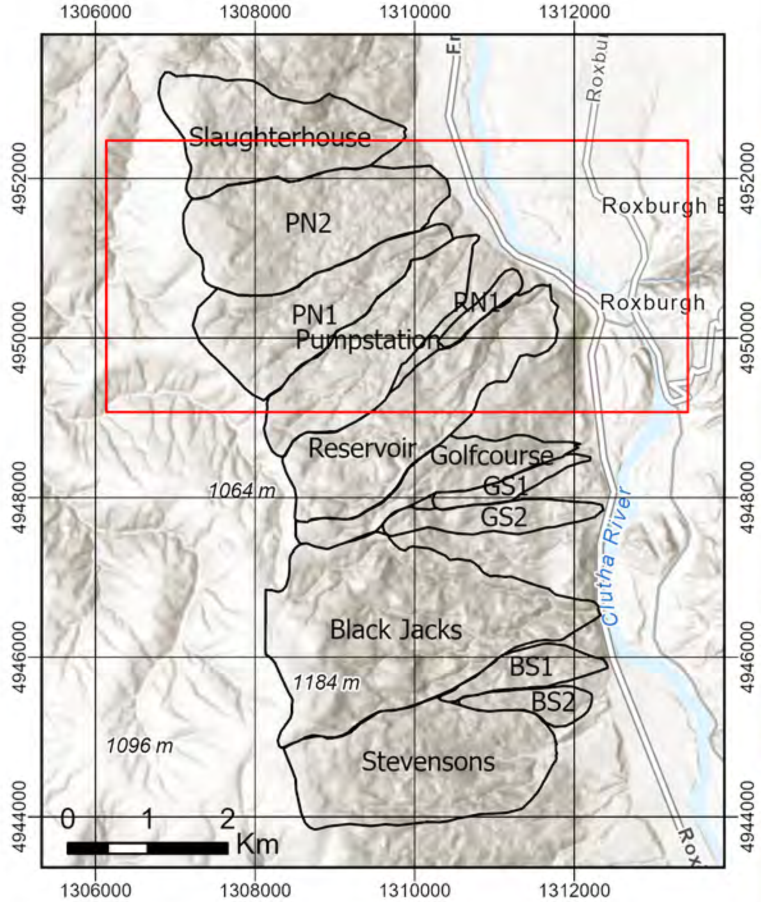
N W E S

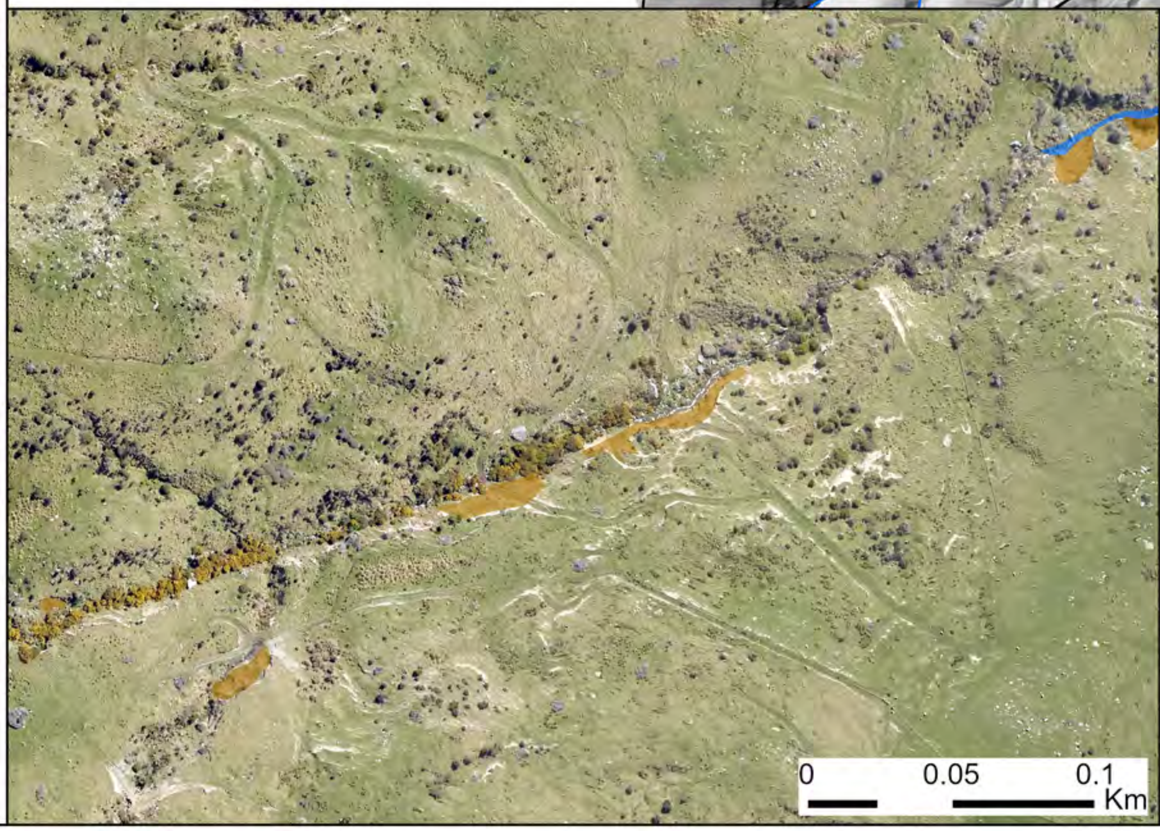
PN1 and PN2

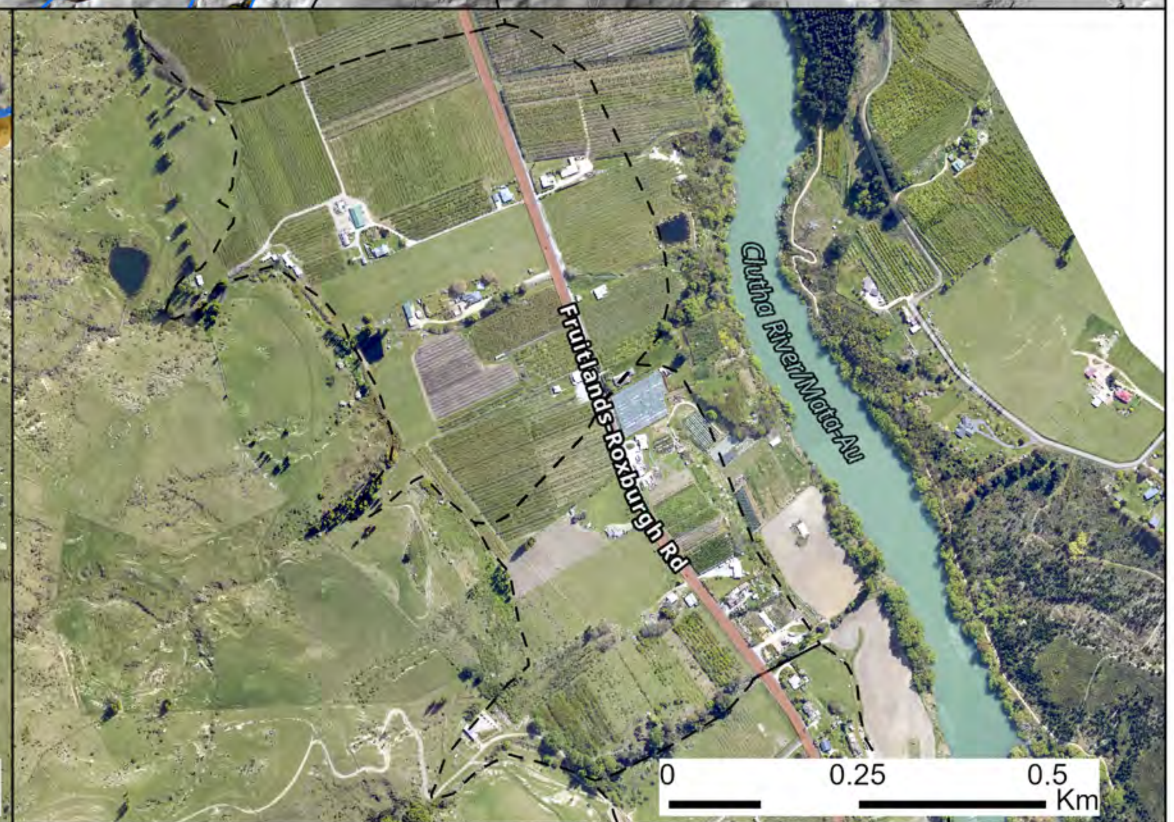
Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel









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wsp

Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - PN1 and PN2

Map 2 of 10

Project: 1-E0173.00

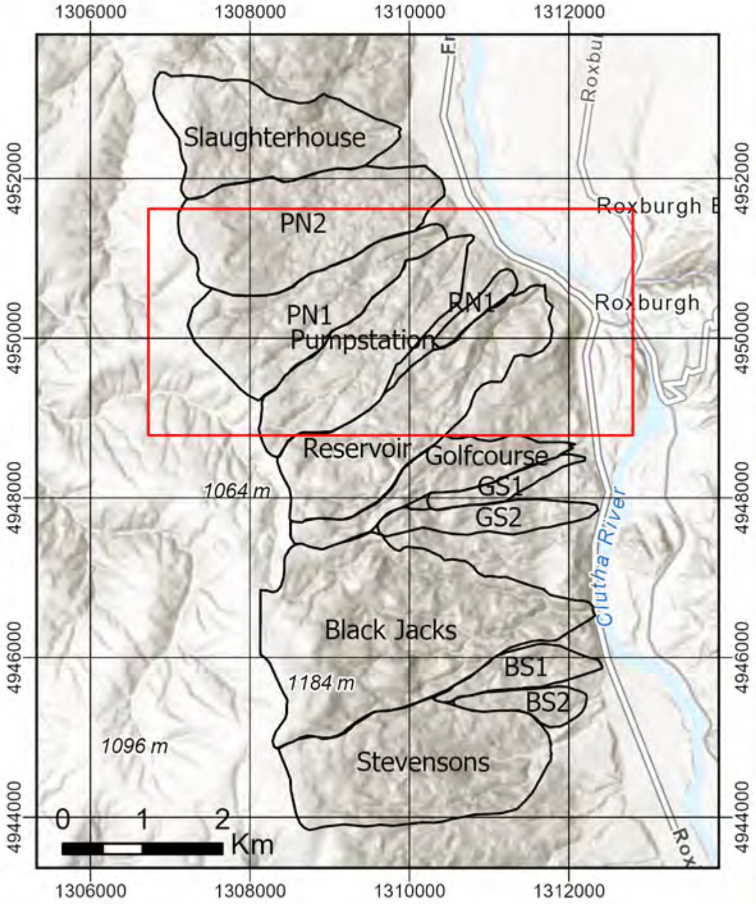
Date: 30/04/2025

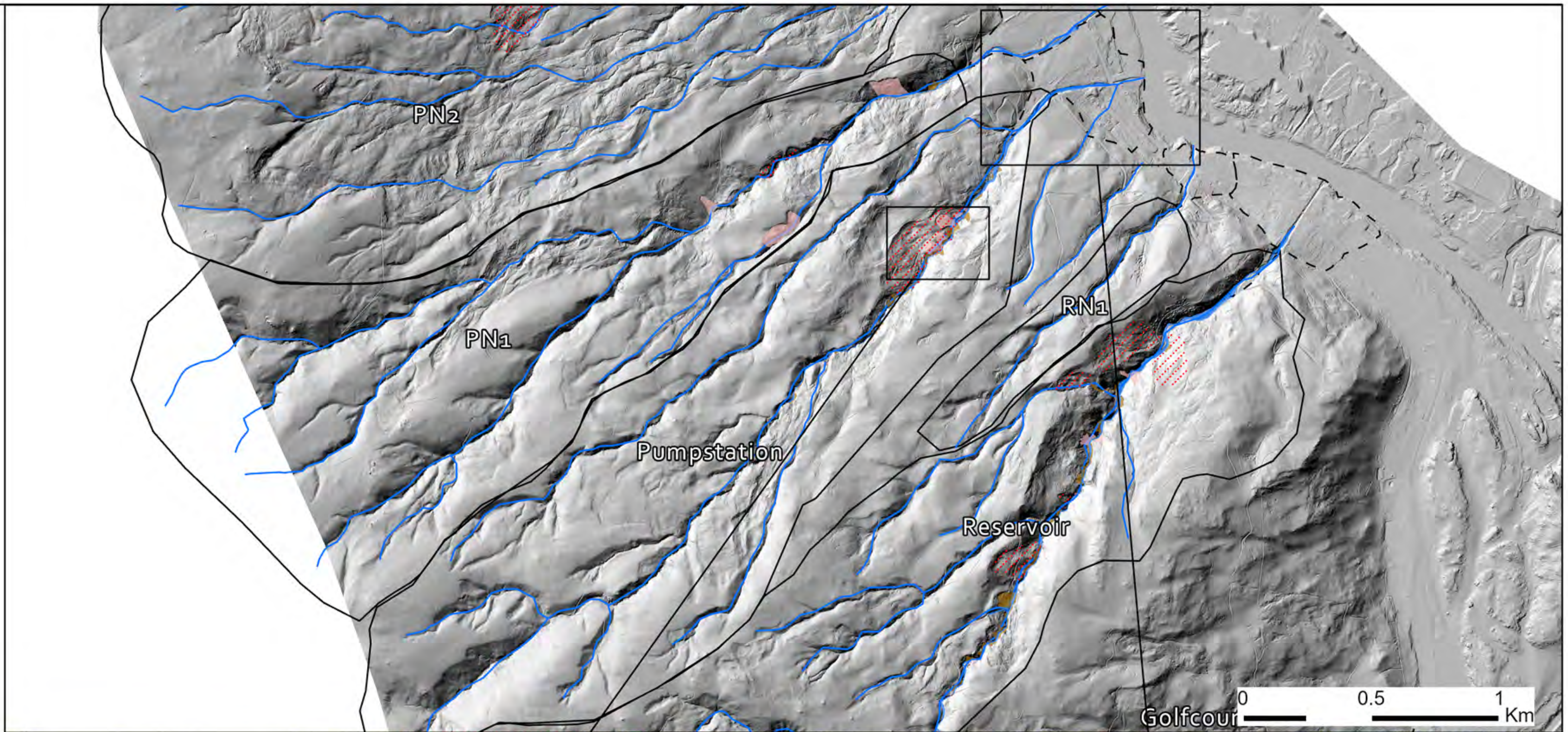
N W E S

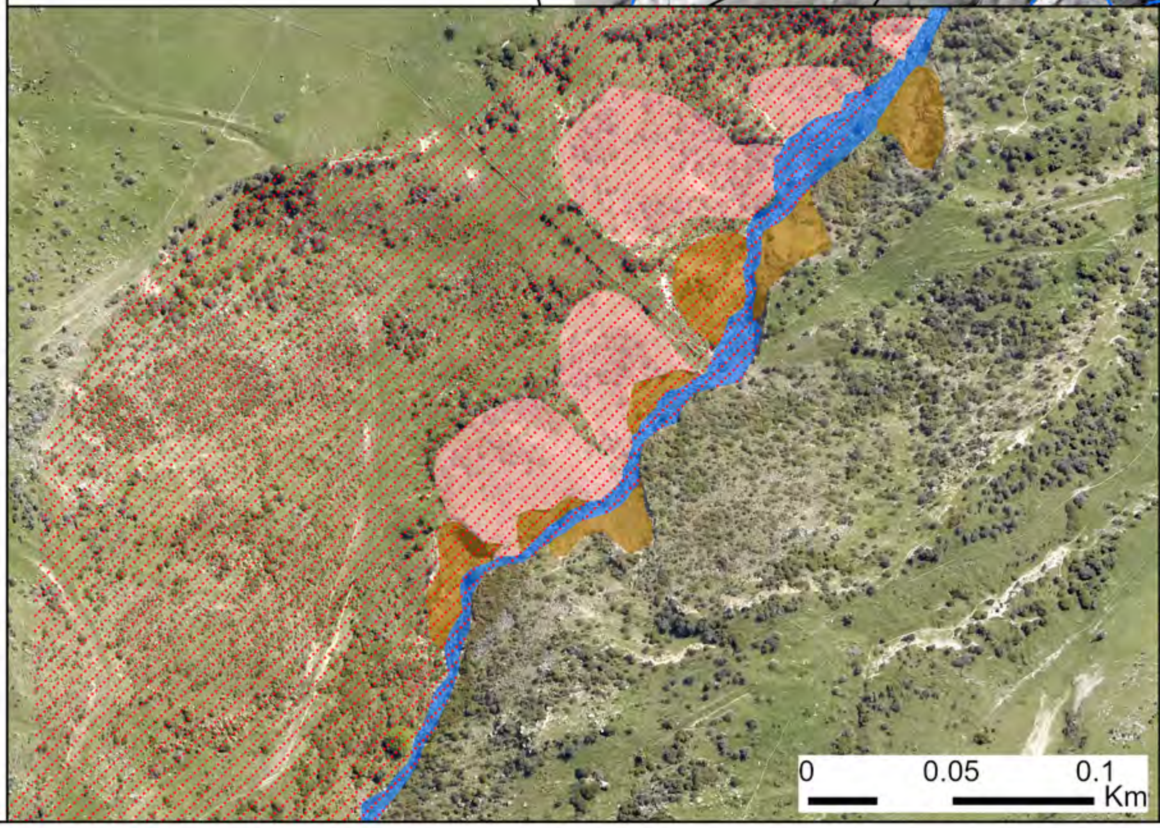
Pumpstation Creek

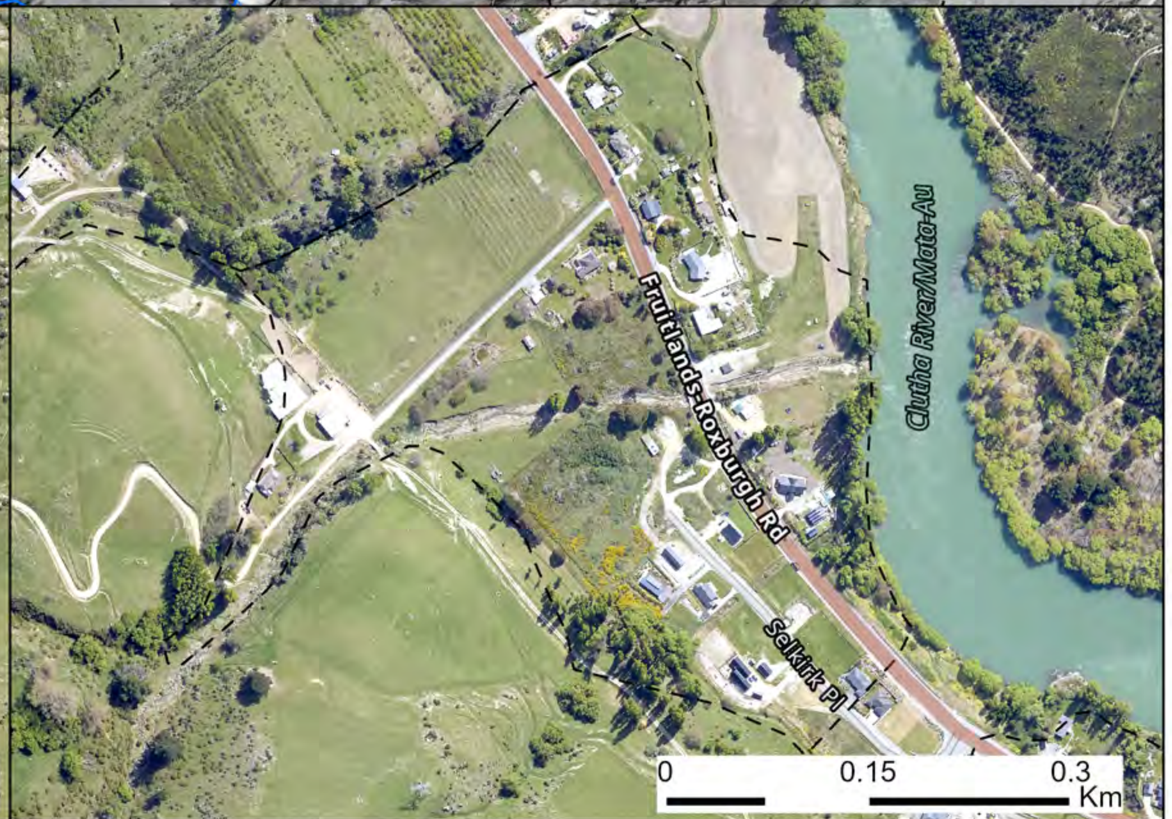
Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel









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wsp

Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - Pumpstation Creek

Map 3 of 10

Project: 1-E0173.00

Date: 30/04/2025

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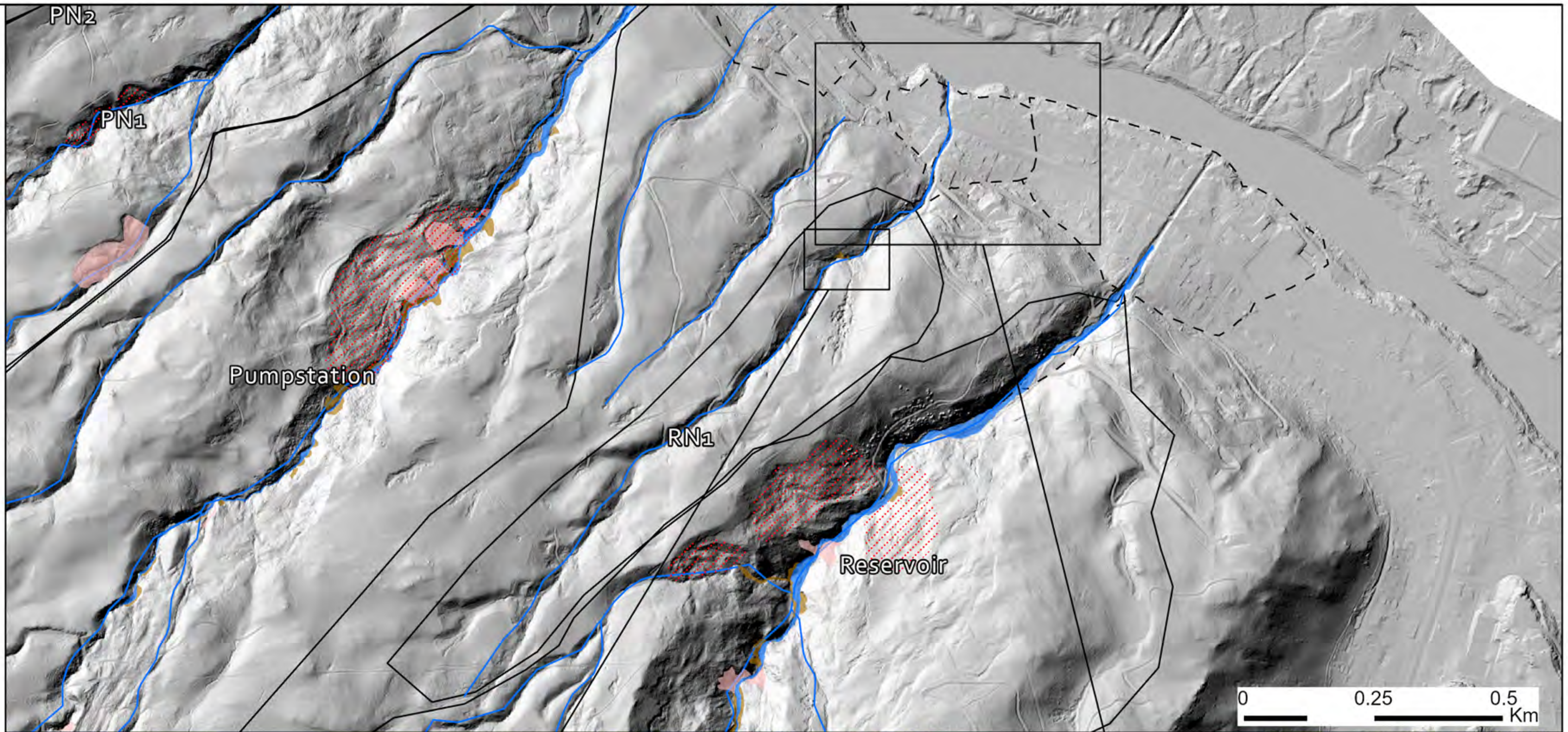
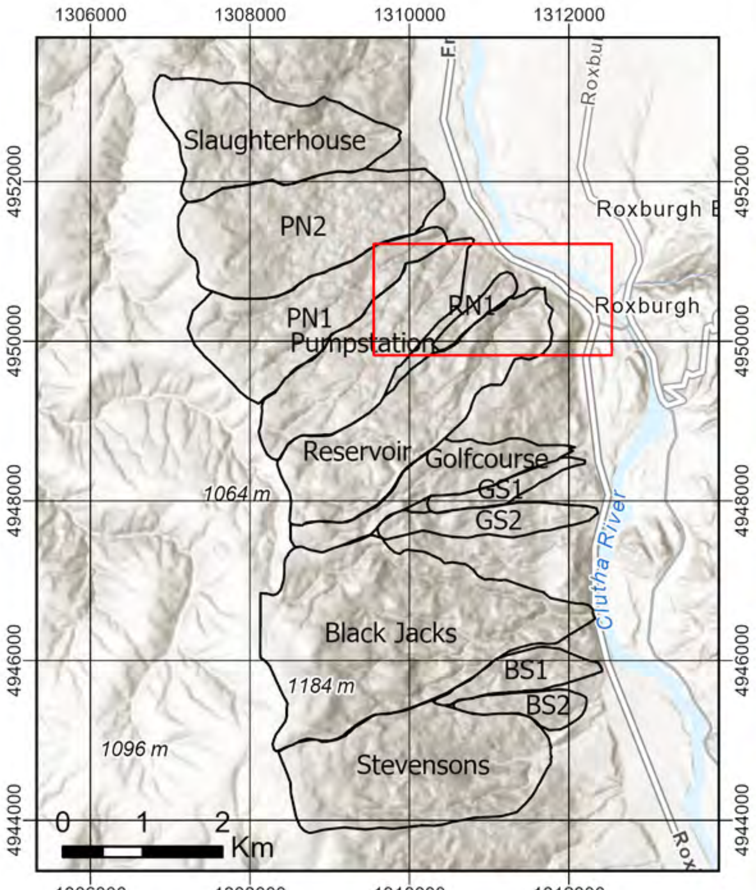
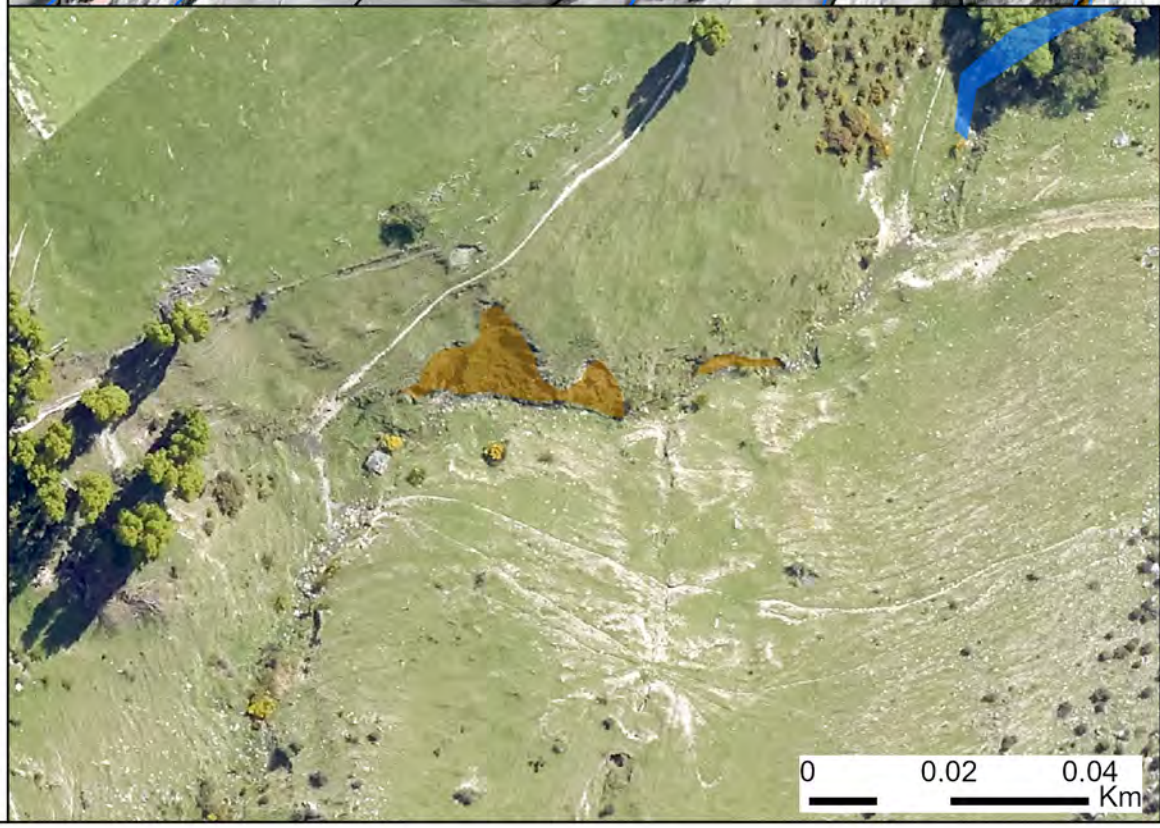
RN1

Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel







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Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - RN1

Project: 1-E0173.00

Date: 30/04/2025

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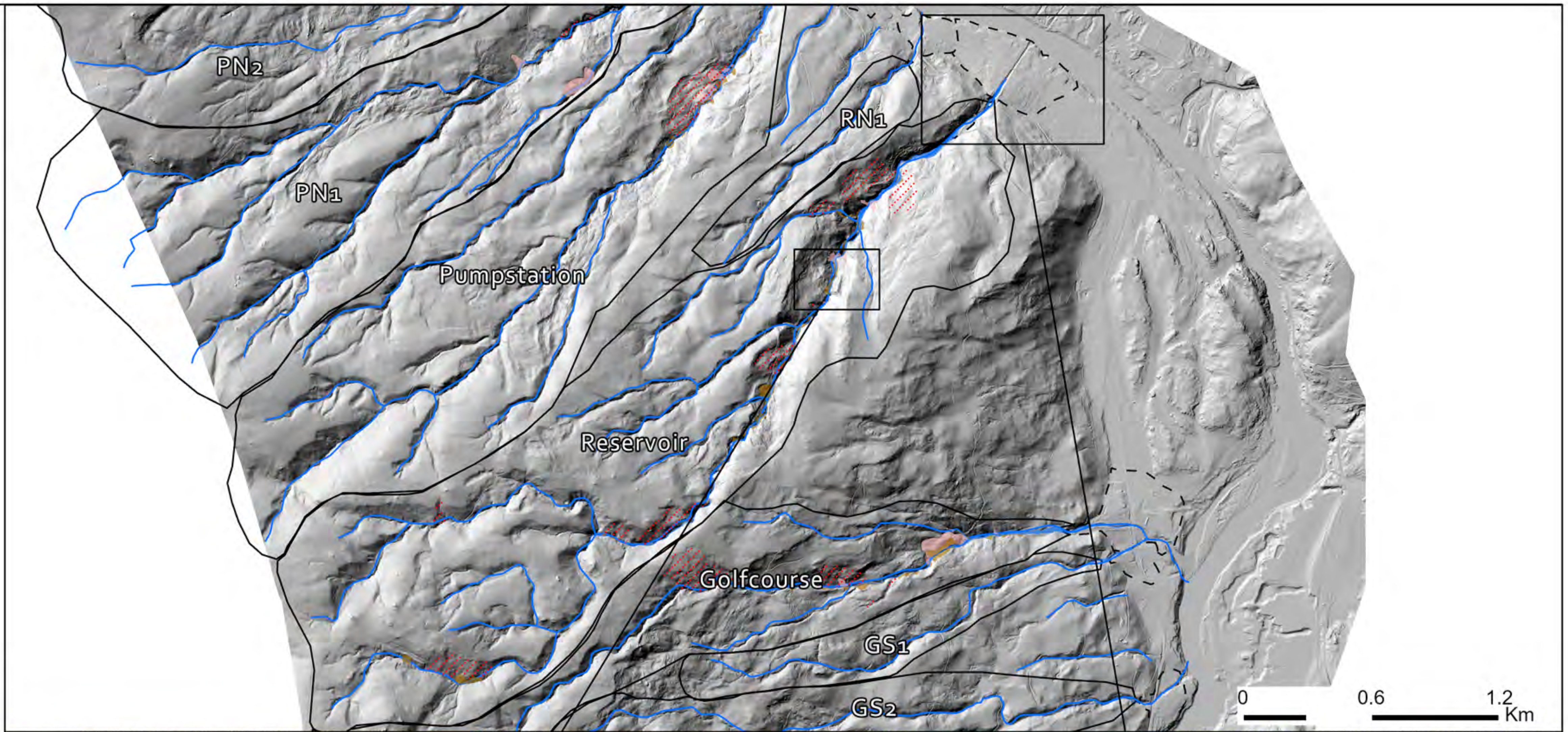
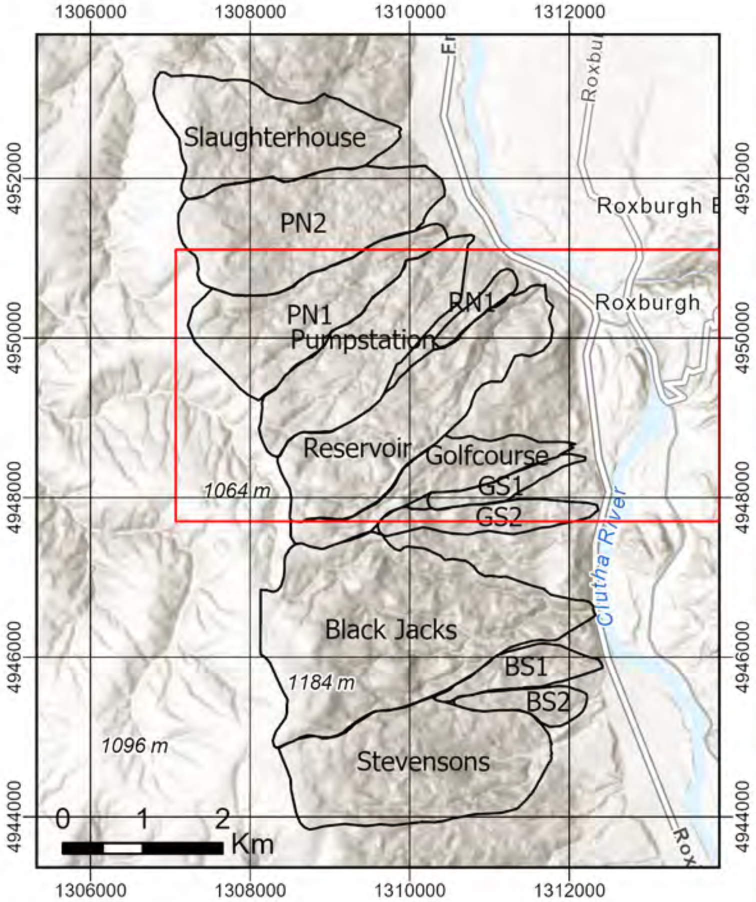
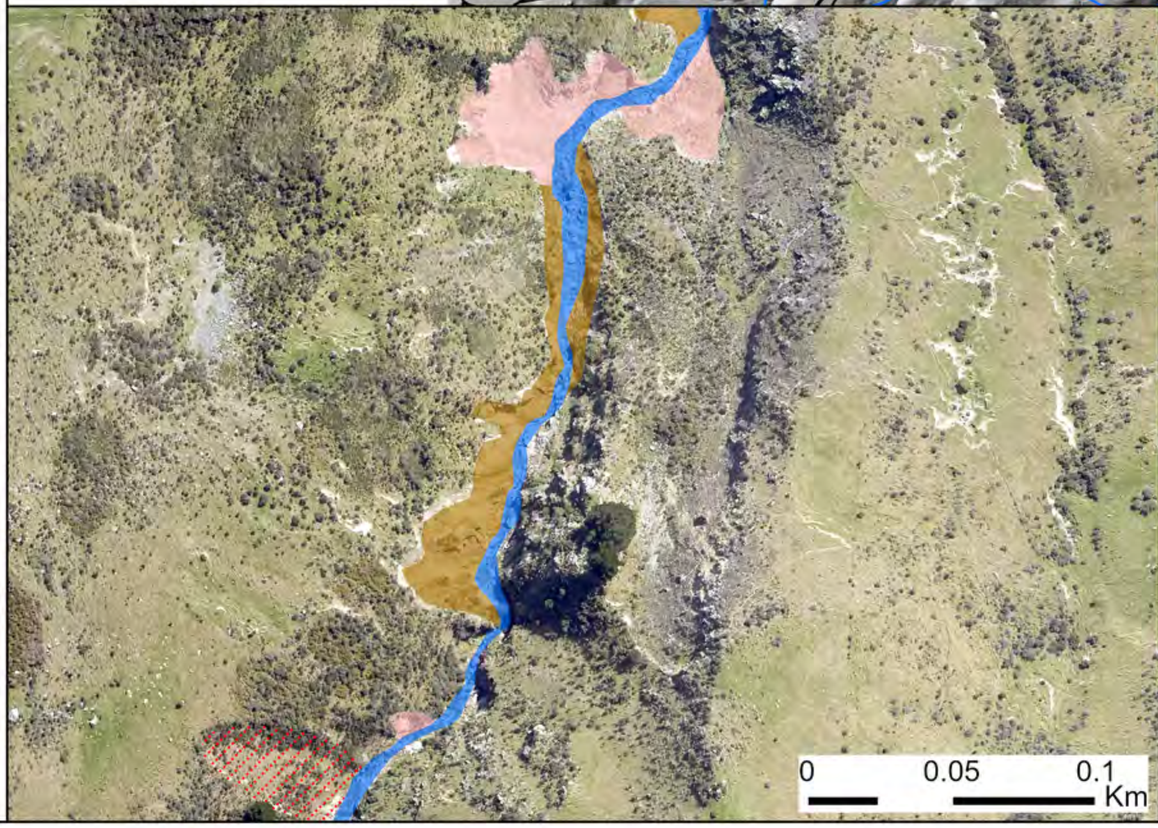
Reservoir Creek

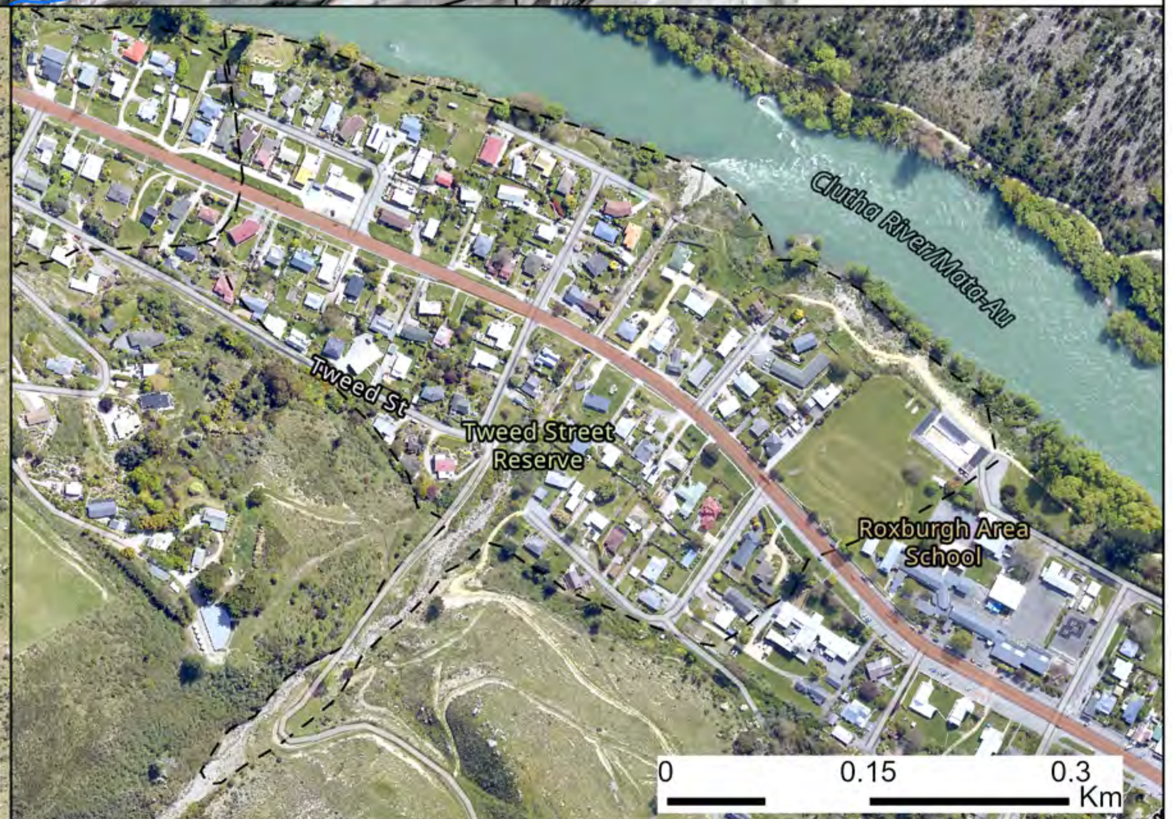
Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel









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Geomorphological Mapping - Reservoir Creek

Map 5 of 10

Project: 1-E0173.00

Date: 30/04/2025

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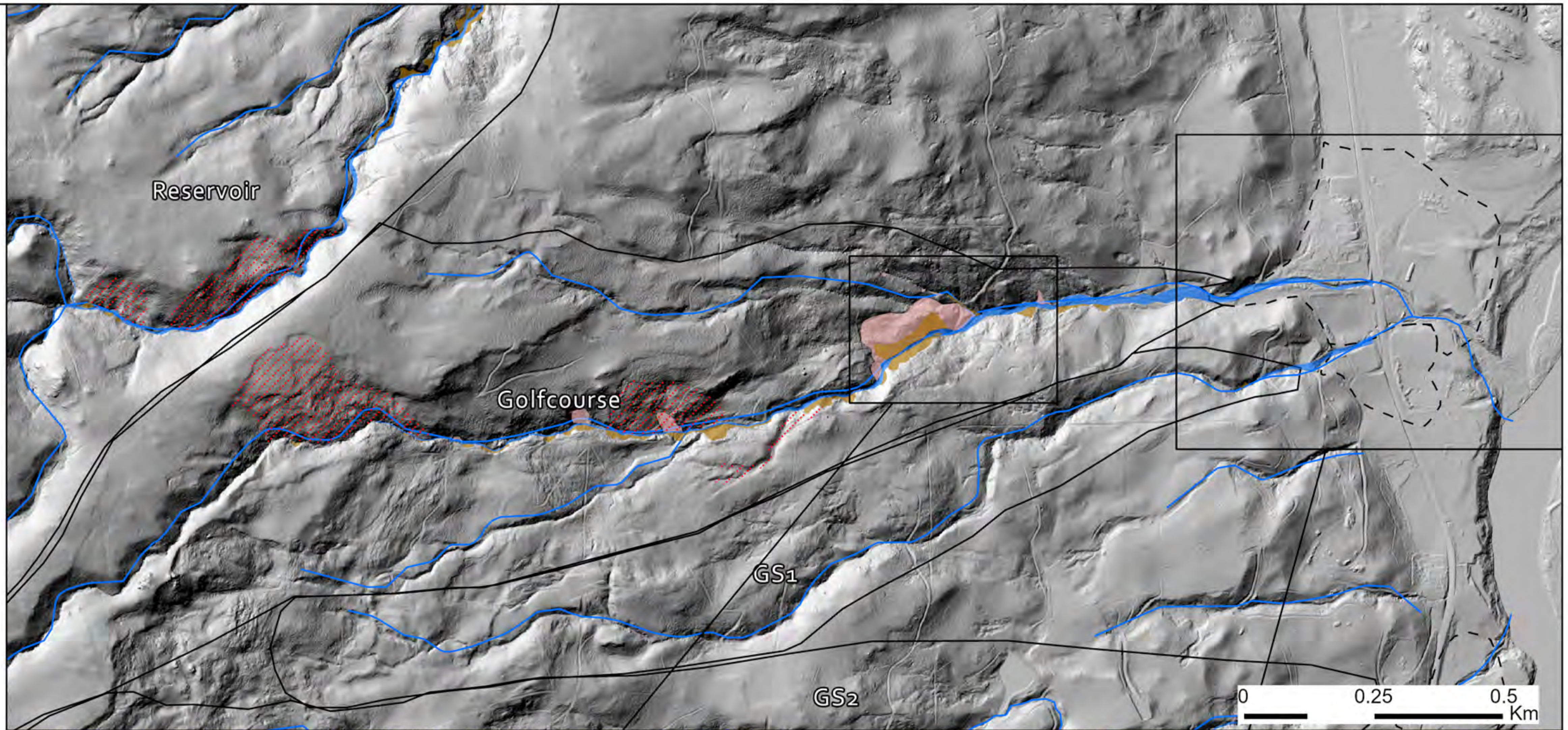
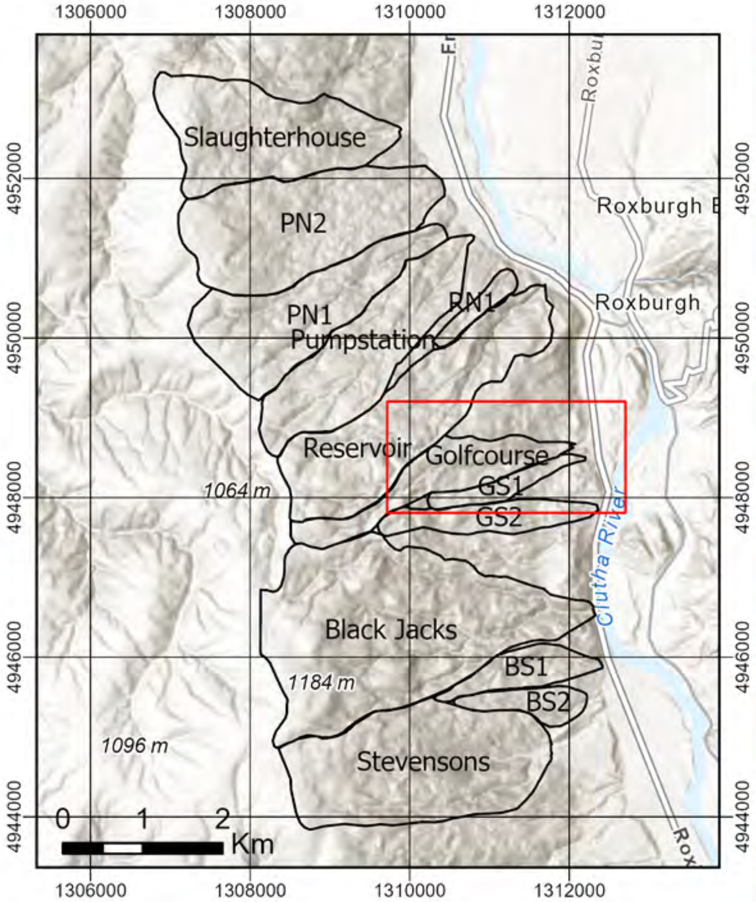
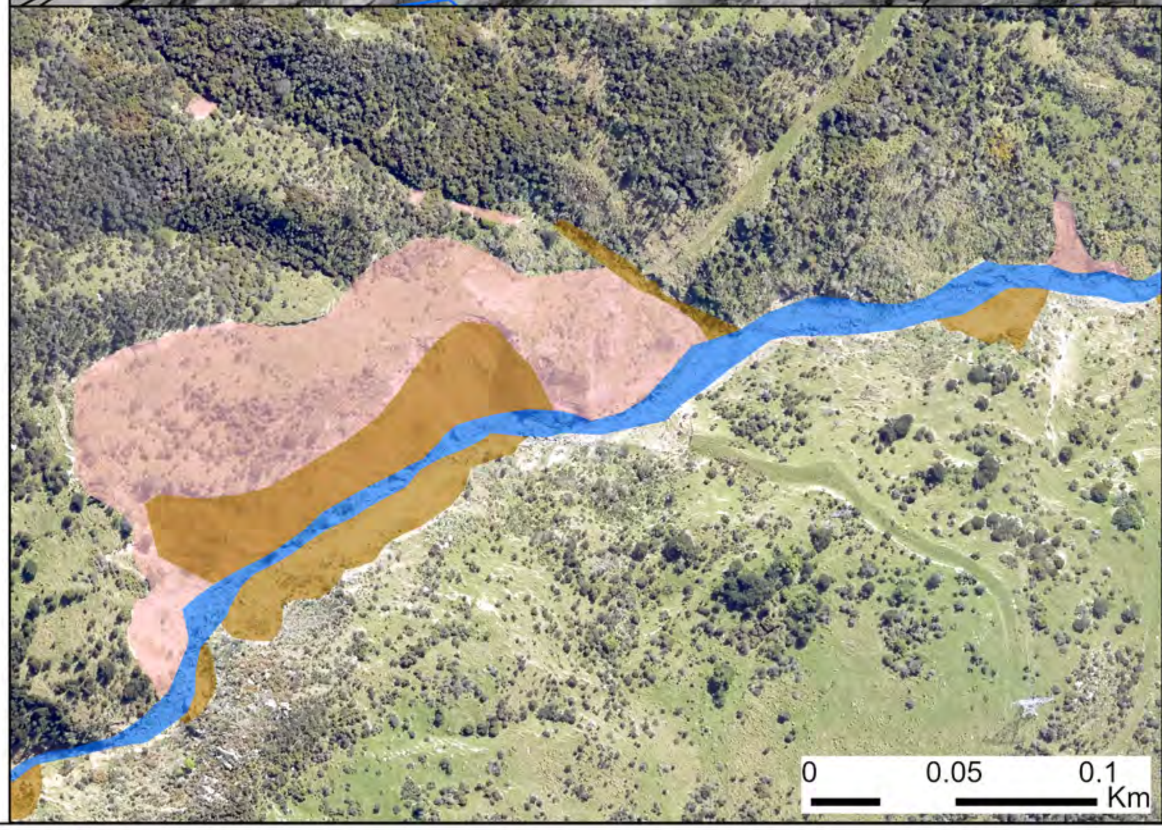
Golf Course Creek and GS1

Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel







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Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - Golf Course Creek and GS1

Map 6 of 10

Project: 1-E0173.00

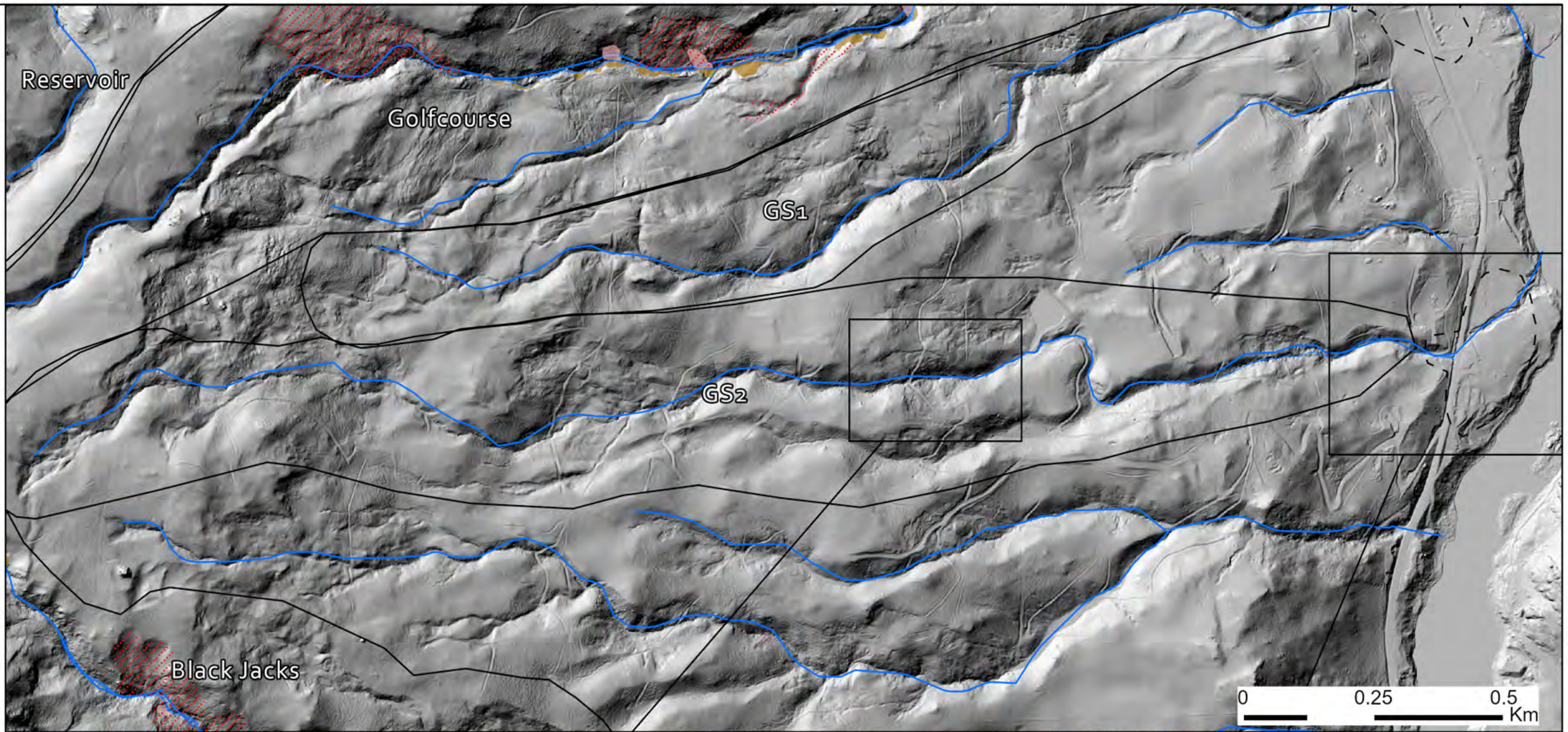
Date: 30/04/2025

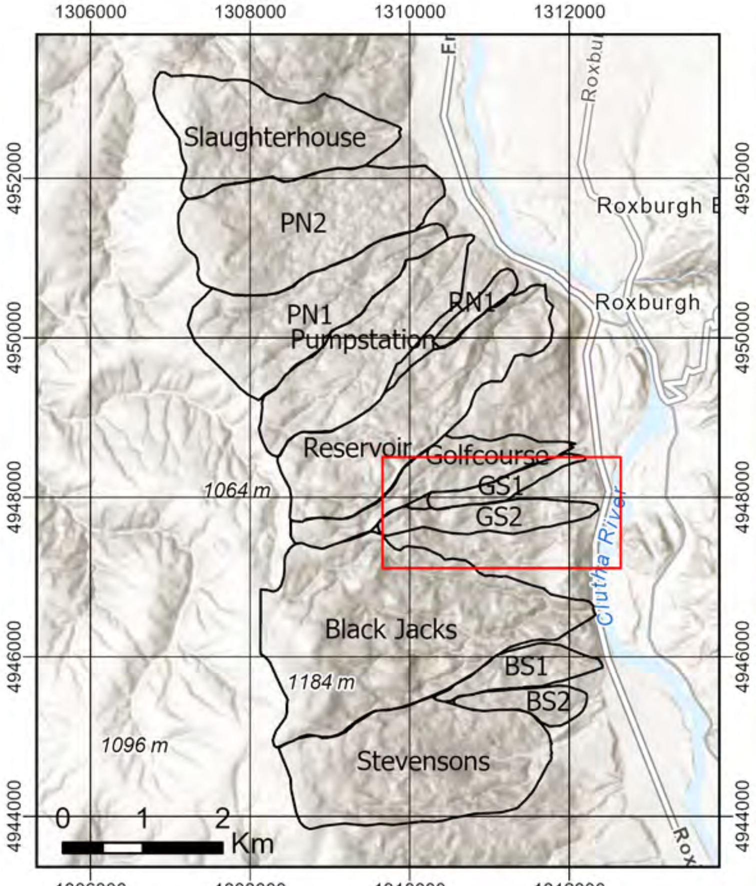
N W E S

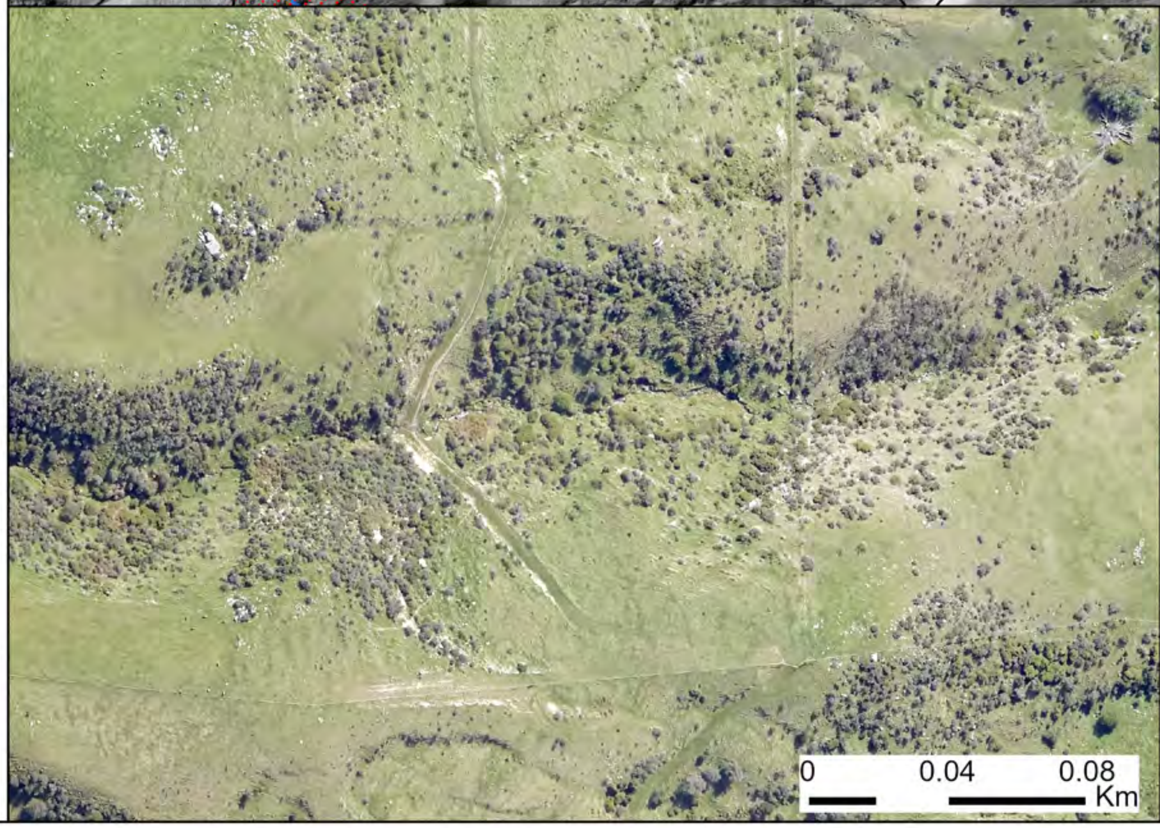
GS2

Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel







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Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - GS2

Map 7 of 10

Project: 1-E0173.00

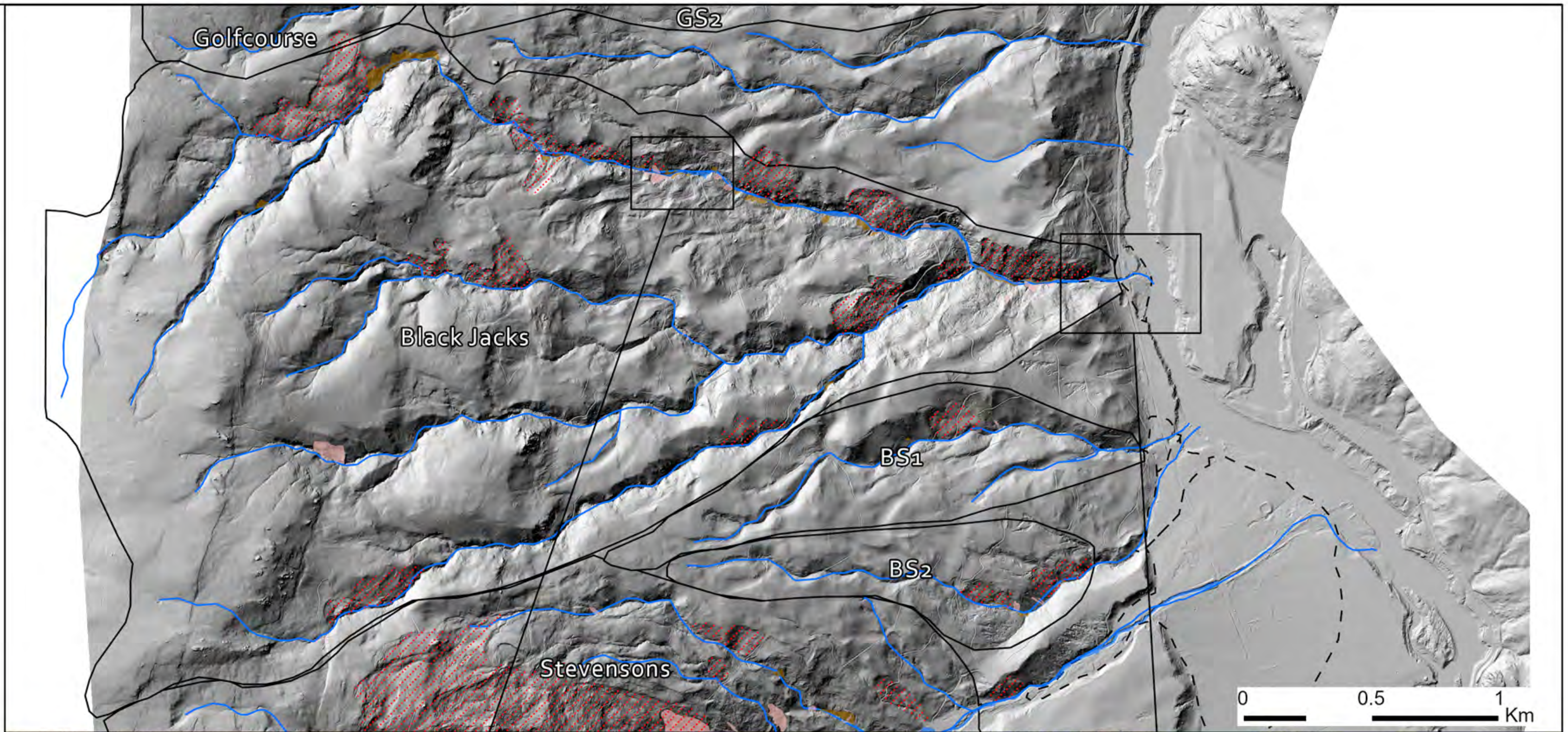
Date: 30/04/2025

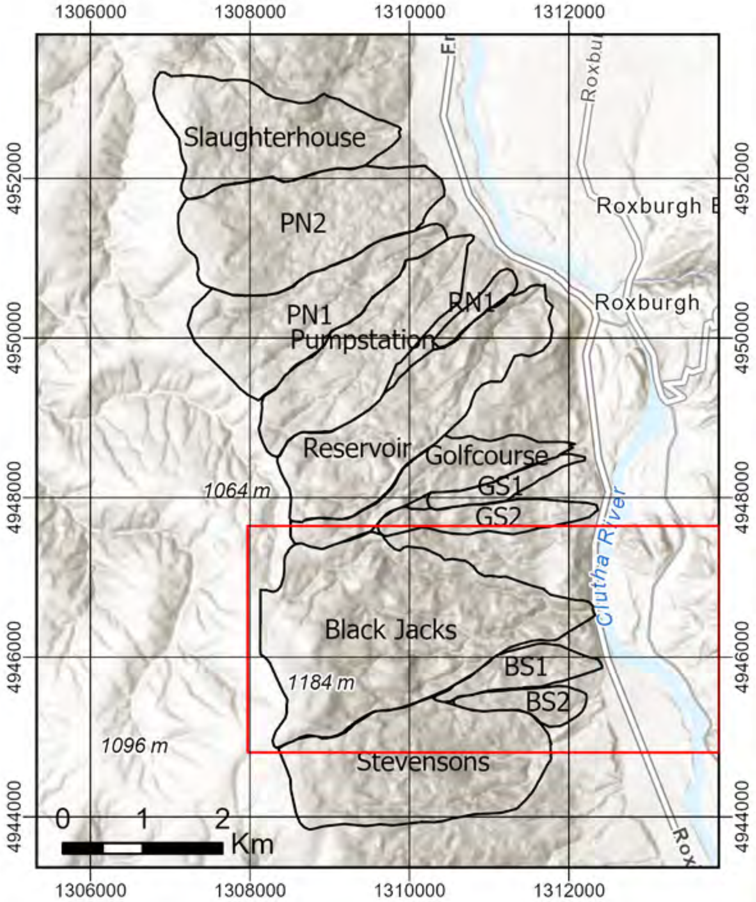
N W E S

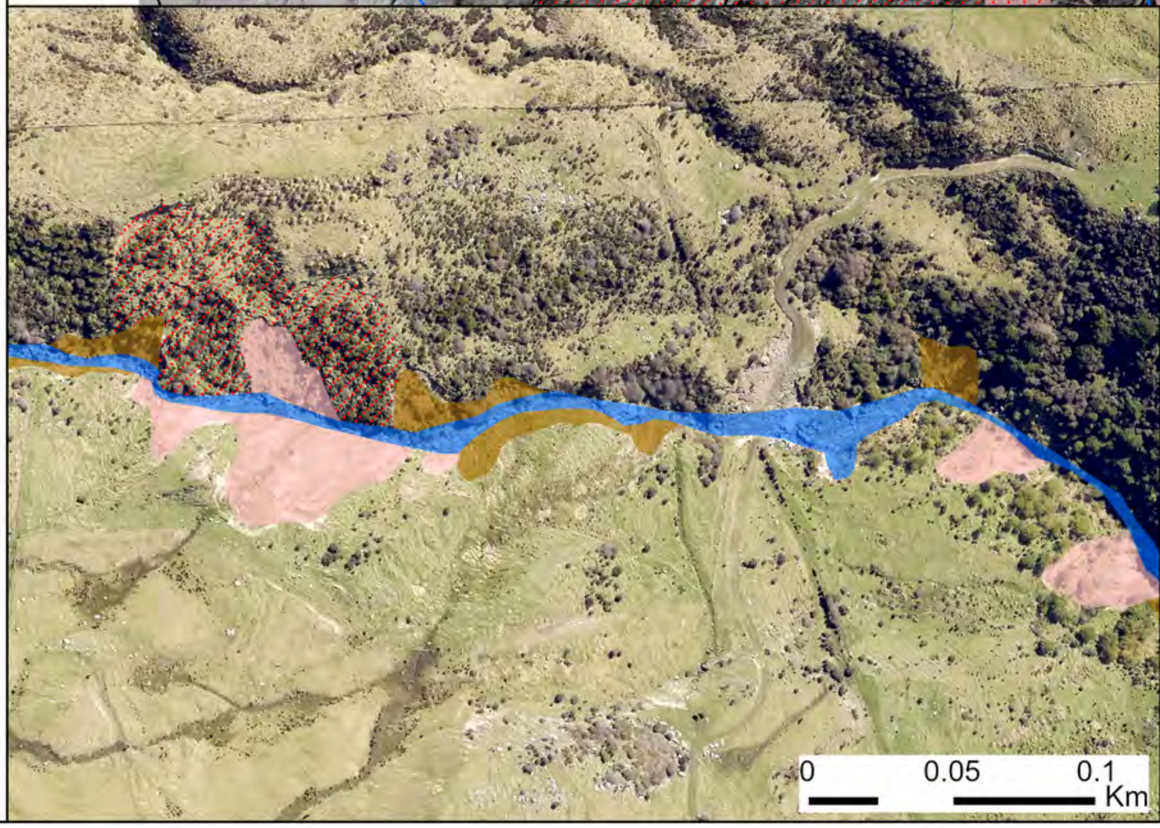
Black Jacks Creek

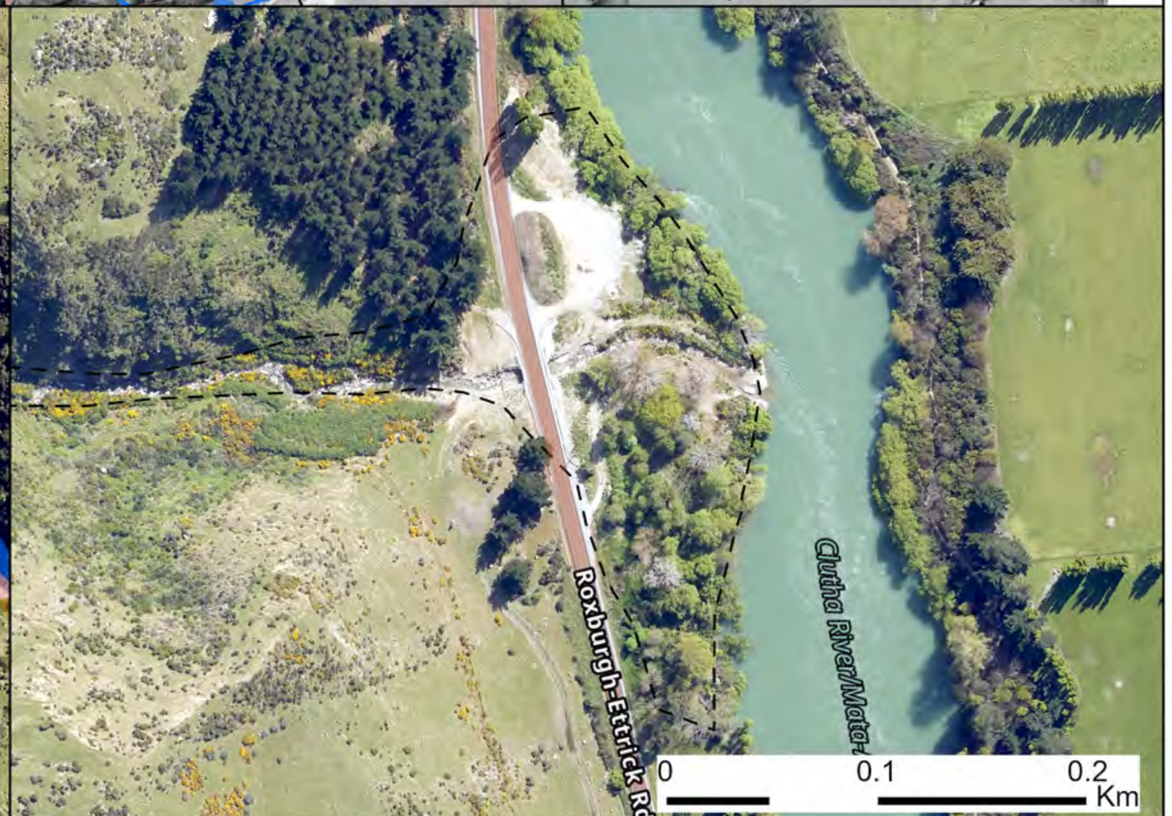
Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel









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wsp

Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - Black Jacks Creek

Map 8 of 10

Project: 1-E0173.00

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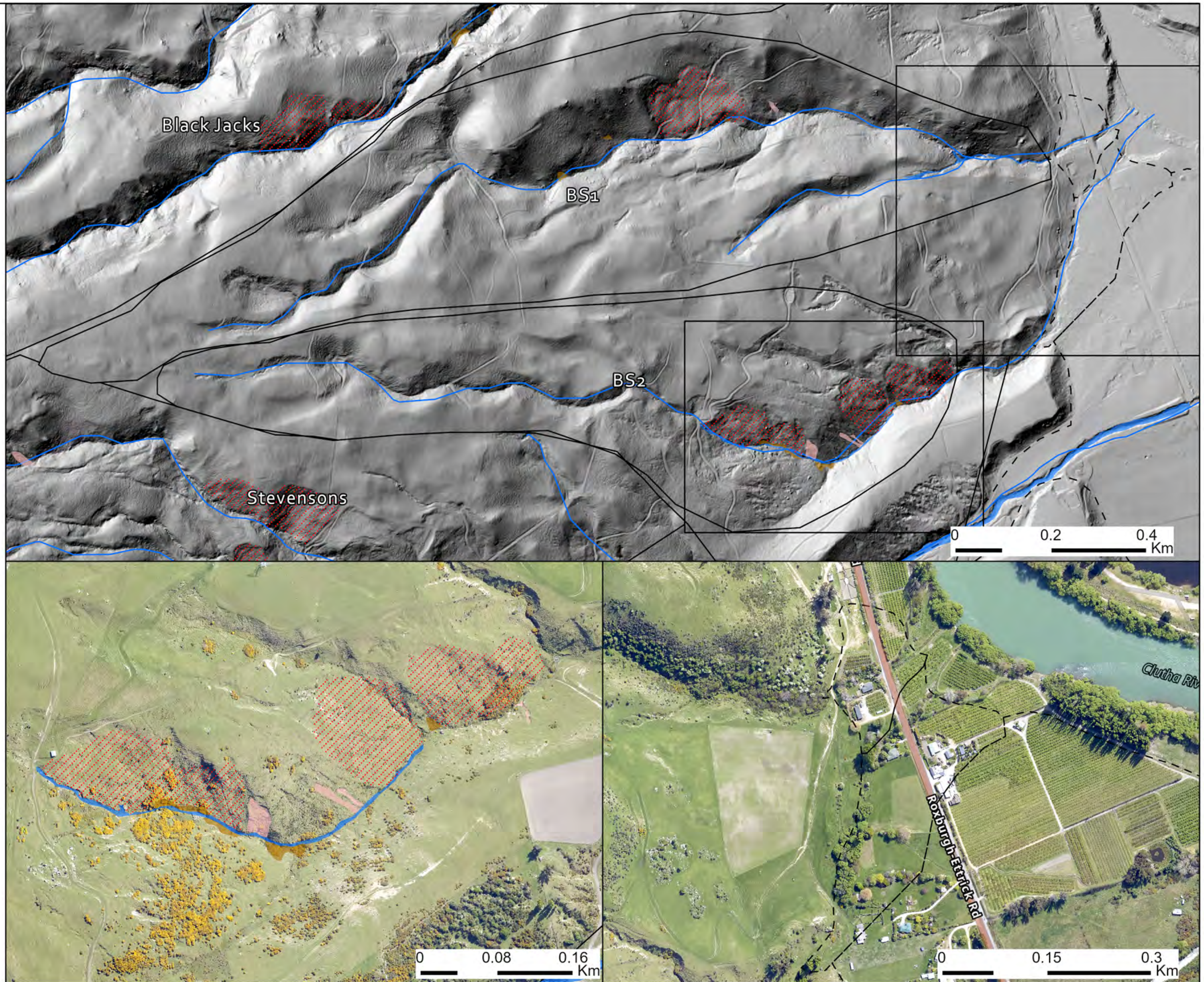
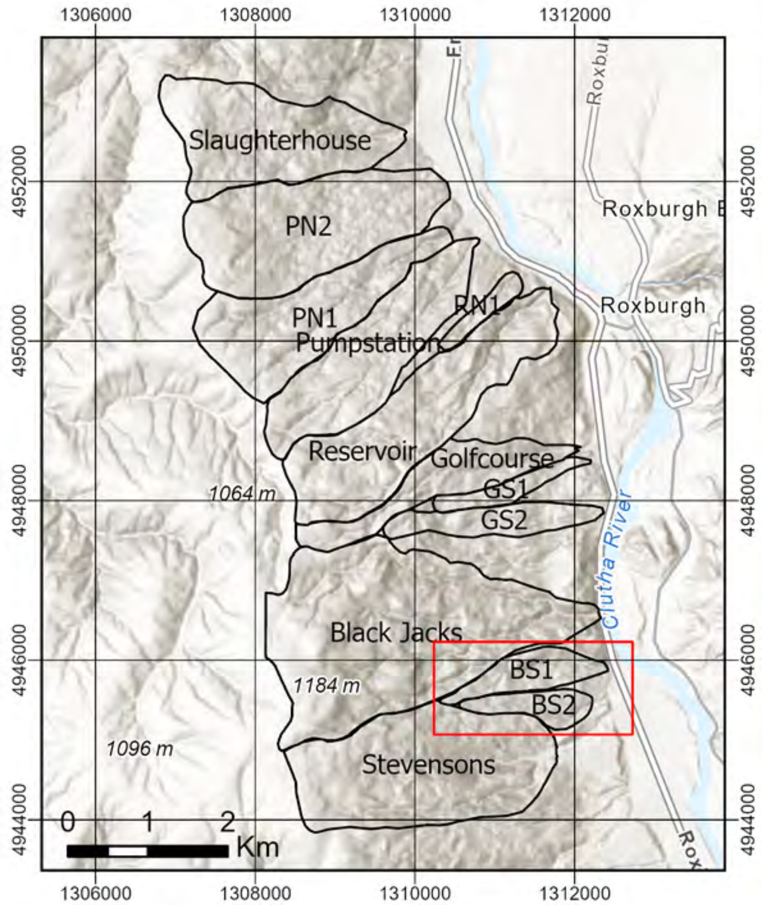
BS1 and BS2

Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel





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Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - BS1 and BS2

Map 9 of 10

Project: 1-E0173.00

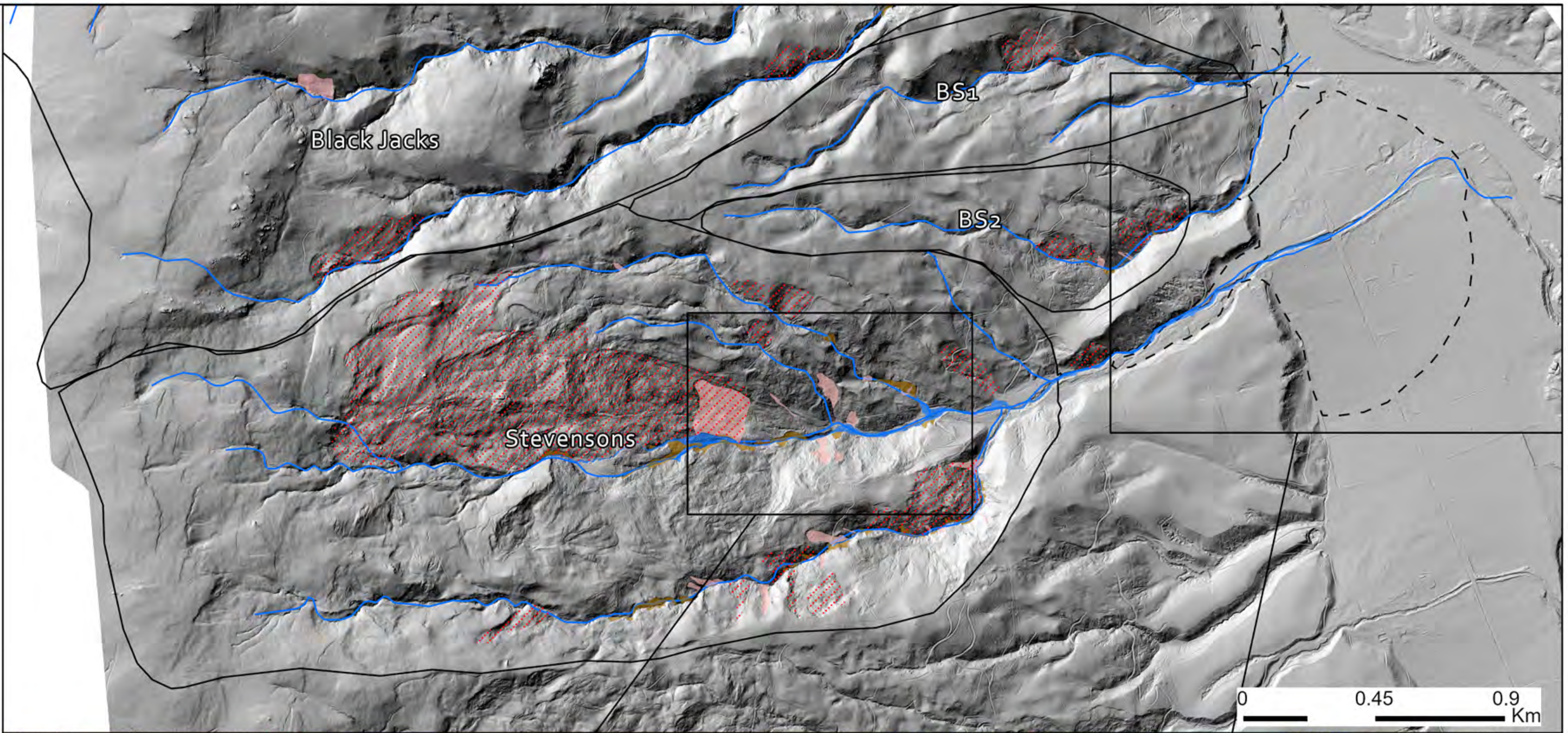
Date: 30/04/2025

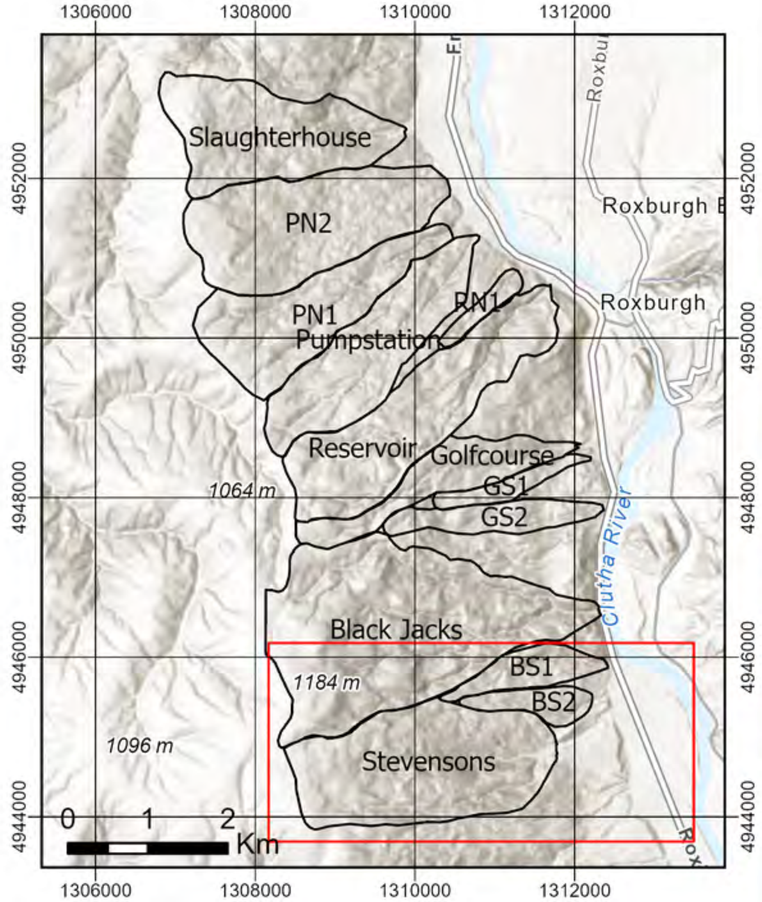
N W E S

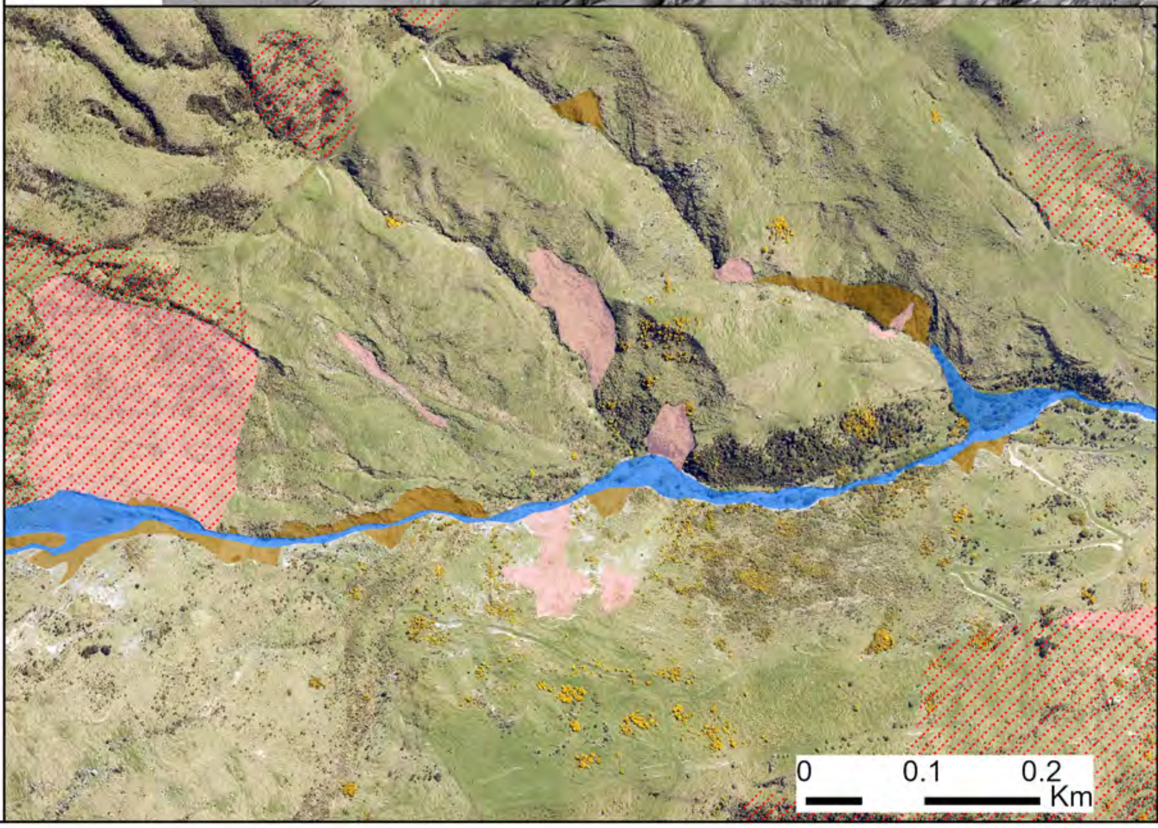
Stevensons Creek

Geomorphic Mapping

- Source - entrained debris
- Source - landslide
- Source - streambank erosion
- Source - deformed slope
- Channel
- Alluvial Fan
- Catchment
- Channel







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Otago Regional Council - Roxburgh Debris Flood

Geomorphological Mapping - Stevensons Creek

Map 10 of 10

Project: 1-E0173.00

Date: 30/04/2025

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APPENDIX C – HYDROLOGICAL ASSESSMENT

METHODOLOGY

The purpose of this assessment is to evaluate the peak flows from each catchment using HEC-HMS modelling (SCS method) as this is a key input for the hydrogeomorphic modelling. As part of this assessment, it was necessary to update the peak flow data for the five catchments within the study area based on the previous assessment carried out by Golder (2019a). In addition, the assessment now includes an evaluation of seven additional catchments. Trigger frequency was analysed as part of this assessment including the effect of climate change scenarios on rainfall intensity and duration.

The methodology applied for this assessment is listed below:

- Data management/collection
  - LiDAR (2024) – sourced from aerial survey conducted for the project
  - Rainfall Depth HIRDS – climate change scenario RCP 8.5 (100yr, 250yr) for the period 2081-2100.
  - Soil drainage classification – Landcare Research
  - Land use – Landcare Research
  - Previous work – Golder (2019a)
- Hydrology assessment
  - Time of concentration calculations – Ramser – Kirpich method
  - Assessed drainage class and land use for each catchment
  - CN calculations for each catchment – weighted CN number using TP108 guidelines.
  - Generated rainfall profile. HEC-HMS modelling set up, update and run
- Peak flow calculations 100yr, 250yr, 500yr, 1000yr, 2500yr
  - SCS method

ASSUMPTIONS AND LIMITATIONS

- **Catchment delineation**: The catchment analysis and delineation have been excluded from this assessment. The catchment boundaries provided by the client were used as is, with no modifications or adjustments.
- **Discharge point locations:** The assessment of discharge point locations for each catchment is not included in the scope of this study. It was assumed that each catchment discharges into a separate culvert for the model setup. However, for estimating the specific peak flow for each catchment, whether combined or not, the discharge point configuration does not affect the peak flow from each catchment.
- **Soil group and drainage classification:** It was assumed for this assessment that Drainage Class 4 is within Soil Group B, while Drainage Class 3 is within Soil Group C. Table 37 shown below from the TP108 Guideline, was used to classify the CN number based on the land use extracted from Landcare Research.

Table 37: Curve numbers from TP108 guideline. Sourced from TP108 Guidelines for stormwater runoff modelling in the Auckland region (page 9).

Curve numbers for typical Auckland conditions			
Land Use	**Group A Soil (volcanic granular loam)**	**Group B Soil (alluvial)**	**Group C Soil (mudstone/ sandstone)**
Bush, humid-climate, not-grazed.	30	55	70
Pasture, lightly grazed, good grass cover	39	61	74
Urban lawns	39	61	74
Crops, straight rows, minimal vegetative cover	72	81	88
Sealed roads, roofs	98	98	98

- **Extrapolation of extreme rainfall events**: Rainfall data for the 1-in-500-year, 1-in-1000-year, and 1-in-2500-year events were extrapolated to generate estimates for these extreme events based on the available rainfall data from HIRDS. Figure 40 below illustrates the extrapolation of these events. The decision to use a power curve to model and extrapolate rainfall events is grounded in both empirical evidence and theoretical justification. Power law relationships are commonly used in hydrology because they effectively capture the non-linear behaviour of extreme events and natural phenomena, particularly where larger events occur less frequently but with disproportionately larger magnitudes.
- **Rainfall duration**: 1 hour as applied in the previous study (Golder, 2019a).

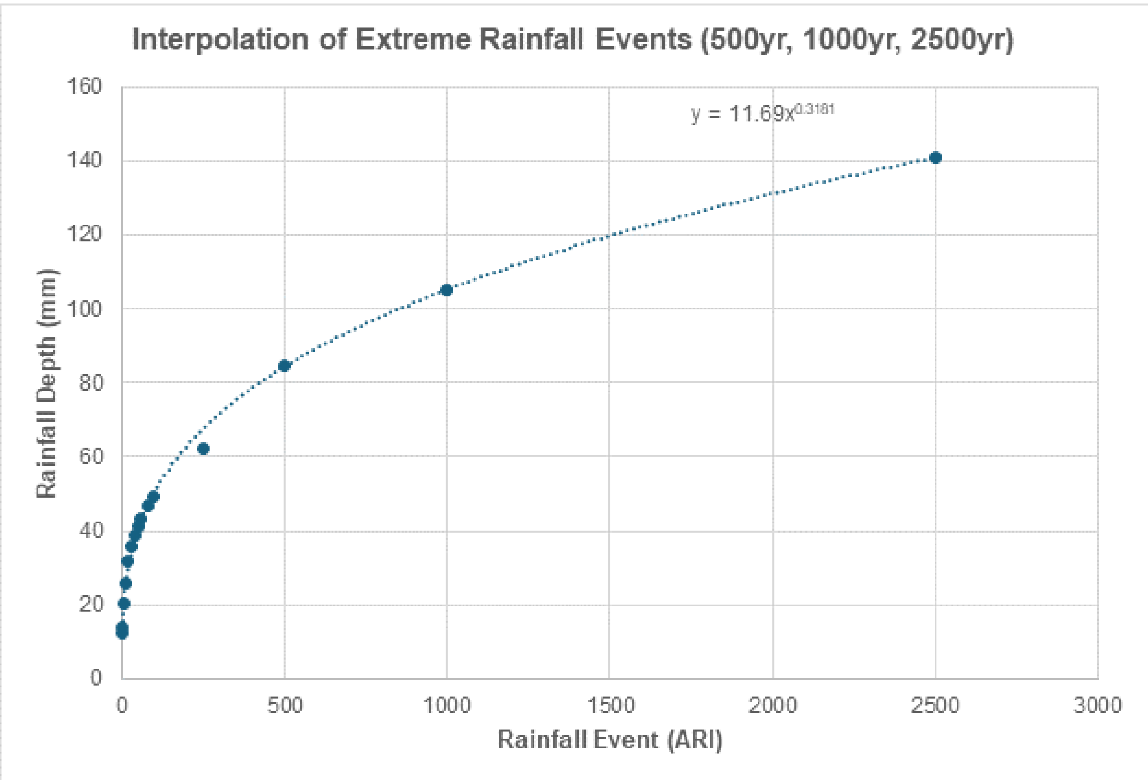


Figure 40: The extrapolation curve used to estimate depth of rainfall events currently not covered by HIRDS.

- **Climate change**: Rainfall and peak flow has been modelled using the RCP 8.5 climate scenario. This is a worst-case climate scenario for Roxburgh with increase in rainfall intensity and peak flow in the catchments assessed in this study. This is a conservative scenario and represents the upper bound of hydrological input variables. The selection of this scenario aligns with GNS landslide planning guidance for Level C and Level D analyses and is appropriate for the purposes of this qualitative risk assessment (de Vilder et al., 2024).

APPENDIX D – DEBRIS FLOOD VOLUME

DEBRIS FLOOD VOLUME CALCULATION METHODOLOGY

EXISTING APPROACHES

Frequency-magnitude (FM) relationships are a useful tool for predicting future debris flood volumes at different return periods based on historical data. Globally, techniques for determining the age and magnitude of past events have included dendrochronology (using impact scars and reaction wood) to date events and identify previous deposits, as well as stratigraphic analysis of natural exposures and test pits excavated with backhoes (Jakob, et al., 2020). FM relationships are typically modelled using statistical methods including regression analysis, probability distributions, and model ensembles, often fitting the data to a power-law distribution. These relationships help predict the likelihood of different sizes of debris floods.

Empirical methods involve analysing historical data and observations to establish patterns and trends in debris flood occurrences. These methods are often combined with expert judgment to improve predictions and understand the factors influencing debris flood. Several empirical relationships have been determined for debris flood peak discharge (Qdp), volume (V), and area based on international regional studies (Jakob et al., 2024). These are summarised in Table 38 below.

Table 38: International empirical relationships for debris flood and debris flow volume.

Equation	Description	Reference
(1) $V_{NA} = A_f[5700\ln(T)-4238]$ **(2) $V_{NV} = V_f[354\ln(T)+218]$**	F-M equations derived for debris flow catchments in British Columbia. Where: V_{NA} = normalised fan area (m^3km^{-3}) V_{NV} is the normalised fan volume (m^3km^{-3}) A_f is the fan area (km^2) V_f is the fan volume (km^3) T is the return period (years)	(Jakob, et al., 2020)
$V = 10^{(0.019I\_1.55)VR0.877}$	Debris flows with channel gradients from approximately 2%-24%. Where: V is debris flood volume (m^3) I is channel slope (%) VR is total rainfall (m^3)	(Jakob, et al., 2022)
$V=1.25V_{ref}I^{1.5}$	Debris flow and debris flood volume. Where: V is debris flood volume (m^3) V_{ref} is effective runoff volume (m^3) I is channel slope (%)	(Rickenmann & Koschni, 2010)
$V=4376*S^{0.73}$	Debris flow on alpine catchments. Where: V is debris flood volume (m^3) S is watershed area (km^2)	(Ma et al., 2013)

Equation	Description	Reference
Qdp = 0.00014V **Derived for V:** **V = Qdp/0.00014**	Muddy debris flow - high sediment concentration. Where: Qdp = debris flow peak discharge (m^3/s) V is debris flow volume (m^3)	(Chen & Chuang, 2014)
Qdp = 0.019$V^{0.79}$ **Derived for V:** **V=$(Qdp/0.019)^{1.27}$**	Muddy debris flow Qdp = debris flow peak discharge (m^3/s) V is debris flow volume (m^3)	(Mizuyama et al., 1992)
Qdp = 0.135$V^{0.78}$ **Derived for V:** **V=$(Qdp/0.135)^{1.28}$**	Bouldery debris flow Qdp = debris flow peak discharge (m^3/s) V is debris flow volume (m^3)	(Mizuyama et al., 1992)
Qdp = 0.04$V^{0.90}$ **Derived for V:** **V=$(Qdp/0.04)^{1.11}$**	Bouldery debris flow Qdp = debris flow peak discharge (m^3/s) V is debris flow volume (m^3)	(Bovis & Jakob, 1999)
Qdp = 0.1$V^{0.83}$ **Derived for V:** **V=$(Qdp/0.1)^{1.2}$**	Debris flows Qdp = debris flow peak discharge (m^3/s) V is debris flow volume (m^3)	(Rickenmann, 1999)

Of the above empirical equations, those that incorporate a variable that can be altered due to event intensity such as rainfall and flow are the most valuable when determining a FM relationship (Jakob, et al., 2022; Rickenmann & Koschni, 2010; Chen & Chuang, 2014; Mizuyama et al., 1992; Bovis & Jakob, 1999; Rickenmann, 1999). These empirical equations determine the relationship between debris flow discharge (Qdp) and volume (Figure 41).

For this assessment, catchments have channel gradients greater than 24% and effective runoff volumes have not been calculated, hence the Jakob et al (2022) and Rickenmann & Koschni et al (2010) are not included.

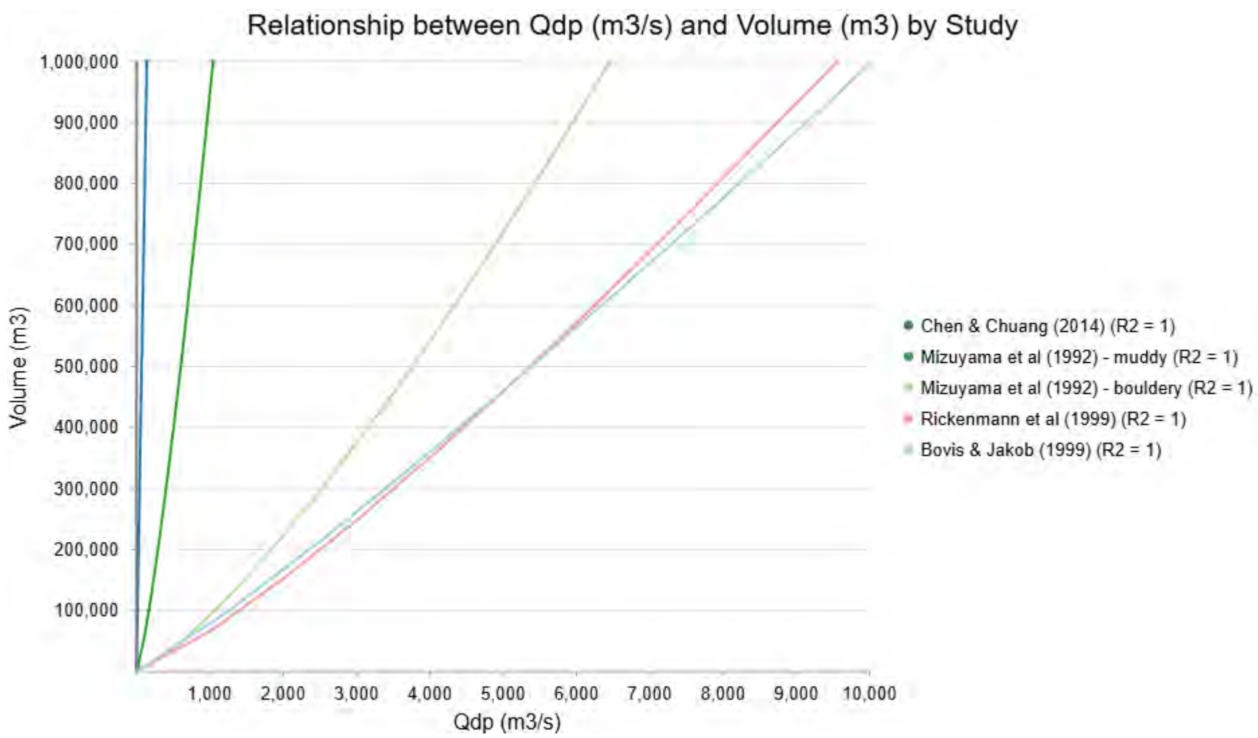


Figure 41: Existing empirical relationships for Peak debris flow discharge (Qdp) and debris flow volume.

In this study we have calculated peak water flow for catchments (Qwp). The relationship between debris flow discharge (Qdp) and peak water flow discharge (Qwp) has been analysed in several studies to date (Figure 42). Generally, these studies have found that water flow discharge is 5 to 40 times smaller than debris flow discharge. This relationship is often referred to as the bulking factor and may differ for more fluid-dominated hydrogeomorphic hazards such as debris floods.

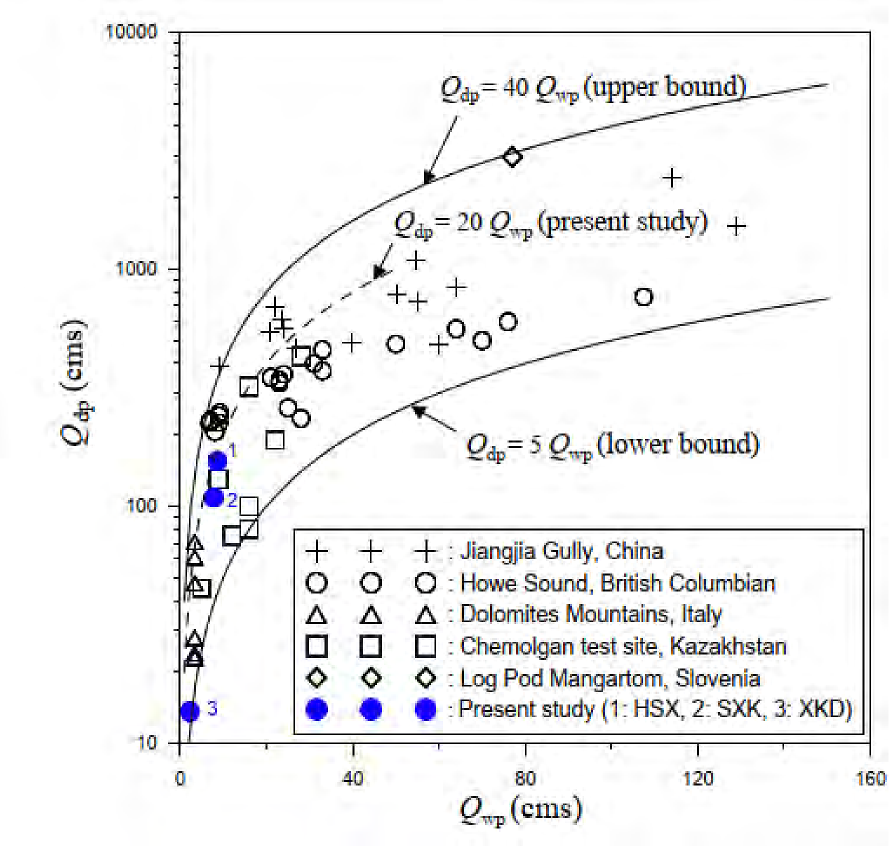


Figure 42: Relationship between debris flow discharge (Qdp) and water-flow discharge (Qwp). From Chen & Chuang (2014).

COMPARING 2017 DEBRIS FLOOD VOLUMES TO EMPIRICAL RELATIONSHIPS

The 2017 debris flood events were attributed a 100–500-year ARI (Golder, 2019a). Based on recorded rainfall during each debris flood, our hydrological assessment of catchments estimates a 48–852 year ARI and peak discharge water flows (Qwp) of between 3 and 92 m^3/s for these events depending on the catchment (Table 39 and Figure 40). The lower bound relationship in Figure 42 is used to estimate the potential peak debris flood discharge (Qdp) for the 2017 event. This results in debris flood discharge values between 15 and 460 m^3/s (Table 39).

Table 39: Peak water flow discharge and peak debris flood discharge for the 2017 debris flood events.

Catchment	Rainfall	ARI (years)	Qwp (m^3/s)	Qdp (m^3/s)
Pumpstation	40 mm in 1 hr	48	3.00	15.00
Reservoir	60 mm in 1 hr	171	11.70	58.50
Golf Course	80 mm in 1 hr	423	13.50	67.50
Black Jacks	100 mm in 1 hr	852	92.00	460.00

The Qdp values in Table 39 are used to estimate total debris volumes for the 2017 event using published empirical relationships, for comparison to the volumes assessed by Dellow et al (2018) following the storm. These are provided in Table 40. Comparison of the volumes in the table highlights the large uncertainty in using empirical relationships to derive total event volumes for FM estimation, as the relationships were developed for specific regions or events which are unlikely to be directly applicable to the catchments at Roxburgh. Furthermore, there is significant uncertainty in Dellow et al (2018) estimates, as illustrated by the broad range in values provided.

Table 40: The 2017 debris flood volumes compared to estimates using published empirical relationships.

Catchment	2017 Event Volume (m^3)					
	Dellow et al. (2018) estimation	Chen & Chuang (2014)	Mizuyama et al. (1992) - muddy	Mizuyama et al. (1992) - bouldery	Bovis & Jakob (1999)	Rickenmann et al. (1999)
Pumpstation	1,000-2,000	107,143	4,782	415	720	409
Reservoir	30,000-350,000	417,857	26,932	2,372	3,260	2,092
Golf Course	1,000-2,000	482,143	32,300	2,849	3,822	2,484
Black Jacks	15,000-262,500	3,285,714	369,560	33,228	32,164	24,849

OUR APPROACH

Review of historical information (Section 2.2) shows there is little historical data to develop detailed, locally specific frequency-magnitude relationships for the study area. The use of published empirical relationships to derive total event volumes is subject to very large uncertainties that result in very large ranges for the calculated volumes (Table 40). Therefore, for this study we estimate three debris flood magnitudes (expressed as volumes) for each catchment using a first principles informed approach based on our geomorphic mapping of source areas. The three debris flood events represent a high likelihood, median likelihood, and maximum credible event. The frequency or likelihood of each event size has been informed using the debris flood inventory, global examples, and our hydrological and geomorphological assessments. Debris flood magnitudes have been compared to the empirical relationships discussed previously and the calculated total volumes of material on the fans.

Our geomorphic mapping identified three potential source area types for debris floods in Roxburgh: entrained debris in the channel, streambank erosion, and landslides. While our mapping is a useful indicator of potential source material in a catchment, it is uncertain which areas of the channel and slope will contribute to future debris floods and how much source debris will be entrained. Further, mapped source areas do not provide an indication of volume without an estimation of likely depth of erosion or landsliding.

Likely debris flood volume for each catchment has been calculated using Equation 1 below:

$$Equation\ 1$$

$$Volume = \sum_{i=0}^{n} SA \times E \times D$$

Where:

- SA = Scaled source area
- E = Scaled entrainment factor
- D = Assumed depth

Deriving hypothetical debris flood event volumes is difficult and such the above equation was developed for this study to provide a repeatable framework for calculating volume and document inputs. A description and rationale for each variable of this equation is provided in the following sections.

SOURCE AREA

Source area refers to areas of each catchment identified as being potential sources within the 3 types described in Section 2.3.2.2. The distances of the centroids of each source area polygon to the nearest active stream channel are shown in Figure 43. This shows that the majority of source centroids are within 25 m of the active channel, and the greatest concentration of source area lies within 10 m of the streams. This reflects the significance of entrained debris in the channel and streambank erosion as source material for future debris floods. For the purposes of this assessment, we have generated 5, 10, and 25 m buffers around sections of the active channel in each catchment with evidence of recent erosional activity to represent source areas. Where recent activity was determined to be exposed ground, entrained debris, eroded or incised streambanks, and landslides. This was assessed during the geomorphic mapping stage of this assessment using aerial imagery and topographical information.

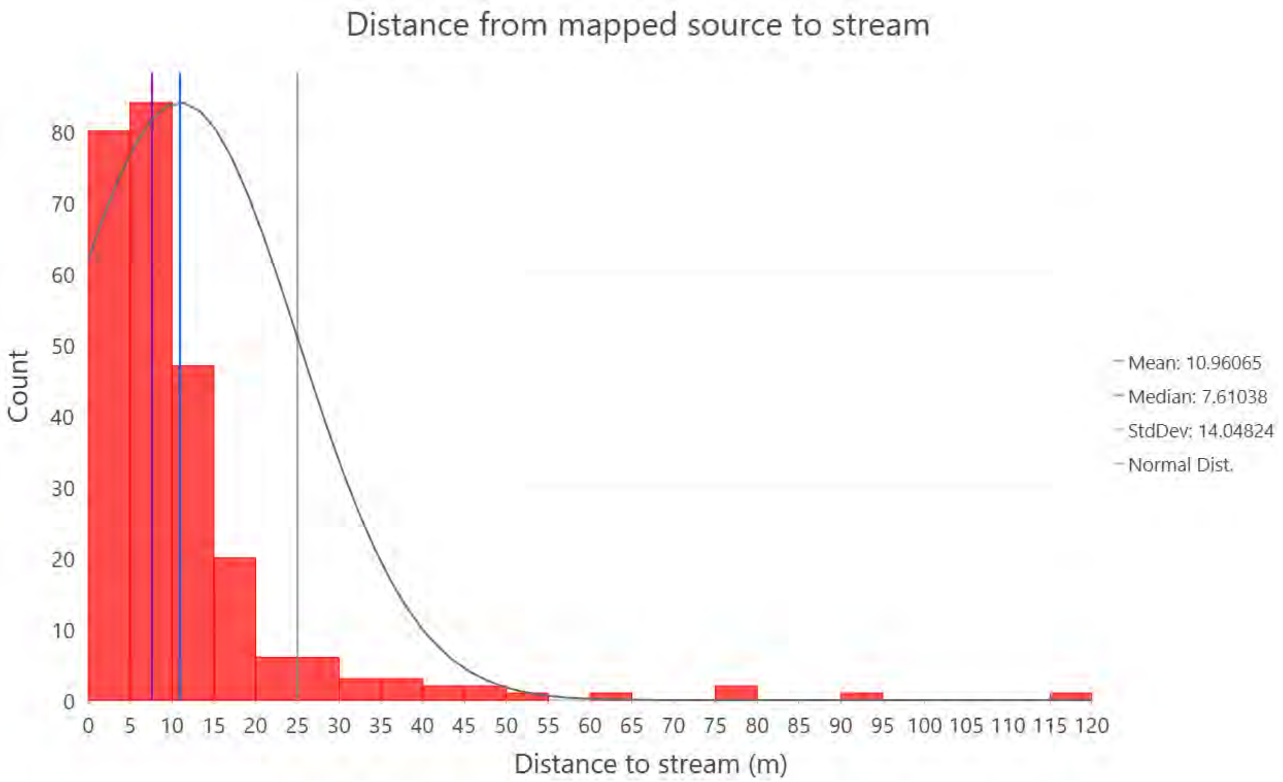


Figure 43: Histogram showing the distributions of distances of the mapped source areas from active streams.

It is unrealistic to assume that all of the land area within these buffers will contribute material to future debris floods equally, so these are scaled by the factors given in Table 41 for input into Equation 1. These factors are based on the measured proportions of the 5, 10, and 25 m buffers that have been mapped as potential source areas (Table 41). Geomorphic mapping can be uncertain due to factors such as data quality and interpretation/personal bias. To reflect this, we use an indicative range of measured proportions (equivalent to ± 0.05 or 5%).

The selection of source area buffers was determined based on the proximity of features to the active channel. The majority of mapped sources are within 25 meters of the active channel (exceeding 68% within one standard deviation from the mean), making this the largest source area. The mean distance was chosen as the upper bound for the next buffer (10 metres), while 5 metres was selected as the upper bound for the final buffer, aligning with the mapped features.

Table 41: Proportion of each buffer mapped as a potential source area.

Distance from channel	Proportion of total buffer area mapped as source area	Indicative range
0 – 5 m	0.55	0.5 - 0.6
5 – 10 m	0.41	0.35 - 0.45
10 – 20 m	0.30	0.2 - 0.4

ENTRAINMENT FACTOR

Entrainment factor refers to the ratio of material that is transitioned from a source to a flow during a debris flood event. This factor is included as it is unlikely that all material within a source area will be entrained into a flow due to topographical friction in the catchment and debris flood dynamics.

To evaluate an entrainment factor for each buffer, we estimated the proportion of debris for each mapped source that was entrained into a flow (i.e. material removed from the feature compared to material remaining). This was assessed in ArcGIS Pro using the 2017 and 2024 orthophotography to estimate the amount of material that had been entrained in the flow or deposited in the channel compared to the amount of material that remained on the slope (Figure 44). The distance from the feature headscarp to the active stream was also recorded. This process was undertaken for all catchments and included approximately 400 data points.

Figure 44: Examples of how data was captured for entrainment factor. Left: Landslide/block slide with headscarp 35 m from stream, 60% (0.6) of material estimated to be entrained in slide or deposited into the channel. Right: Surficial landslide with a headscarp 24 m from stream, a higher proportion estimated to be entrained ~80% (0.8) due to landslide geometry and type (shallow translational landslide).

The entrainment proportions are plotted against the distances of the source head scarps from the active streams in Figure 45. This illustrates that less debris is likely to be entrained in a flow with increasing distance from the stream. Furthermore, landslides in the study area are typically rockslides or debris slides which are less mobile and provide less material to the channel than disaggregated debris avalanches. The relatively subdued topography of the study area consists of hillslopes that are not sufficiently steep or long to generate debris avalanches that would contribute higher volumes of erodible material to become entrained in a flow at greater distances from the streams.

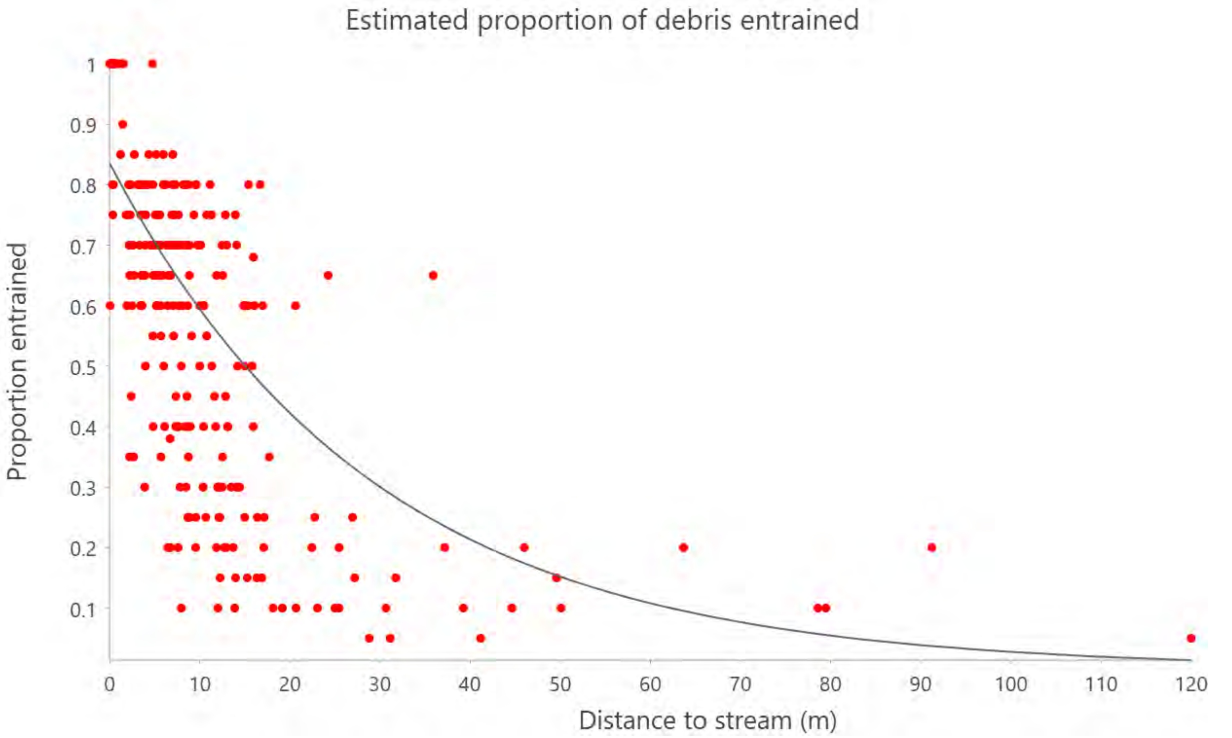


Figure 45: Estimated proportion of material entrained from each source with increasing distance from a stream.

Entrainment factors for each buffer are given in Table 42 and were applied to each catchment in this assessment. These are derived from the data in Figure 45, and illustrate the majority of material < 5 m from the stream is likely to be entrained in a flow. It is important to note that this assessment is relatively simplistic and adopts a study area entrainment factor and does not consider source size. A more detailed assessment could assess entrainment factors for each individual catchments incorporating the distance to the stream and the size of each source. Three entrainment factors are used in this study to capture the relationship that generally, sources closer to the active channel have a greater proportion entrained in a flow.

Table 42: The entrainment factor used for each buffer area in this assessment.

Distance from stream	**Entrainment Factor**	
	Lower	Upper
0 – 5 m	0.70	0.84
5 – 10 m	0.59	0.70
10 – 25 m	0.36	0.59

ASSUMED DEPTH

Assumed depth refers to an assumed depth of erosion or failure for each event size (Table 43). These estimates are based on observations from past events and recent helicopter reconnaissance photographs of the catchments, supplemented by assessment of cross sections drawn through the channel and neighbouring hillslopes using the 1m 2024 DEM. Cross sections through features that were likely developed as a result of the 2017 event were drawn in ArcGIS Pro and used to inform potential failure depths for the three event sizes (e.g. Figure 46). We assume that depth of failure or erosion will increase from the high likelihood to maximum credible event due to increased rainfall and peak flow.

Given the scope of this study and the consideration of various volume factors, we have assessed this factor for the study area as a whole, rather than for individual catchments. Further detailed assessment could capture failure depths for individual catchments.

Table 43: Assumed depths (m) for each source type identified in the study area.

Event	Assumed depth of erosion (m)	
	Lower	Upper
High likelihood	1	2
Median	2	4
Maximum credible	4	8

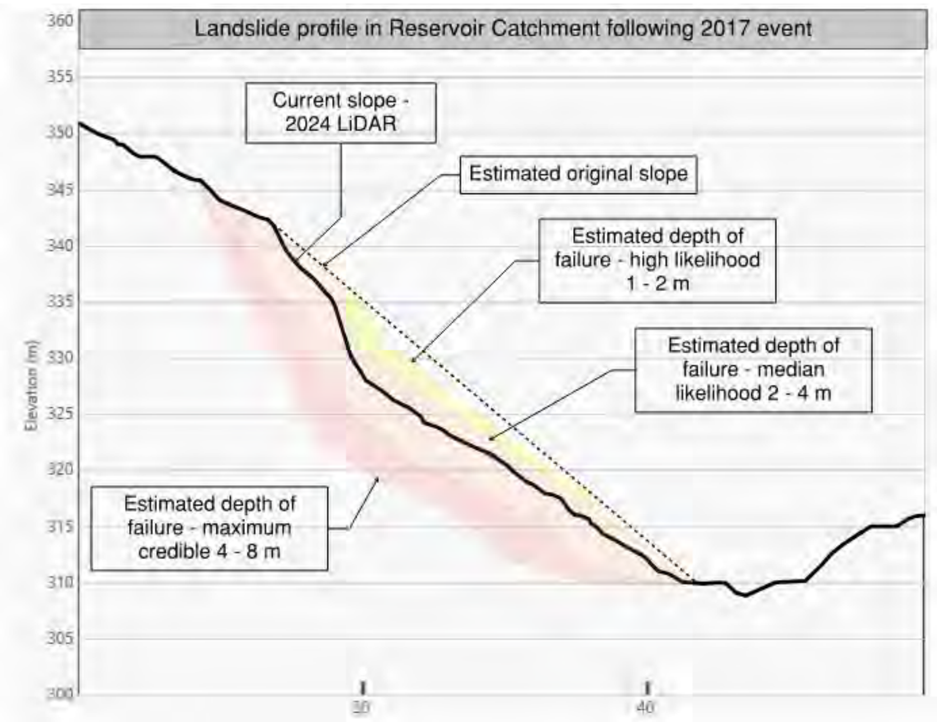


Figure 46: An example of a cross section for a landslide feature in Reservoir Creek with annotations for high likelihood, median, and maximum credible failure depths.

LIMITATIONS

While the first-principles approach adopted in this study provides a transparent and repeatable framework for estimating debris flood volumes, several limitations should be acknowledged:

- Uncertainty in Source Area Mapping
  - The identification of potential source areas is based on geomorphic mapping using aerial imagery and topographic data. This process is subjective and sensitive to image resolution, interpretation bias, and temporal variability in surface conditions. As such, the mapped source areas may not fully represent the actual locations or extents of future debris mobilisation.
- Simplified Representation of Factors
  - The factors applied are generalised across the study area and do not account for catchment-specific variations in slope, vegetation cover, soil cohesion, or hydrological connectivity. Additionally, the entrainment assessment is based on visual comparison of orthophotography, which may not accurately capture subsurface conditions or small-scale erosion processes.
  - The use of consistent parameters across catchments in this study is based on the need for a repeatable, transparent, and coherent framework for estimating debris flood volumes across several catchments. While each catchment has unique geomorphic and hydrological characteristics, the Roxburgh study area shares several overarching features that support the application of uniform parameter sets. These include similar lithologies, topography, vegetation cover, and broadly consistent rainfall.
  - Given the limited availability of detailed historical data and records for individual catchments, applying consistent parameters allows for a structured comparison of debris flood magnitudes across the study area. This approach reduces the influence of subjective variability in parameter selection and ensures that differences in estimated volumes are primarily driven by mapped source area characteristics rather than inconsistent input assumptions.
  - Furthermore, the parameters used—such as entrainment factors and assumed erosion depths—are derived from local observations, post-event imagery, and geomorphic mapping that reflect typical debris flood behaviour in the area. While more detailed, catchment-specific calibration could improve accuracy, it would require extensive field validation. As such, the consistent parameter approach provides a practical balance between methodological rigor and data limitations, while still capturing the key drivers of debris flood volume.
- Assumed Depths of Erosion or Failure
  - Depth estimates are derived from limited cross-sectional analysis and reconnaissance imagery and applied uniformly across the study area. This simplification may not reflect the spatial variability in erosion potential due to differences in lithology, slope gradient, or rainfall intensity. More detailed field surveys or geotechnical investigations could refine these depth assumptions.
- Buffer-Based Source Area Scaling
  - The use of fixed-distance buffers around active channels assumes a consistent relationship between proximity and debris mobilisation. However, debris flood initiation can be influenced by localised slope failures or hydrological triggers that may occur outside these predefined zones.

- Temporal and Climatic Variability
  - The approach does not explicitly account for changes in rainfall patterns, land use, or vegetation cover over time, which can significantly affect debris availability and mobilisation potential. This is particularly relevant given the influence of orographic enhancement and climate variability in the Roxburgh region.

APPENDIX E – RAMMS MODELLING

METHODOLOGY

RAMMS-DF (Rapid Mass Movement Simulation – Debris Flow) is a numerical modelling tool developed by the WSL Institute for Snow and Avalanche Research. It is designed to simulate natural hazard processes, particularly debris flows, using a single-phase model that calculates downslope movement over three-dimensional terrain. The model employs depth-averaged equations to represent debris flood dynamics and allows for a wide range of input parameters, enabling users to tailor simulations to different types of flow behavior.

In the Roxburgh study area, RAMMS-DF was applied to assess potential debris flood hazards across thirteen catchments, including Reservoir Creek, Black Jacks, Pumpstation, and others. Based on geomorphological assessments, the dominant hazard on the alluvial fans below these catchments was classified as debris floods—fluid-dominated events—rather than debris flows, which are more solid-dominated. Accordingly, the model inputs were adjusted to reflect the characteristics of debris floods.

RAMMS-DF is widely accepted by researchers and practitioners for simulating debris flood events. To ensure accuracy, model parameters were calibrated using field observations from past events. This included sensitivity testing to validate assumptions and refine inputs. The calibration process is essential for aligning the model with real-world conditions and improving the reliability of hazard assessments.

PROJECT SETUP AND SIMULATION

To set up a project within RAMMS the following steps were carried out:

1. A 3D terrain of the site was defined using a digital elevation model (DEM), with the addition of an overlain georeferenced aerial map.
2. The initial release conditions were determined to specify the location and type of initiation for the debris flood event.

   An input hydrograph is the preferred event initiation for channelised debris flood scenarios. This method used a hydrograph to specify the flow discharge as a function of time, allowing for a more dynamic and continuous flow simulation.

   A 3-point hydrograph was defined by the following properties within RAMMS-DF:

   - Total Event Flow Volume (V), m^3
   - Peak Flow Rate (Q), m^3/s
3. The flow behaviour of the debris flood was characterised in RAMMS-DF using the following parameters:
   - Frictional Parameter, Mu (μ), unitless. This is a measure of the basal shear interaction occurring between the surface of the flow and the ground surface.
   - Frictional Parameter, Xi (ξ), m/s^2. This is a measure of the viscous-turbulent behaviour of the flow.
   - Flow Density (ρ), kg/m^3. This represents the bulk density of the debris flood including fluid and solid components.

   The recommended approach to determine the modelled input parameters (Mu, Xi, Density) to reflect flow behaviour includes use of default values as suggested in the RAMMS-DF user manual, with model calibration used to adjust the parameters to reflect field observations from previous debris flood events. A sensitivity analysis of modelled input parameters was carried out to demonstrate the impact of parameter variation on modelled outcomes.

SOFTWARE LIMITATIONS

- RAMMS-DF uses a single-phase model which simplifies the complex frictional behaviour of a debris flood movement. The software cannot distinguish between fluid and solid phases, with the mass movement of the material modelled as a bulk flow. Therefore, it cannot be used to inform on the spatial distribution of solid components within the flow deposit e.g. large boulders.
- The simulation results are significantly impacted by the resolution and accuracy of the topographic data source.
- RAMMS-DF can be highly sensitive to input parameters. The precision of simulations depends heavily on the quality and detail of field data collected for model calibration.

MODEL INPUT PARAMETERS

TOPOGRAPHY

The 3D terrain consisted of a 2024 digital elevation model (DEM) with a 1m resolution to adequately define the topographic features. Within the Roxburgh Study area, channel dimensions on the alluvial fans were often of a similar order of magnitude as the DEM resolution (1- 10m).

RELEASE CONDITIONS

POTENTIAL ACTIVE SOURCE AREAS

Geomorphological mapping of each catchment was undertaken to identify the source areas for historical events and potential sources for future events (refer to Section 2.3.2.2). It is likely that during a debris flood, numerous active sources would contribute to a total event volume including streambank erosion, landslides and/or entrained debris within the channel. These active sources are predominantly surficial shallow failures, and relatively consistent across each catchment.

TYPE AND LOCATION OF DEBRIS FLOOD INITIATION

An input hydrograph is the preferred event initiation for modelling of a channelised debris flood scenarios (Figure 47).

A block release to simulate the initiation of a landslide was considered; however, this is not appropriate for the observed ground conditions. The deformed slopes from larger slow creeping landslides typical of the schist landscapes in Central Otago are considered less likely to contribute to debris floods due to much slower rates of movement.

The position of the input hydrograph is at the lowest point of each catchment where all upstream flows converge. This approach enables all of the potential active sources across each catchment to be considered as part of the total event volumes. The position of the hydrograph coincides with the apex of the alluvial fan below each catchment. At this point the dominant process shifts from erosion to deposition; therefore, no significant effect that would increase the total event volume of the debris flood is expected from below this elevation.

The width of the release area for the hydrograph as defined in the RAMMS-DF model is controlled by the diameter of the channel at this location.

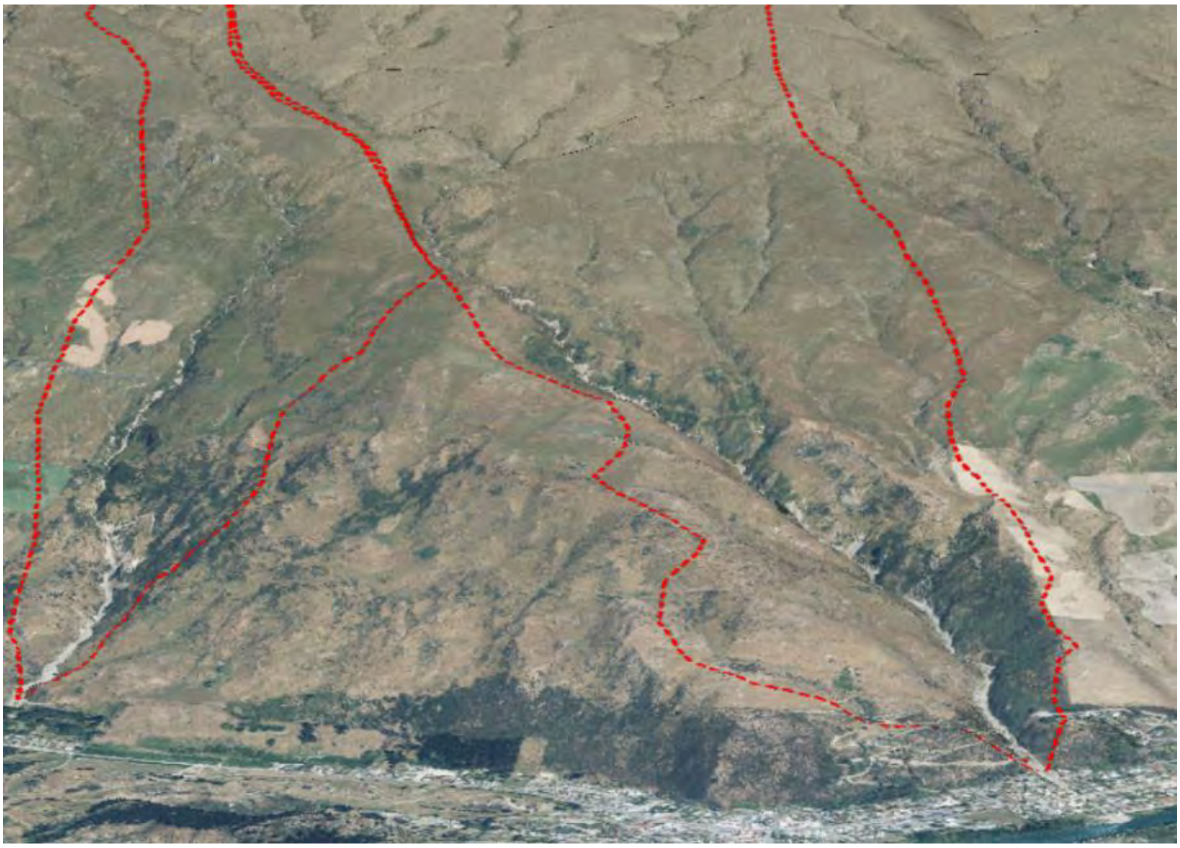


Figure 47: 3D View of Golf Course (Left) and Reservoir Creek (Right) catchments in RAMMS-DF.

EROSION

RAMMS-DF allows for prediction of the depth of erosion as a consequence of sediment entrainment from the channel during the mass movement of the debris flood. The erosion function is not considered as part of the debris flood simulations; therefore, reducing the model complexity and applying a consistent, justifiable approach across each site.

For each catchment, the entrainment of debris from the channel is already considered as a potential active source area for calculation of the total event volume. The initiation for the debris flood event is taken as the apex of the alluvial fan; therefore, incorporating the full length of the channel within the catchment.

For the alluvial fans below each catchment, entrained debris not expected to significantly impact the volume of a debris flood at this elevation. Generally, the alluvial fan slope gradients reduce to < 10° with a smaller amount of erosion occurring on the lower gradient alluvial fans compared to the steeper slopes of the upper catchment. For Reservoir Creek, the concrete lined channel extending from the upper alluvial fan to river level would have impeded any surface erosion.

HYDROGRAPH PARAMETERS

Debris flood simulations were conducted at each catchment for three different likelihood events (High Likelihood - 1 in 100, Median Likelihood - 1 in 500, and Maximum Credible Event - 1 in 2500).

The input data to define a hydrograph consisted of a total event flow volume (V), corresponding peak flow rate (Q) and the time at which the peak flow rate occurred (t). According to the RAMMS-DF user manual, the time the maximum peak flow rate occurs is just behind the leading edge of flow with a recommended value of seconds (10s) after the model initiation. The inflow direction for the hydrograph (based upon channel orientation) is defined as the angle in counterclockwise direction from the x-axis and is summarised for each catchment in Table 44.

The adopted values of total volume and peak flow rates are summarised in Table 45. These values are specific for each catchment with corresponding event size and were derived by WSP. Peak flow rates were based on the hydrological assessment with HEC-HMS modelling completed for each catchment (refer to Section 2.4 and Appendix C). Total volume estimates were determined from the frequency-magnitude relationships of debris flood events (refer to Section 2.5).

Table 44: Inflow direction for RAMMS debris flood simulation.

Catchment	Inflow Direction
Black Jacks	005
BS1	000
BS2	005
Golf Course	000
GS1	010
GS2	350
PN1	025
PN2 - North	005
PN2 - South	005
Pumpstation	030
Reservoir	060
RN1	070
Slaughterhouse	000
Stevensons	030

Table 45: Summary of hydrograph inputs for each catchment.

Catchment	High Likelihood Event (1 in 100)		Median Likelihood Event (1 in 500)		Maximum Credible Event (1 in 2500)	
	Event Volume (m^3)	Peak Flow Rate, Q (m^3/s)	Event Volume (m^3)	Peak Flow Rate, Q (m^3/s)	Event Volume (m^3)	Peak Flow Rate, Q (m^3/s)
Black Jacks	95,000	13.2	204,000	57.5	408,000	159.3
BS1	7,000	0.9	15,000	5.6	31,000	17.8
BS2	20,000	0.6	43,000	4	86,000	12.7
Golf Course	46,000	3	100,000	13.5	200,000	38.2
GS1	6,000	0.4	13,000	3	27,000	9.8
GS2	13,000	1.3	28,000	7.1	56,000	21.5
PN1	8,000	5.1	18,000	24.3	35,000	69.9

PN2 - North	21,000	3.3	44,000	18.7	89,000	57.9
PN2 - South	15,000	1.8	31,000	10.4	62,000	32.2
Pumpstation	37,000	5.7	79,000	25.9	159,000	72.8
Reservoir	71,000	7.3	153,000	31.9	305,000	88.4
RN1	7,000	0.4	16,000	2.4	31,000	7.5
Slaughterhouse	44,000	4.6	95,000	25.4	190,000	76.6
Stevensons	99,000	8.2	213,000	39.3	427,000	112.8

DEBRIS FLOOD CHARACTERISTICS

The default parameters for model input were the recommended values presented in the RAMMS-DF user manual (Table 46). The default parameters were compared with input ranges used for debris flood simulations at other sites across New Zealand (Golder, 2021; Beca, 2020; T&T, 2015).

- Mu is a measure of the basal shear interaction between the ground surface and surface of the flow. RAMMS-DF recommends a default parameter of 0.2 as a first approximation
- For the adopted value by WSP, Mu was adjusted for the slope angle (α) within the alluvial fan deposition zone across the Roxburgh study area (μ = tan α). For the alluvial fans below each catchment, the alluvial fan slopes reduce to 5-7° (maximum gradient of < 10°), whereby μ = 0.1.
- Xi is a measure of the viscous-turbulent behaviour of the flow. RAMMS-DF recommends a default parameter of 200 m/s^2 for a transition between fluid- and solid type flows. A range of 200 – 1000 m/s^2 for fluid like flows consistent with a debris flood,
- ρ represents the flow (bulk) density including fluid and solid components. RAMMS-DF recommends a default parameter of 2000 kg/m^3 if no further information on the debris flood material is available. A typical range for fluid dominated flows is from 1600 - 2000 kg/m^3. - During sensitivity analysis at Reservoir Creek, the flow density was adjusted between 1600 - 2000 kg/m^3 with no observed effect on the model outcome.

Table 46: Adopted input parameters for modelled debris flood scenarios.

Input Parameter	Default Parameters (RAMMS-DF User Manual)	Typical Range for Debris Flood Conditions as per NZ studies*	Adopted Value by WSP
Basal Shear Friction, Mu (μ)	0.2 (0.05-0.4)	0.02 – 0.1	0.1
Viscous-Turbulent Friction, Xi (ξ), m/s^2	200 (200-1000)	200 – 1500	500
Flow Density (ρ), kg/m^3	2000	1600 – 2000	1800
*** (Golder, 2021; Beca, 2020; T&T, 2015)**.			

MODEL CALIBRATION

The model input parameters were adjusted to calibrate model outputs to reflect historic event observations. The model input parameters adopted by WSP are consistent with flow behaviour characteristic of a debris flood event.

There have been seven recorded high-intensity rainfall events that have triggered debris floods in Roxburgh (Table 5). The November 2017 event provides the only case study with enough detail for model calibration (Dellow et al., 2018; Golder, 2019a).

The four main catchments impacted by the 2017 rainfall event include Black Jacks, Reservoir Creek, Golf Course Creek and Pumpstation (Section 2.2.6)

To calibrate the RAMMS-DF model required data including:

- Pre- and post-event aerial imagery used to understand the active sources areas and assess terrain changes which developed as part of the debris flood event.
- Post-event field observations including site records/photographs, geological mapping and/or any anecdotal evidence.
- Hydrological data from during the event of rainfall intensity and duration (Golder, 2019a).
- Estimated debris flood volumes for the catchments affected in this event (Dellow et al. 2018).

The model calibration focused on Reservoir Creek as the most well documented catchment, with supplementary information for Black Jacks, Golf Course Creek and Pumpstation used to validate the refined input parameters and model outputs.

RESERVOIR CREEK

At Reservoir Creek, the mobilised sediment initially remained confined to the concrete debris flood channel which extends from the upper portion of the alluvial fan down to the Clutha River. The capacity of the concrete flume was only exceeded following aggradation of debris at the confluence to the Clutha River which proceeded to backup within the debris flood channel. Subsequent channel avulsion occurred above the SH8 bridge crossing, with fine sediment (silt-sand) and water overtopping onto the road.

Model outputs presented in Appendix F are consistent with site observations recorded at Reservoir Creek during the 2017 event, these include:

- Debris material remained within the concrete channel on the upper extent of the alluvial fan, with the exception of avulsion of fine sediment overtopping from the channel at the SH8 bridge crossing.
- Avulsion of fine sediment at the SH8 bridge overtopped onto the road and subsequently flowed downslope onto the lower portion of the alluvial fan between SH8 and the Clutha River. Maximum flow heights of < 0.5 m, impacting mainly properties adjacent to the concrete debris flood channel.
- Maximum flow heights observed at the river confluence and within the concrete channel consistent with aggradation and backfilling of debris material.
- Due to the absence of roadside drainage in the model, the runout distributions may not accurately reflect actual conditions, especially for thin silt deposits. This is evident at the SH8 bridge, where fine sediment extended beyond the modelled output, reaching the school.

SENSITIVITY ANALYSIS

At Reservoir Creek, a sensitivity analysis was carried out using the 2017 calibration event to demonstrate the effect of parameter variation on the modelled outcomes:

- Mu was varied between 0.05 – 0.4. The higher values of Mu (> 0.2) resulted in more restricted runout distances, with aggradation of material in the channel further upslope on the alluvial fan.
- Xi was varied from 200 to 1500 m/s^2, with minimal effect observed on the runout spatial distribution from parameter sensitivity.
- Flow density was adjusted between 1600 - 2000 kg/m^3 with no observed effect on the model outcome.

MODEL ASSUMPTIONS AND LIMITATIONS

- RAMMS-DF simulations have adopted a topographic resolution of 1 m. The high-resolution DEM resulted in extended processing times for simulations. A lower DEM (< 1m) was trialled but did not sufficiently define topographic features including channels, or localised changes in slope gradients.
- The 2017 calibration event used to refine the modelled input parameters was centred on the Reservoir Creek catchment. Due to the designated project timeframe to cover the extensive Roxburgh study area, and limited availability of calibration data for some catchments, this single calibration event was used to define the modelled input parameters for remaining catchments.
- The modelled input parameters are consistent across all catchments due to the inherent similarities in geomorphological characteristics.
- The model assumes input parameters specific to a debris flood event, as the dominant hazard type defined for each catchment. The modelled outputs do not account for the impacts of flow behaviour related to debris floods.
- The peak flow rates assumed from the hydrological assessment are based on a clear-water flood event. A debris flood event which consists of a combination of water, mud, and rocks has potential for higher peak flow rates from surging. No bulking factor has been applied to the clear-water peak flow rates to account for this.
- For each of the 13 catchments, the main drainage channel on the alluvial fan intersects with State Highway 8 (SH8). The DEM has not been modified to address the impact of culverts on debris flood paths. It is assumed that only a minor amount of debris is required to block the inlet of crossroad culverts, with overtopping of debris flood deposits onto SH8 likely. This is consistent with observations documented during historical events. This assumption takes a conservative approach to modelling when predicting debris flood runout distributions for debris flood hazard maps.
- Exclusion of fine details from the topographic data such as buildings, services and vegetation will affect the debris flood runout distributions. Without these barriers, the model outputs will not fully replicate the observed conditions during the calibration event.
- RAMMS-DF does not account for flow behaviour within the Clutha River. This is not expected to significantly impact the runout distribution of the debris flood across the alluvial fan. However, it is likely to affect the modelling of aggradation of debris at the confluence to the Clutha River with a significant amount of the total debris flood volume lost into the river.

CLIMATE CHANGE

We completed further sensitivity testing on the Reservoir Creek catchment using present-day rainfall and peak flow inputs without any climate change impacts. Peak flows for the ARIs assessed are less under a present day scenario than peak flows under an RCP8.5 scenario, particularly at the 1:2500 ARI interval (Table 47). However, when all other variables are kept the same, debris flood extent and intensity does not significantly decrease when using the present day (historical) rainfall and peak flow rather than the RCP8.5 peak flow for that same ARI (as shown in Figure 48). Therefore, there is unlikely to be a noticeable impact on the results presented in this assessment using a present-day or different climate scenario.

Table 47: Peak flow for Reservoir catchment under a present-day scenario with no climate change impacts and a worst-case RCP8.5 climate scenario.

Climate Scenario	1:100 ARI Peak Flow (m^3/s)	1:500 ARI Peak Flow (m^3/s)	1:2500 ARI Peak Flow (m^3/s)
Present-Day	2	14.5	47.7
RCP8.5	7.3	31.9	88.4
Difference	5.3	17.4	40.7

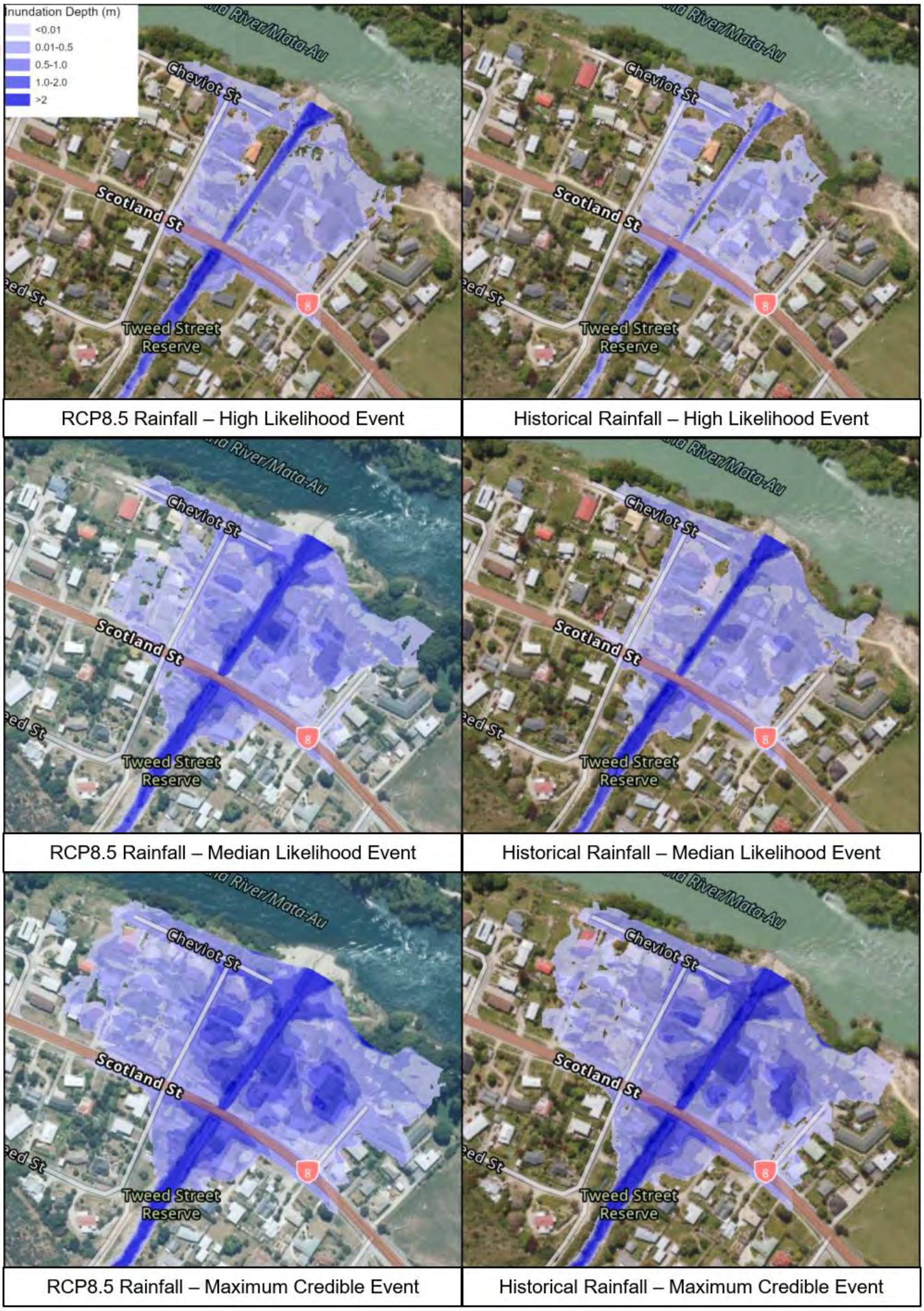


Figure 48: Comparison of debris flood depth using RCP8.5 rainfall and peak flow as inputs (left) and using historical rainfall and peak flow as inputs (right).

MODEL OUTPUTS

Over 50 RAMMS models were produced as part of this study for assessment of 13 catchments to inform the qualitative hazard assessment. A summary of RAMMS simulations performed as is presented in Table 48. The modelled outputs are presented in Appendix B.

Table 48: Overview of RAMMS-DF Simulations

Catchment	**Hydrograph Input Parameters**		**Debris Flood Characteristics**			**Reason/Justification**
	Volume (m^3)	Qmax (m^3/s)	Mu (μ)	Xi (ξ), m/s^2	(ρ), kg/m^3	
Reservoir Creek	160,000	16.5	0.2	200	2000	RAMMS Default Parameters
Reservoir Creek	160,000 Probable volume (Dellow et al., 2018)	16.5 1 in 500 ARI (Golder 2019a)	0.1	500	1800	Model Calibration – 2017 WSP Adjusted Parameters
Golf Course Creek	1,500 Probable volume (Dellow et al., 2018)	8.9 1 in 500 ARI (Golder 2019a)	0.1	500	1800	
Black Jacks	120,000 Probable volume (Dellow et al., 2018)	33.0 1 in 500 ARI (Golder 2019a)	0.1	500	1800	
Pumpstation	1,500 Probable volume (Dellow et al., 2018)	5.2 1 in 100 ARI (Golder 2019a)	0.1	500	1800	

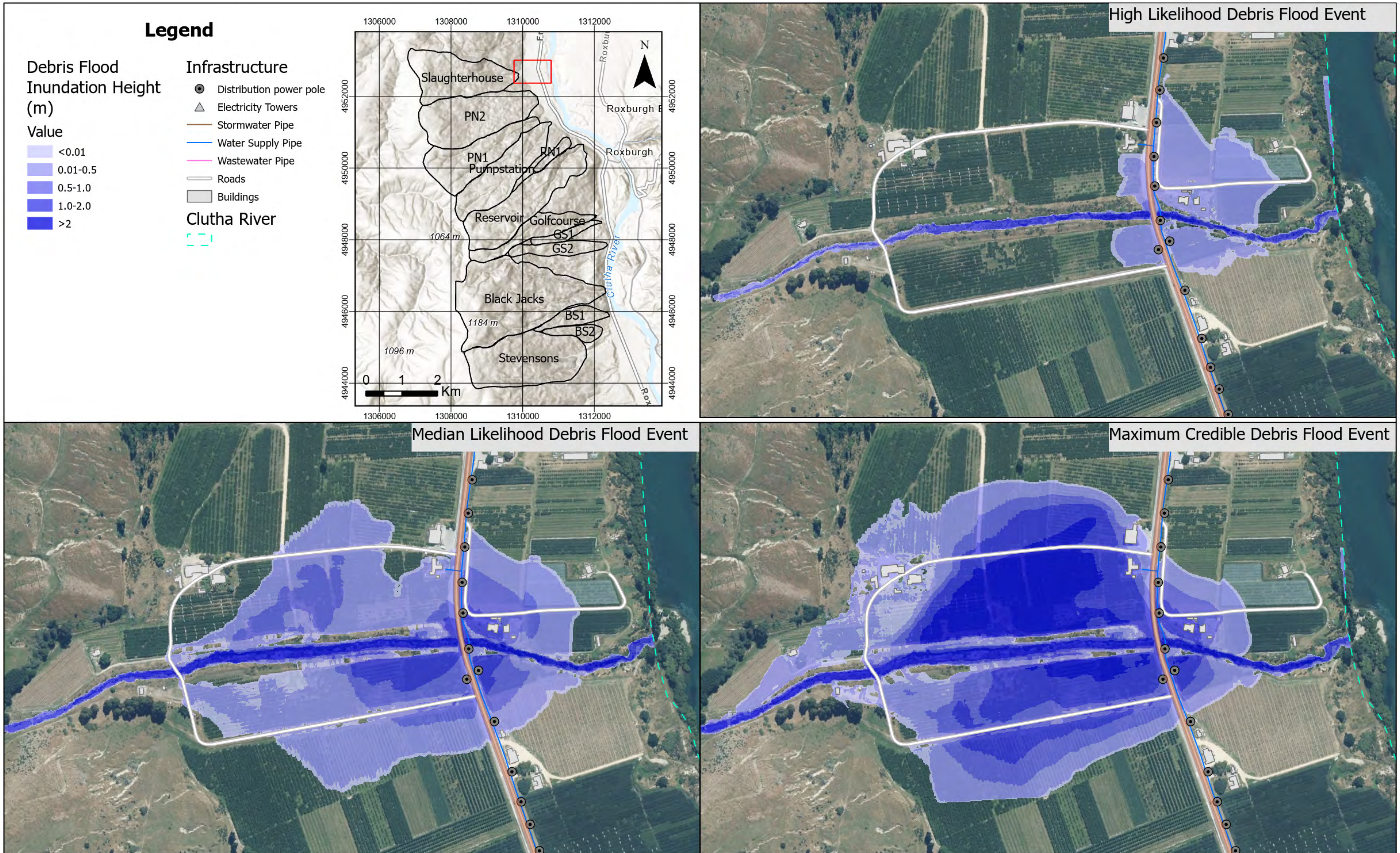
Reservoir Creek	160,000	16.5	0.05	500	1800	Sensitivity Analysis- Mu Variation
	160,000	16.5	0.2	500	1800	
	160,000	16.5	0.4	500	1800	
Reservoir Creek	160,000	16.5	0.1	200	1800	Sensitivity Analysis- Xi Variation
	160,000	16.5	0.1	1000	1800	
	160,000	16.5	0.1	1500	1800	
	160,000	16.5	0.1	500	1600	Sensitivity Analysis- Density Variation
	160,000	16.5	0.1	500	2000	
	160,000	33	0.1	500	1800	Sensitivity Analysis- Q max Variation
	160,000	50	0.1	500	1800	
Modelled Outputs for Hazard Maps (Appendix F)						
Catchment	**Hydrograph Input Parameters Debris Flood Characteristics**		**Debris Flood Characteristics**			**Reason/Justification**
	Volume (m^3)	Qmax (m^3/s)	Mu (μ)	Xi (ξ), m/s^2	(ρ), kg/m^3	
Black Jacks	95,000	13.2	0.1	500	1800	High Likelihood Event
	204,000	57.5	0.1	500	1800	Median Likelihood Event
	408,000	159.3	0.1	500	1800	Maximum Credible Event

BS1	7,000	0.9	0.1	500	1800	High Likelihood Event
	15,000	5.6	0.1	500	1800	Median Likelihood Event
	31,000	17.8	0.1	500	1800	Maximum Credible Event
BS2	20,000	0.6	0.1	500	1800	High Likelihood Event
	43,000	4	0.1	500	1800	Median Likelihood Event
	86,000	12.7	0.1	500	1800	Maximum Credible Event
Golf Course	46,000	3	0.1	500	1800	High Likelihood Event
	100,000	13.5	0.1	500	1800	Median Likelihood Event
	200,000	38.2	0.1	500	1800	Maximum Credible Event
GS1	6,000	0.4	0.1	500	1800	High Likelihood Event
	13,000	3	0.1	500	1800	Median Likelihood Event
	27,000	9.8	0.1	500	1800	Maximum Credible Event
GS2	13,000	1.3	0.1	500	1800	High Likelihood Event
	28,000	7.1	0.1	500	1800	Median Likelihood Event
	56,000	21.5	0.1	500	1800	Maximum Credible Event
PN1	8,000	5.1	0.1	500	1800	High Likelihood Event
	18,000	24.3	0.1	500	1800	Median Likelihood Event
	35,000	69.9	0.1	500	1800	Maximum Credible Event

PN2 - North	21,000	3.3	0.1	500	1800	High Likelihood Event
	44,000	18.7	0.1	500	1800	Median Likelihood Event
	89,000	57.9	0.1	500	1800	Maximum Credible Event
PN2 - South	15,000	1.8	0.1	500	1800	High Likelihood Event
	31,000	10.4	0.1	500	1800	Median Likelihood Event
	62,000	32.2	0.1	500	1800	Maximum Credible Event
Pumpstation	37,000	5.7	0.1	500	1800	High Likelihood Event
	79,000	25.9	0.1	500	1800	Median Likelihood Event
	159,000	72.8	0.1	500	1800	Maximum Credible Event
Reservoir	71,000	7.3	0.1	500	1800	High Likelihood Event
	153,000	31.9	0.1	500	1800	Median Likelihood Event
	305,000	88.4	0.1	500	1800	Maximum Credible Event
RN1	7,000	0.4	0.1	500	1800	High Likelihood Event
	16,000	2.4	0.1	500	1800	Median Likelihood Event
	31,000	7.5	0.1	500	1800	Maximum Credible Event
Slaughterhouse	44,000	4.6	0.1	500	1800	High Likelihood Event
	95,000	25.4	0.1	500	1800	Median Likelihood Event
	190,000	76.6	0.1	500	1800	Maximum Credible Event

Stevensons	99,000	8.2	0.1	500	1800	High Likelihood Event
	213,000	39.3	0.1	500	1800	Median Likelihood Event
	427,000	112.8	0.1	500	1800	Maximum Credible Event

APPENDIX F – DEBRIS FLOOD MAPS



Prepared by:

Otago Regional Council - Roxburgh Debris Flood

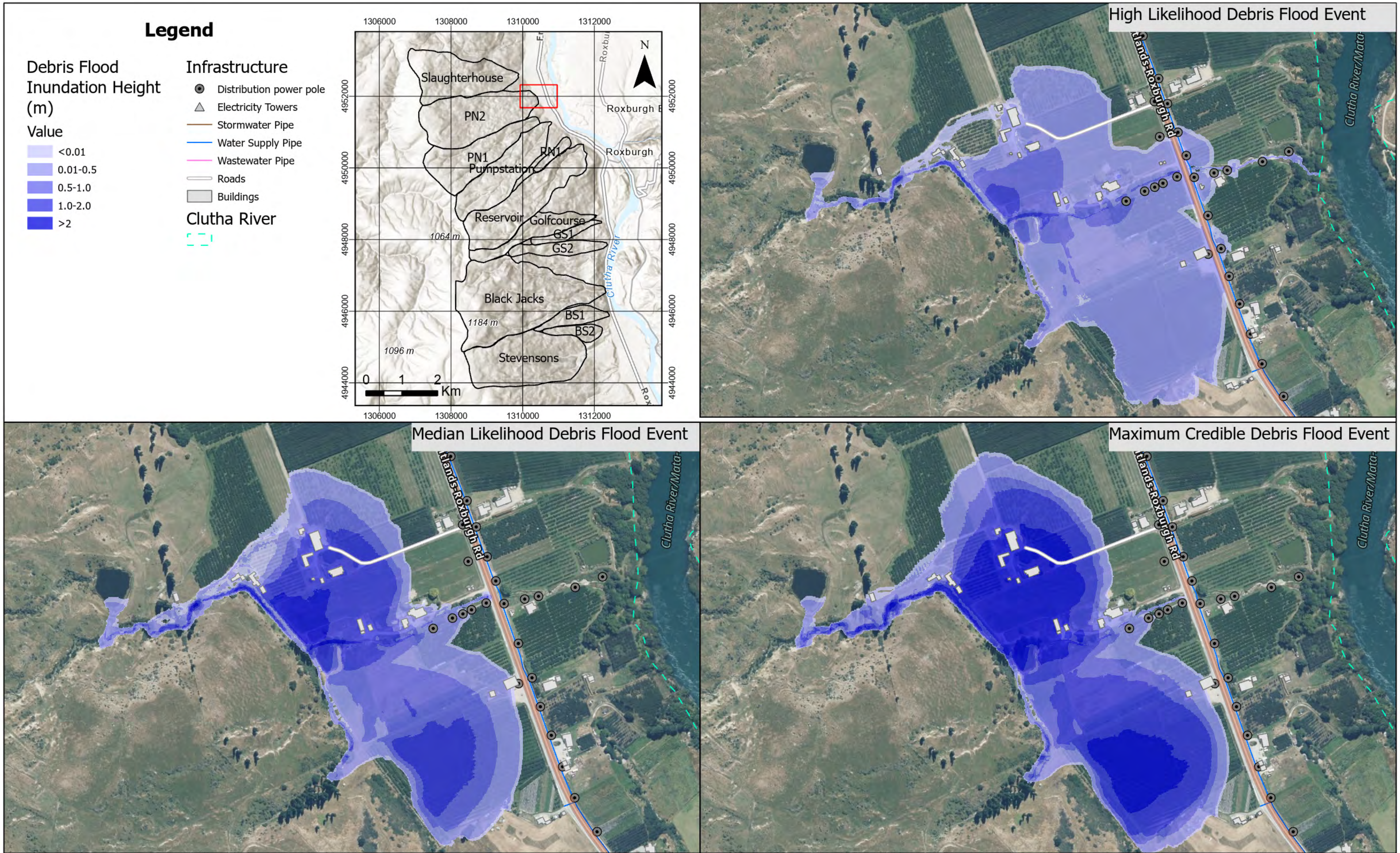
Debris Flood Modelling and Qualitative Risk Assessment - Slaughterhouse Creek

0 0.15 0.3 Km

N W E S

Project: 1-E0173.00

Date: 30/04/2025



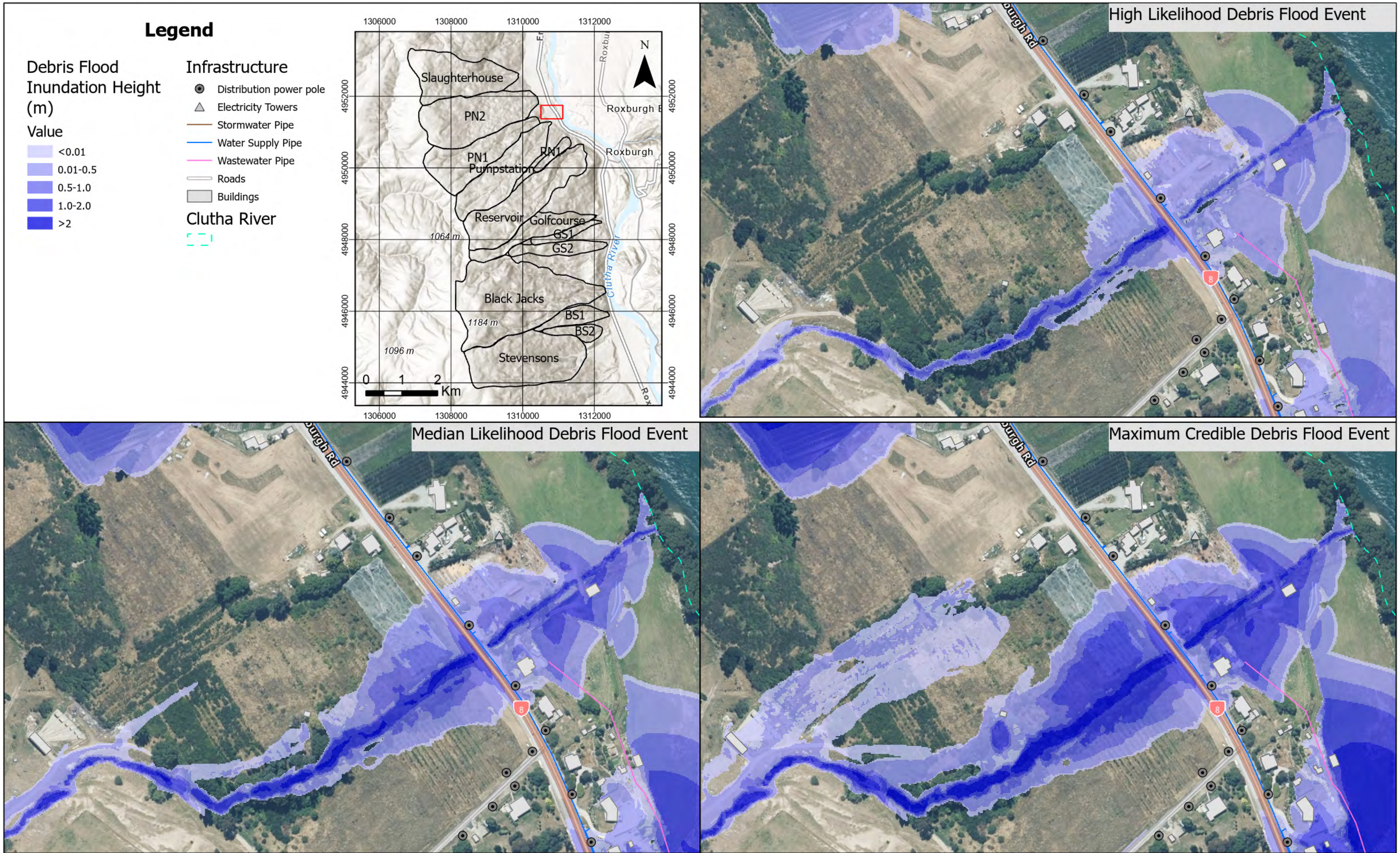
Prepared by:

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - PN2

Project: 1-E0173.00

Date: 30/04/2025



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - PN1

0 0.1 0.2 Km

N W E S

Project: 1-E0173.00

Date: 30/04/2025

Legend

Debris Flood Inundation Height (m)

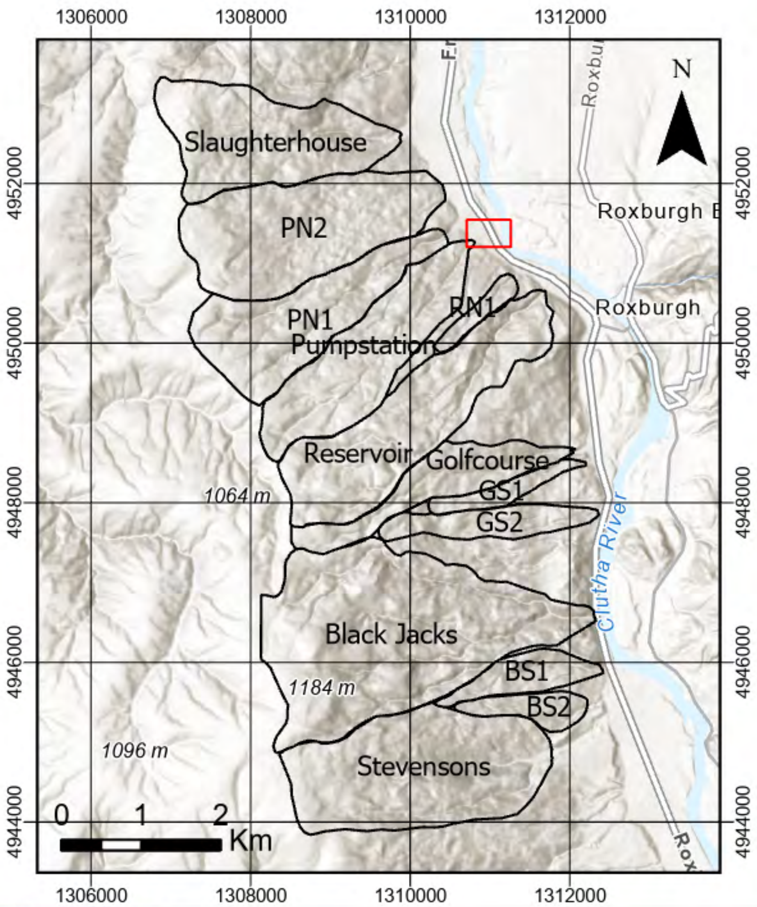
Value

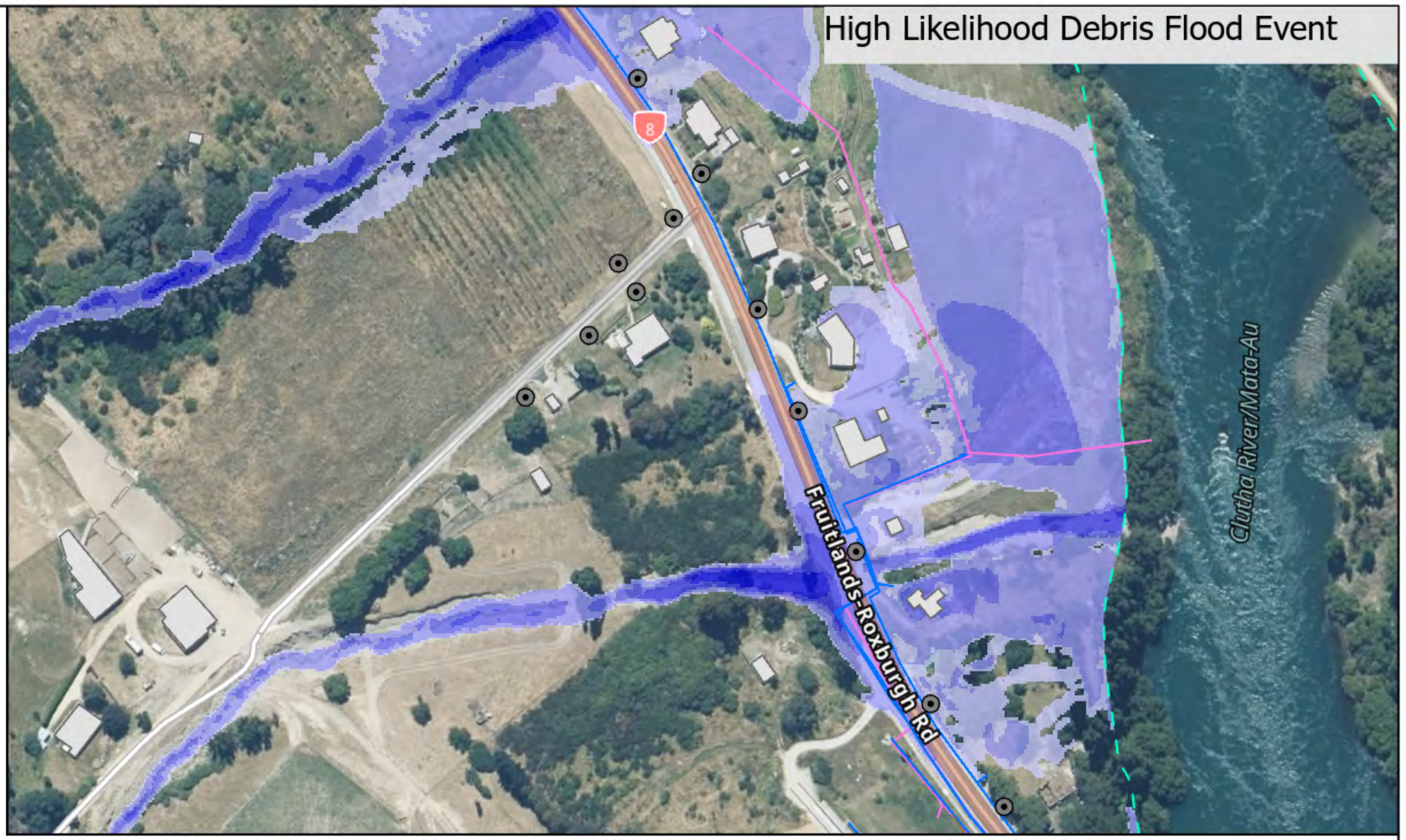
- <0.01
- 0.01-0.5
- 0.5-1.0
- 1.0-2.0
- >2

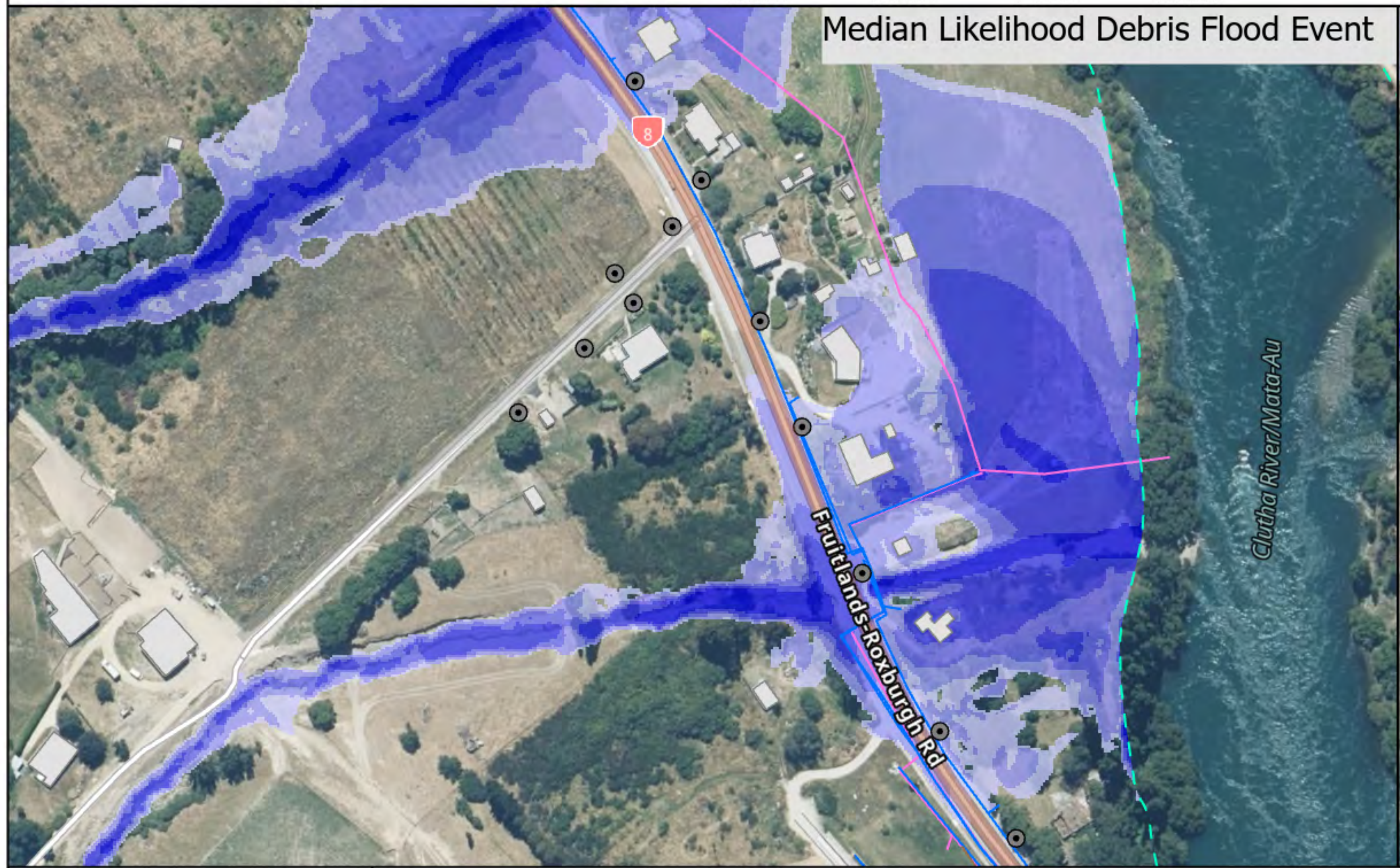
Infrastructure

- Distribution power pole
- Electricity Towers
- Stormwater Pipe
- Water Supply Pipe
- Wastewater Pipe
- Roads
- Buildings

Clutha River







Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - Pumpstation

0 0.1 0.2 Km

N W E S

Project: 1-E0173.00

Date: 30/04/2025

Legend

Debris Flood Inundation Height (m)

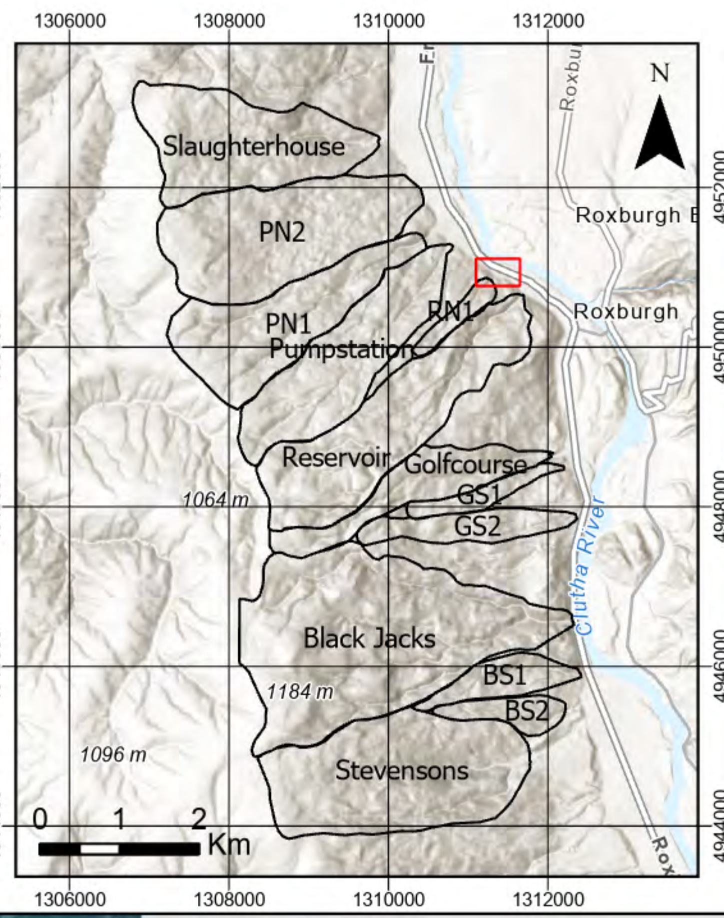
Value

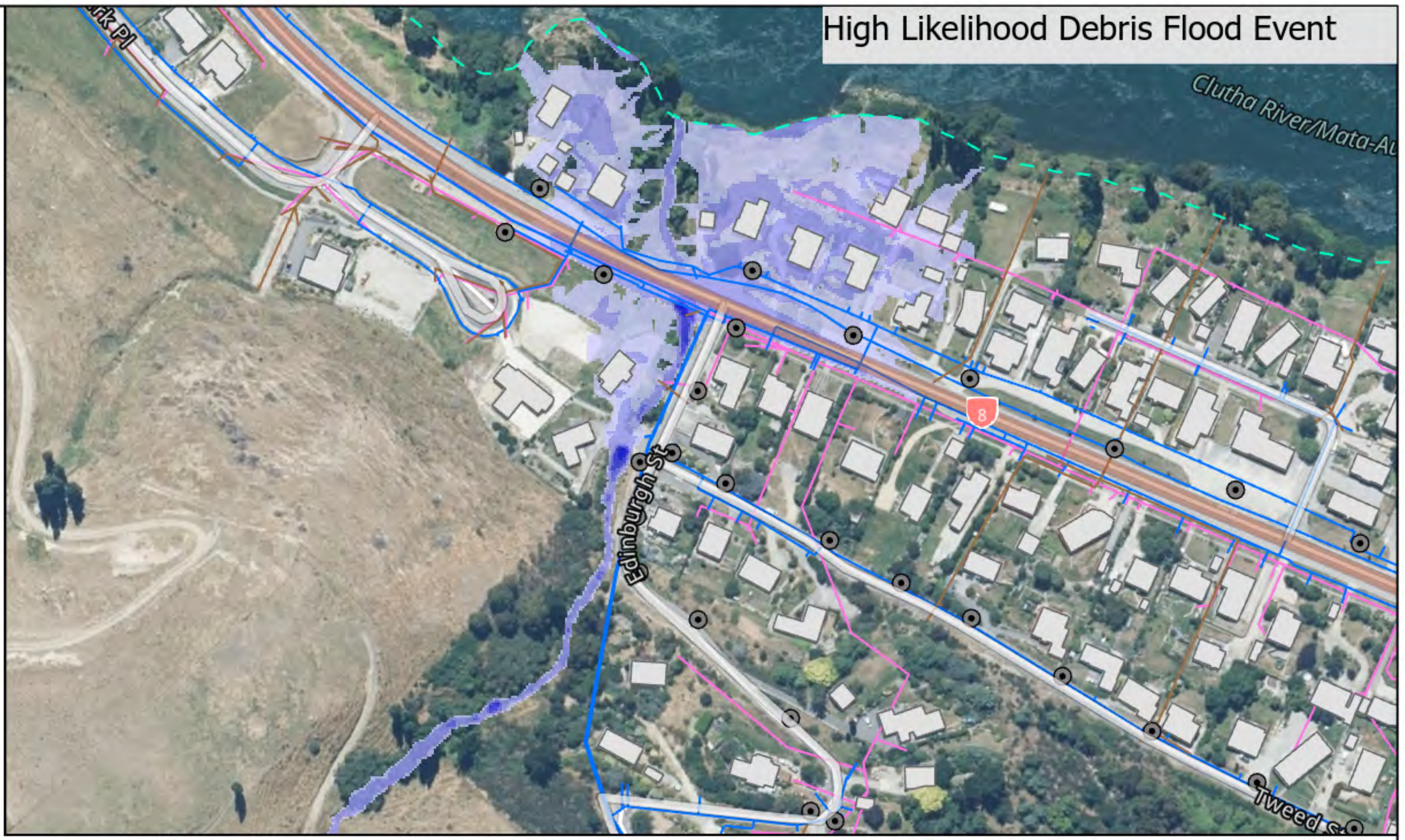
- <0.01
- 0.01-0.5
- 0.5-1.0
- 1.0-2.0
- >2

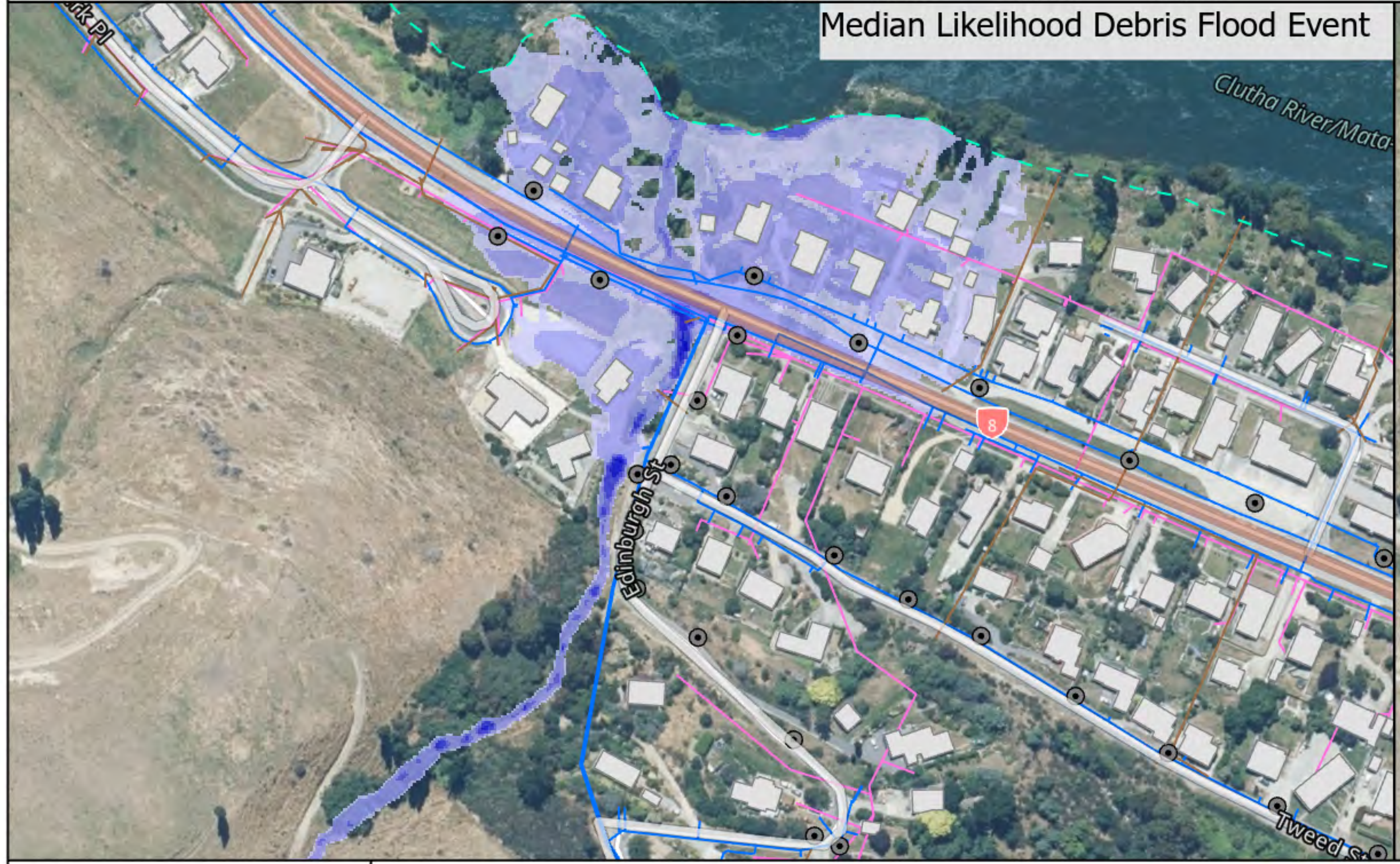
Infrastructure

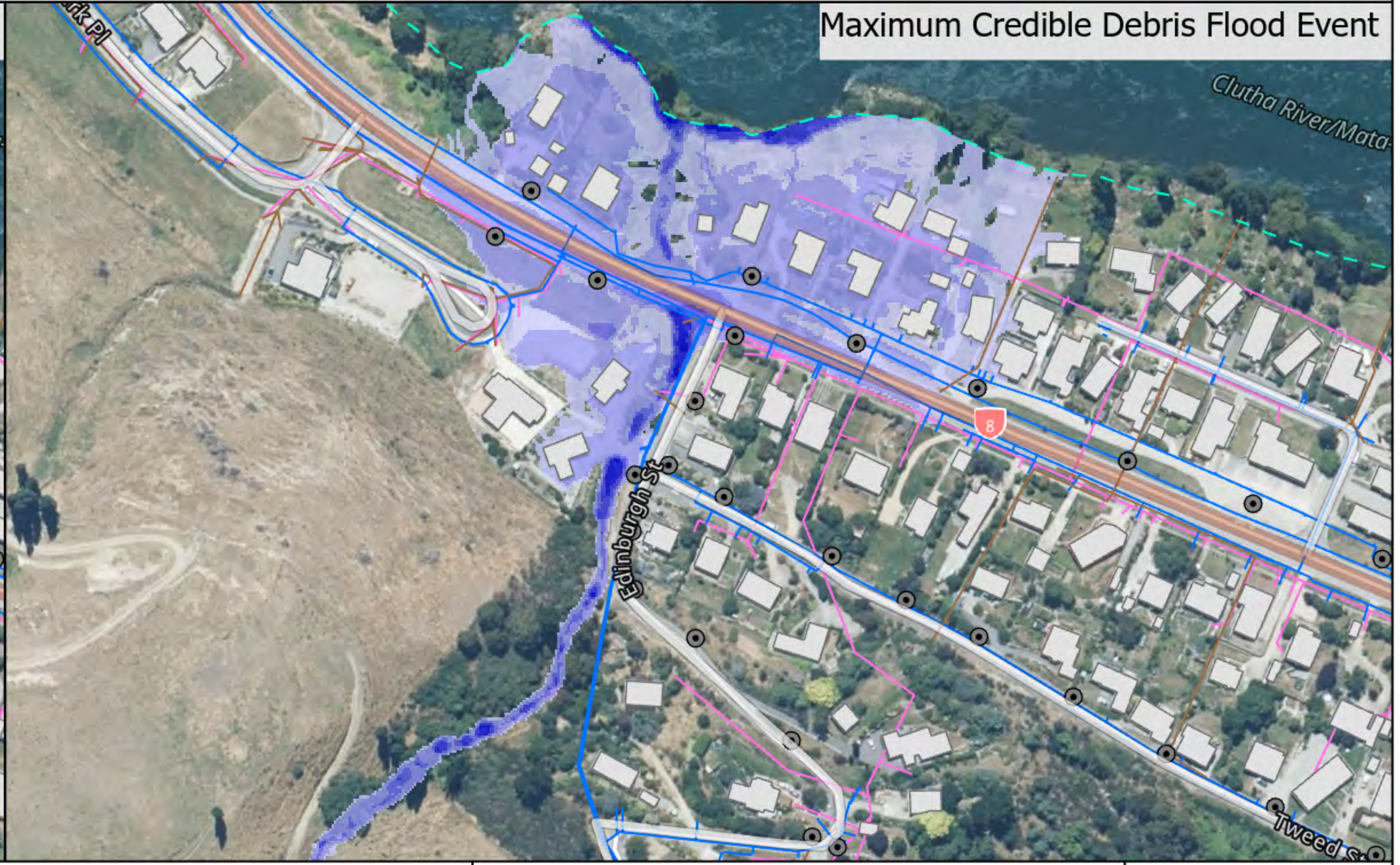
- Distribution power pole
- Electricity Towers
- Stormwater Pipe
- Water Supply Pipe
- Wastewater Pipe
- Roads
- Buildings

Clutha River









Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - RN1

0 0.1 0.2 Km

Project:	**Date:**
1-E0173.00	30/04/2025

N W E S

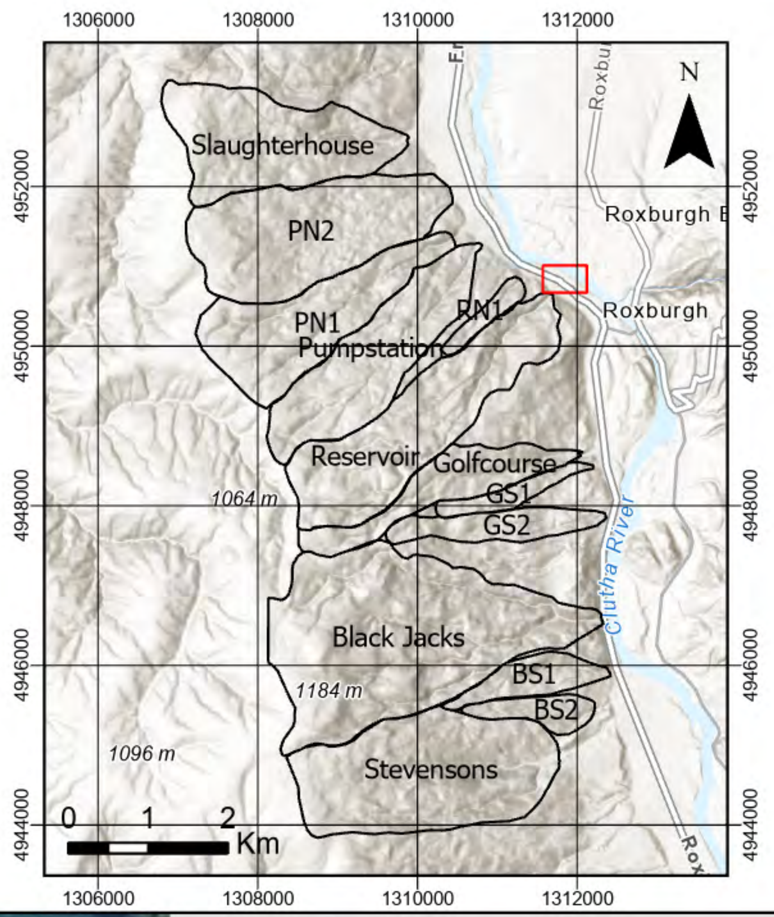
Legend

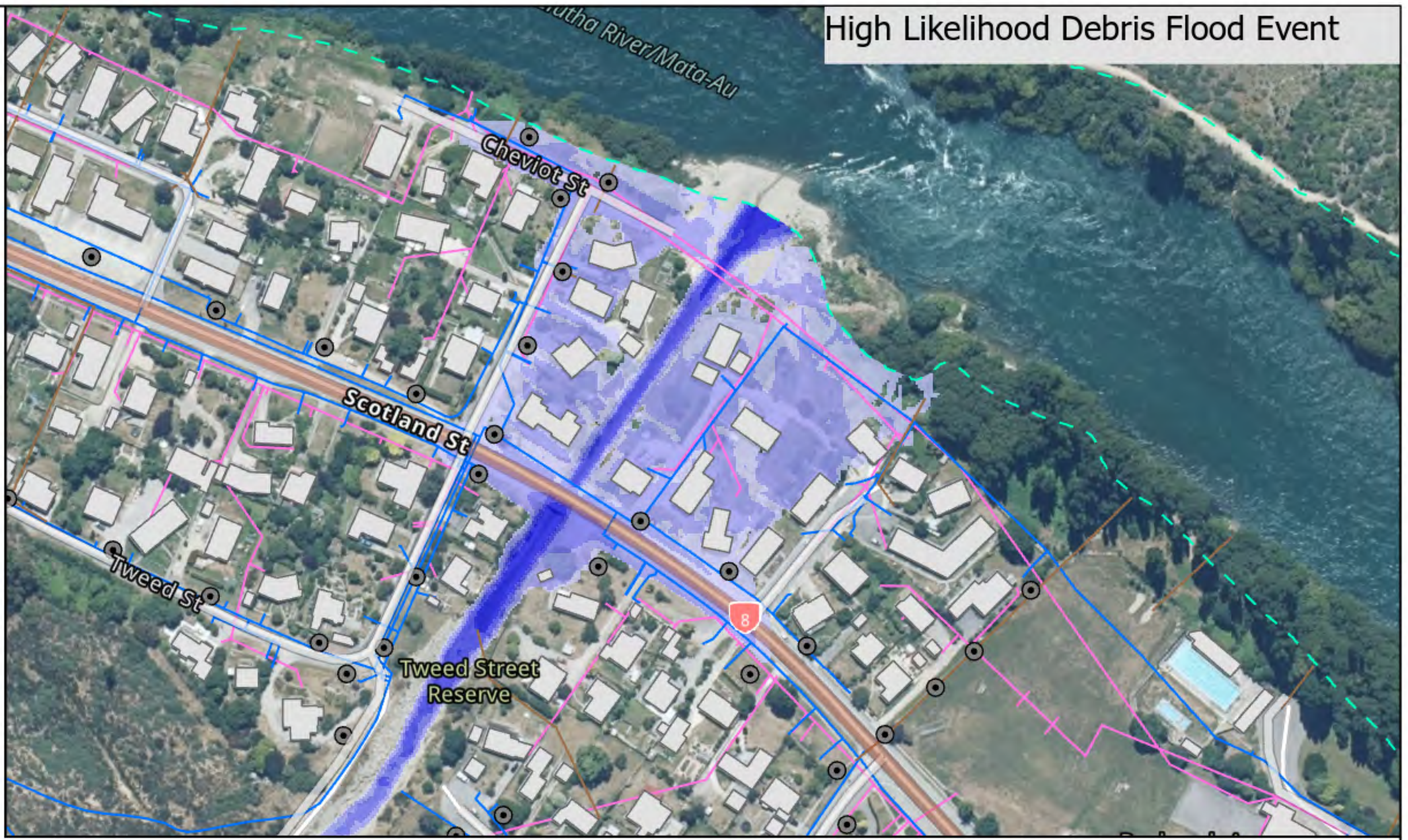
Debris Flood Inundation Height (m)

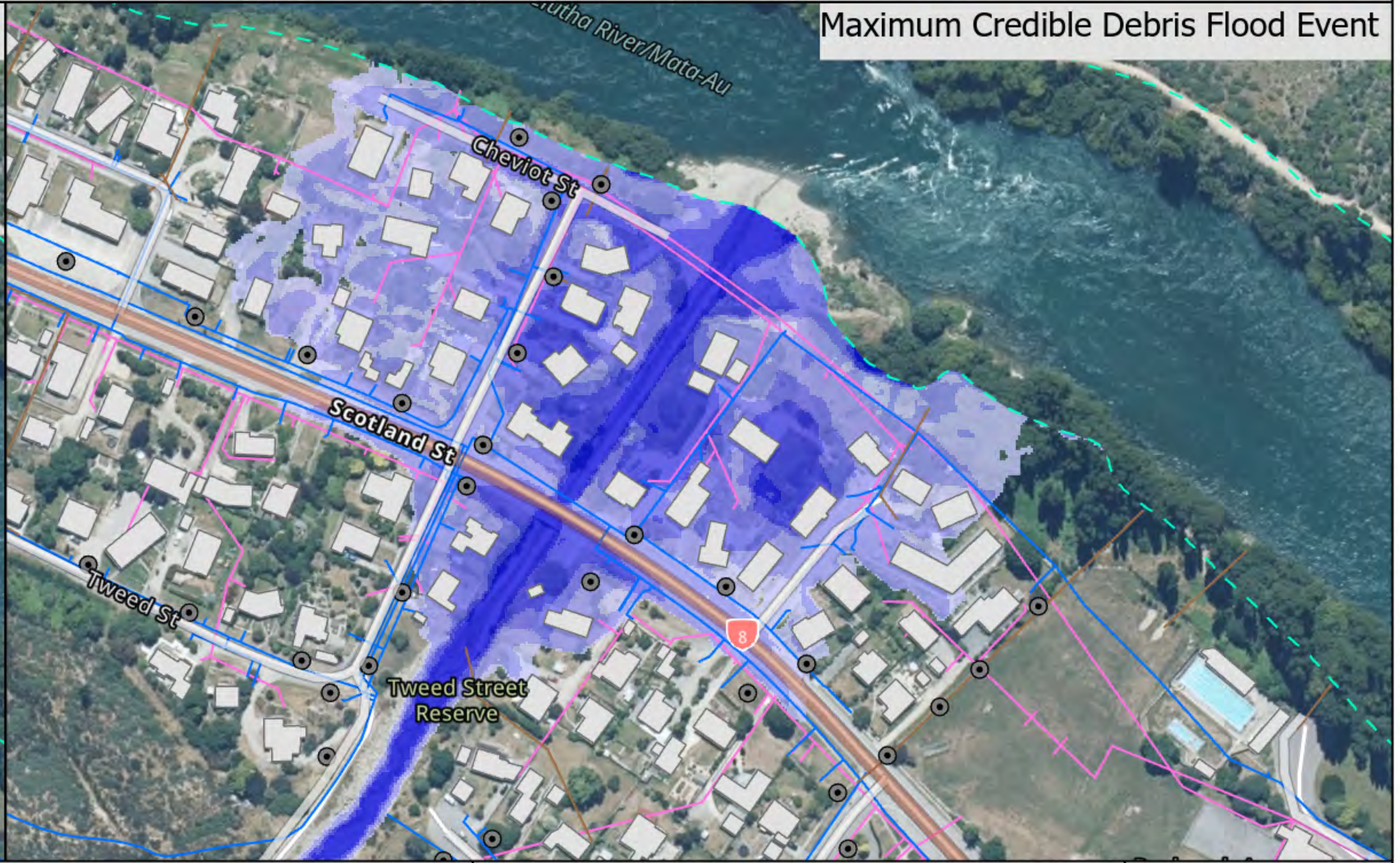
Value
- <0.01
- 0.01-0.5
- 0.5-1.0
- 1.0-2.0
- >2

Infrastructure
- Distribution power pole
- Electricity Towers
- Stormwater Pipe
- Water Supply Pipe
- Wastewater Pipe
- Roads
- Buildings

Clutha River







Prepared by:

Otago Regional Council - Roxburgh Debris Flood

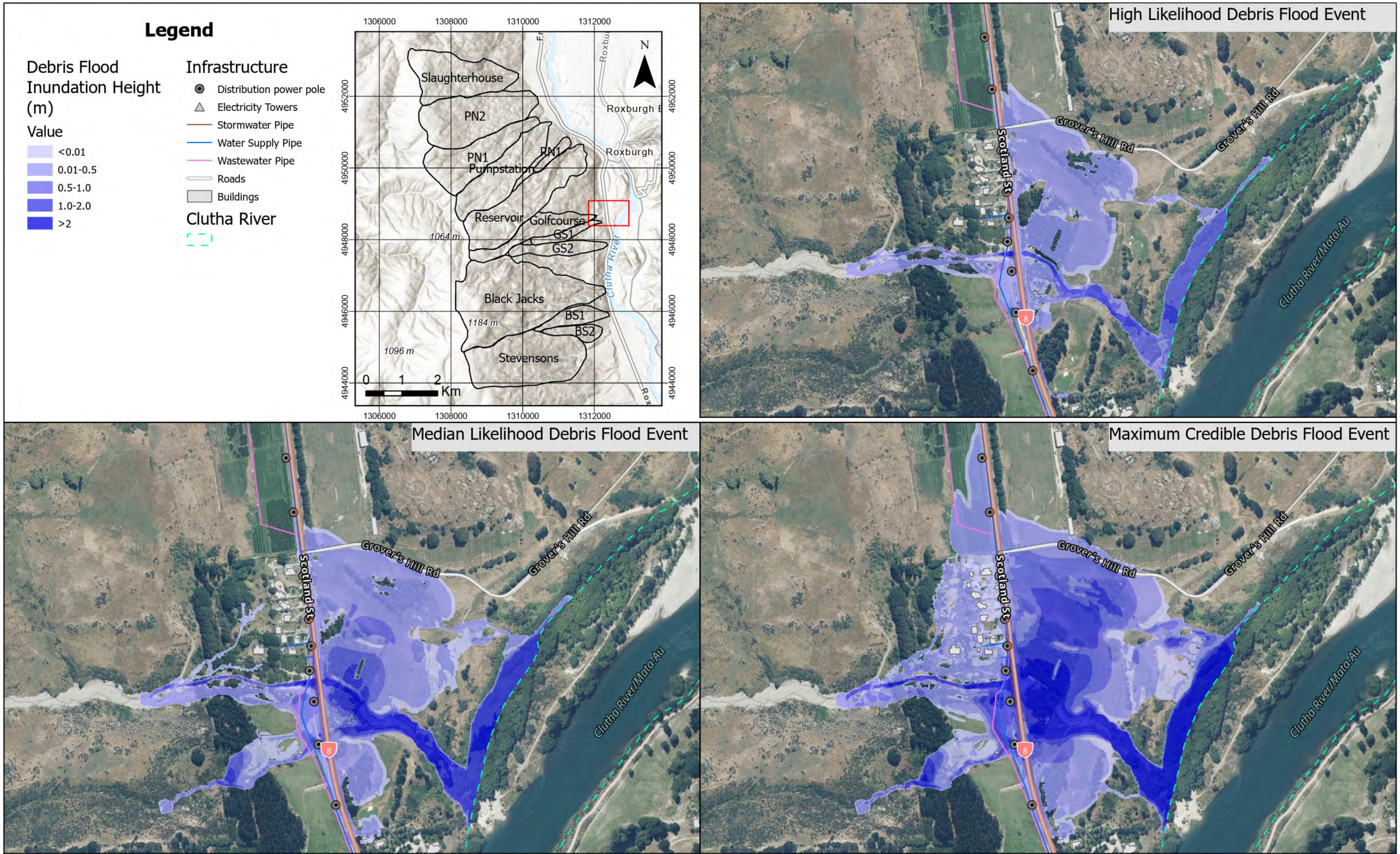
Debris Flood Modelling and Qualitative Risk Assessment - Reservoir Creek

0 0.1 0.2 Km

Project: 1-E0173.00

Date: 07/05/2025

N W E S



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - Golf Course Creek and GS1

0 0.2 0.4 Km

N W E S

Project: 1-E0173.00

Date: 30/04/2025

Legend

Debris Flood Inundation Height (m)

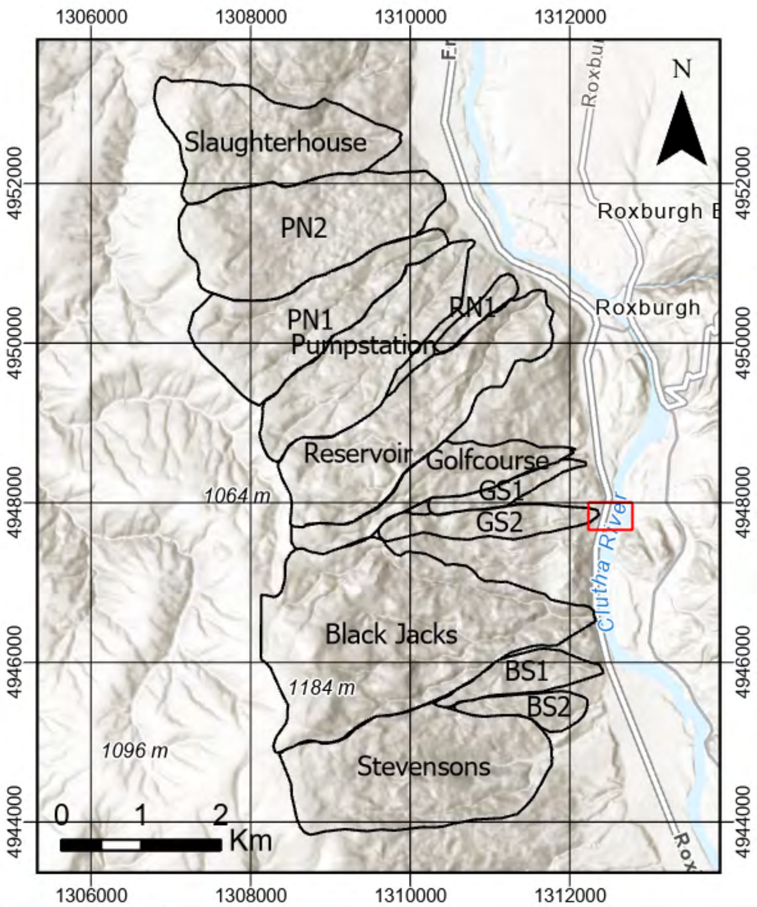
Value

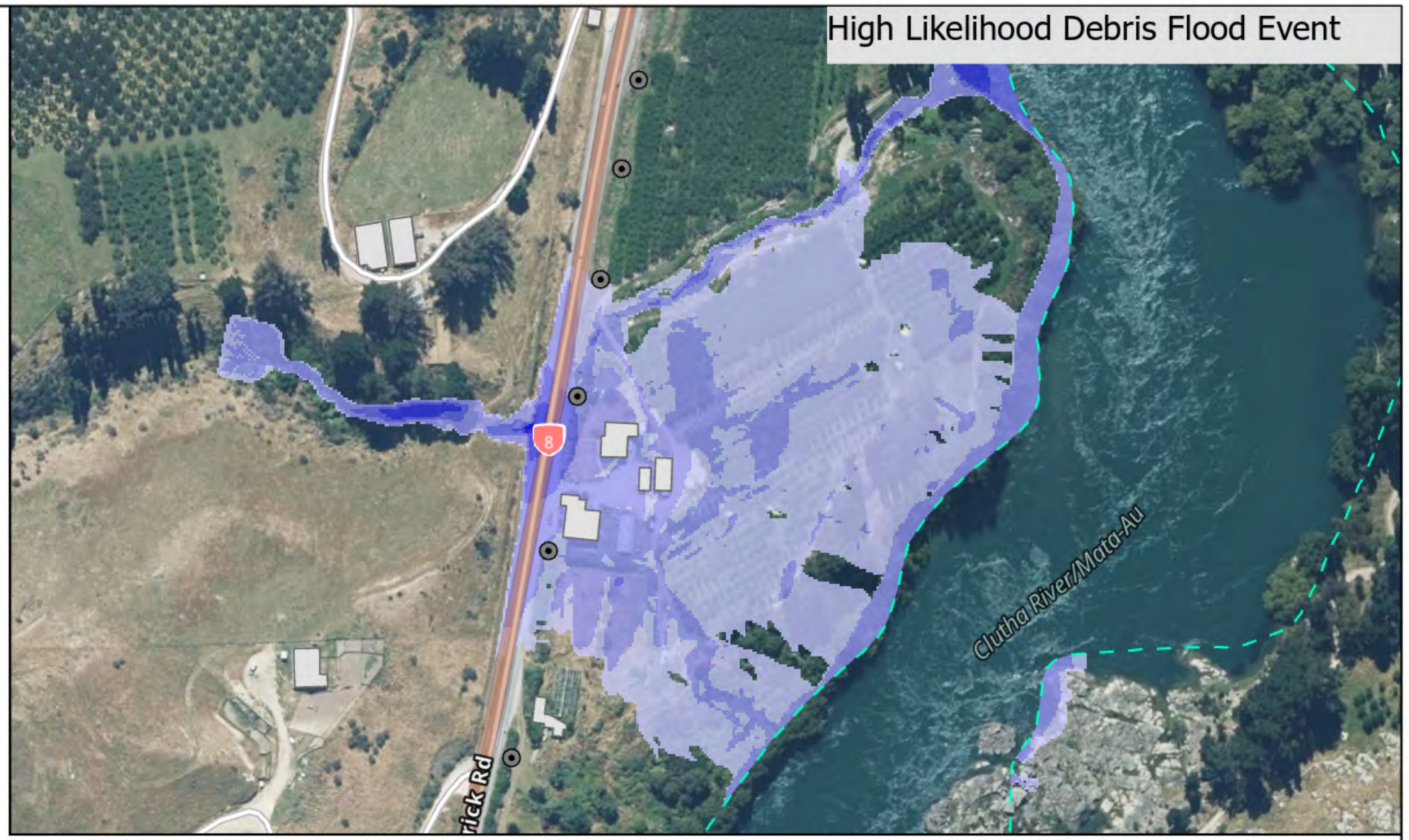
- <0.01
- 0.01-0.5
- 0.5-1.0
- 1.0-2.0
- >2

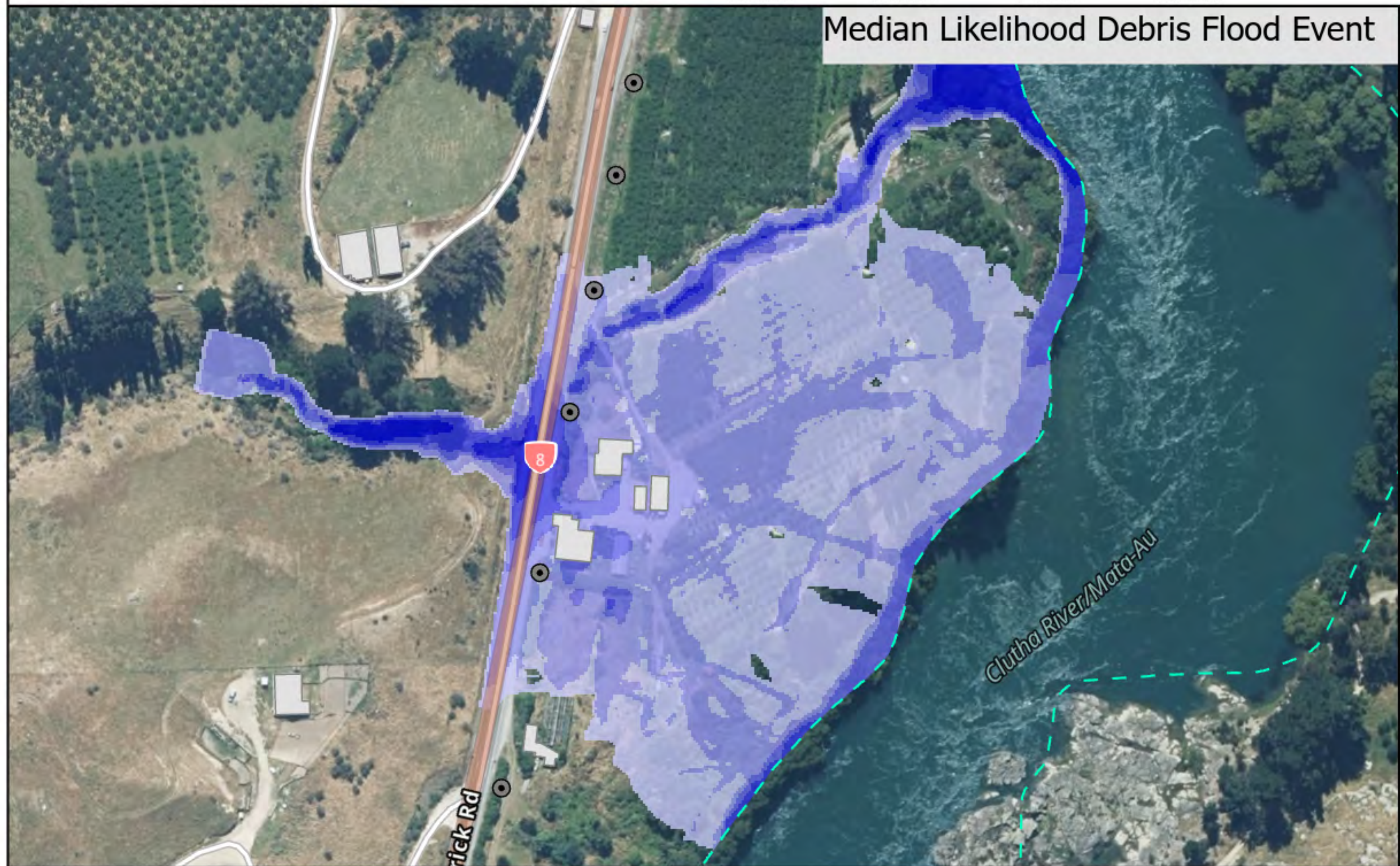
Infrastructure

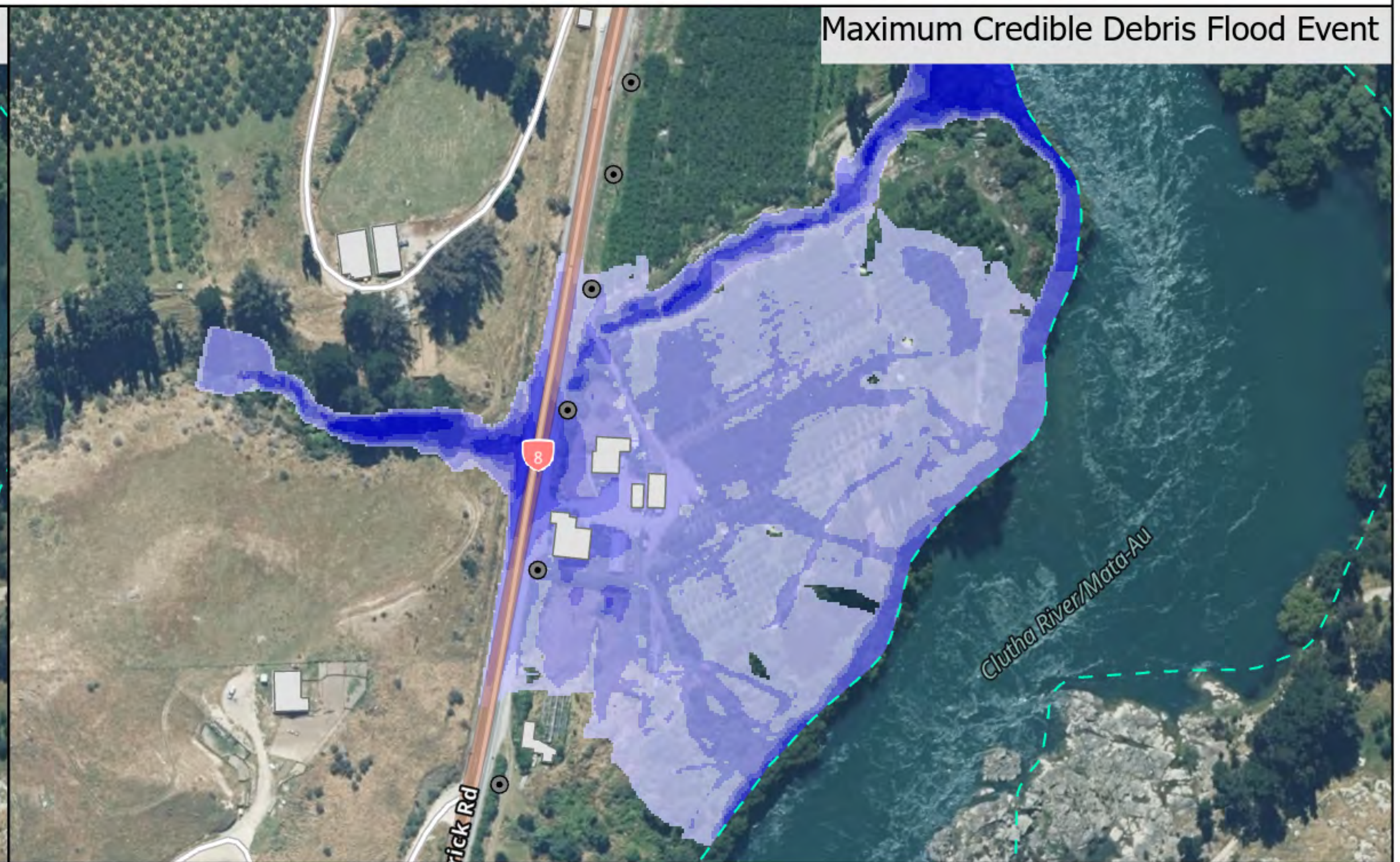
- Distribution power pole
- Electricity Towers
- Stormwater Pipe
- Water Supply Pipe
- Wastewater Pipe
- Roads
- Buildings

Clutha River









Prepared by: wsp

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - GS2

0 0.1 0.2 Km

N E S W

Project: 1-E0173.00

Date: 30/04/2025

Legend

Debris Flood Inundation Height (m)

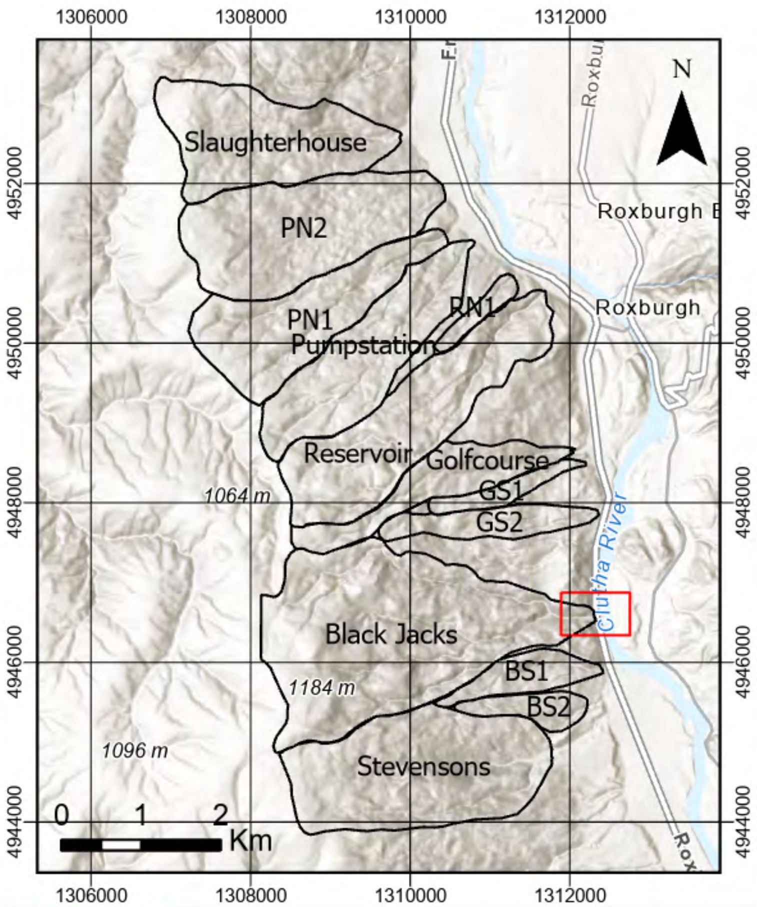
Value

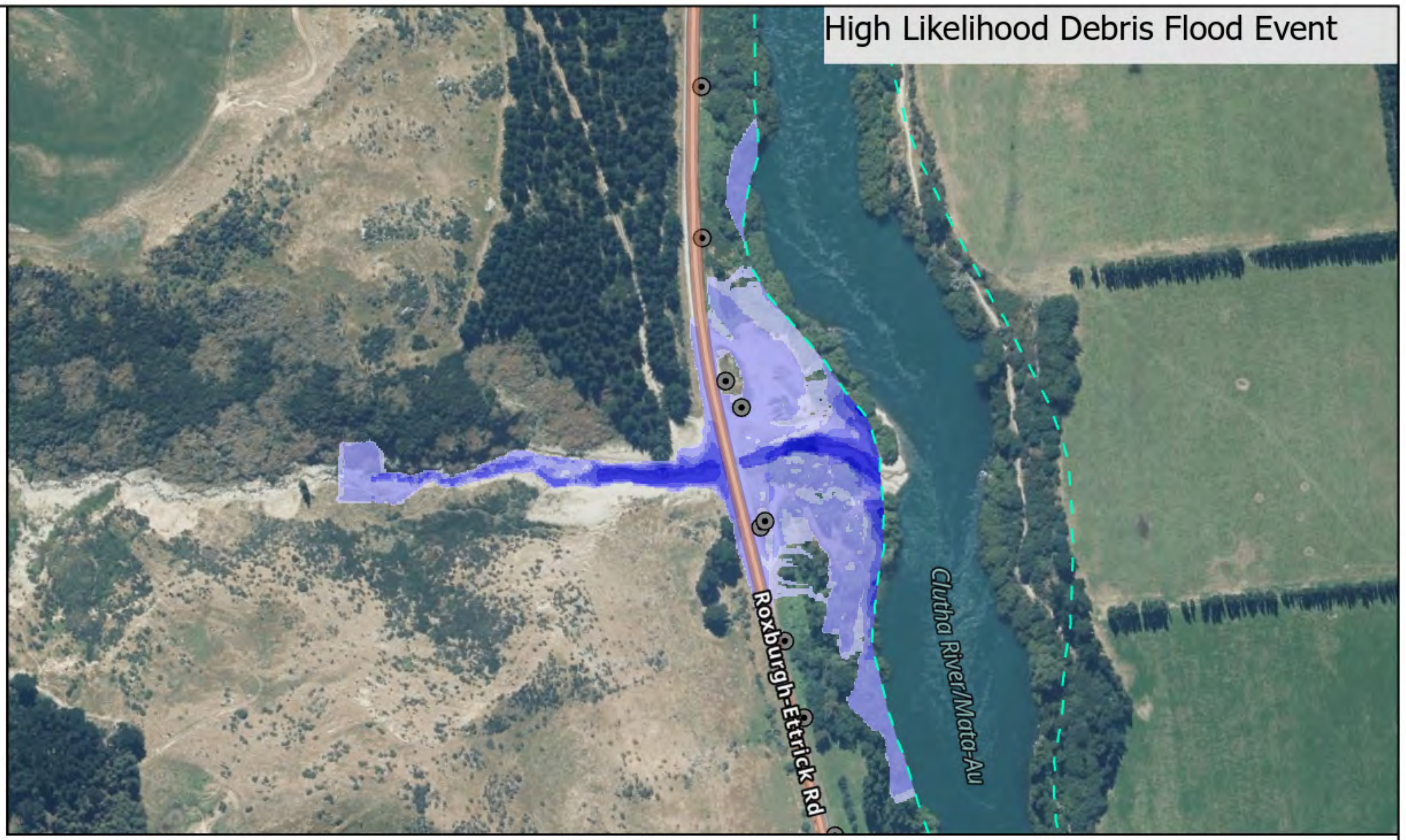
- <0.01
- 0.01-0.5
- 0.5-1.0
- 1.0-2.0
- >2

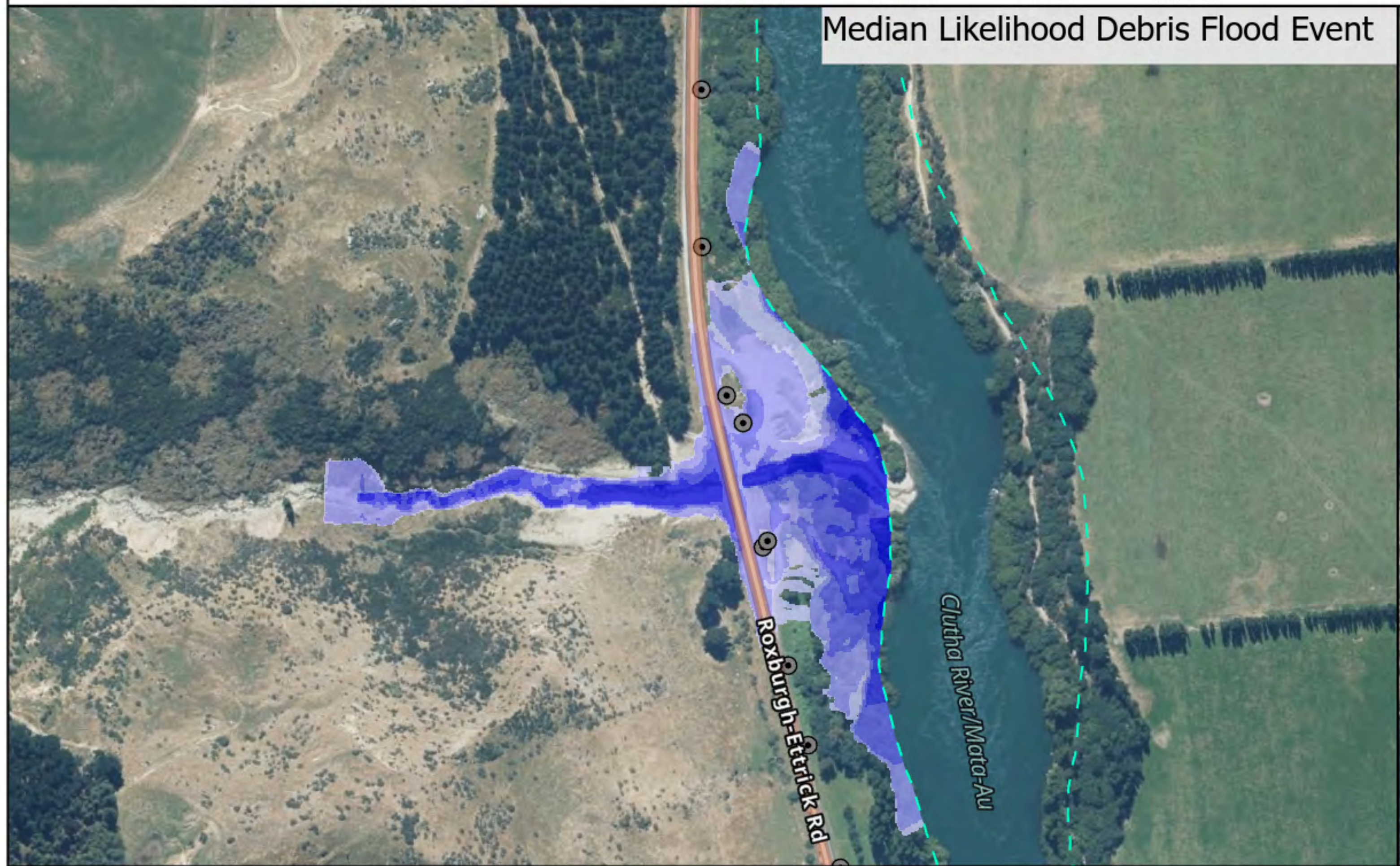
Infrastructure

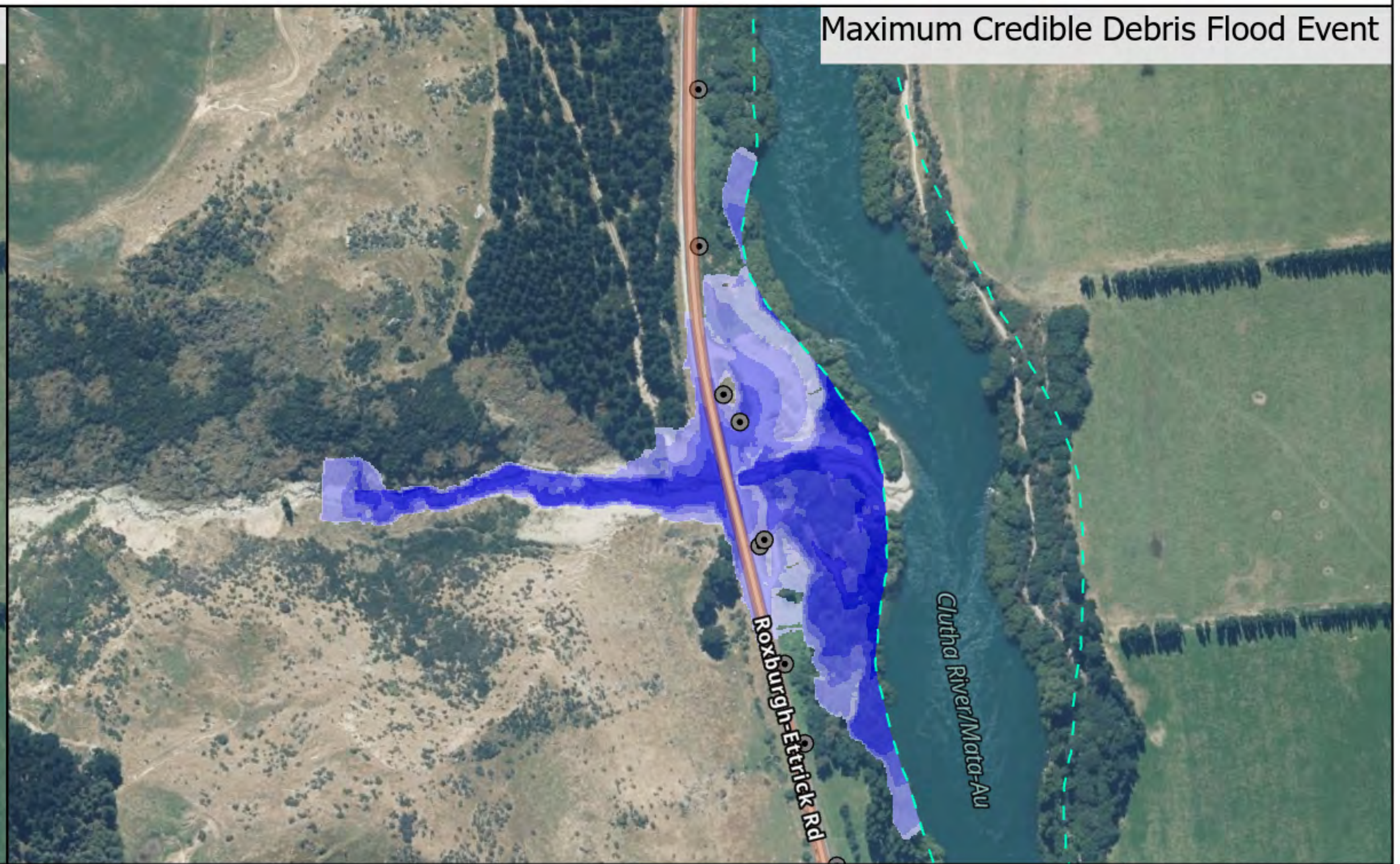
- Distribution power pole
- Electricity Towers
- Stormwater Pipe
- Water Supply Pipe
- Wastewater Pipe
- Roads
- Buildings

Clutha River









Prepared by: wsp

Otago Regional Council - Roxburgh Debris Flood

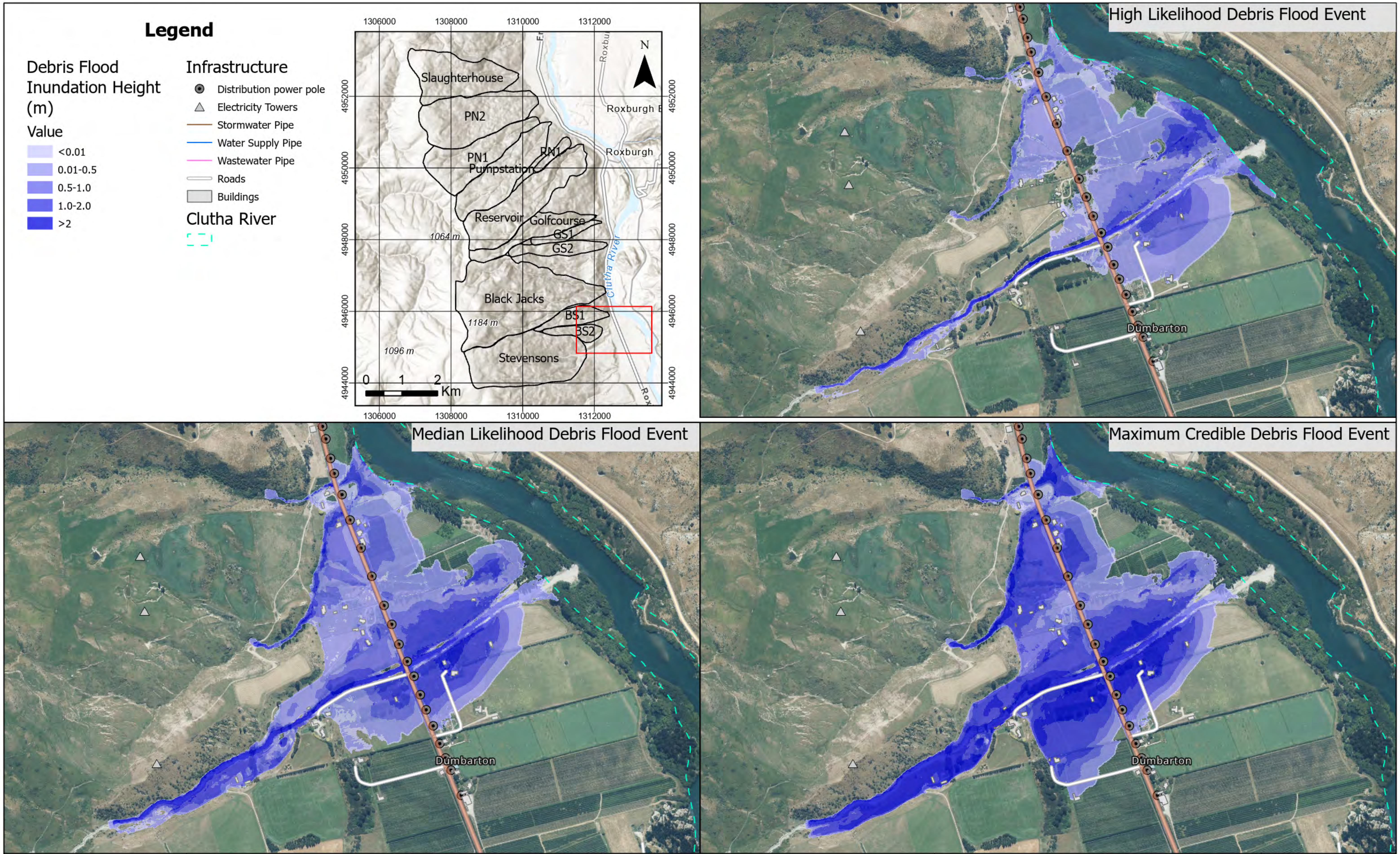
Debris Flood Modelling and Qualitative Risk Assessment - Black Jacks Creek

0 0.15 0.3 Km

N W E S

Project: 1-E0173.00

Date: 30/04/2025



Prepared by:

Otago Regional Council - Roxburgh Debris Flood

Debris Flood Modelling and Qualitative Risk Assessment - Stevensons, BS1, and BS2

0 0.35 0.7 Km

N W E S

Project: 1-E0173.00

Date: 30/04/2025

APPENDIX G – QUALITATIVE RISK ASSESSMENT TABLES

Table 49: Assessed consequences to buildings, people (health and safety), and lifelines in Roxburgh from a high likelihood event in each catchment. Note that no social/cultural buildings or critical buildings were compromised is any scenario and hence, are not included.

Catchment	High Likelihood Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
Slaughterhouse	0	0%	0	0	0.01 - 0.5 m of inundation affecting 170 m section of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
PN2	7	47%	0	0	0.01 - 0.5 m of inundation affecting 160 m section of SH8. Some distribution poles receive 0.5 -1 m inundation - may be partial repair required. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
PN1	1	50%	0	0	0.01 - 0.5 m of inundation affecting 140 m section of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
Pumpstation	4	44%	5	0	0.01 - 0.5 m of inundation affecting 180 m section of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
RN1	0	0%	0	0	0.01 - 0.5 m of inundation affecting 180 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
Reservoir	1	3%	0	0	0.01 - 0.5 m of inundation affecting 300 m of road including SH8, Tweed Street, and Cheviot Street. Wastewater pipe at footbridge crossing exposed to 2 m of inundation and may be damaged. Affected lifelines out for service for 1 day to 1 week affecting ≥20% of population. Moderate consequence.

Catchment	High Likelihood Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
Golf Course	0	0%	0	0	0.01 - 0.5 m of inundation affecting 350 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
GS1	0	0%	0	0	0.01 - 0.5 m of inundation affecting 170 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
GS2	1	20%	0	0	0.01 - 1.0 m of inundation affecting 160 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
Black Jacks	0	0%	0	0	0.01 - 1.0 m of inundation affecting 190 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
BS1	1	33%	0	0	0.01 - 1.0 m of inundation affecting 120 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
BS2	2	29%	0	0	0.01 - 1.0 m of inundation affecting 160 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
Stevensons	4	25%	0	0	0.01 - 1.0 m of inundation affecting 160 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.

Table 50: Assessed consequences to buildings, people (health and safety), and lifelines in Roxburgh from a median likelihood event in each catchment.

Catchment	Median Likelihood Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
Slaughterhouse	5	63%	3	0	0.01 - 2 m of inundation affecting 190 m section of SH8. Culvert exposed to 5 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). Five distribution poles exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
PN2	12	80%	7	0	0.01 - 0.5 m of inundation affecting 40 m section of SH8. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
PN1	2	100%	0	0	0.01 - 1.0 m of inundation affecting 130 m section of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
Pumpstation	4	44%	1	5	0.01 - 2.0 m of inundation affecting 200 m section of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
RN1	0	0%	0	0	0.01 - 0.5 m of inundation affecting 180 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
Reservoir	15	48%	8	0	0.01 - 1.0 m of inundation affecting 490 m of road including SH8, Tweed Street, Cheviot Street, and Leitholm Place. 4 m of inundation in channel at SH8 bridge which could compromise bridge structure and attached infrastructure as a result. Cheviot Street footbridge and wastewater pipe exposed to 4 m of

Catchment	Median Likelihood Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
					inundation and may be severely damaged/destroyed. Affected lifelines out for service for 1 week to 1 month affecting ≥20% of population. Replacement of footbridge unlikely to be a priority. Major consequence.
Golf Course	0	0%	0	0	0.01 - 1.0 m of inundation affecting 530 m of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
GS1	1	50%	0	0	0.01 - 1.0 m of inundation affecting 200 m of SH8. One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
GS2	3	60%	3	0	0.01 - 2.0 m of inundation affecting 180 m of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure. One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.
Black Jacks	0	0%	0	0	0.01 - 1.0 m of inundation affecting 200 m of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.
BS1	1	33%	0	0	0.01 - 1.0 m of inundation affecting 120 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.

Catchment	Median Likelihood Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
BS2	7	100%	1	0	0.01 - 2.0 m of inundation affecting 180 m of SH8. One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.
Stevensons	14	88%	0	0	0.01 - 2.0 m of inundation affecting 180 m of SH8. One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.

Table 51: Assessed consequences to buildings, people (health and safety), and lifelines in Roxburgh from a maximum credible event in each catchment.

Catchment	Maximum Credible Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
Slaughterhouse	8	100%	2	3	0.01 - 2 m of inundation affecting 120 m section of SH8. 4 metres of inundation at culvert which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). Five distribution poles exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
PN2	14	93%	5	2	0.01 - 0.5 m of inundation affecting 40 m section of SH8. One distribution pole servicing an isolated area exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.

Catchment	Maximum Credible Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
PN1	2	100%	0	0	0.01 - 2.0 m of inundation affecting 140 m section of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
Pumpstation	7	78%	0	6	0.01 - 2.0 m of inundation affecting 210 m section of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). One distribution pole exposed to > 0.5 m inundation and may require repair. Water treatment plant exposed to > 1 m of inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
RN1	2	11%	3	0	0.01 - 0.5 m of inundation affecting 200 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
Reservoir	22	71%	18	3	0.01 - 2.0 m of inundation affecting > 500 m of road including SH8, Tweed Street, Cheviot Street, and Leitholm Place. 5 m of inundation in channel at SH8 bridge which could compromise bridge structure and attached infrastructure as a result (water supply pipe, Chorus Cable). Cheviot Street footbridge and wastewater pipe exposed to 5 m of inundation and may be severely damaged/destroyed. Affected lifelines out for service for > 1 month affecting ≥20% of population. Replacement of footbridge unlikely to be a priority. Catastrophic consequence.

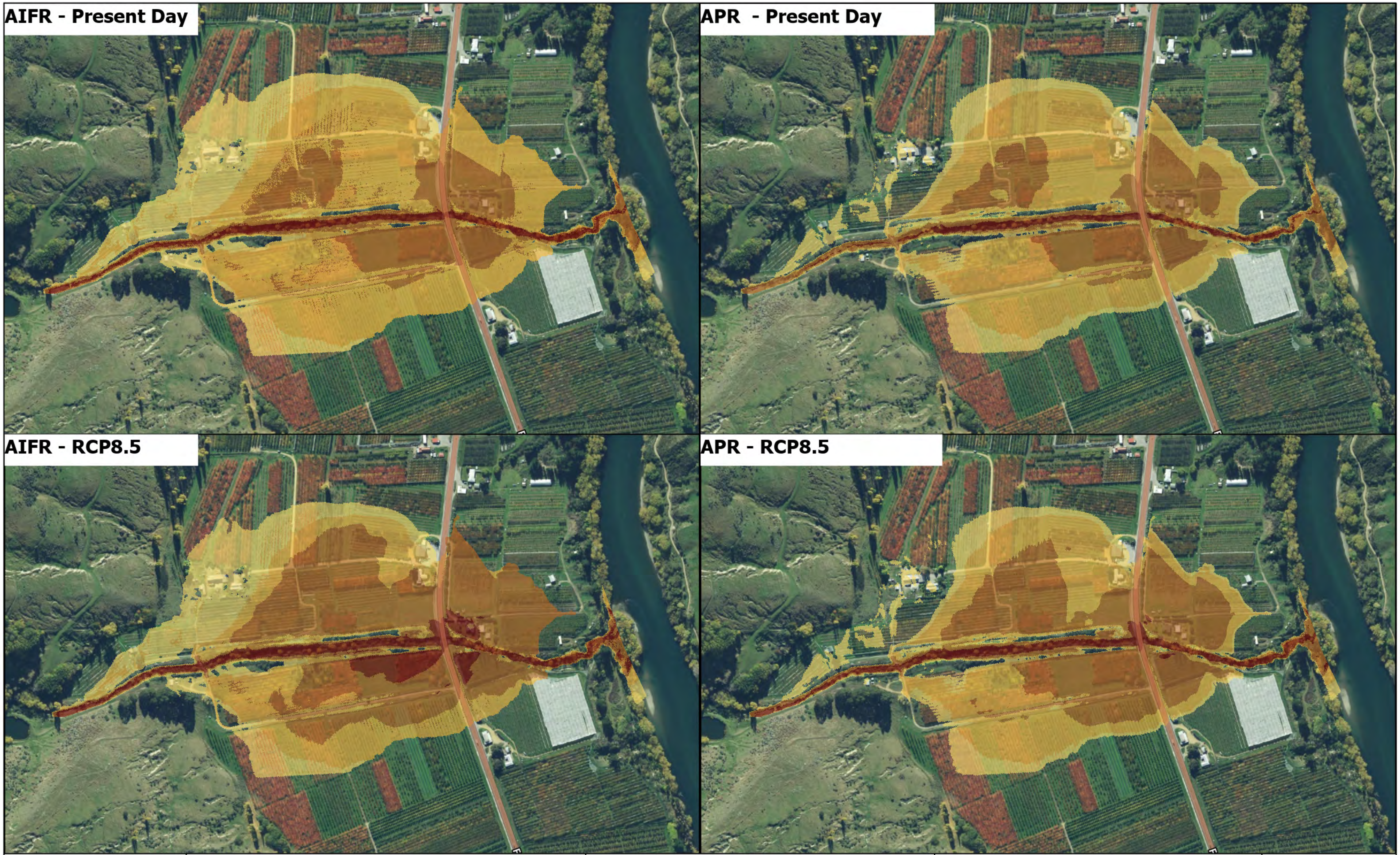
Catchment	Maximum Credible Event				
	Built		Health and Safety		Lifelines
	Number of buildings compromised	% of buildings in hazard area compromised	Injuries	Fatalities	
Golf Course	0	0%	0	0	0.01 - 2.0 m of inundation affecting 760 m of SH8. Culvert exposed to >5 metres of inundation which is likely to damage crossing and attached infrastructure (water supply pipe and chorus cable). Three distribution poles exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.
GS1	1	50%	0	0	0.01 - 1.0 m of inundation affecting 250 m of SH8. Two distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 day to 1 week affecting <20% of town population. Minor consequence.
GS2	3	60%	0	0	0.01 - 2.0 m of inundation affecting 180 m of SH8. Culvert exposed to 4 metres of inundation which is likely to damage crossing and attached infrastructure. One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.
Black Jacks	0	0%	0	0	0.01 - 2.0 m of inundation affecting 210 m of SH8. Culvert exposed to >5 metres of inundation which is likely to damage crossing and attached infrastructure. One distribution pole exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.
BS1	2	67%	0	0	0.01 - 1.0 m of inundation affecting 120 m of SH8. Other infrastructure unlikely to be affected. Affected lifelines out for service for 2 hours to 1 day affecting <20% of town population. Insignificant consequence.
BS2	7	100%	1	0	0.01 - 2.0 m of inundation affecting 180 m of SH8. Three distribution poles exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting <20% of town population. Minor consequence.

Catchment	Maximum Credible Event				
	Built		**Health and Safety**		**Lifelines**
	Number of buildings compromised	**% of buildings in hazard area compromised**	**Injuries**	**Fatalities**	
Stevensons	18	100%	0	3	0.01 - 2.0 m of inundation affecting 480 m of SH8. Culvert exposed to >5 metres of inundation which is likely to damage crossing and attached infrastructure. Five distribution poles exposed to > 0.5 m inundation and may require repair. Affected lifelines out for service for 1 week to 1 month affecting >20% of town population. Major consequence.

Table 52: Likelihood, consequence, and risk level for each catchment and scenario in this study.

Catchment	High Likelihood Event			Median Likelihood Event			Maximum Credible Event		
	Likelihood	**Maximum Consequence Level**	**Risk**	**Likelihood**	**Maximum Consequence Level**	**Risk**	**Likelihood**	**Maximum Consequence Level**	**Risk**
Slaughterhouse	Likely	2	Acceptable	Possible	5	Significant	Rare	5	Tolerable
PN2	Likely	4	Tolerable	Possible	5	Significant	Rare	5	Tolerable
PN1	Likely	5	Significant	Possible	5	Significant	Rare	5	Tolerable
Pumpstation	Likely	4	Tolerable	Possible	4	Tolerable	Rare	5	Tolerable
RN1	Likely	1	Acceptable	Possible	1	Acceptable	Rare	3	Acceptable
Reservoir	Likely	3	Tolerable	Possible	4	Tolerable	Rare	5	Tolerable
Golf course	Likely	2	Acceptable	Possible	4	Tolerable	Rare	4	Acceptable
GS1	Likely	2	Acceptable	Possible	5	Significant	Rare	5	Tolerable
GS2	Likely	4	Tolerable	Possible	5	Significant	Rare	5	Tolerable
Black Jacks	Likely	1	Acceptable	Possible	2	Acceptable	Rare	2	Acceptable
BS1	Likely	4	Tolerable	Possible	4	Tolerable	Rare	5	Tolerable
BS2	Likely	4	Tolerable	Possible	5	Significant	Rare	5	Tolerable
Stevensons	Likely	4	Tolerable	Possible	5	Significant	Rare	5	Tolerable

APPENDIX H – QUANTITATIVE RISK ASSESSMENT MAPS



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- Slaughterhouse

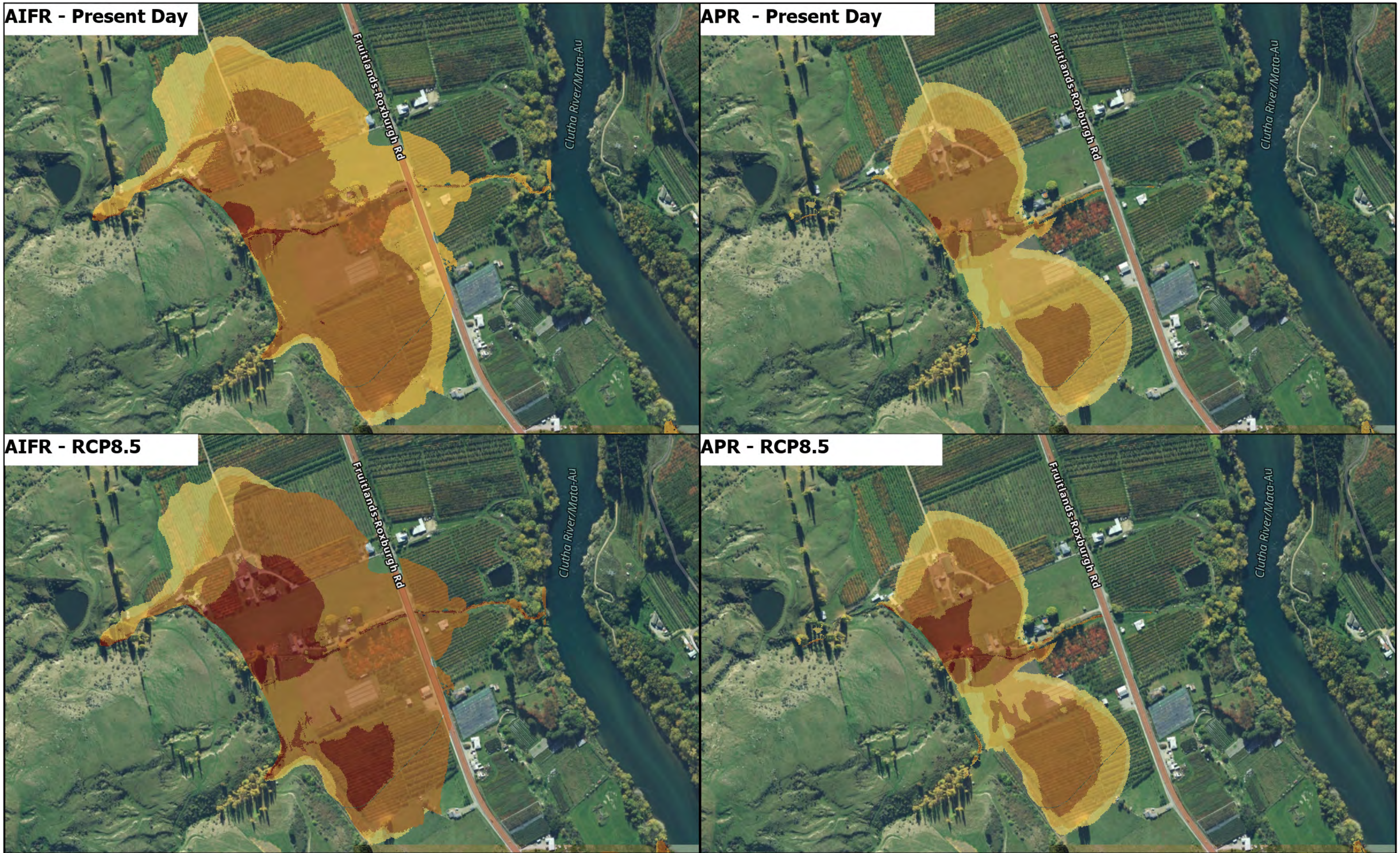
Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.23 0.45
Km

Project: 1-E0173.00

Date: 30/07/2025

N W E S



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- PN2

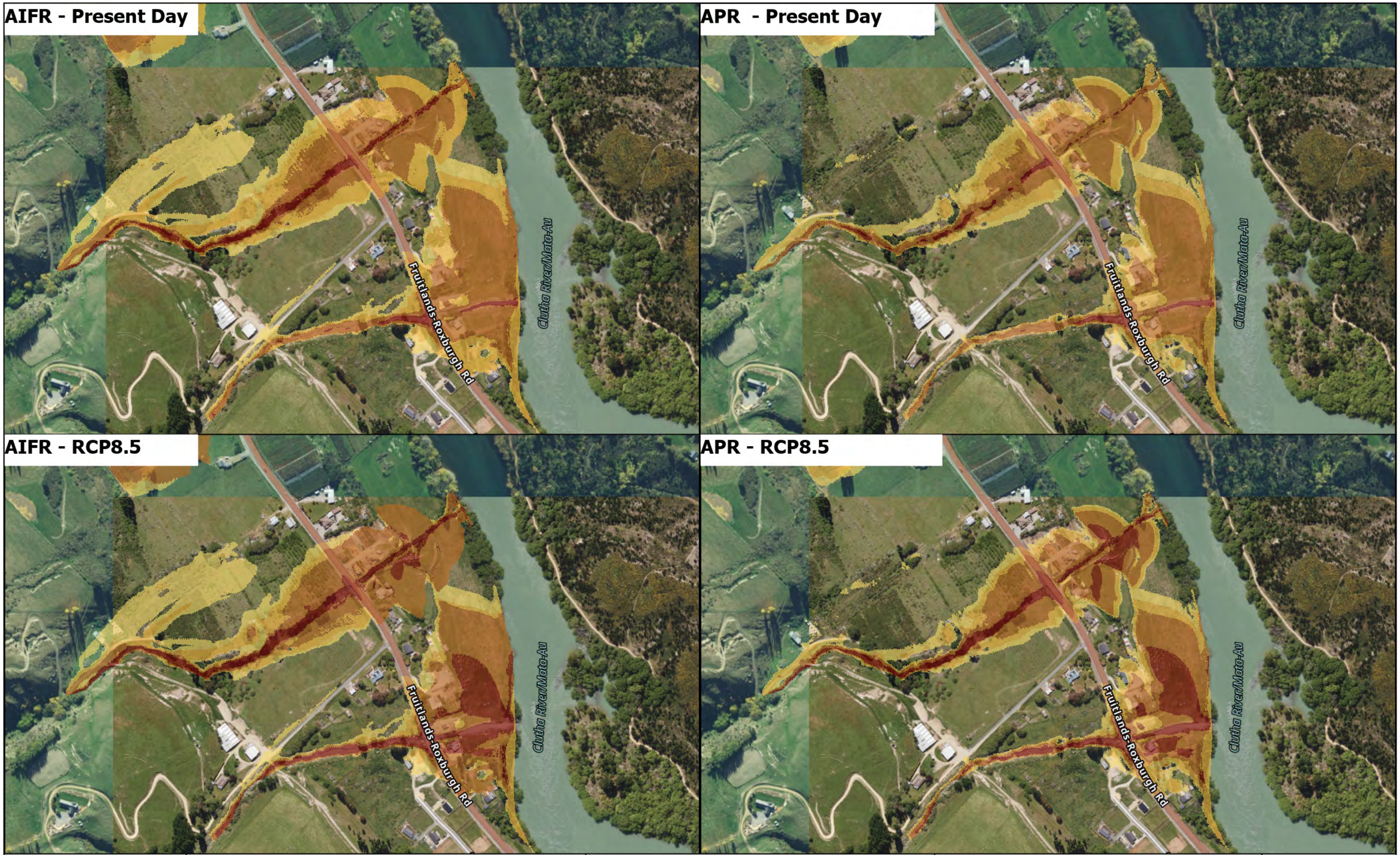
Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.2 0.4
Km

N
W E
S

Project:
1-E0173.00

Date:
30/07/2025



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- PN1 and Pumpstation

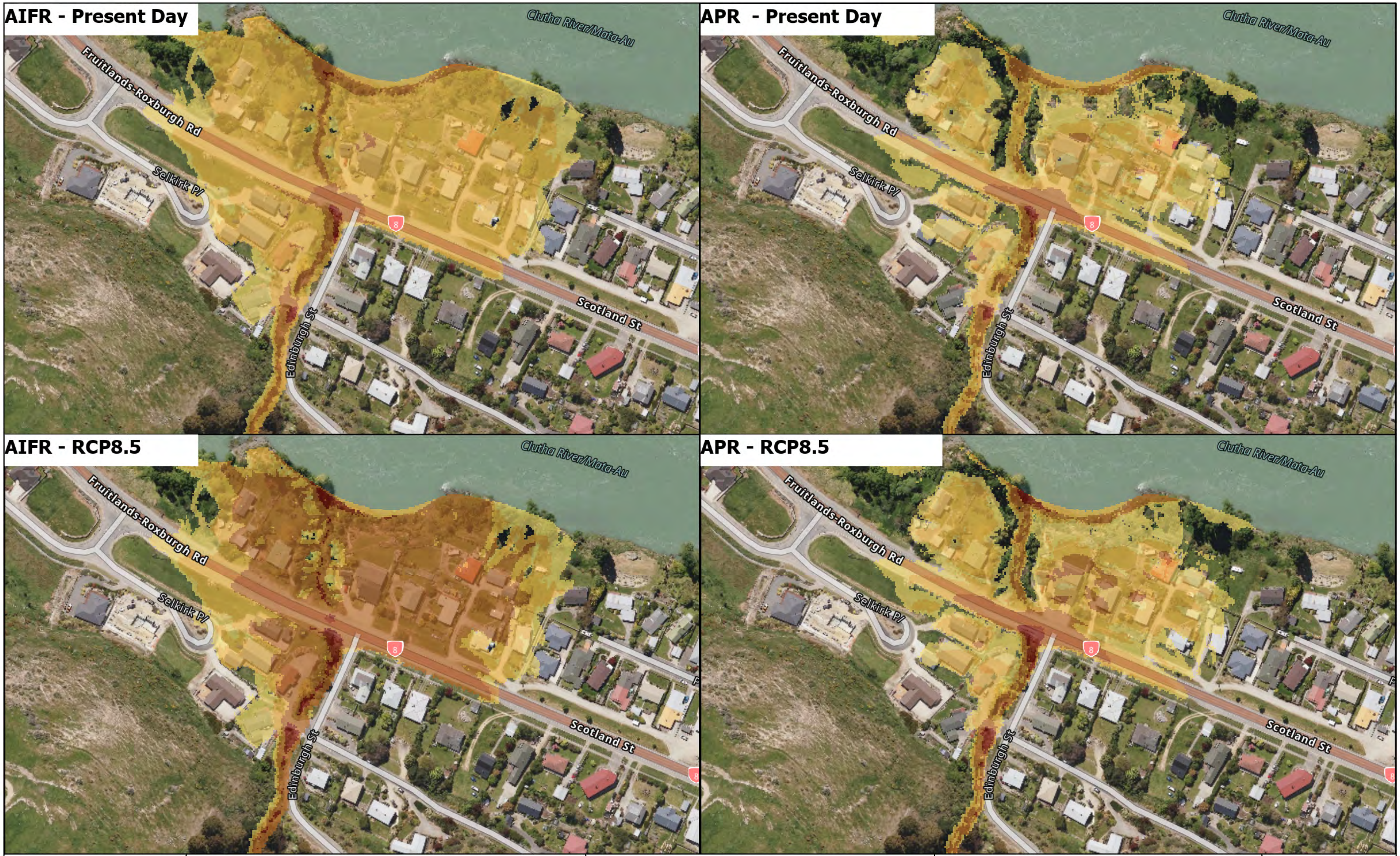
Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.2 0.4
Km

N W E S

Project: 1-E0173.00

Date: 30/07/2025



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- RN1

Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	Significant
	>1E-03	Significant	Significant

0 0.07 0.15
Km

Project: 1-E0173.00

Date: 30/07/2025

N
W E
S

Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment-Reservoir

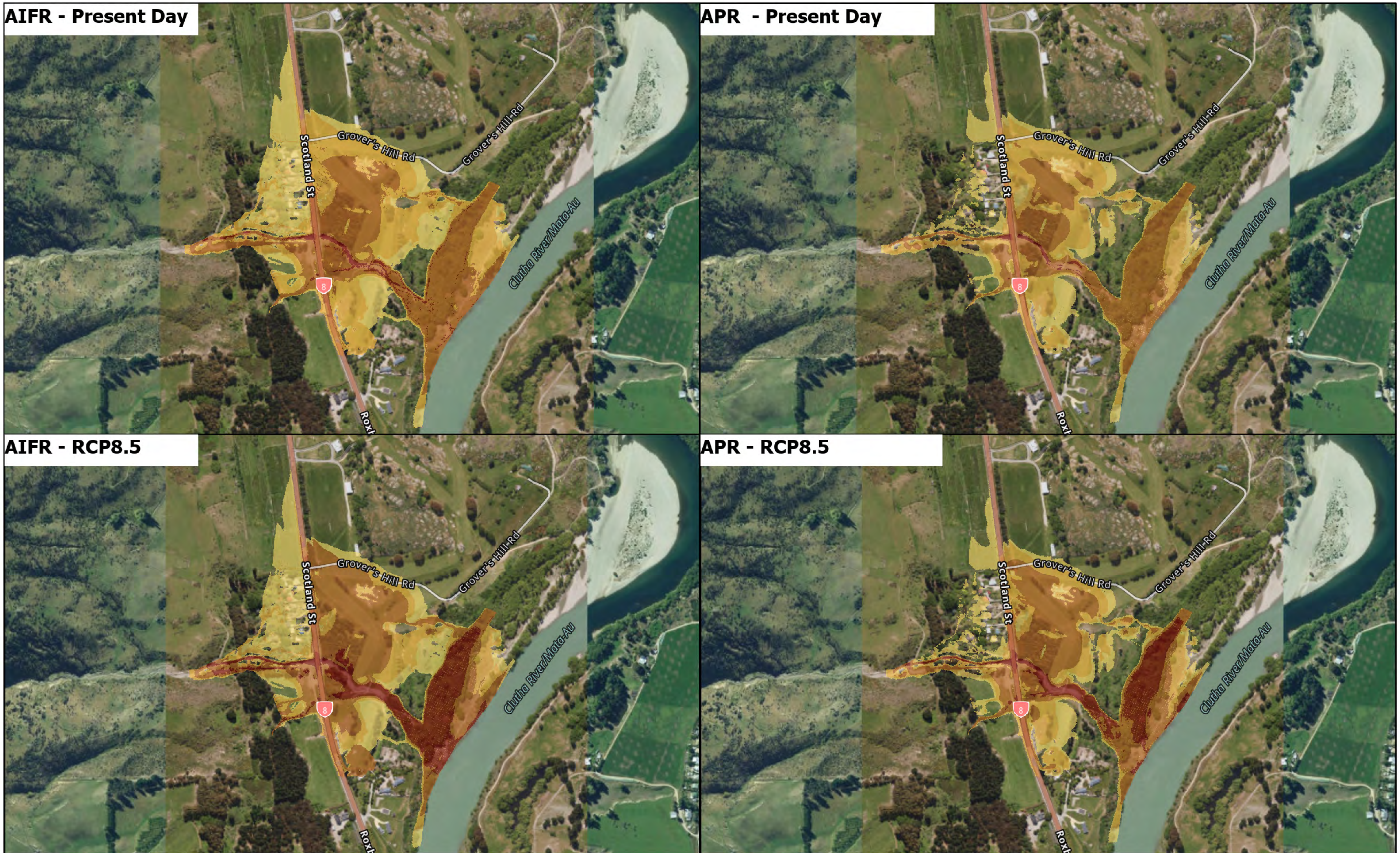
Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.1 0.2
Km

N W E S

Project: 1-E0173.00

Date: 30/07/2025



Prepared by:

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- Golf Course and GS1

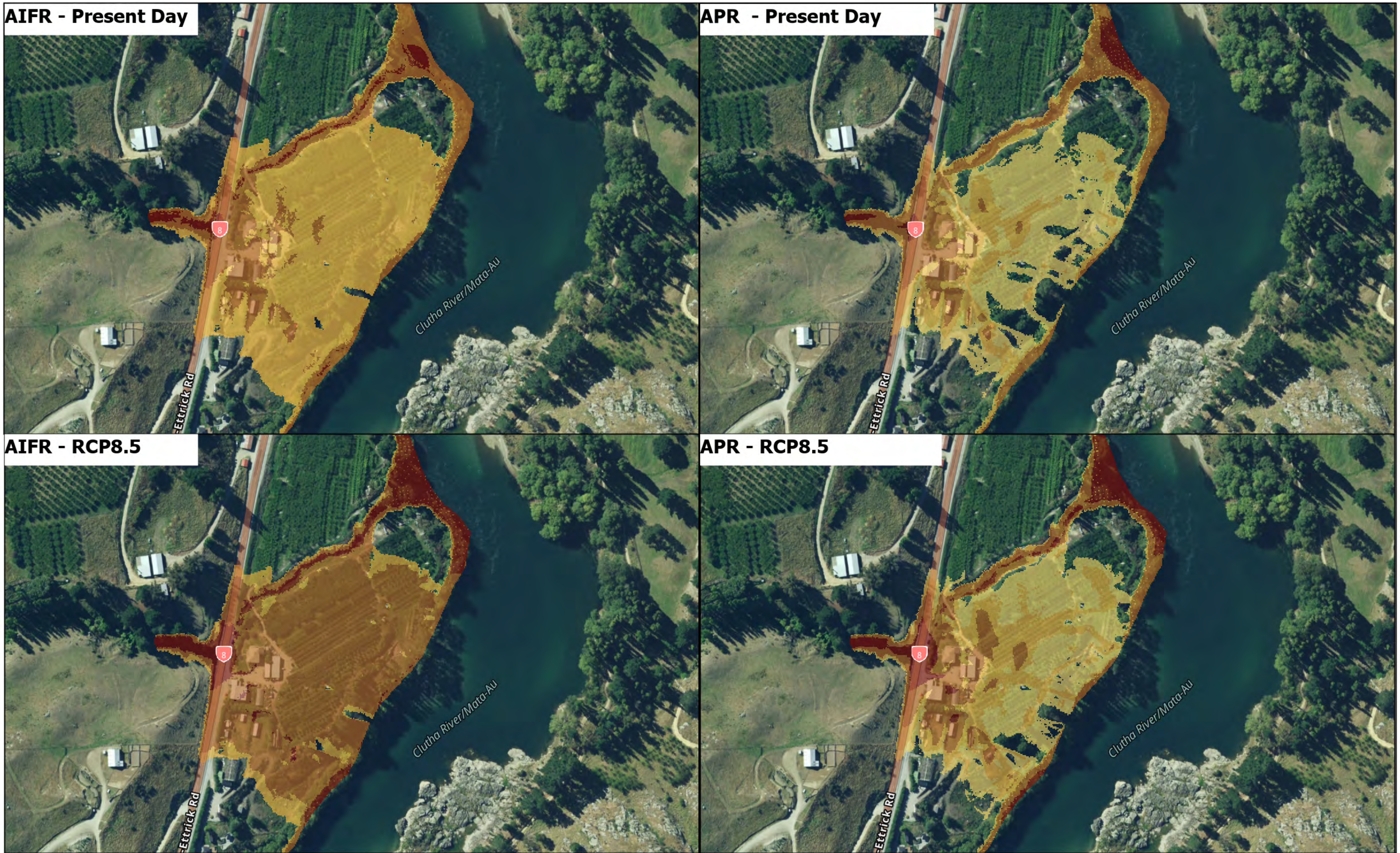
Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.3 0.6
Km

Project:
1-E0173.00

Date:
30/07/2025

N W E S



Prepared by:

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- GS2

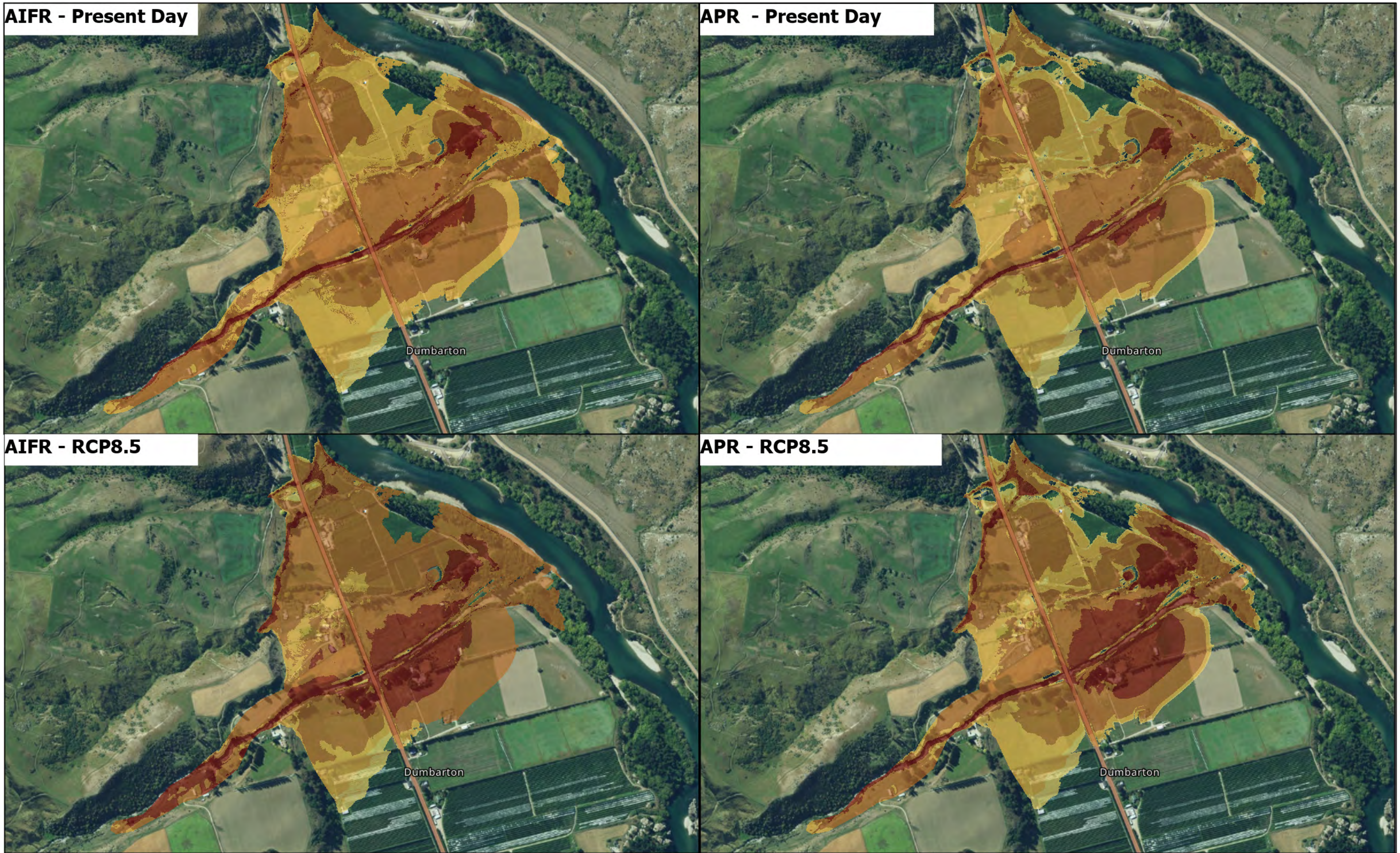
Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.1 0.2
Km

N
W E
S

Project: 1-E0173.00

Date: 30/07/2025



Prepared by:

wsp

Otago Regional Council - Roxburgh Debris Flood

Quantitative Risk Assessment- Stevensons, BS1, and BS2

Colour	Risk Value	Risk Tolerability - Existing Development	Risk Tolerability - New Development
	1E-06 to 1E-05	Acceptable	Tolerable
	1E-05 to 1E-04	Tolerable	Significant
	1E-04 to 1E-03	Significant	
	>1E-03		

0 0.38 0.75
Km

N
W E
S

Project:
1-E0173.00

Date:
30/07/2025

APPENDIX I – SITE INVESTIGATION REPORT

Site Investigation Summary

Introduction

Sub-surface investigations were carried out in November 2025 to supplement the desktop information used to characterise the geomorphology of the debris fans in Roxburgh, Central Otago. The investigations consisted of 8 test pits, which were excavated on two fans (Figure 1). The locations of the test pits were chosen in discussion with the local landowners and were positioned to (i) span the breadth and length of the debris fans as far as practicable, and (ii) avoid local site constraints such as stream channels, driveways, and underground services.

- TP01-TP06 were excavated by a 16-tonne excavator on Stevensons alluvial fan in Dumbarton, approximately 5 km south of Roxburgh township. Of these, TP01 and TP02 were located on the true right bank of the stream, while TP03-TP06 were located on the true left bank of the stream (Figure 2).
- TP07 and TP08 were excavated on Pumpstation alluvial fan just north of Roxburgh township. Both investigations were undertaken on the true left bank due to access restrictions, however, TP08 is on the lower fan downstream of SH8, while TP07 is directly upstream of SH8 (Figure 2).

These investigations aimed to identify and characterise debris flood deposits in the study area and, if possible, collect carbon-rich material suitable for radiocarbon dating to help calibrate the debris flood modelling and risk assessment.

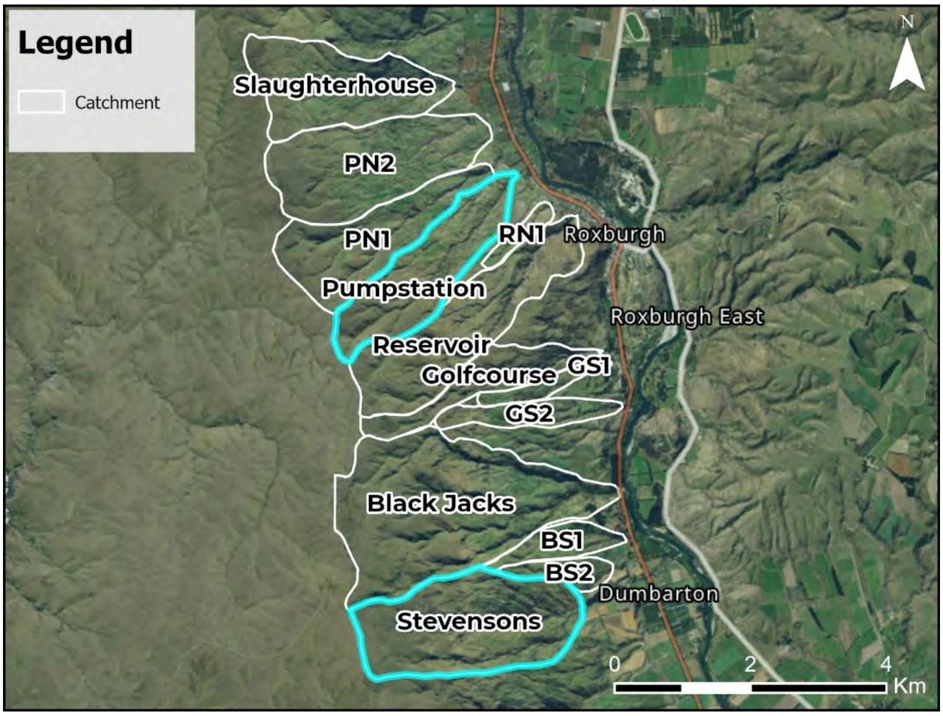


Figure 1: Location of Pumpstation and Stevensons catchments in relation to Roxburgh township and other catchments in this study.

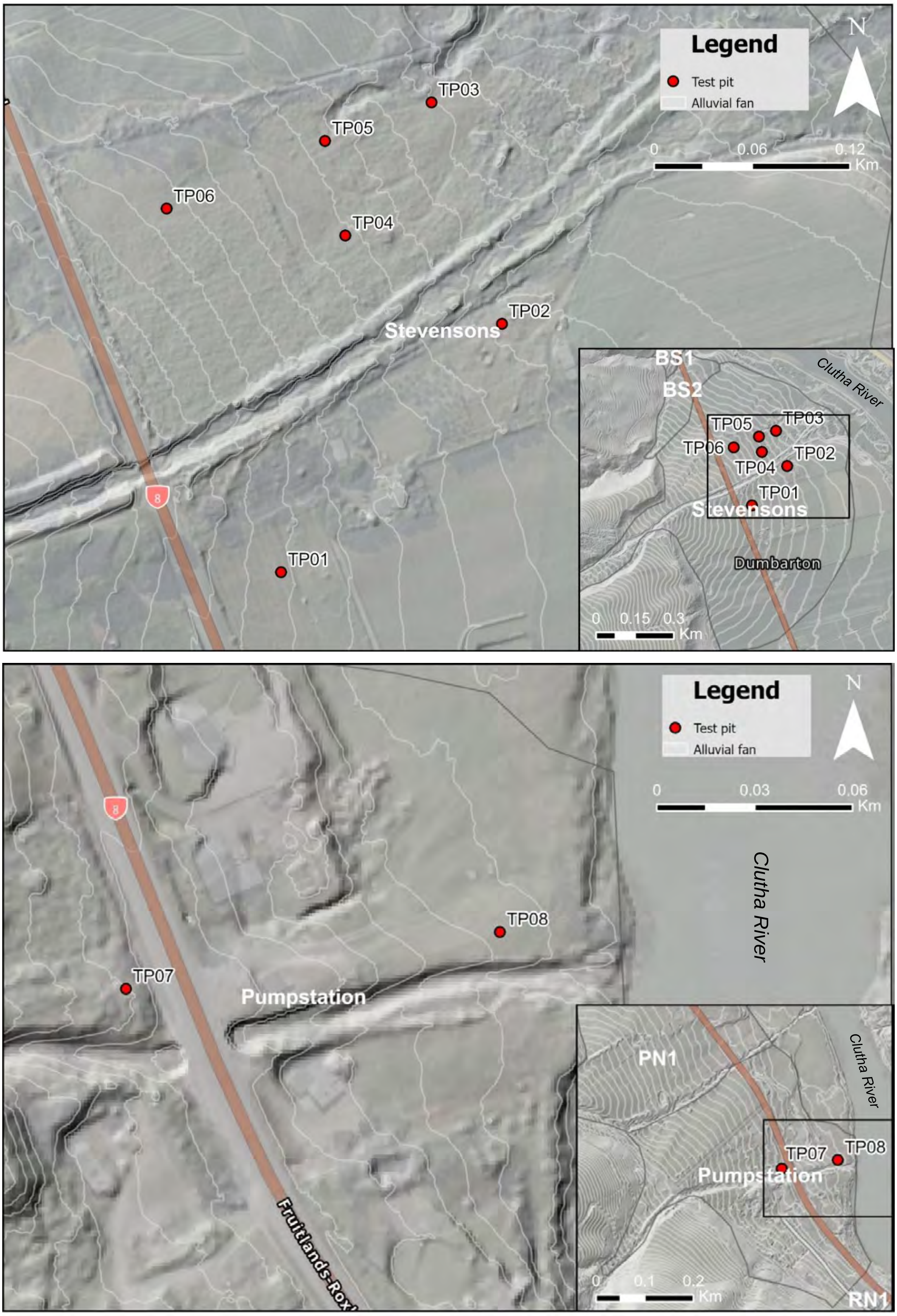


Figure 2: Test pit locations on Stevensons (top) and Pumpstation (bottom) alluvial fans.

Test pit results

The test pits were excavated to depths between 4 m and 7 m. The materials encountered are summarised below:

A. **Silty and sandy gravel with some cobbles and boulders**. These materials dominated the near-surface stratigraphy, and were typically unsorted, loosely packed, and weakly bedded in layers approximately 0.2–4.0 m thick (Figure 3). Significant variability in grainsize, degree of sorting, and bedding was observed in TP01 on the southern side of Stevensons Fan, with some gravel layers that were well sorted and bedded in moderately thin layers. Cobbles and boulders were subrounded schist predominantly 100–200 mm in diameter and up to 1 m diameter. No organic material was observed within these layers.

B. **Sandy silt** (some silty sand and clayey silt) of brownish grey colour, sometimes with thin layers of imbricated fine gravel (Figure 4). Layers were up to 0.2 m thick. A few zones containing small rootlets (<3 cm long and <0.1 cm diameter) were found in these layers below gravels and cobbles (Figure 5). Some plasticity in clayey silt layers.

C. **Thick homogenous gravelly silt layer** with some clay and sand. This was encountered in TP02 at 1.5 m to EOH at 5.0 m depth, TP03 at 5.0 m depth, and TP08 at 1.8 m depth. Above this layer were gravels, cobbles, and boulders in a matrix of fines (Figure 5).

Groundwater was only encountered in TP08 at 4 m depth.

Figure 3: Typical appearance of silty gravels in a test pit – TP03 (left), and in the spoil (TP04).

Figure 4: Possible paleosol layer in TP01 overlain and underlain by silty gravel and cobble layers.

Figure 5: Sandy silt deposit in TP03 (left) and in excavator bucket out of the hole (right).

Figure 6: Organics (rootlets) retrieved from some of the silty layers in the test pits.

Further information

In 2008, McNeill Drilling drilled a borehole on the lower fan of the true RB of Stevensons. Information of this investigation was accessed from WellsNZ (G43/0207)[1] and included layers of sandy and silty gravels interrupted by layers of boulders and clay (Figure 8). Groundwater was encountered at 15.51 m and schist bedrock at 23.5 m bgl.

Further, while undertaking the test pits, a property owner discussed exploratory groundwater boreholes near the TP01 and TP02 sites which encountered lignite and lacustrine deposits at around 6 m depth. Also, bedrock was not encountered in the holes which were up to 30 m bgl. This information is purely anecdotal and the geotechnical report and logs for these boreholes were not provided to WSP.

We have included the above information in the interpretation and drawings in the following section.

Interpretation

The following statements summarise our interpretation of the units observed in the test pits:

- The variability of grainsize and sorting within unit A indicates these materials were deposited during fan aggradation events and represent likely debris flood or debris flow deposits.
- The finer-grained Unit B is likely to represent lower energy flood events or buried paleosols during periods of no to limited deposition.
- Further, in regard to Stevensons, debris flood deposits appear to be thicker on the lower fan of the LB which is consistent with modelling and anecdotal evidence from landowner.

The soil types observed in the test pits are consistent with active fan deposition in a post-glacial environment. Layers of unsorted, chaotic gravel with some large boulders are consistent with material being deposited in a high energy fluvial environment typical of fan aggradation. The thickness of these deposits varied between 0.5–4 m interrupted by thin (0.1–0.3 m) silt and sand layers that are judged to indicate periods of little to no deposition. Well sorted, bedded gravels without the larger boulders were also encountered (to a lesser extent) and indicate lower energy aggradation events such as debris floods. These gravel and boulder layers interbedded with thin silts and sands can be summarised as Holocene alluvial fan deposits (GNS, 2018).

Thick homogeneous layers of gravelly silt and sand observed at depth in a few test pits within 200 m of the modern channel of the Clutha River are consistent with material being deposited in a lower energy environment than the boulder-rich deposits encountered near to the ground surface. The silt deposits are more typical of overbank deposits or floodplain remnants and are interpreted to be alluvium deposits likely to be Pleistocene in age (GNS, 2018)[2].

The basement rock in the area consists of Caples Terrane metamorphic rocks, described as well foliated psammitic and pelitic schist, formed 220 – 275 million years ago. Geological maps and interpretations of the area indicate that thin sequences of marine sandstones, mudstones, and lignite-bearing sediments in local basins may overlay basement rock. The region underwent a period of uplift and further basin

[1] https://wellsnz.teurukahika.nz/wells
[2] GNS, 2018. Geological Map of New Zealand 1:250 000, s.l.: GNS Science.

formation in the late Neogene-Quaternary where the Clutha River entrenched into the schist, forming gorges and terraces. Quaternary glacial and fluvial activity over the last 2 million years has formed extensive river terraces and in some places loess (wind-blown silt) mantles. Our interpretation is that alluvial fan deposits (silty gravels and boulders) derived from debris flows and flood deposits began accumulating on older Clutha River terraces following glacier retreat during the Holocene (Figure 7).

Test pit investigations identified debris flood and flow deposits with thicknesses of approximately 0.5–4 m, located around 30–100 m from the active channel. These observed thicknesses for the Stevensons fan are consistent with the RAMMS modelling results, which indicated deposits approximately 0.5–1 m thick for the high-likelihood event, 1–2 m for the median event, and locally >2 m for the maximum credible event in the areas where the test pits were excavated. Overall, the modelled deposit thicknesses correspond well with those observed and logged in the subsurface investigations, providing confidence that the simulated debris flood behaviour is representative of site conditions and past debris flood deposition, and therefore helps validate the use of the model outputs in the hazard and risk assessments.

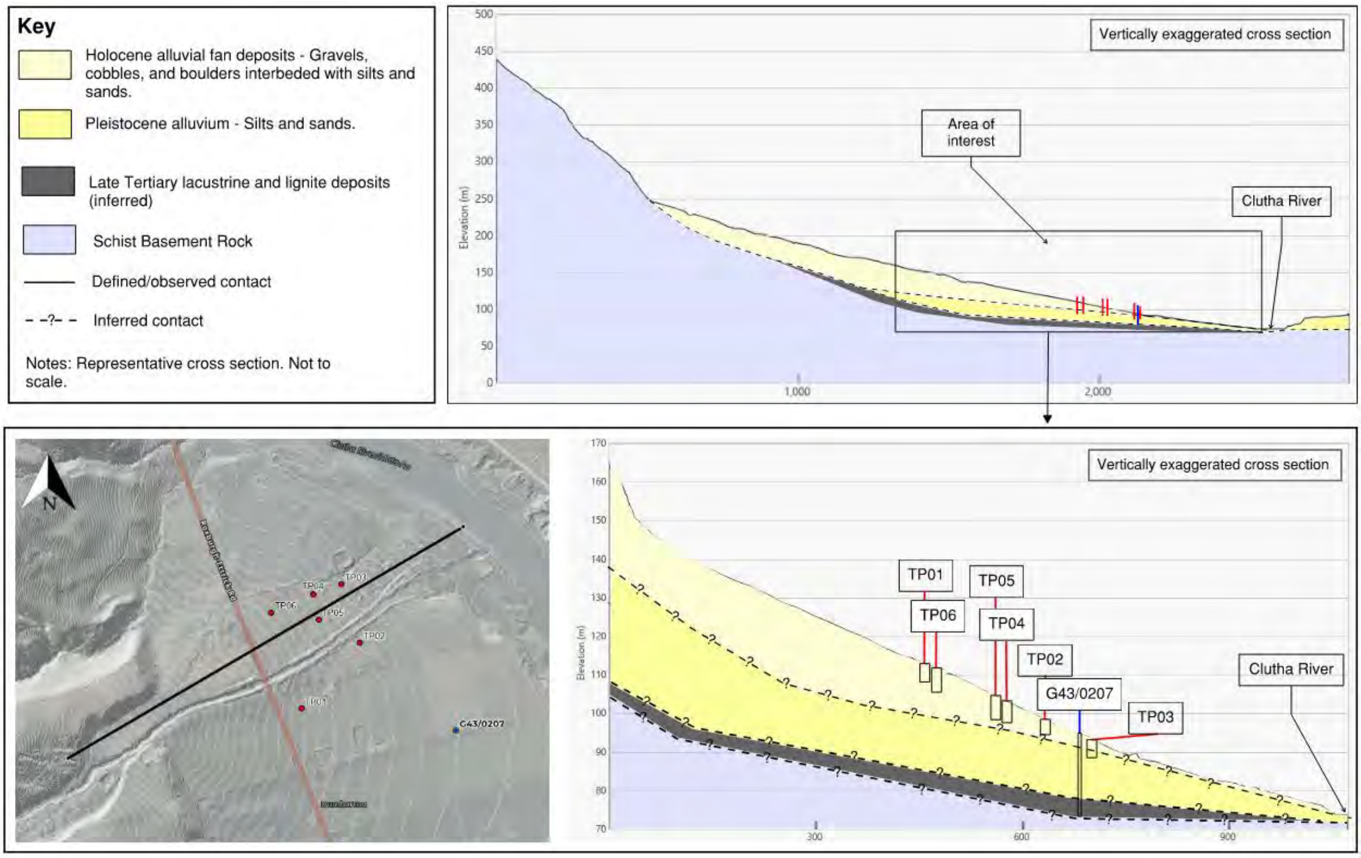


Figure 7: Schematic cross sections of the Stevensons alluvial fan illustrating inferred thicknesses of soil and rock layers.

Radiocarbon dating of material

Three samples of small rootlets were collected during test pitting and sent to the University of Waikato radiocarbon dating laboratory for analysis. Radiocarbon dating was undertaken on wood rootlet material recovered from alluvial sediments at depths of 1.5–2.0 m below ground surface across two fan surfaces (Stevensons Fan and Pumpstation Fan). The results are reported as conventional radiocarbon age expressed as fraction modern carbon ($F^{14}C$%) and calibrated calendar age ranges at 95% confidence (Table 1).

Sample TP01-1, comprising a wood rootlet collected at 1.5 m depth within alluvial deposits on the Stevensons Fan, returned a conventional radiocarbon value of 135.60 ± 0.29 $F^{14}C$%. Calibration of this result indicates two discrete age ranges at 95% confidence, spanning cal AD 1963.51–1963.57 and cal AD 1976.35–1976.75. The elevated $F^{14}C$ value is consistent with incorporation of atmospheric “bomb carbon” derived from mid-20th-century nuclear weapons testing, indicating post-1950s carbon incorporation.

Sample TP06-2, also a wood rootlet from 1.5 m depth within alluvial sediments on the Stevensons Fan, yielded a conventional radiocarbon value of 106.96 ± 0.26 $F^{14}C$%. The calibrated age range at 95% confidence encompasses two possible intervals: cal AD 1957.91–1958.40 and cal AD 2004.54–2007.52. As with TP01-1, the modern $F^{14}C$ value indicates uptake of carbon during the post-bomb period.

Sample TP08-3, a wood rootlet recovered from 2.0 m depth within alluvium on the Pumpstation Fan, returned a conventional radiocarbon value of 105.72 ± 0.23 $F^{14}C$%. This result calibrates to two possible 95% confidence age ranges of cal AD 1957.81–1957.90 and cal AD 2007.87–2011.06. The similarity of the calibrated ranges to those of TP06-2 suggests broadly comparable timing of carbon incorporation within the upper alluvial sequence.

In all cases, the presence of multiple calibrated age ranges reflects the structure of the post-bomb calibration curve and indicates that the dated rootlets represent very young carbon. Because only three samples were able to be collected from relatively shallow depths within the test pits, the depositional history of the alluvial fans is not well constrained by the radiocarbon dating. However, the results of the laboratory analysis suggest late-20th to early-21st-century deposition or post-depositional root penetration within the shallow alluvial sediments, consistent with the observed history of debris flood deposition in the Roxburgh area.

The laboratory report for these samples is provided as an attachment to this appendix.

Table 1: A summary of radiocarbon dating lab results for three wood rootlet samples taken from Stevensons and Pumpstation alluvial fans.

Sample	Description	Fan	Conventional age (F 14C%)	95% confidence age (cal AD)
TP01-1	Wood rootlet at 1.5 m depth within alluvium	Stevensons	135.60 ± 0.29	• 1963.51-1963.57 • 1976.35-1976.75

TP06-2	Wood rootlet at 1.5 m depth within alluvium	Stevensons	106.96 ± 0.26	• 1957.91-1958.40 • 2004.54-2007.52
TP08-3	Wood rootlet at 2.0 m depth within alluvium	Pumpstation	105.72 ± 0.23	• 1957.81-1957.90 • 2007.87-2011.06

Conclusions

The subsurface investigations support and validate the debris flow modelling and associated risk assessments. Key findings include:

- Investigations identified materials characteristic of debris flow and debris flood deposits, consistent with episodic active fan deposition. This confirms that the fans are susceptible to these hydrogeomorphic processes.
- The extent and thickness of these deposits across fan surfaces aligns with RAMMS modelling outputs, indicating that the modelled debris inundation scenarios are realistic and well-founded.
- The findings corroborate geological interpretations presented in Section 2.3.1, confirming that the fans have built out onto older Clutha River terrace deposits.
- Radiocarbon dating of wood rootlets recovered from alluvial deposits yielded modern (“post-bomb”) $F^{14}C$ values, with calibrated 95% confidence age ranges spanning the late 1950s to early 2010s, indicating very young carbon consistent with late-20th to early-21st-century deposition and/or post-depositional root penetration.

Overall, this site investigation summary provides a basis for understanding and interpreting debris flow hazards in the Teviot Valley.

Geotechnical Logs

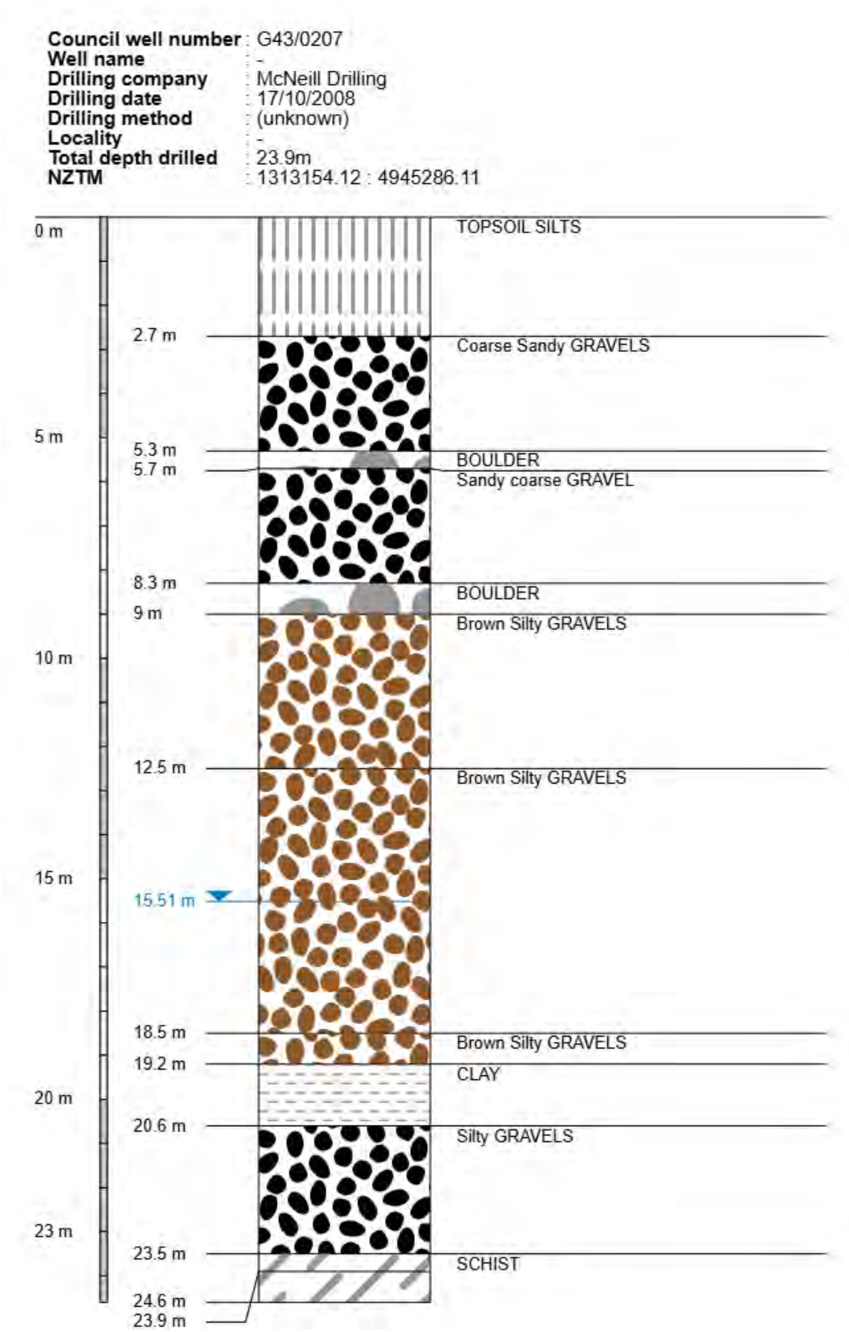


Figure 8: WellsNZ log data from Stevensons alluvial fan for a borehole done in 2008 by McNeil Drilling.

Radiocarbon Dating Laboratory Report

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Radiocarbon Dating Laboratory

Private Bag 3105
Hamilton,
New Zealand.
Ph +64 7 838 4278
email c14@waikato.ac.nz

Report on Radiocarbon Age Determination for WkA-60579

Friday, 16 January 2026

Submitter	Harley Porter
Submitter's Code	TP08-3
Site & Location	Stevensons alluvial fan.
Sample Material	Wood Rootlets?
Physical Pretreatment	Sample cleaned and ground.
Chemical Pretreatment	Sample washed in hot HCl, rinsed and treated with multiple hot NaOH washes. The NaOH insoluble fraction was treated with hot HCl, filtered, rinsed and dried.

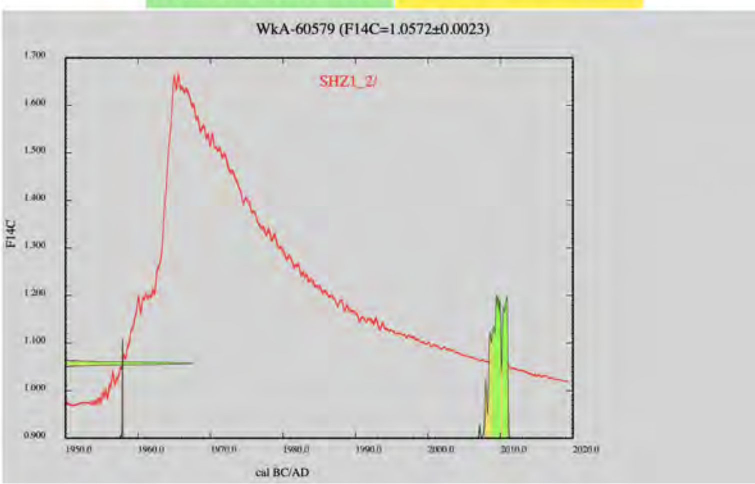
$D^{14}C$	57.23 ± 2.3 ‰
$F^{14}C$ %	105.72 ± 0.23 %
Result	**105.72 ± 0.23 F 14C %**

Comments

CALIBomb

Cite as: Reimer, R.W. & Reimer, P.J. 2026 CALIBomb [WWW program] at http://calib.org accessed 2026-01-16

68% confidence	95% confidence	Curve
• [cal AD 2008.52:cal AD 2008.60]0.036 • [cal AD 2008.89:cal AD 2010.01]0.573 • [cal AD 2010.27:cal AD 2010.98]0.391	• [cal AD 1957.81:cal AD 1957.90]0.020 • [cal AD 2007.87:cal AD 2011.06]0.980	SHZ1_2



• Explanation of the calibrated OxCal plots is now found at URL https://c14.arch.ox.ac.uk/explanation.php

• Conventional Age or $F^{14}C$% (also known as Percent Modern Carbon [pMC] is following Stuiver and Polach, 1977, Radiocarbon, 19:355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and WkA number.

• Quoted errors are 1 standard deviation due to counting statistics with additional uncertainty added in quadrature to account for sample-to-sample variability.

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Radiocarbon Dating Laboratory

Private Bag 3105
Hamilton,
New Zealand.
Ph +64 7 838 4278
email c14@waikato.ac.nz

Report on Radiocarbon Age Determination for WkA-60578

Friday, 16 January 2026

Submitter	Harley Porter
Submitter's Code	TP06-2
Site & Location	Stevensons alluvial fan.
Sample Material	Wood Rootlets?
Physical Pretreatment	Sample cleaned and ground.
Chemical Pretreatment	Sample washed in hot HCl, rinsed and treated with multiple hot NaOH washes. The NaOH insoluble fraction was treated with hot HCl, filtered, rinsed and dried.

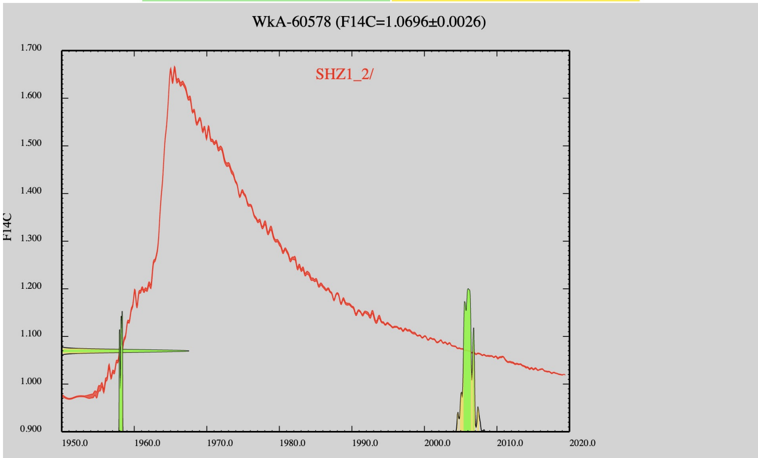
$D^{14}C$	69.59 ± 2.57 ‰
$F^{14}C$ %	106.96 ± 0.26 %
Result	**106.96 ± 0.26 F14C%**

Comments

CALIBomb

Cite as: Reimer, R.W. & Reimer, P.J. 2026 CALIBomb [WWW program] at http://calib.org accessed 2026-01-16

68% confidence	95% confidence	Curve
• [cal AD 1957.94:cal AD 1958.37]0.163 • [cal AD 2005.40:cal AD 2006.41]0.758 • [cal AD 2006.69:cal AD 2006.83]0.079	• [cal AD 1957.91:cal AD 1958.40]0.170 • [cal AD 2004.54:cal AD 2004.66]0.009 • [cal AD 2004.88:cal AD 2006.98]0.799 • [cal AD 2007.28:cal AD 2007.52]0.022	SHZ1_2



• Explanation of the calibrated OxCal plots is now found at URL https://c14.arch.ox.ac.uk/explanation.php

• Conventional Age or $F^{14}C$% (also known as Percent Modern Carbon [pMC] is following Stuiver and Polach, 1977, Radiocarbon, 19:355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and WkA number.

• Quoted errors are 1 standard deviation due to counting statistics with additional uncertainty added in quadrature to account for sample-to-sample variability.

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Radiocarbon Dating Laboratory

Private Bag 3105
Hamilton,
New Zealand.
Ph +64 7 838 4278
email c14@waikato.ac.nz

Report on Radiocarbon Age Determination for WkA-60577

Friday, 16 January 2026

Submitter	Harley Porter
Submitter's Code	TP01-1
Site & Location	Stevensons alluvial fan.
Sample Material	Wood Rootlets?
Physical Pretreatment	Sample cleaned and ground.
Chemical Pretreatment	Sample washed in hot HCl, rinsed and treated with multiple hot NaOH washes. The NaOH insoluble fraction was treated with hot HCl, filtered, rinsed and dried.

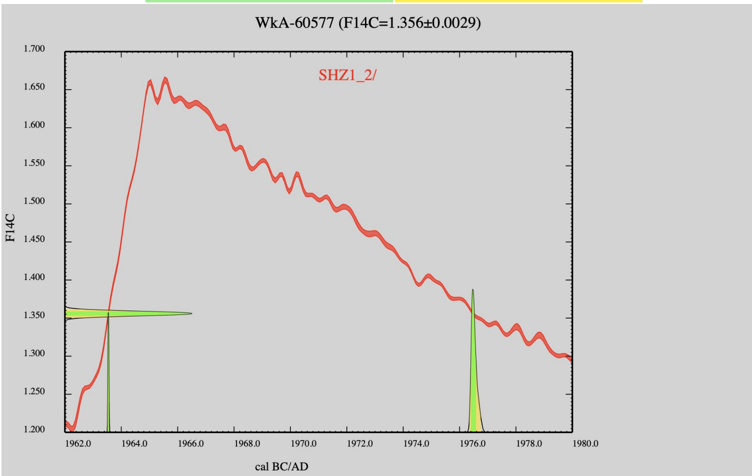
$D^{14}C$	356.02 ± 2.86 ‰
$F^{14}C$ %	135.6 ± 0.29 %
Result	**135.60 ± 0.29 F14C%**

Comments

CALIBomb

Cite as: Reimer, R.W. & Reimer, P.J. 2026 CALIBomb [WWW program] at http://calib.org accessed 2026-01-16

68% confidence	95% confidence	Curve
• [cal AD 1963.52:cal AD 1963.56]0.146 • [cal AD 1976.40:cal AD 1976.58]0.854	• [cal AD 1963.51:cal AD 1963.57]0.130 • [cal AD 1976.35:cal AD 1976.75]0.870	SHZ1_2



• Explanation of the calibrated OxCal plots is now found at URL https://c14.arch.ox.ac.uk/explanation.php

• Conventional Age or $F^{14}C$% (also known as Percent Modern Carbon [pMC] is following Stuiver and Polach, 1977, Radiocarbon, 19:355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and WkA number.

• Quoted errors are 1 standard deviation due to counting statistics with additional uncertainty added in quadrature to account for sample-to-sample variability.

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