Queenstown Debris Flow and Rockfall Loss Modelling for Land-Use Planning Policy Options

RJ Woods
S Canessa
K-L Thomas
NA Horspool
FR Scheele

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EXECUTIVE SUMMARY

To effectively manage the risk posed by future debris flows and rockfalls in Queenstown, the Queenstown Lakes District Council (QLDC) seek to understand the implications of various land-use policy intervention options for their District Plan. The study area includes the Reavers Lane and Brewery Creek active alluvial fan areas. To understand how the risk profile of each alluvial fan changes for differing policy interventions, RiskScape 2.0 was used to estimate direct monetary losses to buildings.

The RiskScape 2.0 software calculated monetary loss due to building damage expected for a variety of hazard scenarios supplied by Beca. These scenarios included small, moderate and large debris flows and an array of potential rockfall events. RiskScape 2.0 was used to estimate losses for the following policy intervention options:

- 2020 Baseline
- 2120 Uncontrolled development
- 2120 Managed development through existing uses
- 2120 Reduced development based on level of risk, and
- 2120 Up-zoned with engineering works.

A metric for risk was developed by QLDC that could be used in the proposed District Plan rules as a basis for managing debris flow and rockfall risk in the study areas. To complement land-use planning policy interventions and address the remaining residual risk, this report also details emergency management guidance.

For debris flow hazards, the study has identified that the Uncontrolled policy option results in increased direct losses for all scenarios modelled due to increased exposure of buildings. The Managed policy option results in reduced direct building losses for all events at both locations when compared to the 2120 Uncontrolled policy option. Due to a reduction in exposed buildings in high hazard locations, the Reduced policy option results in reduced direct building losses at both study locations for all hazard scenarios. The modelled Engineering scenarios (modelling the effect of a debris fence) results in reduced direct building losses for all events at both locations when compared to the 2120 Uncontrolled policy option. Finally, for rockfall hazards, all modelled policy options result in a reduction in direct losses when compared to the 2120 Uncontrolled policy option.

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1.0 TERMINOLOGY

Alluvial fans are a build-up of river or stream sediments that form a sloping landform, shaped like an open fan. They typically occur between hillslopes, for example, where a steep gully merges onto a flatter valley floor. They are formed due to natural drainage processes where the river or stream propagates across the gradient decrease to accumulate sediment across the fan over time. Alluvial fans have an elevated profile with good drainage, making them attractive places for people to live (Otago Regional Council 2021). However, these locations are exposed to hazards, including flooding, rockfall and debris flows. The alluvial fans relevant to this report are the Reavers Lane and Brewery Creek fans in Queenstown that have been developed with a mixture of residential and commercial use.

Damage ratio is a ratio that describes economic loss. It is calculated by dividing the cost to repair a damaged asset by the cost of replacing the asset.

Damage states describe the degree of damage that an object or the level of impact a person has sustained, in relation to its ability to function, following impact by a hazard of a given intensity. Damage states can be described quantitively or qualitatively and are usually expressed on a scale from no damage (0) to destroyed (1).

Debris flows are a hazard caused by falling debris. Falling debris includes soil, rock, snow or ice that may fall or 'runout' onto a property (e.g. dwelling, garage, shed and/or land) from upslope (the landslide source area), inundating the property (Massey et al. 2019). Debris flows have been defined by some (Nomitsu and Seno 1959; Tani 1968; Murano 1968) as the "gravitational motion of a porridge-like mixture of sediment and water, in which the volume of sediment is much larger than the volume of water" (Takahashi 2009). If societal assets are exposed to debris flows, they can be very destructive and fatal. Aotearoa New Zealand examples include the 2005 Matatā, 2011 Golden Bay and 2017 Roxburgh debris flow events.

Exposure refers to "the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" (UNDRR c2021).

Hazard is defined by the United Nations Office for Disaster Risk Reduction (UNDRR) as: "A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (c2021). Landslides are a natural process that become hazardous when societal assets are exposed to them.

Hazard intensity, as described in this report, is a quantifiable metric used to express the magnitude, or damage potential, of the landslide. Landslide intensity metrics include debris height (m), velocity (ms^{-1}), pressure (kPa) or proportion undercut (percentage of building footprint).

Risk is defined by UNDRR as "The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity." (c2021). This can be expressed as:

$$Risk = f(Hazard, Exposure, Vulnerability)$$

RiskScape is risk modelling software designed to assist users in assessing risk to buildings, infrastructure and people from natural hazards. The modelled outputs from RiskScape, such as direct damage, replacement cost, fatalities and injuries, can be used to inform risk-based decision-making for emergency management, land-use planning policy, infrastructure and asset management investment options.

Rockfall is also a hazard caused by falling debris. Rockfall, as defined by Turner and Schuster (2012) is:

> *"a very rapid slope movement in which bedrock material is detached from a steep slope and descends by falling, bouncing, rolling or sliding. It can involve gravel-size particles up to large rock masses and relates to the fall of individual or several rock blocks, where there is little interaction between the individual blocks. Rockfall events can be defined over a continuum from the fall of a single block to the fall of many thousands of blocks such as occurs in a rockfall avalanche-type event."*

Examples of rockfall events in Aotearoa New Zealand include the Port Hills rockfall in the 2012 Christchurch earthquakes and the 2016 Kaikōura earthquakes rockfalls.

Vulnerability can be defined as the "conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (UNDRR c2021). For example, conditions that may affect a buildings vulnerability to natural hazards include structure type, construction materials, number of storeys, age, foundation type, etc.

Vulnerability functions allow the severity of damage to an asset to be estimated based on the hazard intensity and the potential, or lack thereof, of the asset to resist damage (Massey et al. 2019). There are two types of functions: fragility functions/curves and consequence/ damage functions. Fragility functions are equations that describe the probability of a degree of damage for various hazard intensities, e.g. for a range of hazard intensities, the probability that a dwelling will be destroyed. Consequence functions relate likely damage to hazard intensity, where damage is usually described as a damage ratio.

2.0 INTRODUCTION

To effectively manage the risk posed by future debris flows and rockfalls in Queenstown, the Queenstown Lakes District Council (QLDC) seek to understand the implications of various land-use planning policy intervention options for their District Plan. The study area includes the Reavers Lane and Brewery Creek active alluvial fan areas (Figure 2.1). To understand how the risk profile of each alluvial fan changes for differing policy options, RiskScape 2.0 was used to estimate direct monetary losses to buildings.

This collaborative project involved staff from QLDC (planning, policy and GIS), Beca (hazard modelling) and GNS Science (risk modelling) and was co-funded using the GNS Science Strategic Science Investment Fund (SSIF) as a case-study for RiskScape 2.0 implementation.

The next-generation RiskScape 2.0 software calculated monetary loss due to building damage expected for a variety of hazard scenarios supplied by Beca. These scenarios included small, moderate and large debris flows and an array of potential rockfall events. RiskScape 2.0 was used to estimate losses for the following policy intervention options:

- 2020 Baseline
- 2120 Uncontrolled development
- 2120 Managed development through existing uses
- 2120 Reduced development based on level of risk, and
- 2120 Up-zoned with engineering works.

A metric for risk was developed by QLDC that could be used in the proposed District Plan rules as a basis for managing debris flow and rockfall risk in the study areas. To complement land-use planning policy interventions and address the remaining residual risk, this report also details emergency management guidance.

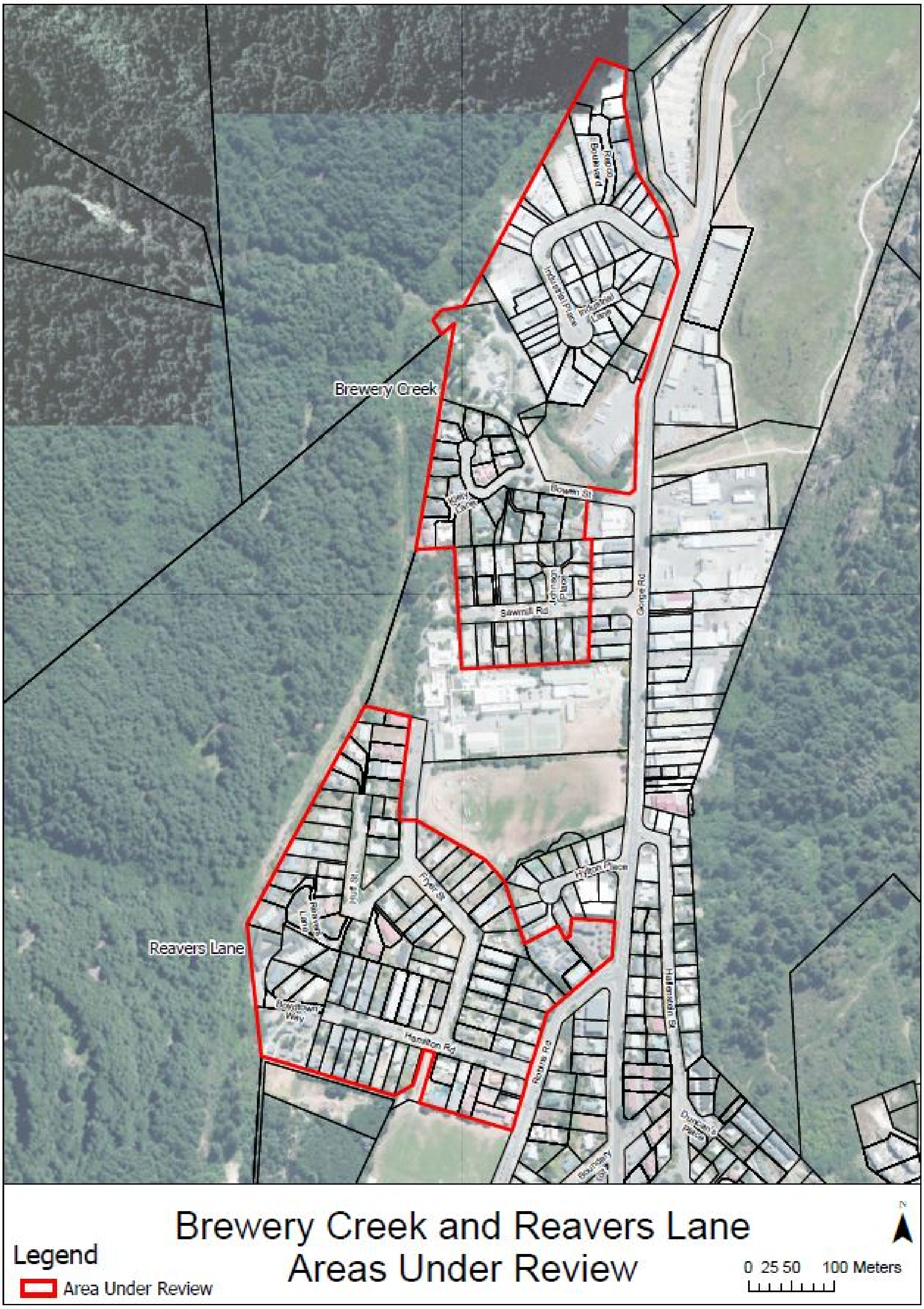

Figure 2.1 Study areas for debris flow and rockfall risk assessment. Supplied by Queenstown Lakes District Council.

3.0 METHODOLOGY

This study was undertaken in four stages: determination of risk-modelling specifications, debris flow and rockfall loss modelling, risk metric development for land-use planning rules and emergency management guidance. Determination of the risk metric was led by QLDC and is not detailed in this report.

3.1 Determination of Risk-Modelling Specifications

A series of online workshops were held in September and October 2019 between GNS Science, QLDC and Beca to confirm the hazard parameters and asset attributes required for risk modelling in RiskScape 2.0. These sessions included QLDC planning and policy staff, risk specialists and engineers from GNS Science and geotechnical staff from Beca.

These sessions agreed that the primary hazard parameters to be used were depth of flow for debris flow and kinetic energy for rockfall. Agreed asset attributes are described in Section 3.2.3.

3.2 Debris Flow and Rockfall Loss Modelling

3.2.1 Hazard Data

QLDC contracted Beca to model both debris flow and rockfall hazards across a range of magnitudes and associated frequencies (Table 3.1). The methodology and respective hazard results are described in Beca (2020). Outputs from the hazard modelling (Figure 3.1) were supplied to GNS Science in ASCII format to be used in RiskScape 2.0.

Table 3.1 Hazard layers modelled by Beca and their respective return period ranges.

	Hazard Layer	Return Period (Years)
Reavers Lane	Debris Flow – Small	100–2500
	Debris Flow – Moderate	2500–6700
	Debris Flow – Large	6700–20,000
	Rockfall – True Left	N/A
	Rockfall – True Right	N/A
Brewery Creek	Debris Flow – Small	50–200
	Debris Flow – Moderate	200–2500
	Debris Flow – Large	2500–10,000
	Rockfall – True Left	N/A
	Rockfall – True Right	N/A
	Rockfall – Bird Park	N/A

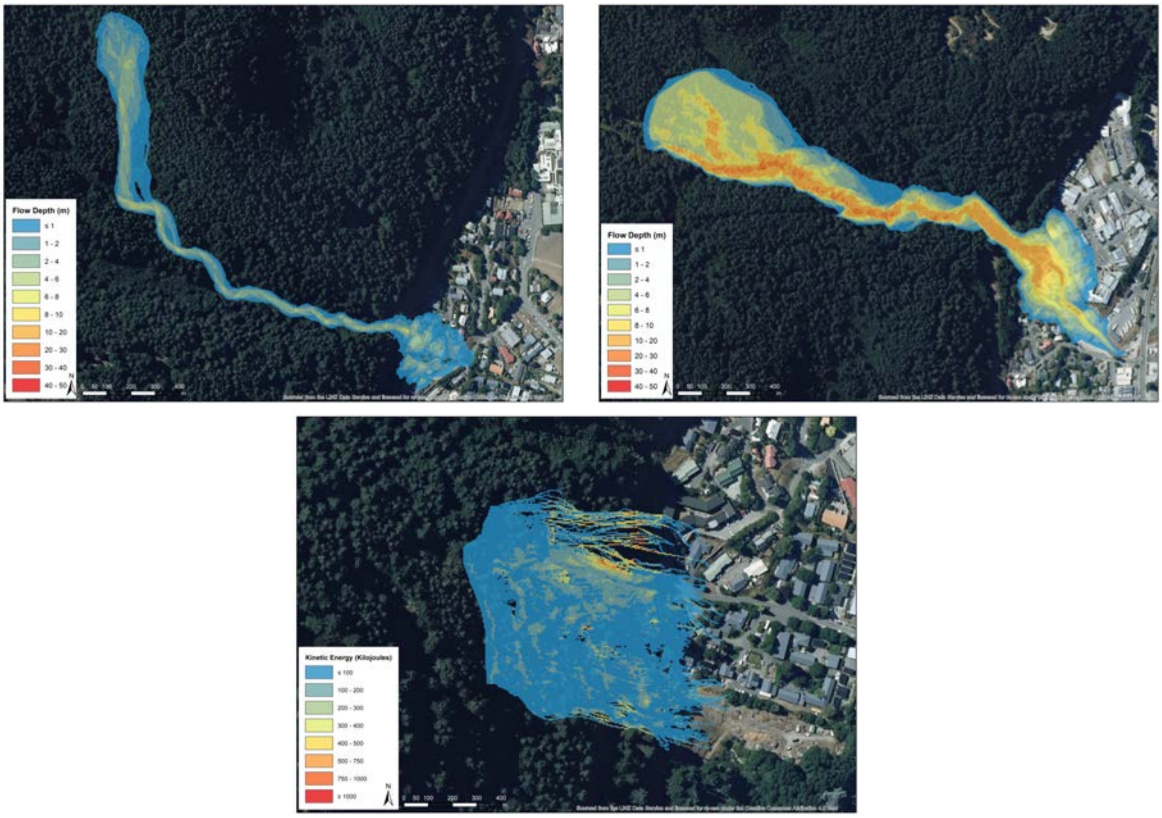

Figure 3.1 Examples of hazard layers produced by Beca showing Reavers Lane debris flow depth (top left), Brewery Creek debris flow depth (top right) and Reavers Lane rockfall kinetic energy (bottom centre).

3.2.2 Asset Data

A site visit was conducted in December 2019, and, using the data capture application Fulcrum, relevant building attributes were collected for debris flow and rockfall (landslide) risk modelling. As landslide vulnerability functions are not yet available for specific construction types of buildings in Aotearoa New Zealand.

Actual replacement costs were not available for individual buildings in the study area; therefore, these were calculated using Earthquake Commission (EQC) average replacement costs for Queenstown buildings, which was \$2363/m^2 for dwelling + appurtenant structures as at 1 June 2020. The relevant building attributes collected were:

- building location
- footprint area, and
- number of storeys (which allows floor area, in m^2, to be calculated).

Other attributes were also collected, as recommended by Massey et al. (2019), for future reference if more vulnerability functions are created. These attributes were:

- building use;
- construction type;
- floor height;
- number of windows, height of window and proportion of house exterior occupied by openings (windows and doors); and
- number of doors and type (wood, glass, metal).

Fulcrum software was used to capture each building and the associated attributes as point data, which were later reconciled with building platform polygon data for the RiskScape 2.0 analysis. This exposure dataset was used for the ‘2020 Baseline’ scenario to estimate the loss incurred if any of the respective hazard scenarios occurred in 2020.

To model each of the policy intervention options in RiskScape 2.0, the asset layer required modification to reflect the impact that each option would have on the built environment in 2120. During the site visit, workshops were held with QLDC policy planners to determine how each policy intervention option would be represented in the asset layers. For each policy, QLDC GIS staff adapted the buildings dataset to create changes based on the identified planning provisions (Appendix 1). These changes primarily affect the placement, number and value of the buildings exposed by changing building footprint extents and the number of storeys (either increasing, restricting or removing, depending on the policy scenario). QLDC provided new asset geospatial layers (Figure 3.2) for the following policies:

- 2120 Uncontrolled development
- 2120 Managed development through existing uses, and
- 2120 Reduced development based on level of risk.

These policy options involve a combination of measures, with more restrictive provisions applying in the high-hazard areas and less restrictive provisions applying in the moderate- and low-hazard areas. The Uncontrolled development asset layer was also used for estimating losses for the scenario incorporating engineering solutions.

Figure 3.2 Spatial representations of each of the policy options: 2020 Baseline (top left), 2120 Uncontrolled (top right), 2120 Manage (bottom Left), 2120 Reduce (bottom right).

3.2.3 Vulnerability Functions

As described above, the hazard and asset attributes required are defined by the availability of vulnerability functions. Aotearoa-New-Zealand-specific rockfall and landslide vulnerability functions were generated by Massey et al. (2019). Figures 3.3 and 3.4 show the functions selected for this study for debris flow and rockfall, respectively. They are considered the best available predictors for landslide and rockfall damage for Aotearoa New Zealand buildings.

These vulnerability functions combine empirical EQC and GNS Science data from Aotearoa New Zealand landslide events for timber-framed buildings (the majority of the building stock). Data from international landslide events are also included for a range of building types and quality (steel, timber, concrete frames) (Massey et al. 2019). The functions present a mathematical relationship between hazard intensity (debris height for debris flow and kinetic energy for rockfall) and damage ratio. The damage ratio is a value between 0 and 1 (inclusive) that can be defined as the repair cost divided by the replacement cost:

$$Damage\ Ratio = Repair\ Cost\ /\ Replacement\ Cost$$

A damage ratio of 1 is complete destruction, and a damage ratio of 0 is no damage. No empirical damage data from the study areas could be obtained to incorporate into the vulnerability functions for calibration.

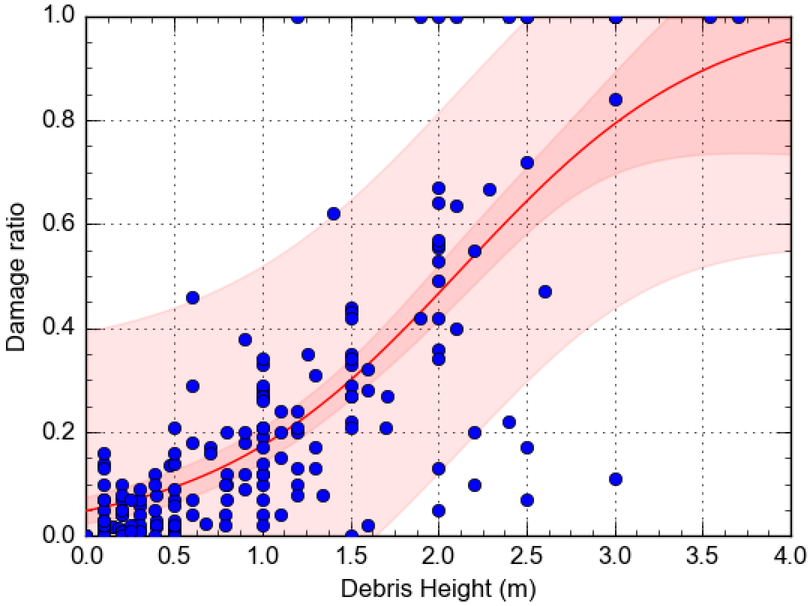

Figure 3.3 Damage ratio versus debris height for falling debris: debris flows, combining both the literature and Aotearoa New Zealand (EQC) datasets, N = 168, for all building types. A sigmoid logistic damage function was fitted to the data. The darker red and lighter red shaded areas represent the 1σ and 95% confidence ranges, respectively (Massey et al. 2019).

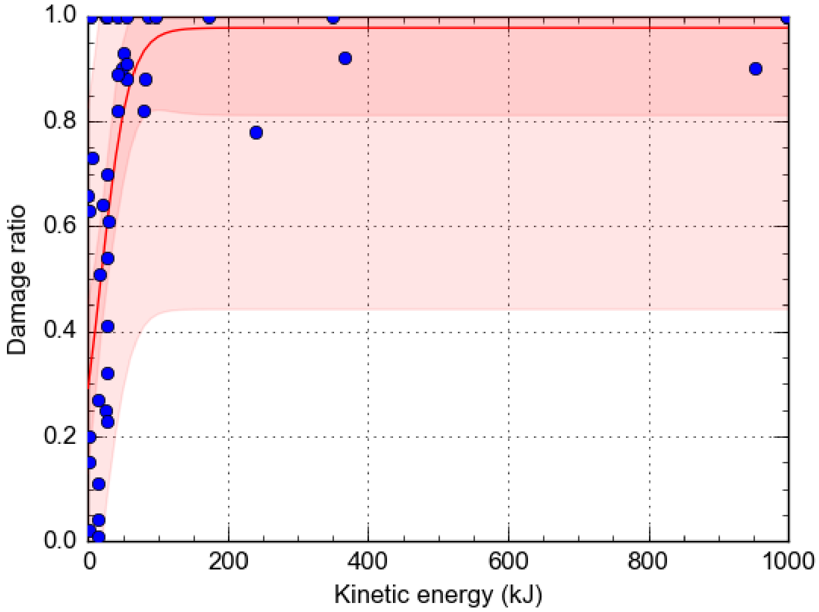

Figure 3.4 Damage ratio versus the kinetic energy for falling debris: rockfalls, combining both the literature and Aotearoa New Zealand (EQC) datasets, N = 41, for all building types. A sigmoid logistic damage function was fitted to the data. The darker red and lighter red shaded areas represent the 1σ and 95% confidence ranges, respectively (Massey et al. 2019).

3.2.4 Emergency Management Guidance

While the preferred land-use policy option will reduce the risk from debris flows and rockfalls in the study areas, there will still be a component of residual risk to life and property. A workshop was held on 11 December 2019 with staff from Emergency Management Otago (EMO) and QLDC to determine whether existing local emergency management arrangements could be used to address the remaining residual risk.

EMO has an existing programme of work to develop Community Response Plans. These plans cover the key risks and hazards, targeted public education solutions, messaging and evacuation guidance. The study areas include a mix of residential, industrial and visitor accommodation. It is recommended that information regarding the identified debris flow and rockfall hazard areas should be shared with residents and visitor accommodation providers.

While no official warning will be issued should a debris flow or rockfall occur in the study areas, natural warnings, such as strange or loud noises from catchments, particularly during or following heavy rainfall, may indicate that a debris flow is occurring. In this instance, people should move to locations outside of the identified hazard areas as soon as possible. Visitor accommodation providers may include information regarding safe areas and evacuation routes in individual units for transient populations.

The National Emergency Management Agency (NEMA) also provide consistent messaging[1] that could be incorporated into the local community response plan. These include:

- Develop an evacuation plan. If your home could be damaged in a landslide, you should know where to go if you have to leave. Making plans at the last minute can be upsetting, create confusion and waste precious time. Contact local authorities to learn about the emergency response and evacuation plans for your area and develop your own emergency plans for your family and business.

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[1] https://www.civildefence.govt.nz/assets/Uploads/publications/consistent-messages-part-B-landslides.pdf

- Familiarise yourself with the land around you. Knowing the land can help you assess your risk.
- Discuss landslides and debris flows with members of your household – everyone should know what to do to stay safe if one occurs.
- Listen to radio stations for heavy rainfall warnings or check the MetService website (www.metservice.com). Short bursts of heavy rain may be particularly dangerous, especially after longer periods of wet weather.
- Consider leaving if it is safe to do so. Remember that driving during a severe storm can be hazardous. If you remain at home, move to a second storey if possible. Staying out of the path of a landslide or debris flow can save your life.
- Listen for any unusual sounds that might indicate moving debris, such as trees cracking or boulders knocking together. A trickle of flowing or falling mud or debris may precede a large landslide. Moving debris can flow quickly and sometimes without warning.
- If you are near a stream or channel, be alert for any sudden increase or decrease in water flow and for a change from clear to muddy water. Such changes may indicate landslide activity upstream, so be prepared to move quickly. Act quickly. Save yourself, not your belongings.
- Evacuate immediately. Getting out of the path of a landslide or debris flow path is your best protection.
- Inform neighbours. Your neighbours may not be aware of the potential hazard. Advising them of a threat may save their lives. Help neighbours who need assistance to evacuate.

4.0 RESULTS

4.1 Risk Modelling Outputs

This section presents loss outputs from RiskScape for Reavers Lane and Brewery Creek, respectively. Tabulated results show aggregated building losses as well as the differences between each policy option as compared to the 2020 baseline. Annualised losses are also presented using the average and most frequent return periods from the respective range. Maps showing the spatial distribution of 2020 baseline losses and building damage states are presented in Appendix 2.

4.1.1 Reavers Lane Debris Flow

Tables 4.1 and 4.2 present a summary of the losses for the 2020 scenario and each policy or engineering option. Figures 4.1, 4.2 and 4.3 provide a graphical representation of the estimated total and annualised losses.

Table 4.1 Total aggregated building debris flow losses for Reavers Lane. Red figures show the actual and percentage differences between the Uncontrolled and Baseline scenarios. Green figures show the actual and percentage differences between Managed, Reduced and Engineering scenarios compared to Uncontrolled.

	Return Period (Years)	**2020 Baseline ($M)**	**2120 Uncontrolled ($M)**	**2120 Managed ($M)**	**2120 Reduced ($M)**	**2120 Engineering ($M)**
Total Losses	100–2500 (Small)	13.5	19.1 (5.5) (41%)	10.3 (8.8) (-46%)	0 (19.1) (-100%)	N/A
	2500–6700 (Moderate)	17.1	34.6 (17.4) (102%)	15.4 (19.2) (-55%)	1 (33.6) (-97%)	27.1 (7.5) (-22%)
	6700–20,000 (Large)	39.2	132.5 (93.3) (238%)	66 (66.5) (-50%)	20.9 (111.6) (-84%)	127.2 (8.3) (-6%)

Table 4.2 Annualised aggregated building debris flow losses for Reavers Lane. Red figures show the actual and percentage differences between the Uncontrolled and Baseline scenarios. Green figures show the actual and percentage differences between Managed, Reduced and Engineering scenarios compared to Uncontrolled.

	Return Period (Years)	**2020 Baseline ($000s)**	**2120 Uncontrolled ($000s)**	**2120 Managed ($000s)**	**2120 Reduced ($000s)**	**2120 Engineering ($000s)**
Annualised (Mean)	1300	10.4	14.7 (4.3) (41%)	7.9 (6.8) (-46%)	0 (14.7) (-100%)	N/A
	4600	3.7	7.5 (3.8) (103%)	3.3 (4.2) (-56%)	0 (7.5) (-100%)	5.9 (1.6) (-21%)
	13,350	2.9	9.9 (7) (241%)	4.9 (5) (-51%)	1.6 (8.3) (-84%)	9.5 (0.4) (-4%)
Annualised (Maximum)	100	135.8	190.9 (55.1) (41%)	103 (87.9) (-46%)	0 (190.9) (-100%)	N/A
	2500	6.9	13.8 (6.9) (100%)	6.1 (7.7) (-56%)	0 (13.8) (-100%)	10.8 (3) (-22%)
	6700	5.9	19.8 (13.9) (236%)	9.9 (9.9) (-50%)	3.1 (16.7) (-16%)	19 (0.8) (-4%)

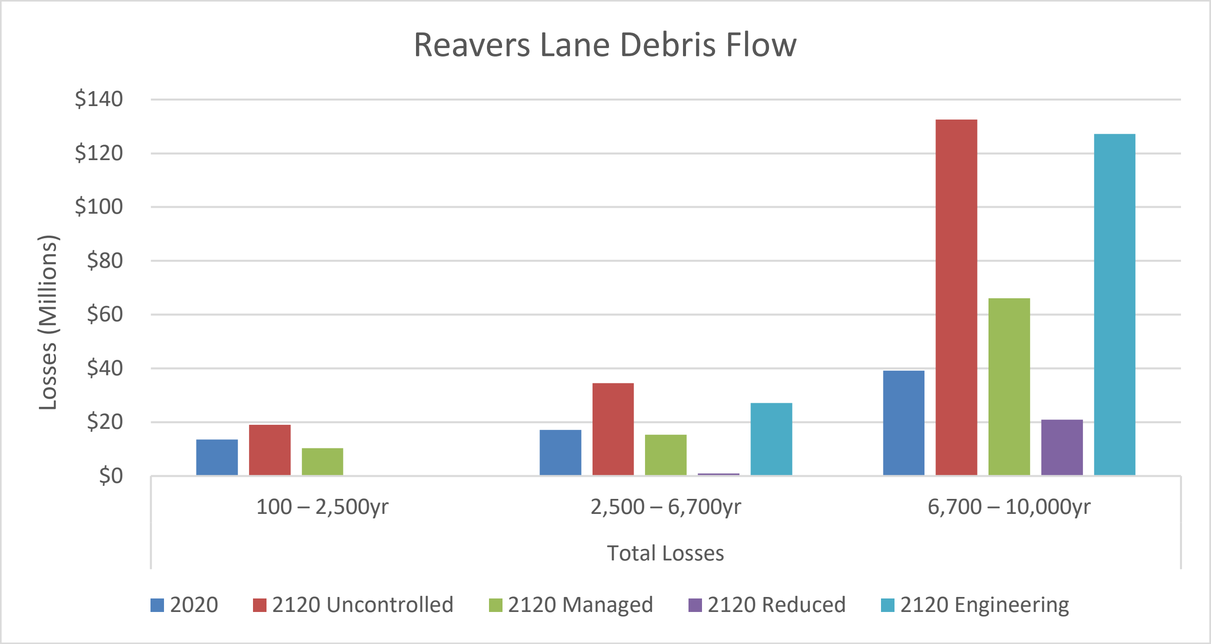

Figure 4.1 Total aggregated building debris flow losses for Reavers Lane for small, moderate and large events.

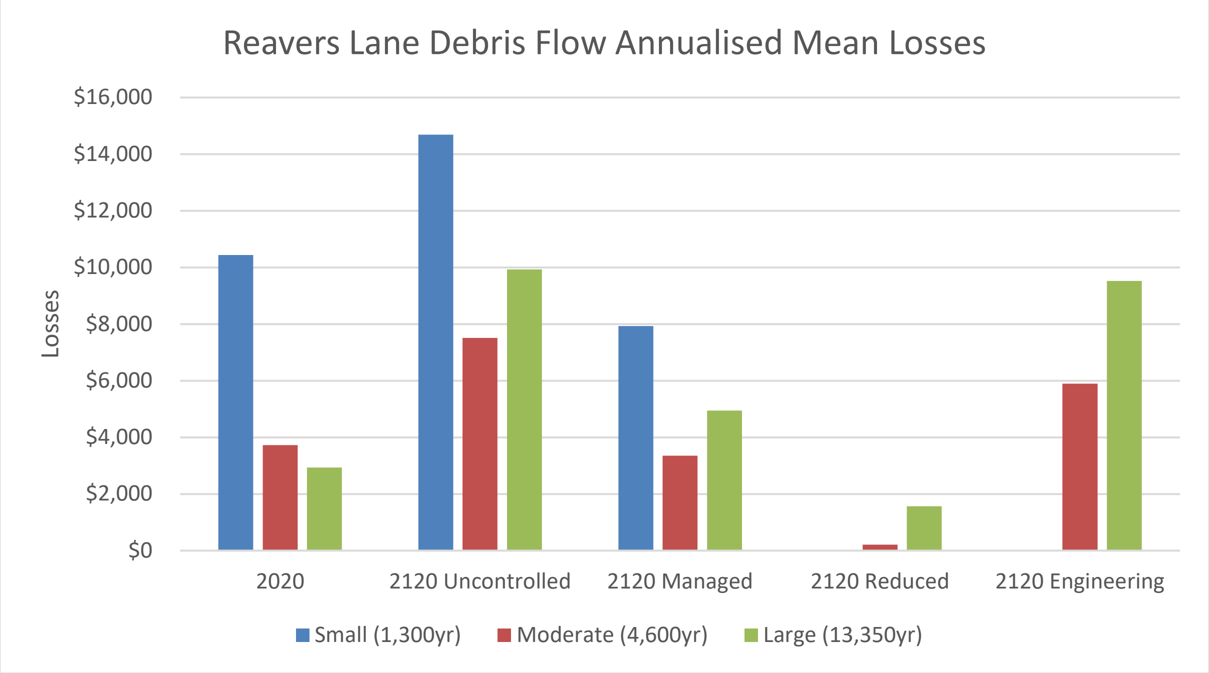

Figure 4.2 Annual aggregate building debris flow losses for Reavers Lane using the average return period.

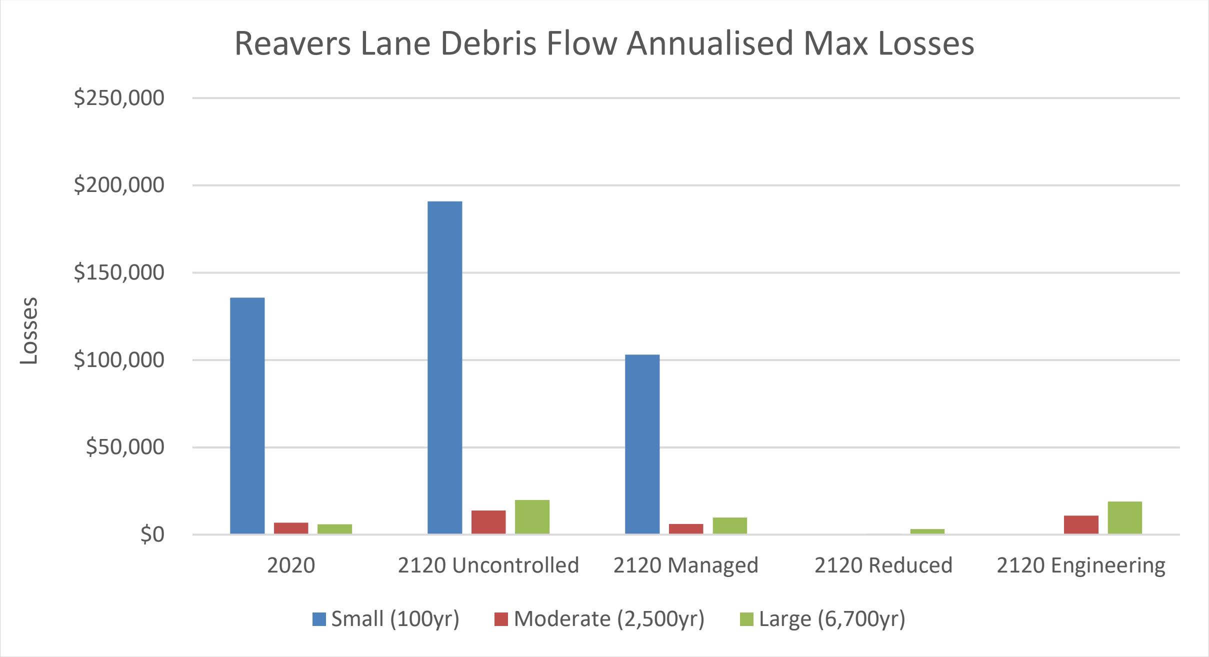

Figure 4.3 Annual aggregate building debris flow losses for Reavers Lane using the most frequent return period.

4.1.2 Brewery Creek Debris Flow

Tables 4.3 and 4.4 present a summary of the losses for the 2020 scenario and each policy or engineering option. Total losses for each scenario are summarised, and losses have been annualised using the mean and most frequent return periods within each range. Figures 4.4, 4.5 and 4.6 provide a graphical representation of the estimated total and annualised losses.

Table 4.3 Total aggregated building debris flow losses for Brewery Creek. Red figures show the actual and percentage differences between the Uncontrolled and Baseline scenarios. Green figures show the actual and percentage differences between Managed, Reduced and Engineering scenarios compared to Uncontrolled.

	Return Period (Years)	2020 Baseline ($M)	2120 Uncontrolled ($M)	2120 Managed ($M)	2120 Reduced ($M)	2120 Engineering ($M)
Total Losses	50–200 (Small)	1.1	29.6 (28.5) (2591%)	1 (28.6) (-3%)	0 (29.6) (-100%)	N/A
	200–250 (Moderate)	11.1	93.7 (82.6) (744%)	28.4 (65.3) (-70%)	7.8 (85.9) (-8%)	51.3 (42.4) (-45%)
	2500–10,00 (Large)	14.1	122.2 (108.1) (867%)	41.6 (80.6) (-70%)	10.6 (111.6) (-91%)	121.3 (0.9) (-1%)

Table 4.4 Annualised aggregated building debris flow losses for Brewery Creek. Red figures show the actual and percentage differences between the Uncontrolled and Baseline scenarios. Green figures show the actual and percentage differences between Managed, Reduced and Engineering scenarios compared to Uncontrolled.

	Return Period (Years)	2020 Baseline ($000s)	2120 Uncontrolled ($000s)	2120 Managed ($000s)	2120 Reduced ($000s)	2120 Engineering ($000s)
Annualised (Mean)	125	9.1	237.3 (228.2) (2508%)	7.9 (229.4) (-97%)	0 (237.3) (-100%)	N/A
	1300	8.5	72.1 (63.6) (748%)	21.8 (50.3) (-70%)	6 (66.1) (-8%)	39.5 (32.6) (-45%)
	6250	2.2	19.6 (17.4) (791%)	6.7 (12.9) (-66%)	1.7 (17.9) (-91%)	19.4 (0.2) (-1%)
Annualised (Maximum)	50	22.9	593.2 (570.3) (2490%)	19.7 (573.5) (-97%)	0 (593.2) (-100%)	N/A
	200	55.5	468.7 (413.2) (745%)	141.9 (326.8) (-70%)	39 (429.7) (-92%)	256.8 (211.9) (-45%)
	2500	5.6	48.9 (43.3) (773%)	16.6 (32.3) (-66%)	4.2 (44.7) (-91%)	48.5 (0.4) (-8%)

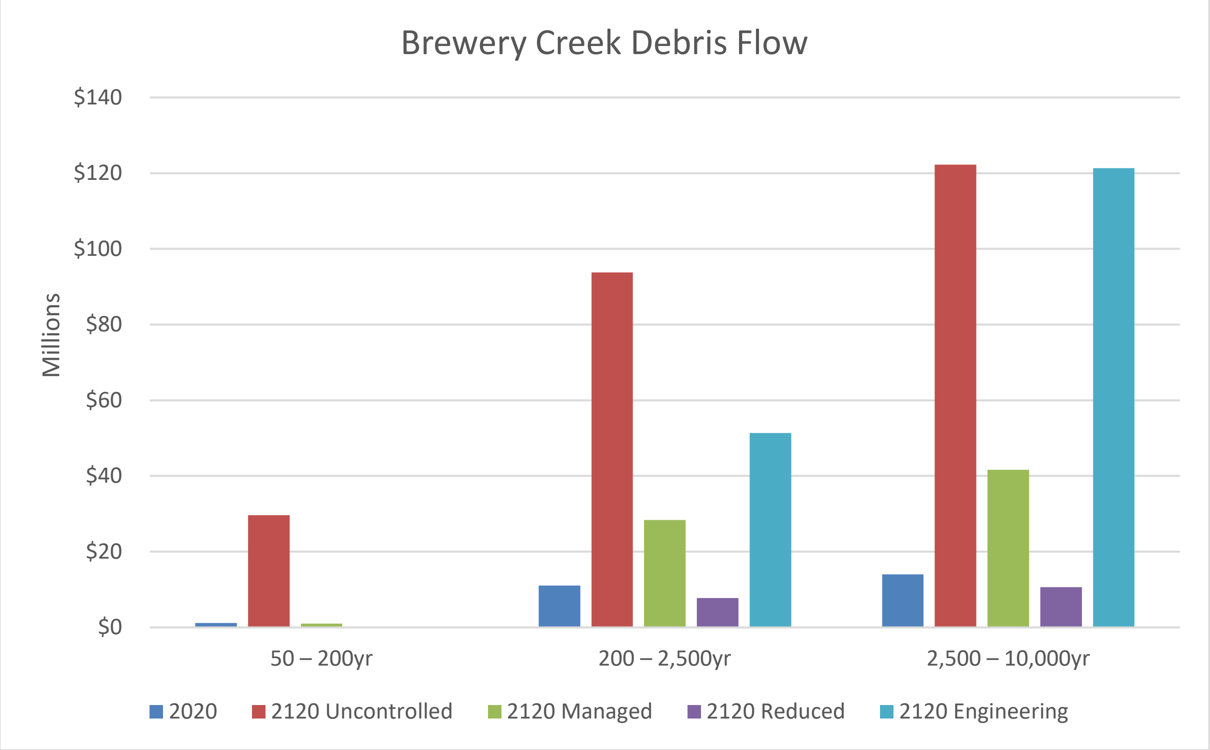

Figure 4.4 Total aggregated building debris flow losses for Brewery Creek.

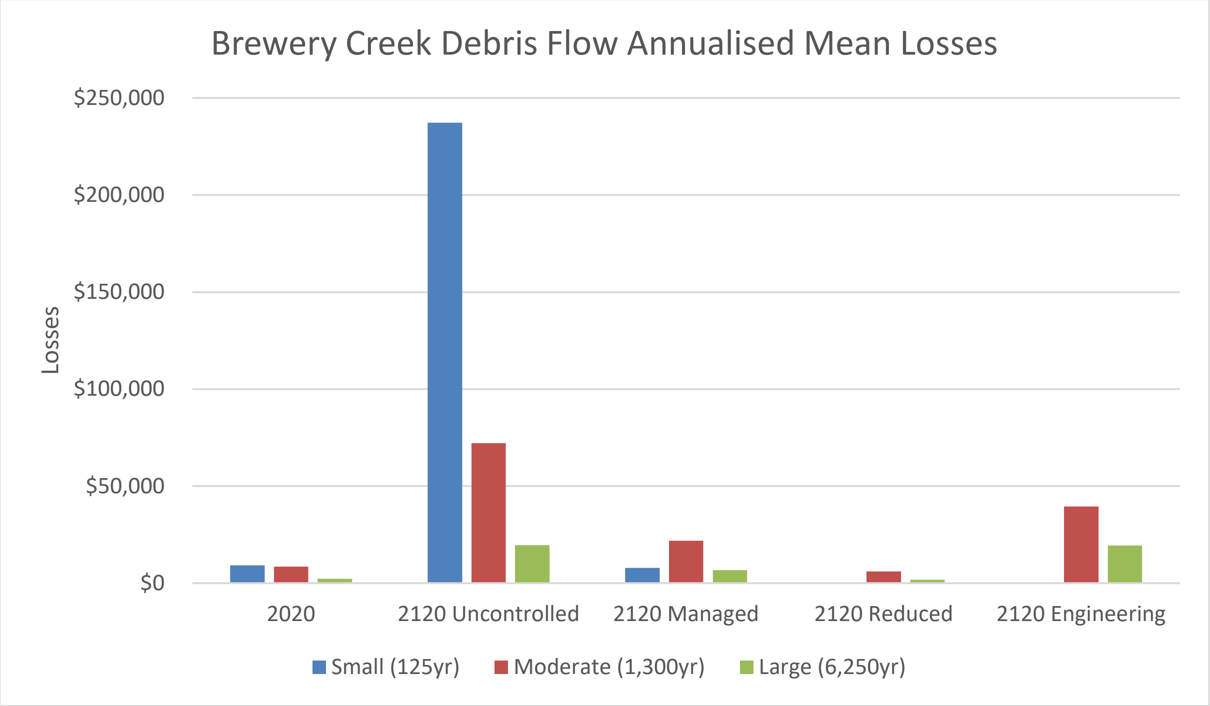

Figure 4.5 Annual aggregate building debris flow losses for Brewery Creek using the average return period.

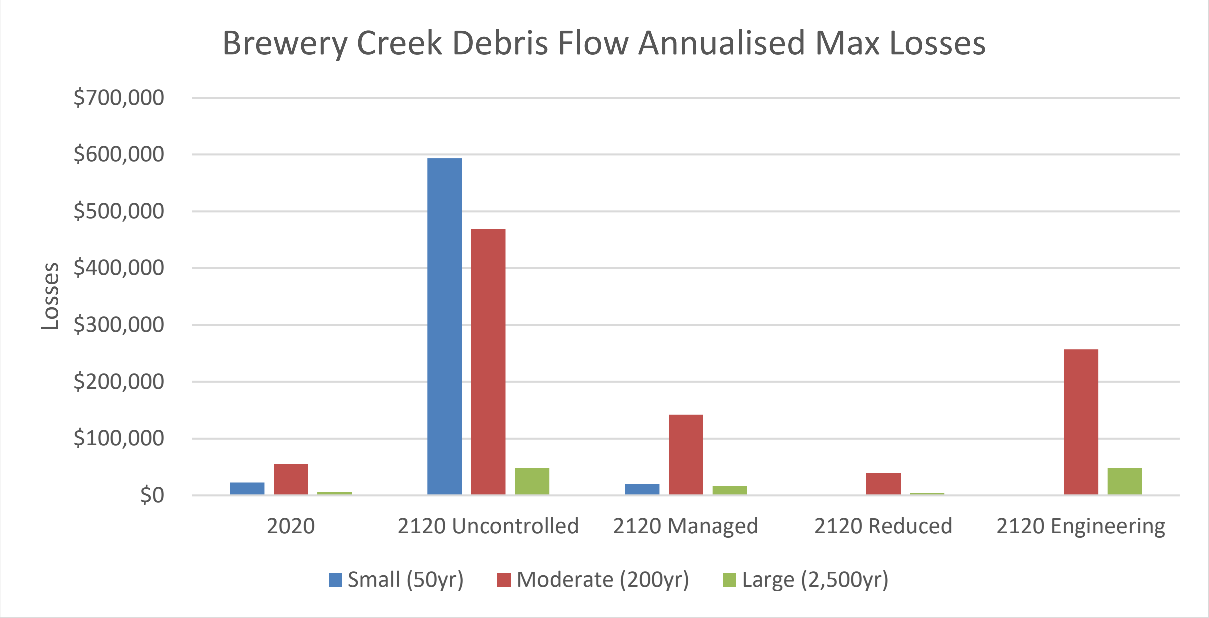

Figure 4.6 Annual aggregate building debris flow losses for Brewery Creek using the most frequent return period.

4.1.3 Reavers Lane and Brewery Creek Rockfall

Table 4.5 presents a summary of the losses for the 2020 scenario and each policy or engineering option. Losses for rockfall engineering options could not be quantified, as there is no modelling software that incorporates rockfall fences into the hazard modelling. As the rockfall scenarios do not have return periods, results are expressed as total losses and cannot be annualised. Figure 4.7 provides a graphical representation of the estimated total losses.

Table 4.5 Total aggregated building rockfall losses for Brewery Creek and Reavers Lane. Red figures show the actual and percentage differences between the Uncontrolled and Baseline scenarios. Green figures show the actual and percentage differences between Managed, Reduced and Engineering scenarios compared to Uncontrolled.

	Rockfall Scenarios	2020 Baseline ($M)	2120 Uncontrolled ($M)	2120 Managed ($M)	2120 Reduced ($M)
Total Losses	Reavers Lane	11.8	26 (14.2) (120%)	12.8 (13.2) (-51%)	3.4 (22.6) (-87%)
	Brewery Creek	0.7	5.6 (4.9) (700%)	4.3 (1.3) (-23%)	2.4 (3.2) (-57%)

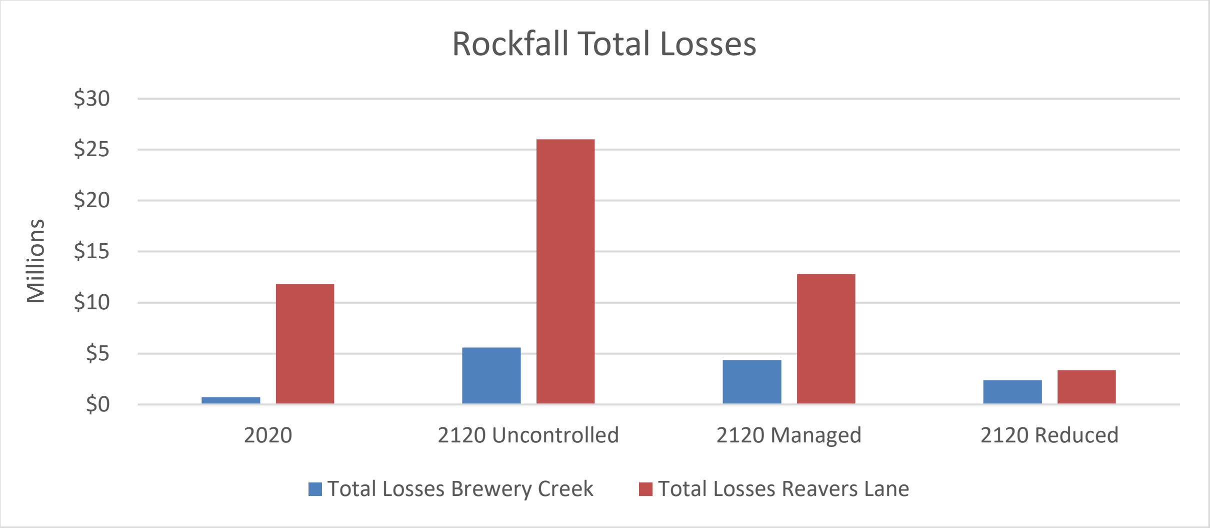

Figure 4.7 Aggregated building rockfall losses for Brewery Creek and Reavers Lane.

5.0 DISCUSSION

This study estimated the probable losses if debris flows and/or rockfalls were to impact residential parts of Queenstown (Figures and 4.1–4.7 and Tables 4.1–4.5) for a range of scenarios. In addition, several policy and engineering options were modelled in RiskScape to understand what losses would be incurred in 2120 if each of these options were implemented. This section discusses the findings of the project and presents uncertainties identified throughout the loss modelling process.

The Reavers Lane results estimate 2020 baseline losses of between $13.5M to $39.2M for the modelled debris flow scenarios. For the Uncontrolled policy option, estimated losses range from $19.1M to $132.5M, which are the highest losses from all policy and engineering options. The Managed policy option results range from $10.3M to $66M, having a reduction in losses of $8.8M, $19.2M and $66.5M for small, moderate and large events, respectively, when compared to the 2120 Uncontrolled scenario. The Reduced policy option results have a range of zero losses for small events to $20.9M for large events. Comparatively, there is a reduction in losses of $19.1M, $33.6M and $111.6M for small, moderate and large events, respectively, when compared to the 2120 Uncontrolled scenario. Notably, while all Reduced scenarios have a reduction in losses, this study has not analysed the cost of implementing the policy or engineering options (cost versus benefit analysis).

Hazard scenarios for smaller events mitigated by engineering options were not provided for loss modelling. Results show that there is a reduction in losses of $7.5M and $8.3M for moderate and large events, respectively, when compared to the 2120 Uncontrolled scenario. For rockfall hazards at Reavers Lane, estimated losses were $26M (Uncontrolled), $12.8M (Managed) and $3.4M (Reduced) with reductions of $13.2M and $22.6M, respectively, when compared to the 2120 Uncontrolled scenario.

The Brewery Creek results estimate 2020 baseline losses of between $1.1M to $14M for the modelled debris flow scenarios. For the Uncontrolled policy option, estimated losses range from $29.6M to $122.2M, which are the highest losses from all policy and engineering options. The Managed policy option results range from $1M to $41.6M, having a reduction in losses of $28.6M, $65.3M and $80.6M for small, moderate and large events, respectively, when compared to the 2120 Uncontrolled scenario. The Reduced policy option results have a range of zero losses for small events to $10.6M for large events. Comparatively, there is a reduction in losses of $29.6M, $85.9M and $111.6M for small, moderate and large events, respectively, when compared to the 2120 Uncontrolled scenario. Again, while all Reduced scenarios have a reduction in losses, this study has not analysed the cost of implementing the policy or engineering options.

Engineering options were not modelled for small events and resulted in reduced losses of $42.4M and $0.9M for moderate and large events when compared to the 2120 Uncontrolled scenario. For rockfall hazards at Brewery Creek, estimated losses were $5.6M (Uncontrolled), $4.3M (Managed) and $2.4M (Reduced), with reductions of $1.3M and $3.2M, respectively, when compared to the 2120 Uncontrolled scenario.

Overall, for debris flow hazards, the study has identified that the Uncontrolled policy option increases direct losses for all scenarios modelled due to increased exposure of buildings. The Managed policy option will reduce direct building losses for all events at both locations when compared to the 2120 Uncontrolled policy option. Due to a reduction in exposed buildings in high hazard locations, the Reduced policy option decreases direct building losses at both study locations for all hazard scenarios. The modelled Engineering scenarios (modelling the effect of a debris fence) reduce direct building losses for all events at both locations when compared to the 2120 Uncontrolled policy option. For rockfall hazards, all modelled policy options result in a reduction in direct losses when compared to the 2120 Uncontrolled policy option.

5.1 Uncertainties

Uncertainty is inherent throughout all stages of the risk modelling process. It is important when interpreting results that these uncertainties are understood and, where possible, appropriately addressed. Here we describe how uncertainty is accounted for in this study.

The debris flow and rockfall hazard models were created by Beca, and the associated uncertainties with these models are described in Beca (2020). There is also uncertainty in aspects of the building datasets and vulnerability models used.

For the baseline 2020 building dataset, the actual cost of building replacement could not be acquired. Therefore, replacement costs were estimated using EQC average replacement costs for Queenstown buildings, which was \$2,363/m^2 for dwelling + appurtenant structures as at 1 June 2020. As a result, uncertainty exists in the economic value of the buildings, which is carried through to the replacement costs. The actual individual building replacement costs may be higher or lower than used in this study.

For each of the other scenarios, building layers were created by QLDC using expert judgement to provide a representation of what the urban environment could look like, assuming maximum development under each of the modelled policies. Therefore, it is recognised that the representation of buildings in each dataset may not represent reality but rather development allowed by District Plan rules. Future development in the study areas would depend on investor interest and market forces.

The vulnerability functions used in this study are considered the best available for estimating loss from debris flows and rockfalls. They are based on a combination of data from landslides (debris flows and rockfalls) that impacted only Aotearoa New Zealand timber-framed dwellings and from international landslide events. There is some uncertainty when using international data as proxies for Aotearoa New Zealand buildings, as often the construction type may be undefined or the buildings may have been constructed to different standards. As such, buildings that are constructed of steel or concrete may perform better than estimated in this study, meaning that losses here may be overestimated.

The vulnerability functions were also created using relatively small datasets (combined Aotearoa New Zealand and international data): 168 data points for debris flows and 41 for rockfall. Further research, including the capture of empirical data following future debris flow or rockfall events, will help constrain the uncertainty associated with these functions. In addition, more empirical data will help constrain loss estimates and reduce uncertainty for individual construction types and other critical attributes, such as floor height and building openings (windows and doors).

This study used the 95th percentile of the mathematical vulnerability functions to provide a conservative estimate. The losses would be less if the average functions were used.

6.0 CONCLUSION

This study presents estimated losses from a range of debris flow and rockfall hazard scenarios for the Reavers Lane and Brewery Creek study areas using RiskScape 2.0. Four different land-use policy options (Uncontrolled, Managed, Reduced and Engineering) have been modelled to determine the impact of each policy on future losses. In summary, for debris flow hazards, the study has identified that the Uncontrolled policy option increases direct losses for all scenarios modelled due to increased exposure of buildings. The Managed policy option will reduce direct building losses for all events at both locations when compared to the 2120 Uncontrolled policy option. Due to a reduction in exposed buildings in high hazard locations, the Reduced policy option decreases direct building losses at both study locations for all hazard scenarios. The modelled Engineering scenarios (modelling the effect of a debris fence) reduce direct building losses for all events at both locations when compared to the 2120 Uncontrolled policy option. For rockfall hazards, all modelled policy options result in a reduction in direct losses when compared to the 2120 Uncontrolled policy option. To address the remaining residual risk, emergency management guidance is presented in the context of the study areas.

7.0 ACKNOWLEDGEMENTS

We would like to thank Emily Grace and Luke Place from Queenstown Lakes District Council for the collaborative approach and contribution to shaping the methodology for the study. We also wish to thank Emma Turner from Queenstown Lakes District Council for creating and providing the policy options GIS files.

We thank Anna Punt from Beca for the collaborative approach in providing hazard data and model outputs required for RiskScape 2.0.

We also wish to thank the Earthquake Commission for the building value calculation and empirical data used to generate the vulnerability functions used in this assessment.

Christina Magill and Scott Kelly are thanked for their reviews of the report.

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APPENDICES

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APPENDIX 1 QUEENSTOWN LAKES DISTRICT COUNCIL FUTURE BUILT ENVIRONMENTS METHODOLOGY

A1.1 Introduction

This report, prepared by Queenstown Lakes District Council describes the method and assumptions for the GIS modelling that created the 'future built environments' used in the loss modelling for the Reavers Lane and Brewery Creek Natural Hazards District Plan Review project.

As part of the review, consideration is being given to how built form can be managed by the District Plan to reduce losses in a natural hazard event. The purpose of the modelling was to explore how modifications to planning provisions result in on-the-ground change in the built form.

Four scenarios, or options, for managing built form are being investigated. Each option involves a different set of modifications to the planning provisions, resulting in different 'future built environments'. Each of these future built environments are then applied in the loss modelling software RiskScape, which generates losses expected from the occurrence of a particular hazard event. When the same hazard event is applied to each of the four future built environments, it is possible to compare how effective each option is at reducing losses.

Three of the options were developed using ArcPro, based on the parcels in the study area. No separate modelling was required for Option 2: Engineering, as the future built environment under this option is the same as under Option 1: Max Build.

A1.2 Key Assumptions

One of the key assumptions of the GIS modelling was the approach of maximising the amount of development provided for by the planning provisions under each of the scenarios to emphasise the comparison between the options. As the comparison was key, no attempt was made to apply a filter to reflect a level of development that might realistically be expected over a 100-year timeframe. This would have added a level of complexity that was not considered necessary in order to understand the comparison between options.

A second key assumption was a focus on the three types of planning provisions that provide the greatest control on risk to property. These are building height, building coverage and building density. The loss modelling takes account of the floor area and height of buildings when estimating losses, and a focus on these provisions focuses on these factors. Other planning provisions, such as recession planes, were not taken into account. Again, to do this would have added a level of complexity that was not considered necessary in order to understand the comparison between options.

A1.3 Option 1: Maximum Build

For this option, the goal was to maximise development allowed by the planning provisions on each site in the area. The parameters used for Option 1 are shown in Table A1.1.

Table A1.1 Max scenario parameters.

	High-Density Residential Zone	**Business Mixed-Use Zone**	**General Industrial Zone (as recommended through Stage 3 hearing)**
Coverage	70%	75%	75%
Height/Storeys	10 m or 3 storeys on flat 7 m or 2 storeys on slope	12 m or 3 storeys	10 m or half 2 storeys and half 1 storey
Subdivision	At 900 m^2, subdivide into two sections	At 400 m^2, subdivide into two sections	At 2000 m^2, subdivide into two sections
Setbacks	2 m from every boundary	Adjoining residential zone 3 m	Adjoining residential zone 7 m Adjoining road 3 m
Density	3 units	-	-

Where subdivision was required, the subdivision tool in ArcPro was used. This resulted in new parcels that would not necessarily be created in the same way in the real world as there was no accounting for access provision. For example, if a parcel could be divided by four, it was split into four equal squares as shown in Figure A1.1 below.

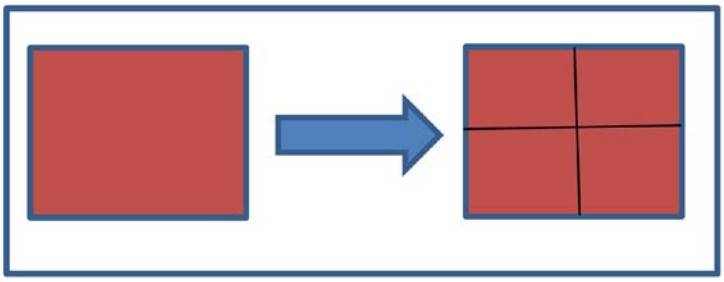


Figure A1.1 Example of how subdivision of large parcels was undertaken.

Interesting observations from this option include that, when setbacks were applied to the existing parcels that did not need subdivision within the High-Density Residential, the build area was usually less than the maximum coverage parameter, i.e. the setback provided the maximum coverage parameter, which was less. To provide for the coverage reductions where required after setbacks were applied, the ArcGIS Pro tool *Scale* was used to reduce building coverage.

A1.3.1 Additional Assumption Used for Some Parcels

There were three large parcels that were not subdivided in the Business Mixed-Use Zone due to access and other constraints on the site; for two of these, the existing buildings were used. For one parcel, currently used as car parking, this was used as the building area due to the Brewery Creek channel running through the site.

A1.4 Option 2: Engineering

The future built environment for Option 2 is the same as for Option 1. The assumption for this option is that development continues without specific hazard restrictions, as for Option 1, because engineering structures are able to provide risk reduction. The change in the loss modelling comes from an alteration in the hazard event scenario, due to the effect of the engineering structures at reducing the extent of the hazard.

A1.5 Option 3: Manage

For this option, the goal was to manage the development in the higher-risk areas while allowing maximum build to occur in areas of lower risk. There were three management bands based on levels of risk; these are described further below.

- Below the 10^{-6} line: Same as Option 1: Maximum build scenario
- Between the 10^{-6} and the 10^{-4} lines: Replace existing built form with maximum built development within following parameters:

	High-Density Residential Zone	**General Industrial Zone**	**Business Mixed-Use Zone**
Coverage	50%	55%	55%
Height	8 m or 2 storeys	7 m everywhere: 25% 2 storeys and 75% 1 storey	8 m or 2 storeys
Subdivision	600 m^2 lot size – one building per 600 m^2	1400 m^2 lot size – one building per 1400 m^2	300 m^2 – one building per 300 m^2

All other standards are the same as the maximum build scenario (e.g. setbacks).

- Between the 10^{-4} and the 10^{-3} lines: Maintain the existing built form and, in the High-Density Residential Zone and Business Mixed-Use Zone, add one 30 m^2 addition to half of the existing buildings, and, for the General Industrial Zone, add one 50 m^2 addition to half of the existing buildings. No change in heights or subdivision.
    - This was undertaken very basically by creating a square of 30 m^2 and adding it to a side of the building that it fitted on while still observing setbacks.
- Within the 10^{-3} line: Maintain the existing built form with no change.
    - Existing buildings were received from GNS Science (RiskScape) and did not include detached garages.

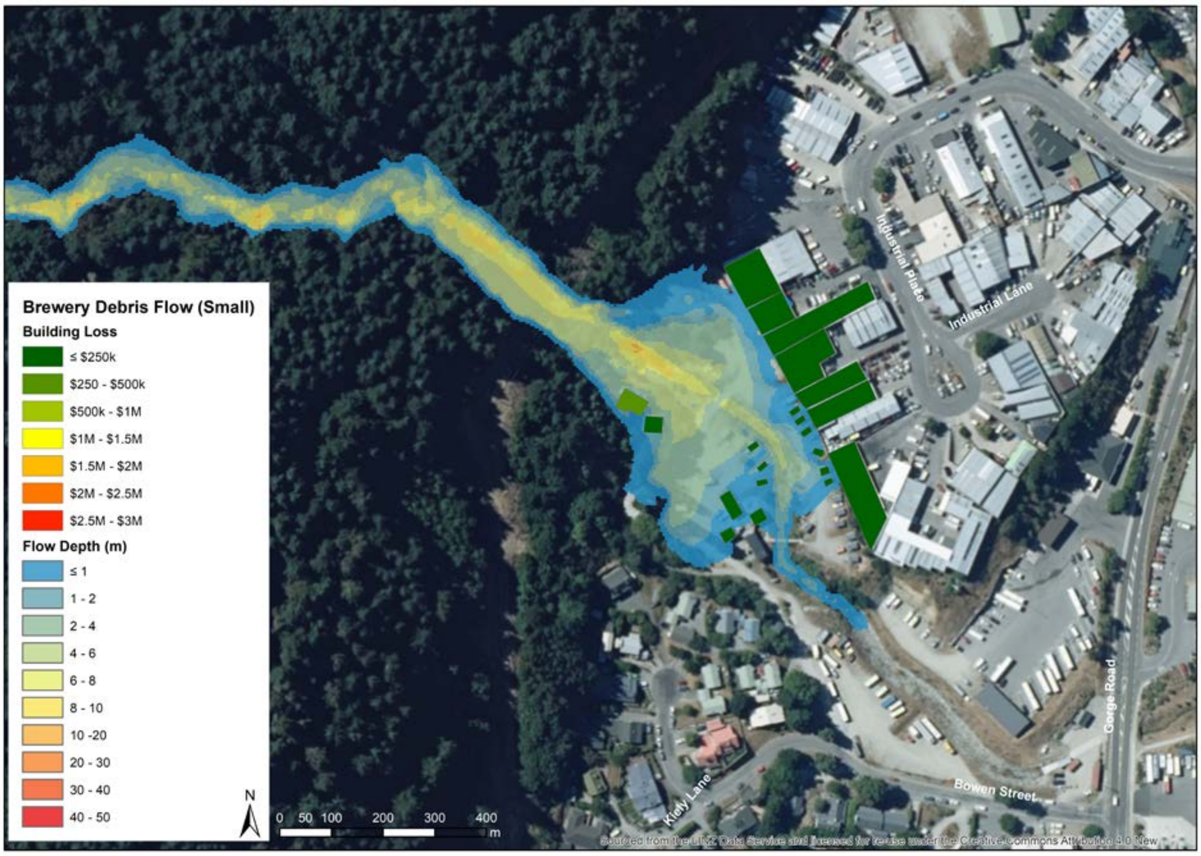
To provide for the coverage reductions where required after setbacks were applied, the ArcGIS Pro tool *Scale* was used to reduce building coverage.

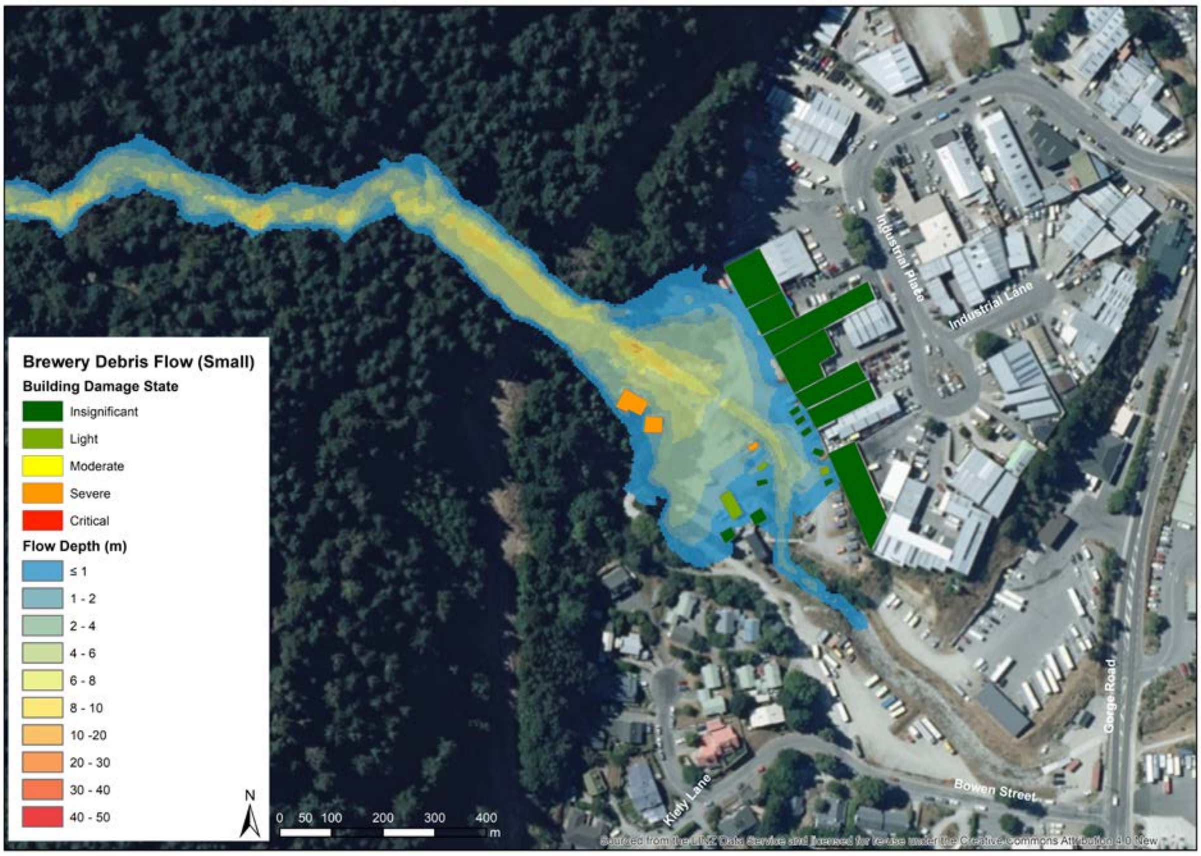
A1.6 Option 4: Reduce

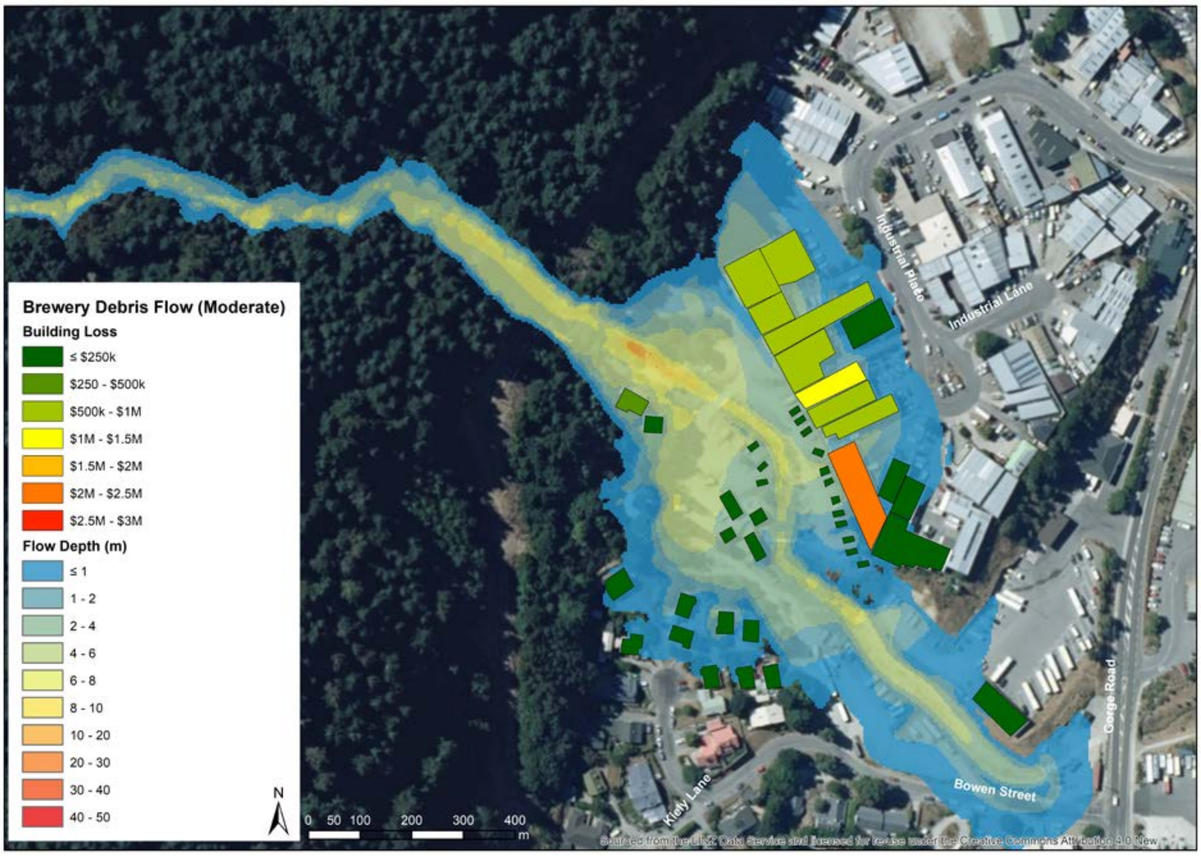
For this option, the goal was to reduce risk to property. This option required removal of buildings in higher-risk areas while maintaining existing buildings in areas of lower risk.

All buildings from above the 1 x 10^{-4} boundary were removed. Between the 1 x 10^{-4} and 1 x 10^{-6} boundaries, existing buildings were used with no additional built form added to the site. Where the property parcel goes across the 1 x 10^{-4} boundary, the part of the existing building that is above the 1 x 10^{-4} was removed.

APPENDIX 2 BASELINE MAPS






Brewery Debris Flow (Moderate)
Building Loss
≤ $250k
$250 - $500k
$500k - $1M
$1M - $1.5M
$1.5M - $2M
$2M - $2.5M
$2.5M - $3M
Flow Depth (m)
≤ 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
N
0 50 100 200 300 400 m
Industrial Place
Industrial Lane
Gorge Road
Bowen Street
Kiely Lane
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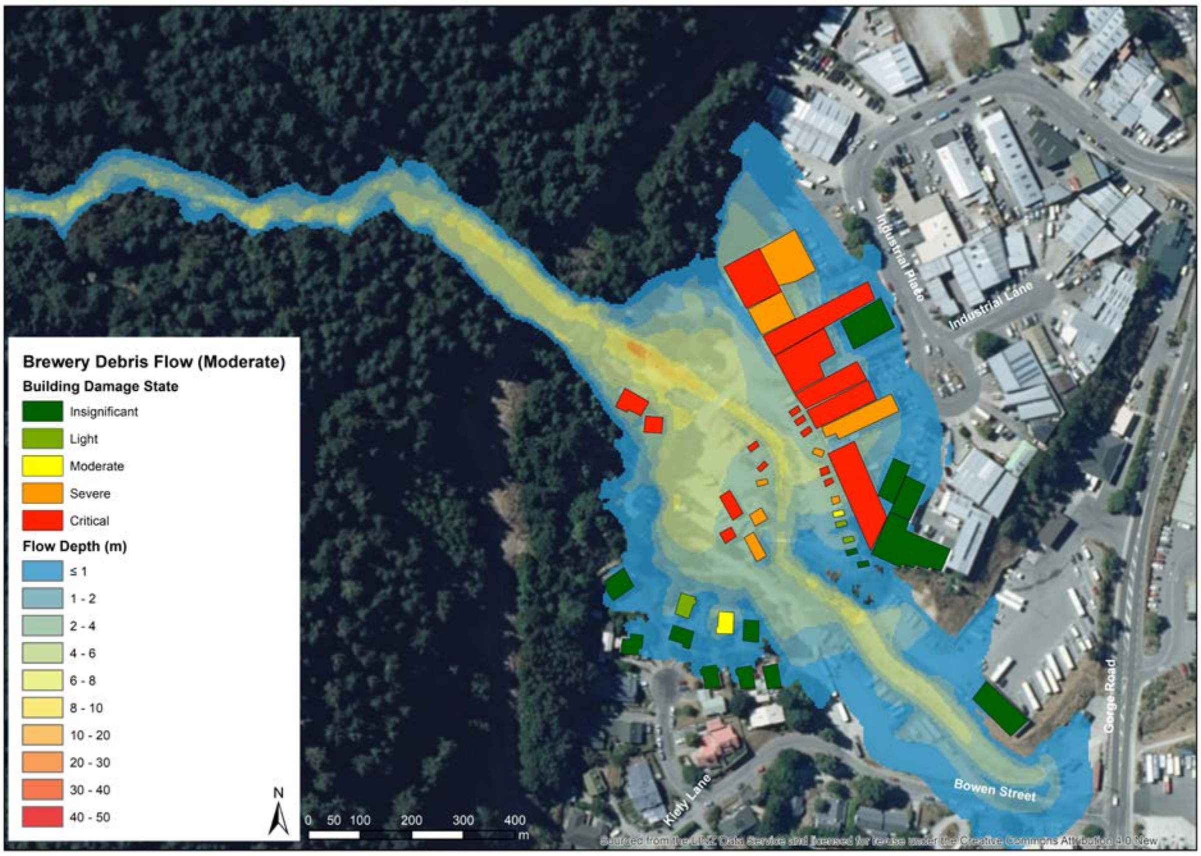
Brewery Debris Flow (Moderate)
Building Damage State
Insignificant
Light
Moderate
Severe
Critical
Flow Depth (m)
≤ 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
N
0 50 100 200 300 400 m
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Industrial Lane
Gorge Road
Bowen Street
Kiely Lane
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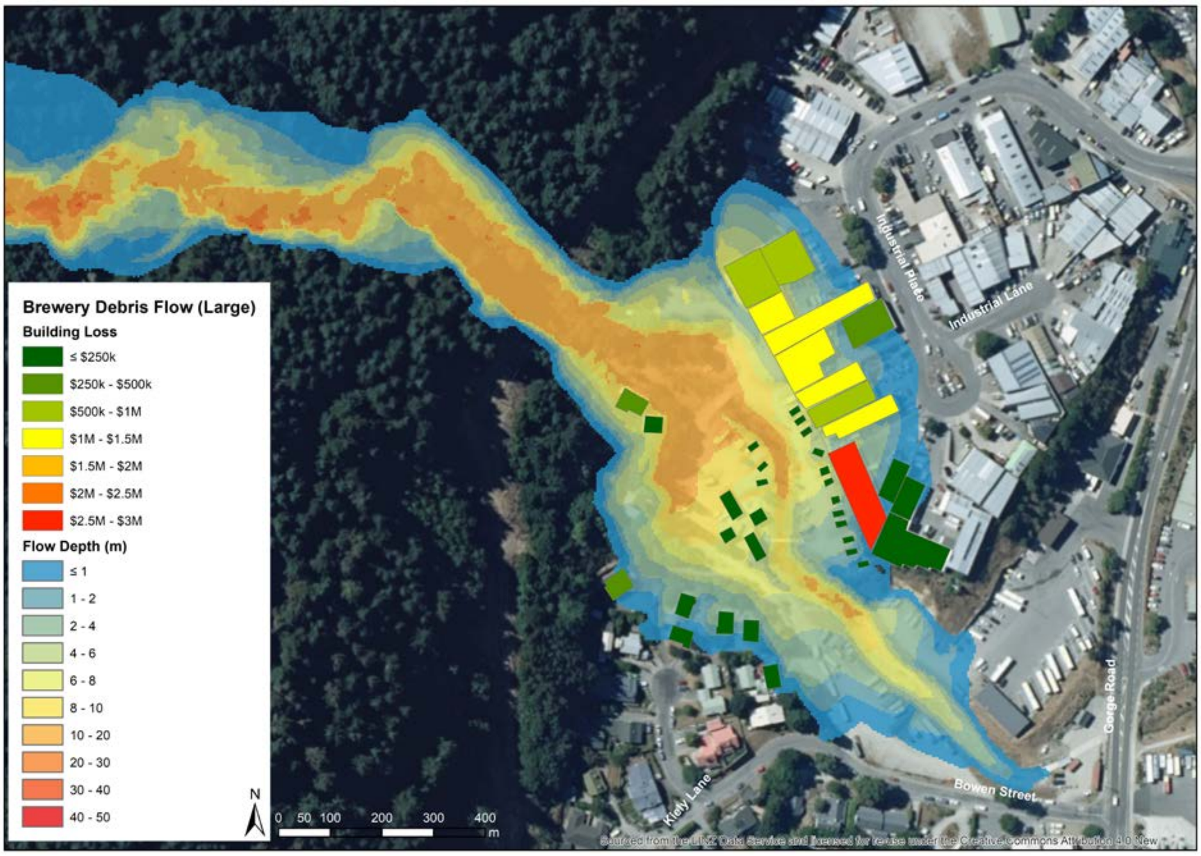
Brewery Debris Flow (Large)
Building Loss
≤ $250k
$250k - $500k
$500k - $1M
$1M - $1.5M
$1.5M - $2M
$2M - $2.5M
$2.5M - $3M
Flow Depth (m)
≤ 1
1 - 2
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4 - 6
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10 - 20
20 - 30
30 - 40
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N
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Industrial Lane
Gorge Road
Bowen Street
Kiely Lane
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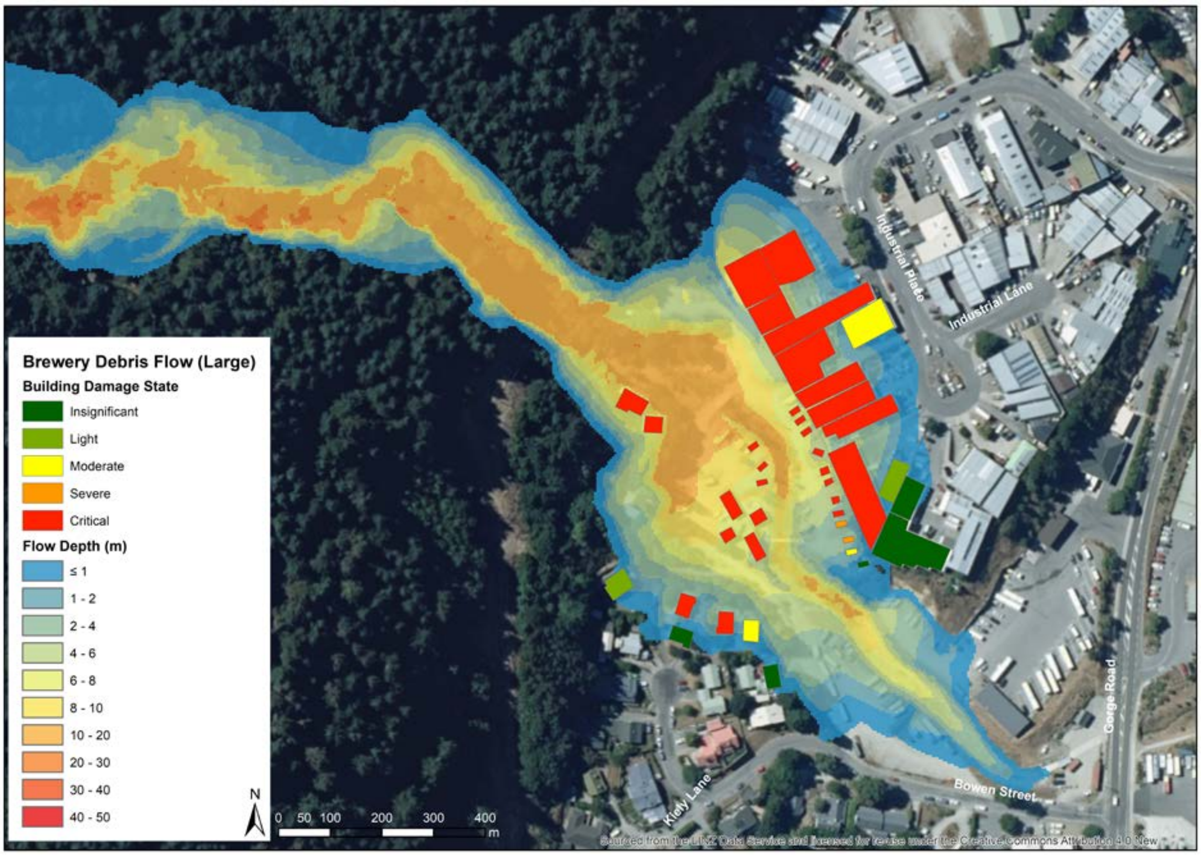
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Building Damage State
Insignificant
Light
Moderate
Severe
Critical
Flow Depth (m)
≤ 1
1 - 2
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40 - 50
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Gorge Road
Bowen Street
Kiely Lane
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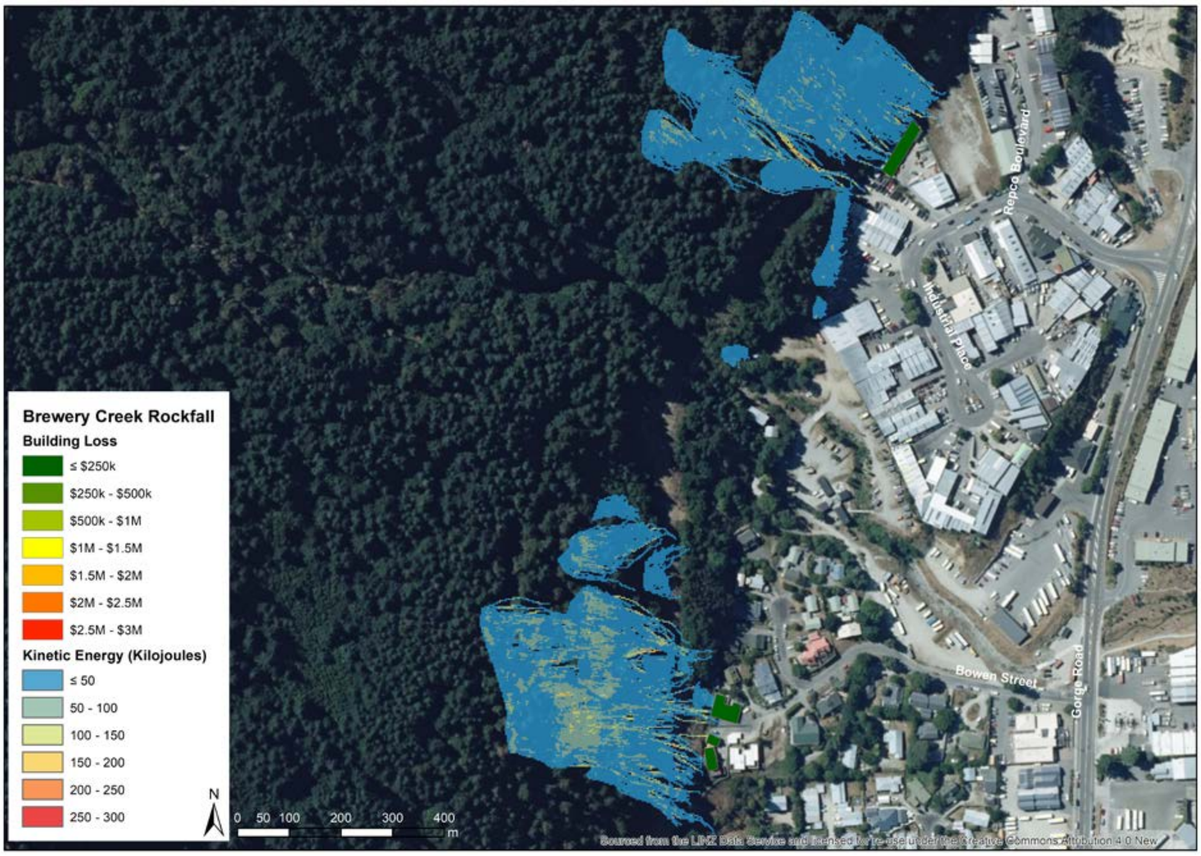
Brewery Creek Rockfall
Building Loss
≤ $250k
$250k - $500k
$500k - $1M
$1M - $1.5M
$1.5M - $2M
$2M - $2.5M
$2.5M - $3M
Kinetic Energy (Kilojoules)
≤ 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
N
0 50 100 200 300 400 m
Repco Boulevard
Industrial Place
Bowen Street
Gorge Road
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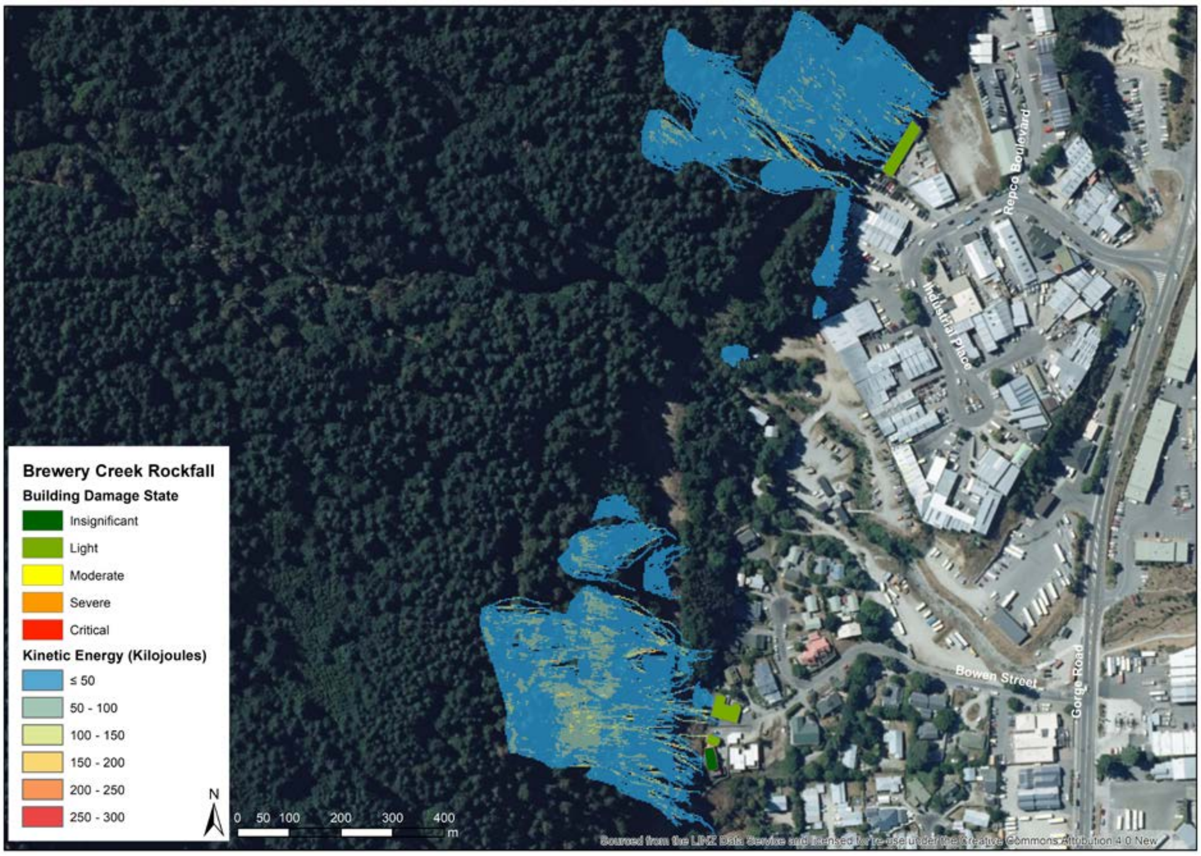
Brewery Creek Rockfall
Building Damage State
Insignificant
Light
Moderate
Severe
Critical
Kinetic Energy (Kilojoules)
≤ 50
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Industrial Place
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Gorge Road
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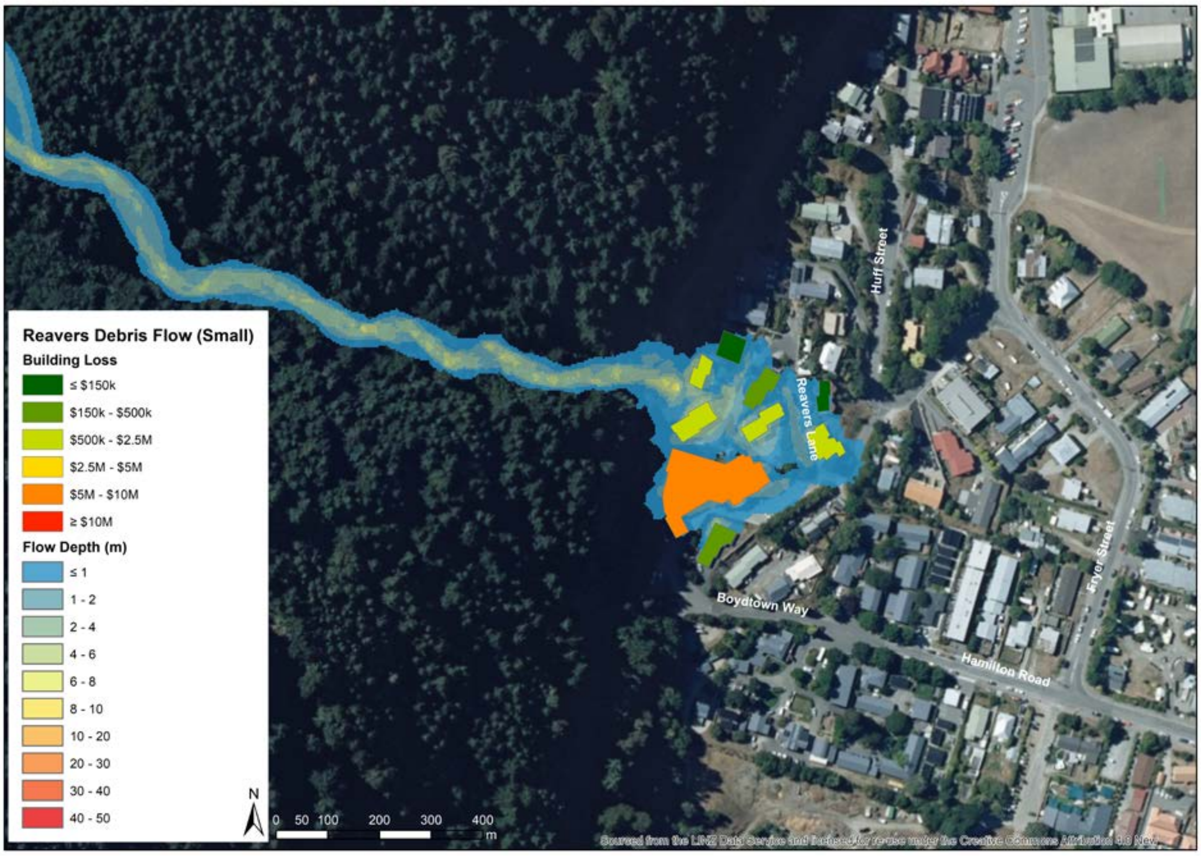
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Building Loss
≤ $150k
$150k - $500k
$500k - $2.5M
$2.5M - $5M
$5M - $10M
≥ $10M
Flow Depth (m)
≤ 1
1 - 2
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6 - 8
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40 - 50
N
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Fryer Street
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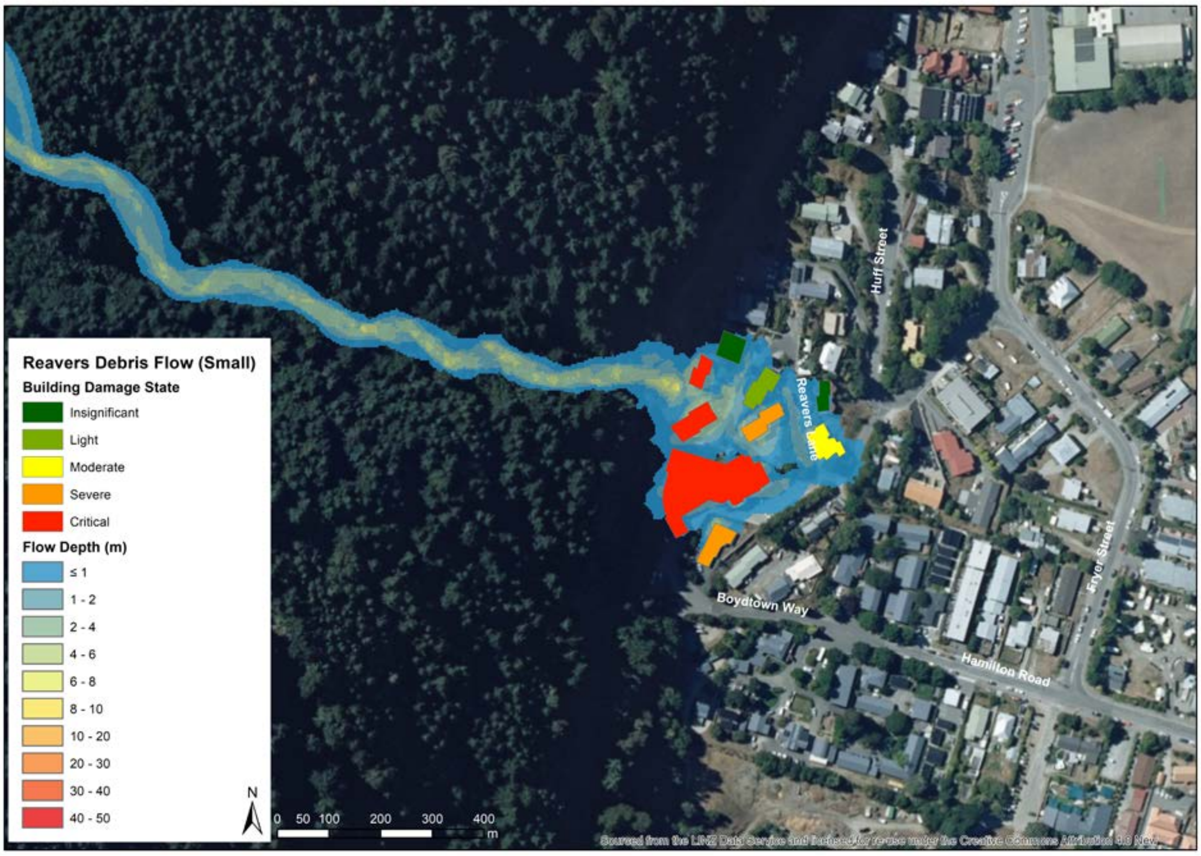
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Insignificant
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Flow Depth (m)
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Huff Street
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Boydtown Way
Hamilton Road
Sourced from the LINZ Data Service and licensed for re-use under the Creative Commons Attribution 4.0 New


Reavers Debris Flow (Moderate)
Building Loss
≤ $150k
$150k - $500k
$500k - $2.5M
$2.5M - $5M
$5M - $10M
≥ $10M
Flow Depth (m)
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Huff Street
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Hamilton Road
Fryer Street
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Reavers Debris Flow (Moderate)
Building Damage State
Insignificant
Light
Moderate
Severe
Critical
Flow Depth (m)
≤ 1
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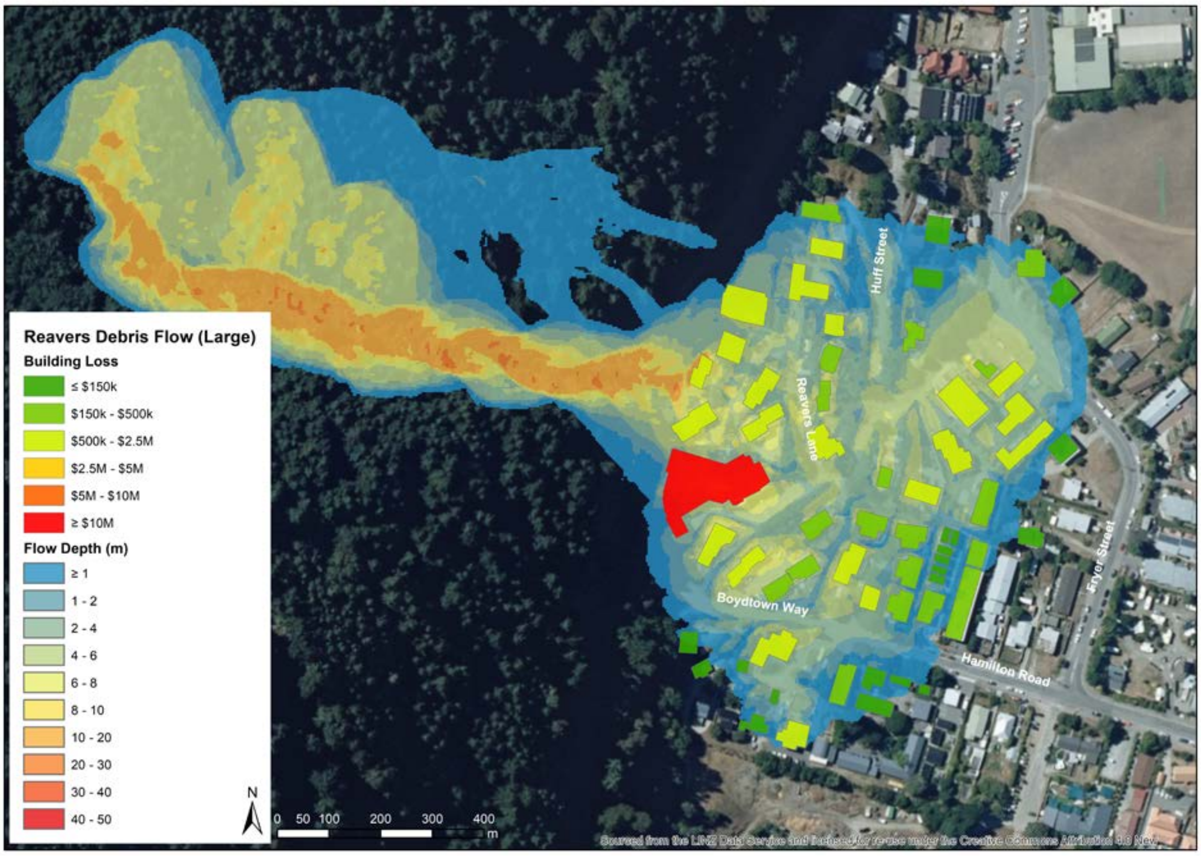
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$2.5M - $5M
$5M - $10M
≥ $10M
Flow Depth (m)
≥ 1
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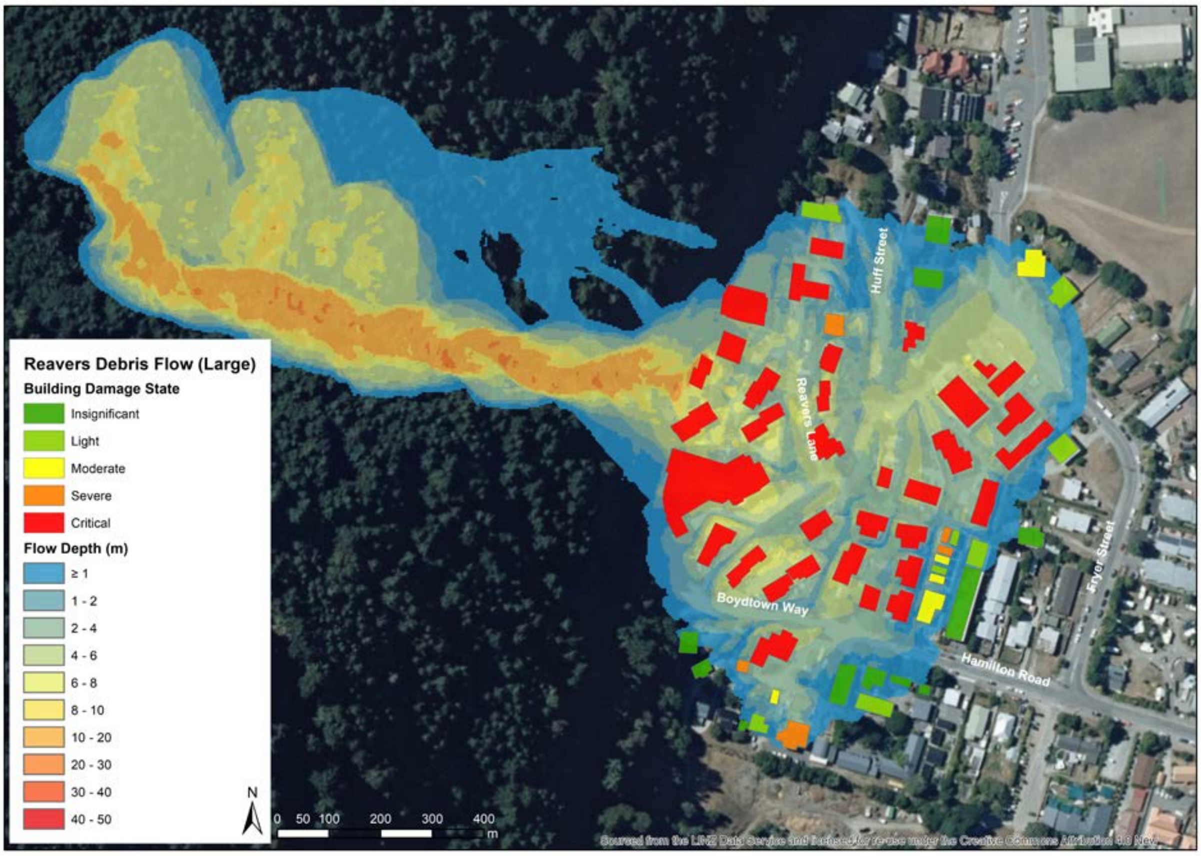
Reavers Debris Flow (Large)
Building Damage State
Insignificant
Light
Moderate
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Flow Depth (m)
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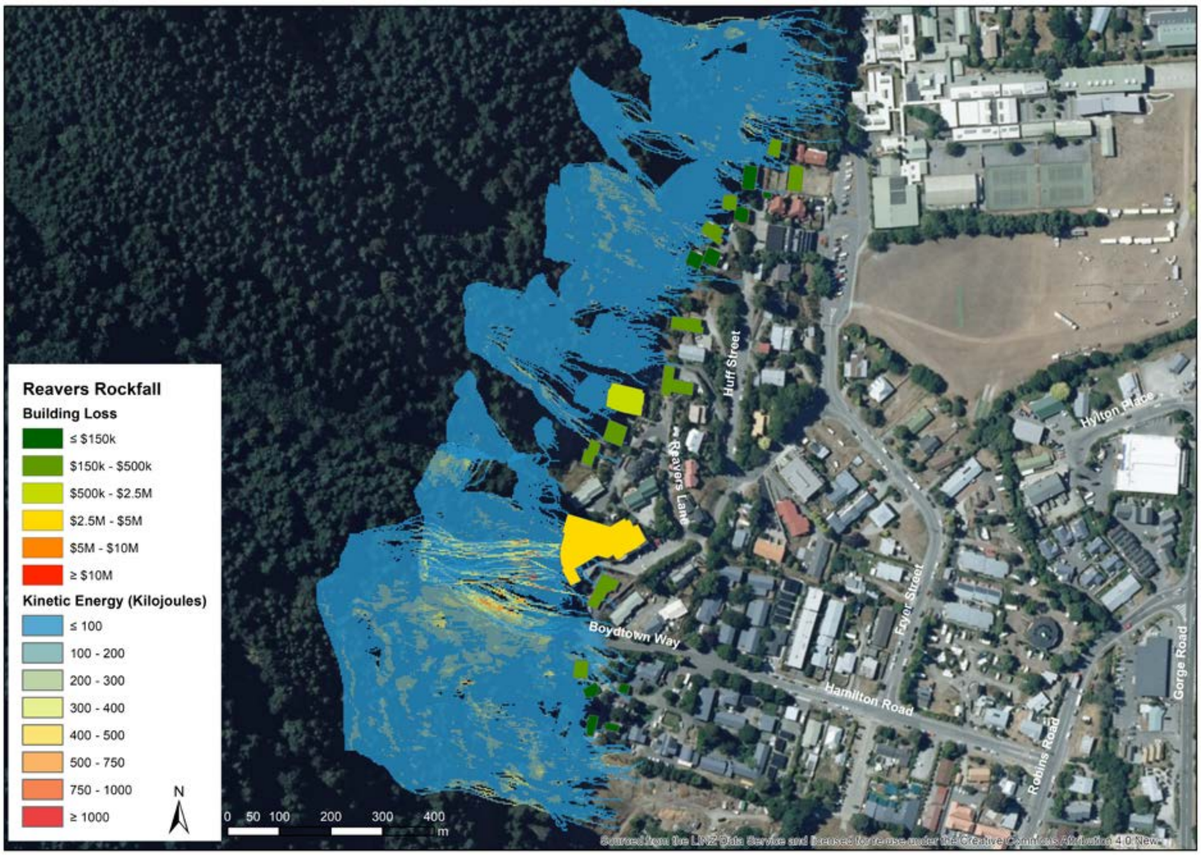
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Building Loss
≤ $150k
$150k - $500k
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≥ $10M
Kinetic Energy (Kilojoules)
≤ 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 750
750 - 1000
≥ 1000
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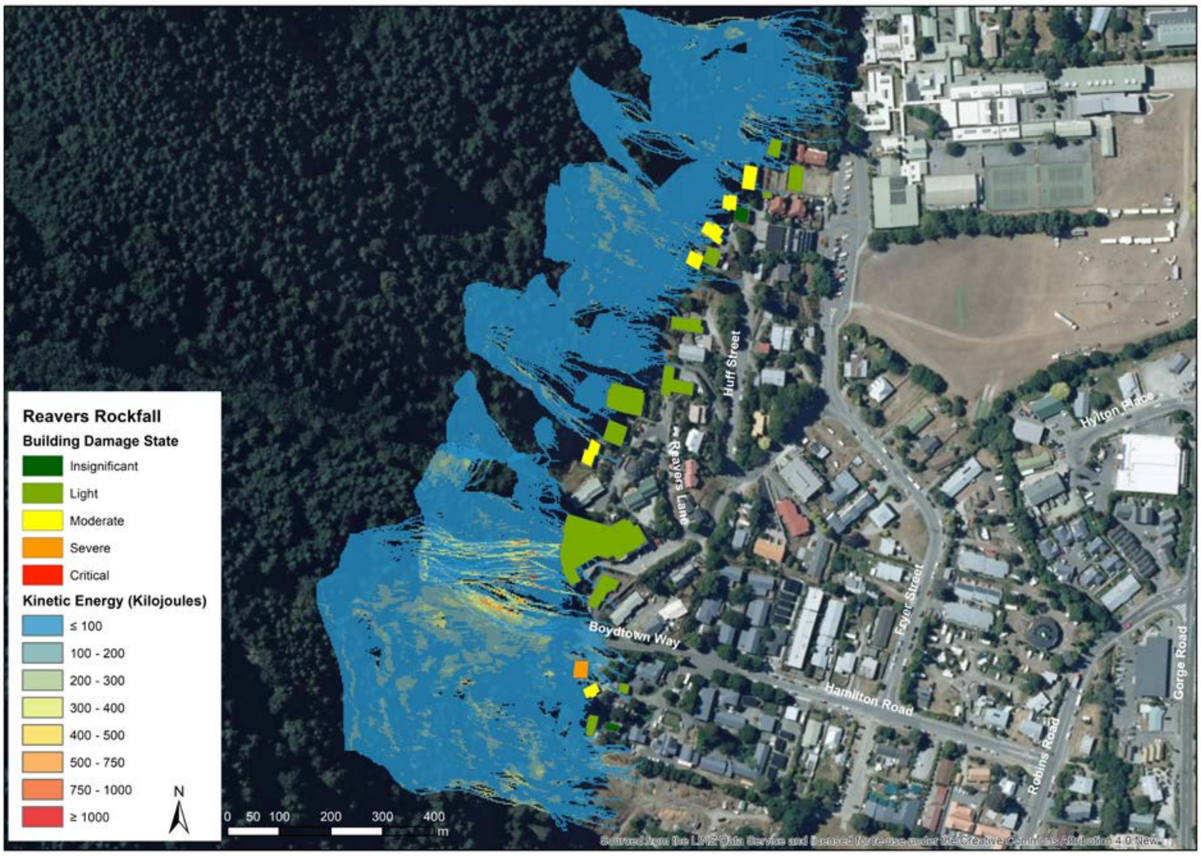
Reavers Rockfall
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Moderate
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Critical
Kinetic Energy (Kilojoules)
≤ 100
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200 - 300
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400 - 500
500 - 750
750 - 1000
≥ 1000
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Huff Street
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Fryer Street
Hylton Place
Gorge Road
Robins Road
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Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657