Natural Hazards Affecting Gorge Road, Queenstown

Prepared for Queenstown Lakes District Council

Prepared by Beca Limited

12 November 2020

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Revision History

Revision Nº	Prepared By	Description	Date
0	Anna Punt Sarah Bastin Michael Eatson	Issued to QLDC for consultation	06/05/2019
1	Anna Punt	Final	15/09/2020
2	Anna Punt	Final – peer reviewed	12/11/2020

Document Acceptance

Action	Name	Signed	Date
Prepared by	**Anna Punt**		12/11/2020
Reviewed by	**Paul Horrey**		12/11/2020
Approved by	**Paul Horrey**		12/11/2020
on behalf of	Beca Limited		

Executive Summary

Introduction

Queenstown Lakes District Council (QLDC) is undertaking a review of the Queenstown Lakes District Plan, which includes considering changes to land use in the Brewery Creek and Reavers Lane areas, located near Gorge Road, Queenstown. This area is known to be susceptible to natural hazards including debris flows, rockfall, liquefaction and flooding.

As part of this process, Beca Limited (Beca) has been commissioned to undertake a review of natural hazards affecting this area. The intention of this work is to provide a greater understanding of the level of risk posed by natural hazards to allow QLDC to make informed decisions relating to land use planning.

Beca's work has been conducted in two phases, as summarised below:

- An initial review of natural hazards in the Gorge Road area, including debris flow, rockfall, liquefaction and flooding. A qualitative assessment of risk to property from debris flow and rockfall was also undertaken. This work was summarised in the report titled *Natural Hazards Affecting Gorge Road, Queenstown* (Beca, 2019).
- A second phase of work extends the original qualitative property risk study to include a quantification of both life risk and property risk.

This report sets out all phases of work undertaken by Beca to date relating to natural hazards in the Gorge Road area, and provides Annual Individual Fatality Risk (AIFR) and Annual Property Risk (APR) contour plans for the study areas. GNS Science are providing peer review of the study.

Site Characterisation

Setting

The study area comprises two alluvial fans located approximately 1km north of Queenstown centre.

Brewery Creek Fan is occupied by residential properties in the southern and western limits, to the south of Brewery Creek. To the north of Brewery Creek, the fan is occupied by industrial and service activities. Reavers Fan is the smaller and steeper of the two fans and is predominantly occupied by residential properties, with some properties in the upper fan used for commercial visitor accommodation.

History

Urban development on both fans commenced in the 1950s. There are no historical reports of debris flow events having impacted property on Reavers Fan. There are two documented historic debris flow and flood events in the Brewery Creek catchment, in May 1986 and November 1999. The 1999 event resulted in debris covering parts of the fan surface and extending over Gorge Road.

There are no records of rockfall events having impacted buildings on either fan in the reviewed data sources, although there is evidence of isolated rockfall having occurred.

Slope Stability Risk Assessment

The annual risk to life (AIFR) and property (APR) from debris flow and rockfall hazards have been assessed quantitively. The resulting risk values are presented as probabilities which can be expressed in a number of ways, as shown in the below table.

Ways of expressing risk probabilities (after GNS Science, 2012b).

Probability 1 in… (per year)	Is the same as (per year)	Is the same as (per year)	Is the same as (per year)	Is the same as (over lifetime)*	Is the same as (over building life)†
1,000	10^{-3}	0.001	0.1%	8%	5%
10,000	10^{-4}	0.0001	0.01%	0.8%	0.5%
100,000	10^{-5}	0.00001	0.001%	0.08%	0.05%
1,000,000	10^{-6}	0.000001	0.0001%	0.008%	0.005%

*Based on average New Zealand life expectancy of approximately 80 years, from 2008 mortality and population data.
†Based on minimum building design life of 50 years in accordance with the New Zealand Building Code.

Slope Stability Life Risk Assessment

A quantitative assessment of life risk posed by debris flow and rockfall hazards 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 debris flow or rockfall.** The methodology adopted to assess this follows the Australian Geomechanics Society (AGS) Guidelines for Landslide Risk Management (2007).

An estimate of AIFR can be developed from:

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

Where:

$P_{(H)}$ is the annual probability of a hazard (debris flow or rockfall) occurring.

$P_{(S:H)}$ is the spatial probability that, given the hazard has occurred, the resulting debris traverses a location that could be occupied by the person most at risk.

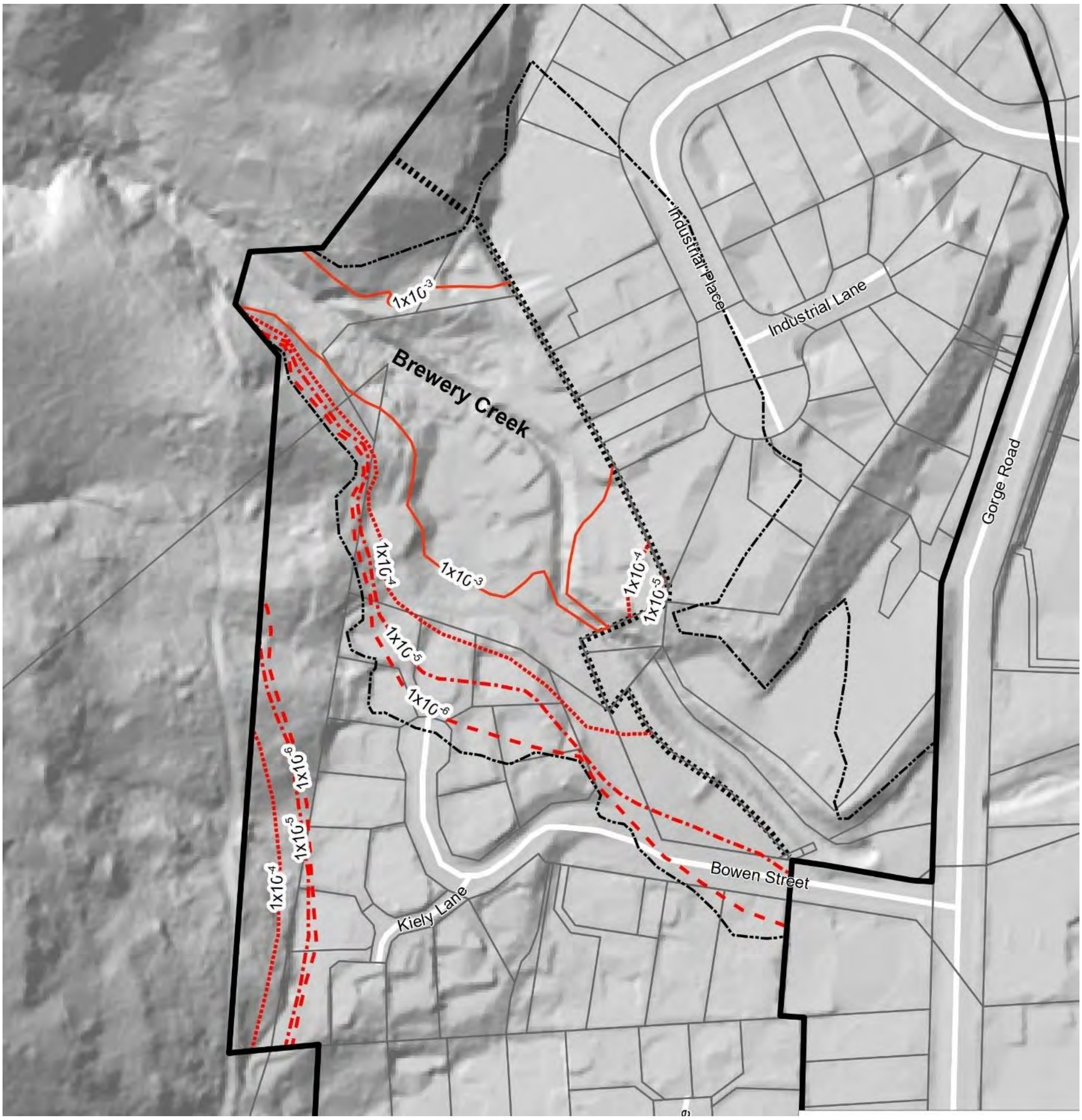
$P_{(T:S)}$ is the temporal spatial probability incorporating the proportion of the time the person most at risk is present and allowing for the possibility that there may be enough warning of the hazard to allow self-evacuation.

$V_{(D:T)}$ is the vulnerability, or probability of death of the person most at risk in the event of an interaction with the hazard.

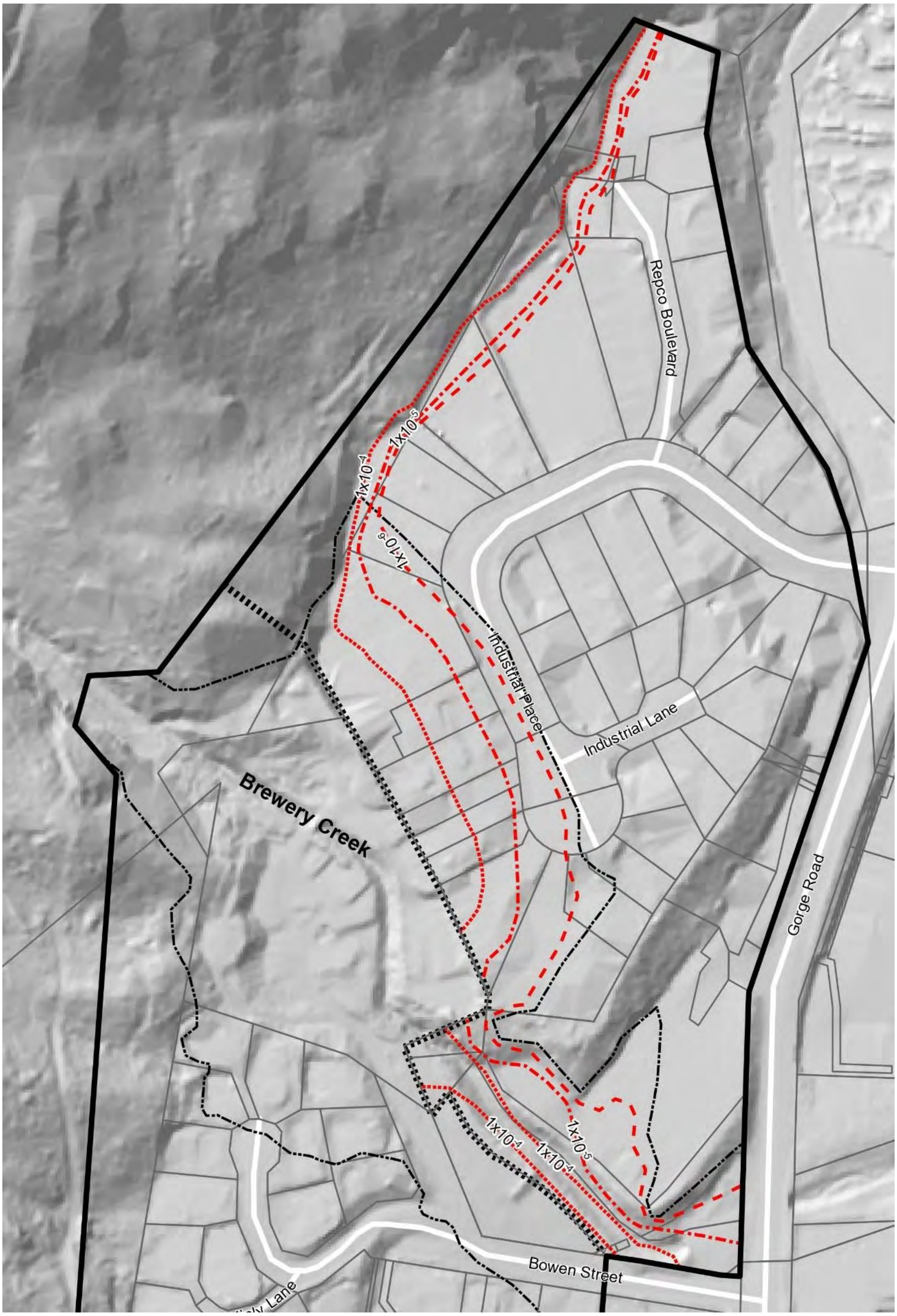
AIFR has been assessed for both fans based upon field mapping, ground investigation, historical events and numerical modelling.

Debris flow and rockfall risk are evaluated differently and separately but are then summed to provide a combined slope stability risk, presented as slope stability risk zone maps in this report.

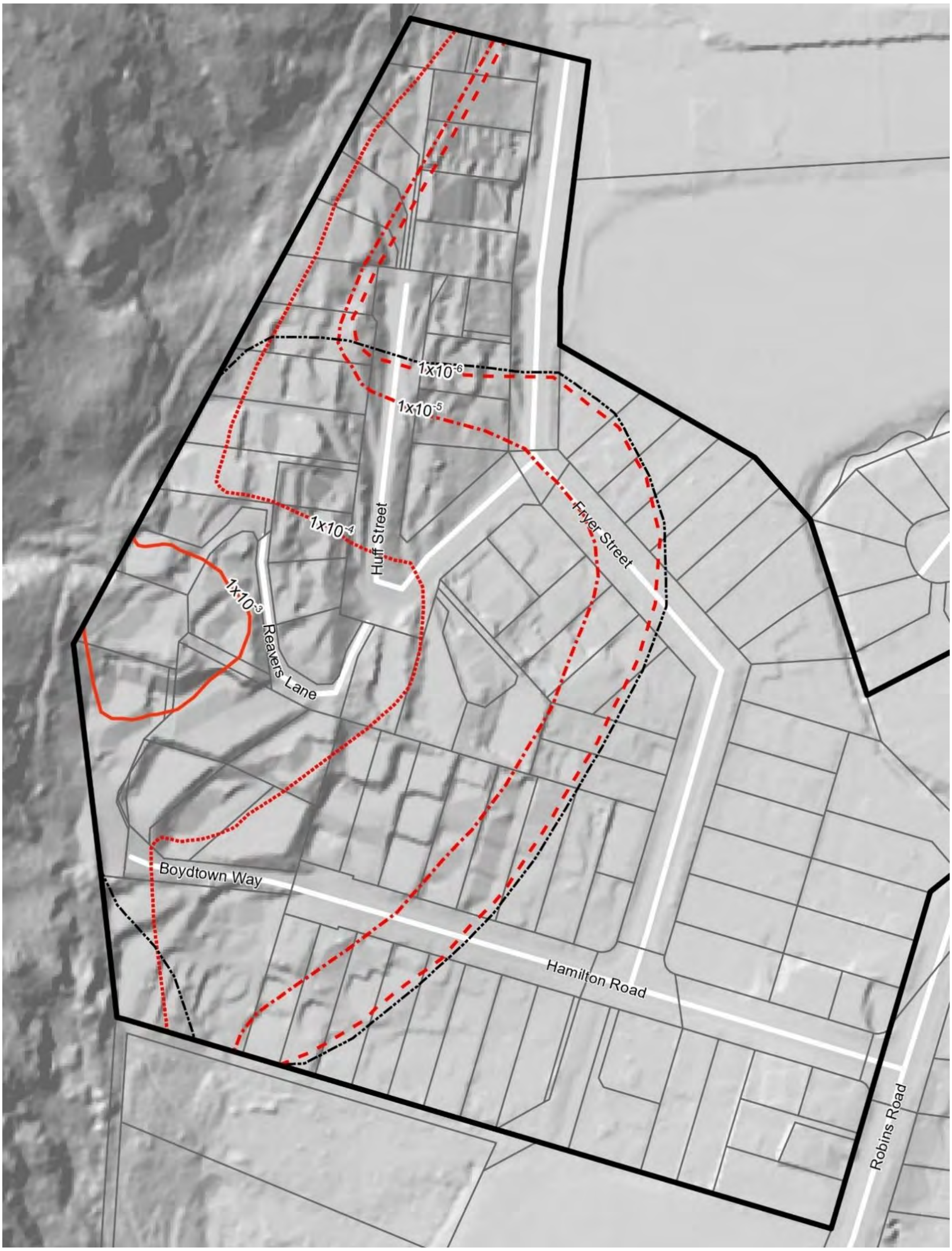
AIFR contours were then developed for combined debris flow and rockfall risk, using average AIFR values for the current (forested) situation. The resulting AIFR contour plans are shown below, with contours ranging from 10^{-3} to 10^{-6}.



AIFR contours Brewery Creek Fan – Residential Zone. Extract from drawing J013 – Appendix J. Refer to Appendix for full drawing.



AIFR contours Brewery Creek Fan – Business Zone. Extract from drawing J014 – Appendix J. Refer to Appendix for full drawing.



AIFR contours Reavers Fan. Extract from drawing J015 – Appendix J. Refer to Appendix for full drawing.

Climate Change Impacts on Slope Stability

The AIFR assessment for debris flow is based on historical rainfall data. An indicative sensitivity analysis was conducted to assess the likely effect of climate change on debris flow AIFR. The results indicated an increase in AIFR of just under one order of magnitude between current climate conditions and the most extreme climate change scenario for the year 2090.

It is anticipated that the effect of climate change on rockfall would be considerably less significant than for debris flow as climate triggers do not dominate the rockfall risk profile.

Slope Stability Property Risk Assessment

The risk of property damage was assessed qualitatively in the first phase of this natural hazards study. The most recent scope of work, as reported below, supersedes the property risk assessment provided in the Beca 2019 report.

A quantitative assessment of APR posed by the debris flow and rockfall hazards has been carried out for the study area. **APR is the annual probability of total property loss (relating to permanent structures) as a result of the hazards occurring**, on the assumption that the site is developed. The methodology adopted follows the AGS Guidelines for Landslide Risk Management (2007).

An estimate of APR can be developed from:

$$APR = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(Prop:S)} \times E.$$

Where:

$P_{(H)}$ is the annual probability of a hazard (debris flow or rockfall) occurring.

$P_{(S:H}$) is the spatial probability of impact (by debris flow or rockfall) on the property, taking into account the travel distance and travel direction.

$P_{(T:S)}$ is the temporal spatial probability. For houses and other buildings (i.e. fixed elements), P(T:S) = 1.0

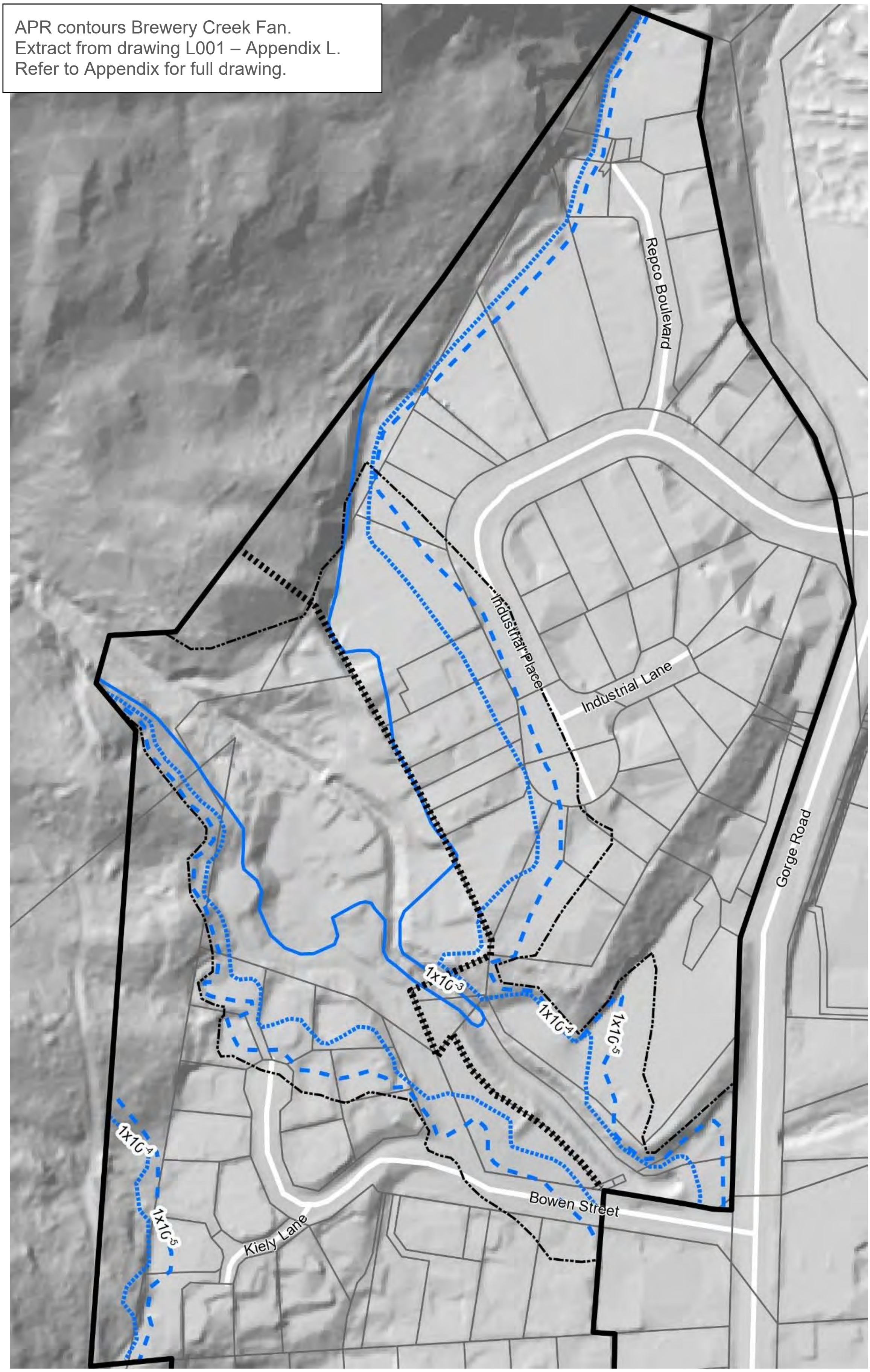
$V_{(D:T)}$ is the vulnerability of the property to the spatial impact (or expected proportion of property value lost in the event of impact).

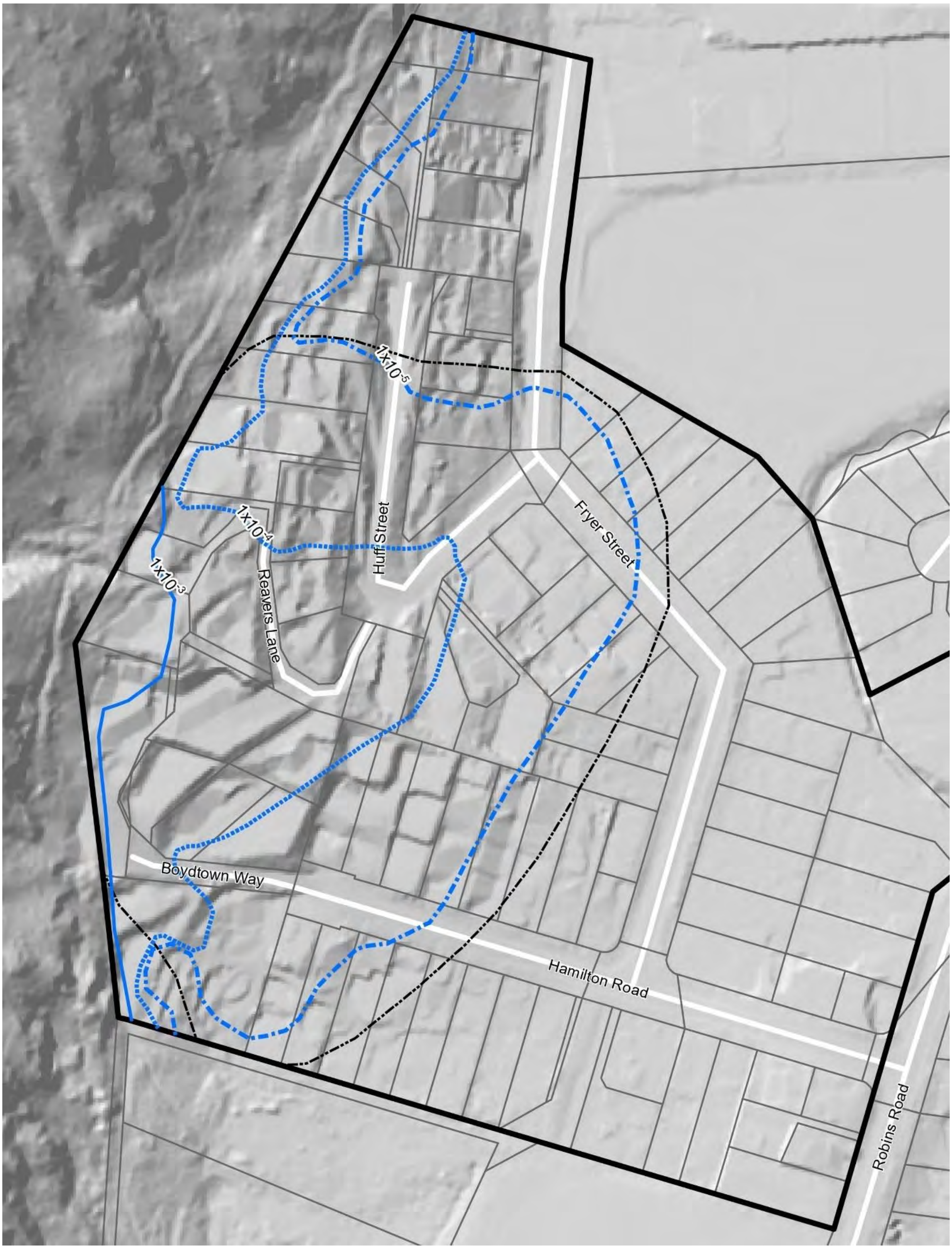
E is the value of the element at risk (e.g. the replacement value of the property).

APR has been assessed utilising the annual and spatial probability parameters from in the AIFR assessment, along with vulnerability parameters obtained from the loss modelling software RiskScape (https://www.riskscape.org.nz/), provided by GNS Science.

APR values for debris flow and rockfall were overlaid to produce combined APR, with values ranging from 10^{-3} to 10^{-6}. The resulting APR values have been contoured as shown in the below plans.

APR contours Brewery Creek Fan.
Extract from drawing L001 – Appendix L.
Refer to Appendix for full drawing.





APR contours Brewery Creek Fan. Extract from drawing L002 – Appendix L. Refer to Appendix for full drawing.

Liquefaction Vulnerability

Cone Penetration Testing (CPT) was undertaken on the distal (lower) margins of the Brewery Creek and Reavers alluvial fans to inform liquefaction assessment, which considered a total of 17 CPTs conducted by Beca and others. This information was used to inform the liquefaction susceptibility analysis using the Boulanger and Idriss (2014) methodology. Vertical settlement during a 1/500 year Mw 6.5 earthquake (equivalent to a 0.41g peak ground acceleration) ranged from less than 30mm to 320mm across the study area.

Liquefaction hazard has been assessed based on the vulnerability of damage to land during a design seismic event, in accordance with MBIE (2017). Liquefaction damage is possible for the distal areas of both Brewery Creek and Reavers Fans, and unlikely for the upper fans. The liquefaction vulnerability plan is included in Appendix M – Liquefaction Vulnerability, with extracts shown overleaf for Brewery Creek and Reavers Fan.

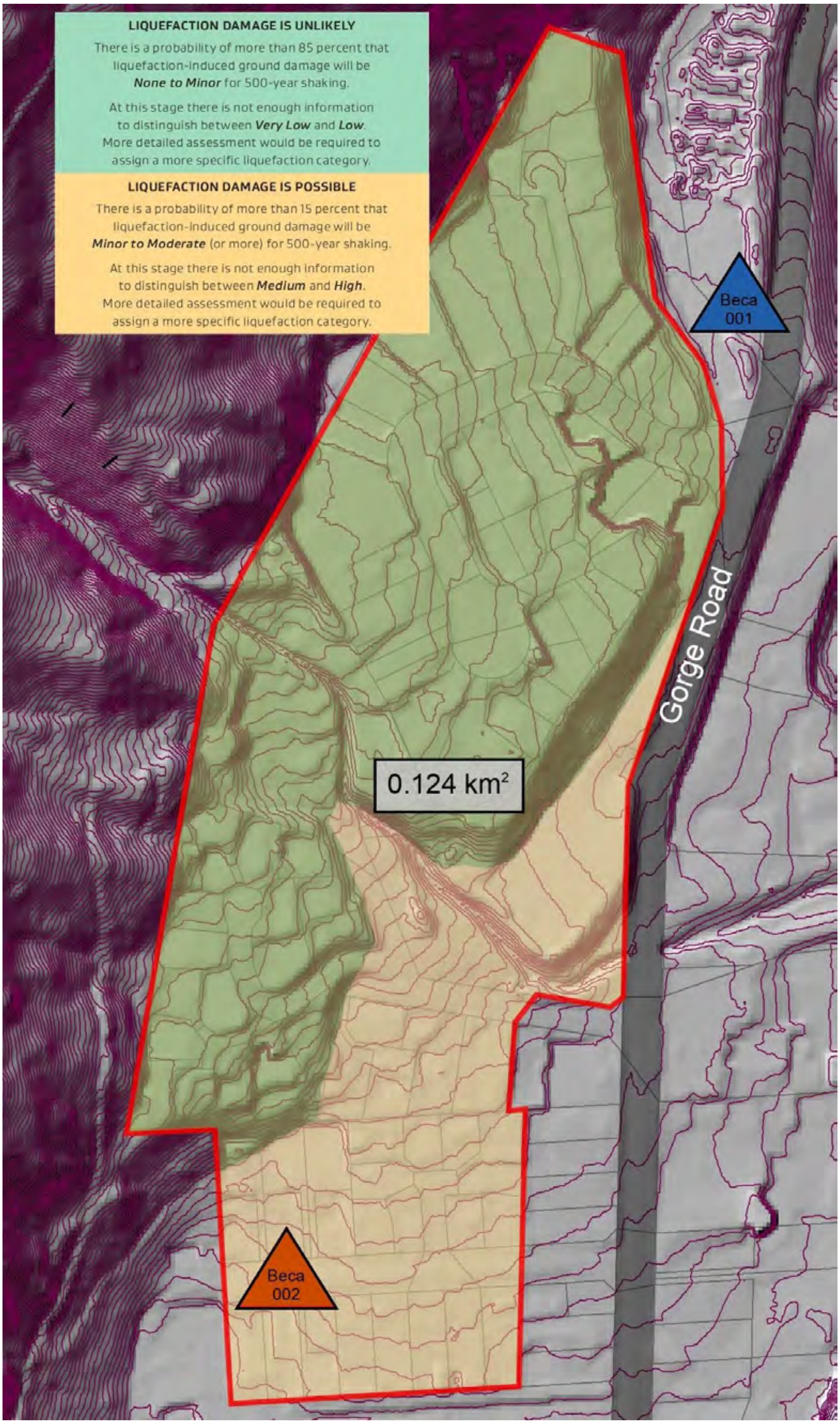
Flooding

An assessment of flood hazard to property has been undertaken for the study area. Beca has updated the previous QLDC flood models to include the ability to consider surface flow (2D). The model now includes the stormwater pipe network, stream channels and land surface but with buildings removed.

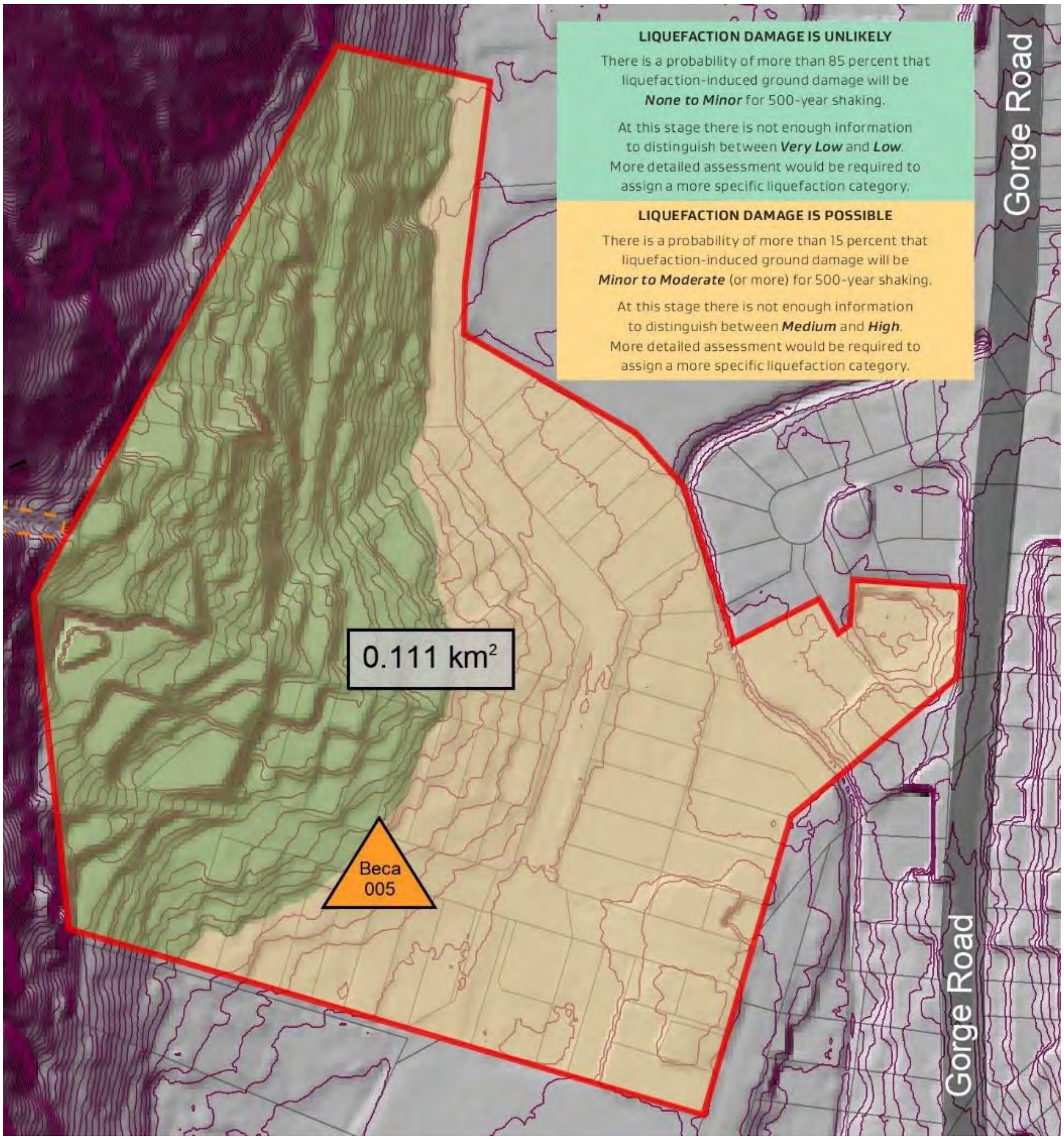
The engineered channel downstream of the Brewery Creek Fan apex has the capacity to convey a 100-year flow from the Brewery Creek catchment. No overflow occurs from Brewery Creek channel until it reaches the wetlands north of the Creek. Minor flooding is indicated from a small catchment south of Brewery Creek which is not conveyed by the pipe network. This flow travels south towards Sawmill Road/Fryer Street and on towards the Ngai Tahu development site (former Wakatipu High School).

The intake structure at Reavers Creek is shown to be unable to contain the flood water from a 100-year event, resulting in overflow across the fan surface at depths of 100mm-200mm, even without considering entrained debris. The flood water is not confined to the roading network and finds its way across private property. Flooding in the lower part of the fan is caused by Horn Creek. The Robins Road bridge cannot convey the full 100-year flow causing an increase in water level upstream of this point and flooding into the Creeksyde Holiday Park.

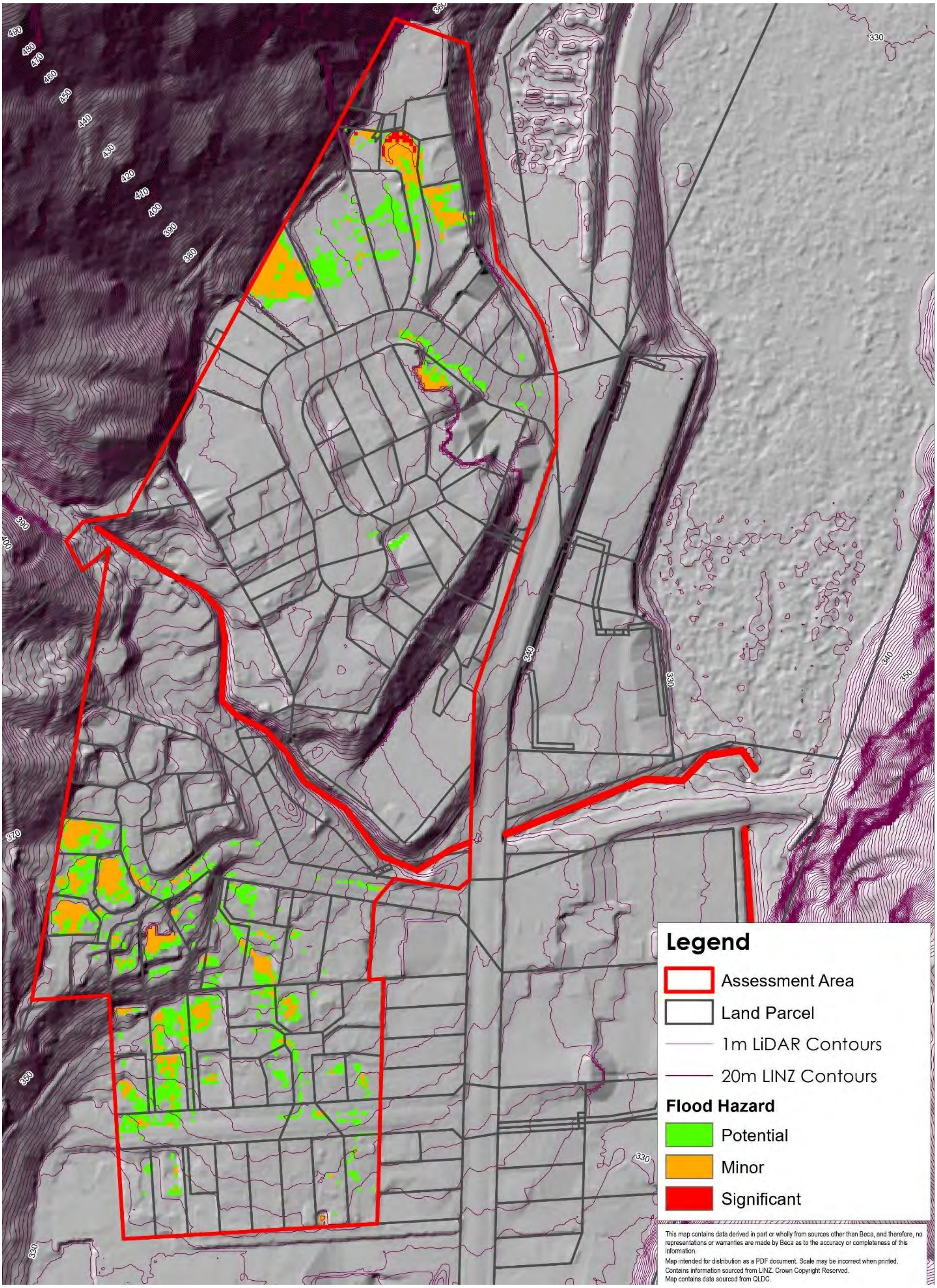
The flood modelling does not allow for debris flows which have the ability to change the course of the flood water depending on the size of debris moved by the flood waters. Flood maps and flood hazard maps are included in Appendix N – Flood Maps. Extracts of the flood hazard maps for a 100 year ARI event are shown in the following pages.



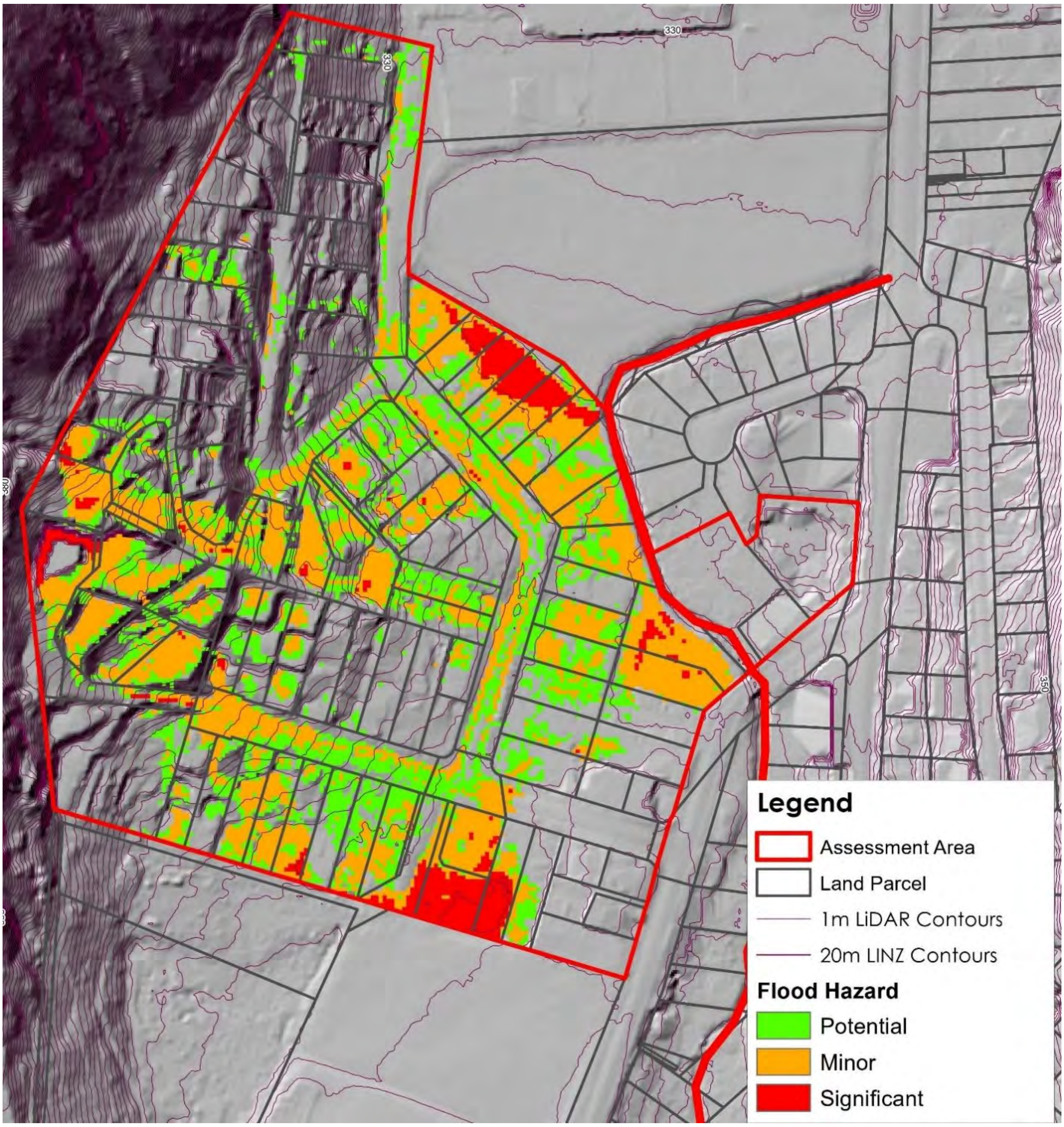
Liquefaction Vulnerability Brewery Creek Fan. Extract from drawing M001 – Appendix M. Refer to Appendix for full drawing and legend.



Liquefaction Vulnerability Reavers Fan. Extract from drawing M001 – Appendix M. Refer to Appendix for full drawing and legend.



100 Year ARI Flood Hazard Brewery Creek Fan. Extract from drawing N003 – Appendix N. Refer to Appendix for full drawing.



100 Year ARI Flood Hazard Reavers Fan. Extract from drawing N004 – Appendix N. Refer to Appendix for full drawing.

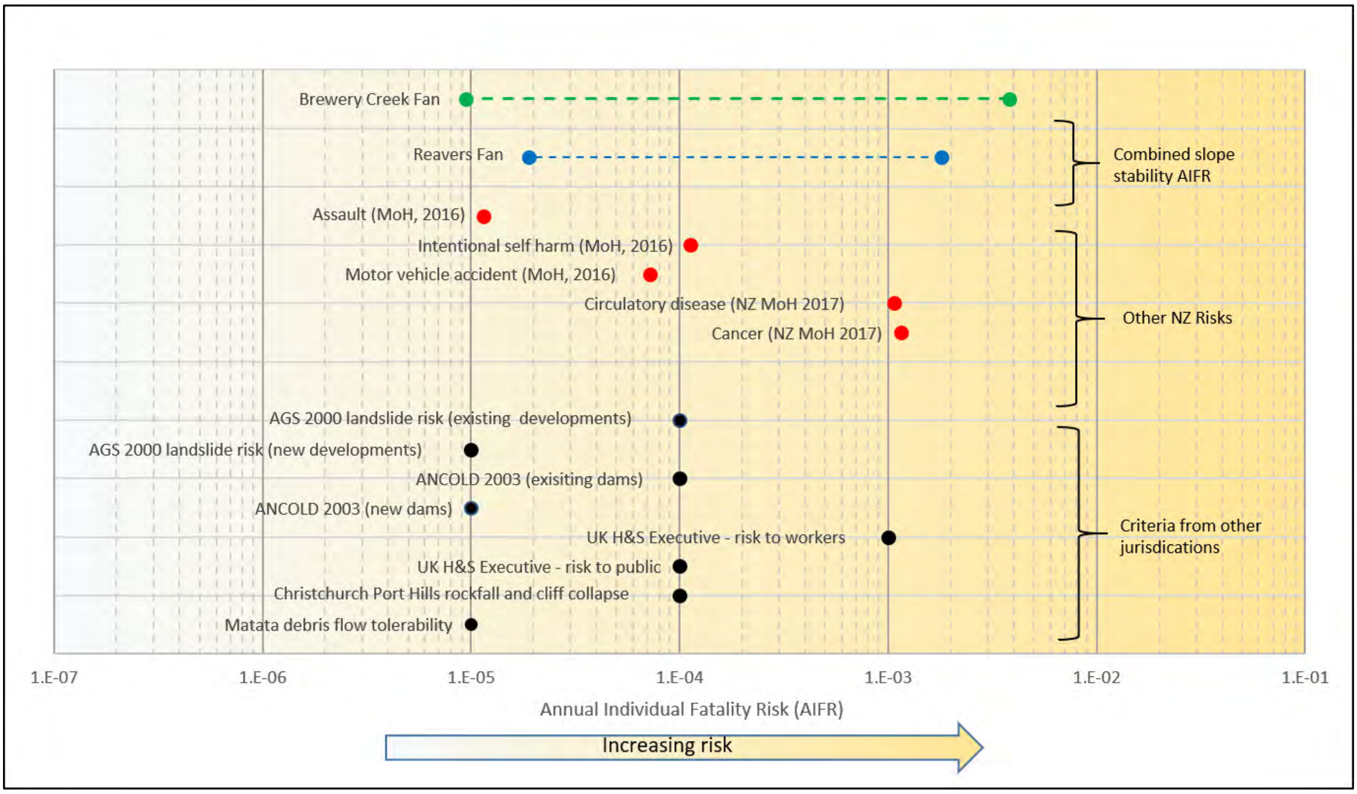
Risk Management

AIFR Tolerability

There are currently no national guidelines for determining tolerable limits to life risk in New Zealand. AIFR tolerability guidelines for slope stability are provided for Australia by AGS (2007), with a maximum recommended AIFR of 1 x 10^{-4} (1 in 10,000) for existing slopes/developments, and 1 x 10^{-5} (1 in 100,000) for new slopes/developments.

The former value saw widespread application on Christchurch's Port Hills following the 2010-11 Canterbury Earthquakes and is widely considered to be the boundary of tolerable risk, e.g. 1.1 x 10^{-4} would not be considered tolerable. A further example of AIFR tolerability precedent in New Zealand is the Awatarariki Fanhead at Matata, where Whakatāne District Council applied 1 x 10^{-5} as the limit of tolerability for all developments, requiring retreat of the developed fan (Campbell et al, 2020). This is more conservative than the AGS and Port Hills approaches.

A comparison of common risks and tolerability limits is shown below, along with combined debris flow and rockfall AIFR for Brewery Creek and Reavers Fans.



Summary of common risks and risk tolerability limits

AIFR values determined through this study exceed published guidance on risk tolerability for both new and existing developments on some areas of both fans. The number of properties exceeding these tolerability guidelines in accordance with AGS (2007) are shown in the below table.

Number of properties with AIFR exceeding tolerable guidelines recommended by AGS (2007)

AIFR	Tolerability (AGS, 2007)	Brewery Creek Fan Residential	Brewery Creek Fan Business	Reavers Fan
> 1×10^{-4}	Not tolerable for new or existing slopes/developments	5	12	25
> 1×10^{-5}	Not tolerable for new slopes/ developments	10*	14*	41*

*Includes properties >1×10^{-4}.

Note 1 – Count includes properties where relevant contour line crosses any part of the property.

Note 2 – Count based on Property Number from QLDC GIS Maps, not Legal Description.

QLDC is investigating future consultation options to assess public tolerability of the risks detailed in this report.

APR Tolerability

Unlike AIFR, no recommendations are made regarding quantitative APR tolerability by AGS (2007), which states '*the regulator is the appropriate authority to set standards for tolerable risk*'.

APR values are not directly comparable to AIFR, and different tolerability levels will likely apply (i.e. people have a different level of tolerance to loss of life compared to loss of buildings).

Quantitative property risk assessment has not been adopted as broadly as quantitative life risk assessment in New Zealand to date. As a result, there are no known examples of precedent in assessing public tolerability to property risk. This may be the result of a lower community tolerance of life risk than property risk, meaning that if life risk tolerability is assessed and actions taken, property risk is also addressed.

A way forward may be to consider AIFR tolerability boundaries initially to define planning zones and then using APR to inform stakeholders of the corresponding property risk.

Hazard Management Options

It has been identified in this report that the risk to life exceeds published guidance on tolerability for both existing and new developments for some properties on Brewery Creek and Reavers Fans. Both planning and physical hazard management options are currently being considered by QLDC areas part of the District Plan review.

A Beca study assessing the potential for reducing life risk from slope stability hazards to tolerable levels through physical hazard management options has been commissioned by QLDC and is currently in progress. The study considers the effectiveness of physical management options (or a combination of options) in reducing the combined risk from debris flow and rockfall. The study is due for completion in late 2020.

Physical options for the management of liquefaction hazard include use of ground improvement techniques and/or foundations specifically designed to resist liquefaction. The latter is usually more cost effective for smaller properties. A map showing where liquefaction is likely and unlikely in the assessment areas has been provided and recommendations made for issuing building consents in line with MBIE Guidance.

Flooding risk management options are being considered as part of the debris flow physical works.

1 Introduction

1.1 Background

Queenstown Lakes District Council (QLDC) is undertaking a review of the Queenstown Lakes District Plan, which includes considering changes to land use in the Brewery Creek and Reavers Lane areas, near Gorge Road, Queenstown. The assessment area defined by QLDC comprises two separate zones located on Brewery Creek Fan in the north and Reavers Fan in the south, as shown in Figure 1.

This area is known to be susceptible to natural hazards including debris flows, rockfall, liquefaction and flooding.

As part of this process, Beca Limited (Beca) has been commissioned to undertake a review of natural hazards affecting this area.

1.2 Previous Work by Others

Previous studies have been conducted on hazards in the Gorge Road area. An initial investigation into hazards associated with alluvial fans in Otago was conducted by GNS Science on behalf of Otago Regional Council (ORC), reported in 2009 and 2011. Following this, QLDC commissioned studies into natural hazards in the Gorge Road area, as reported by Opus. The following reports should be referred to for full details of these studies:

- GNS Science (2009). Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago. Barrell, D., Cox, S. and Greene, D. April 2009. Report reference 2009/052.
- Otago Regional Council (2011). Otago Alluvial Fans: High Hazard Fan Investigation. Woods, R.
- Tonkin and Taylor, (2012). Queenstown Lakes District 2012 Liquefaction Hazard Assessment - Summary Report.
- Opus International Consultants Ltd (2015a). Hazard Issues for Land Use Intensification in the Gorge Road Area, Queenstown. Queenstown Lakes District Council. Brabhaharan, P. February 2015. Report reference GER 2015 – 4.
- Opus International Consultants Ltd (2015b). Alluvial Fan Hazards in the Gorge Road Area, Queenstown. Queenstown Lakes District Council. Brabhaharan, P. May 2015. Report reference GER 2015 – 020.
- Otago Regional Council (2015). Seismic Hazard in Queenstown Lakes District. B Mackey, August 2015.

1.3 Beca Scope of Work

Beca's scope of work was to assess the potential effects of natural hazards in the study area, specifically debris flow, rockfall, liquefaction and flooding. The work was conducted in phases, as summarised below:

- Review of natural hazards in the Gorge Road area and qualitative assessment of risk to property from these hazards. This work included a desk study, fieldwork, hazard assessment and risk analysis.
- Two dimensional rockfall modelling was later added to the original scope, to inform the rockfall hazard assessment.
- The first two phases were summarised in the report titled *Natural Hazards Affecting Gorge Road, Queenstown* (May 2019).
- Following an initial round of public consultation, the next phase of work involved a quantitative assessment of risk to life from debris flow and rockfall, utilising the Annual Individual Fatality Risk (AIFR) method. The life risk assessment comprised:
  - Further field mapping to assess evidence of past and potential for future events.
  - Additional site investigations to assess the nature of fan deposits to inform the assessment of past events.

  - Debris flow and rockfall runout modelling, to further refine the areas at risk.
  - AIFR assessment for debris flow and rockfall, utilising a zone-based approach.
  - Development of slope instability AIFR contours for Brewery Creek and Reavers Fans.
- A quantitative assessment of property risk (APR) from debris flow and rockfall was also conducted, comprising:
  - Utilisation of the data obtained during the AIFR process (mapping, site investigations, runout models etc).
  - Obtaining property damage data from RiskScape software (https://www.RiskScape.org.nz/) through GNS Science.
  - APR assessment for debris flow and rockfall.
  - Development of slope instability APR contours for Brewery Creek and Reavers Fan.

This most recent phase of work extends the original qualitative property risk study to include a quantification of property risk. The full study is summarised in this report, which supersedes our May 2019 report. This report sets out all phases of work undertaken by Beca to date relating to natural hazards in the Gorge Road area, culminating in AIFR and APR contour plans for the study area.

1.4 Peer Review

A peer review of the draft version of this report was conducted by Sally Dellow of GNS Science in March 2020 (GNS Science, 2020a). Suggestions made during the peer review process were responded to and the report and appendices updated accordingly for the final issue of this report.

A peer review of the final report (version 1, September 2020) was conducted by Sally Dellow in October 2020 (GNS Science, 2020b). All peer review queries have been responded to and closed out in this final report (Revision 2, November 2020).

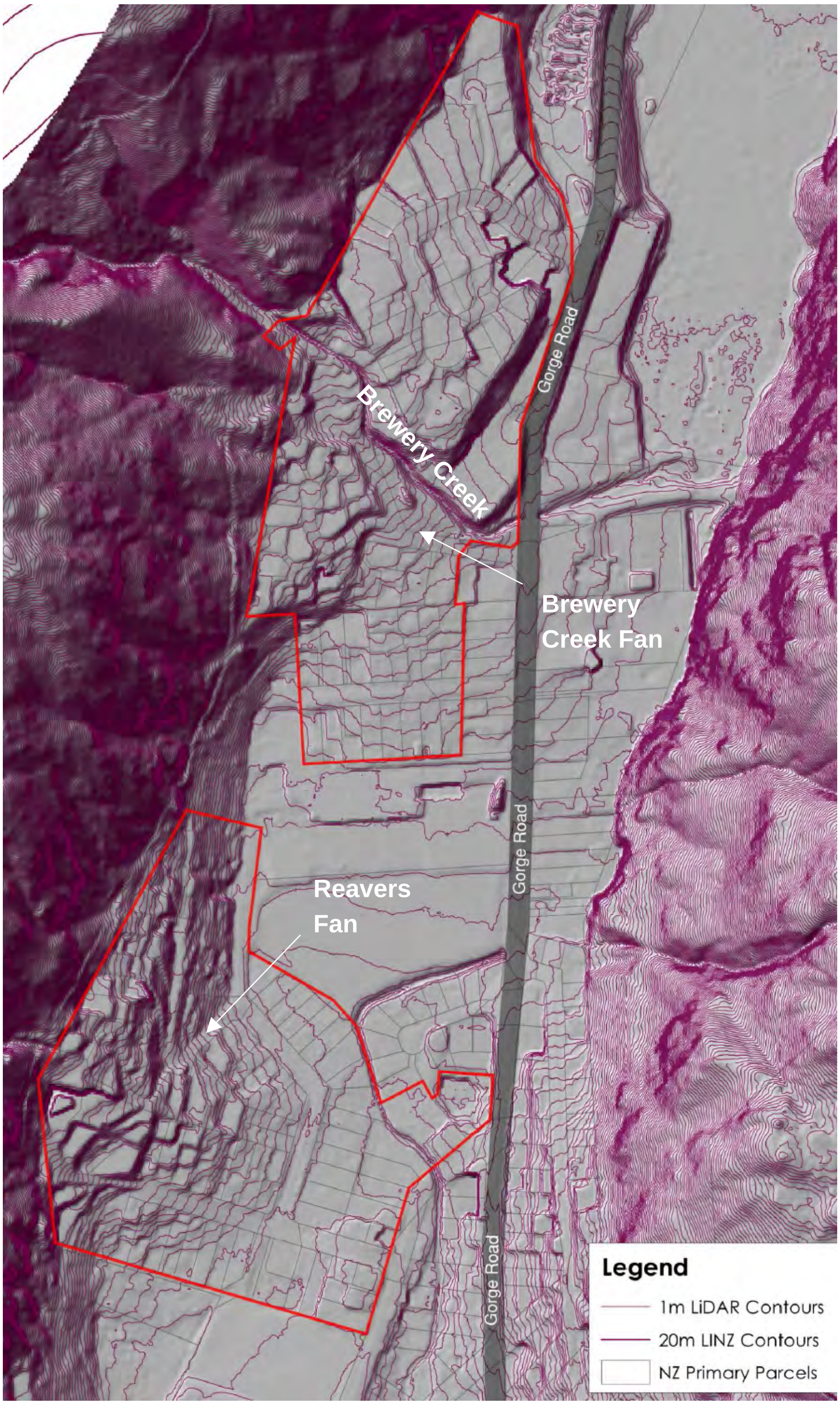


Figure 1 - Gorge Road study assessment areas (outlined in red)

2 Natural Hazards Overview

Previous studies (GNS, 2009; Tonkin & Taylor, 2012; Opus, 2015a & 2015b) have identified the following hazards as being present in the Gorge Road area:

- Debris flow
- Rockfall
- Soil liquefaction
- Flooding.

These hazards are addressed in this study.

A brief description of each hazard is provided in the following section, while a glossary of terms relevant to this study is provided in Appendix A – Glossary.

Background information on the hazards considered in this study is provided below, with details on the extent and magnitude of the hazards provided in Sections 4 and 5 (Slope Stability), 7 (Liquefaction) and 8 (Flooding).

2.1 Debris flows

The majority of the two study areas are located on alluvial fans. These are cone shaped landforms comprising alluvial sediments which typically form where streams emerge from hill country onto valley floors (GNS, 2009). The fans form when debris comprising rock, soil and vegetation in the upper catchment areas is entrained during periods of high flow and deposited on the fan at the mouth of the catchment. Deposition may occur as pulses of saturated material of varying magnitude known as debris flows. Debris flows constitute a significant hazard to people and property located adjacent to the channel or in the depositional area.

Debris flows require a supply of loose sediment which will primarily depend on the geology, existing or potential slope instability, the catchment area, and the steepness of the catchment and stream channels. Debris flows are typically triggered by short duration (30 min to 3 hour), high intensity rainfall. GNS Science (2018a) state that short duration (one hour), high intensity (more than 40mm/hour) rainfall can cause debris flows in vulnerable stream catchments. GNS (2005) reports initiation of debris flows in the western Southern Alps of New Zealand occurs at rainfall intensities above about 1mm per minute. Widespread debris flows may be expected once rainfall intensity reaches around 2mm per minute. Where debris flows exceed the capacity of a drainage channel, material will escape the channel and affect surrounding areas. Forested areas can inhibit both initiation and transport of debris flows compared to open slopes.

If debris flows reach a culvert, bridge or other structure not specifically designed to pass debris they are likely to be damaged and/or overtopped.

Reference should be made to the studies by GNS (2009) and ORC (2011) for detailed analyses on the characteristics, nature and classification of alluvial fans in the wider Otago region.

2.2 Rockfall

The existing QLDC hazard mapping defines areas at risk from landsliding but does not differentiate between different types of landsliding. This study has considered individual rockfall (individual rocks or small groups of rocks rolling, falling or bouncing down a slope) from the rock slopes to the west as the failure mode dominating the rockfall risk in the study areas. Rockfall is usually triggered by earthquakes but may also occur at other times due to gradual effects of weathering and erosion of outcrops in the source areas.

The trajectory that a falling rock follows, and the point that it comes to rest depends on the block size and shape, slope angle, the geological materials forming the slope, surface roughness and ground cover. Rockfall poses an obvious hazard to people or property that may be impacted.

2.3 Soil liquefaction

The Gorge Road valley floor area has previously been mapped as possibly susceptible to liquefaction based on the presence of Quaternary (recent) aged alluvial sediments. Previous versions of QLDC hazard mapping have identified only the northern assessment area (Brewery Creek Fan) as being susceptible to liquefaction, as detailed in the Opus (2015b) report, however recent updates show most of the valley floor as being possibly susceptible.

The following characteristics are required for liquefaction to occur during an earthquake:

- Low relative soil density (typical of geologically recent, unconsolidated and uncemented sediments).
- Grain size distribution dominated by silty fine to medium sand.
- Saturation due to high groundwater levels.

Figure 2 sets out the potential consequences of soil liquefaction.

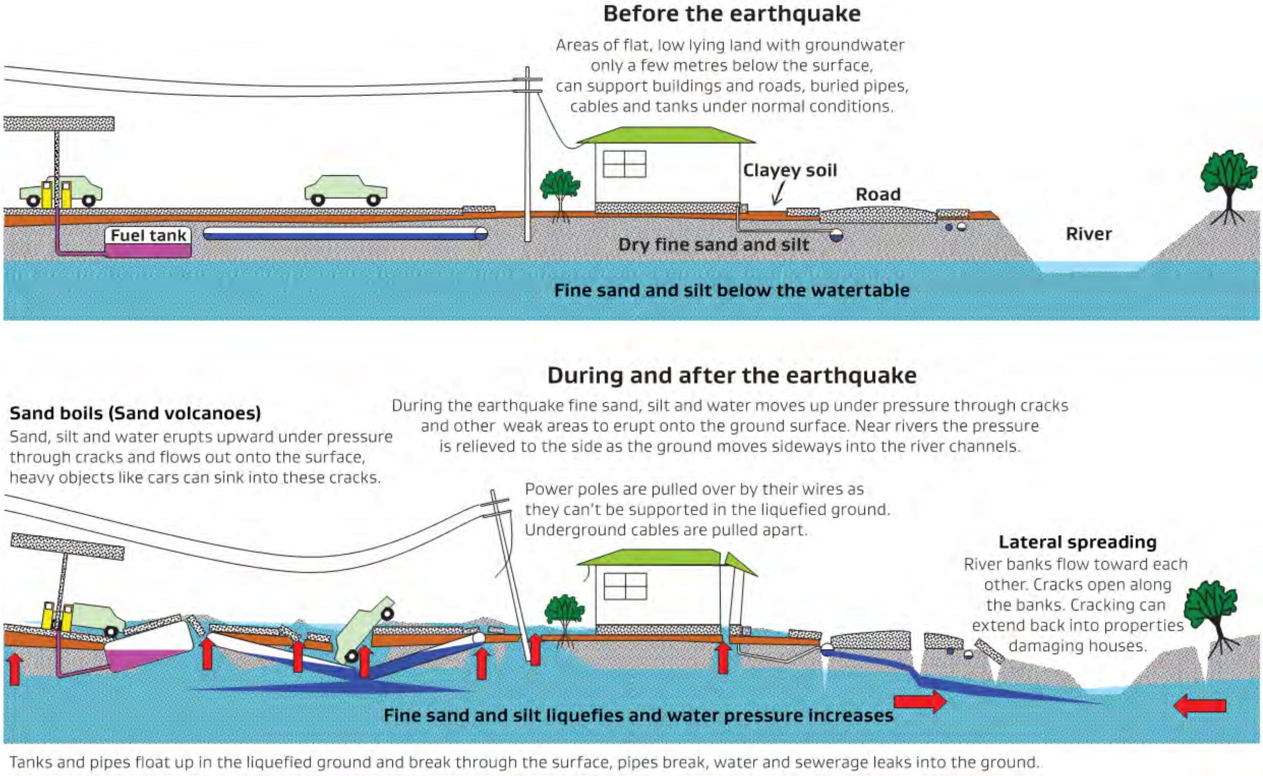


Figure 2 - Liquefaction and its potential effect on ground surface. Source: Engineering NZ

2.4 Flooding

Previous studies have focused on the potential of flooding from Lake Wakatipu and from Horn Creek near the town centre. QLDC hazard mapping does not currently map the assessment area as being at risk from flooding.

A stormwater model developed by GHD Ltd for QLDC in 2009 was used to assess the critical parts of the stormwater network (including creeks) and to define a Level of Service (LoS). This work determined that the pipe network had a LoS close to the 5yr Average Recurrence Interval (ARI). In larger events, the network will surcharge and flood water will continue overland. Further modelling completed by Opus in 2015 focused on the overland flow by excluding the pipe network from the model.

The 2009 (GHD) modelling was one-dimensional and therefore was unable show potential flood risk in the study area. The 2015 modelling (Opus) showed that both Reavers Creek and Brewery Creek could over-top their current channels creating a flood hazard across the alluvial fans. Modelling work conducted by Beca for this study has involved an update of the 2009 GHD model to include LiDAR-based surface flow.

3 Site Characterisation

Details of the geology, formation and history of the study area as obtained from published information are included in Section 3.1. Information obtained from Beca site investigations are included in Section 3.1.6b.

3.1 Site History

3.1.1 Site Description

The study area is located on the floor of a steep sided glacial valley approximately 1km north of Queenstown centre. Queenstown Hill is located to the east and Ben Lomond to the west.

The assessment areas are located on two distinct alluvial fans separated by open ground in the form of Warren Park and the former Wakatipu High School site (as shown in Figure 1 and Figure 3). The northern fan has been described in previous reports based on the name of the creek that crosses it, variously termed Bush Creek, Brewery Creek, Horn Creek and Horne Creek. For the purposes of this study, the northern fan is referred to as Brewery Creek Fan, in keeping with the term applied in more recent studies. Brewery Creek meets Horn Creek to the east of Gorge Road and flows south towards Lake Wakatipu. The southern fan is known as Reavers Fan.

Brewery Creek Fan is occupied by residential properties in the southern and western limits, south of Brewery Creek. To the north of Brewery Creek, the fan is occupied by industrial and service activities. Brewery Creek bisects the fan in a northwest-southeast direction, with the channel having been modified and deepened in recent years. The topographic apex of Brewery Creek Fan is located at an elevation of approximately 370m, falling to approximately 340m at the eastern boundary of the assessment area at Gorge Road.

Reavers Fan is the smaller and steeper of the two fans and is predominantly occupied by residential properties, with a number of properties in the upper fan providing commercial visitor accommodation. A stream exits the steep tributary valley at the apex of the fan, at which point it enters a culvert and is channelled below ground until east of Fryer Street. There is no overland channel below the culvert intake. The topographic apex of Reavers Fan is at an elevation of 370m, while the distal parts of the fan sit at an elevation of approximately 330m in the vicinity of Fryer Street.

3.1.2 Geology

The geology of the assessment areas was mapped at 1:250,000 scale by Turnbull (2000), which shows the site to be underlain by Quaternary aged gravels, sands and silts of alluvial fan and glacial till origin. The hillsides are mapped as Caples Terrane schist rock.

The Eastern Province metamorphic basement rocks form much of the mountain landscape of the Queenstown region. Locally, the Caples Terrane (chlorite greenschist), displays strong foliation (repetitive layering) dipping to the south west and well-developed jointing, both of which have influenced the geomorphic development of slopes in the assessment area.

Tectonic uplift, faulting, folding and most recently glacial erosion have formed the steep mountain ridges and deep valleys with narrow alluvial flats.

The mapped geology has been reviewed based on aerial photo analysis and site observations as part of this study, with an updated interpretation included as drawing 3209881-B001 in Appendix B – Geological Map.

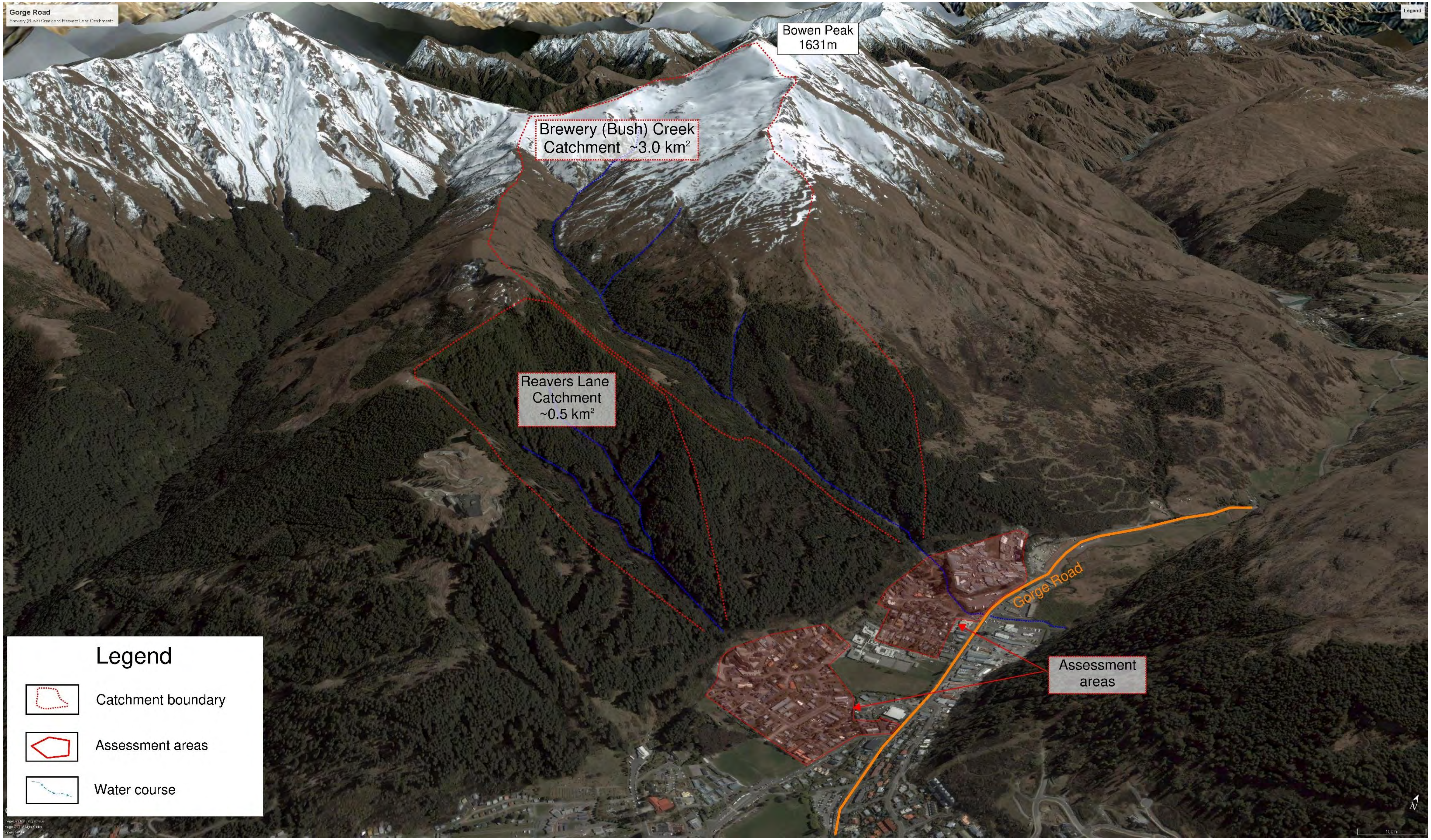


Figure 3 - Study areas and catchments. Base image source: Google Earth (2018).

a. Faults

The Institute of Geological and Nuclear Sciences (GNS) database indicates that a number of active faults exist in the wider Queenstown region. GNS define an active fault to be one which shows evidence of rupture in the last 125,000 years. The known active faults include:

- Skippers Fault, located approximately 16km to the north of the assessment area.
- Cardrona Fault, located approximately 20km to the east.
- Mt Nicholas Fault, located approximately 19km to the south-west, on the southern shore of Lake Wakatipu.

The assessment area is also within 80km of the Alpine Fault. The Alpine Fault has a high probability (estimated at 30%) of rupturing in the next 50 years (see http://projectaf8.co.nz/). An Alpine Fault rupture could produce one of the biggest earthquakes since European settlement of New Zealand, and will have a major impact on the lives of many people (GNS, 2018b).

Lineaments (linear features indicating underlying geological structures) recognised from aerial photographs across Queenstown Hill suggest faulting has influenced landscape development in the assessment area, although no evidence of active fault displacement was noted.

3.1.3 Geomorphology

a. Literature Review

Brewery Creek and Reavers Fans are thought to have commenced formation as long ago as the end of the "Last Glacial Maximum" (LGM), approximately 18,000 years ago. At this time Lake Wakatipu's level was thought to be approximately 50m higher (RL 356m) than the present day, extending through the assessment area. The two prominent alluvial fans (Brewery Creek and Reavers) formed on the lake margin, interfingering with soft silty lacustrine materials in the valley floor.

An estimated 7,000 years ago, Lake Wakatipu water level dropped in a staged manner. Continued lake level lowering resulted in complete abandonment of the Gorge Road valley with the fan/delta complexes now standing above water level (Thomson, 2012). The present-day Brewery Creek incised through relict beach and fan/delta sediments in response to lowering lake levels.

Full details of a review of published information on the formation of landforms in the study area is included in Appendix C – Geomorphology Background.

b. Aerial Imagery

The geomorphology of the area was reviewed as part of the desk study, utilising the following data sources:

- Aerial photographs (digital) (1956, 1959, 1978, 1983, 1984, 1988, 2001).
- Stereo pair photographs (contact prints) (1954, 2001).
- LiDAR topography and imagery (QLDC, April 2016).
- Google Earth imagery (2008, 2018, 2019).

The Brewery Creek catchment is the larger of the two, at approximately 3.0km^2. Woody vegetation occupied only the lower reaches of the channel in aerial imagery from 1954 (8% of total catchment area). By 2019 this had increased to 29% of the catchment area.

The Reavers Fan catchment is approximately 0.44km^2. Historical aerial photo analysis shows that the catchment contained little woody vegetation in 1954 (10% of the total catchment area), and by 2019 was almost entirely forested (91% of the total catchment area).

Evidence of historic landslides and rockfall exists within the catchments. A number of 'well defined' and 'poorly defined' mass movement scarps have been identified within both catchments upstream of the assessment area. There is evidence of mass slope movement having contributed to geomorphic development, particularly on the dip slope (eastern) sides of the valley. Many of the associated scarps have been obscured by the present-day vegetation.

Full details of aerial imagery analysis are included in Appendix C – Geomorphology Background. Geomorphological maps included in previous versions of this report have been superseded by the latest mapping programme, which is detailed in Section 3.2.2.

3.1.4 Past Events

There are two documented historic debris flow and flood events in the study area, as summarised below with photos shown in Figure 4:

- May 1986 event involving failure of a man-made dam in the Brewery Creek catchment.
  - Data obtained from the National Institute of Water and Atmospheric Research's (NIWA) CliFlo database for Queenstown Aero weather station (approximately 6km to the east of site), saw 47.8mm of rain in 24 hours on 31 May 1986. This is equivalent to an ARI of between 1.58 and 2 years, or an Annual Exceedance Probability (AEP) of between 63% and 50%. The ARI and AEP figures were obtained from NIWA's High Intensity Rainfall Design System v4 (HIRDS, https://hirds.niwa.co.nz/).
  - No record was found of details of damage to buildings or injury to people as a result of this event.

- November 1999 event resulted in "large volumes of debris and sediment inundating a large portion of the (*Brewery Creek*) fan surface" (ORC, 2011). Debris flows occurred elsewhere in the Wakatipu region during this event, including a significant debris flow at Walter Peak Station.
  - Mapping undertaken by GNS (2009) observed debris flow heights mapped from scars on mature trees, ranging from 4.4m above ground level in the upper reaches of the fan, to approximately 1m in the mid-section of the fan. The results of this mapping are shown in Figure 5 with examples shown in Figure 6.
  - Data obtained from NIWA's CliFlo database for Queenstown Aero weather station and HIRDS for the Gorge Road area showed significant rainfall between the period 15 to 18 November inclusive. Maximum rainfall totals and equivalent ARI values for this period are summarised in Table 1.

Table 1 - Rainfall depths and ARI for the November 1999 event at Gorge Road (source: Cliflo, HIRDS)

Duration	Rainfall Depth (mm)	ARI (years)
1 hour	9.2	1.5
24 hours	102*	36†
72 hours	188*	220†
96 hours	188.6*	155†

*Relates to rolling 24/72/96 hour maximum rainfall over the four day period.

†Interpolated from HIRDS plots.

  - The above ARI values indicate the exceptional nature of this event was the persistence over a three day period, which is somewhat at odds with published commentary stating that debris flows are typically caused by short duration, high intensity events (Section 2.1).
  - NIWA broadly report this event as having an ARI of 150 years in their Historic Weather Events catalogue (https://hwe.niwa.co.nz/). The above HIRDS data suggest a 72 hour return period of 220 years and a 96 hour return period of 155 years.

- One reference was found of the 1999 event being exacerbated by channel blockage dam failure upstream resulting in a significant amount of material being released over a short time (Hamilton, 2014).

Figure 4 - Debris from the May 1986 debris flow on Brewery Creek Fan (left); and the 1999 event at the intersection of Bowen Street and Gorge Road (right). After ORC, 2011.

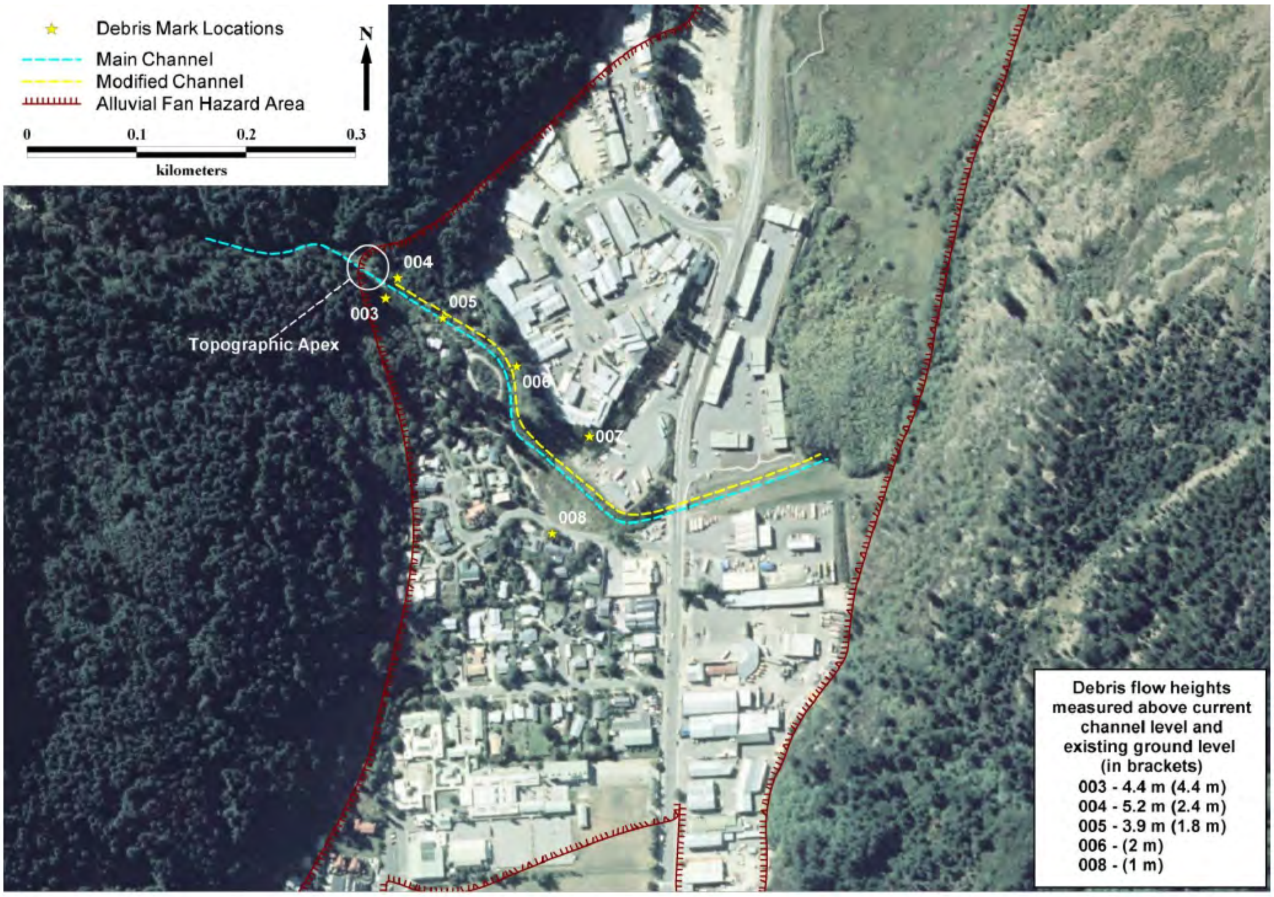


Figure 5 - Brewery Creek Fan mapped debris flow heights (GNS, 2009)

Figure 6 - Debris height from past events on trees scars in the Brewery Creek alluvial fan. Left photo is upstream of point 005 and right is at point 005 as shown in Figure 5 (ORC, 2011).

Urban development on both fans commenced in the 1950s. There are no historical reports of debris flow events having impacted property on Reavers Fan. Additionally, there are no records of rockfall events having impacted property on either fan in the above data sources.

3.1.5 Resource Consents

QLDC supplied Beca with Resource Consents relating to natural hazards in the study areas. These files were reviewed with the objective of understanding past occurrences of natural hazards. A table summarising resource consents containing reference to natural hazards is included in Appendix D – Resource Consent Summary. Observations are as follows:

- The management of hazards to date in the assessment area has largely been by means of the resource consent process. This has at times resulted in an inconsistent approach to risk mitigation measures.

- Of the 18 resource consents containing reference to natural hazards, the breakdown of hazards considered is as follows:
  - Instability (local/site specific relating to cuts) 8 (44%)
  - Debris flow/alluvial fan 10 (55%)
  - Liquefaction 9 (50%)
  - Rockfall 3 (17%)
  - Flooding/overland flow 5 (28%).

- Five of the above 18 resource consents contained recommendations for physical management of natural hazards risk (not including site specific stability of cut slopes, or the modifications to Brewery Creek channel, summarised below).
  - All five contained recommendations relating to engineered foundations to manage liquefaction risk.
  - In addition, RM140407 also recommended elevation of building platform to 0.5m above surrounding ground to mitigate risk of debris flows.
  - RM190626 made comment relating to elevation of finished floor levels to mitigate risk of flooding.

- Of particular relevance is the modification of Brewery Creek channel from the topographic apex of the fan to its confluence with Horn Creek to the east of Gorge Road. The channel is shown in Figure 8. The pertinent points relating to this work are as follows:
  - The first available record of a modification to Brewery Creek included a design by David Hamilton & Associates Limited for Brewery Creek Holdings at 1 Bowen Street, conducted in 2004. The design criterion was to contain debris flow events in excess of 1% Annual Exceedance Probability (AEP),

determined from the maximum observed debris height from the November 1999 debris flow event of approximately 4m above ground level.
- The channel was further modified as part of QLDC resource consents RM120326, RM140776 and RM140924 in 2015 to 2016, which involved widening and re-lining of the channel with rip-rap, while maintaining the original design criteria of >1% AEP.
- The box culvert under Gorge Road is owned and maintained by QLDC and is designed to accommodate flows of $13m^3/s$, equivalent to 2.5% AEP (floodwater only). The 2015/2016 modifications involved an extension to the box culvert and provision of an overflow channel.
- Otago Regional Council consent 2005.230 (24 June 2005) relates to the application by Bowen Street Enterprises Ltd at 21 Bowen Street, located upstream from 1 Bowen Street. The application was to increase the capacity of the channel and line with riprap, in order to contain a 1% AEP debris flow event (4m depth).
- The above resource consents require Brewery Creek to be designed to contain a 1% AEP debris flow event from the topographic apex of Brewery Creek alluvial fan to Gorge Road.
- The resource consents require the landowners to make provision for maintenance and inspections of the channel.

3.1.6 Debris Flow Literature Review

a. Comparable events

A literature review focussing on past debris flows in comparable settings was conducted to provide insight into the likelihood of debris flows in the study area.

Notable historical events are outlined in Table 2. The Average Recurrence Interval (ARI) of these events has been estimated from HIRDS v4 (NIWA). Events considered broadly in line with Gorge Road small and medium events (see Section 4) are observed. While acknowledging the differences between catchments, general trends are observed. The information has been used to inform judgement-based decisions in relation to the probability of occurrence parameter included in the AIFR assessment (Section 5.2).

Table 2 - Summary of Previous Debris Flows in New Zealand

Location	Date	Description	Initiating Rainfall	Reference	HIRDS Station	ARI (HIRDS)
Reservoir Creek, Roxburgh, Otago	October 1978	Channelised debris flow affecting Roxburgh township, avulsed from channel downstream blocking SH8 and impacting residential properties.	Rainfall totals of 116 mm rain over 24 hours.	GNS, 2018a	Roxburgh East	>250
Brewery Creek, Queenstown	May 1986	Debris flow and flood event involving failure of man-made dam.	47.8mm rainfall in 24 hrs recorded ~8km west of catchment.	ORC, 2011	Arthurs Point	1.58
Pipson Creek, Makarora Valley	10 events 1989-2011	Repeated debris flows resulting in continued damage to SH6 bridge downstream.	Rainfall intensities of between 8.5mm/hr and 26.5mm/hr.	ORC, 2011	Makarora Station	20
Slaughterhouse Creek, Roxburgh, Otago	December 1993	Debris flow causing downstream impacts and damage to SH8.	Reported as localised heavy rainstorm; rainfall totals not documented.	GNS, 2018a	N/A	unknown
Brewery Creek, Queenstown	November 1999	Debris flow resulting in large volumes of debris inundating a large portion of the Brewery Creek Fan surface.	188.2mm rainfall over 96hr period; equivalent to ARI of 100 and 250 years.	GNS, 2009.	Arthurs Point	150-220
Rees River, Otago	January 2002	Debris flow in tributary stream leading to death of a tramper.	Rainfall of 240mm rain over 24 hours.	GNS, 2002.	Dart River at the Hillocks Glenorchy	>250
Matata Bay, Bay of Plenty	May 2005	Debris flow resulting in the destruction of 27 homes and damaged to a further 87 residential properties.	Rainfall peak of 30.5 mm in 15 minutes measured 5km to the SSE of Matata.	GNS, 2005	Ohinekoao at Harris Saddle	>250 (double)
Pohara-Ligar Bay, Tasman District	December 2011	Debris flows from recently felled catchments affecting homes and properties.	284mm rain 24 hours	GNS, 2012a	Takaka Pohara	250
Shaggery Forest, Tasman District	June 2013	Debris flows originating on logged slopes; resulting in loss of bridge approaches on Motueka River West Bank Road.	Rainfall peak of 36mm in 1 hour measured ~2 km to the east.	GNS, 2013.	Big Pokororo Raws	50
Roxburgh, Otago	November 2017	Debris flows occurred in four stream catchments along the range front to the west of Roxburgh, locally impacting SH8 and flooding residential properties.	Between 40 and 100 mm of rainfall over a 1-hour period.	GNS, 2018a	Roxburgh Power Station	100 - >250

b. Debris flow classification

i. Morphometric classification

A study of catchment morphometrics in determining debris flow hazard type was conducted by Wilford et al (2004). Catchment length and Melton Ratio (catchment relief divided by the square root of the catchment area) were used to differentiate between 'debris flow', 'debris flood' and 'flood' prone catchments. Definitions of the type of event are summarised briefly below, after Hungr (2001):

- Debris flows – very rapid flow of saturated non-plastic debris in a steep channel. Debris flows have peak discharges 5 to 40 times greater than floods. Deposits often have inverse grading (largest clasts close to the flow surface) resulting in boulders forming the front of the flow.
- Debris floods – very rapid surging flow of water and debris, in which most of the sediment is transported as bedload. Debris floods have peak discharges twice that of floods.
- Floods - sediment concentrations of less than 20% by volume.

Classification of event type based on morphometric data is summarised in Figure 7.

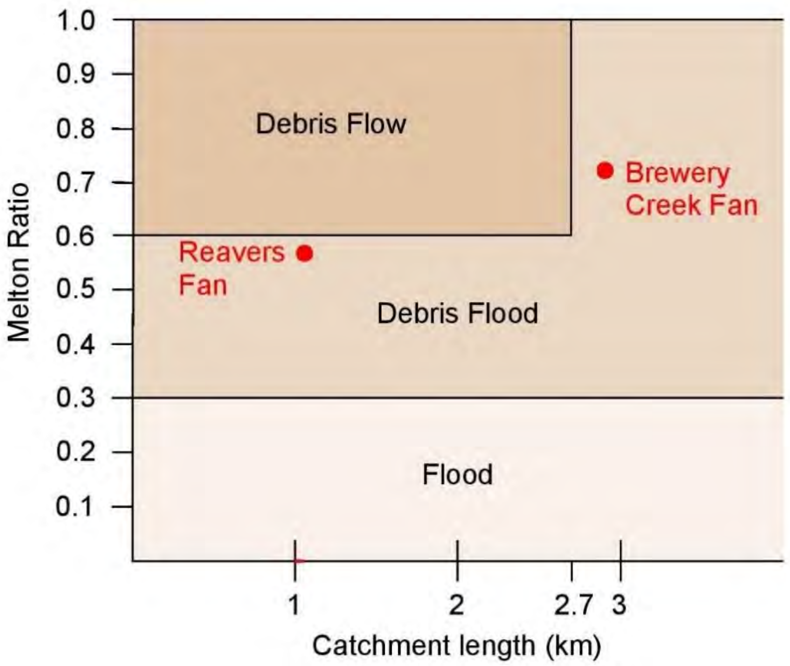


Figure 7 - Classification of hydrogeomorphic processes (after Wilford et al, 2004)

Based on catchment morphometrics, the dominant process likely to affect both Brewery Creek and Reavers Creek would be debris flood events, with Reavers Creek close to the boundary with debris flow events, as shown in Table 3 and Figure 7.

Table 3 - Catchment classification (after Wilford et al, 2004)

Catchment	Catchment relief (km)	Catchment area (km^2)	Catchment length (km)	Melton Ratio	Dominant hydrogeomorphic process
Brewery Creek	1.21	2.85	2.87	0.72	Debris flood
Reavers Creek	0.37	0.43	1.05	0.57	Debris flood / debris flow

ii. Deposit classification

Wilford et al (2004) also differentiate fan deposits on the basis of sorting and sediment concentrations by weight:

- Debris flows 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.

Brewery Creek Fan deposits comprise sandy cobbly gravel inter-layered with silt. The deposit characteristics suggest deposition during debris floods interspersed with floods.

Reavers Fan comprise silty sandy gravel. The deposit characteristics are consistent with debris flow and debris flood deposits. No silt layers were observed at Reavers Fan, providing no evidence of flood deposits.

iii. Debris flow type

Based on both morphometrics and deposits characteristics, Brewery Creek Fan is likely to be subject to debris flood and flood events, while Reavers Fan would be more prone to debris flow and debris flood events. Debris flow events may still occur in either catchment, or initiate as debris flow events in the steeper upper catchment, and transition to debris flood or flood events in the lower catchment, as indicated by modelling detailed in Section 5.2.1b.

For the purposes of this report, the generic term of 'debris flow' will be used to describe any debris-laden flood or flow events, unless otherwise stated.

3.2 Site Investigations

3.2.1 Fan Surface Mapping

A site walkover of the fan surfaces was conducted on 24 and 25 October 2018 by a Senior Engineering Geologist from Beca. Particular emphasis was placed on mapping of any outcrops within the assessment area, evidence of geohazard occurrence, and identification of suitable locations for subsurface ground investigation for liquefaction assessment.

Few exposures of alluvial fan materials exist within the assessment areas, and much of the fan surfaces have been modified through installation of retaining walls and creation of building platforms, roads etc.

The findings of the site walkover with reference to rockfall, debris flow and liquefaction hazard are described in Appendix E – Mapping, with a brief summary included below.

a. Debris Flows

The status of the channels on each fan was noted during the walkover. Brewery Creek channel is shown in Figure 8. At the time of the site visit the channel appeared to be well maintained with little build-up of sediment or debris in the channel invert.

Figure 8 - Brewery Creek modified channel at 1 Bowen Street (2018)

Reavers Stream is culverted from the apex of the fan above 9-11 Reavers Lane to a point below Fryer Street. The culvert is covered by a grate, presumably to limit debris entering, although there is nothing to prevent build-up of material in a debris flow event. As shown in Figure 9, a significant amount of vegetation had built up around the culvert over time, which could inhibit flow into the culvert. The culvert was cleared of debris following this initial walkover.

During the site walkover approximately 10mm rain fell in a 24-hour period (25 October 2018, source NIWA). Reavers Fan culvert was dry, and conversely Brewery Creek was flowing rapidly at this time.

Figure 9 - Comparison of the Reavers Fan culvert in January 2009 (GNS) and October 2018 (Beca)

b. Rockfall

On the alluvial fan surfaces, little evidence of previous rockfall events was found. Beyond the upper margin of the fans, at the boundary with the steep schist slope, numerous boulders were observed, ranging in size from 200mm to greater than 1m diameter. These boulders are located sporadically between the trees. The source areas of these boulders are likely the schist bluffs located upslope.

Isolated boulders were also noted just beyond the upper reaches of the properties at the western margin of the fans, in particular on Kiely Lane (as shown in Figure 10) and Reavers Lane. Additionally, the presence of large boulders used as low retaining walls (as shown Figure 11) throughout much of the upper reaches of both fans suggests a supply of boulders may have been available from the pre-development fan surface.

Boulders observed on the fan surface may be remnants from previous debris flow events, or physical works to create the transmission line bench, rather than rockfall. Analysis of historical aerial photos shows no evidence of rockfall occurrence, although this may not be apparent due to photo resolution.

Figure 10 – Surface boulders visible at the upper limit of Brewery Creek Fan (above Kiely Lane, 2018)

Figure 11 - Numerous boulders used to construct informal retaining wall on the surface of Reavers Fan (2018)

3.2.2 Catchment Mapping

Mapping of areas upslope of Brewery Creek and Reavers Fans was undertaken as part of the additional study scope commissioned in August 2019. The information obtained from the mapping programme was used to inform the rockfall and debris flow modelling and AIFR assessment, as described in Section 4. This subsection outlines the scope and summary observations made during field mapping, with full commentary included in Appendix E – Mapping.

a. Scope

Field mapping was undertaken in the catchment areas of Brewery Creek and Reavers Creek and the intervening lower slopes. The aim of the mapping exercise was to capture the following features:

Debris flow

- Evidence of previous debris flows, including scarring, vegetation damage, debris deposition, large blocks and/or boulders.
- Evidence of active or potentially active landslides which could contribute to debris flows.
- Availability and nature of channel bedload that may be mobilised in future debris flow events.
- Presence of large tree debris, including dead trees, and potential to form log jams or temporary dams during future rainfall events.
- Suitable sites for test pitting/trenching.
- Suitable sites for in-channel mitigation works (including foundation/anchor conditions), to inform potential future studies.

Rockfall

- Mapping of potential rockfall source areas and evidence of past events.
- Delineation and measurement of all outcrops, not just those potentially providing source material.
- State of outcrop, including the presence of loose boulders, open jointing, moisture/seepage, foliation, evidence of boulders peeled off from main outcrop etc.

b. Mapping process

Field mapping was undertaken between the 21 and 25 October 2019. Mapping involved recording and photographing features of relevance to the assessment of debris flow and rockfall hazards. Observations made during the mapping are summarised as a geomorphic map presented in Appendix E – Mapping.

c. Summary of Key Observations

i. Debris Flow Hazard

Evidence of debris flow hazard in the two catchments is summarised below:

- Surficial deposits on the true left/northern banks of both Brewery and Reavers Creeks generally comprise landslide deposits. The true right/southern banks contain outcrops interspersed with colluvium and are generally steeper than the opposing banks.
- Banks along Brewery Creek
  - Outcrops on the true right bank generally contain loose material/rocks that may fall into the channel.
  - Colluvium outcrops on the true left bank provide an abundance of loose material that may be entrained/eroded and/or slump into the channel. Much of the deposits contain younger vegetation to no vegetation, potentially indicating relatively recent scour.
  - The stream bed contains many boulders and tree logs/debris.

- Banks along Reavers Creek
  - No evidence for recent water flow was observed through much of the channel.
  - The valley floor is significantly broader than Brewery Creek.
  - Outcrops present along the channel have loose boulders which may fall into channel. Accumulations of boulders were present beneath outcrops. Boulders are covered in moss and do not show evidence of recent movement except in an area at the top of the catchment beneath the cliff (near the Skyline Gondola station).
  - Colluvium along the true left bank is generally covered in vegetation with no evidence of recent movement/scour. The exception was one scree-slope which lacked vegetation and appeared to have moved relatively recently. This was selected as an input source for debris flow modelling.
  - The channel base contains leaf litter, vegetation including trees, and soil cover. Material could be eroded during flow however no evidence of channelised water flow was present (i.e. no channel for flowing water).

ii. Rockfall Hazard

- Many outcrops are present on the lower slopes to approximately 660m above sea level.
- Outcrops contain loose boulders. Smaller cobbles to boulders appear to have broken off along foliation planes while larger boulders present at the intersection of joint sets.
- Evidence for recent localised rockfall on slopes immediately below the outcrops however appear to only move <100m downslope.
- Presence of loose rocks appears to be controlled by foliation pattern and joint sets in the schist. Outcrops where foliations dip into the slope have flat faces with only small loose cobbles to boulders present on the surface of the outcrop which have broken along foliation planes.

3.2.3 Test Pits

Test pitting by hydraulic excavator was conducted in both fan surfaces. The aim of the test pits was to investigate whether the near surface deposits comprised coarse, poorly sorted, matrix supported material indicative of high energy debris flows, or finer grained, well sorted sand and gravel-dominated materials more representative of lower energy alluvial processes.

Wilson Contractors were engaged to excavate test pits on 13 and 14 February 2020.

- Four test pits were excavated at 1 Bowen Street on Brewery Creek Fan. Excavations were completed by a 14-tonne hydraulic excavator and reached final depths of between 2.6m and 3.0m.
- One test pit was excavated at 14 Huff Street on Reavers Fan to a depth of 2.0m by a 1.7 tonne excavator. The lack of space precluded further investigations on Reavers Fan.

Material excavated from the test pits was logged and sampled. Five samples of organic material were taken for radiocarbon dating to constrain approximate depositional ages.

a. Summary of Test Pit Investigations

The five test pits exposed stratigraphy comprising silts, sands, and gravels to cobbles consisting of sub-angular to sub-rounded unweathered schist.

Test pit locations, logs and interpreted field photos are shown in Appendix F – Ground Investigations.

b. Laboratory testing

Testing of the samples was completed by the University of Waikato Radiocarbon Dating Laboratory using the Accelerator Mass Spectrometry (AMS) technique. Three of the five samples of organic material taken were considered suitable for radiocarbon dating, the results of which are shown in Table 4.

Table 4 - Radiocarbon dates of organic test pit samples

Sample ID	Depth (m bgl)	Depth (m below base of fill)	Age (year)*
BS_TP02_S2	1.2	0.2	1972
BS_TP02_S3	1.3	0.3	1967
BS_TP02_S4	2.6	1.6	1961

Laboratory test results and an explanation of the test plots (Oxford Radiocarbon Accelerator Unit, 2020) are presented in Appendix F – Ground Investigations.

c. Depositional environment

The inter-layered silts, sands and gravels/cobbles exposed at the Bowen and Huff Street sites suggest varying modes of sediment deposition. The poorly graded nature of the silts and sands suggest a uniform relatively low energy depositional environment, likely comprising a bank-overtopping or fan-covering flood event. In comparison, the well graded, matrix supported nature of the fine to coarse sandy, fine to coarse gravelly cobbles indicate deposition under higher energy flows and are indicative of debris flows. The inter-layering of fluvial and debris flow deposits and variations in the thicknesses of the deposits suggests deposition by bank over-topping events is punctuated by larger-scale debris flow events.

A review of ground investigations in the fan surfaces conducted by others was undertaken, with conditions encountered broadly in alignment with the Beca findings.

The findings of the test pits investigation have been used to inform the probability of occurrence parameter for debris flows in the AIFR and APR assessments (Sections 5.2 and 6.2).

3.2.4 Cone Penetration Testing

McMillan Drilling were contracted to undertake Cone Penetrometer Testing (CPT) on the distal (lower) margins of the Brewery Creek and Reavers alluvial fans to inform liquefaction assessment. Three CPTs were completed on 15 January 2019 with a Beca Engineering Geologist present for the testing. McMillan provided a Geomil Panther 100 rig capable of applying a static load of up to 70MPa. Tests were undertaken in accordance with the ASTM Standard D3441. Test locations are given in Appendix F – Ground Investigations.

a. Summary of Liquefaction Field Investigations

CPT001 was carried out near the Industrial Place intersection with Gorge Road. Results indicate this site has a soil profile of sandy gravel with high permeability. CPT001 refused at 16mBGL due to inclination gauge exceedance. Groundwater was not observed.

CPT002 was carried out adjacent to 29 Sawmill Road. Results indicate the site is underlain by ~3 meters of thin silt and sand beds before encountering 10+ metres of gravelly sands and silty sands. For this area groundwater was ‘not encountered’ but is estimated to be at ~3mBGL based on nearby observations in Wakatipu High School. CPT002 was terminated at the target depth of 20mBGL

CPT005 was carried out adjacent to 30 Hamilton Road. The CPT rig had to be removed from the truck at this site reducing static load capabilities to 50MPa. Results indicate this site is underlain by thin beds of silty sands and silty clays. CPT005 refused at a depth of 17.3mBGL reaching the maximum static load of 50MPa.

CPT003 and CPT004 were met with complications in land access and were not carried out.

b. Liquefaction Assessment

The Beca liquefaction assessment considered a total of 17 CPTs:

- Three CPTs conducted as part of this study (Beca, 2019), as described above.
- Eight CPTs at the former Wakatipu High School site (GHD, 2017).
- Five CPTs at the former Wakatipu High School site (ENGEO, 2019).
- One CPT to the east of Gorge Road (Geosolve, 2013).

CPT data from the last two bullet points were downloaded from the New Zealand Geotechnical Database (NZGD). The GHD, Engeo and Geosolve investigations all fall just outside the study area but provide useful additional information on the alluvial deposits in the valley floor. The locations of these CPTs are also shown in Appendix F – Ground Investigations.

The assessment methodology follows MBIE published guidelines (MBIE, 2017).

Liquefaction susceptibility and liquefaction-induced settlement estimation has been carried out for each CPT using the software CLiq by GeoLogismiki (v2.2.1.14). The analysis follows the Boulanger & Idriss (2014) method and uses the default fines correction. CPT plots and analysis results are presented in Appendix F – Ground Investigations. Settlement results for the three CPTs within the study area are given in Table 1.

Table 5 - Liquefaction Settlements for CPTs within the study area.

CPT	Location	Groundwater[1] (m BGL)	Vertical Settlement[2] (mm)	Differential Settlement[3] (mm)	Liquefaction Damage[4]
CPT001	Industrial Place	10	< 30	< 15	None to Minor
CPT002	Sawmill Road	3	320	160	Moderate to Severe
CPT005	Hamilton Road	1.7	120	60	Minor to Moderate

[1] Estimated groundwater using available resources. [2] Total vertical settlement in a 1/500 year M_w6.5, 0.41$_{PGA}$ EQ.
[3]Differential settlement estimated as 50% of the vertical settlement. [4] From MBIE (2017) guidelines.

The following analysis inputs have been assumed for the purposes of this hazard zonation study. In some cases these are necessarily generalised for the study area and may therefore differ from assumptions that would be made for site or development-specific studies.

- A site-specific peak ground acceleration (PGA) of 0.41g and an earthquake magnitude of M_w 6.5 (1/500 year ULS) were used in accordance with NZTA Bridge Manual (BM) SP/M/022 Third addition Amendment 2, Section 6.2.2. The 1/500-year event is recommended for liquefaction assessments for residential properties by MBIE (2017).
- The site subsoil class has been assessed in accordance with NZS 1170.5.
  - Site Subsoil Class C was adopted to reflect an assumed shallow soil profile.
  - Site Class E (soft soils) was not adopted due to soil strength (Su) encountered in CPTs being greater than 12.5kPa.
  - A Site Class D (deep soils) is plausible for the sites but cannot be inferred from the existing ground information, in accordance with NZS 1170.5.
  - Site Class C has therefore been adopted due to the limitations of the ground model for the region and no deep boreholes or geophysical data mapping out the sediment to rock interface.
- 20m cut-off depth. MBIE (2017) recommends considering at least 10m - 15m depth for residential or light commercial developments, and at least 20m - 25m for heavier structures or critical facilities. A 20m cut-off depth was used for all CPTs in this assessment.

- Groundwater levels vary but have been estimated at 1.7mBGL at CPT005 and 3 mBGL at CPT002, with CPT001 not encountering groundwater. Test pits in Warren Park (pers comms ENGEO, 2019) encountered groundwater at around 1.5mbGL.
- Variability exists within the deposits in the study area. A likely scenario would be for Site Class C (shallow soil) conditions along the margins of the valley, where sediments are anticipated to be thinner and comprise of predominantly colluvial/alluvial gravels. Towards the centre of the valley, deeper silt and clay sediments that reflect lacustrine deposition may be further assessed to meet the requirements for Site Class D (deep soils). The swampy ground to the north and east of Brewery Creek alluvial fan (Matakauri Wetland) may comprise Site Class E (soft soils) sediments.

A summary of the liquefaction risk zoning derived from the results of the assessment is included in Section 6.

4 Slope Stability Risk Assessment

The annual risk to life (AIFR) and property (APR) from debris flow and rockfall hazards have been assessed quantitively as set out in Sections 5 and 6. The resulting risk values are presented as probabilities which can be expressed in a number of ways, as shown in Table 6.

Table 6 - Ways of expressing risk probabilities (after GNS Science, 2012b).

Probability 1 in… (per year)	Is the same as (per year)	Is the same as (per year)	Is the same as (per year)	Is the same as (over lifetime)*	Is the same as (over building life)†
1,000	10^{-3}	0.001	0.1%	8%	5%
10,000	10^{-4}	0.0001	0.01%	0.8%	0.5%
100,000	10^{-5}	0.00001	0.001%	0.08%	0.05%
1,000,000	10^{-6}	0.000001	0.0001%	0.008%	0.005%

*Based on average New Zealand life expectancy of approximately 80 years, from 2008 mortality and population data.
†Based on minimum building design life of 50 years in accordance with the New Zealand Building Code.

Debris flow and rockfall are not the only slope failure modes that could affect the site. Landsliding and larger-scale cliff collapse are also credible failure modes. Unlike debris flow and rockfall however, no evidence has been found to suggest other hazards have significantly affected the study area since the landscape achieved close to its current form (7,000 to 10,000 years ago). As such this study has focussed on debris flow and rockfall as the hazards substantially contributing to the slope stability risk profile in the area.

5 Slope Stability Life Risk Assessment

5.1 Quantitative Risk Assessment Process

A quantitative assessment of the life risk (AIFR) posed by debris flow and rockfall 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 the hazards occurring. The methodology adopted follows the Australian Geomechanics Society (AGS) Guidelines for Landslide Risk Management (2007).

An estimate of AIFR can be developed from:

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

Where:

$P_{(H)}$ is the annual probability of a hazard (debris flow or rockfall) occurring.

$P_{(S:H)}$ is the spatial probability that, given the hazard has occurred, the resulting debris traverses the location that could be occupied by the person most at risk.

$P_{(T:S)}$ is the temporal spatial probability incorporating the proportion of the time the person most at risk is present and allowing for the possibility that there may be enough warning to allow the person to evacuate.

$V_{(D:T)}$ is the vulnerability, or probability of death of the person most at risk in the event of an interaction with the hazard.

Uncertainty surrounding some of the inputs to the assessment is accounted for by considering the likely range of values that could occur. This ultimately provides an AIFR range (minimum and maximum) for each risk zone. An average AIFR is also provided for each risk zone, which forms the basis of the risk contouring work (Section 5.5). The average AIFR was determined through averaging the input probabilities.

Debris flow and rockfall risks are evaluated differently and separately and are then summed to provide a combined slope stability risk. Descriptions of the assessment process implemented for debris flow and rockfall risk respectively are presented below.

The process for life risk assessment is described in the following subsections and comprises:

- Use of field mapping findings detailed in Section 3.2.2 to inform rockfall and debris flow source areas and probabilities of occurrence.
- Conducting debris flow and rockfall runout modelling using RAMMS software to inform spatial probability of hazard interacting with people at risk.
- Assessment of AIFR for the person most at risk using the process defined in AGS (2007).
- Development of maps showing risk zones and associated AIFR.
- Development of AIFR contour maps for each planning zone (Section 5.5).

The life risk assessment has been carried out for debris flow and rockfall considering both the current situation, i.e. largely forested lower catchments, and a non-forested condition. The non-forested condition has been considered to understand the potential effect of deforestation on slope stability hazards.

5.2 Debris Flow

5.2.1 AIFR Methodology Debris Flow

The parameters used in assessing AIFR were determined as follows.

a. Annual Probability of Failure $P_{(H)}$

- The annual probability of an event occurring was assessed for three debris flow magnitude classes for Brewery Creek Fan, based on literature review, historical information, field investigations and radiocarbon dating of samples from test pits at 1 Bowen Street. The three magnitude classes defined were:

Table 7 - AIFR return periods and associated probabilities for three magnitude classes at Brewery Creek Fan

Parameter	Small event		Medium event		Large event	
	Min	Max	Min	Max	Min	Max
Return period (years)	50	200	200	2,500	2,500	10,000
Annual probability	0.02	0.005	0.005	0.0004	0.0004	0.0001

- The small event was partly defined based on previous events at Brewery Creek:
  - The 1999 debris flow was triggered by a 150-220 year ARI (average recurrence interval) storm event, based on 96 and 72 hour rainfall totals respectively (Section 3.1.4).
  - Radiocarbon dating (Section 3.2.3) provides evidence of events occurring in the 50-60 year range, with no known injuries or fatalities resulting.
- The moderate size event was selected as a reasonable mid-point between the small and large event ranges.
- The large event was selected based on the knowledge that the fan was at least partially formed by the time Lake Wakatipu retreated from the valley around 7,000 years ago (due to the interfingering of debris flow and lake deposits on the lower margins of the fan). A large event within this time period is considered a reasonable scenario.
- In the absence of historical records of events at Reavers Fan, and based upon a geomorphic assessment of the catchment, the return periods were longer, with the categories shown in Table 8 considered.

Table 8 - AIFR return periods and associated probabilities for three magnitude classes at Reavers Fan

Parameter	Small event		Medium event		Large event	
	Min	Max	Min	Max	Min	Max
Return period (years)	100	2,500	2,500	6,700	6,700	20,000
Annual probability	0.01	0.0004	0.0004	0.00015	0.00015	0.00005

- The smaller event was allocated a return period of greater than 100 years, in the absence of any historical record of a debris flow event, and in the absence of any debris flow during the 1999 rainfall event.
- The medium and larger return periods are greater than those at Brewery Creek, which was partially informed by the mapping exercise which did not show any evidence of recent debris flow deposits, no build-up of material in the channel which could mobilise in an event, or stream flow on the channel floor in fine weather conditions.

b. Spatial Probability $P_{(S:H)}$

Runout distances, debris depth and velocity were assessed using RAMMS (Rapid Mass Movement System) software, which models rockfall and debris flows in 3D alpine terrain. Potential source regions upslope of the study areas were identified during field mapping, and supplemented with an assessment of a Digital Elevation Model (DEM) developed from the 1m LiDAR survey.

Details of the RAMMS debris flow modelling methodology and adopted parameters are included in Appendix G – Debris Flow Modelling, along with plans showing modelling results for each scenario.

i. Debris Flow Modelling Results

For each of the three event magnitude classes selected for each fan, a number of RAMMS models were run based on different release areas, volumes and types of failure (hydrograph channelised release or block release on the valley sides). These models were refined to up to three representative scenarios for each size event. The model results for each scenario are shown in Appendix G – Debris Flow Modelling.

Cut-off parameters for debris flow velocity (2m/s) and depth (1m) were applied to the models, with any areas beyond this discounted. The trimmed models for the representative scenarios for each magnitude class were overlaid, with a single extent developed from a smoothed maximum of the events. These extents were used to develop the debris flow risk zones. The lower risk zone (Zone 4) occupies the area between the cut off extents of the models described above, and the maximum extent of the model run out for the largest size event.

This process was followed for both forested (current situation) and non-forested cases. The resulting maps are shown in Appendix J – Slope Stability Life Risk Maps.

ii. Spatial Probability Assessment

$P_{(S:H)}$, the spatial probability that the debris flow traverses the location potentially occupied by the person most at risk was developed based on the RAMMS modelling scenarios detailed above. The average fan area covered by the scenarios for each of the magnitude classes was considered as a function of the maximum fan area that could be covered by any event of a similar magnitude. This resulted in values of 0.8 for Brewery Creek Fan and 0.9 for Reavers Fan. In other words, each individual scenario covered approximately 80% to 90% of the total area of all scenarios in the same magnitude class.

c. Temporal Spatial Probability $P_{(T:S)}$

- Temporal spatial probability was defined as the proportion of the time the person most at risk is present (TIMARP), allowing for the ability of that person to become aware of the hazard in time to evacuate (probability of self-evacuation, PSE). This was considered separately for each planning zones (i.e. business and residential), and for persons inside and outside at the time of the event.
  - TIMARP
    - For residential areas the time an individual most at risk is present was taken to be 80% inside and 10% outside.
    - For business areas (Brewery Creek Fan only) the time an individual most at risk present considered a person working 12 hour days, 245.5 days per year (365 days less weekends, 4.5 sick days[1] and 11 public holidays), located inside 40% of a 24 hour period and outside 10%. This equates to a P(T:S) of 0.27 inside and 0.07 outside.
  - Probability of self-evacuation

[1] Workplace Wellness Report 2019, BusinessNZ. www.businessnz.org.nz/resources/surveys-and-statistics

  - The probability of self-evacuation was assessed in proportion to average debris flow velocities on the fan area, for the three magnitude classes (i.e. the greater the velocity the lower the PSE).
  - PSE values are slightly higher when a person is outside, given the potential for them to see/hear the debris approaching and take evasive action (Taig et al, 2015).
  - For a single sized event, the probability of self-evacuation increases with distance from the fan apex, given the increased ability to take evasive action to avoid the debris flow.

d. Vulnerability $V_{(D:T)}$

- The vulnerability of a person inside is linked to the ability of debris to enter a building; while outside is linked to the ability of a person to survive the impact. Vulnerability parameters were therefore determined based on the outputs of the RAMMS models (debris depth and velocity). The range of vulnerability parameters has been developed in line with the recommendations included in AGS (2007) and GNS (2018c).
- Inside:
  – Where model velocity and depth indicated a debris flow has the ability to enter a building through ground floor windows and doors, vulnerability values in the range of 0.5 to 0.9 were applied.
  – Depths of <1m were discounted from the models (Section 5.2.1b.i). GNS (2018c) indicates that fatalities that have occurred in light timber framed structures related to debris flows greater than 1.0m depth.
  – Where model velocity and depths indicated debris flow is unlikely to penetrate a building at least conforming to NZS 3604 (i.e. risk zone 4), values of 0.05 were applied in accordance with AGS.
- Outside:
  – Where model velocity and depth indicated a debris flow would bury a person (i.e. depth >1m, velocity >2m/s), vulnerability parameters in the range of 0.6 to 1.0 were applied. AGS recommends values of 0.8 to 1.0 in this situation, however a value of 0.6 was applied for the smaller event, where model depths were marginally in excess of 1m in places.
  – Where model velocity and depth indicated a person would not be buried (risk zone 4) a vulnerability parameter of 0.1 was applied in accordance with AGS.

Vulnerability parameters are summarised graphically in Figure 12.

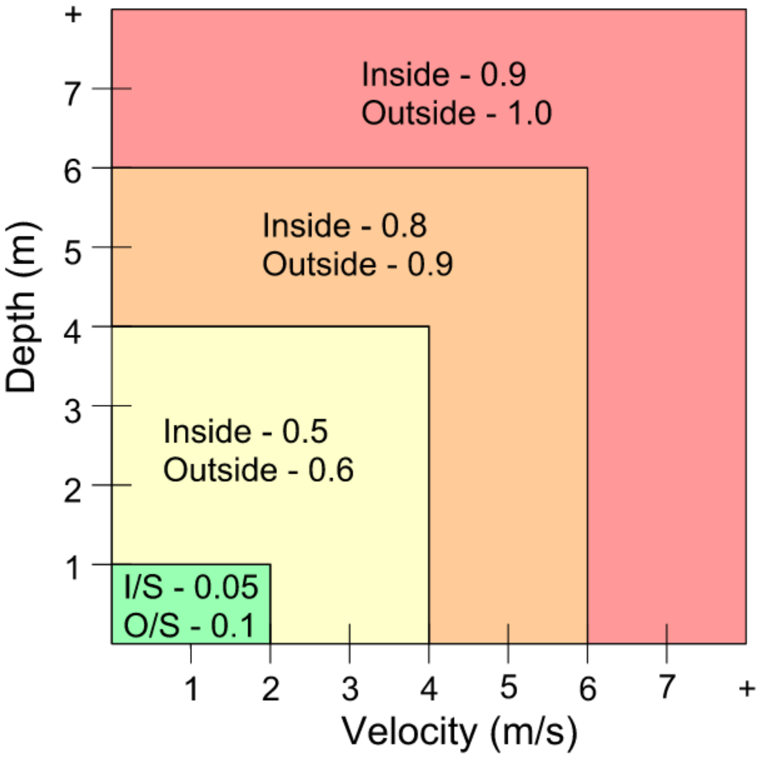


Figure 12 - Debris flow vulnerability classification based on RAMMS model outputs

e. AIFR calculation

The resulting AIFR values were summed for the three event magnitudes, for all areas susceptible to each sized event. For example, risk zone 1 (top of Brewery Creek fan) has the potential to be affected by small, medium and large events, and therefore the risk contribution from each must be considered.

5.2.2 AIFR Debris Flow Results

The full AIFR assessment results are tabulated in Appendix I – Annual Individual Fatality Risk . AIFR values corresponding to the various zones are summarised in Table 9, Table 10 and Appendix I – Annual Individual Fatality Risk .

Table 9 - Summary of Debris Flow AIFR for Brewery Creek Fan

Debris Flow Zone	AIFR Brewery Creek Fan					
	Residential			Business		
	Minimum	Average	Maximum	Minimum	Average	Maximum
1	$7.3x10^{-4}$	$3.1x10^{-3}$	$6.4x10^{-3}$	$2.7x10^{-4}$	$1.2x10^{-3}$	$2.4x10^{-3}$
2	$1.4x10^{-4}$	$9.1x10^{-4}$	$2.0x10^{-3}$	$5.2x10^{-5}$	$3.4x10^{-4}$	$7.4x10^{-4}$
3	$3.2x10^{-5}$	$9.6x10^{-5}$	$1.8x10^{-4}$	$1.2x10^{-5}$	$3.6x10^{-5}$	$6.8x10^{-5}$
4	$1.5x10^{-6}$	$4.8x10^{-6}$	$9.3x10^{-6}$	$6.0x10^{-7}$	$1.9x10^{-6}$	$3.7x10^{-6}$

Table 10 - Summary of Debris Flow AIFR for Reavers Fan

Debris Flow Zone	AIFR Reavers Fan		
	Minimum	Average	Maximum
1	$1.3x10^{-4}$	$1.0x10^{-3}$	$2.3x10^{-3}$
2	$6.2x10^{-5}$	$1.4x10^{-4}$	$2.5x10^{-4}$
3	$1.8x10^{-5}$	$4.3x10^{-5}$	$7.6x10^{-5}$
4	$8.6x10^{-7}$	$2.2x10^{-6}$	$3.9x10^{-6}$

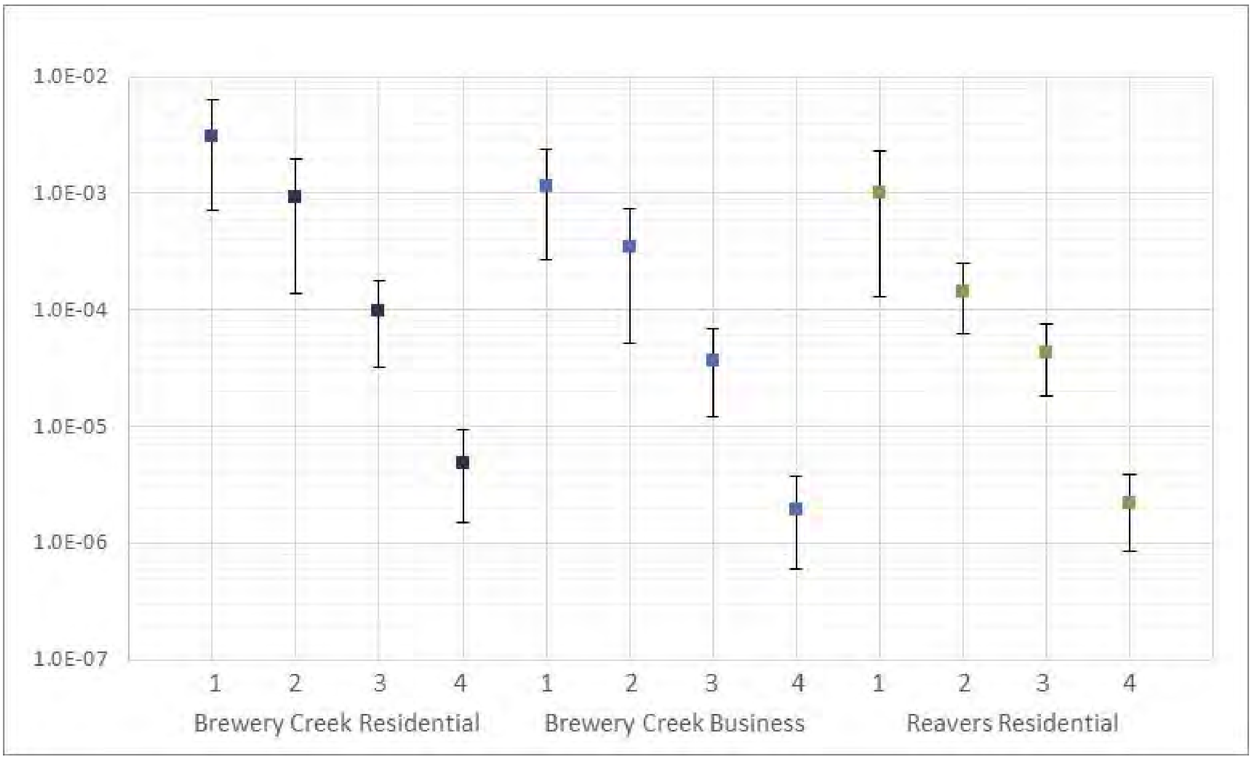


Figure 13 - Debris Flow AIFR by risk zone. Error bars show the range of values (minimum to maximum).

5.2.3 Debris Flow Risk Zones

The above AIFR values correspond to risk zones which were developed from the RAMMS modelling as described above. AIFR values for each zone are included on the risk map shown in Appendix J – Slope Stability Life Risk Maps.

The AIFR values for each zone apply to both forested (current situation) and non-forested conditions. The zone boundaries however are different. Zones for the non-forested scenarios cover a higher proportion of the fan surface, as informed by the zones of deposition from the non-forested debris flow models. Vegetation inhibits both initiation and transportation of debris flows compared to open slopes.

5.3 Rockfall

5.3.1 AIFR Methodology Rockfall

Further to Section 5.1, AIFR for rockfall is derived from four parameters:

- Annual probability of an isolated rockfall occurring, $P_{(H)}$.
- Spatial probability that a rock traverses an area potentially occupied by the person most at risk, $P_{(S:H)}$.
- Temporal spatial probability considering the percentage of the time the person is present $P_{(T:S)}$.
- Vulnerability of a person in the event of impact, $V_{(D:T)}$.

The process for assessing AIFR for rockfall risk is detailed below.

a. Annual Probability of Failure $P_{(H)}$

- Annual probability of an isolated rockfall occurring from an outcrop. In the absence of historical information on rockfall occurrence, three scenarios were considered.
  - Small rockfall with a non-seismic trigger (predominantly heavy rainfall or gradual weathering effects), with a return period of 1 year (annual probability of 1.0).

  - Seismically triggered rockfall from a far-field earthquake with a return period of 100 years (annual probability of 0.01) was considered as the moderate sized event. This is analogous to an Alpine Fault event.
  - Seismically triggered rockfall from a large near-field earthquake with a return period of 500 years (annual probability of 0.002) was considered as the large rockfall scenario.
- P(H) annual probability of a rockfall occurring was assessed as a function of an isolated rockfall being released (above) and the likely number of individual rocks involved. The number of rocks released was considered to range between:
  - 1 and 10 per small event (1 year).
  - 10 and 100 per moderate event (100 year).
  - 100 and 1,000 per large event (500 year).

The number of rocks released in the near field seismic event is broadly consistent with observations from the Ports Hills following the 2010-11 Canterbury Earthquakes (GNS Science, 2012c).

b. Spatial Probability $P_{(S:H)}$

Given a rock has fallen, the spatial probability of impact between the rock and the person most at risk has two components as follows:

- The Probability of Travel, $P_{(T)}$, that a single fallen rock rolls far enough down the hill to reach the location of the person most at risk, and
- Given a single rock gets far enough down the slope to reach a person, the probability that the rock moves through a section of slope width potentially occupied by that person, ($P_{1(S:H)}$).

i. RAMMS Rockfall Modelling Methodology

The probability that a single fallen rock rolls far enough down the hill to reach the location of the person most at risk was assessed using RAMMS (Rapid Mass Movement System) software. Full details of the RAMMS: Rockfall and RocFall modelling methodologies and parameters adopted in the analyses are included in Appendix H – Rockfall Modelling, along with plans showing the results of the RAMMS modelling.

Modelling aimed to capture trajectories and run-out distances of rocks from the source outcrops assuming two conditions - forested and unforested. Two dimensional rockfall modelling was additionally undertaken using the RocFall modelling software to provide an independent check of modelled run-out distances.

All source outcrops identified during the mapping programme and inferred from the DEM were entered in to the RAMMS rockfall model. The models were refined to only include outcrops which could release rocks into the study area, with models run at a finer resolution and divided into a series of smaller sections along the hillside.

ii. RAMMS Rockfall Modelling Results

Brewery Creek Fan:

- Modelling of outcrops on the true-right of Brewery Creek shows the 99th percentile rockfall runout distance continues approximately 30m downslope of the transmission line, and approximately 20m into the residential properties.
- Rockfall debris sourced from outcrops on the true-left of Brewery Creek is shown to accumulate at the base of the slope and extending approximately 5m into the industrial properties.

Reavers Fan:

- Modelling of outcrops identified on the slope to the true right of Reavers Fan shows 99% of rockfall debris is confined to the area 30m downslope of the transmission line.

- The 99th percentile of rockfall debris sourced from outcrops to the true left of the Reavers Fan continues 20m downslope of the transmission line.

iii. Spatial Probability Determination

- The probability that a single fallen rock rolls far enough down the hill to reach the location of the person most at risk (Probability of travel, $P_{(T)}$) has been developed based on the RAMMS modelling scenarios. For each refined model, zones were generated based on the final resting position of the number of rocks released, as follows:
  - Zone 1 - greater than 10% of released rocks came to rest.
  - Zone 2 - 1-10% of released rocks came to rest.
  - Zone 3 - 0-1% of released rocks came to rest.
- The three lines generated (0%, 1% and 10%) were located at the furthest point downslope for the three rockfall risk zones.
- A single probability value has been assigned to each of the three rockfall risk zones. The following values were adopted (Figure 14):
  - Zone 1 – 10% probability of travel.
  - Zone 2 – 5% probability of travel.
  - Zone 3 – 1% probability of travel.

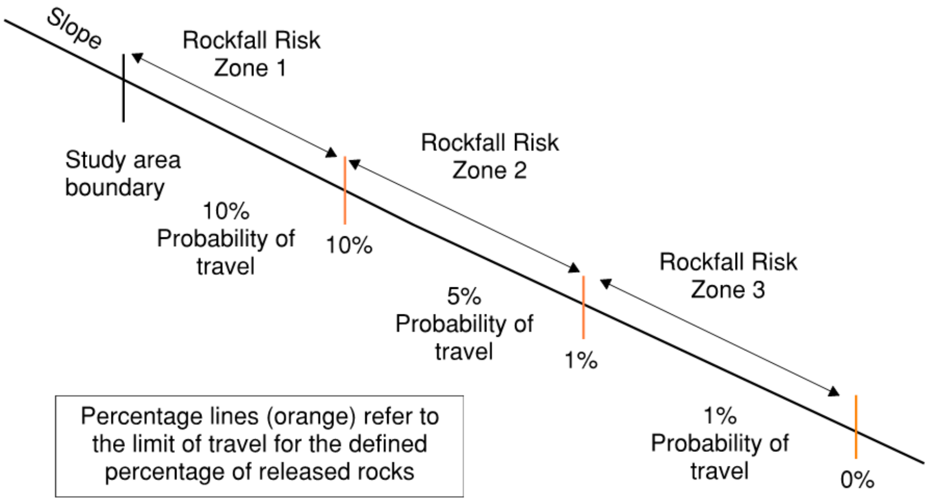


Figure 14 - Rockfall Spatial Probability Determination

The above process was followed for both forested (current situation) and non-forested conditions. The resulting maps are shown in Appendix J – Slope Stability Life Risk Maps.

Given a single rock gets far enough down the slope to reach a person, the probability that the rock moves through a section of slope width potentially occupied by that person, $P_{1(S:H)}$, is taken to be twice the width of the average sized boulder (1m) plus the width of the person at risk (approximated as a 1m diameter cylinder) per unit width of slope (Figure 15).

$P_{1(S:H)}$ is then divided by the width of the slope considered in the analysis, in this case full width (along slope) of the study area (1220m).

$P_{1(S:H)}$ is then adjusted to account for the number of rocks (N) expected to fall in a particular event, giving ($P_{N(S:H)}$). $P_{N(S:H)}$ is given by $1-(1-P_{1(S:H)}{}^{N})$. As more rocks fall, $1-(1-P_{1(S:H)}{}^{N})$ tends to 1.0.

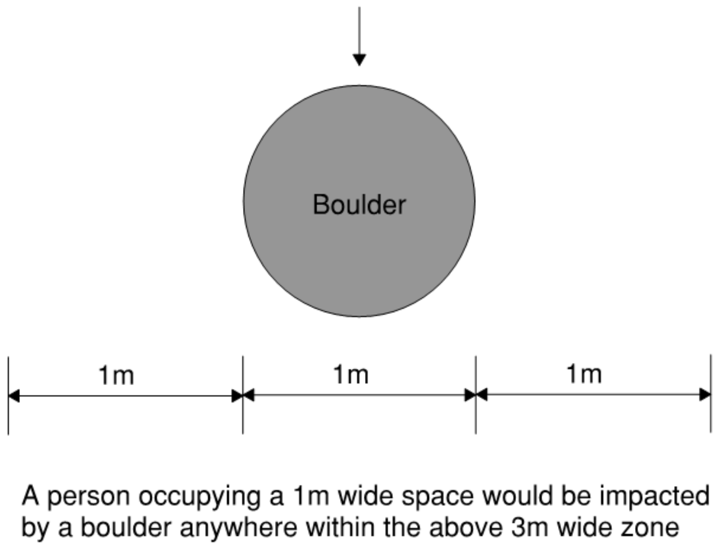


Figure 15 - Probability of a rock moving through a section of slope occupied by a person

c. Temporal Spatial Probability $P_{(T:S)}$

- Temporal spatial probability was defined as a function of:
  - The time the person most at risk is present (temporal), as defined in Section 5.2.1, and
  - The probability that a person is able to move out of the path of a falling rock, which is considered to be zero for non-seismic rockfall, and between 0.1 and 0.2 for seismically triggered rockfall, where the earthquake would provide some warning for people outside.

d. Vulnerability $V_{(D:T)}$

- Vulnerability parameters were determined in line with the recommendations included in AGS (2007), with a vulnerability of 0.1 for inside occupancy and 0.5 for outside occupancy.

5.3.2 AIFR Rockfall Results

The full AIFR assessment results are shown in Appendix I – Annual Individual Fatality Risk . AIFR values corresponding to the various likelihood zones are shown in Table 11 and Figure 16.

Table 11 - Summary of Rockfall AIFR

Rockfall Zone	AIFR Entire Study Area					
	Residential			Business		
	Minimum	Average	Maximum	Minimum	Average	Maximum
1	$1.5x10^{-4}$	$7.4x10^{-4}$	$1.3x10^{-3}$	$5.7x10^{-5}$	$2.9x10^{-4}$	$5.2x10^{-4}$
2	$4.5x10^{-5}$	$2.3x10^{-4}$	$4.1x10^{-4}$	$1.8x10^{-5}$	$9.0x10^{-5}$	$1.6x10^{-4}$
3	$3.4x10^{-6}$	$1.7x10^{-5}$	$3.1x10^{-5}$	$1.5x10^{-6}$	$7.5x10^{-6}$	$1.3x10^{-5}$

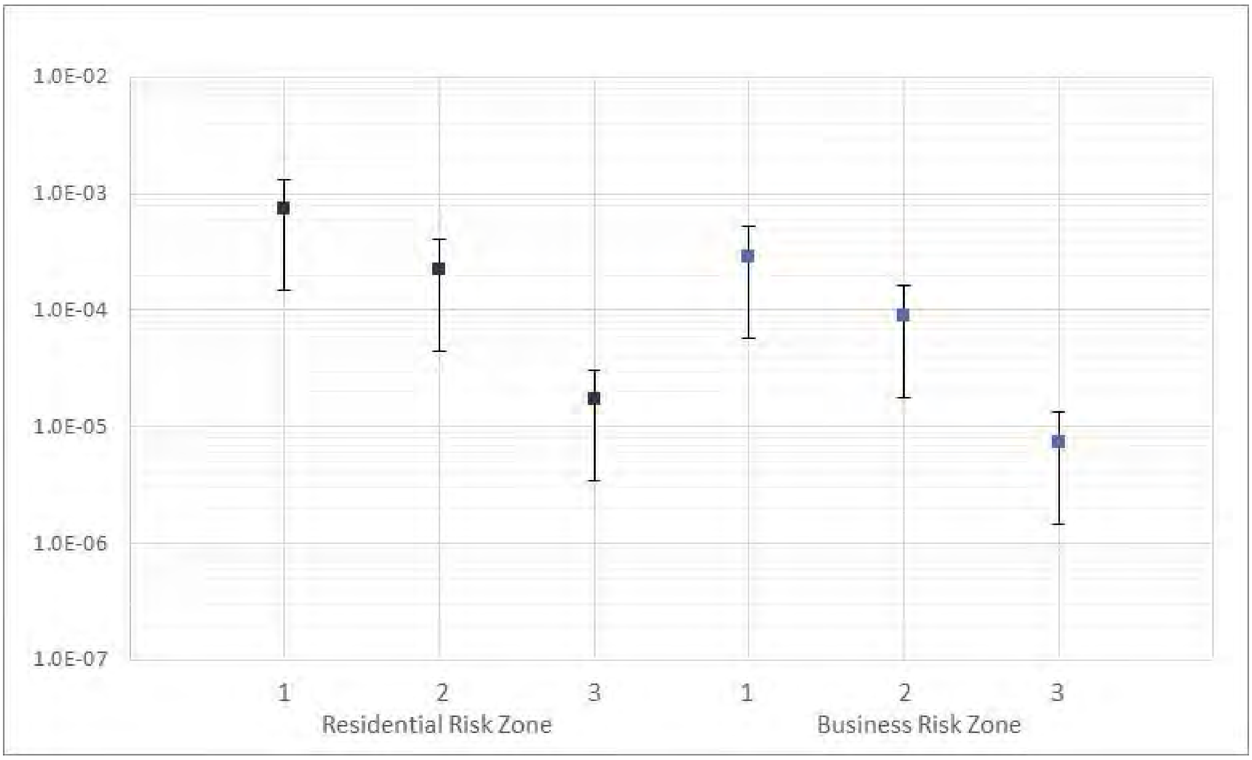


Figure 16 - Rockfall AIFR by risk zone. Error bars show the range of values (minimum to maximum).

5.3.3 Rockfall Risk Zones

The above AIFR values correspond to risk zones which were developed based on the percentage of released rocks reaching each zone from the RAMMS models, as detailed in Section 5.3.1c. AIFR values for each zone are included on the risk maps shown in Appendix J – Slope Stability Life Risk Maps.

The AIFR values for each zone apply to both forested (current situation) and non-forested conditions. Zones for the non-forested condition extend further downslope, which reflects further run-out distances of the modelled boulders without the forest drag co-efficient.

5.4 Combined Debris Flow and Rockfall AIFR

Combined AIFR slope stability maps for Brewery Creek and Reavers Fans have been developed by superimposing the risk zones from debris flow and rockfall. The AIFR values for each hazard have been added together where zones overlap. AIFR combined risk values are summarised in Table I 1 to Table I 3 inclusive (Appendix I – Annual Individual Fatality Risk Worksheets). The combined risk maps for forested and unforested conditions are included in Appendix J – Slope Stability Life Risk Maps.

5.5 AIFR Contours

AIFR contours were developed for combined debris flow and rockfall risk, using average AIFR values for the current (forested) situation. The process involved interpolating the spatial extent of AIFR risk zone values to develop contour plans, through:

- Drawing a series of radial lines from zones of high to low risk on the combined risk maps.
- Developing semi-logarithmic plots of combined risk plotted against chainage for each radial line.
- Linear interpolation between the mid-points of two risk zones straddling risk orders of magnitude (i.e. 1×10^{-4} and 1×10^{-5}).
- Locating the chainages of risk orders of magnitude (as shown in Figure 17).

- Plotting the location of risk orders of magnitude on a map and combining to generate AIFR contour plots. Some smoothing of the contours was undertaken with judgement applied where required to provide reasonable contour locations.

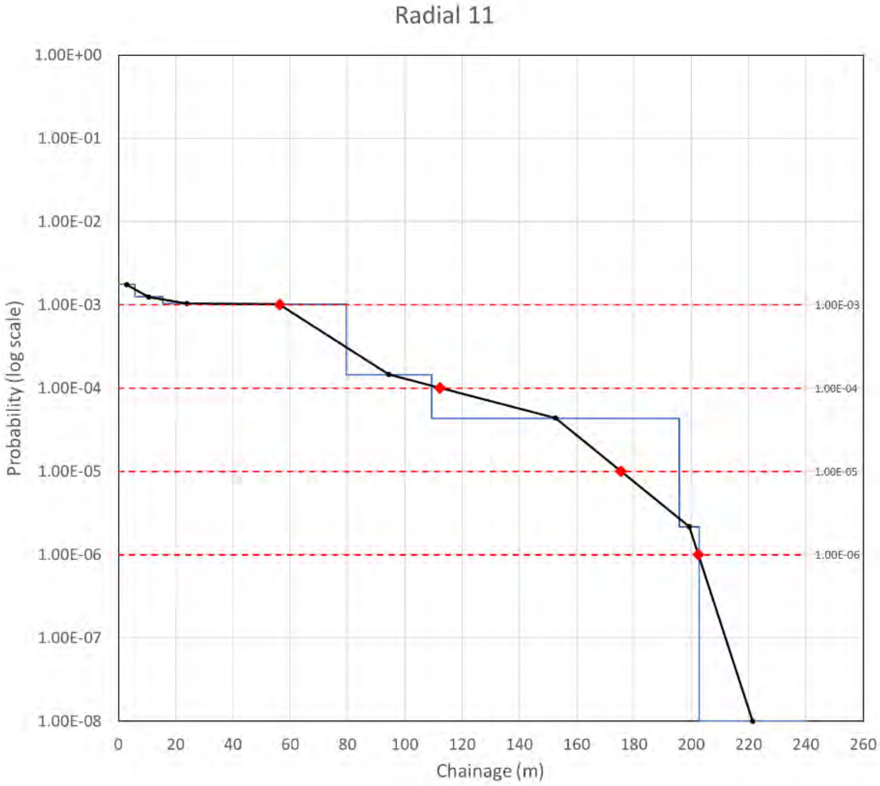


Figure 17 - Example radial line risk plot, using linear interpolation to determine the chainage of risk magnitude contours.

Assumptions involved in the above process include:

- Use of average AIFR values, as presented in Section 5.4.
- The assumption that the risk zone AIFR value is located at the mid-point within the zone.
- The limit of rockfall risk was taken to be just outside the limit of the RAMMS model runouts; and the limit of debris flow risk was taken to be the maximum extent of the largest credible scenario for each fan. Both of these lines were assigned a risk of 1 x 10^{-8}, as required to determine the location of the 1 x 10^{-5} and 1 x 10^{-6} contours.

Three AIFR contour plots have been developed, one each for Brewery Creek Fan residential zone, Brewery Creek Fan business zone and Reavers Fan, with contours ranging from 10^{-3} to 10^{-6}. These are shown in Appendix J – Slope Stability Life Risk Maps.

5.6 Climate Change Impacts on Slope Stability

5.6.1 Debris Flows

a. Rainfall predictions

The AIFR assessment for debris flow detailed in the above sections is based on current climate conditions, with the assessment considering the November 1999 event to inform the annual probability of occurrence parameter.

NIWA's HIRDS v4 database predicts rainfall depths for various time periods and ARIs for all locations in New Zealand for current climatic conditions. HIRDS additionally considers four climate change scenarios or

Representative Concentration Pathways (RCPs), ranging from 2.6 to 8.5, with RCP 8.5 being the most extreme. By way of illustration, comparison of historic and predicted rainfall under all four climate change scenarios at an ARI of 250 years is shown in Table 12, with the associated rainfall percentage increases shown in Table 13. The ARI of 250 was selected for comparative purposes only, as events with longer ARIs are more likely to initiate debris flows. This process is in alignment with the methodology followed in climate studies conducted by QLDC and ORC (Bodeker Scientific, 2019 and NIWA, 2019).

Table 12 - Historic and modelled predicted rainfall (mm) in the Gorge Road area under four climate change scenarios for an ARI of 250 years (source: HIRDS).

Climate change scenario	Time Horizon	Period (hours)			
		0.5	1	24	72
Current	2020	24.4	35.8	143	193
RCP 2.6	2040	26.4	38.7	150	201
	2090	26.4	38.7	150	201
RCP 4.5	2040	26.9	39.4	152	203
	2090	28.4	41.7	158	209
RCP 6.0	2040	26.7	39.1	151	202
	2090	29.8	43.8	163	214
RCP 8.5	2040	27.2	40	153	204
	2090	33.0	48.4	175	227

Table 13 - Modelled rainfall increases in the Gorge Road area under four climate change scenarios for an ARI of 250 years (after HIRDS).

Climate change scenario	Time period	Period (hours)			
		0.5	1	24	72
RCP 2.6	Current-2040	8%	8%	5%	4%
	Current-2090	8%	8%	5%	4%
RCP 4.5	Current-2040	10%	10%	6%	5%
	Current-2090	16%	16%	10%	8%
RCP 6.0	Current-2040	9%	9%	6%	5%
	Current-2090	22%	22%	14%	11%
RCP 8.5	Current-2040	11%	12%	7%	6%
	Current-2090	35%	35%	22%	18%

The above information shows:

- Rare, extreme events such as these (ARI of 250 years) are predicted to increase in intensity under all four climate change scenarios.
- Short duration, high intensity events have larger relative increases in rainfall than longer duration events.
- By 2090 under RCP8.5 (the most extreme prediction), rainfall totals will be up to 35% higher than historical averages.
- The shorter duration high intensity events that have the potential to trigger debris flows in vulnerable catchments are predicted to increase in intensity by between 8% and 35% (RCP 2.6 and RCP 8.5 respectively).

b. Climate change impacts on debris flow AIFR.

An illustration of the effects of climate change on debris flow AIFR has been conducted using HIRDS, for a short duration, high intensity event with the potential to trigger a debris flow in a susceptible catchment (40mm in one hour, refer to Section 2.1). Table 14 shows the change in AIFR under all four climate change scenarios for the 2081-2100 time period (typically termed '2090'). Equivalent ARIs for the event have been determined using HIRDS data, and extrapolated or interpolated as required, as HIRDS ARI data is limited to 250 years. This information has been fed into an AIFR assessment where all other variables remain the same. The assessment is based on a small event in the residential zone of Brewery Creek.

Table 14 - Effects of climate change on AIFR for a short duration, intense rainfall event (after HIRDS).

Climate change scenario	Average Recurrence Interval (ARI)	Annual Individual Fatality Risk (AIFR)
Current historical	450*	3.2×10^{-4}
RCP 2.6 2090	300*	4.7×10^{-4}
RCP 4.5 2090	215†	6.6×10^{-4}
RCP 6.0 2090	175†	8.1×10^{-4}
RCP 8.5 2090	100	1.4×10^{-3}

*Extrapolated from HIRDS charts (beyond 250 year maximum)

†Interpolated from HIRDS charts

The data in Table 14 show an increase in AIFR of just under one order of magnitude between current data (based on historical averages) and RCP 8.5 2090 (the most severe climate change scenario) for a short, intense rain event; with an associated change in ARI from 450 to 100 years respectively.

It should be noted that the AIFR values in Table 14 are for comparison only, as they do not directly relate to a risk zone in the study area. Risk zone AIFRs are determined by adding AIFR values for small, medium and large events for a given zone; however the data required to assess climate change impacts on medium and large events is not readily available (see below).

c. Climate change impacts for larger events

Current climate change assessment tools, including HIRDS, are based on climate model simulations recommended in the IPCC Fifth Assessment Report (AR5, 2015), which considers a range of timeframes from present day to 'long term', classed as 2080-2100, and typically termed the 2090 scenario.

A climate change scenario AIFR assessment for the moderate and large sized events has not been conducted, as the time range considered (200 to 10,000 years) is outside the limit of the climate change model simulations, and any attempt at considering this would have a margin of uncertainty significantly greater than the existing AIFR calculations.

5.6.2 Rockfall

Climate change effects on rockfall risk have not been considered, as climate triggers are only one of several potential triggers of rockfall events, and it is not possible to quantify the effect of increased frequency of intense rain events on rockfall occurrence. It is anticipated that the effect of climate change on rockfall would be considerably less significant than for debris flow.

6 Slope Stability Property Risk Assessment

The risk of property damage was assessed qualitatively in previous versions of this natural hazards study. This has been updated to include a quantitative property risk assessment in accordance with AGS (2007).

6.1 Quantitative Risk Assessment Process

A quantitative assessment of Annual Property Risk (APR) due to debris flow and rockfall has been carried out. APR is the annual probability of total property loss (relating to permanent structures) as a result of the hazards occurring, on the assumption that the site is developed in accordance with the current planning zone. The methodology adopted follows the Australian Geomechanics Society (AGS) Guidelines for Landslide Risk Management (2007).

An estimate of APR can be developed from:

$$APR = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(Prop:S)} \times E.$$

Where:

$P_{(H)}$ is the annual probability of a hazard (debris flow or rockfall) occurring.

$P_{(S:H)}$) is the spatial probability of impact (by debris flow or rockfall) on the property, taking into account the travel distance and travel direction.

$P_{(T:S)}$ is the temporal spatial probability. For houses and other buildings, P(T:S) = 1.0

$V_{(D:T)}$ is the vulnerability of the property to the spatial impact (or proportion of property value lost).

E is the value of the element at risk (e.g. the replacement value of the property).

APR has been assessed utilising the annual and spatial probability parameters from in the AIFR assessment, along with parameters obtained from the loss modelling software RiskScape (https://www.RiskScape.org.nz/), provided by GNS Science.

As with AIFR, debris flow and rockfall risks were evaluated separately and then summed to provide combined slope stability APR. The primary difference between the AIFR and APR assessment processes is the provision of risk zone maps for life risk, with an associated range of AIFR values. This step was not required in the APR process, and only risk contour maps are provided. Average values were adopted in both the AIFR and APR risk contouring processes.

The process for property risk assessment is described in the following subsections and comprises:

- Use of the field mapping, ground investigations, debris flow and rockfall RAMMS modelling outputs to inform hazard occurrence, temporal and spatial probabilities, as utilised in the AIFR assessment.
- Incorporating RiskScape loss ratio data as the vulnerability parameter.
- Assessment of APR using the guidelines provided in AGS (2007).
- Development of APR contour maps for each planning zone (Section 6.4).

The APR assessment has been undertaken for debris flow and rockfall considering only the current situation, i.e. largely forested lower catchments.

6.2 Debris Flow

6.2.1 APR Methodology for Debris Flow

a. Annual Probability of Failure $P_{(H)}$

- The annual probability of an event occurring was estimated for the three debris flow magnitude classes utilised in the AIFR assessment; and based on literature review, historical information and radiocarbon dating of samples from test pits.
- The average of the return period ranges used in the AIFR analysis were adopted, as shown in Table 15. Details of the rationale behind these parameters is included in Section 5.2.1a.

Table 15 - APR approximate return periods and associated probabilities for three magnitude classes

Fan	Parameter	Small event	Medium event	Large event
Brewery Creek Fan	Return period	125 years	1,500 years	6,000 years
	Annual probability	0.008	0.0007	0.0002
Reavers Fan	Return period	1,500 years	5,000 years	13,000 years
	Annual probability	0.0008	0.0002	0.000075

b. Spatial Probability $P_{(S:H)}$

The spatial probability assessment was used to inform the debris flow risk extents, utilising RAMMS modelling software, as with the AIFR process. Section 5.2.1b and Appendix G – Debris Flow Modelling should be referred to for details of the process followed and assumptions made. Unlike AIFR, physical APR risk zone maps were not produced, with the software outputs used directly to inform the APR contouring exercise.

The spatial probability that the debris flow traverses the location of the property was assessed using the RAMMS model outputs, for a single representative model for each magnitude event. The outputs of each model were used to form a 1m x 1m grid, with the extents of the three magnitude events overlaid. These cells had annual probability and vulnerability parameters applied, with the cells not affected by debris flow given zero values.

c. Temporal Spatial Probability $P_{(T:S)}$

In line with AGS (2007) the temporal spatial probability of a house or other building being present is 1.0.

d. Vulnerability $V_{(D:T)}$

Vulnerability when applied to property risk is the proportion of property value lost in the event of impact. The metric used to assess this is the loss ratio (also known as the damage ratio), which is a value between 0 and 1 representing the ratio of repair cost to replacement cost.

The loss ratio parameter was supplied on a 1m x 1m grid over the study area by the GNS RiskScape team in accordance with the methodology defined in GNS Science (2019c) and the GNS technical note in Appendix K – Property Risk Vulnerability Methodology (GNS). For the purpose of zoning property risk, the loss ratios represent hypothetical buildings located in each grid cell.

Loss ratios were determined, from the maximum debris height in each grid cell. The loss ratio for each of the three representative magnitude scenario models was calculated for each grid cell.

e. Value E

PR can optionally be multiplied by the value of the property (E) to provide financial loss risk. However the purpose of this exercise is to obtain APR contours to inform planning provisions, and as such the current property values are not relevant. As a result the E parameter was not incorporated in the APR calculations.

f. APR calculation

The relevant parameters listed above were multiplied to produce APR, then summed for the three debris flow event magnitudes, on a 1m x 1m grid for all areas affected by each event. Areas outside of the debris flow risk zones were given zero values.

6.2.2 APR Results Debris Flow

The resulting APR values from debris flow range from 10^{-3} to 10^{-6}.

6.3 Rockfall

6.3.1 APR Methodology for Rockfall

a. Annual Probability of Failure $P_{(H)}$

- The annual probability of a single rockfall occurring form an outcrop was based on the three rockfall scenarios considered in the AIFR assessment (Section 5.2.1a):
  - Small rockfall with a non-seismic trigger (predominantly heavy rainfall or gradual weathering effects), with a return period of 1 year (annual probability of 1.0).
  - Seismically triggered rockfall from a far field earthquake with a return period of 100 years (annual probability of 0.01) was considered as the moderate sized event. This is analogous to an Alpine Fault event.
  - Seismically triggered rockfall from a large near field earthquake with a return period of 500 years (annual probability of 0.002) was considered as the large rockfall scenario.

b. Spatial Probability $P_{(S:H)}$

Spatial probability was determined for the three rockfall scenarios described above, using a similar approach to the AIFR rockfall process detailed in Section 5.3.1b.iii.

The probability that a single fallen rock rolls far enough down the hill to reach the location of the property (Probability of travel, $P_{(T)}$) is based on the RAMMS modelling scenarios, as defined for AIFR. The resulting three zones relate to probabilities of 0.1, 0.05 and 0.01.

Given a single rock gets far enough down the slope to reach a building, the probability that the rock moves through a section of slope potentially occupied by that building, $P_{1(S:H)}$, is taken to be the width of a grid cell (1m), divided by the width of the slope considered in the analysis (780m and 440m for Brewery Creek and Reavers Fans respectively).

$P_{1(S:H)}$ is then adjusted to account for the number of rocks (N) expected to fall in a particular event, giving $P_{(S:H)}$ for each rockfall zone:

Rockfall Zone $P_{(S:H)} = \Sigma$ 3 rockfall scenarios $[(1-(1-P_{1(S:H)}{}^{N}))*P_{(T)}]$

The three rockfall scenarios (small, moderate and large events) were summed to produce $P_{(S:H)}$ for each rockfall zone, on a 1m x 1m grid.

c. Temporal Spatial Probability $P_{(T:S)}$

In line with AGS (2007) the temporal spatial probability of a house or other building being present is 1.0.

d. Vulnerability $V_{(D:T)}$

Loss ratio was used to assess vulnerability of property to rockfall, as detailed in 6.2.1d, GNS Science (2019c) and Appendix K – Property Risk Vulnerability Methodology (GNS). The data was supplied by the GNS RiskScape team based on the outputs of the RAMMS rockfall models, specifically the mean kinetic energy (kJ) of a rockfall strike against a theoretical property on each grid cell on a rockfall trajectory path. The mean kinetic energy value was utilised where more than one rockfall trajectory traverses a cell.

e. Value E

As with debris flow, individual property value has not been incorporated in the APR assessment.

f. APR calculation

The relevant parameters listed above were multiplied to produce APR, on a 1m x 1m grid for all areas affected by rockfall. The three rockfall zones do not overlap. Areas outside of the rockfall risk zones were given zero values.

6.3.2 APR Results Rockfall

The resulting APR values from rockfall range from 10^{-3} to 10^{-6}.

6.4 Combined APR Contours

APR values for debris flow and rockfall risk were overlaid on a 1m grid, to produce combined APR. The resulting values, representing the annual probability of property loss as a result of the hazards occurring, were contoured, as shown in Appendix L – Slope Stability Property Risk Maps. Some manual smoothing of the contours was undertaken with judgement applied where required to ensure reasonable position of contour.

7 Liquefaction Vulnerability Assessment

Liquefaction hazard has been assessed based on the vulnerability of damage to land during a design seismic event (Section 3.2.4).

The CPT assessments provide an indication of sub-soil susceptibility to liquefaction and the resulting amount of vertical ground settlement that may be expected during the design earthquake. This combined with an understanding of the geological model for the site has allowed a refined zonation of the study area for liquefaction susceptibility. The study area has been zoned based on the second level of precision shown in Figure 18. This is considered analogous to a "calibrated desktop assessment" based upon the guidance provided in Figure 19.

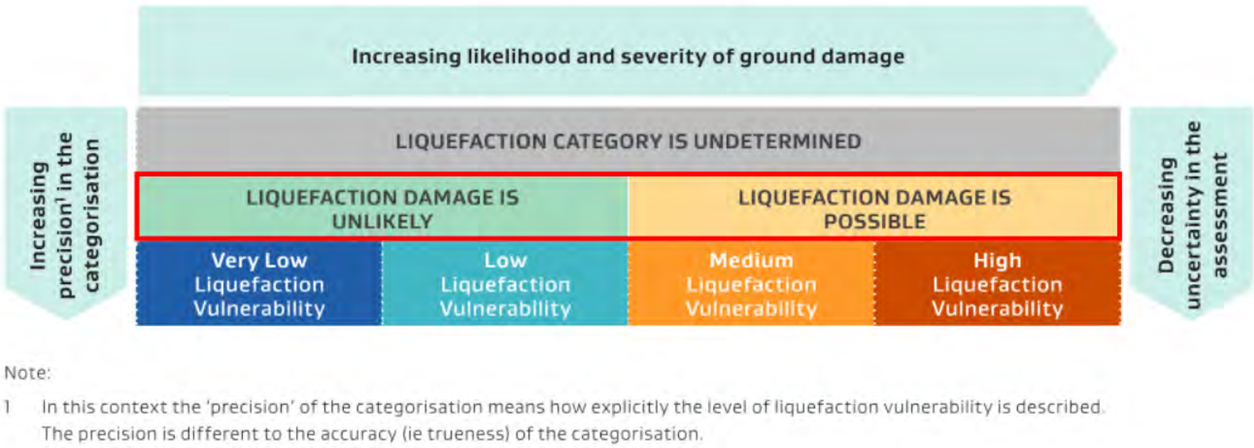


Figure 18 - Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes (MBIE 2017). The "Low" and "Medium" categories have been used for this study.

This zonation is not a substitute for site or development-specific investigations. Rather, is intended to provide enough insight into the spatial distribution of the hazard for assessing an appropriate management response to development proposals.

It is difficult to precisely and accurately identify liquefaction-prone land, so an important part of the risk assessment process is understanding and managing uncertainty. In most circumstances the primary means for reducing uncertainty is to increase the level of detail in the liquefaction assessment study, however there are cost and practical limitations to this.

The primary factors that influence the degree of uncertainty for a liquefaction assessment are:

- The types of information examined in the assessment.
- The amount and spatial density of subsurface investigation data used to 'ground truth' assumptions about soil type, soil strength, subsurface profile and groundwater conditions.
- The degree of variability in the ground conditions.
- How well the seismic behaviour can be predicted for the particular soil types present (e.g. there is particular uncertainty regarding the influence of fines content and interbedded silty soil layers, so for liquefaction analysis in present-day engineering practice it is common to allow for this uncertainty by making conservative assumptions).
- How much is known about how an area has been or will be developed (e.g. the types of land preparation, infrastructure and buildings).

LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT [1,2]	AVERAGE INVESTIGATION DENSITY	AVERAGE SPACING BETWEEN	MINIMUM TOTAL NUMBER OF INVESTIGATIONS
Level A[3] Basic desktop assessment	0.01 to 1 per km^2	1 to 10 km	–
Level B Calibrated desktop assessment	0.5 to 20 per km^2	220 to 1400 m	3 for each geological sub-unit
Level C Detailed area-wide assessment	0.1 to 4 per Ha	50 to 320 m	5 if area > 1 Ha 3 if area 0.25 – 1 Ha 2 if area < 0.25 Ha
Level D[4] Site-specific assessment	2 to 40 per Ha	15 to 70 m	2 within or very close to the building footprint

Notes:

1 Investigation densities listed in this table are cumulative – suitable data from investigations undertaken in previous stages of work should be incorporated in subsequent stages.

2 The key feature defining each level of detail is the degree of residual uncertainty in the assessment (refer Table 3.1), not necessarily the spatial density of ground investigations. In some circumstances a significantly higher or lower investigation density might be appropriate to provide the required degree of certainty for a particular target level of detail or purpose. For example, the lower end of the recommended minimum range might be appropriate where investigations show ground conditions to be reasonably consistent (eg some marine or lake deposits), while the upper end of the range may be more appropriate if ground conditions prove to be highly variable (eg many river deposits).

3 There are no minimum investigation density requirements for a ***Level A*** liquefaction assessment. However, the geological maps that are normally used for a ***Level A*** assessment have often been 'ground-truthed' at approximately the density shown. New ground investigations are unlikely to be required, provided that existing information such as geology, geomorphology and groundwater maps is suitable (relative to the scale and purpose of the assessment), and categories are assigned with appropriate consideration of the uncertainties.

4 For a ***Level D*** assessment, the key requirement is to confidently characterise the ground conditions at the specific location of the proposed building. Therefore the particular arrangement and proximity of investigations within and surrounding the building footprint will often be of greater importance than the minimum investigation density criteria.

Figure 19 - Indicative spatial density of deep ground investigation for adequate ground characterisation for liquefaction assessments to inform planning and consenting processes MBIE (2017).

The current liquefaction zoning used by QLDC (Tonkin and Taylor, 2012) is based on an earlier version of the MBIE guidance for liquefaction hazard assessment. The Beca categories for “Low” and “Medium” vulnerability may be considered generally equivalent to QLDC LIC 1 and LIC 2 categories respectively.

The liquefaction vulnerability plan is included in Appendix M – Liquefaction Vulnerability.

7.1 Climate Change Impacts on Liquefaction Vulnerability

Specific assessment of climate change effects on liquefaction vulnerability has not been conducted as part of this study. In coastal areas, sea level rise (i.e. rising groundwater levels) has the potential to affect liquefaction vulnerability. While climate change may have a small effect on groundwater levels in the study area, this would not be significant in relation to the resolution of the study.

8 Flooding

8.1 Background

An assessment of flood hazard to property has been undertaken for the study area. Beca has updated the 2009 GHD flood model to include the ability to consider surface flow (2D). The model now includes the stormwater pipe network, stream channels and land surface but with buildings removed. Flood maps produced for this report only show water depths greater than 0.05m. This depth cut off represent uncertainties and resolution of flood models.

The hydrology for both Brewery and Reavers Creek catchments has been developed in the HEC-HMS hydrologic modelling package. Flood flow hydrographs have been inserted into the model at the exit from the bush for Brewery Creek and at Reavers Creek intake.

Flood maps generated for this project are included in Appendix N – Flood Maps. These maps are outputs from a model that has not been peer reviewed and are not intended to be used as a basis for setting site-specific mitigation measures..

8.2 Model Results

8.2.1 Brewery Creek

The flooding from Brewery Creek is shown in drawing 3209881-L001, Appendix N – Flood Maps. The engineered channel downstream of the fan apex (Figure 8) has the capacity to convey the 100-year flow from the Brewery Creek catchment. No overflow occurs from Brewery Creek channel until it reaches the wetlands north of the Creek.

Minor flooding is indicated from a small catchment south of Brewery Creek which is not conveyed by the pipe network. This flow travels south towards Sawmill Road/Fryer Street and on towards the Ngai Tahu development site (former Wakatipu High School).

8.2.2 Reavers Creek

Drawing 3209881-L002 (Appendix N – Flood Maps) shows the expected flooding associated with the 100-year event from Reavers Creek catchment. The intake structure is shown to be unable to contain the flood water resulting in overflow across the fan surface at depths of 100mm-200mm, even without considering entrained debris. The flood water is not confined to the roading network and finds its way across private property. The stepped appearance in flood depth occurs where houses have been removed from the LiDAR surface to represent the building platform/excavation. The removal of houses from LiDAR is an automated process and may not reflect the true ground level under houses.

Flooding in the lower part of the study area is caused by Horn (Brewery) Creek. The Robins Road bridge cannot convey the full 100-year flow causing an increase in water level upstream of this point and flooding into the Creeksyde Holiday Park.

The modelling does not allow for debris flows which have the ability to change the course of the flood water depending on the size of debris moved by the flood waters.

8.3 Flood Hazard Assessment

The QLDC flood hazard mapping guidance (contained within the hydraulic modelling specification) has been based on the New South Wales Floodplain Development Manual (NSW, 2005). Figure 20 shows the hazard classification used in mapping of flood hazard based on water depth and velocity. Significant hazard occurs at depths over 0.3m or velocities over 2m/s, Minor hazard is identified as depth between 0.1m and 0.3m and velocities up to 2m/s. Potential hazard is any velocity and depths of between 0.05 and 0.1m.

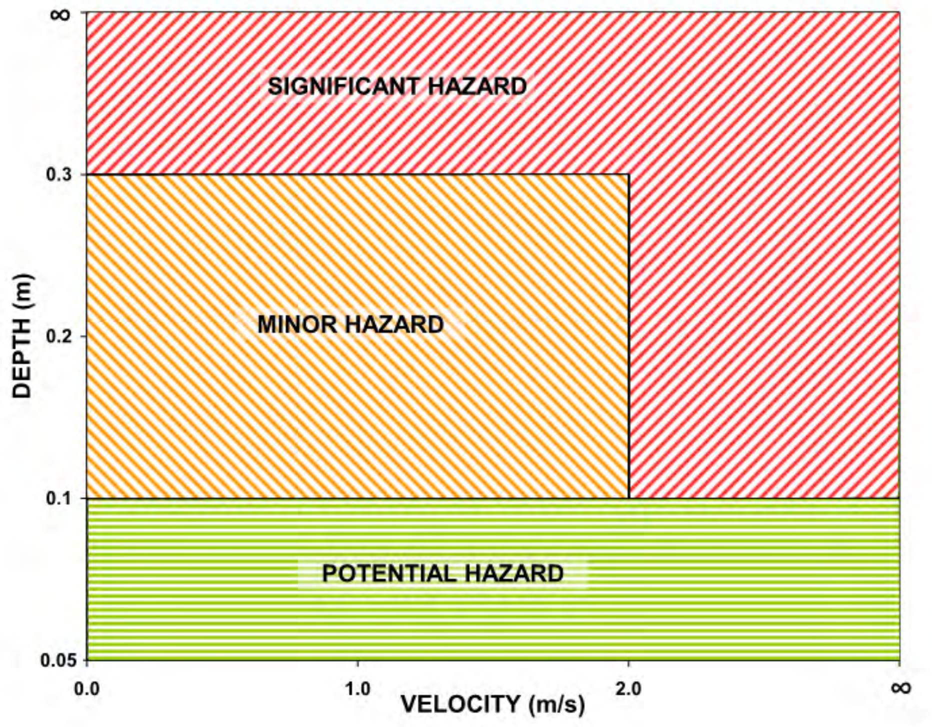


Figure 20 - Flood Hazard Classification

The minor and significant hazard can be defined as:

Significant hazard; Possible danger to personal safety; evacuation by truck difficult; able bodies adults would have difficulty in wading to safety; potential for significant damage to properties.

Minor hazard; should it be necessary, truck could evacuate people and their possessions; able bodied adults would have little difficulty in wading to safety.

Potential hazard is confined to depths of less than 100mm and any velocity. This may cause a hazard to less able-bodied people within the community.

The hazard maps produced represent hazard based on the model results only. There are a series of factors that determine a true flood risk. Factors such as:

- Size of the flood
- Effective warning time
- Flood readiness
- Rate of rise of flood waters
- Duration of flooding
- Evacuation problems
- Effective flood access
- Type of development

Hazard identification for the Brewery Creek catchment (drawing 3209881-L003 in Appendix N – Flood Maps) shows a similar case as the flood depth data. No flood waters exit the main channel downstream of the bush. As expected, high hazard occurs within the channel. Some Potential and Minor flood hazard exists on the Brewery Creek Fan from a small unnamed stream which originates near Kiely Lane and traverses south down the fan towards Fryer Street.

The Flood Hazard map (drawing 3209881-004 in Appendix N – Flood Maps) of Reavers Creek shows that flood water originating from Reavers Creek poses a potential to minor hazard. High hazard areas toward the east and south of the assessment area tend to be in areas where water depth is over 0.3m rather than a very high velocity (over 2m/s). The significant hazard area on the eastern boundary of the assessment area is due to flooding from Horn Creek. The Robins Road bridge is restricting flow causing an increase in upstream water level which encroaches on low lying land upstream of the bridge. Given this is a 100-year ARI event it is expected that bridges and culverts will cause a restriction.

8.4 Factors Affecting Flood Flows

A discussion on factors affecting flood flows is included in Appendix O – Flooding Technical Background, with details of the modelling conducted included below.

Sensitivity

Flow hydrographs were produced from the HEC-HMS model for sixty scenarios; two catchments, each with two land uses, for five storm events, for three climate change horizons (2*2*5*3=60). Table M 3 and Table M 4 in Appendix O – Flooding Technical Background show the peak flow and percentage runoff for each modelled scenario.

The results indicate that:

- Removing forestry from the catchments would increase peak flows by 25%-30% in the Reavers catchment and 7%-10% in the Brewery catchment. That is an increase of nine % runoff points for Reavers and three % runoff points for Brewery.
- Peak flows in 2040 will be about 10% higher than current peak flows.
- By 2090, peak flows will be 30%-35% higher than currently, with a 16% increase in flood volume.

The figures listed above align with investigations documented in *Climate Change implications for the Queenstown Lakes District (Bodeker Scientific, 2019).* Overall the annual rainfall depth is not likely to change much over the district although Climate Change is predicted to increase the intensity of rainfall events and therefore producing higher peak flows. They also suggest an increase in river flow variability due to the lifting of snowline (higher altitude). This will only have a minor effect on peak flows in these catchments as it has limited snowpack through winter.

Both Climate Change and removal or changes in the forested upper catchments will increase flood flows and therefore flood risk. This can be limited to some degree by maintaining current land cover (trees and tussock) in the upper reaches. As part of a separate study, QLDC is currently quantifying the effects of climate change and associated flooding implications on the stormwater network.

9 Risk Management

Risk to life and property from slope stability hazards in the Gorge Road study areas have been assessed in this study. Public tolerability of these risks is discussed in this section, along with planning and physical risk management options.

9.1 Slope Stability AIFR

9.1.1 AIFR Results

Combined slope stability AIFR results are summarised in Table 16. Comments on life risk tolerability are provided below.

Table 16 - Combined Slope Stability AIFR Ranges for the Gorge Road study area

Location	Minimum AIFR*	Maximum AIFR
Brewery Creek Fan Residential Zone	2.2×10^{-5}	3.8×10^{-3}
Brewery Creek Fan Business Zone	9.4×10^{-6}	4.3×10^{-4}
Reavers Creek Fan	1.9×10^{-5}	1.8×10^{-3}

*Minimum AIFR of properties affected by slope stability hazards. Properties exist on both fans outside of the identified risk zones. Risk zone locations are shown in Appendix J – Slope Stability Life Risk Maps.

9.1.2 AIFR Tolerability

There are currently no national guidelines for determining tolerable limits to life risk in New Zealand. Life risk tolerability guidelines for slope stability are provided for Australia by AGS (2007), with a maximum recommended AIFR of 1×10^{-4} (1 in 10,000) for existing slopes/developments, and 1×10^{-5} (1 in 100,000) for new slopes/developments.

- Existing slopes / developments in accordance with AGS are those slopes and structures which are not part of a recognisable landslide, and have demonstrated non-failure performance over a period of 10-20 years.
  - This definition would generally apply to existing properties on Brewery Creek and Reavers Fans, and as such the maximum tolerable risk of 1×10^{-4} would apply.
- New slopes / developments in accordance with AGS include any new structures or changes to existing slopes or structures. The exceptions to this are:
  - Where changes to an existing slope results in a vertical cut of less than 1m, it may be considered an existing slope.
  - Where changes to an existing structure do not increase the building footprint or result in an overall change in footing loads, it may be considered an existing development.
  - Aside from the above exceptions, the tolerable risk for any new structures or slopes on Brewery Creek and Reavers Fans would therefore be 1×10^{-5}.

The value of 1×10^{-4} saw widespread application on Christchurch's Port Hills following the 2010-11 Canterbury Earthquake Sequence and is widely considered to be the boundary of tolerable risk, i.e. 1.1×10^{-4} would not be considered tolerable. A further example of AIFR tolerability precedent in New Zealand is the Awatarariki Fanhead at Matata, where Whakatāne District Council applied 1×10^{-5} as the limit of tolerability for all developments, requiring retreat of the developed fan (Campbell et al, 2020). This is more conservative than the AGS and Port Hills approaches.

A comparison of common risks and tolerability limits with combined debris flow and rockfall AIFR for Brewery Creek and Reavers Fans is shown in Figure 21.

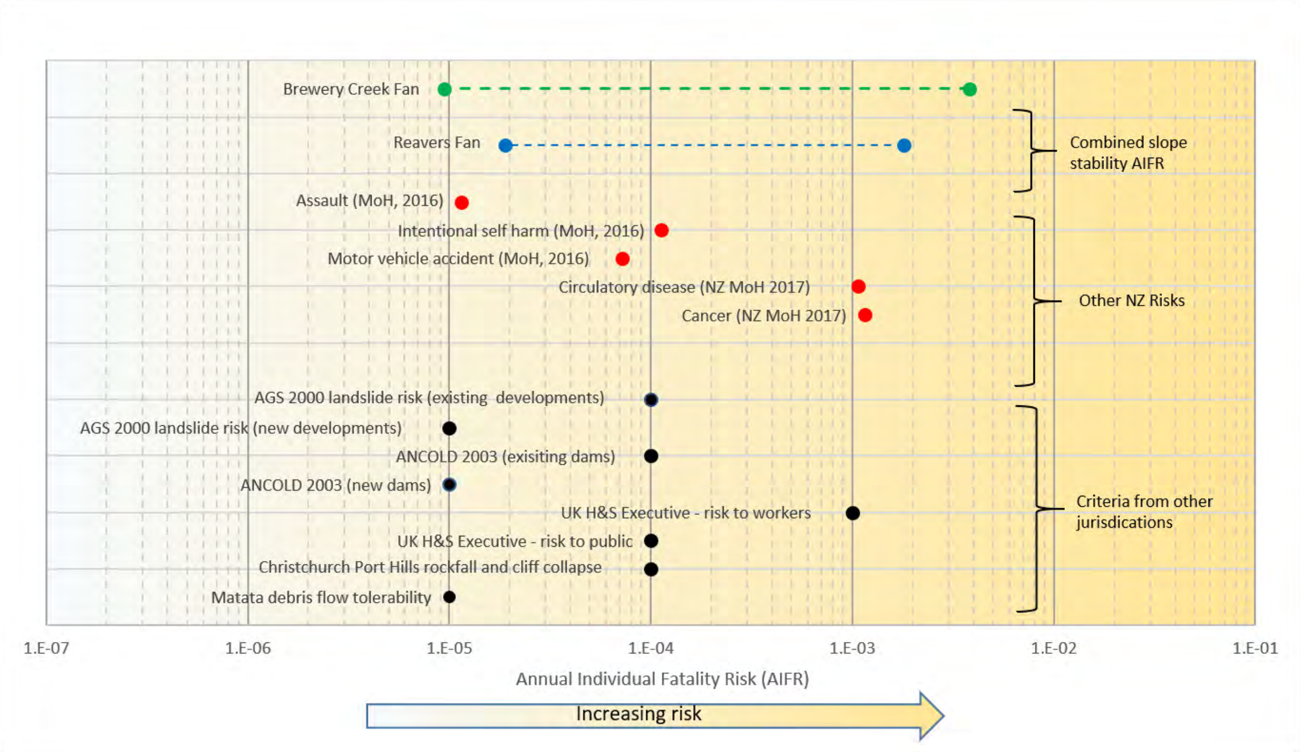


Figure 21 - Summary of common risks and risk tolerability limits

AIFR values determined through this study exceed published guidance on risk tolerability for both new and existing developments on some areas of both fans. The number of properties exceeding these tolerability guidelines in accordance with AGS (2007) are shown in Table 17. The spatial extents of the areas exceeding AGS tolerability guidelines are shown as drawings 3209881-J016 to 3209881-J018 in Appendix J – Slope Stability Life Risk Maps.

Table 17 - Number of properties with AIFR exceeding tolerable guidelines recommended by AGS (2007)

AIFR	Tolerability (AGS, 2007)	Brewery Creek Fan Residential	Brewery Creek Fan Business	Reavers Fan
> 1×10^{-4}	Not tolerable for new or existing slopes/developments	5	12	25
> 1×10^{-5}	Not tolerable for new slopes/ developments	10*	14*	41*

*Includes properties >1×10^{-4}.

Note 1 – Count includes properties where relevant contour line crosses any part of the property.

Note 2 – Count based on Property Number from QLDC GIS Maps, not Legal Description.

QLDC is investigating future consultation options to assess public tolerability of the risks detailed in this report.

9.2 Slope Stability APR

9.2.1 APR Results

Combined slope stability APR results are summarised in Table 18. Comments on property risk tolerability are provided below.

Table 18 - Combined Slope Stability APR Ranges for the Gorge Road study area

Location	Minimum APR*	Maximum APR
Brewery Creek Fan	8.3×10^{-6}	9.6×10^{-3}
Reavers Creek Fan	3.9×10^{-6}	2.5×10^{-3}

*Minimum APR of the properties affected by slope stability hazards. Properties exist on both fans outside of the identified risk zones. Risk contours are shown in Appendix L – Slope Stability Property Risk Maps.

9.2.2 APR Tolerability

No recommendations are made regarding quantitative APR tolerability by AGS (2007), which states '*the regulator is the appropriate authority to set standards for tolerable risk*'.

AGS (2007) does however provide guidance on qualitative property risk implications and associated recommendations for the level of work required to reduce risk to an acceptable level. These recommendations have been considered, however adapting them to apply to quantitative property risk would be extending them beyond their original intent and would not be appropriate.

Quantitative property risk assessment has not been adopted as broadly as quantitative life risk assessment in New Zealand to date. As a result, there are no known examples of precedent in assessing public tolerability to property risk. This may be the result of a lower community tolerance of life risk than property risk, meaning that if life risk tolerability is assessed and actions taken, property risk is also addressed.

It should be noted that APR values are not directly comparable to AIFR, and different tolerability levels will likely apply (i.e. people have a different level of tolerance to loss of life compared to loss of buildings).

A way forward may be to consider AIFR tolerability boundaries initially to define planning zones and using APR to inform stakeholders of the corresponding property risk.

9.3 Planning Hazard Management Options

This report has identified that the risk to life exceeds published guidance on tolerability for both existing and new developments for some properties on Brewery Creek and Reavers Fans. QLDC are considering planning controls as part of the District Plan review.

9.4 Physical Risk Management

Along with planning controls, engineering options to manage the risk to life from debris flow and rockfall on Brewery Creek and Reavers Fans are also being considered by QLDC.

9.4.1 Slope Stability Risk Management

A Beca study assessing the potential for reducing life risk from slope stability hazards through physical hazard management options has been commissioned by QLDC and is currently in progress. The study considers the effectiveness of physical management options (or a combination of options) in reducing the combined risk from debris flow and rockfall. The study is due for completion in late 2020.

9.4.2 Liquefaction Risk Management

Physical options for the management of liquefaction hazard include use of ground improvement techniques and/or foundations specifically designed to resist liquefaction. The latter is usually more cost effective for smaller properties. A map showing where liquefaction is likely and unlikely in the assessment areas has been provided and recommendations made for issuing building consents in line with MBIE Guidance.

Management is best achieved by requiring a specific assessment and mitigation of liquefaction risk for future development in the potentially susceptible areas. In some instances, site specific investigations may indicate further mitigation is not required.

The heterogeneity of alluvial sediments introduces significant uncertainty in the location of, and the boundaries between the different categories of liquefaction vulnerability. Whilst additional investigation may allow some refinement of the hazard zonation, it is unlikely to significantly change the management response.

9.4.3 Flooding Risk Management

Within the scope of this study, flooding risk management options are being considered only as part of the debris flow physical works.

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11 Applicability Statement

This report has been prepared by Beca on the specific instructions of our Client. It is solely for our Client's use for the purpose for which it is intended in accordance with the agreed scope of work. Any use or reliance by any person contrary to the above, to which Beca has not given its prior written consent, is at that person's own risk.

Should you be in any doubt as to the applicability of this report and/or its recommendations for the proposed development as described herein, and/or encounter materials on site that differ from those described herein, it is essential that you discuss these issues with the authors before proceeding with any work based on this document.

A

Appendix A – Glossary

Acceptable risk – A level of risk that people are prepared to live with knowing that no measures will be taken to reduce it (GNS, 2015).

Alluvial fan – An accumulation of alluvial (river or stream) sediments that form sloping landforms. Alluvial fans typically develop where a steep gully emerges onto a valley floor. Significant hazards associated with alluvial fans include debris flows. For the purposes of this report, an alluvial fan is a generic term for fans comprising debris flow, debris flood and flood deposits.

Alluvion – Deposition of sediment by a stream or river, resulting in the formation of new land.

Annual Exceedance Probability (AEP) – The probability of a defined size event occurring in a single year. A 1% AEP has a 1 in 100 chance of occurring in any one year.

Average Recurrence Interval (ARI) – The average or expected time period between exceedances of a given rainfall total over a given duration.

Avulsion – Breaking out of existing stream channels and the forging of new channels.

Consequence – the results of a hazard impacting an element at risk.

Debris Flood – very rapid surging flow of water and debris, in which most of the sediment is transported as bedload. Debris floods have peak discharges twice that of floods.

Debris Flow – A form of mass movement in which a combination of loose soil, rock, organic matter, air and water mobilise as a slurry that flows rapidly downslope. They are typically confined to a steep channel and running out onto low-gradient fans and valley floors, often resulting from intense surface water flow as a result of high-intensity rainfall. The likelihood of debris flows increases with other factors such as deforestation, fires and seismic events. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of alluvial fans at the mouths of gullies. Debris flows have peak discharges 5 to 40 times greater than floods.

Element at risk – An element (person or property) that may be affected by a hazard.

Geohazard – Events caused by geological features and processes that have the potential to cause harm.

Geomorphology – The study of the origin and evolution of physical features of the Earth's surface.

Hazard – A process or event which has the potential to cause harm.

LiDAR – Light Detection and Ranging – a remote sensing method that uses light in the form of pulsed laser to measure distances to the Earth.

Likelihood – the chance that an event might happen. Likelihood can be defined objectively or subjectively and can be expressed either qualitatively or quantitatively.

Liquefaction – a process by which the strength and stiffness of saturated, unconsolidated soils (typically silt or fine sands) are reduced by earthquake shaking or other rapid loading.

Mitigation – An activity undertaken to reduce hazard and/or consequence.

Qualitative Risk Analysis – Evaluation of risk in qualitative terms using a pre-defined rating scale. This method is typically used for uncertain events that could have many potential outcomes.

Quantitative Risk Analysis – Evaluation of risk in quantitative terms for a specific set of circumstances.

Quaternary – The current geologic period, encompassing period from 2.6 million years ago to the present day.

Residual Risk – The level of risk remaining after inherent risks have been reduced by risk controls.

Risk – The effect of uncertainty on objectives (as defined in AS ISO 31000:2018). It is estimated by considering and combining consequences and likelihoods.

Rockfall – The fall of individual blocks or a small number of blocks from localised areas on steep slopes resulting in individual blocks rolling falling or bouncing down the slope.

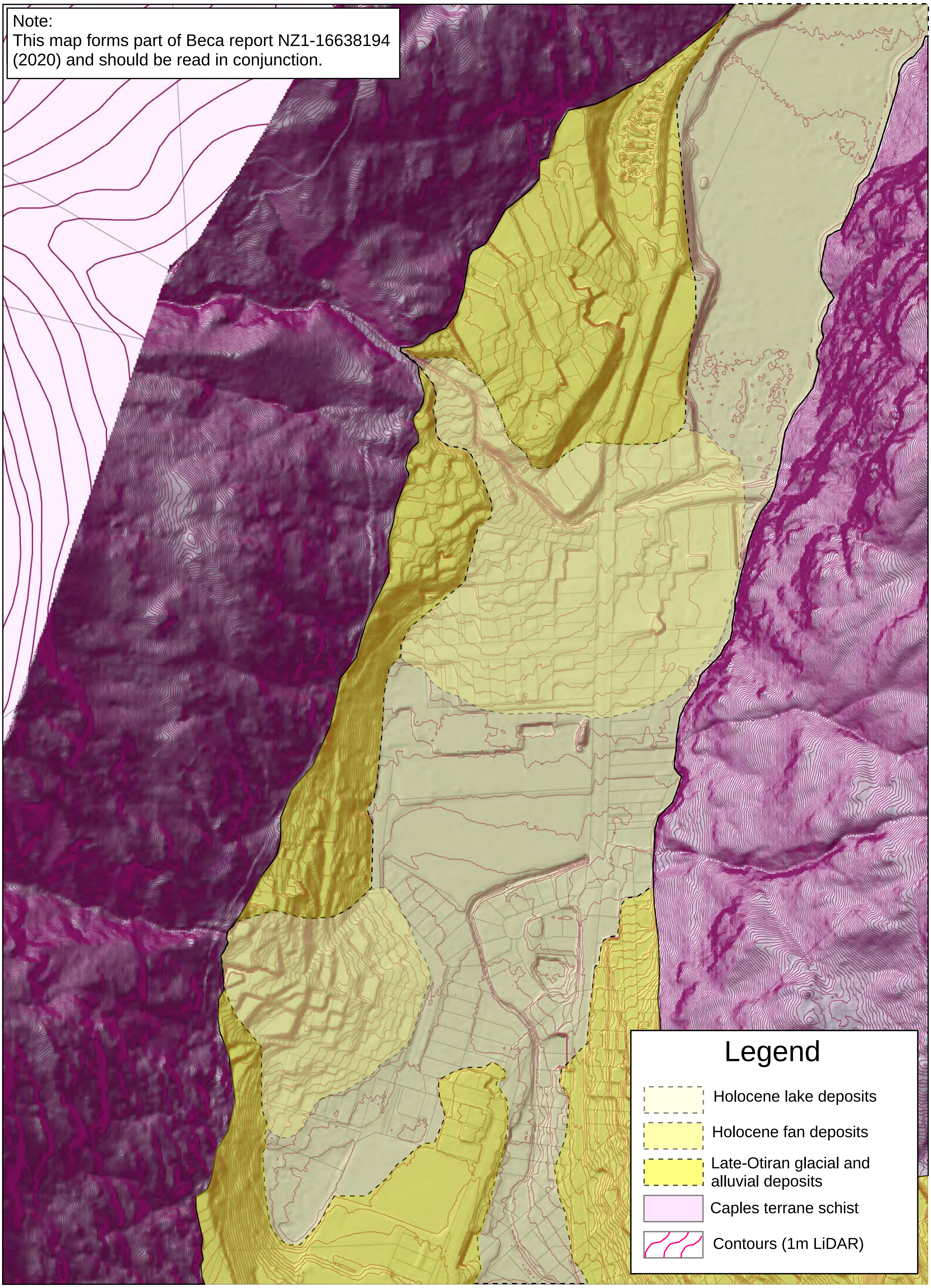
Rockfall Barrier – A man made structure designed to intercept and retain rockfall (typically a net fence system or similar).

Significant Risk – As referenced in the RPS (2018), is considered to be analogous to High Risk as defined in AGS (2007).

Tolerable Risk – A level of risk deemed acceptable by society, with the expectation that measures will be taken to reduce it.

B

Appendix B – Geological Map



Map Scale @ A3: 1:4,000

0 50 100
Metres

Revision	Author	Verified	Approved	Date
2	SB/ME	ARP	PJH	04/08/2020
1	ME	BDJ	ARP	08/11/2018

Title:

Geological Map

Client: Queenstown Lakes District Council

Project: **Natural Hazards Affecting Gorge Road**

N

Discipline: GIS

Drawing No: **3209881-B001**

C

Appendix C – Geomorphology Background

Geomorphology Background

Background

Episodic glaciation during the late Quaternary has formed much of the present-day surfaces in the Wakatipu region, including those found in Gorge Road. The two most recent glacial advances of the Ōtiran glacial period (10,000 to 11,000 years before present) have been well preserved.

Approximately 28,000 years ago, the ice surface of the Wakatipu Glacier was significantly higher than the present-day lake level (Ehlers, et al. 2011) and extended east to the township of Arrowtown (indicated in Figure C 2). Queenstown Hill featured as a nunatak (glacial island) (see Figure C 2). The next ice advance, referred to as the “Last Glacial Maximum” (LGM), approximately 18,000 years ago, saw the top of ice approximately 100m above present lake level. The LGM is likely responsible for the deposition of the glacial till on the south west flank of Queenstown hill (Turnbull, 1988). Till is also likely to be present on lower slopes adjacent to the assessment areas.

Following the LGM, Lake Wakatipu’s level was thought to be approximately 50m higher (RL 356m) than the present day. The lake’s outflow was at Kingston, not the present-day Kawarau River (see Figure C 2; Henderson 1937, Healy and Willett 1938). At this time Lake Wakatipu extended through the assessment area. Two prominent alluvial fan complexes (Reavers and Brewery Creek) formed on the lake margin, interfingering with soft silty lacustrine materials in the valley floor.

An estimated 7,000 years ago when the present-day Kawarau outlet formed, Lake Wakatipu water level dropped in a staged manner, with numerous beaches forming on the lake’s outer margins (see Figure C 2). Continued lake level lowering resulted in complete abandonment of the Gorge Road valley with the fan/delta complexes now standing above water level (Thomson, 2012). The present-day Brewery Creek incised through relict beach and fan/delta sediments in response to lowering lake levels.

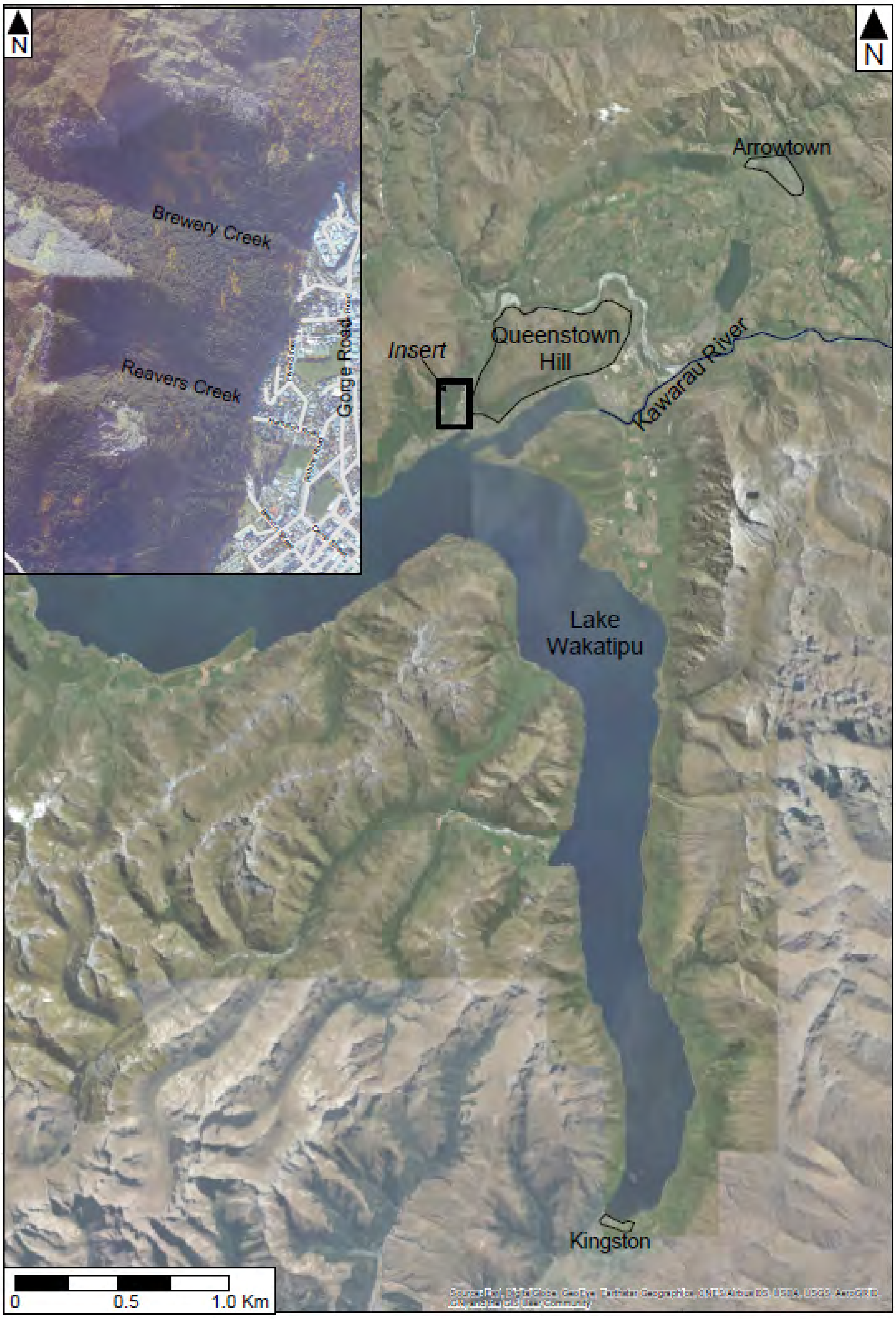


Figure C 1: Annotated aerial photograph outlining the distribution of townships and geomorphic features of relevance to the geomorphic history of the wider Queenstown region.

Aerial Imagery

Brewery Creek

The Brewery Creek catchment is approximately 3.0km^2 with the top of the catchment extending to Bowen Peak (1631m above sea level), as shown in Figure C 2. The catchment flows south for 1.5km before deviating east and flowing towards Gorge Road. The stream emerges from the foothills and has formed a low angled alluvial fan. The topographic apex of the fan is at approximately 370m elevation.

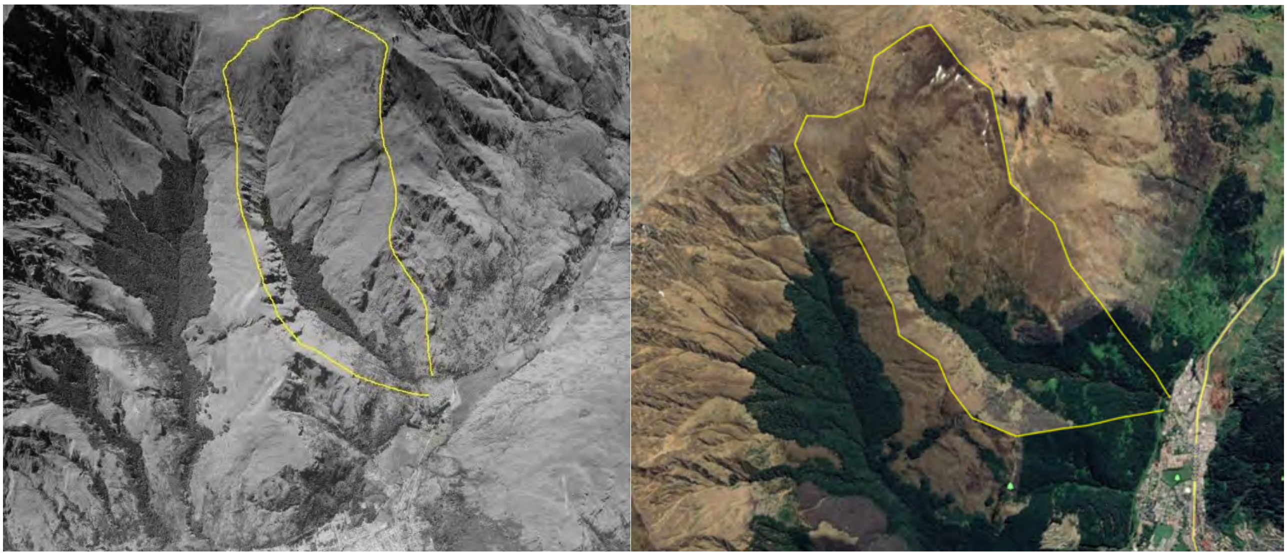


Figure C 2 - Annotated aerial photograph (1954) and Google Earth (2019) image showing the approximate Brewery Creek catchment.

There is evidence of a number of landslides and rockfalls in the Brewery Creek catchment (shown in Figure E001 in Appendix E – Mapping). High terrain in the catchment, particularly on eastern slopes displays characteristic signs of foliation-controlled landsliding which may be undergoing intermittent creep.

On the lower eastward-flowing section of Brewery Creek further evidence of slope instability can be observed. A scarp on the north-eastern margin has been identified as a rockfall source area (ORC, 2011) and is a potential source of debris flows in the Brewery Creek assessment area. Over-steepened streambanks throughout the catchment also provide potential debris sources. Additionally, tree trunks and other vegetation may form small dams which can fail and cause pulses of debris during significant rain events.

The southern margin of the lower reach of Brewery Creek is also the margin of another significant landslide. The scarp for this landslide can be observed clearly in LiDAR.

The present-day fan surface has been extensively modified with the main flow now channelised for the entire length of the fan (see Section 3.1.5).

Reavers Fan

The Reavers catchment basin is approximately 0.48km^2, with the top of the catchment at an elevation of approximately 1050m. The catchment drains to the southeast with an average slope angle of approximately 32° from top of catchment to the topographic apex of the fan.

Surface exposure in the upper catchment appears to be highly fractured rock with significant contributions of both coarse and fine sediments. Various scattered bluff outcrops are a potential source for the large boulders.

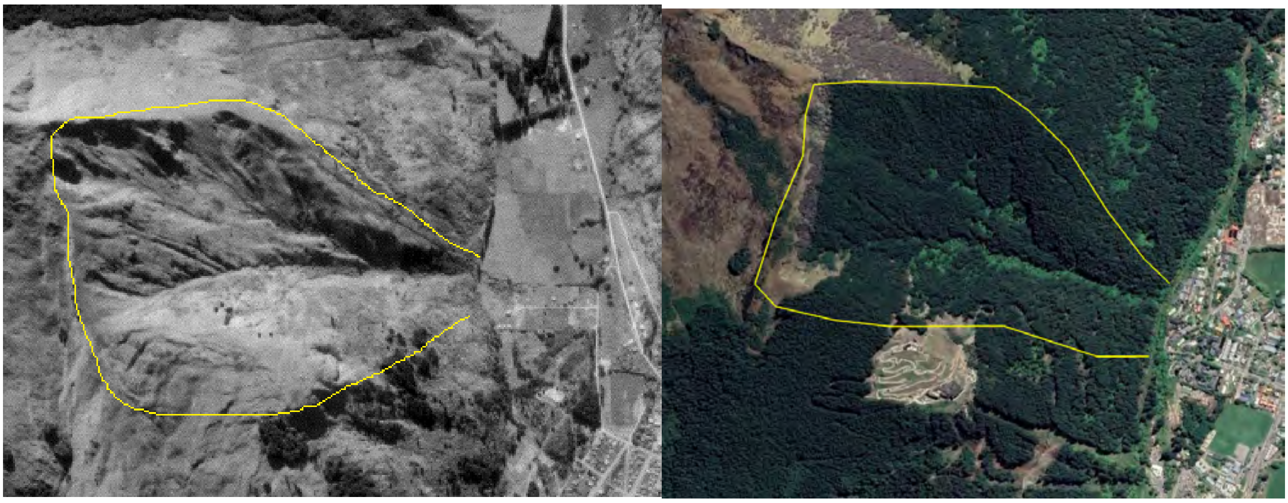


Figure C 3 - Approximate perimeter of the Reavers Catchment, from historical aerial photo (1954, left) and Google Earth images (2019, right). Note vegetation changes over this time

Younger trees and scrub are present close to the catchment drainage lines indicating that scour erosion has continued to occur into recent times, although no evidence of debris flows reaching the apex of the fan within the period covered by historical aerial photographs (1954 to present) has been found. Air photograph interpretation indicates erosion in the upper catchment continues to provide a potential sediment supply (Figure E001 in Appendix E – Mapping).

Evidence of the inter-figuring of alluvial fan and lacustrine beach depositional environments co-existing can be seen in a recent (October 2018) excavation in the Reavers Fan for a building foundation at 62 Fryer Street. In this exposure (Figure C 4), alluvial fan deposits have draped over beach ridge sediments (well sorted pebbles, flat disc shape). Faint soil horizons within the alluvial fan sediments indicate episodic deposition. The lower margins of this fan inter-finger with soft silty lake bed sediments.

Figure C 4 - Exposure of interfingering sediments within the Reavers Fan at 62 Fryer Street (October 2018).

D

Appendix D – Resource Consent Summary

Resource Consent #	Hazard identified	Geotechnical report recommendations	RC recommendations and considerations	Details summarised by QLDC (Resource consent or report comments shown in italics).
RM50350 8 Industrial Place, Queenstown	Instability	No significant hazard associated with development of the site	Approved. Construction method measures to be implemented.	Remove existing building and erect two story building with showroom and storage areas *A Geotechnical report has been prepared by Jeff Bryant Geoconsulting Ltd and has made comment on the subsurface conditions in relation to the proposed development. Schist bedrock is expected to be at least 10m below ground level at this locality. The report includes recommendations for the construction method as this will have some bearing on how the lower ground floor platform is excavated. The applicant has stated that there is very minimal likely hood hard rock will be struck.* *There have been geotechnical assessments carried out by Jeff Bryant Geoconsulting Ltd in order to assess the subsurface conditions of the subject site. The report has identified that there is no significant hazard (in terms of stability) associated with development of the site.* *Schist bedrock is expected to be at least 10m below ground level at this locality. The report includes recommendations for the construction method as this will have some bearing on how the lower ground floor platform is excavated. The applicant has stated that there is very minimal likely hood hard rock will be struck.* *A CivicCorp engineer has also assessed the application and agrees with the comments made in the geotechnical report. Conditions of consent are to be included so that the measures are implemented as per the report.*
RM071053 Bobs Peak	Slope instability, rockfall	Care to be taken when clearing vegetation and trees	Accepted.	Vary resource consent RM071053 pertaining to the introduction of an alternative 6th zip line and to erect tree structures which sit above the maximum height limit for buildings. Note the following comment re hazards in the doc titled '*RM071053_APPROVAL'* *The Tonkin and Taylor geotechnical report submitted with the application concludes that the works involved with this proposal will result in geotechnical risks that can be appropriately managed during construction, on a case by case basis. This assessment is accepted and due to the unique nature of the works and platforms to be created it is considered that on site assessments at the time of construction are appropriate. Overall no adverse effects in terms of land stability and natural hazards are anticipated with this proposal.* The geotech report – doc titled '*RM071053-02 RM071053_APPLICATION_2'*
RM081183 21 Bowen St, Queenstown	Flooding, slope instability		Approved – then withdrawn. Appropriate mitigation measures to be taken (details not available).	To construct VA/res units Resource consent was granted to redevelop this site in January 2005 for 120 residential apartments. The resource consent reference is RM040887 - RM040887 was subsequently varied earlier in 2008 (reference RM071146). Note – Appendix D of the doc titled '*RM081183_APPLICATION*' contains the consent decisions of RM040887 and RM071146 as noted above (existing consents for this site) – page 10 of Appendix D outlines the planner's comments on land stability – states that a geotechnical report has been prepared by Tonkin and Taylor Limited (ref 890691 dated September 2004). There is also a comment on flooding at page 11 of Appendix D in regard to flooding - *David Hamilton and Associates Limited have designed the works within Bush Creek. The works include excavation of the creek bed and banks to design lines and levels to enable the placing of rock riprap to the design sizing, grading and levels defined. This consent should not commence until the applicant has obtained the consent of the Otago Regional Council for the works to upgrade Bush Creek. The works will be completed prior to occupation of any building.* *p. 57 (issued decision of RM071146) of the PDF doc '*RM081183_APPLICATION*' Hazards:* *The subject site is susceptible to flooding and instability due to both the proximity of Bowen Creek and the sites steep topography. As a result, the original application was supported by engineering and geotechnical assessments to determine the suitability of the site for development. Both reports concluded that subject to appropriate mitigation measures the site could accommodate a development of the nature proposed. A number of recommendations were made, however, to ensure any potential adverse effects would be mitigated. This included, but was not restricted to, recommendations in the Tonkin and Taylor reports dated September 2004 and the Duffill Watts and King Ltd report dated 18 January 2005. The proposed redesign will not compromise the ability of the development to meet these recommendations. Any adverse effects as a result of the development and proposed variation will continue to be mitigated by way of compliance with the approved conditions of consent.* ORC consents (to disturb/alter the bed of Bush Creek) for the work associated with RM071146 are included at Appendix E of the doc titled '*RM081183_APPLICATION*' Plans for the proposed development are located in the doc titled '*RM081183_APPLICATION_2'*.

Resource Consent #	Hazard identified	Geotechnical report recommendations	RC recommendations and considerations	Details summarised by QLDC (Resource consent or report comments shown in italics).
				Engineering reports form Appendix 1 in the doc titled '*RM081183_APPLICATION_2*' including the Duffill Watts and King Ltd Tonkin and Taylor reports referred to above.
RM110192 Lot 1 DP 20748 47 Industrial Place, Queenstown	Slope instability (local)	Alluvial fan deposit. Retaining wall required to retain boundary slope.	Approved – with conditions.	To carry out remedial works on an existing commercial/industrial building which was damaged by landscape collapse *Overloading of the elevated ground on the neighbouring property to the West of the subject site caused partial collapse of the North and West walls of the building; this resulted in demolition of approximately 17.5m of the North wall and 20.75m of the West wall, starting from the West corner.* *The applicant has provided a report from an Engineer in relation to the stability of the slope adjoining the property along the western boundary.* *The Engineers report states that the slope is made up of alluvial fan material with a soil angle of friction of 35° which is the maximum slope batter angle the material will maintain over the long term. The current batter angle of the slope shown in figure 2 is 70°. This means the material cannot maintain that steep batter slope in the long term and it has therefore been concluded that a retaining wall is required along the western boundary to retain the slope should it settle towards the proposed new building.* *The wall adjoining the property to the west will be designed and built as a retaining wall to ensure any load from the adjoining elevated property is appropriately retained. The applicant has volunteered a condition of consent ensuring that a Chartered Professional Engineer will design a retaining structure with suitable subsoil drainage to minimise hydraulic surcharges and that final design will be in accordance with the New Zealand Building Code. This will appropriately mitigate potential adverse effects in terms of stability.* Note – A Report by Tonkin and Taylor is included at p 12 of the doc titled '*RM110192_PROCESSING*'
RM110097 61 – 65 Gorge Rd, Queenstown	Horne Creek bank stability			Earthworks to install an underground LGP tanks and construct 3 buildings. The Horne Creek culvert runs underground through the property. Note – The hazard comments by Council's engineer in the doc titled '*Engineering Report RM110097*'. Note – The report from Hadley Consultants Ltd dated December 2008 indicating remedial works relating to bank stability – titled '*61-65 Gorge Road – Hadleys'.*
RM110546 45 – 47 Industrial Place, Queenstown	Slope instability (local)	Retaining wall required.		To operate retail and change the external appearance of the existing building. Note – this application appears to relate to RM110192 – see comments below. *The building under construction is to replace a building that was damaged by a landslip caused by overloading on elevated ground on the neighbouring property. The new building was approved under RM110192.* *The building currently under construction that will be used for the proposed activity is to replace a building that was damaged by unstable land on the adjoining property. RM110192, which approved the construction of the new building, has addressed the issue of land stability. The south western wall, which adjoins the boundary, will be constructed as an engineer-designed retaining wall that will retain the slope behind it should it settle towards the building.*
RM120592 6 Huff Street, Queenstown	Debris flow/alluvial fan, liquefaction	Liquefaction risk considered very low; debris flow risk very low and will be managed within the existing road network.	Granted. No consent conditions related to hazards required.	Erect a multi-unit building containing eight residential units *p. 9 of the doc titled 'RM120592 Decision'* *The site is identified on Council's hazard register as being within an area of alluvial fan and liquefaction risk. The applicant has provided an assessment report from an engineering consultant firm who have undertaken an analysis and concluded that liquefaction risk can be considered very low and that mitigation measures will be sufficient for any risk from alluvial debris flow to also be very low. Lakes Environmental's engineer has reported that this is accepted and no potential adverse effects on the environment which are more than minor are likely.* Note – Council's engineer report – doc titled '*RM120592 Engineering Report'* Hadley Consultants Ltd report – doc titled '*Engineer Statement'* – comments on liquefaction hazard and alluvial fan hazard

Resource Consent #	Hazard identified	Geotechnical report recommendations	RC recommendations and considerations	Details summarised by QLDC (Resource consent or report comments shown in italics).
RM140453 34 to 48 Hamilton Road, Queenstown	Debris flow/alluvial fan, liquefaction	Alluvial fan risk mitigated by Council measures. Liquefaction considered to be low risk.	Granted	To relocate two units to the site for the purposes of visitor accommodation Re Natural Hazards – from p. 4 of the doc titled '*RM140453 Decision'* *The site of the proposed relocated buildings has been identified as an area of high risk from natural hazards as it is within the Reavers Lane Alluvial Fan and identified as being at risk to liquefaction. The applicant has addressed the natural hazard risk in an email dated 4 July 2014 in which they refer to a report commissioned by Hadley Consultants Limited Reference 142676 dated 27 June 2014 for the proposed development at nearby 35 Huff Street. Further, the applicant has provided a letter from Hadley Consultants Ltd, dated 30 July 2014 in respect to 35, 36 & 48 Hamilton Road & 14 Huff Street, which concludes that in regards to the alluvial fan hazard they consider it to be mitigated by Council Infrastructure and that both potential hazards including liquefaction are considered to be low risk. It is therefore considered that any effect in terms of natural hazards as a result of the proposed development is likely to be less than minor.* Note – the emails and hazard report (Hadley) are located in the folder for this consent – the emails are attached to the decision report titled *RM140453 Decision'* starting at p. 21 of the PDF
RM140407 75 to 83 Gorge Road, Queenstown	Debris flow/alluvial fan, overland flow, liquefaction	▪ Liquefaction - building foundations to be designed to accommodate risk. ▪ Alluvial fan – elevate building platform to 0.5m above adjacent ground; landscaped diversion bund. ▪ Flooding – further assessment required.	Granted subject to conditions (listed left)	To establish a mixed use commercial development with associated signage, car parking, landscaping and earthworks. Note – p. 13 of the doc titled '*RM140407 Decision'* – considers liquefaction hazard (Lewis Bradford Consulting Engineers), alluvial fan hazard (Geosolve), and overland channel (David Hamilton and Associates Limited) – '*Overall it is considered that adverse effects in terms of natural hazards can be mitigated to a level no more than minor subject to recommended conditions of consent'* Note – the Council engineers report titled '*RM140407 Te Tiringa Investments Engineering Report'* Note the alluvial fan hazard assessment – doc titled '*Appendix F - Alluvial Fan Hazard Assessment'* Note the overland flow assessment – doc titled '*Appendix K - Overflow Channel Report' and 'Appendix H - Overland Stormwater Flow'* Note the liquefaction hazard assessment – doc titled '*Appendix G - Engineers Report'*
RM150495 47 Industrial Place, Queenstown	Slope instability	No geotechnical report completed	Granted subject to conditions.	To undertake additions/alterations to the existing building onsite and to breach parking requirements associated with the provision of an off-street loading area. Comment on natural hazards – p 18 of the doc titled '*RM150495 Decision*' *The building was damaged by unstable land and consequently the affected area was replaced. Ref RM 110192* *The building was designed and engineered to address the stability issue and now retains the slope should it settle behind the building. Adverse effect will be nil in terms of natural hazards*.
RM160962 Gorge Road, Queenstown	Liquefaction	Report did not assess liquefaction risk specifically.	Granted subject to conditions. Considered that building is 'not a risk to any natural hazards'.	Land use consent to construct a storage building Note p. 17 of the doc titled '*RM160962 s95 & Decision'* RM100572 granted consent to construct the existing building on site including a volume of earthworks to establish a level building platform, access and parking. In terms of natural hazards this consent decision commented: *"The site is identified in Council's Hazards Register as being possibly susceptible to seismic liquefaction. However, a site-specific geotechnical investigation has been undertaken for this development, which did not identify any issues in terms of the suitability of the ground conditions for building development. It is therefore not anticipated that there will be any adverse effects in terms of natural hazards."* A geotechnical report was submitted with RM100572 which is contained in Attachment [G] to this application. Based upon previous assessments and the nature and scale of the proposed development it is considered that the proposed building structure is not a risk to any natural hazards.
RM161011 39 Sawmill Road, Queenstown	Debris flow/alluvial fan, liquefaction	Report did not assess risk but recommended a geotechnical report be completed prior to construction	Granted subject to ground investigation prior to works commencing.	Construction of a two unit residential dwelling at the rear of an existing single dwelling residential site with associated earthworks and landscaping Note comment in doc titled '*RM161011 s95 & Decision'* re natural hazards *Although not a matter of discretion for this application, it is noted that the Applicant provided a geotechnical assessment from Geosolve that recommended that prior to construction a geotechnical completion report and a Schedule 2A "Statement of professional opinion as to suitability of land*

Resource Consent #	Hazard identified	Geotechnical report recommendations	RC recommendations and considerations	Details summarised by QLDC (Resource consent or report comments shown in italics).
				for building construction" be provided. The Applicant has volunteered this condition and it has therefore been included in the conditions attached to this consent. Note the applicant's comments re the effects of natural hazards at p. 31 (application/AEE) of the doc titled '*RM161011 s95 & Decision'* The geotech assessment described and referred to above has been included in the folder – doc titled '*Appendix E - Natural Hazard Assessment'*
RM161265 20 Bowen Street, Queenstown	Debris flow/alluvial fan, flooding	Report completed by applicant: Risk assumed to be low. "Stone walls diminish flood risk."	Granted.	To convert an existing garage into a second residential unit. Note the comments on p. 10 of the doc titled '*RM161265 s95 & Decision*' In context to the risks of a natural disaster, the stone walls contribute to the visual amenity of the site and is designed to diminish flood risk to the occupants and the property. Maintaining suitable sized entrances to minimise sandbagging if ever needed. *Bearing in mind that the only recorded history of a flooding incident being close to this site was in November 1999. During the flooding of November 1999, Brewery Creek flow was exacerbated by a failure of a manmade dam in the catchment in May of 1986 and by partial blockages in culverts. The creek flooded carrying sediment and tree debris down onto its alluvial fan. The edge of the flow of water only just reached the north eastern most tip of the site where once a temporary woodpile was sited at the time which diverted the edge of the flow that was heading east and downhill. The flow of water and sediment effecting properties east down Bowen St. and Gorge Rd. but not in any way effecting 20 Bowen St. Today if the exact event was to occur the property of 20 Bowen St. would be missed. Outside 18a Bowen St. was the beginning of the debris evidence. Over the last 5 years there have been extensive works carried out by ORC on Brewery Creek to update and provide further precautions in a natural event. The proposal is utilising the existing building without changes that expose the building to any increased risk. If required to extend the existing onsite parking within the landscaping of the site, the most north western end of the rock wall will have an enlarged driveway entrance to accommodate the two onsite carparks.*
RM170596 131 Gorge Road, Queenstown	Debris flow/alluvial fan, liquefaction	▪ Debris flow risk managed by existing controls. ▪ Liquefaction – foundations to be designed by Chartered Professional Engineer.	Granted – subject to conditions.	Land Use consent for the alteration of an existing building. Note the comments at p. 4 of the doc titled '*RM170596 s95 & Decision'* *Consent Notice 9625105.3 is registered on the Certificate of Title, which specifies that prior to the construction of any new buildings on the site, a detailed hazard assessment shall be completed due to the risk associated with flooding and debris flow from Horn Creek (Bush Creek) alluvial fan, or any other liquefaction risk within the site. Given this, the Applicant's AEE included a Hazard Report by Geosolve that identifies the proposed building would be outside of the direct path of flood or debris flows for an 80 to 100-year return period event. Overall, the Hazard Report concludes the site is suitable for the proposed building work. I accept the findings of this report. A consent condition has been recommended to ensure that the detailed design of the building and foundations are completed by a suitably qualified and experienced Chartered Professional Engineer, which is also required by the aforementioned Consent Notice.* *It is considered that there is no potential adverse natural hazard effects as a result of the proposed extension being constructed, provided the works are undertaken in accordance with the consent conditions.* The Geosolve hazard report referred to above is included in the folder – doc titled '*Appendix D - Geosolve Hazard Report'*
RM170128 62 Fryer Street, Queenstown	Debris flow/alluvial fan, slope stability	Risks considered to be low – no mitigation measures required	Granted.	To erect three residential units on site that breach outdoor living space requirements, internal setback requirements, landscape coverage requirements vehicle crossing width, and associated earthworks totalling approximately 910m³ involving cuts of up to 3.6m and fill of up to 3.0m. Note the doc titled '*Geotechnical Report'* – considers debris flow and landslide hazards *We consider the alluvial fan and landslide risks at this site to be low, with no mitigation measures required for the proposed development*
RM171459 51 Brecon Street, Queenstown	Debris flow/alluvial fan, liquefaction	▪ Alluvial fan – risk not assessed, reference to ORC (2011) made. No additional controls recommended. ▪ Liquefaction - foundation recommendations provided.	Granted.	To relocate an existing kiwi enclosure and construct an additional enclosure that will breach maximum building footprint, continuous building length, nature and scale standards for non-residential activities, parking standards, maximum earthworks volume, cut depth, fill height and proximity to boundary rules, and to house kiwis within the proposed building Note the hazard comments at p. 6 of the doc titled '*RM171459 s95 & Decision*' *The site, as identified by Council's hazards register, is affected by liquefaction, seismicity and alluvial fan hazards. The report conducted by GeoSolve, accompanying the application, has been assessed by Mr Hyde, who is satisfied that the findings and recommendations adequately address the hazards and issues present on the site. Conditions are recommended in this respect and have been adopted.* *The effects on the environment in respect of natural hazards are considered to be less than minor.* The Geosolve report referred to above is in the folder – titled '*Appendix G - Geotechnical Report'* – note the reference to CPT analysis at p. 31 of this report.

Resource Consent #	Hazard identified	Geotechnical report recommendations	RC recommendations and considerations	Details summarised by QLDC (Resource consent or report comments shown in italics).
RM190120 40 Fryer Street, Queenstown	Liquefaction, debris flow, rockfall, flooding	▪ Alluvial fan risk – considered nil to very low. ▪ Liquefaction risk – considered to be nil to very low	TBC – in progress	Geotechnical assessment for proposed five level apartment complex, including ground investigations. Information provided includes the following from RDA Consulting: ▪ Geotechnical Assessment Report – 40 Fryer Street, Queenstown. Report reference 50627, dated 24 April 2018. ▪ Email from David Rider at RDA, dated 28 August 2019 (through to 23 July 2019). Report primarily an engineering assessment, providing foundation and construction recommendations. Email provides response to queries on natural hazard risk from QLDC: ▪ *…a debris flow is possible with an ARI of 100 -1,000 years and the risk tolerance should be defined by the applicant.* ▪ *Based on the Beca Reporting we consider minor damage an acceptable risk for low flow and level estimates and these would be considered a rather standard risk for any site in similar terrain. The risk for loss of life is considered very low based on the likely outcome of an extreme event as reported by Beca.*
RM190626 20-26 Fryer Street, Queenstown	Liquefaction, debris flow, rockfall, flooding	▪ Liquefaction – moderate risk. Site investigation and foundation recommendations made. ▪ Risk from rockfall considered to be low. ▪ Risk from flooding considered to be low – recommendations made regarding floor levels. ▪ Risk from debris flow assessed as low.	TBC – in progress	Natural hazards assessment to support resource consent application for multi-unit development at 20-26 Fryer Street. Report prepared to meet requirements of RMA Section 106. Information provided includes the following reports by Ground Consulting Limited: ▪ Natural Hazards Assessment report – 20-26 Fryer Street. Report reference R4331-2A, dated 14/9/2018. ▪ Letter - reference L4331-2A, dated 12 June 2019. ▪ Letter – reference L4331-4A, dated 6 August 2019. Initial risk assessment summarised: ▪ *Table 3 indicates the risk classification for the identified natural hazards is low to negligible for all risks, with the exception of liquefaction and ground shaking associated with an earthquake.* Letter report of 12 June 2019 in response to queries on risk, making reference to the first draft of this report (Beca, May 2019): *Based on our interpretation of the reporting and data observation made above, GCL are of the opinion that the risk to 20-26 Fryer Street from debris flow is LOW.* Letter report of 6 August 2019 provided comments on debris flow risk, following further queries from QLDC: ▪ Reference was made to nearby properties with approved resource consent applications. Report conclusions: ▪ *1.Liquefaction may be significant under a ULS event, but this can be mitigated through appropriate design at building consent stage.* ▪ *2. We believe there is sufficient argument presented above to downgrade the risk of debris flow impacting the project site to within tolerable and acceptable levels of risk.* ▪ *3. Rockfall does not pose a risk to the property and require no mitigation.* ▪ *4. Current modelling of flooding impacts only a small area of the site. In addition, we believe that the current road and drainage network in place will also divert/accommodate flood waters sufficiently to further reduce the impact on the property.*

E

Appendix E – Mapping

Fan Surface Mapping

Fan surface mapping was completed by a Senior Engineering Geologist from Beca during a site-walkover on 24 and 25 October 2018.

Debris Flows

Modified cut slopes were observed in the upper section of the Reavers Fan adjacent to 45 Boydtown Way, as shown in Figure E 1. These deposits ranged from silt to boulder sized although were predominantly gravel sized.

Figure E 1 - Alluvial fan deposits in the upper fan adjacent to 45 Boydtown Way, with boulders visible (2018).

One example of the distal portion of Reavers Fan was noted in the cut slope at 62 Fryer Street, which was undergoing development at the time of mapping, as shown in Figure E 2. This shows younger alluvial fan deposits draped over beach/lake sediments. The alluvial fan deposits in this location are predominantly fine-grained silts and sands, representative of sheet flows typical of a fan's lower margin.

An example of mid-fan deposits was observed on the Brewery Creek Fan at 1 Bowen Street, as shown in Figure E 3. The fan deposits were typically sandy gravel with some cobbles. The absence of coarser sized deposits is as anticipated with increased distance from the fan apex.

Figure E 2 - Alluvial fan and beach deposits at 62 Fryer Street (under development, 2018).

Figure E 3 - Alluvial fan deposits in the mid-reaches of the fan at 1 Bowen Street (2018).

Rockfall

Rockfall commentary is contained within the body of the report in Section 3.2.1.

Catchment Mapping

Field mapping of the Brewery and Reavers Creek catchments was undertaken between the 21 and 25 October 2019 by two Beca Engineering Geologists, alongside a Principal Engineering Geologist on the 23 October.

Areas covered during the field survey are summarised below:

- Day 1: Transmission line between Fryer Creek to Brewery Creek, and alluvial fan on the true-left of Brewery Creek from 375m to 680m above sea level (asl).
- Day 2: Alluvial fan and slopes along true left margin of Brewery Creek from 680m to 1060m asl.
- Day 3: Intervening slope between Brewery and Reavers Creeks from the transmission line to 600m asl, and Reavers Creek catchment from the culvert to the Skyline Gondola.
- Day 4: Intervening slope between Brewery and Reavers Creeks from the transmission line to 600m asl targeting rock outcrops.
- Day 5: Brewery Creek catchment from the Ben Lomond track at 1100m asl then following the creek-bed to 550m asl, and the true-left bank to the transmission line.

Debris Flow

Brewery Creek

The catchment for Brewery Creek spans an approximate area of 3km^2 extending from the southern flank of Bowen Peak to the apex of the alluvial fan between Industrial Place and Bowen Street. The area ranges in elevation from approximately 1580m asl to approximately 370m asl. The slopes are generally forested below 1000m asl, however dead trees from localised spraying are present on the upper east-facing slopes between 1000m and 900m asl. The stream is fed from several small gullies and emerges onto a low angled alluvial fan at the base of the valley. The channel bisects the alluvial fan from the north-east to south-east and has undergone modifications in recent years including deepening to mitigate flooding.

Evidence of landslides and rockfall have previously been documented in the catchment and appear to be largely controlled by foliation and jointing within the Caples Terrance schist. Field mapping primarily covered the forested slopes on the true left margin of the channel. Observations of the true right banks were generally made from the true left slope due to the steep topography and predominance of bluff outcrops.

Observations from field mapping

The true left slopes of Brewery Creek are covered in pine forest with ground cover comprising fallen leaves, branches, and dead trees. Dead trees and branches were noted immediately adjacent Brewery Creek and may be transported into the channel (see Figure E 4). Younger trees exhibiting deformation and warping were locally observed and suggest localised creep is occurring on the slope (i.e. Figure E 5). In some areas the deformed trees were accompanied by tension cracks.

Figure E 4 - Photograph showing forest and ground cover on the true left of Brewery Creek taken looking towards the true right bank (-45.142699°; 168.392485°; 470m asl).

Figure E 5 - Photograph showing deformed young trees present on the true left of Brewery Creek taken looking north (45.149800°; 168.393140; 442m asl).

Colluvium and localised outcrops of schist were observed on the hillslope below approximately 500m asl (Figure E 6). Tree roots were observed to be both holding loose rocks in place and causing mechanical wedging of the rock. The slope above 500m asl contains colluvium with boulders ranging in size from approximately 1000mm x 1000mm x 500mm up to approximately 6000mm x 5000mm x 4000mm (Figure E 7). The frequency of large boulders increased with increasing elevation; no consistency in the orientations of the boulders was observed. Localised boulders ranging from approximately 50mm x 20mm x 10mm up to 2000mm x 1000mm x 500mm were observed beneath some of the outcrops (Figure E 8). The boulders were generally covered in moss and did not exhibit evidence of recent movement. The surrounding vegetation did not exhibit damage or deformation that would suggest recent rockfall.

Figure E 6 - Photograph of localised schist outcrop observed to the true left of Brewery Creek. Outcrop approximately 3m high and 10m in length. Photograph taken facing west (45.112099; 168.391194; 570m asl).

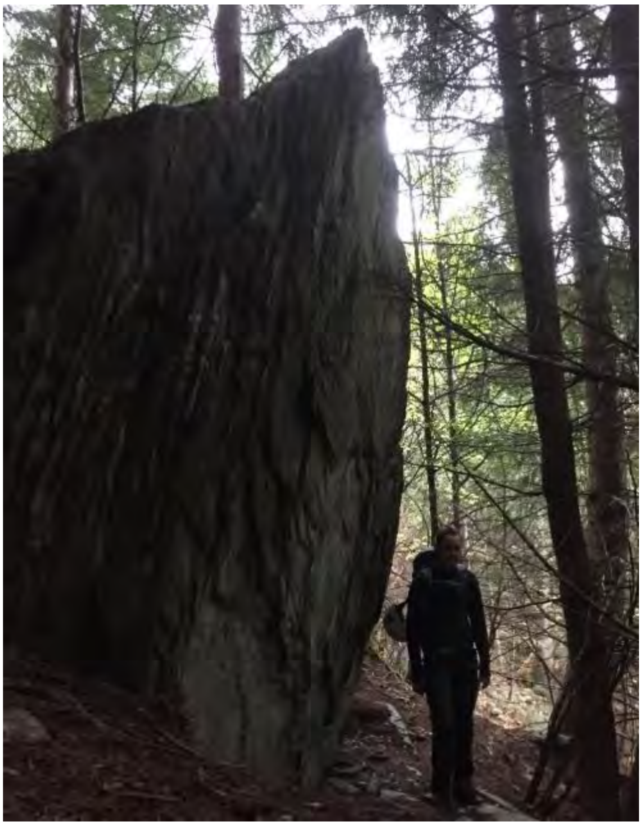


Figure E 7 - Photograph taken on the true left of Brewery Creek looking south and showing large boulder encountered on slope (45.056130; 168.391518; 630m asl).

Figure E 8 - Photograph of boulders beneath schist outcrop on the true left of Brewery Creek. Taken looking north (45.112739; 168.392168; 790m asl).

A high concentration of randomly orientated boulders ranging from 200mm x 100mm x 20mm up to 4000mm x 3000mm x 1000mm were observed between 980m and 1100m asl (Figure E 9). Outcrops were not present immediately above the boulders. Foliation within the larger boulders appeared to be consistent with the regional trend suggesting that the boulders represent in-situ fracturing of outcrops.

Figure E 9 - Boulders present on the true left of Brewery Creek. Foliations within larger boulders are consistent with the regional trend suggesting they were sourced from in situ fracturing of outcrop. Photograph taken looking south (45.046299; 168.391134; 870m.

Ridgelines present between 1000m and 1100m asl on the true left side of Brewery Creek exhibit localised outcrops of schist (Figure E 10). The outcrops appeared highly fractured and contain loose boulders ranging from 100mm x 50mm x 10mm up to 1000mm x 500mm x 100mm. Scree slopes with evidence of recently deposited boulders to cobbles were observed beneath these outcrops (Figure E 11). The ridgeline at the northern-most extent of the catchment comprised an approximately 10m to 15m tall outcrop spanning 80m along the cliff (Figure E 12). Loose boulders up to 3000mm x 1000mm x 500mm were observed at the intersection of joints (Figure E 13). Boulders of similar dimensions were observed immediately beneath the cliff and in the area approximately 300m downslope (Figure E 13).

Figure E 10 - Photograph taken at base of ridgeline looking west and showing fractured outcrop with scree slope below (45.04169 168.39476; 960m asl)

Figure E 11 - Close-up photograph of recent scarp and rockfall debris on outcrop present on ridgeline looking west and shown in Figure E10 (45.042570 168.385761; 985m asl).

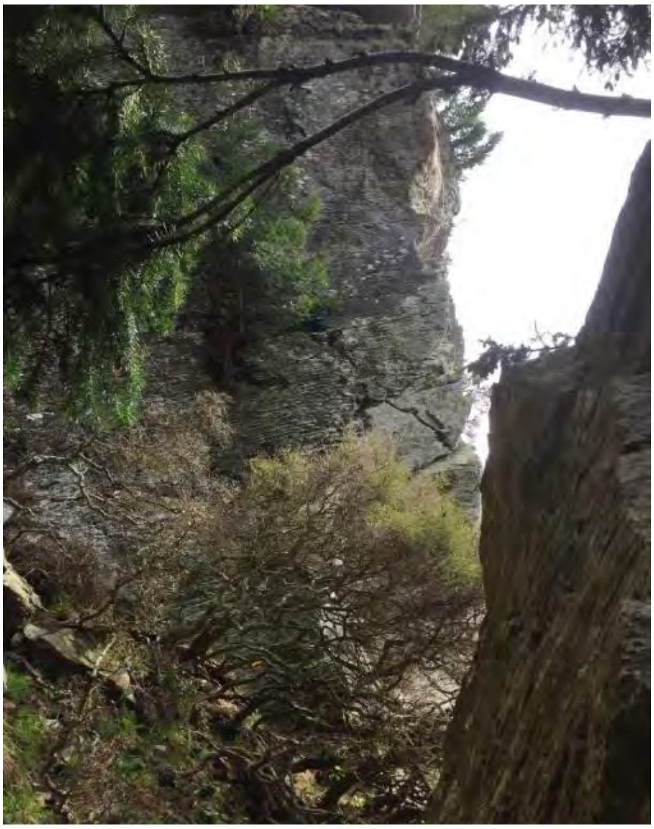


Figure E 12 - Photograph taken looking north and showing cliff outcrop present along ridgeline with loose boulders (45.046089; 168.391190; 830m asl).

Figure E 13 - Photograph looking downslope (north-east) showing rockfall debris below the cliff shown in Figure E 12 (45.045369; 168.3912449; 825m asl).

The true right slope of Brewery Creek contains cliffs with localised linear outcrops of schist (Figure E 14). Loose boulders up to 2000mm x 800mm x 500mm were present at the intersection of joints within the schist. Boulders of similar dimensions were observed downslope of the cliffs and appeared to be sourced from the upslope outcrops.

Figure E 14 - Photograph taken from top of the true right slope of Brewery Creek looking east and showing schist outcrops (45.051459; 168.381927; 1110m asl).

The channel of Brewery Creek generally exhibited slumping of colluvial deposits along the true left bank and outcrops of schist along the true right bank (Figure E 15). Loose rocks ranging from 200mm x 100mm x 50mm up to 3000mm x 2000mm x 500mm were present on the outcrops (Figure E 16). In some areas scarps up to 2000mm x 1000mm were observed on the outcrops and indicated recent dislodging of material (Figure E 17). The corresponding boulders were not observed in the channel suggesting downstream transport. Localised colluvium deposits were observed on the true right bank where outcrops were not present adjacent to the stream.

Figure E 15 - Photograph taken in Brewery Creek looking downstream (east). True left bank contains colluvial deposits while true right bank comprises schist outcrop (45.005100; 168.381773; 950m asl).

Figure E 16 - Photograph of schist outcrop surrounded by colluvial deposits on true right bank of Brewery Creek. Photograph taken facing south-west (45.042829; 168.382238; 920m asl).

Figure E 17 - Photograph of outcrop on true right bank of Brewery Creek. Lighter area is scarp of recent rockfall. Photograph taken facing south (45.046170; 168.382772; 885m asl).

Dead trees that appear to have fallen into the channel were observed where the channel was relatively steep and narrow (Figure E 18). Accumulations of dead trees within, and adjacent to, the channel were present where the channel widened (Figure E 19). The logs are a source of debris that could be transported to form log jams and other small dams in the watercourses. Failure of these dams would generate larger pulses within debris flow and/or debris flood events.

Figure E 18 - Photograph looking upstream along Brewery Creek (looking west) showing accumulation of dead trees in narrow section of the channel (45.040700; 168.381806; 965m asl).

Figure E 19 - Photograph looking downstream (west) in Brewery Creek showing accumulation of logs within a wider section of the creek bed (45.043989; 168.382652; 900m asl).

The stream channel contains dense pine saplings below approximately 550m asl. Observations below this point were limited to the top of the river bank, however suggest that the stream channel continues to comprise colluvium on the true left bank, outcrops with loose boulders on the true right bank, and an abundance of logs within the creek bed (Figure E 20). The saplings were all approximately 3m to 4m tall suggesting a period of vegetation clearance followed by regrowth along the channel. No relationship between sapling age and height has been documented for the Queenstown region therefore the age of the saplings is uncertain.

Figure E 20 - Photograph taken from slope above true left bank of Brewery Creek looking south and showing the density of pine saplings within the channel (45.059519; 168.396410; 630m asl).

Reavers Creek

The catchment basin for Reavers Creek spans approximately 0.48km^2 from the eastern flank of Jan's Peak (1050m asl) to the alluvial fan near Reavers Lane (370m asl). The catchment drains to the southeast with an average slope angle of approximately 32°. The creek enters a culvert at the fan apex and is channelised below ground until east of Fryer Street (Figure E 21). The area below the culvert intake is occupied by residential properties with some tourist accommodation and contains a channel which takes overland flow where the culvert is over-topped (Figure E 22).

Previous observations have indicated that scattered bluff outcrops with fractured rock are present in the upper reaches of the catchment which may provide source material for debris flows. Younger trees have also been reported along drainage lines and are inferred to indicate scour erosion. Field mapping was primarily confined to within the channel up to the Skyline Gondola due to the steep topography and presence of bluff outcrops.

Figure E 21 - Photograph of grating covering culvert intake for Reavers Stream located at the fan apex. Taken looking east (45.128489; 168.392309; 370m asl).

Figure E 22 - Photograph of small channel through residential properties directly above culvert intake. Taken looking east (45.126229; 168.391439; 365m asl).

Observations from field mapping

At the time of field mapping the creek was flowing from approximately 430m asl to around 370m asl where it drained underground approximately 20m upstream of the stream culvert. The gully immediately upstream from the fan apex is moderately-to-steeply sloping and varies in width from 10m to 30m. Colluvium was observed on the true left bank of the creek while outcrops of schist and localised colluvium were observed on the true right bank (Figure E 23). Localised boulders up to 500mm x 200mm x 100mm in size, broken tree branches, and leaf litter were observed on the gully floor (Figure E 23).

Figure E 23 - Photograph looking downstream along Reavers Creek towards the culvert and showing the vegetation cover within the gully (45.129700; 168.393897; 380m asl).

The channel above 430m asl varies from open and moderately-to-steeply sloping, interspersed with narrower steep sections. The moderately sloping sections range in width from approximately 10m to 50m with colluvial deposits generally observed on the true left bank, and outcrops of schist and colluvial deposits on the true right bank (Figure E 24). The gully margins and floor contain trees of varying sizes, leaf litter, and vegetation debris (Figure E 24). No evidence for recent water flow was observed however some trees within the channel exhibit deformation/warping suggesting localised creep (Figure E 25). Localised moss-covered cobbles to boulders up to 1000mm x 500mm x 200mm were additionally observed on the channel floor, and in some cases were up to 4500mm x 3000mm x 2000mm (Figure E 26).

Figure E 24 - Photograph looking upstream along Reavers Creek showing the vegetation present within open sections of the channel and state of the gully floor (45.126670; 168.391179; 430m asl).

Figure E 25 - Photograph looking upstream along Reavers Creek showing localised warping and deformation of trees within an open section of the channel (45.124980; 168.394920; 560m asl).

Figure E 26 - Photograph showing large boulder present within wide section of the channel (45.122959; 168.385986; 665m asl).

Localised accumulations of boulders were observed where outcrops intersect the channel (Figure E 27). Boulders range in size from 200mm x 100mm x 50mm up to 1000mm x 800mm x 500mm and are covered in moss with no evidence for recent water-flow observed (Figure E 27).

Figure E 27 - Photograph looking upstream along Reavers Creek showing accumulations of boulders within the channel. Boulders are covered in moss and leaf litter with no evidence for recent water flow (45.126220; 168.391400; 440m asl).

A localised field of boulders was observed on the true right bank of the channel at approximately 680m asl. The boulders appeared well graded and range in size from 300mm x 200mm x 50mm to

5000mm x 2000mm x 1000mm and possibly larger (Figure E 28). The boulders exhibited varying states of weathering and appeared to be sourced from the overhead bluff outcrop at 730m asl (Figure E 29).

Figure E 28 - Photograph of boulders observed near true right bank of Reavers Creek channel and located beneath cliff at 735 m asl. Rocks appear to be randomly orientated and exhibit varying degrees of weathering (45.124950 168.385328; 680m asl).

Figure E 29 - Photograph looking towards cliff above boulder the field in the channel. Cliff outcrops along ridgeline next to the Skyline Gondola and is approximately 20-50m high (45.124640; 168.385355; 735m asl).

Rockfall

Field mapping covered the slopes between Brewery and Reavers Creeks and south towards the Kiwi Birdlife Park from the transmission line to approximately 600m asl. General observations on the locations, heights and lengths of the outcrops, seepage, and the presence and sizes of loose boulders were noted for each outcrop. The steep topography, dense forest cover, and the presence of leaf litter and tree debris on the forest floor limited the ability to identify outcrops. Observations made during field mapping are summarised below and are divided into lower slopes immediately behind the transmission line, mid-slope, and higher slope outcrops above 500m asl.

Lower slope from transmission line to 440m asl

Localised outcrops ranging from approximately 10m to 80m in length and 2m to 10m in height were observed immediately behind the transmission line (Figure E 30). Loose rocks ranging from approximately 70mm x 50mm x 20mm to 500mm x 500mm x 100mm were observed on the surface of the outcrops and appeared to have broken along foliation planes. Rocks of similar dimensions were observed immediately beneath the outcrops. In some cases, rocks were resting on young trees suggesting active shedding of material from the outcrops (Figure E 31 and Figure E 32). Some of the young trees exhibited damage to bark suggested repeated damage from shredded rocks albeit the trees were still alive (Figure E 31) Localised larger blocks up to 2000mm x 800mm x 500mm were identified at the intersections of joint sets on some outcrops (Figure E 33). The outcrop faces generally appeared weathered and covered in moss; no seepage was observed.

Figure E 30 - Photograph showing outcrop present immediately above the transmission line. Taken looking north (45.119400; 168.393881; 340m asl).

Figure E 31 - Photograph of rocks stacked adjacent to small (10cm diameter) tree indicating recent shedding of material of the above cliff (45.124570; 168.391300; 530m asl). Damage to bark suggests repeated impact damage from shredded material, albeit the tree is still alive.

Figure E 32 - Photograph taken from base of cliff looking upslope and showing block fallen from cliff onto slope blow (45.114299; 168.392974; 540m asl).

Figure E 33 - Photograph showing large loose block present on outcrop immediately behind the Kiwi Birdlife Park. Taken looking towards the north with properties behind the trees in the background (45.136690; 168.392309; 380m asl).

Mid-slope from 440m asl to approximately 520m asl

The slope immediately behind the Kiwi Birdlife Park on the true right bank of Reavers Creek contains outcrops of similar dimensions and states to those observed behind the transmission line. The outcrops were found to range from 20m to 80m in length to 4m to 20m in height (Figure E 34). Loose rocks approximately 70mm x 50mm x 20mm to 500mm x 500mm x 100mm were present on the outcrops, and rocks of similar dimensions were observed on the underlying slopes. Localised larger blocks up to 2000mm x 800mm x 500mm were identified at the intersection of joint sets on some outcrops. Localised blocks of similar dimensions were observed beneath some outcrops. In one case a boulder appeared to have fallen off relatively recently due to a lack of weathering on the outcrop scar and fresh faces present on the boulder below (Figure E 35).

Figure E 34 - Photograph of outcrop observed mid-slope in the area behind the Kiwi Birdlife Park and south of Reavers Creek (45.132709; 168.391859; 450m asl).

Figure E 35 - Recent scar on outcrop (white colouration) with fresh boulders below suggesting recent rockfall (45.127630; 168.391316; 515m asl).

The mid-slope region in the area between Brewery and Reavers Creeks contains localised outcrops of similar dimensions to that observed near the transmission line, albeit the outcrops are less frequent. A localised depression containing an accumulation of boulders ranging from 500mm x 300mm x 100mm to 1200mm x 800mm x 300mm was identified in an area of smaller trees at approximately 540m asl (Figure E 36).

Figure E 36 - Photograph showing accumulation of boulders and younger trees in a topographic depression on the slope between Brewery and Reavers Creeks (45.18950 168.3918599; 540m asl.

Upper slope above 520m asl

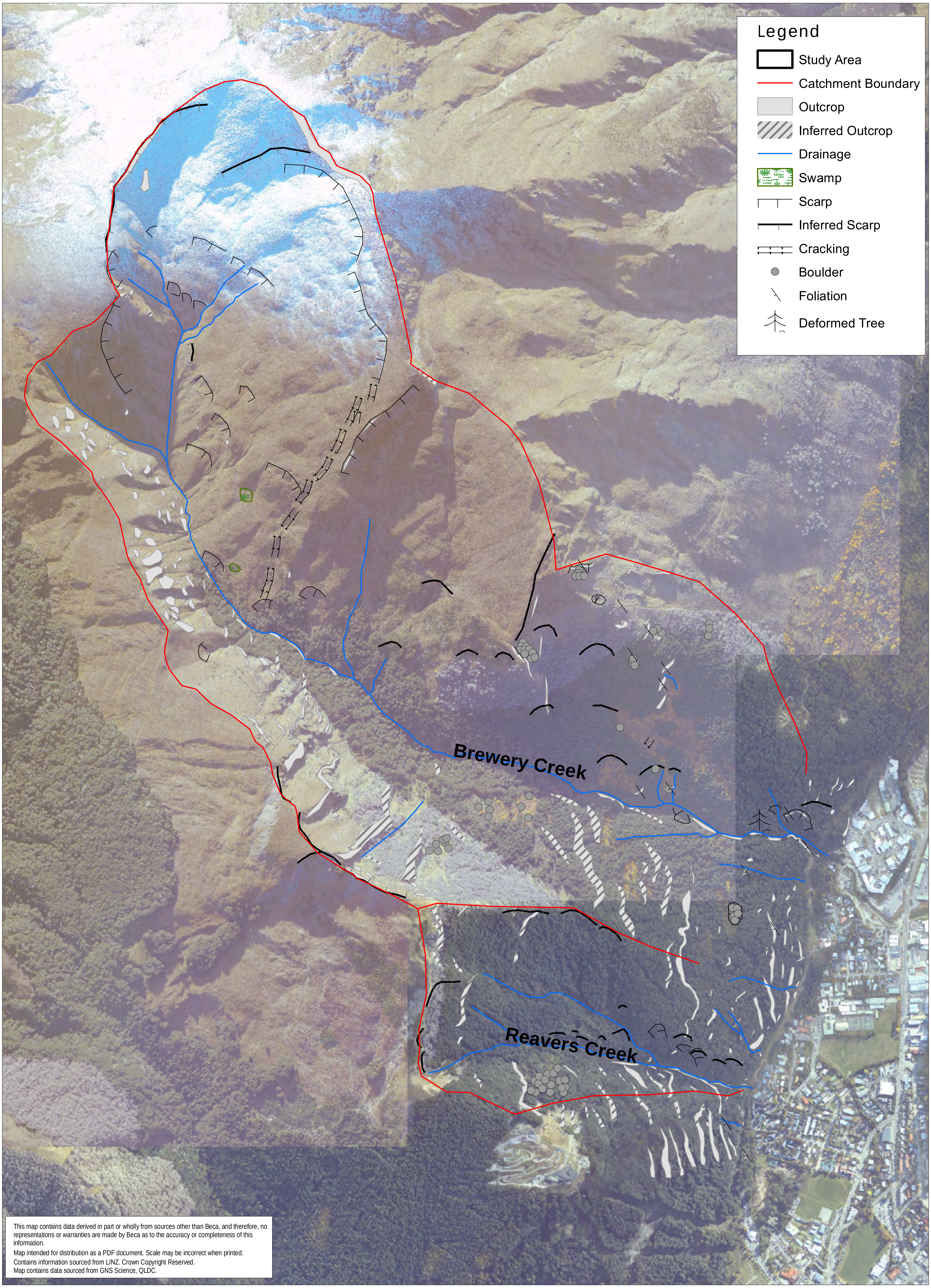
A continuous cliff ranging in height from 10m to 30m was identified on the slope between Brewery and Reavers Creek and extending from 540m to approximately 630m asl. Loose cobbles to boulders were observed on the surface of the outcrop and range in size from 100mm x 80mm x 50mm up to 2500mm x 1000mm x 500mm. Larger blocks were observed at the intersection of joints (Figure E 37). Cobbles to boulders of similar dimensions were observed on the slope immediately beneath the cliff and extending downslope to approximately 490 m asl. The cliff appeared to be the source of the accumulation of boulders shown in Figure E 36. Boulders leaning on young trees and scars on the trees likely due to flying rocks were observed beneath the cliff and suggest that the outcrop is actively shedding material (Figure E 39 and Figure E 40).

Figure E 37 - Photograph looking up at cliff present between Brewery and Reavers Creek. A loose block is present at the intersection of two joint sets. Photograph taken looking upslope towards the west (45.11414; 168.391672; 580m asl).

Figure E 38 - Photograph of boulder observed at the base of the cliff present between Brewery and Reavers Streams (45.1788; 168.391645; 610m asl).

Figure E 39 - Photograph showing rock leaning against young tree. The rock appears to have caused recent damage to the tree suggesting recent movement (45.117179; 168.391492; 600m asl).

Figure E 40 - Photograph of damage to tree trunk believed to have been caused by flying rockfall debris. Taken looking downslope towards the east (45.127089; 168.391267; 545m asl).



Map Scale @ A3: 1:10,000

0 200 400

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	14/08/2020

Title:

Geomorphology

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

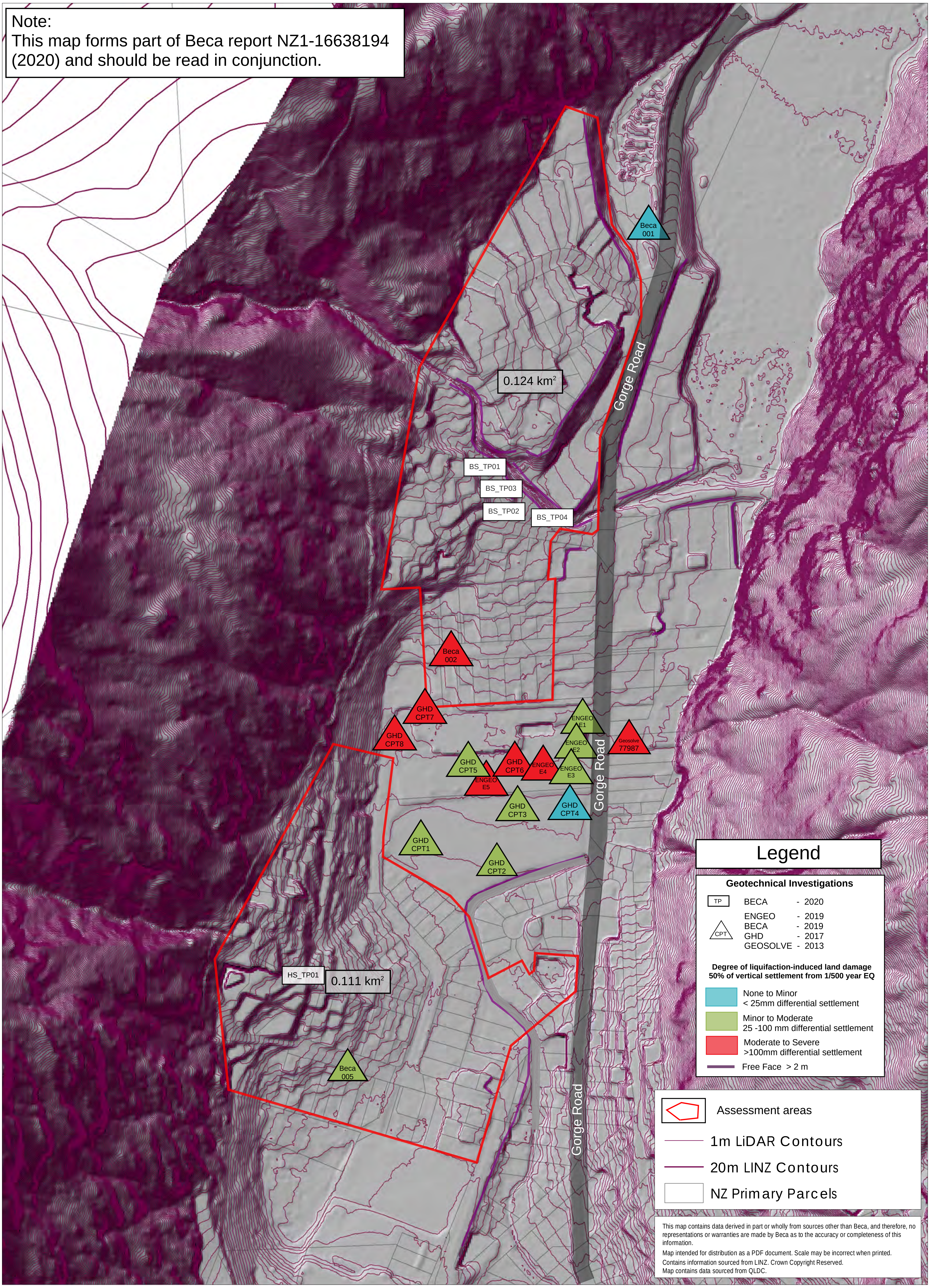
Drawing No: 3209881-E001

File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix E\3209881-E001.mxd Author: SHB Date: 28/08/2020

GIS@beca.com

F

Appendix F – Ground Investigations



GIS@beca.com

File: P:\3203209253\09 TGI\01 Map\MXD_3209253_03_LiDAR_ZoomedIn.mxd Author: BJD2 Date: 30/10/2018

Map Scale @ A3: 1:4,000

0 50 100
Metres

Revision	Author	Verified	Approved	Date
2	SB/ME	ARP	PJH	04/08/2020
1	ME	BDJ	ARP	08/11/2018

Title:

Gorge Road
Ground Investigation Location Plan

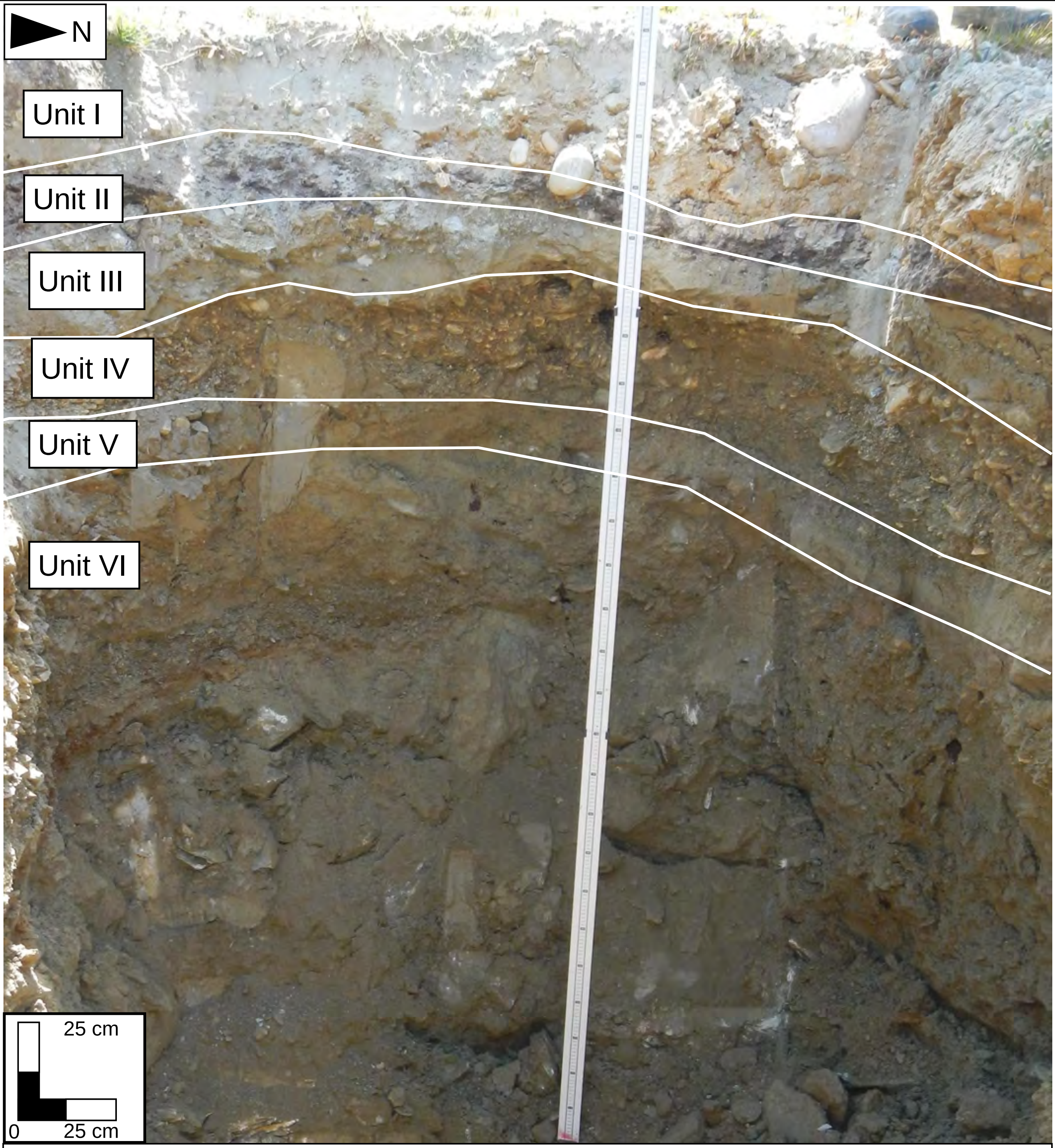
Client: Queenstown Lakes District Council

Project: **Natural Hazards Affecting Gorge Road**

Discipline: GIS

Drawing No: 3209881-F001

Test Pit Investigations



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Unit I - Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded unweathered sandstone and schist [Fill].

Unit II - Tightly packed SILT, some fine sand and fine to medium gravel, trace cobbles; dark grey, dry, poorly graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist [Buried Topsoil].

Unit III - Tightly packed SILT, some fine sand, minor fine gravel; tan, dry, poorly graded, non-plastic. Gravel sub-angular to sub-rounded unweathered schist [Quaternary alluvium].

Unit IV - Loosely packed fine to medium sandy, cobbly fine to coarse GRAVEL some silt, trace boulders; grey, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded unweathered schist [Quaternary debris flow].

Unit V - Tightly packed fine sandy SILT, trace fine gravel and fibrous organics, grey; dry, poorly graded, non-plastic. Gravel sub-angular to sub-rounded unweathered schist [Quaternary alluvium].

Unit VI - Tightly packed fine to coarse sandy, cobbly, fine to coarse GRAVEL, trace fibrous organics, some silt; grey, dry, well graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist [Quaternary debris flow].

No.	Revision	By	Chk	Appd	Date
2	FINAL	SB	ARP	PJH	06/08/2020
1	DRAFT	SB			25/02/2020

Beca

Client: QUEENSTOWN LAKES DISTRICT COUNCIL

Project: NATURAL HAZARDS AFFECTING GORGE ROAD

Design	N/A	
Drawn	SB	25/02/2020
Dsg Verifier	N/A	
Dwg Check	ARP	25/02/2020

Title: BOWEN STREET - TEST PIT 01 INTERPRETED FIELD PHOTOGRAPH

Approved for Construction *

Date: N/A

* Refer to Revision 1 for Original Signatures

Scale as drawn (A4)

Discipline 320

Drawing No. 3209881-GG-BS_TP01

Rev. A

DO NOT SCALE

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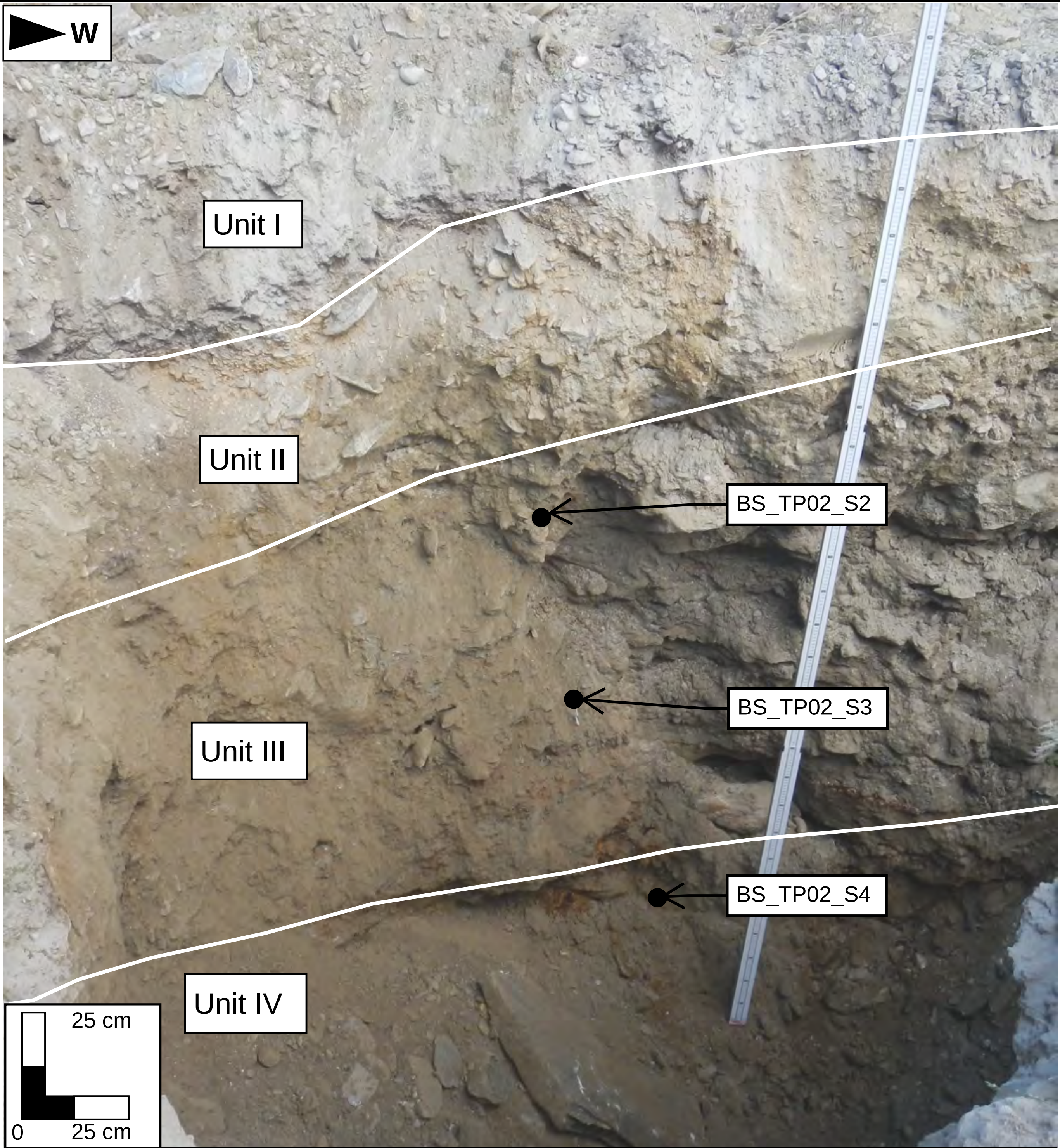

Unit I - Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded un-weathered sandstone and schist [Fill].

Unit II - Loosely packed silty, fine sandy fine to coarse GRAVEL, trace cobbles; tan, dry, well-graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded un-weathered schist [Fill].

Unit III - Loosely packed fine to coarse sandy, fine to coarse gravelly COBBLES, some boulders; light brown, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded un-weathered schist.Trace fibrous organics (1.2 m and 1.5 m) [Quaternary debris flow].

Unit IV - Tightly packed fine sandy fine to coarse gravelly SILT, some cobbles; light brown, dry, well graded, non-plastic. Gravel to cobbles sub-angular to sub-rounded unweathered schist. Trace fibrous organics (2.6 m) [Quaternary alluvium].

No.	Revision	By	Chk	Appd	Date
2	FINAL	SB	ARP	PJH	04/08/2020
1	DRAFT	SB			25/05/2020

Client: QUEENSTOWN LAKES DISTRICT COUNCIL

Project: NATURAL HAZARDS AFFECTING GORGE ROAD

Design	N/A	
Drawn	SB	25/02/2020
Dsg Verifier	N/A	
Dwg Check	ARP	25/02/2020

Beca

Title: BOWEN STREET - TEST PIT 02 INTERPRETED FIELD PHOTOGRAPH

Approved for Construction *

Date: N/A

* Refer to Revision 1 for Original Signatures

Scale as drawn (A4)

Discipline 320

Drawing No. 3209881-GG-BS_TP02

Rev. A

DO NOT SCALE

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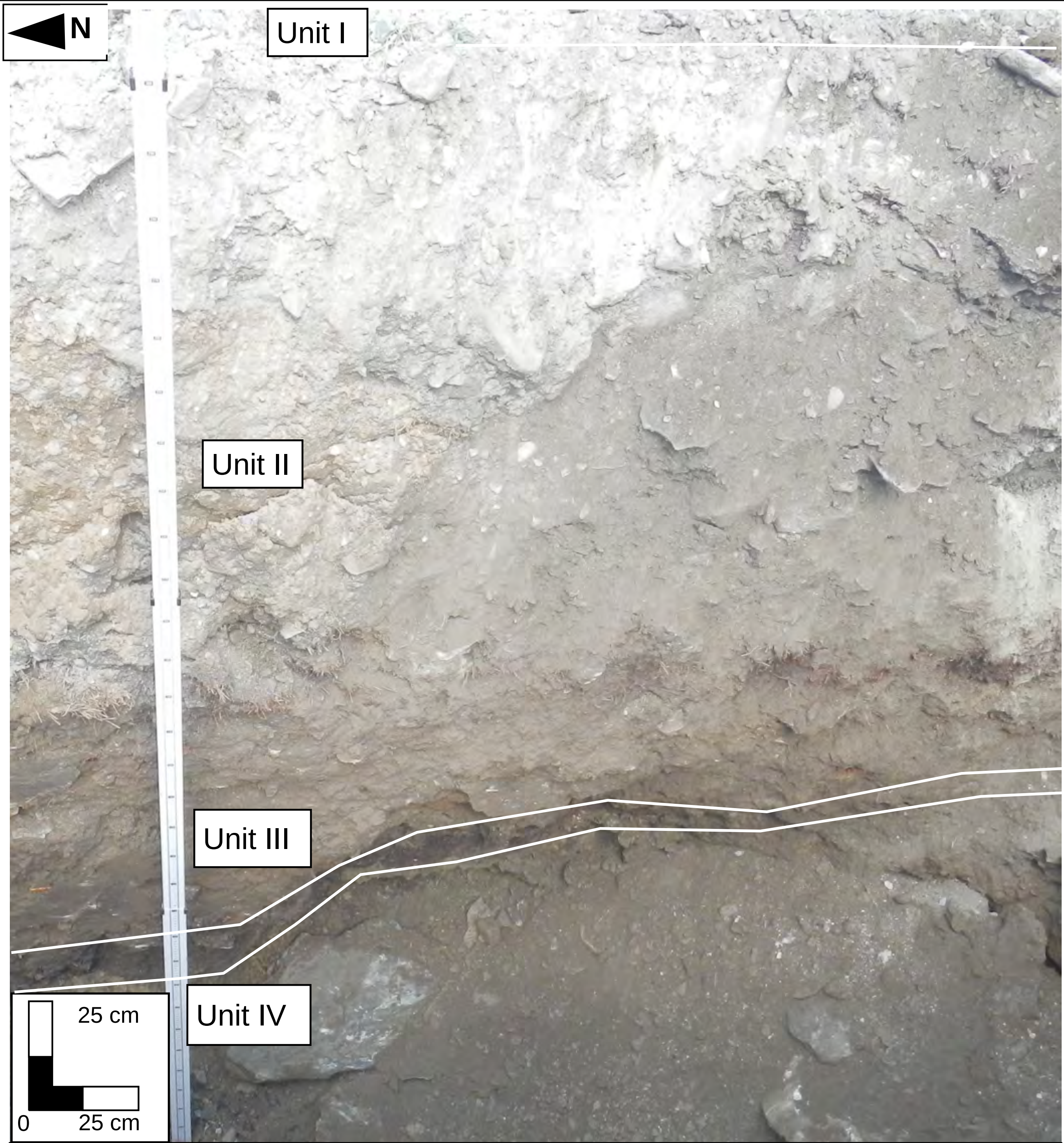

Unit I - Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded un-weathered sandstone and schist [Fill].

Unit II - Loosely packed fine sandy fine to coarse gravelly COBBLES, some silt, trace boulders; tan, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded un-weathered schist.Trace fibrous organics at 1.4m and red bricks 1.7m [Fill].

Unit III - Tightly packed fine sandy SILT, some fine gravel; brown, dry, well graded, non-plastic. Gravel sub-angular to sub-rounded un-weathered schist [Buried topsoil].

Unit IV - Tightly packed fine to coarse sandy, fine to coarse gravelly, COBBLES, some silt; tan, dry, well graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist [Quaternary debris flow].

No.	Revision	By	Chk	Appd	Date
2	FINAL	SB	ARP	PJH	04/08/2020
1	DRAFT	SB			25/02/2020

Beca

Client: QUEENSTOWN LAKES DISTRICT COUNCIL

Project: NATURAL HAZARDS AFFECTING GORGE ROAD

Design	N/A	
Drawn	SB	25/02/2020
Dsg Verifier	N/A	
Dwg Check	ARP	25/02/2020

Title: BOWEN STREET - TEST PIT 03 INTERPRETED FIELD PHOTOGRAPH

Approved for Construction *

Date: N/A

* Refer to Revision 1 for Original Signatures

Scale as drawn (A4)

Discipline 320

Drawing No. 3209881-GG-BS_TP03

Rev. A

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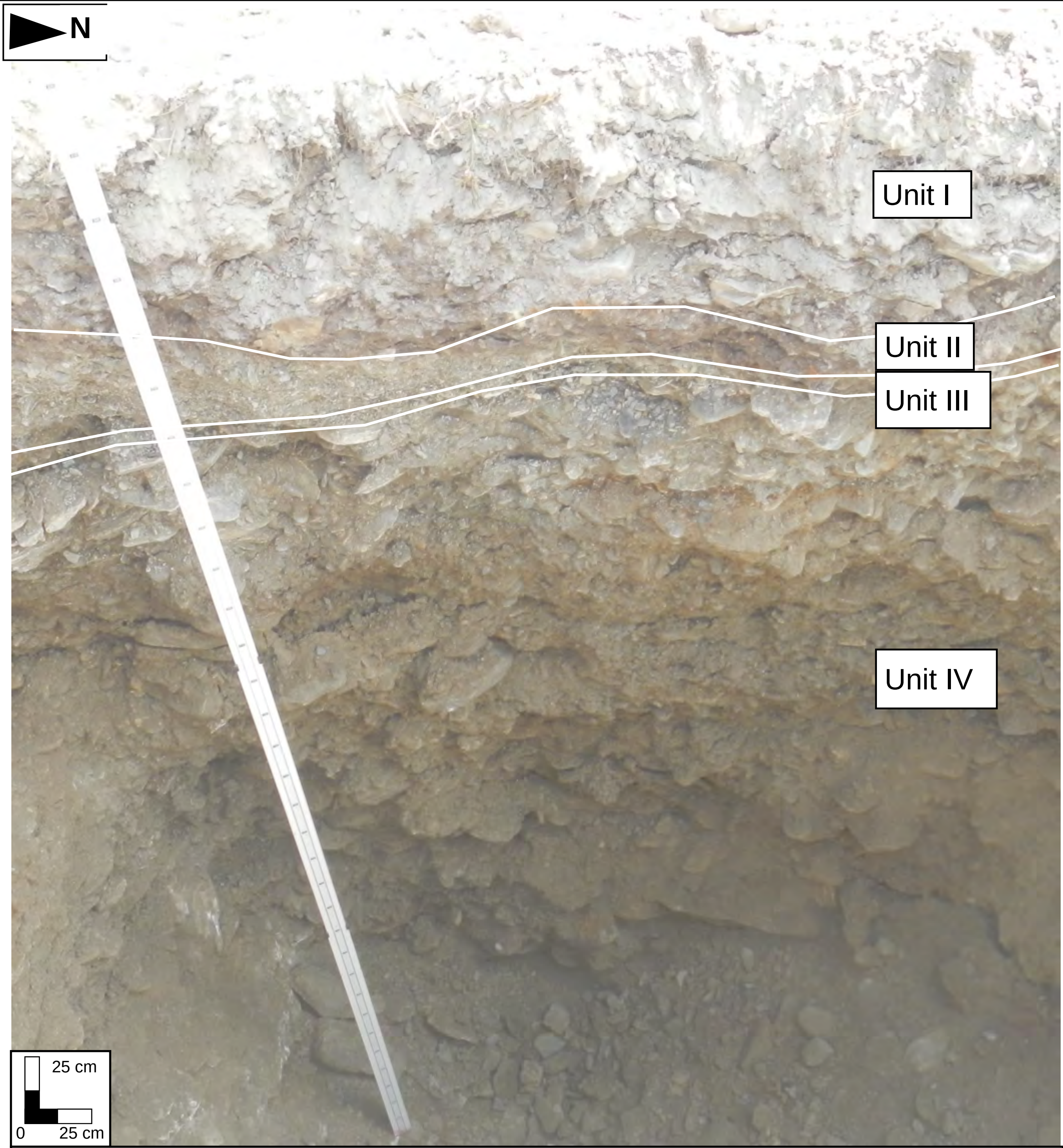

Unit I - Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded un-weathered sandstone and schist [Fill].

Unit II - Loosely packed silty fine SAND, some fine gravel, trace fibrous organics; light brown, dry, well graded, non-plastic. Gravel sub-angular to sub-rounded un-weathered schist [Quaternary alluvium].

Unit III - Tightly packed sandy SILT; tan, dry, poorly graded, non-plastic [Quaternary alluvium].

Unit IV - Tightly packed fine to coarse sandy, fine to coarse gravelly COBBLES, some boulders, trace silt; light brown, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded un-weathered schist.Some boulders; sub-angular to sub-rounded un-weathered schist at 2.1m [Quaternary debris flow].

No.	Revision	By	Chk	Appd	Date
2	FINAL	SB	ARP	PJH	04/08/2020
1	DRAFT	SB			25/02/2020

Beca

Client: QUEENSTOWN LAKES DISTRICT COUNCIL

Project: NATURAL HAZARDS AFFECTING GORGE ROAD

Design	N/A	
Drawn	SB	25/02/2020
Dsg Verifier	N/A	
Dwg Check	ARP	25/02/2020

Title: BOWEN STREET - TEST PIT 04 INTERPRETED FIELD PHOTOGRAPH

Approved for Construction *

Date: N/A

* Refer to Revision 1 for Original Signatures

Scale as drawn (A4)

Discipline 320

Drawing No. 3209881-GG-BS_TP04

Rev. A

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DO NOT SCALE

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Unit I - Loosely packed fine sandy SILT, trace fibrous organics (rootlets); dark brown, dry, poorly graded, non-plastic [Quaternary alluvium].

Unit II - Loosely packed silty fine sandy COBBLES, some medium to coarse gravel, trace boulders; tan, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-rounded to sub-angular un-weathered schist [Quaternary debris flow].

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No.	Revision	By	Chk	Appd	Date
2	FINAL	SB	ARP	PJH	04/08/2020
1	DRAFT	SB			25/02/2020

Beca

Client: QUEENSTOWN LAKES DISTRICT COUNCIL

Project: NATURAL HAZARDS AFFECTING GORGE ROAD

Design	N/A	
Drawn	SB	25/02/2020
Dsg Verifier	N/A	
Dwg Check	ARP	25/02/2020

Title: HUFF STREET - TEST PIT 01 INTERPRETED FIELD PHOTOGRAPH

Approved for Construction *

Date:

* Refer to Revision 1 for Original Signatures

Scale as drawn (A4)

Discipline 320

Drawing No. 3209881-GG-HS_TP01

Rev. A

DO NOT SCALE IF IN DOUBT ASK.

BOREHOLE No: BS_TP01

MACHINE BOREHOLE LOG

SHEET 1 of 1

PROJECT: Natural Hazards Affecting Gorge Road
JOB NUMBER: 3209881
SITE LOCATION: Queenstown
CLIENT: Queenstown Lakes District Council

CIRCUIT: NZTM
COORDINATES: N 5,005,657 m
E 1,258,134 m
BOREHOLE LOCATION: 1 Bowen Street
R L: 354 m
DATUM: NZVD2016
COORDINATE ORIGIN: hhGPS
ACCURACY: ±5m

Method	Depth (m)	Soil / Rock Description	Geological Unit	RL (m)
E	0.0–0.3	Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded unweathered sandstone and schist.	Fill	
	0.3–0.45	Tightly packed SILT, some fine sand and fine to medium gravel, trace cobbles; dark grey, dry, poorly graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist [Buried Topsoil; QUATERNARY ALLUVIUM].	QA	
	0.45–0.6	Tightly packed SILT, some fine sand, minor fine gravel; tan, dry, poorly graded, non-plastic. Gravel sub-angular to sub-rounded unweathered schist [QUATERNARY ALLUVIUM].	QA	353.5 (0.5)
	0.6–1.2	Loosely packed fine to medium sandy, cobbly fine to coarse GRAVEL some silt, trace boulders; grey, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded unweathered schist [QUATERNARY DEBRIS FLOW].	QDF	353.0 (1.0)
	1.2–1.35	Tightly packed fine sandy SILT, trace fine gravel and fibrous organics, grey; dry, poorly graded, non-plastic. Gravel sub-angular to sub-rounded unweathered schist [QUATERNARY ALLUVIUM].	QA	
	1.35–2.6	Tightly packed fine to coarse sandy, cobbly, fine to coarse GRAVEL, trace fibrous organics, some silt; grey, dry, well graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist. Some boulders; sub-angular unweathered schist.	Quaternary Debris Flow	352.5 (1.5), 352.0 (2.0), 351.5 (2.5)
	2.6	END OF LOG @ 2.6 m		

Depth scale: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 m; RL scale: 353.5, 353.0, 352.5, 352.0, 351.5, 351.0, 350.5, 350.0, 349.5

Columns: FLUID LOSS | DAILY WATER LEVEL | CORE RECOVERY | METHOD | CASING | RQD | IN-SITU TESTS (SV, τ (kPa), SPT 'N') | SAMPLES | DEPTH (m) | GRAPHIC LOG | SOIL / ROCK DESCRIPTION | GEOLOGICAL UNIT | R L (m)

DATE STARTED: 13/2/20
DATE FINISHED: 13/2/20
LOGGED BY: SB
SHEAR VANE No:
DRILLED BY: Wilsons Contractors
EQUIPMENT: Hitachi Zaxis 135 US (14t)
DRILL METHOD: E
DRILL FLUID:
DIAMETER/INCLINATION: -/ 90°

COMMENTS:
End of test pit at 2.6 m. Test pit terminated early due to collapse.
Groundwater not encountered.
Coordinates and RL obtained from handheld GPS with reference to WGS84.

FOR EXPLANATION OF SYMBOLS AND ABBREVIATIONS SEE KEY SHEET

A4 Scale 1:25

BOREHOLE No: **BS_TP02**

MACHINE BOREHOLE LOG

PROJECT: Natural Hazards Affecting Gorge Road
JOB NUMBER: 3209881
SITE LOCATION: Queenstown
CLIENT: Queenstown Lakes District Council

CIRCUIT: NZTM
COORDINATES: N 5,005,630 m, E 1,258,144 m
BOREHOLE LOCATION: 1 Bowen Street
R L: 351 m
DATUM: NZVD2016
COORDINATE ORIGIN: hhGPS
ACCURACY: ±5m

Method	Samples	Depth (m)	Soil / Rock Description	Geological Unit	RL (m)
E		0.0–0.2	Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded unweathered sandstone and schist.	Fill	351.0
		0.2–1.0 (0.5)	Loosely packed silty, fine sandy fine to coarse GRAVEL, trace cobbles; tan, dry, well-graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist.	Fill	350.5
	S1, S2, S3	1.0–2.4 (1.5, 2.0)	Loosely packed fine to coarse sandy, fine to coarse gravelly COBBLES, some boulders; light brown, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded unweathered schist. Trace fibrous organics. Tree stump (1.5 m)	Quaternary Debris Flow	350.0
	S4	2.4–3.0 (2.5)	Tightly packed fine sandy fine to coarse gravelly SILT, some cobbles; light brown, dry, well graded, non-plastic. Gravel to cobbles sub-angular to sub-rounded unweathered schist. Trace fibrous organics.	Quaternary Debris Flow	348.5
		3.0	END OF LOG @ 3 m		348.0

DATE STARTED: 13/2/20
DATE FINISHED: 13/2/20
LOGGED BY: SB
SHEAR VANE No:
DRILLED BY: Wilsons Contractors
EQUIPMENT: Hitachi Zaxis 135 US (14t)
DRILL METHOD: E
DRILL FLUID:
DIAMETER/INCLINATION: -/ 90°

COMMENTS:
End of test pit at 3.0 m at target depth.
Groundwater not encountered.
Coordinates and RL obtained from handheld GPS with reference to WGS84.

FOR EXPLANATION OF SYMBOLS AND ABBREVIATIONS SEE KEY SHEET

A4 Scale 1:25

BOREHOLE No: **BS_TP03**

MACHINE BOREHOLE LOG

PROJECT: Natural Hazards Affecting Gorge Road — JOB NUMBER: 3209881
SITE LOCATION: Queenstown — CLIENT: Queenstown Lakes District Council

CIRCUIT: NZTM
COORDINATES: N 5,005,644 m, E 1,258,153 m
BOREHOLE LOCATION: 1 Bowen Street
R L: 352 m
DATUM: NZVD2016
COORDINATE ORIGIN: hhGPS
ACCURACY: ±5m

Depth (m)	Method	Soil / Rock Description	Geological Unit	R L (m)
0.0–0.15	E	Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded unweathered sandstone and schist.	Fill	
0.15–2.1		Loosely packed fine sandy fine to coarse gravelly COBBLES, some silt, trace boulders; tan, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded unweathered schist.	Fill	
~1.4		Some fibrous organics.		
~1.7		Trace red bricks		
2.1–2.3		Tightly packed fine sandy SILT, some fine gravel; brown, dry, well graded, non-plastic. Gravel sub-angular to sub-rounded unweathered schist [Buried topsoil; QUATERNARY ALLUVIUM].	QA	
2.3–3.0		Tightly packed fine to coarse sandy, fine to coarse gravelly, COBBLES, some silt; tan, dry, well graded, non-plastic. Gravel and cobbles sub-angular to sub-rounded unweathered schist.	Quaternary Debris Flow	
3.0		END OF LOG @ 3 m		349.0

Depth scale: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 m; RL scale: 351.5, 351.0, 350.5, 350.0, 349.5, 349.0, 348.5, 348.0, 347.5 m.

Columns: FLUID LOSS | DAILY WATER LEVEL | CORE RECOVERY | METHOD | CASING | RQD | IN-SITU TESTS (SV, τ (kPa), SPT 'N') | SAMPLES | DEPTH (m) | GRAPHIC LOG | SOIL / ROCK DESCRIPTION | GEOLOGICAL UNIT | R L (m)

DATE STARTED: 13/2/20
DATE FINISHED: 13/2/20
LOGGED BY: SB
SHEAR VANE No:
DRILLED BY: Wilsons Contractors
EQUIPMENT: Hitachi Zaxis 135 US (14t)
DRILL METHOD: E
DRILL FLUID:
DIAMETER/INCLINATION: -/ 90°

COMMENTS:
End of test pit at 3.0 m at target depth.
Groundwater not encountered.
Coordinates and RL obtained from handheld GPS with reference to WGS84.

FOR EXPLANATION OF SYMBOLS AND ABBREVIATIONS SEE KEY SHEET

A4 Scale 1:25

BOREHOLE No: BS_TP04

MACHINE BOREHOLE LOG

PROJECT: Natural Hazards Affecting Gorge Road
JOB NUMBER: 3209881
SITE LOCATION: Queenstown
CLIENT: Queenstown Lakes District Council

CIRCUIT: NZTM
COORDINATES: N 5,005,617 m
E 1,258,172 m
BOREHOLE LOCATION: 1 Bowen Street
R L: 345 m
DATUM: NZVD2016
COORDINATE ORIGIN: hhGPS
ACCURACY: ±5m

DEPTH (m)	METHOD	SOIL / ROCK DESCRIPTION	GEOLOGICAL UNIT	R L (m)
0.0–0.4	E	Loosely packed silty fine sandy fine to coarse GRAVEL, trace cobbles; grey, well graded, dry, non-plastic. Gravel sub-rounded unweathered sandstone and schist.	Fill	
0.4–0.7		Loosely packed silty fine SAND, some fine gravel, trace fibrous organics; light brown, dry, well graded, non-plastic. Gravel sub-angular to sub-rounded unweathered schist [QUATERNARY ALLUVIUM].	QA	344.5 (0.5)
0.7–0.8		Tightly packed sandy SILT; tan, dry, poorly graded, non-plastic [QUATERNARY ALLUVIUM].	QA	
0.8–3.0		Tightly packed fine to coarse sandy, fine to coarse gravelly COBBLES, some boulders, trace silt; light brown, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-angular to sub-rounded unweathered schist.	Quaternary Debris Flow	344.0 (1.0), 343.5 (1.5), 343.0 (2.0)
2.1		Some boulders; sub-angular to sub-rounded unweathered schist.	Quaternary Debris Flow	342.5 (2.5)
3.0		END OF LOG @ 3 m		342.0

Depth scale: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5
R L scale: 344.5, 344.0, 343.5, 343.0, 342.5, 342.0, 341.5, 341.0, 340.5

Column headings: DRILLING (FLUID LOSS, DAILY WATER LEVEL, CORE RECOVERY, METHOD, CASING, RQD); IN-SITU TESTS (SV, τ (kPa), SPT 'N'); SAMPLES; DEPTH (m); GRAPHIC LOG; SOIL / ROCK DESCRIPTION; GEOLOGICAL UNIT; R L (m)

DATE STARTED: 13/2/20
DATE FINISHED: 13/2/20
LOGGED BY: SB
SHEAR VANE No:
DRILLED BY: Wilsons Contractors
EQUIPMENT: Hitachi Zaxis 135 US (14t)
DRILL METHOD: E
DRILL FLUID:
DIAMETER/INCLINATION: -/ 90°

COMMENTS:
End of test pit at 3.0 m at target depth.
Groundwater not encountered.
Coordinates and RL obtained from handheld GPS with reference to WGS84.

FOR EXPLANATION OF SYMBOLS AND ABBREVIATIONS SEE KEY SHEET

Beca

BOREHOLE No: HS_TP01

MACHINE BOREHOLE LOG

PROJECT:	Natural Hazards Affecting Gorge Road	JOB NUMBER:	3209881
SITE LOCATION:	Queenstown	CLIENT:	Queenstown Lakes District Council

CIRCUIT:	NZTM	BOREHOLE LOCATION:	14 Huff Street		
COORDINATES:	N 5,005,080 m	R L:	350 m	COORDINATE ORIGIN:	hhGPS
	E 1,257,912 m	DATUM:	NZVD2016	ACCURACY:	±5m

METHOD	SAMPLES	DEPTH (m)	SOIL / ROCK DESCRIPTION	GEOLOGICAL UNIT	R L (m)
E		0.0 – 0.3	Loosely packed fine sandy SILT, trace fibrous organics (rootlets); dark brown, dry, poorly graded, non-plastic [QUATERNARY ALLUVIUM].	QA	
	S1	0.3 – 2.0	Loosely packed silty fine sandy COBBLES, some medium to coarse gravel, trace boulders; tan, dry, well graded, non-plastic. Gravel, cobbles, and boulders sub-rounded to sub-angular unweathered schist.	Quaternary Debris Flow	349.5 (0.5), 349.0 (1.0), 348.5 (1.5), 348.0 (2.0)
		2.0	END OF LOG @ 2 m		

Other column headings (no entries): DRILLING: FLUID LOSS, DAILY WATER LEVEL, CORE RECOVERY, CASING, RQD; IN-SITU TESTS: SV, τ (kPa), SPT 'N'; GRAPHIC LOG.

Depth scale: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 — R L (m): 349.5, 349.0, 348.5, 348.0, 347.5, 347.0, 346.5, 346.0, 345.5

DATE STARTED:	14/2/20	DRILLED BY:	Wilsons Contractors
DATE FINISHED:	14/2/20	EQUIPMENT:	Kubota U17-3 (1.7t)
LOGGED BY:	SB	DRILL METHOD:	E
SHEAR VANE No:		DRILL FLUID:	
		DIAMETER/INCLINATION:	-/ 90°

COMMENTS:
End of test pit at 2.0 m at target depth.
Groundwater not encountered.
Coordinates and RL obtained from handheld GPS with reference to WGS84.

FOR EXPLANATION OF SYMBOLS AND ABBREVIATIONS SEE KEY SHEET

A4 Scale 1:25

THE UNIVERSITY OF WAIKATO
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email c14@waikato.ac.nz

Radiocarbon Dating Laboratory

Tuesday, 10 March 2020

Report on Radiocarbon Age Determination for Wk- 51012

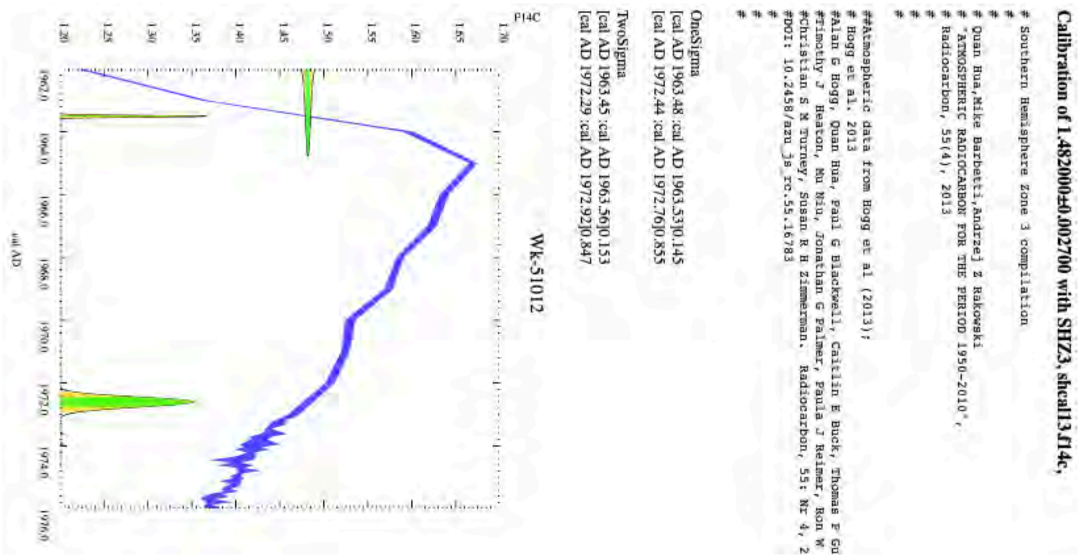
Submitter	A Punt
Submitter's Code	BS_TP02_S2
Site & Location	1 Bowen Strreet, Queenstown, New Zealand
Sample Material	root/twig
Physical Pretreatment	Sample cleaned and ground.
Chemical Pretreatment	Sample washed in hot HCl, rinsed and treated with multiple hot NaOH washes. The NaOH insoluble fraction was treated with hot HCl, filtered, rinsed and dried.

$D^{14}C$	482.1 ± 2.7 ‰
$F^{14}C\%$	148.2 ± 0.3 %
Result	**148.2 ± 0.3 %**

(AMS measurement)

Comments

Please note: The Carbon-13 stable isotope value ($\delta^{13}C$) was measured on prepared graphite using the AMS spectrometer. The radiocarbon date has therefore been corrected for isotopic fractionation. However the AMS-measured $\delta^{13}C$ value can differ from the $\delta^{13}C$ of the original material and it is therefore not shown.



- Explanation of the calibrated Oxcal plots can be found at the Oxford Radiocarbon Accelerator Unit's calibration web pages (http://c14.arch.ox.ac.uk/embed.php?File=explanation.php)
- Result is *Conventional Age or Percent Modern Carbon (pMC)* 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 Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier.
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB and is measured on sample CO_2.
- $F^{14}C\%$ is also known as *Percent Modern Carbon (pMC).*

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Radiocarbon Dating Laboratory

Tuesday, 10 March 2020

Report on Radiocarbon Age Determination for Wk- 51013

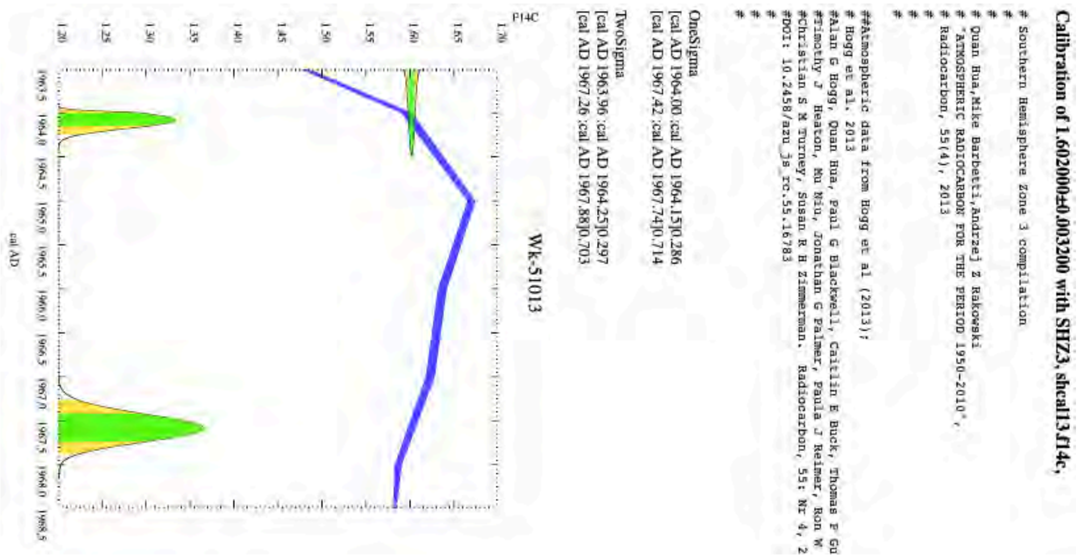
Submitter	A Punt
Submitter's Code	BS_TP02_S3
Site & Location	1 Bowen Strreet, Queenstown, New Zealand
Sample Material	root/twig
Physical Pretreatment	Sample cleaned and ground.
Chemical Pretreatment	Sample washed in hot HCl, rinsed and treated with multiple hot NaOH washes. The NaOH insoluble fraction was treated with hot HCl, filtered, rinsed and dried.

$D^{14}C$	601.8 ±	3.2 ‰
$F^{14}C\%$	160.2 ±	0.3 %
Result	**160.2 ± 0.4 %**	

(AMS measurement)

Comments

Please note: The Carbon-13 stable isotope value ($\delta^{13}C$) was measured on prepared graphite using the AMS spectrometer. The radiocarbon date has therefore been corrected for isotopic fractionation. However the AMS-measured $\delta^{13}C$ value can differ from the $\delta^{13}C$ of the original material and it is therefore not shown.



- Explanation of the calibrated Oxcal plots can be found at the Oxford Radiocarbon Accelerator Unit's calibration web pages (http://c14.arch.ox.ac.uk/embed.php?File=explanation.php)
- Result is *Conventional Age or Percent Modern Carbon (pMC)* 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 Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier.
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB and is measured on sample CO_2.
- $F^{14}C\%$ is also known as *Percent Modern Carbon (pMC).*

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Radiocarbon Dating Laboratory

Tuesday, 10 March 2020

Report on Radiocarbon Age Determination for Wk- 51014

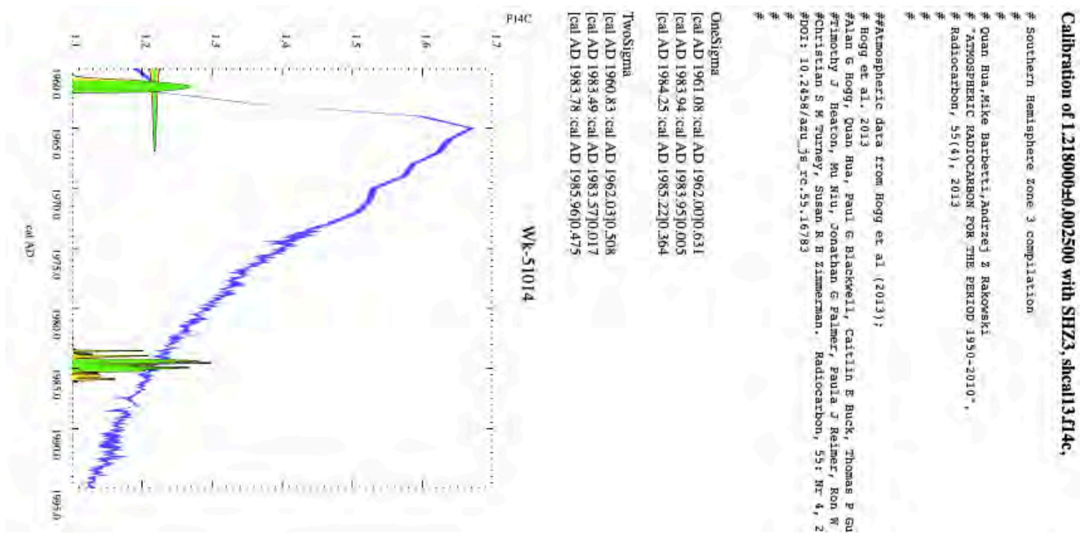
Submitter	A Punt
Submitter's Code	BS_TP02_S4
Site & Location	1 Bowen Strreet, Queenstown, New Zealand
Sample Material	root/twig
Physical Pretreatment	Sample cleaned and ground.
Chemical Pretreatment	Sample washed in hot HCl, rinsed and treated with multiple hot NaOH washes. The NaOH insoluble fraction was treated with hot HCl, filtered, rinsed and dried.

$D^{14}C$	218.1 ±	2.5 ‰
$F^{14}C\%$	121.8 ±	0.2 %
Result	**121.8 ± 0.3 %**	

(AMS measurement)

Comments

Please note: The Carbon-13 stable isotope value ($\delta^{13}C$) was measured on prepared graphite using the AMS spectrometer. The radiocarbon date has therefore been corrected for isotopic fractionation. However the AMS-measured $\delta^{13}C$ value can differ from the $\delta^{13}C$ of the original material and it is therefore not shown.



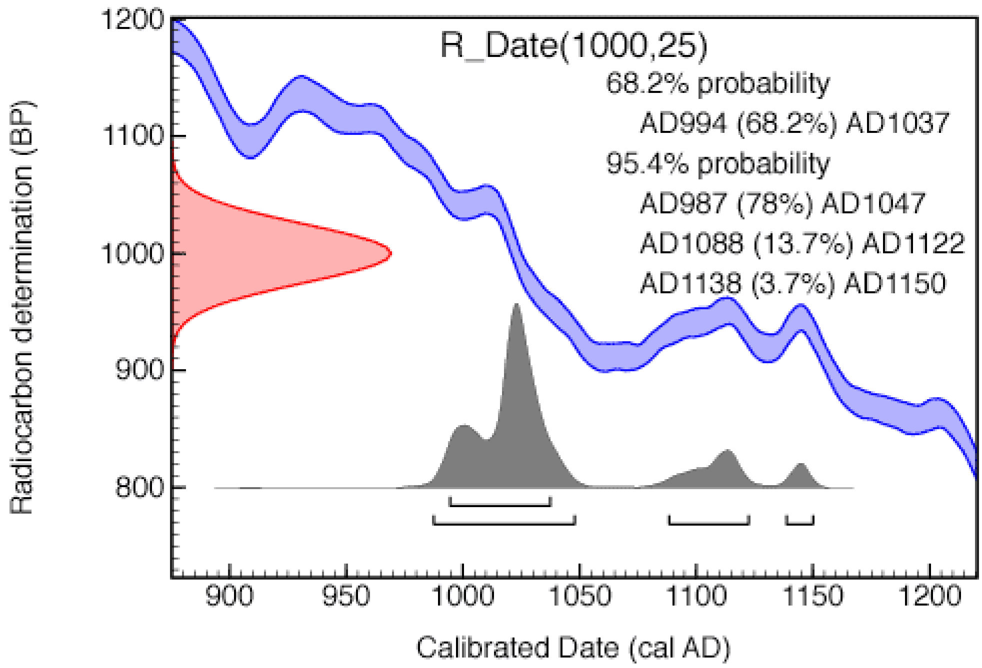
- Explanation of the calibrated Oxcal plots can be found at the Oxford Radiocarbon Accelerator Unit's calibration web pages (http://c14.arch.ox.ac.uk/embed.php?File=explanation.php)
- Result is *Conventional Age or Percent Modern Carbon (pMC)* following Stuiver and Polach, 1977, Radiocarbon 19, 355-363. 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 Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier.
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB and is measured on sample CO_2.
- $F^{14}C\%$ is also known as *Percent Modern Carbon (pMC).*

Explanation of radiocarbon results

A radiocarbon determination is a measure of the amount of radiocarbon in a sample. While any organism is alive it continues to incorporate radiocarbon from the atmosphere. Once it has died the amount gradually declines because of radioactive decay.

Measurements of radiocarbon concentration are usually expressed in terms of a notional age, in numbers of years before 1950. For example, the radiocarbon result 1000±25BP indicates that the notional age is 1000 years with a standard uncertainty of 25 years. This notional age is calculated on the simplistic assumption that the amount of radiocarbon in the atmosphere has always been the same. This is not quite the case and so for anything other than a very rough indication of age the measurement must be calibrated.

Calibration is performed by comparing the radiocarbon measurements on the sample to those made on material (usually tree rings) of known age. This comparison allows one to determine the possible calendar age of the sample. An example calibration is shown here:



The main elements of this plot are:

- the radiocarbon determination itself shown on the left hand axis
- the measurements on known age material shown as the uneven double line
- the likelihood of different possible ages of the sample shown as the solid grey distribution - from this you can see that the most likely date is just after AD1000

The range of possible ages is also shown for two different levels of confidence. We can be 68% sure that the sample dates to between cal AD 994 and cal AD 1037 but there is a reasonable chance (32%) that it is older or younger than this. However we can be 95% certain that it dates to the period cal AD 987 to AD1047, the period cal AD 1088 to cal AD1122 or the period cal AD 1138 to cal AD 1150. The values given within the brackets give the relative likelihood of the individual ranges.

See also Explanation of radiocarbon results from the modern period.

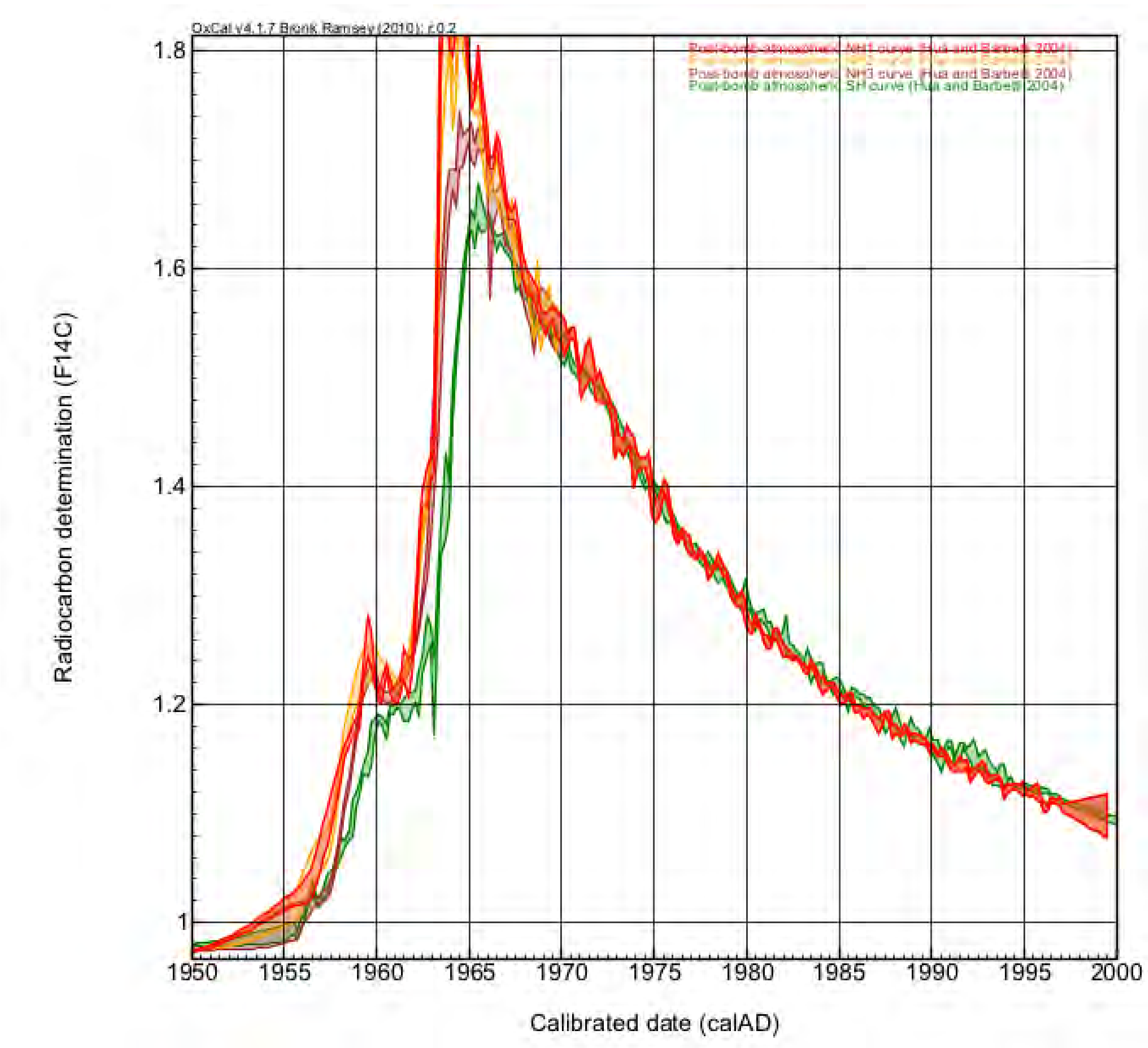
Document:14/3 version 6

ORAU > Dating services > Results > Explanation of modern results

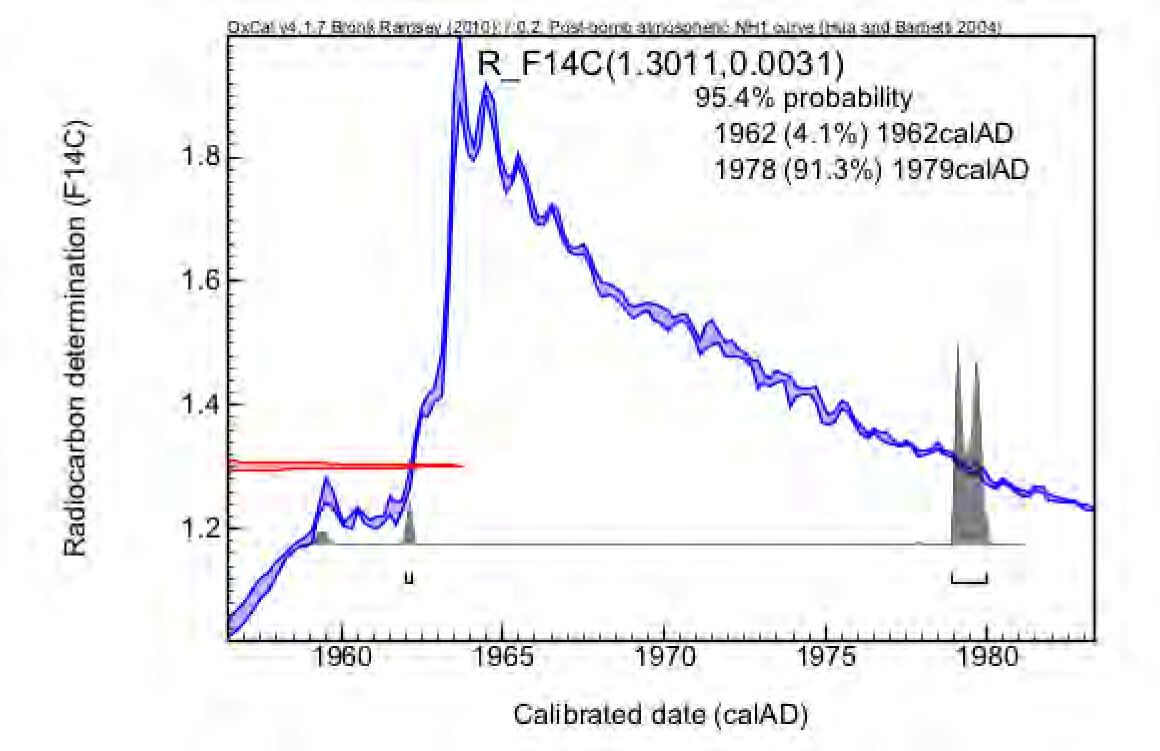
Explanation of radiocarbon results from the modern period

A radiocarbon determination is a measure of the amount of radiocarbon in the sample. When any organism is alive it continues to take up radiocarbon from the atmosphere, but once it has died the amount gradually declines because of radioactive decay.

In the 1940s, the first atomic nuclear bombs were exploded. Radiocarbon (14C) is created artificially through this process. In the 1950s and 60s atmospheric testing saw large amounts of 'bomb' radiocarbon created, such that in the mid 1960s the radiocarbon in the atmosphere was double its natural amount. Since then, the level has declined as radiocarbon enters the biosphere. The illustration below shows atmospheric radiocarbon measurements, collected from three latitudinal stations in the northern hemisphere, and in the southern hemisphere, showing the precise concentration of atmospheric radiocarbon throughout the mid to late 20th century.



Calibration is performed by comparing the radiocarbon measurement (or measurements) made on your sample to these known age records of atmospheric radiocarbon. An example is given below.



The main elements of this plot are:

- the radiocarbon measurement in fraction modern shown on the left hand axis in red
- the measurements of the known age atmospheric 'bomb' carbon, shown as the wiggly blue line
- the likelihood of the different possible ages, shown as the solid grey distribution - from this you can see that the most likely date in this example is 1978-1979 AD

The range of possible ages is also shown for other levels of confidence. We can be 68% sure that the sample dates to 1979. At 95% confidence we can be more than 90% confident that the sample dates between 1978-1979, but there is a small chance (4%) that the sample age dates from 1962.

See also Explanation of radiocarbon results.

Document:14/4 version 3

CPT Investigations

McMILLAN Drilling

CONE PENETRATION TEST

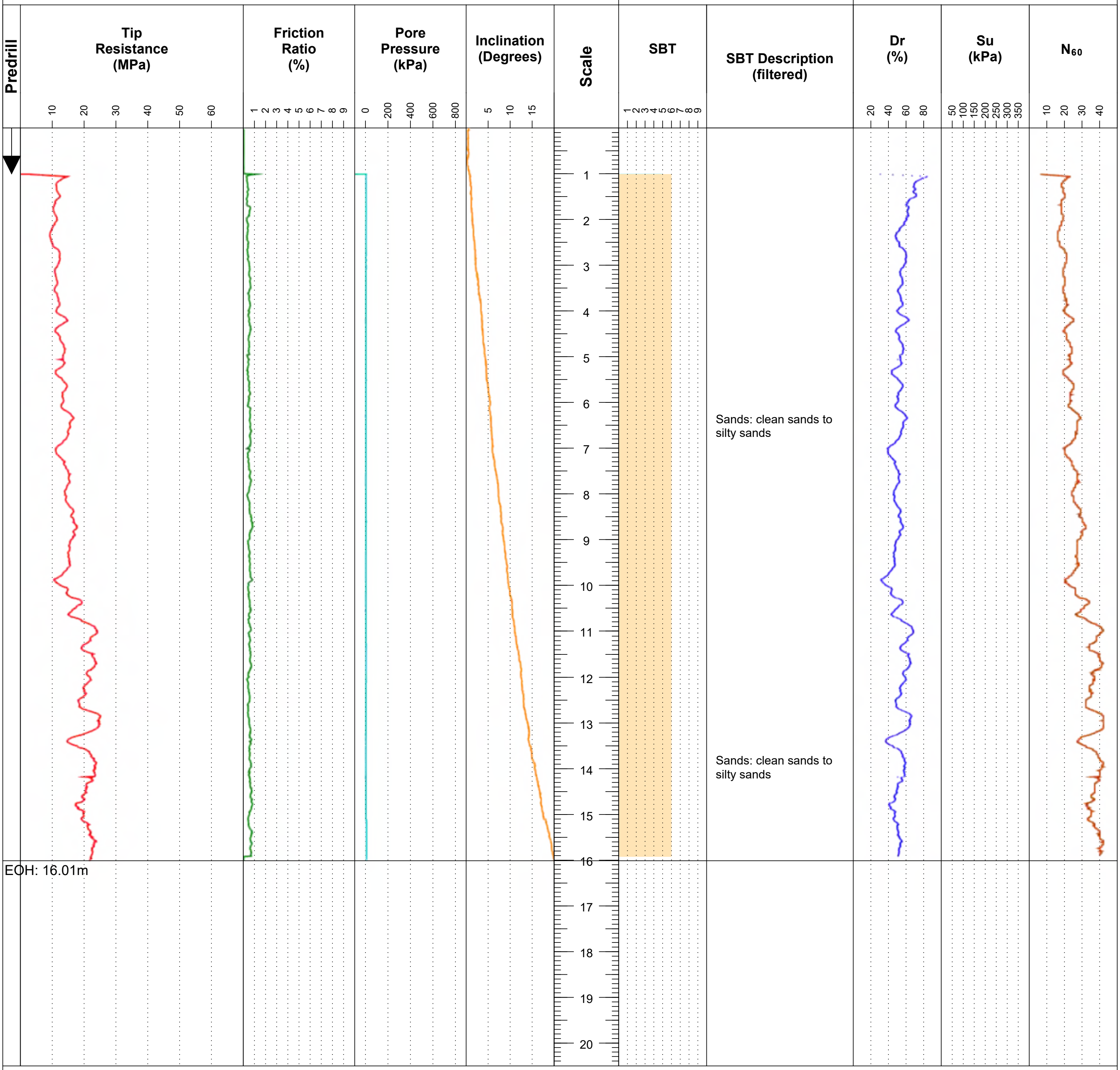
Job:	17839
CPT No.:	CPTu001

Name: Various locations, Queenstown
Client: Beca
Location: Industrial Place - Gorge Road, Queenstown

Hole Depth (m): 16.01
Elevation (m): 0.00
Datum: Ground

North (m): 5005897.62
East (m): 1258305.93
Grid: NZTM

RAW DATA	SOIL BEHAVIOUR TYPE (NON-NORMALISED)	ESTIMATED PARAMETERS



Operator: R. Wyllie
Rig: Geomil Panther 100
Cone Reference: 170302
Cone Area Ratio: 0.75
Cone Type: I-CFXYP20-15
Tip Resistance (MPa) Initial: -1.6032 **Final:** -1.4522
Local Friction (MPa) Initial: 0.027 **Final:** 0.0139
Pore Pressure (MPa) Initial: -0.007 **Final:** -0.0053

Date: 15/01/2019
Predrill: 1.00
Water Level: -
Collapse: 7.50

Effective Refusal
Tip:
Gauge:
Inclinometer: ✓
Other:

Target Depth:

Soil Behaviour Type (SBT) - Robertson et al. 1986

0	Undefined	5	Sand mixtures: silty sand to sandy silt
1	Sensitive fine-grained	6	Sands: clean sands to silty sands
2	Clay - organic soil	7	Dense sand to gravelly sand
3	Clays: clay to silty clay	8	Stiff sand to clayey sand
4	Silt mixtures: clayey silt & silty clay	9	Stiff fine-grained

Notes & Limitations

Data shown on this report has been assessed to provide a basic interpretation in terms of Soil Behaviour Type (SBT) and various geotechnical soil and design parameters using methods published in P. K. Robertson and K.L. Cabal (2010), Guide to Cone Penetration Testing for Geotechnical Engineering, 4th Edition. The interpretations are presented only as a guide for geotechnical use, and should be carefully reviewed by the user. Both McMillan Drilling Ltd & Geroc Solutions Ltd do not warranty the correctness or the applicability of any of the geotechnical soil and design parameters shown and does not assume any liability for any use of the results in any design or review. The user should be fully aware of the techniques and limitations of any method used to derive data shown in this report.

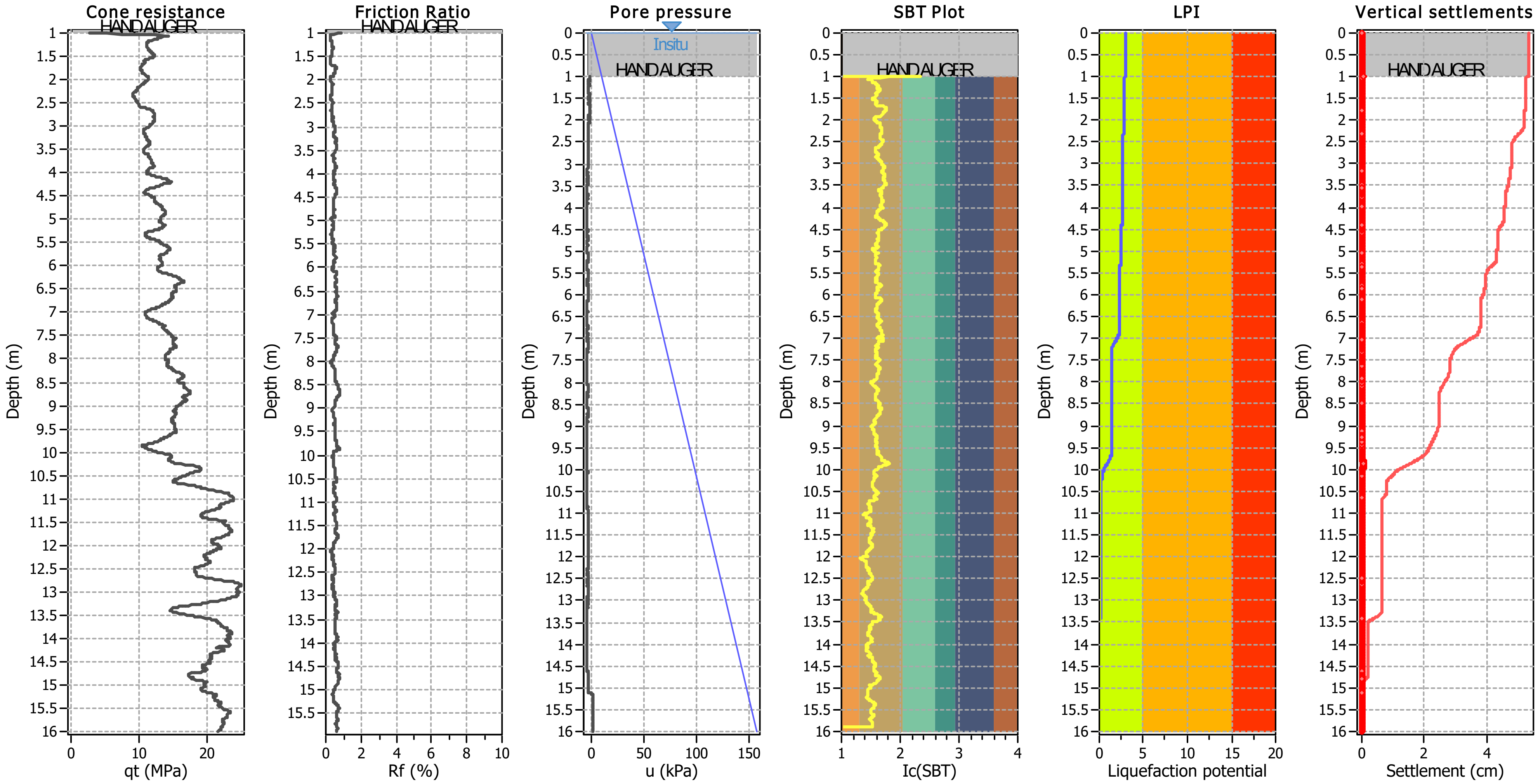
Remarks

Hole Depth (m): 16.01

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: Industrial Place.
Total depth: 16.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	0.00 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	0.00 m	Fill height:	N/A	Limit depth applied:	Yes
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	20.00 m
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

CONE PENETRATION TEST

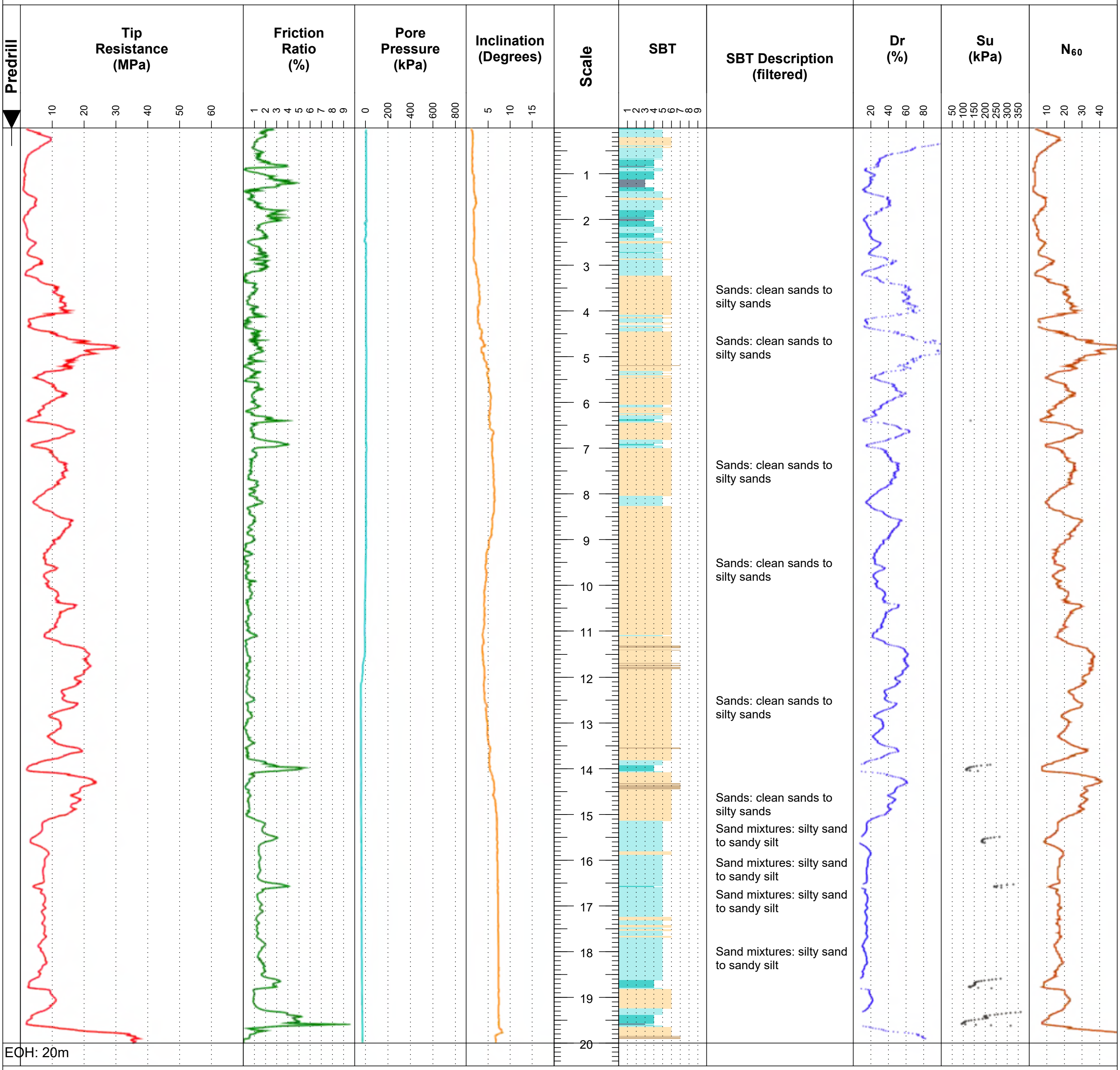
McMILLAN Drilling

Job: 17839
CPT No.: CPTu002

Name: Various locations, Queenstown
Client: Beca
Location: 29 Sawmill Road, Queenstown

Hole Depth (m): 20.00
Elevation (m): 0.00
Datum: Ground

North (m): 5005467.09
East (m): 1258078.55
Grid: NZTM



Operator: R. Wyllie
Rig: Geomil Panther 100
Cone Reference: 170302
Cone Area Ratio: 0.75
Cone Type: I-CFXYP20-15
Tip Resistance (MPa) Initial: -1.5499 **Final:** -1.5371
Local Friction (MPa) Initial: 0.0042 **Final:** -0.0005
Pore Pressure (MPa) Initial: -0.0026 **Final:** -0.0008

Date: 15/01/2019
Predrill: 0.00
Water Level: -
Collapse: 8.00

Effective Refusal
Tip:
Gauge:
Inclinometer:
Other:
Target Depth: ✓

Soil Behaviour Type (SBT) - Robertson et al. 1986

0	Undefined	5	Sand mixtures: silty sand to sandy silt
1	Sensitive fine-grained	6	Sands: clean sands to silty sands
2	Clay - organic soil	7	Dense sand to gravelly sand
3	Clays: clay to silty clay	8	Stiff sand to clayey sand
4	Silt mixtures: clayey silt & silty clay	9	Stiff fine-grained

Notes & Limitations

Data shown on this report has been assessed to provide a basic interpretation in terms of Soil Behaviour Type (SBT) and various geotechnical soil and design parameters using methods published in P. K. Robertson and K.L. Cabal (2010), Guide to Cone Penetration Testing for Geotechnical Engineering, 4th Edition. The interpretations are presented only as a guide for geotechnical use, and should be carefully reviewed by the user. Both McMillan Drilling Ltd & Geroc Solutions Ltd do not warrant the correctness or the applicability of any of the geotechnical soil and design parameters shown and does not assume any liability for any use of the results in any design or review. The user should be fully aware of the techniques and limitations of any method used to derive data shown in this report.

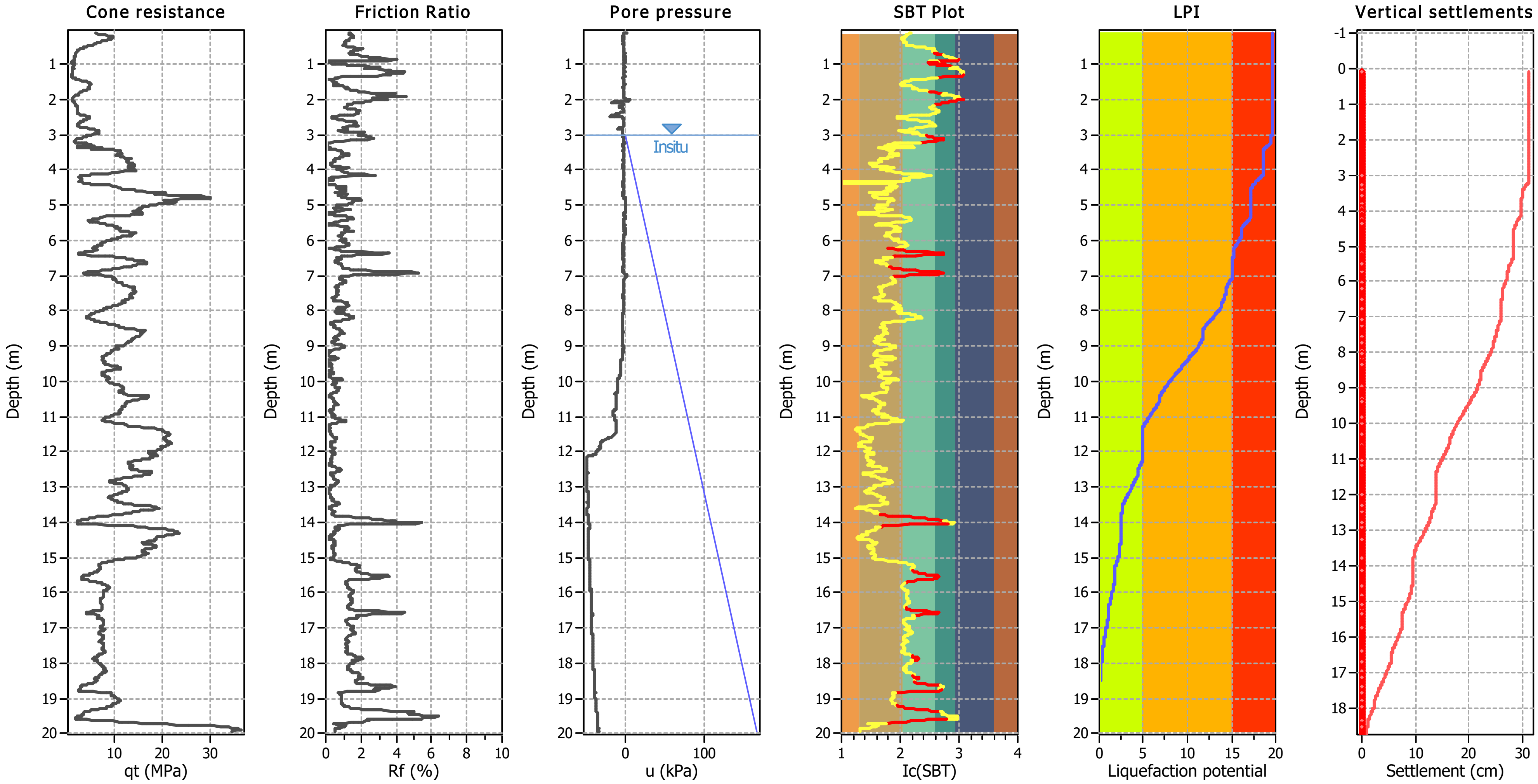
Remarks

Hole Depth (m): 20.00

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: 29 Sawmill Road
Total depth: 19.94 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	3.00 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	3.00 m	Fill height:	N/A	Limit depth applied:	Yes
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	20.00 m
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

CONE PENETRATION TEST

McMILLAN Drilling

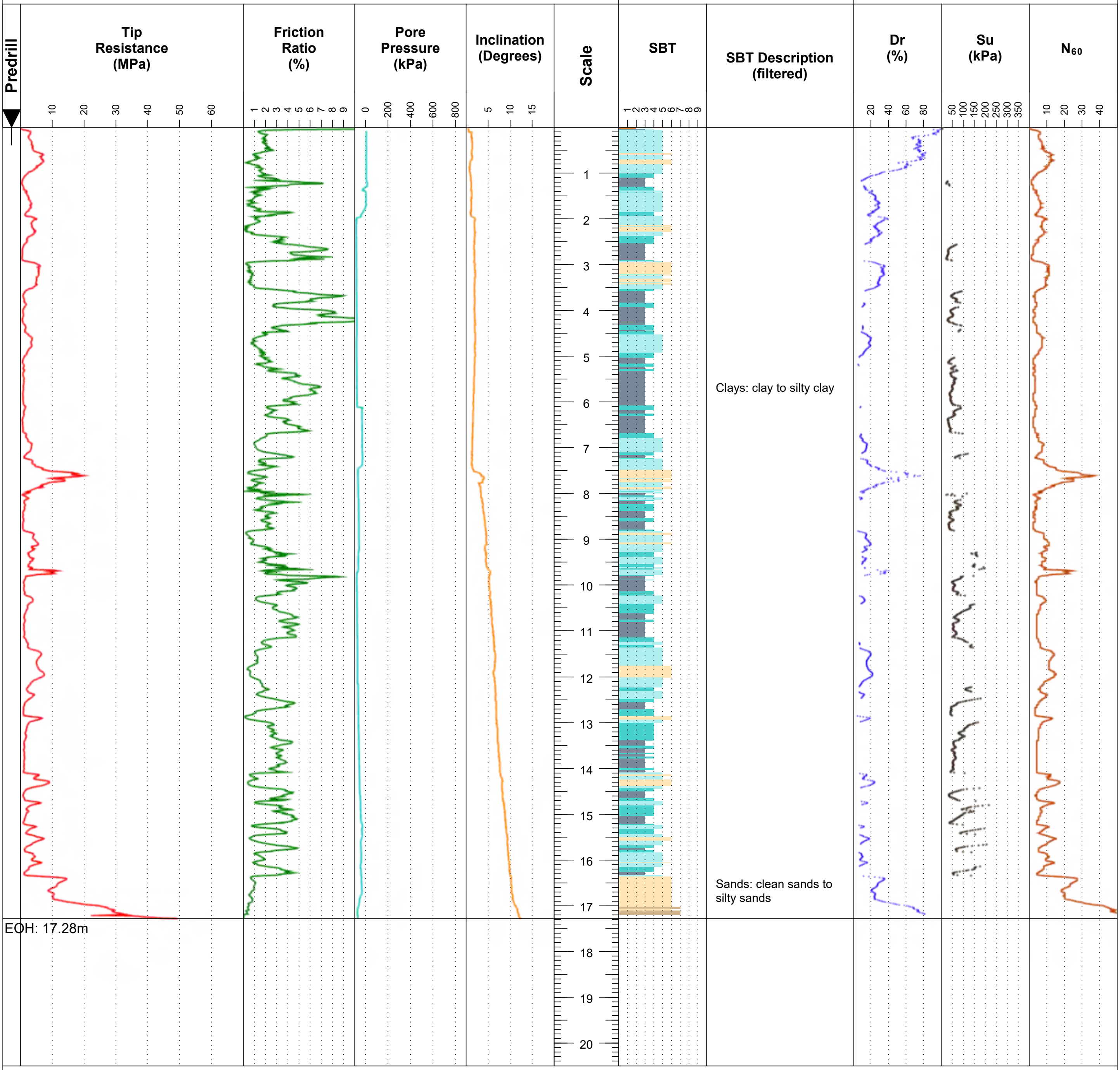
Job:	17839
CPT No.:	CPTu005

Name: Various locations, Queenstown
Client: Beca
Location: 30 Hamilton Road, Queenstown

Hole Depth (m): 17.28
Elevation (m): 0.00
Datum: Ground

North (m): 5004967.57
East (m): 1257974.88
Grid: NZTM

RAW DATA | SOIL BEHAVIOUR TYPE (NON-NORMALISED) | ESTIMATED PARAMETERS



Operator: R. Wyllie
Rig: Geomil Panther 100
Cone Reference: 160925
Cone Area Ratio: 0.75
Cone Type: I-CFXYP20-15
Tip Resistance (MPa) Initial: 0.1417 **Final:** 0.1319
Local Friction (MPa) Initial: 0.0066 **Final:** 0.0069
Pore Pressure (MPa) Initial: -0.02 **Final:** -0.0218

Date: 15/01/2019
Predrill: 0.00
Water Level: -
Collapse: 1.70

Effective Refusal
Tip:
Gauge: ✓
Inclinometer:
Other:
Target Depth:

Soil Behaviour Type (SBT) - Robertson et al. 1986

0	Undefined	5	Sand mixtures: silty sand to sandy silt
1	Sensitive fine-grained	6	Sands: clean sands to silty sands
2	Clay - organic soil	7	Dense sand to gravelly sand
3	Clays: clay to silty clay	8	Stiff sand to clayey sand
4	Silt mixtures: clayey silt & silty clay	9	Stiff fine-grained

Notes & Limitations

Data shown on this report has been assessed to provide a basic interpretation in terms of Soil Behaviour Type (SBT) and various geotechnical soil and design parameters using methods published in P. K. Robertson and K.L. Cabal (2010), Guide to Cone Penetration Testing for Geotechnical Engineering, 4th Edition. The interpretations are presented only as a guide for geotechnical use, and should be carefully reviewed by the user. Both McMillan Drilling Ltd & Geroc Solutions Ltd do not warranty the correctness or the applicability of any of the geotechnical soil and design parameters shown and does not assume any liability for any use of the results in any design or review. The user should be fully aware of the techniques and limitations of any method used to derive data shown in this report.

Remarks

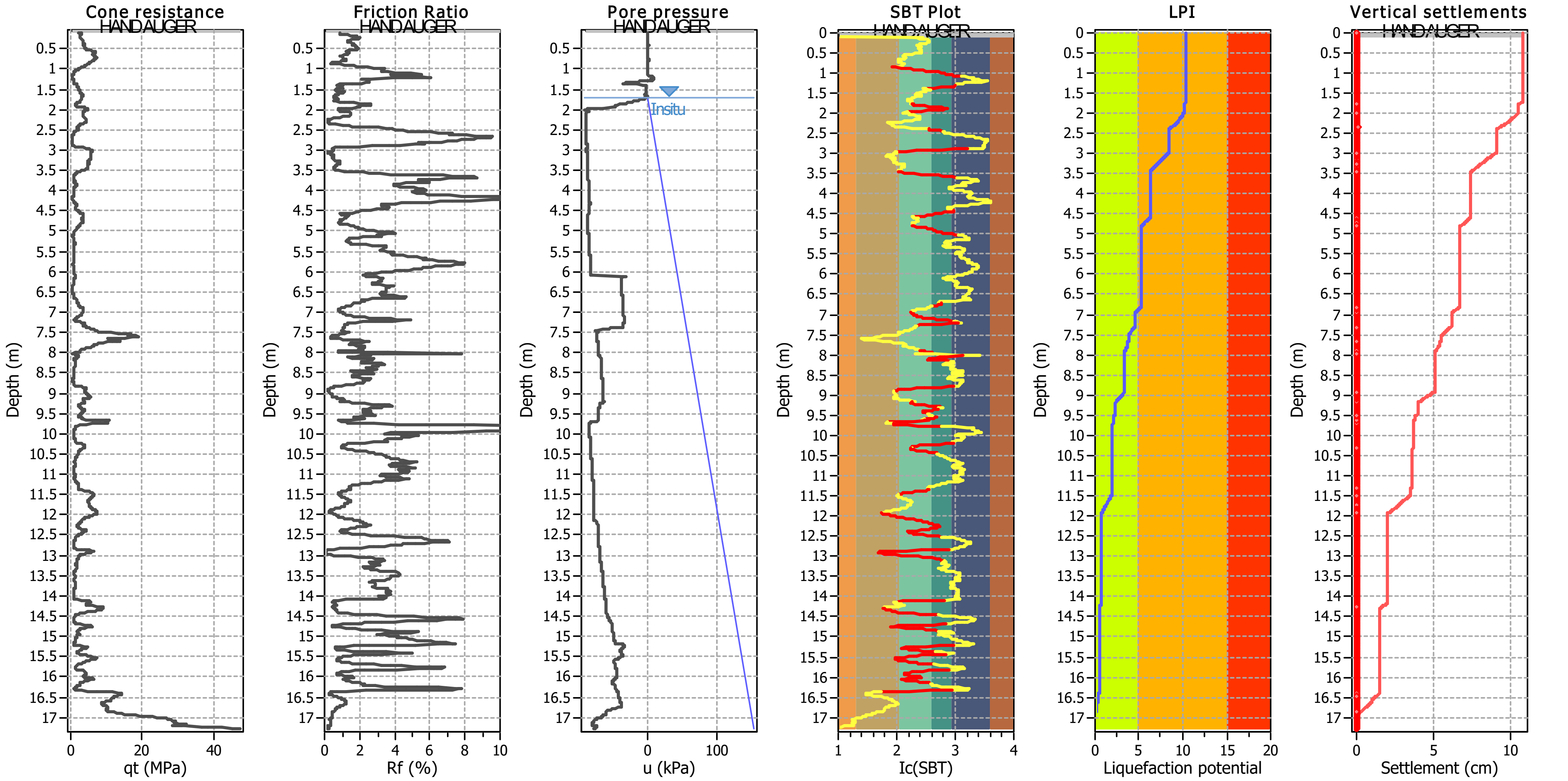
Hole Depth (m): 17.28

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: 30 Hamilton Road

Total depth: 17.28 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	1.70 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	1.70 m	Fill height:	N/A		
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth applied:	Yes
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	Limit depth:	20.00 m
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes	MSF method:	Method based

TEST DETAIL

PointID: CPTu001
Sounding: 1

Operator:	R. Wyllie	**Date:**	15/01/2019	**Effective Refusal**	
Cone Reference:	170302	**Predrill:**	1.00	**Tip:**	
Cone Area Ratio:	0.75	**Water Level:**	-	**Gauge:**	
Cone Type:	I-CFXYP20-15	**Collapse:**	7.50	**Inclinometer:**	✓
				Other:	
Tip Resistance (MPa) Initial:	-1.6032	**Final:**	-1.4522		
Local Friction (MPa) Initial:	0.027	**Final:**	0.0139		
Pore Pressure (MPa) Initial:	-0.007	**Final:**	-0.0053	**Target Depth:**	

PointID: CPTu002
Sounding: 2

Operator:	R. Wyllie	**Date:**	15/01/2019	**Effective Refusal**	
Cone Reference:	170302	**Predrill:**	0.00	**Tip:**	
Cone Area Ratio:	0.75	**Water Level:**	-	**Gauge:**	
Cone Type:	I-CFXYP20-15	**Collapse:**	8.00	**Inclinometer:**	
				Other:	
Tip Resistance (MPa) Initial:	-1.5499	**Final:**	-1.5371		
Local Friction (MPa) Initial:	0.0042	**Final:**	-0.0005		
Pore Pressure (MPa) Initial:	-0.0026	**Final:**	-0.0008	**Target Depth:**	✓

PointID: CPTu005
Sounding: 5

Operator:	R. Wyllie	**Date:**	15/01/2019	**Effective Refusal**	
Cone Reference:	160925	**Predrill:**	0.00	**Tip:**	
Cone Area Ratio:	0.75	**Water Level:**	-	**Gauge:**	✓
Cone Type:	I-CFXYP20-15	**Collapse:**	1.70	**Inclinometer:**	
				Other:	
Tip Resistance (MPa) Initial:	0.1417	**Final:**	0.1319		
Local Friction (MPa) Initial:	0.0066	**Final:**	0.0069		
Pore Pressure (MPa) Initial:	-0.02	**Final:**	-0.0218	**Target Depth:**	

CPT CALIBRATION AND TECHNICAL NOTES

These notes describe the technical specifications and associated calibration references pertaining to the following cone types:

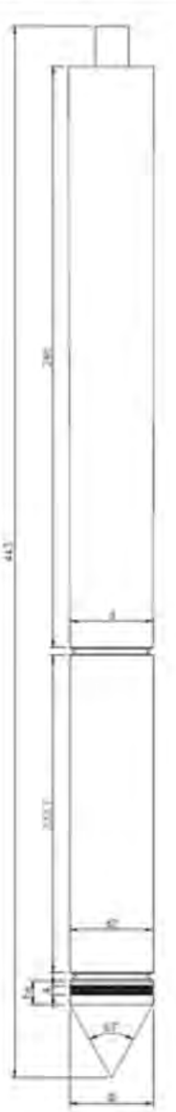
- I-CFXY-10 measuring cone resistance, sleeve friction and inclination (standard cone, 10cm²);
- I-CFXY-15 measuring cone resistance, sleeve friction and inclination (standard cone, 15cm²);
- I-CFXYP20-10 measuring cone resistance, sleeve friction, inclination and pore pressure (piezocone, 10cm²);
- I-CFXYP20-15 measuring cone resistance, sleeve friction, inclination and pore pressure (piezocone, 15cm²);
- I-C5F0p15XYP20-10 measuring sensitive cone resistance, sleeve friction, inclination and pore pressure (piezocone, 10cm²).

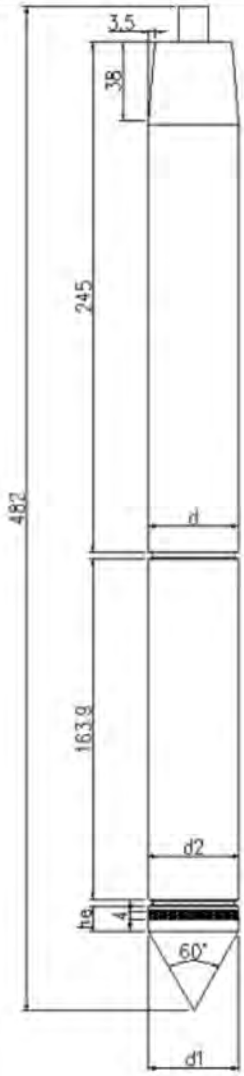
Dimensions

Dimensional specifications for all cone types are detailed below. All tolerances are routinely checked prior to testing and measurements taken are electronically recorded. All records are kept on file and available on request.

A.P. van den Berg Machinefabriek tel.: +31 (0)513-631355 info@apvandenberg.com	**DEVIATION of Straightness + MINIMUM Dimensions tip, friction jacket, cone adapter**	Standards: EN ISO 22476-1 APB-standard

Type of cone:	Icone 10 cm²	Icone 15 cm²
ALLOWABLE SIZE VARIATION		
Diameter of tip:	$35,3 \le d1 \le 36,0$	$43,2 \le d_1 \le 44,1$
Diameter of centering ring CFP	$35,3 \le d1 \le 36,0$	$43,2 \le d_1 \le 44,1$
Diameter of friction jacket:	$d_1 \le d_2 < d_1 + 0,35$	$d_1 \le d_2 < d_1 + 0,43$
Height dimension of tip edge:	$7 \le h_e \le 10$	$9 \le h_e \le 12$
PRODUCTION DIMENSIONS		
Tip:	$d_1 = 35,7\ ^{+0,2}_{0}$	$d_1 = 43,8\ ^{+0,2}_{0}$
Jacket (C-cone):	$d_2 = 35,7\ ^{+0,2}_{0}$	$d_2 = 43,7\ ^{+0,3}_{0}$
Friction jacket (CF-cone):	$d_2 = 35,9\ ^{+0,1}_{0}$	$d_2 = 44,0\ ^{+0,1}_{0}$
Tip for used cone:	$d_1 = 35,5\ ^{+0,1}_{0}$	$d_1 = 43,5\ ^{+0,1}_{0}$
MINIMUM DIMENSIONS		
Minimum diameter jacket (C-cone):	d_2 = 35,2 (APB standard)	d_2 = 43,0 (APB standard)
Minimum diameter friction jacket (CF-cone):	d_2 = 35,3	d_2 = 43,2
Use "used cone"-tip when friction jacket diameter:	$d_2 \le 35,65$	$d_2 \le 43,7$
Minimum diameter of cone adaptor:	d = 35,3	d = 43,8
Maximum deviation of straightness:	1 mm on a length of 1000 mm (max. oscillation 1,0 mm.)	1 mm on a length of 1000 mm (max. oscillation: 2.0 mm)

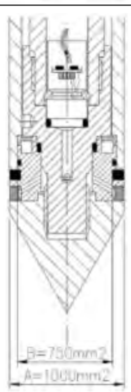




Tip and Local Friction sensor displacement

The different distances of the sensors are compensated depending on the cone types:

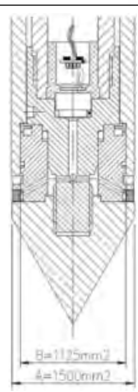
- 10cm² cones: 80mm
- 15cm² cones: 100mm



Cone area ratio

α = B / A = 0.75

β = 1 - B / A = 0.25



McMILLAN Drilling

CPT CALIBRATION AND TECHNICAL NOTES (cont.)

Calibration

Each cone has a unique identification number that is electronically recorded and reported for each CPT test. The identification number enables the operator to compare 'zero-load offsets' to manufacturer calibrated zero-load offsets.

The recommended maximum zero-load offset for each sensor is determined as ± 5% of the nominal measuring range.

In addition to maximum zero-load offsets, McMillan Drilling also limits the difference in zero load offset before and after the test as ± 2% of the maximum measuring range. See table below:

	Tip (MPa)	**Friction (MPa)**	**Pore Pressure (MPa)**
Maximum Measuring Range:	150	1.50	3.00
Nominal Measuring Range:	75	1.00	2.00
Max. 'zero-load offset':	7.5	0.10	0.20
Max 'before and after test':	3	0.03	0.06

Note: The zero offsets are electronically recorded and reported for each test in the same units as that of each sensor.

TEST CERTIFICATE
Icone (all versions)

Supplier:	A.P. v.d. Berg Machinefabriek, Heerenveen The Netherlands
Production-order:	81262
Client:	mc millan
Cone-type:	I-CFXYP20-15
Cone-number:	160925

To test / To check item	Required value	Checked value	
Check Quad-ring groove behind friction sleeve with check ring; **Sample testing: 1 of every 5 Icones is tested.**	Sleeve fixed	\	
Isolation-resistance.	>0.5 GΩ	2 GΩ	
Straightness: Icone 5, 10 and 15 cm^2 S < 2.2. mm. At Icone base: S < 0,2 mm	S<= 2,2 mm	0,2 mm	
"Classic calibration" NOT present! Check of calibration-file: "Classic calibration" removed.	O.K.	\	
Check alarm-settings Icone. Alarm values are set. (Kill Shutdown).	O.K.	O.K.	
Software version - check at opening screen. (from 18 Jan 2018 v. 2.3)	version: 2.3	O.K	
Calibration date of Icone; check cone data [F1]..[F1].	Yes	O.K.	
Initial zero-Value Tip after calibration – within 1.0 % of nominal load.	O.K.	-0.039	-0.002
Initial zero-Value Local Friction after calibration – within 1.0% of nominal load.	O.K.	-0.0018	0.001
Initial zero-Value Pore Pressure after calibration – within 1.0% of nominal load.	O.K.	-1,5	-1.3
Initial zero-Value Inclination X. Initial zero-Value Inclination Y.	-1°< X <+1° -1° < Y <+1°	-1.0 ° -0.3 °	
Measurements Tip resistance OK?	Tested range:	0-75mPa	
Influence Tip load on **Local Friction and Pore Pressure:** Max. tip load: 5 cm^2: 100 MPa; 10 cm^2: 100 MPa; 15 cm^2: 75 MPa.	LF < 10 kPa PP <½% nom	6,5 kPa 0,2 kPa	
Measurements local friction OK?	Tested range:	0-1mPa	
Local friction at max. load.	Tested value:	1,5 mPa	
Measurements Pore Pressure OK?	Tested range:	0-2000 kPa	
Measure Pore Pressure to 150%.	Tested value:	3000 kPa	
Measurements Inclination OK?	Tested range:	24°-0-24°	
Cone recognition on disconnecting and connecting Icone again?	Yes	O.K.	

Remarks:

Calibrated by: C. J. Ouwejan	Date: 17-10-18	Sign.: [signature]
Final check: T. Bossche	Date: 17-10-18	Sign.: [signature]

R:\E&D\Beproevingsprotocollen\Beproevingsprotocol Icone English ver 3.1.docx

TEST CERTIFICATE
Icone (all versions)

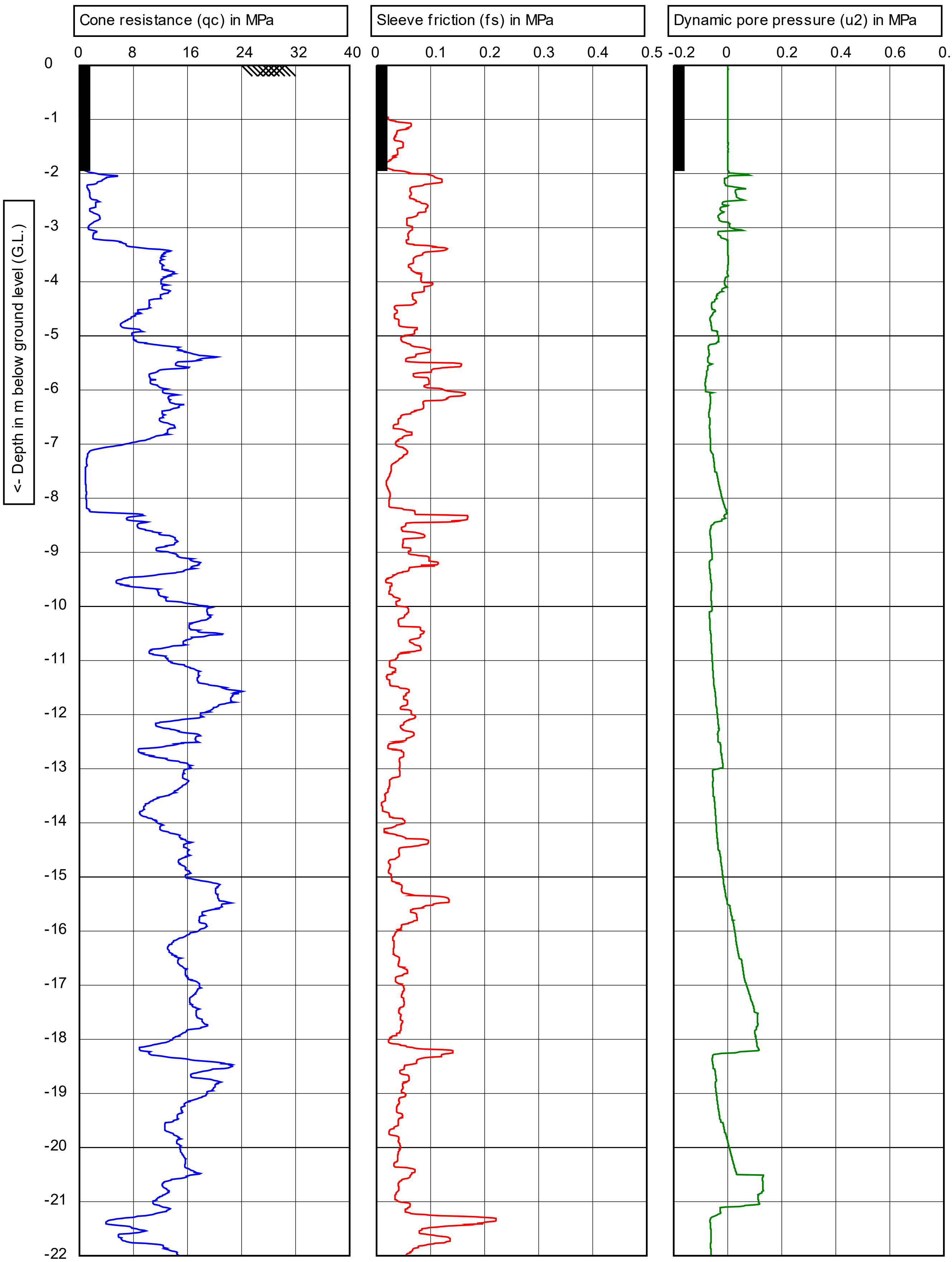
Supplier:	A.P. v.d. Berg Machinefabriek, Heerenveen The Netherlands
Production-order:	80591
Client:	mc millan
Cone-type:	I-CFXYP20-15
Cone-number:	170302

To test / To check item	Required value	Checked value	
Check Quad-ring groove behind friction sleeve with check ring; **Sample testing: 1 of every 5 Icones is tested.**	Sleeve fixed	\	
Isolation-resistance.	>0.5 GΩ	0,5 GΩ	
Straightness: Icone 5, 10 and 15 cm² S < 2.2. mm. At Icone base: S < 0,2 mm	S<= 2,2 mm	0,8 mm	
"Classic calibration" NOT present! Check of calibration-file: "Classic calibration" removed.	O.K.	\	
Check alarm-settings Icone. Alarm values are set. (Kill Shutdown).	O.K.	O.K.	
Software version - check at opening screen. (from 18 Jan 2018 v. 2.3)	version: 2.3	O.K.	
Calibration date of Icone; check cone data [F1]..[F1].	Yes	O.K.	
Initial zero-Value Tip after calibration – within 1.0 % of nominal load.	O.K.	0.043	-0.007
Initial zero-Value Local Friction after calibration – within 1.0% of nominal load.	O.K.	0.009	0.001
Initial zero-Value Pore Pressure after calibration – within 1.0% of nominal load.	O.K.	-2,5	2.3
Initial zero-Value Inclination X. Initial zero-Value Inclination Y.	-1°< X <+1° -1° < Y <+1°	0.9° 0.5°	
Measurements Tip resistance OK?	Tested range:	0-75 MPa	
Influence Tip load on **Local Friction and Pore Pressure:** Max. tip load: 5 cm²: 100 MPa; 10 cm²: 100 MPa; 15 cm²: 75 MPa.	LF < 10 kPa PP <½% nom	3 kPa 0,2 kPa	
Measurements local friction OK?	Tested range:	0-1 MPa	
Local friction at max. load.	Tested value:	1,5 MPa	
Measurements Pore Pressure OK?	Tested range:	0-2000 kPa	
Measure Pore Pressure to 150%.	Tested value:	3000 kPa	
Measurements Inclination OK?	Tested range:	24°-0-24°	
Cone recognition on disconnecting and connecting Icone again?	Yes	O.K.	

Remarks:

Calibrated by: C.J. Onwejan	Date: 18-09-'18	Sign.: [signature]
Final check: T. Bosscher	Date: 18-09-'18	Sign.:

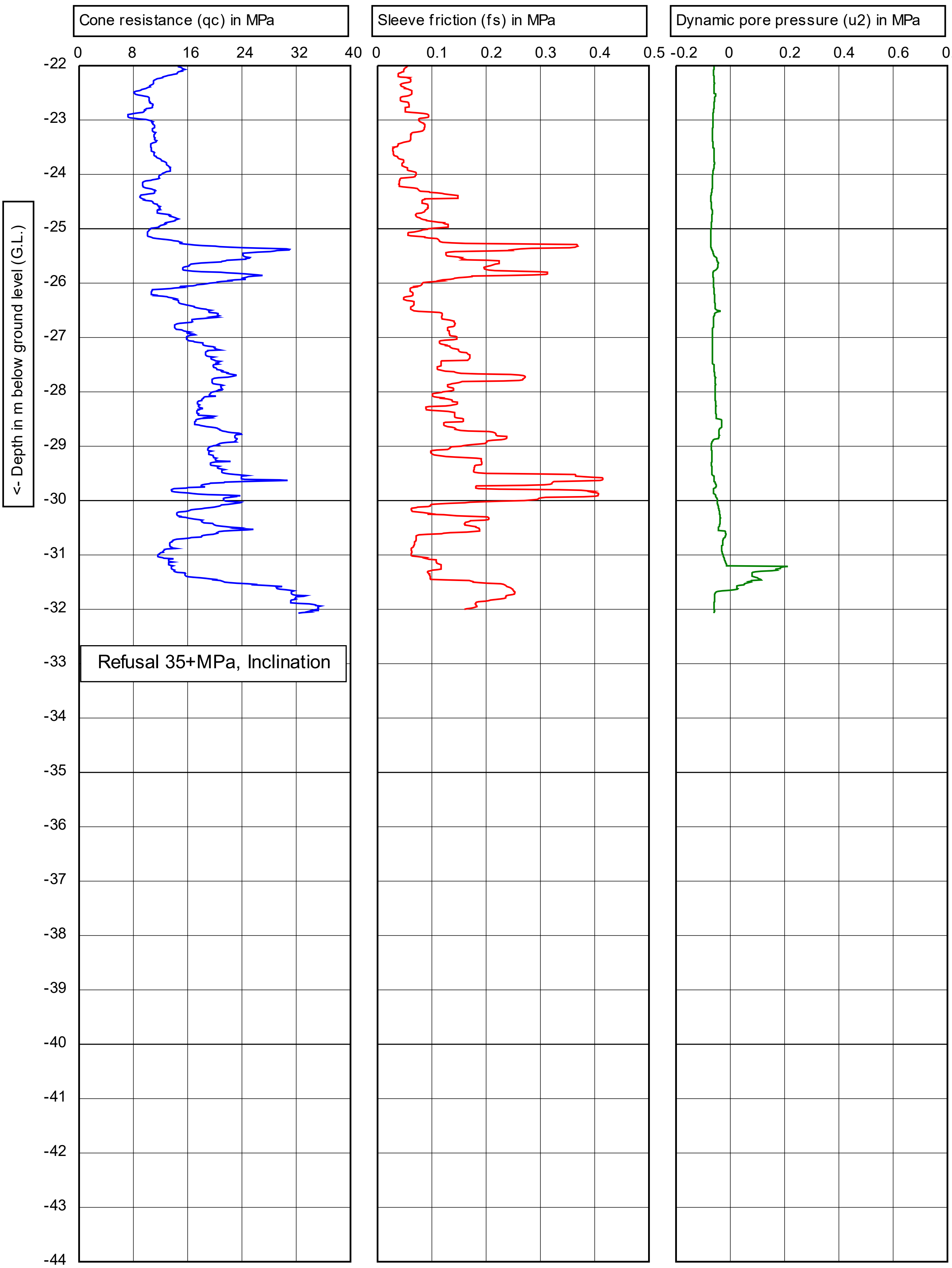
R:\E&D\Beproevingsprotocollen\Beproevingsprotocol Icone English ver 3.1.docx



OPUS

u2 150 cm² 10 cm²	Test according to A.S.T.M standard D-5778-12		Predrill : **1.95 m Predrilled**
	G.L. 0	W.L.: **0**	Date: **10/12/2013**
Project: **Queenstown- 75 Gorge Rd**			Cone no.: **C10CFIIP.C10204**
Location: **GPS: E1258304 N5005359**			Project no.: **2-68287.13**
Position:			CPT no.: **CPT02A** **1/12**

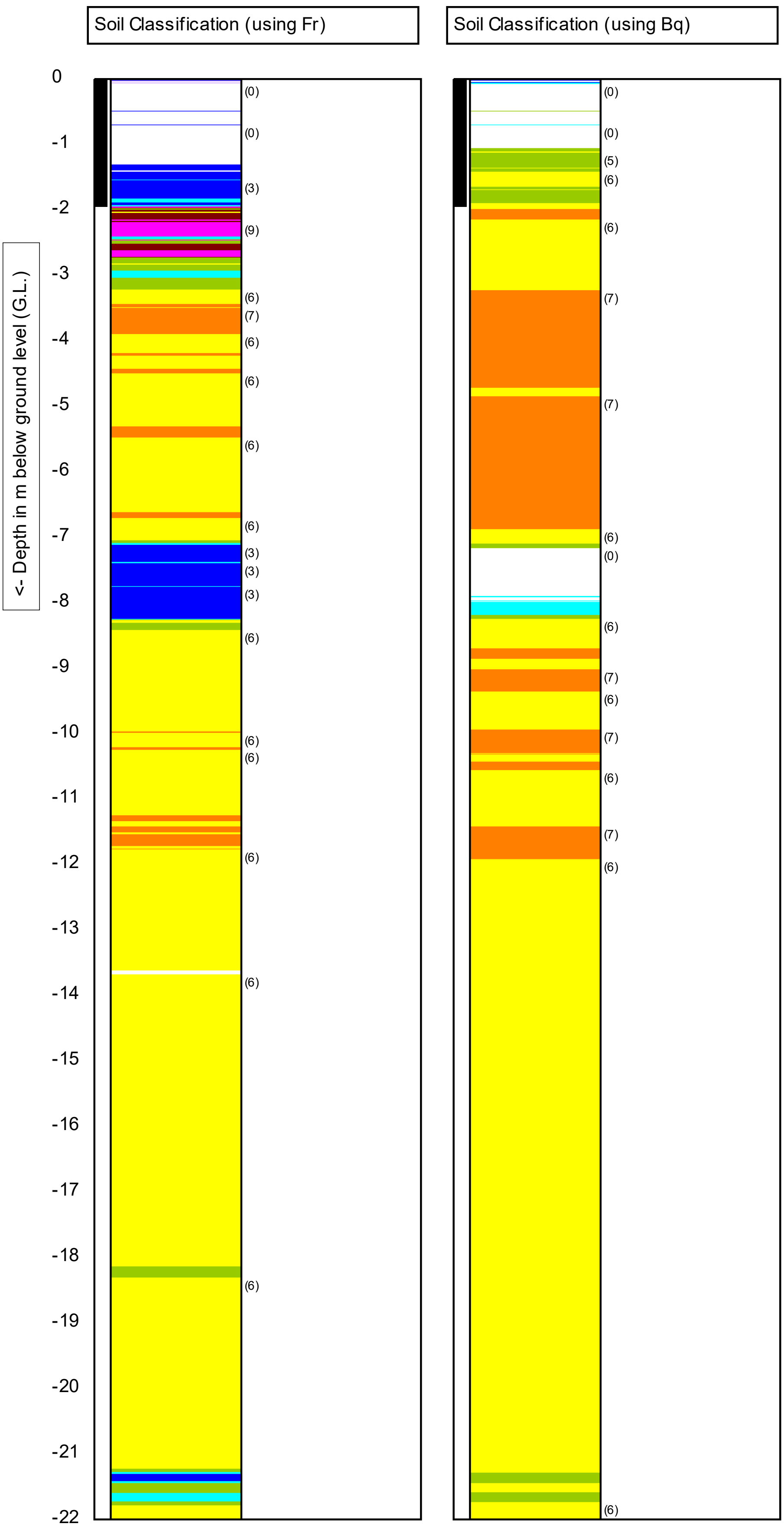
1.40



No w ater level found

u2 150 cm² 10 cm²	Test according to A.S.T.M standard D-5778-12	Predrill :	**1.95 m Predrilled**
	G.L. 0 W.L.: **0**	Date:	**10/12/2013**
OPUS	Project: **Queenstown- 75 Gorge Rd**	Cone no.:	**C10CFIIP.C10204**
	Location: **GPS: E1258304 N5005359**	Project no.:	**2-68287.13**
	Position:	CPT no.:	**CPT02A** 2/12

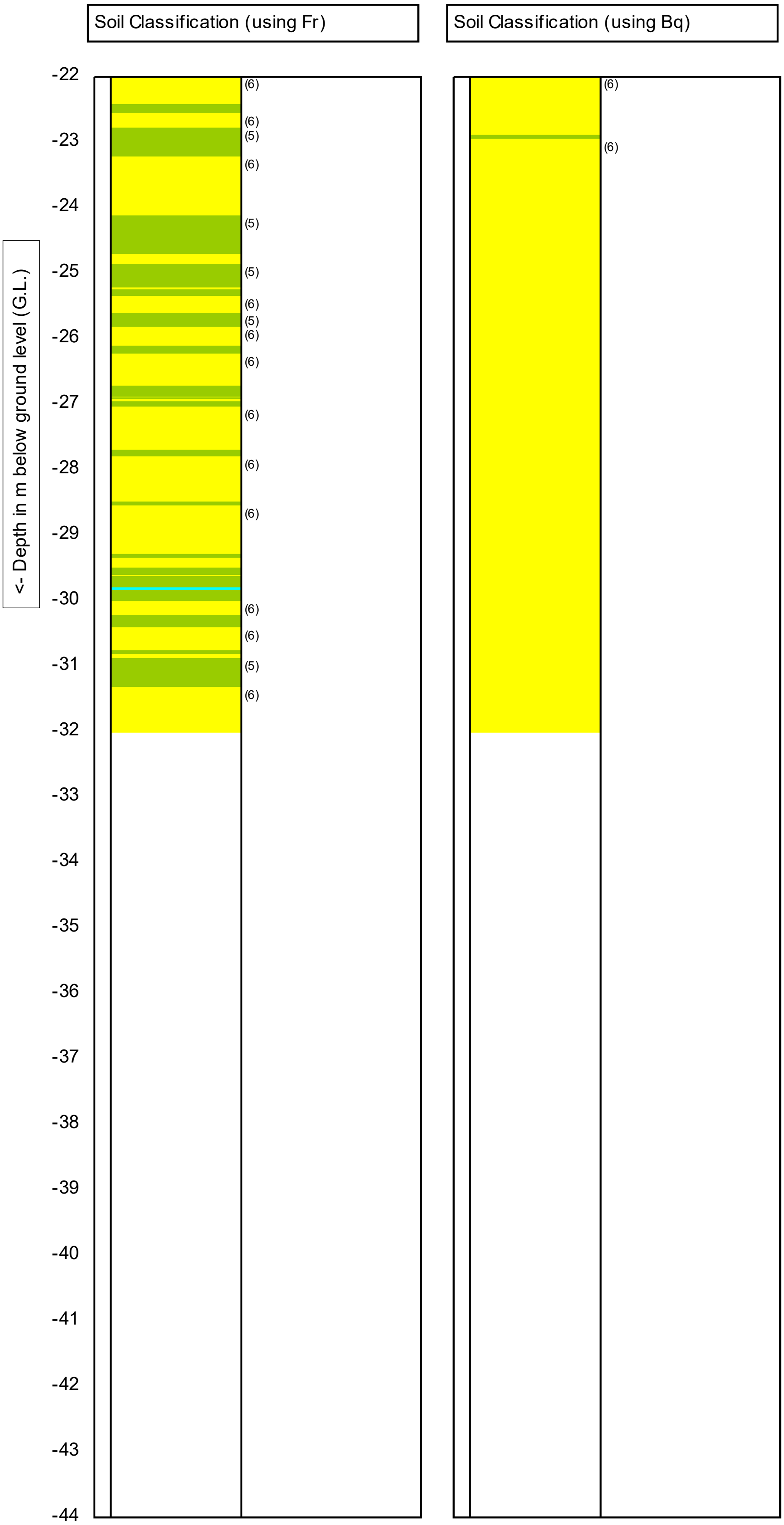
1.40



(0) Not defined
(1) Sensitive, fine grained
(2) Organic soils-peats
(3) Clays-clay to silty clay
(4) Clayey silt to silty clay
(5) Sand mixtures
(6) Sands
(7) Gravelly sand to sand
(8) Very stiff sand to clayey sand
(9) Very stiff fine grained

OPUS	u2 150 cm² 10 cm²	Test according to A.S.T.M standard D-5778-12	Predrill : **1.95 m Predrilled**
		G.L. 0 W.L.: **0**	Date: **10/12/2013**
		Project: **Queenstown- 75 Gorge Rd**	Cone no.: **C10CFIIP.C10204**
		Location: **GPS: E1258304 N5005359**	Project no.: **2-68287.13**
		Position:	CPT no.: **CPT02A** 7/12

1.40



(0) Not defined
(1) Sensitive, fine grained
(2) Organic soils-peats
(3) Clays-clay to silty clay
(4) Clayey silt to silty clay
(5) Sand mixtures
(6) Sands
(7) Gravelly sand to sand
(8) Very stiff sand to clayey sand
(9) Very stiff fine grained

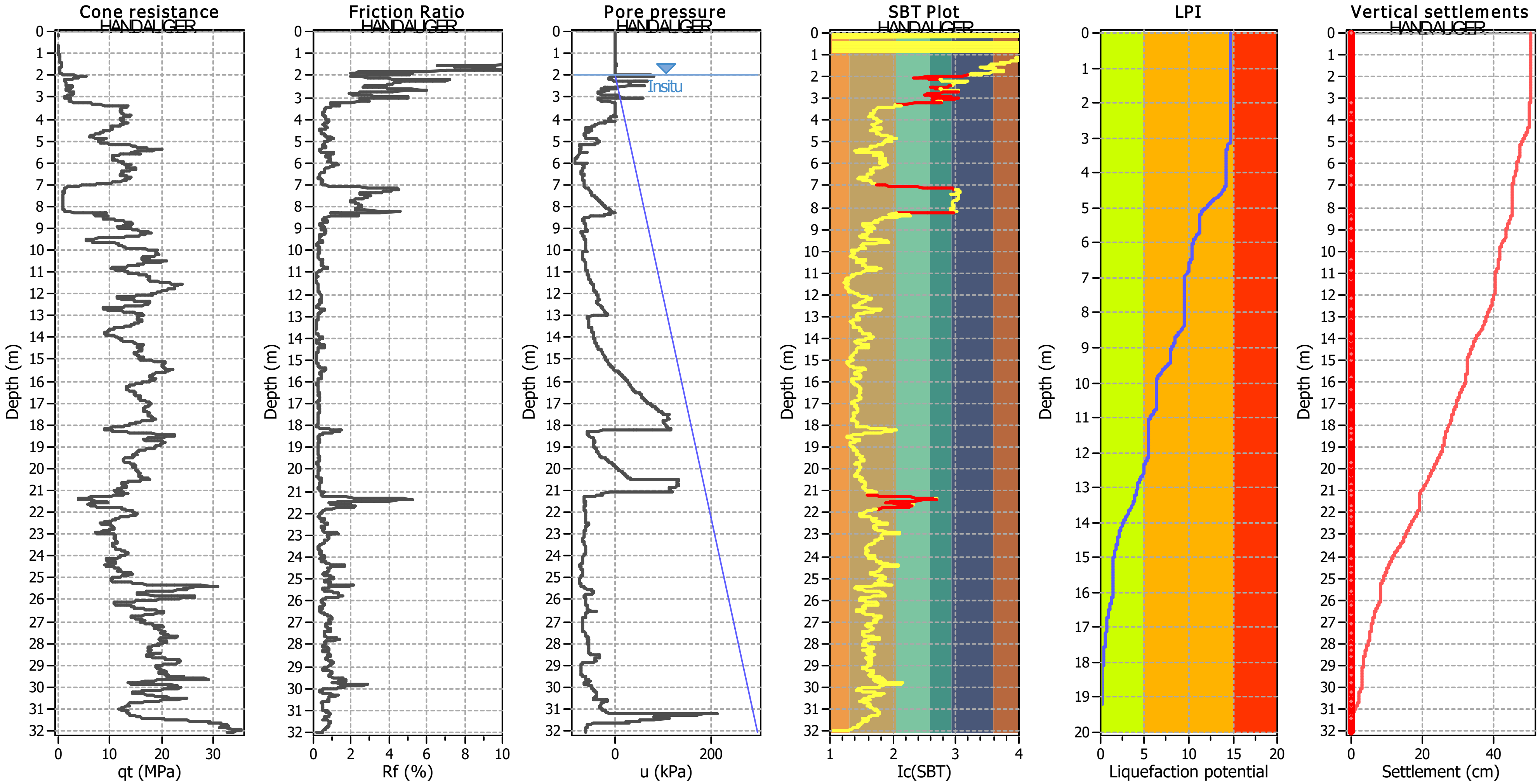
OPUS	u2 150 cm² 10 cm²	Test according to A.S.T.M standard D-5778-12	Predrill : **1.95 m Predrilled**
		G.L. 0 / W.L.: **0**	Date: **10/12/2013**
		Project: **Queenstown- 75 Gorge Rd**	Cone no.: **C10CFIIP.C10204**
		Location: **GPS: E1258304 N5005359**	Project no.: **2-68287.13**
		Position:	CPT no.: **CPT02A** 8/12

1.40

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

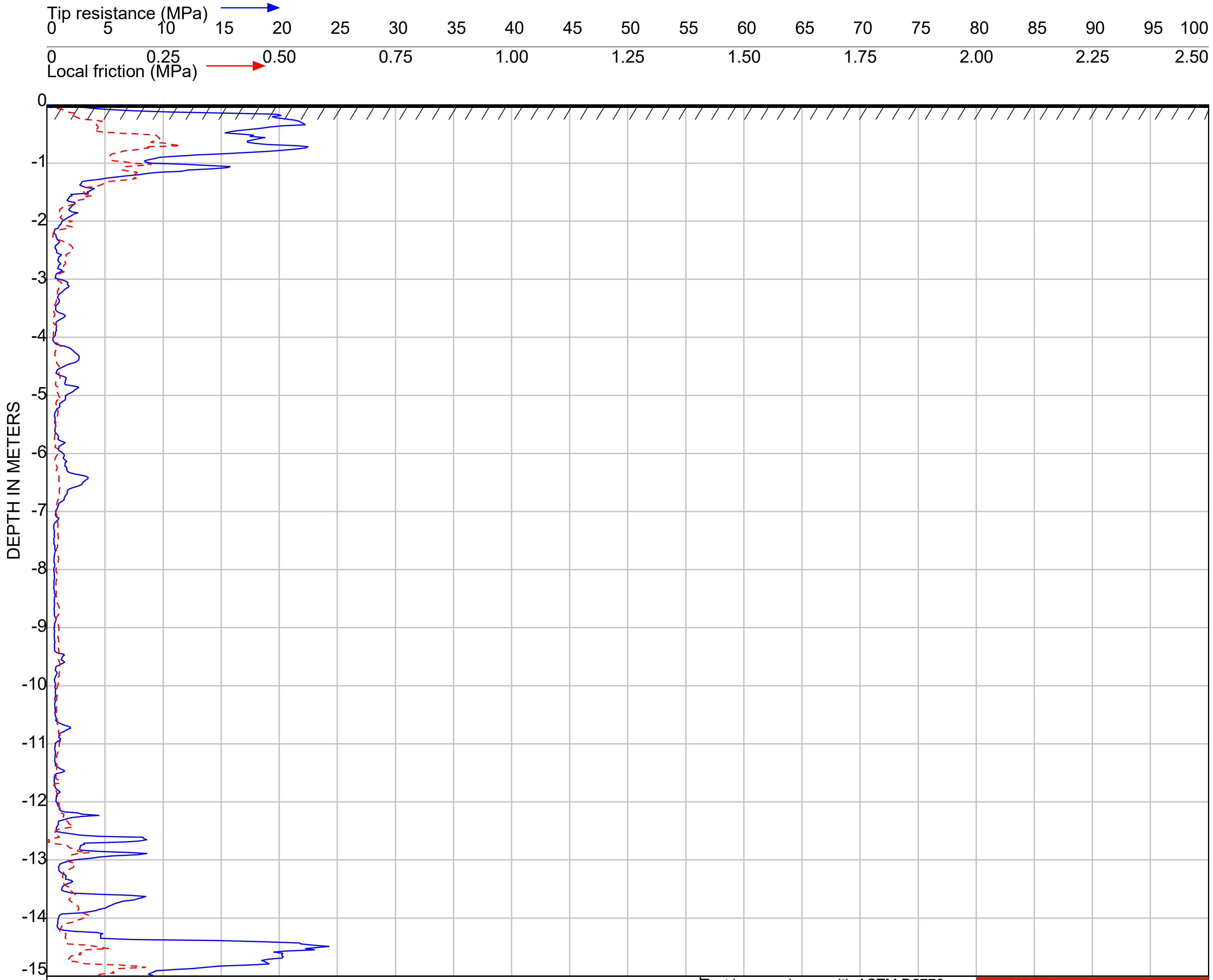
Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

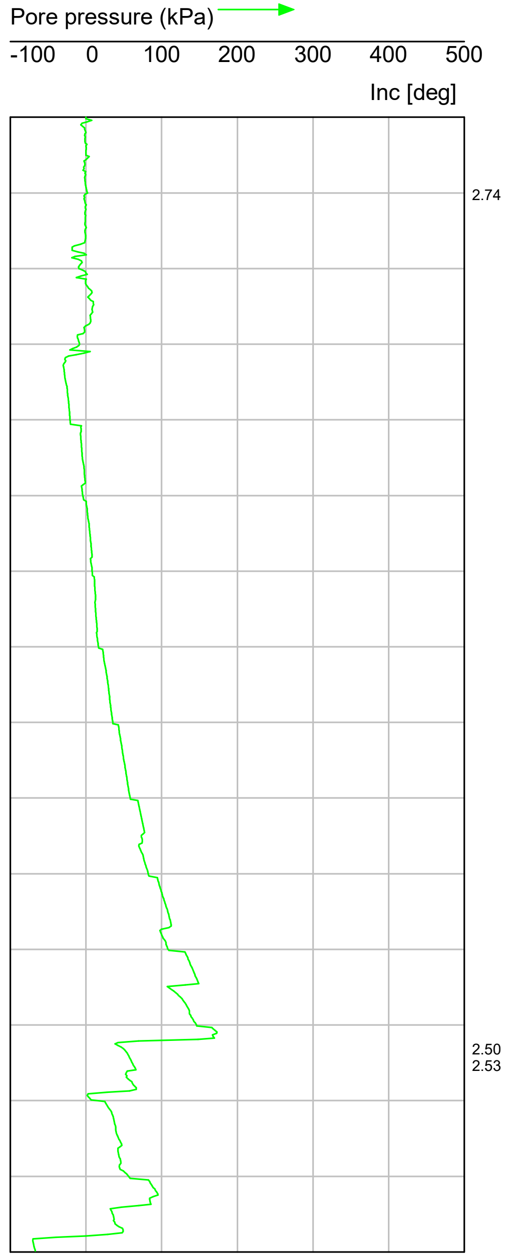
CPT: 77987.00
Total depth: 32.07 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	2.00 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	2.00 m	Fill height:	N/A	Limit depth applied:	No
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

CLiq v.2.2.1.14 - CPTU data presentation & interpretation software - Report created on: 2/05/2019, 12:12:32 p.m.
Project file: \\Beca.net\projects\320\3209253\06 Deliverables\Appendices\Appendix K- Liquifaction\ss\Gorge Road Liquifaction.clq





Operator : JC
Date : 18-1-2017
Time : 9:47

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm [2]
Easting [m] 1258029
Northing [m] 5005235

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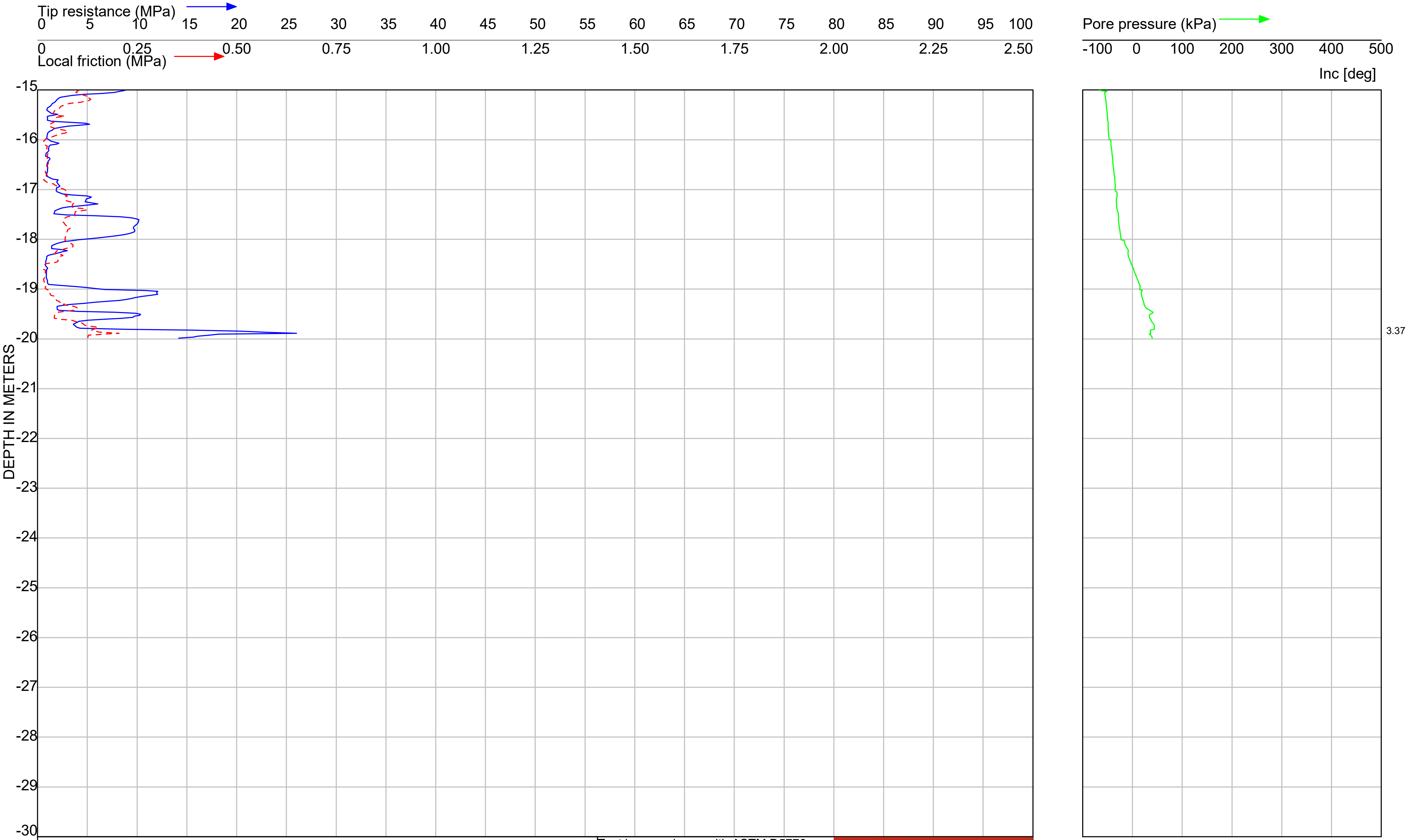
Project No : 4095
Location : CPT1

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School



Operator :	JC	Cone :	I-CFXYP20-15
Date :	18-1-2017	Cone Serial No :	160610
Time :	9:47	Remark :	

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ²
Easting [m] 1258029
Northing [m] 5005235

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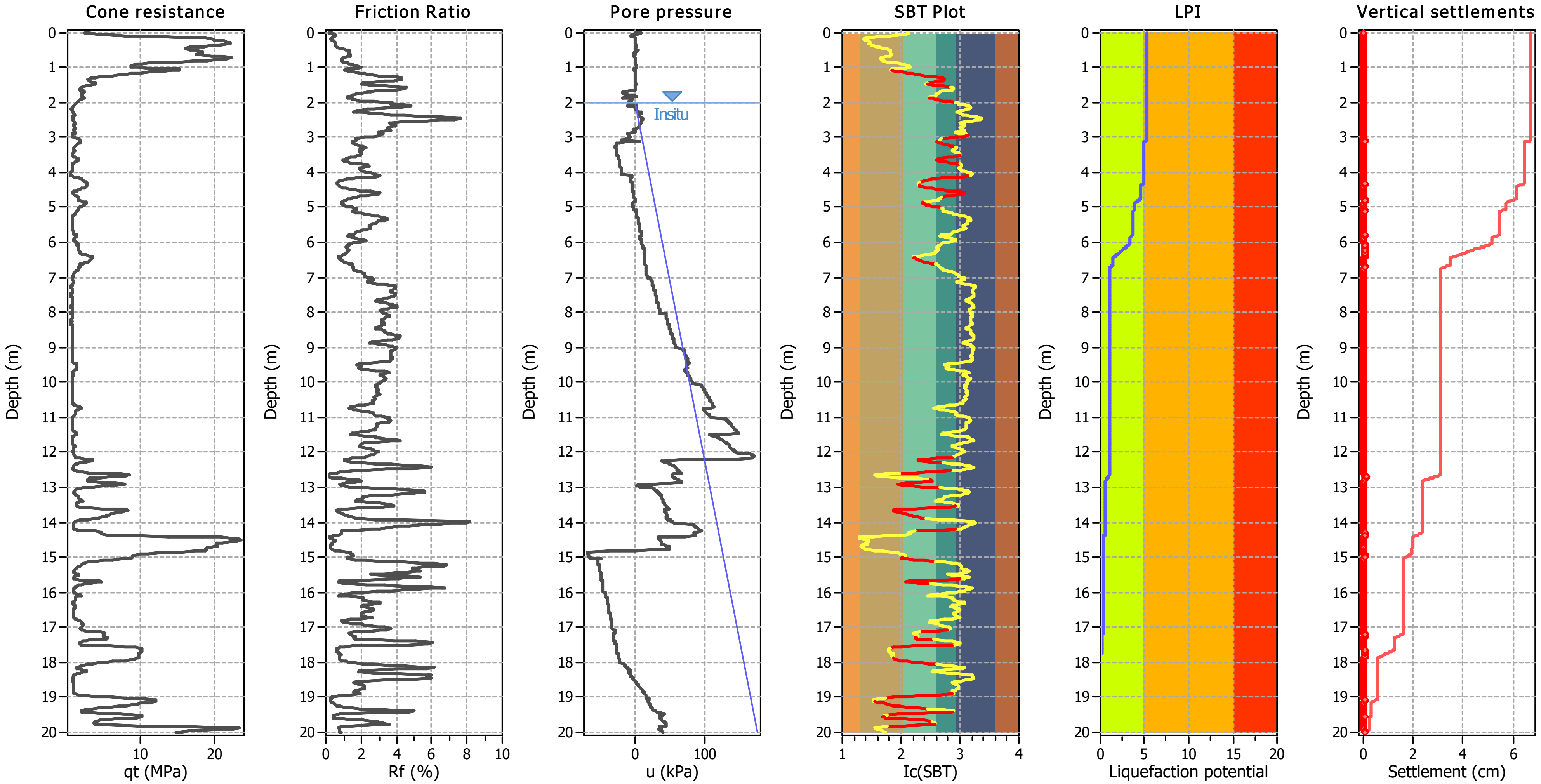
Project No : 4095
Location : CPT1

PIEZO CONE PENETRATION TEST

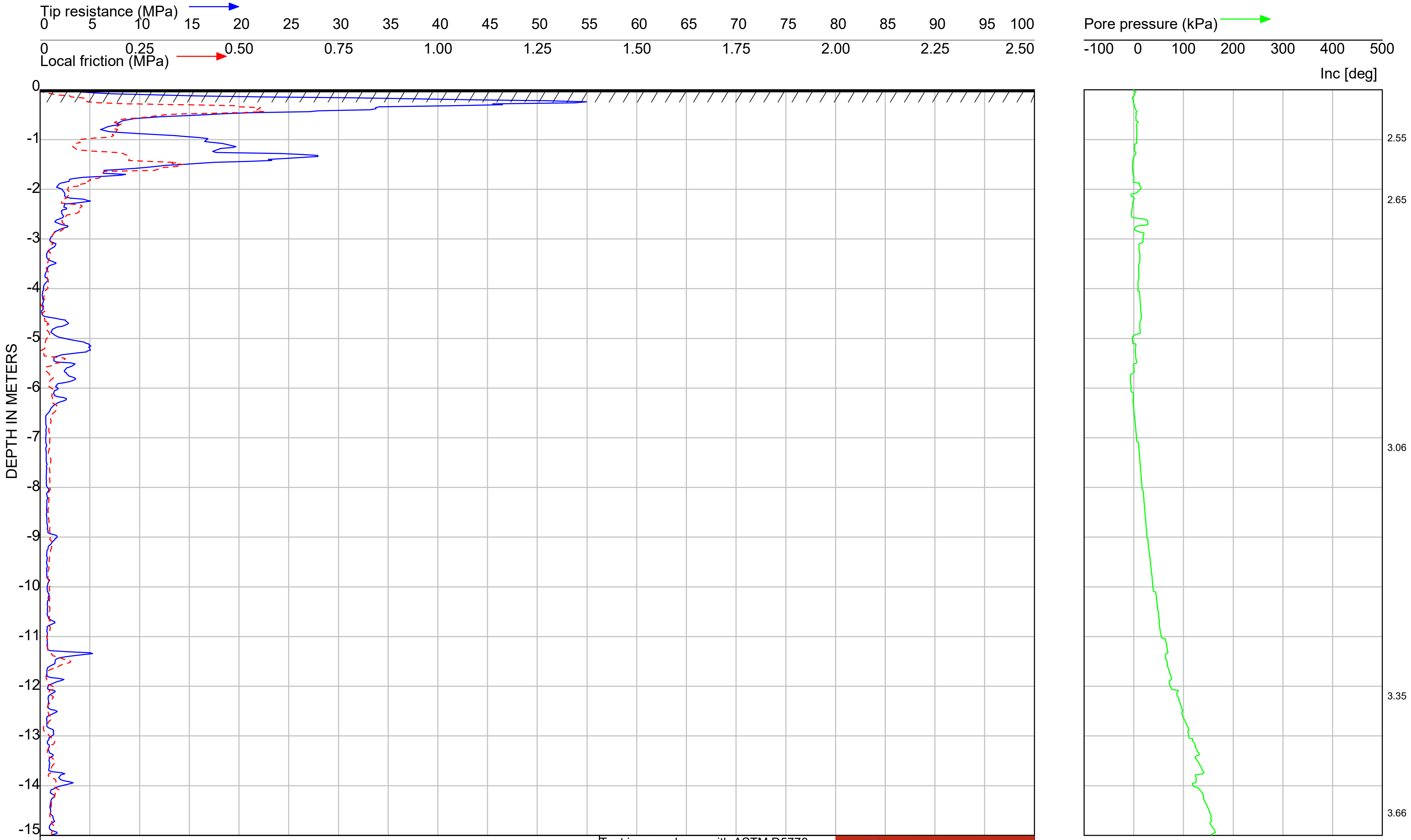
Client : GHD
Project : Wakitipu High School

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment **CPT: GHD1**
Location: Gorge Road, Queenstown Total depth: 20.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	2.00 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	2.00 m	Fill height:	N/A	Limit depth applied:	No
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		



Operator : JC
Date : 18-1-2017
Time : 10:35

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ^{2}
Easting [m] 1258109
Northing [m] 5005219

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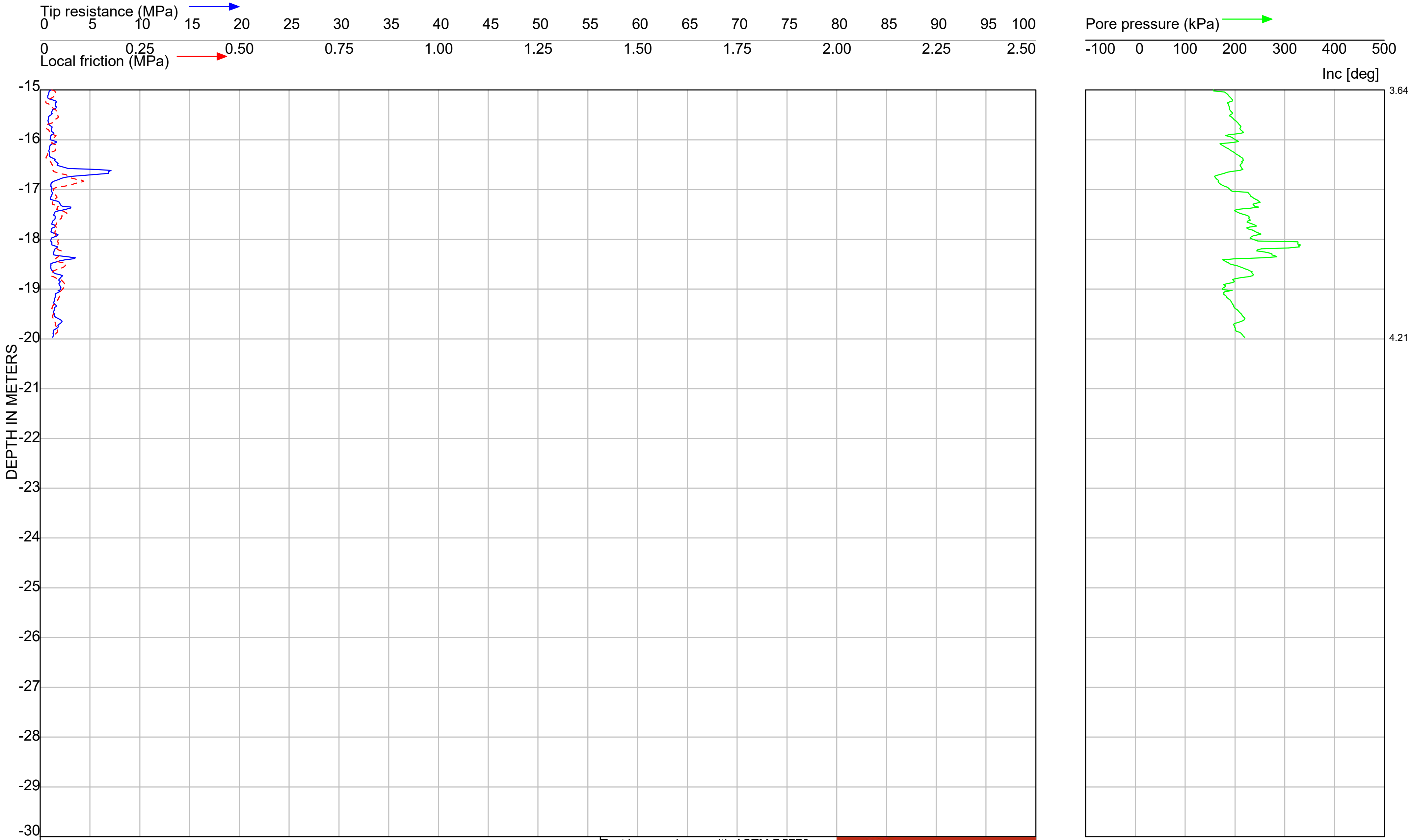
Project No : 4095
Location : CPT2

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School



Operator : JC
Date : 18-1-2017
Time : 10:35

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm [2]
Easting [m] 1258109
Northing [m] 5005219

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Project No : 4095
Location : CPT2

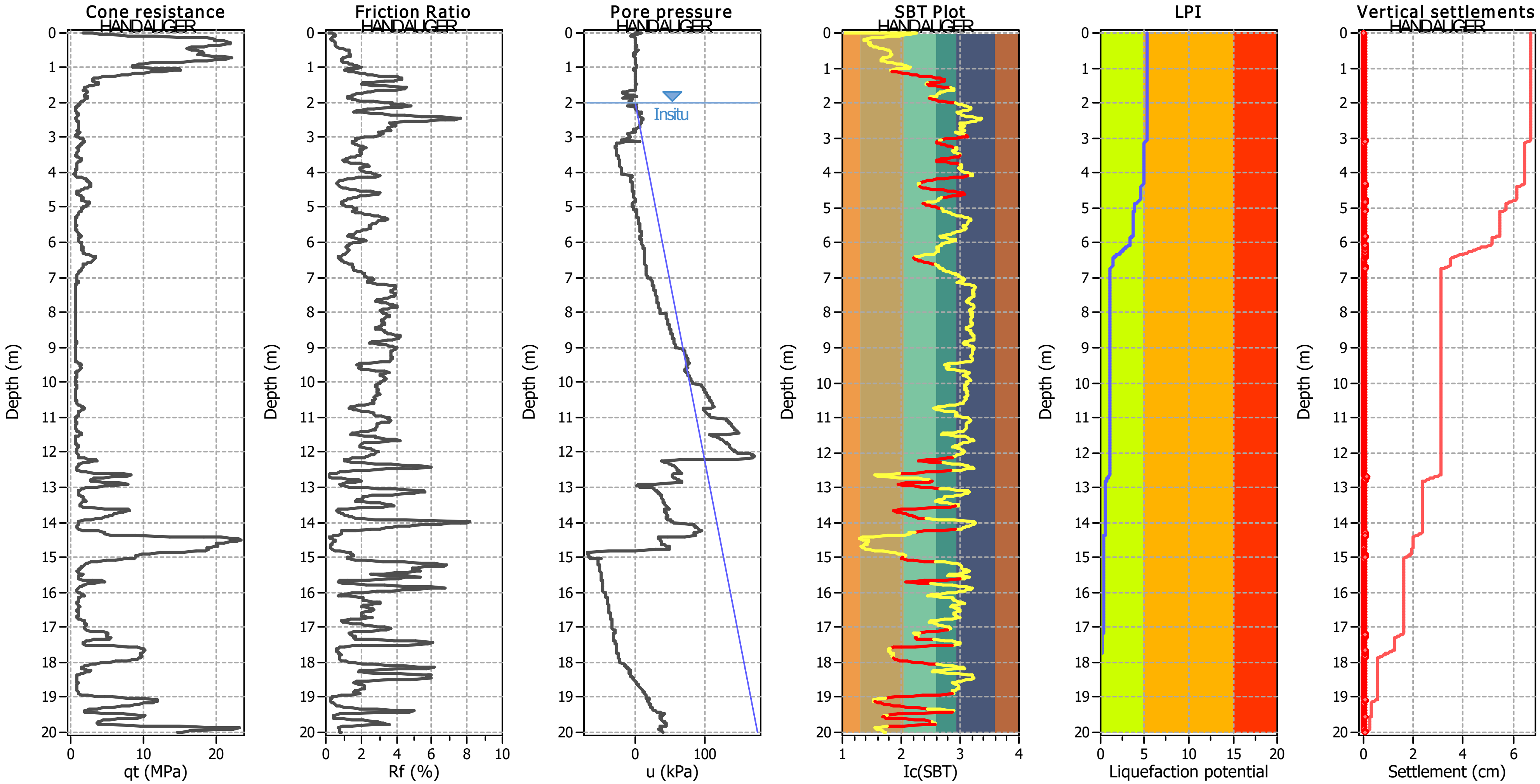
PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School

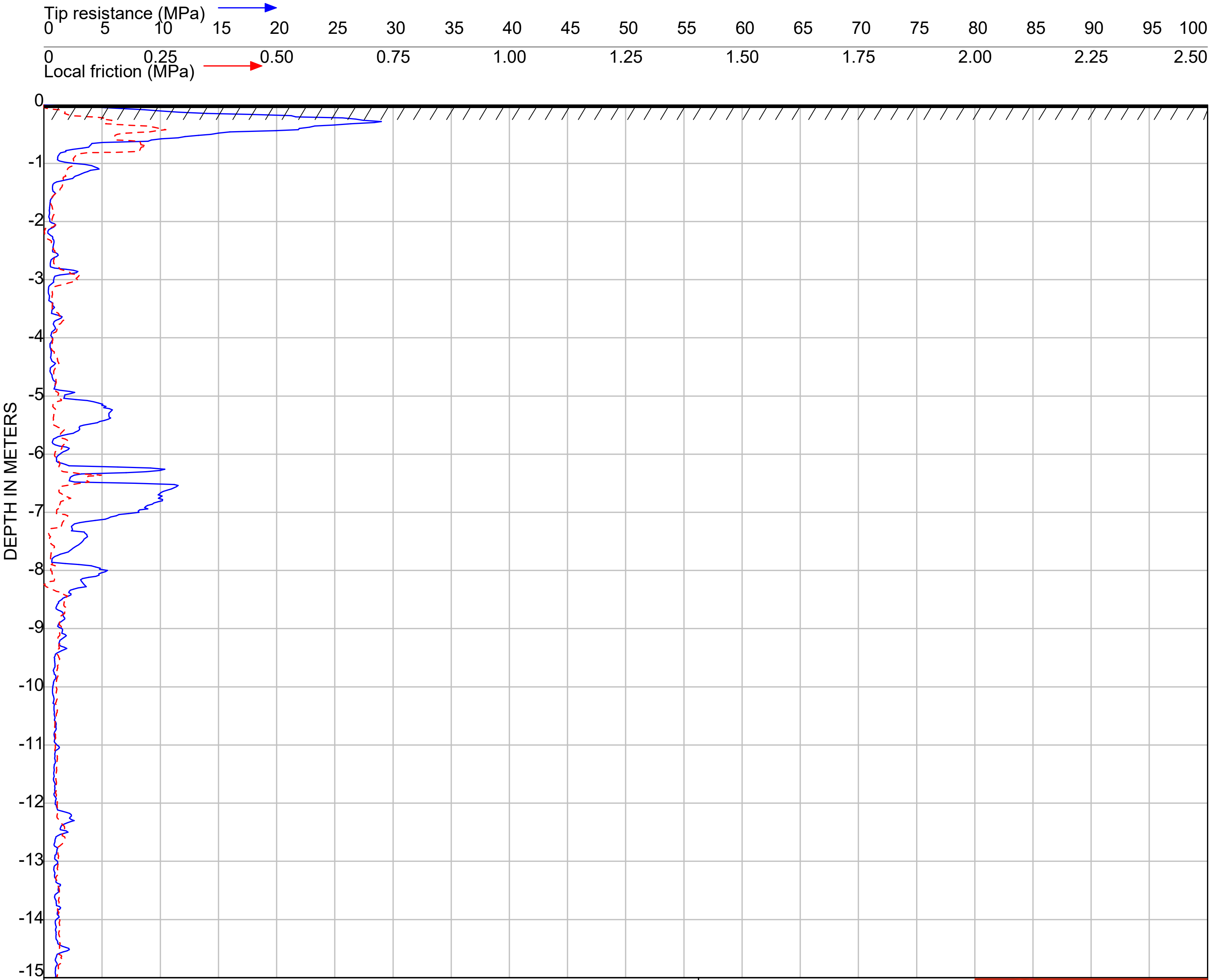
Beca Ltd.
267 High St
Christchurch
http://www.beca.com

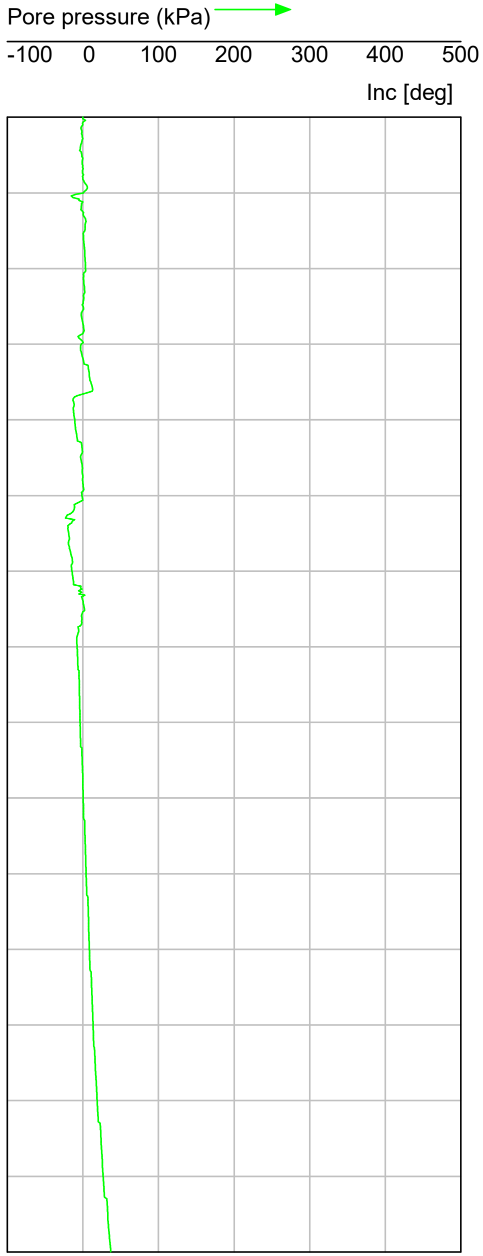
Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD2
Total depth: 20.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	2.00 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	2.00 m	Fill height:	N/A	Limit depth applied:	No
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		





Operator : JC
Date : 18-1-2017
Time : 11:19

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

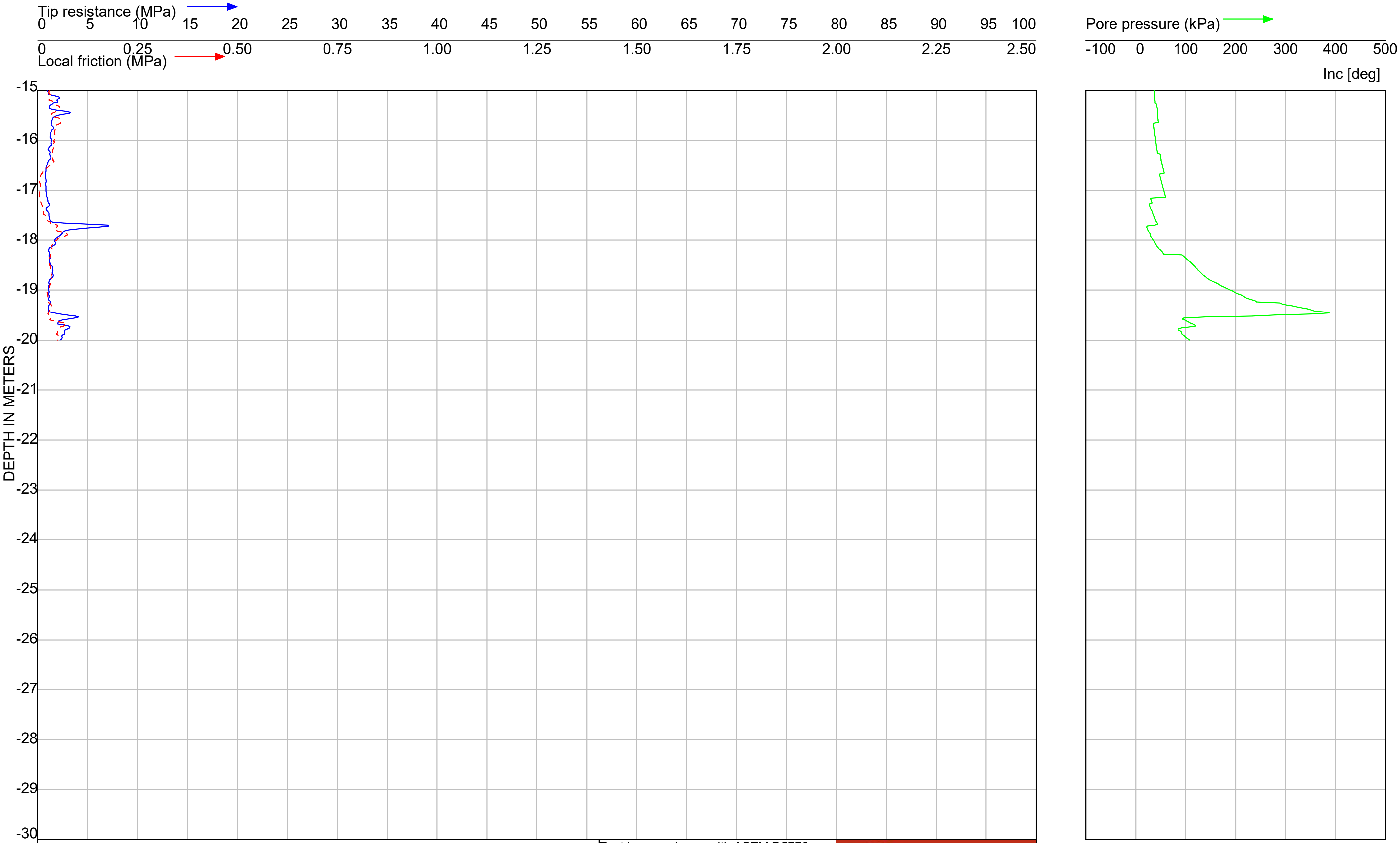
Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm²
Easting [m] 1258157
Northing [m] 5005280

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT3

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School



Operator : JC
Date : 18-1-2017
Time : 11:19

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ^{2}
Easting [m] 1258157
Northing [m] 5005280

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT3

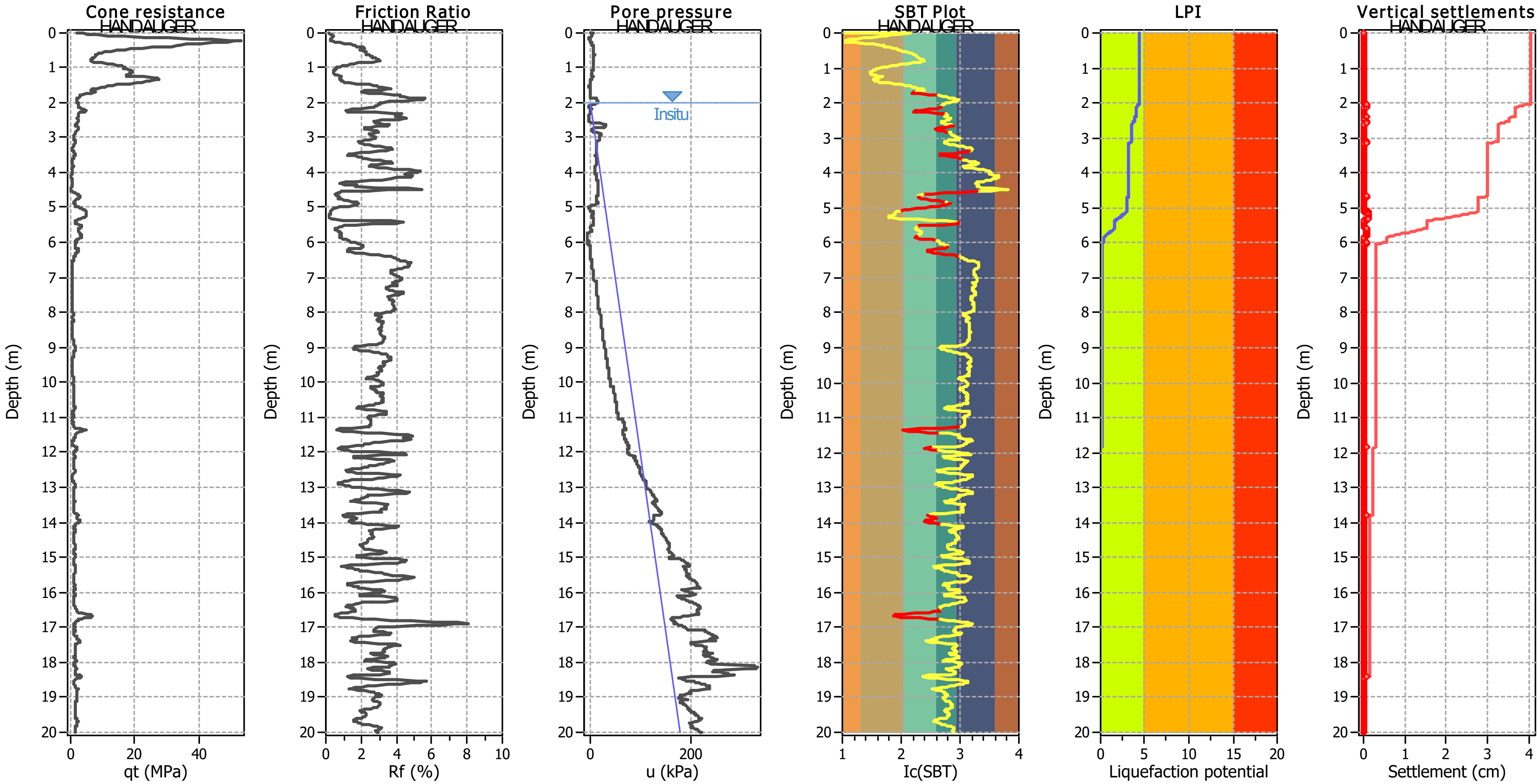
PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School

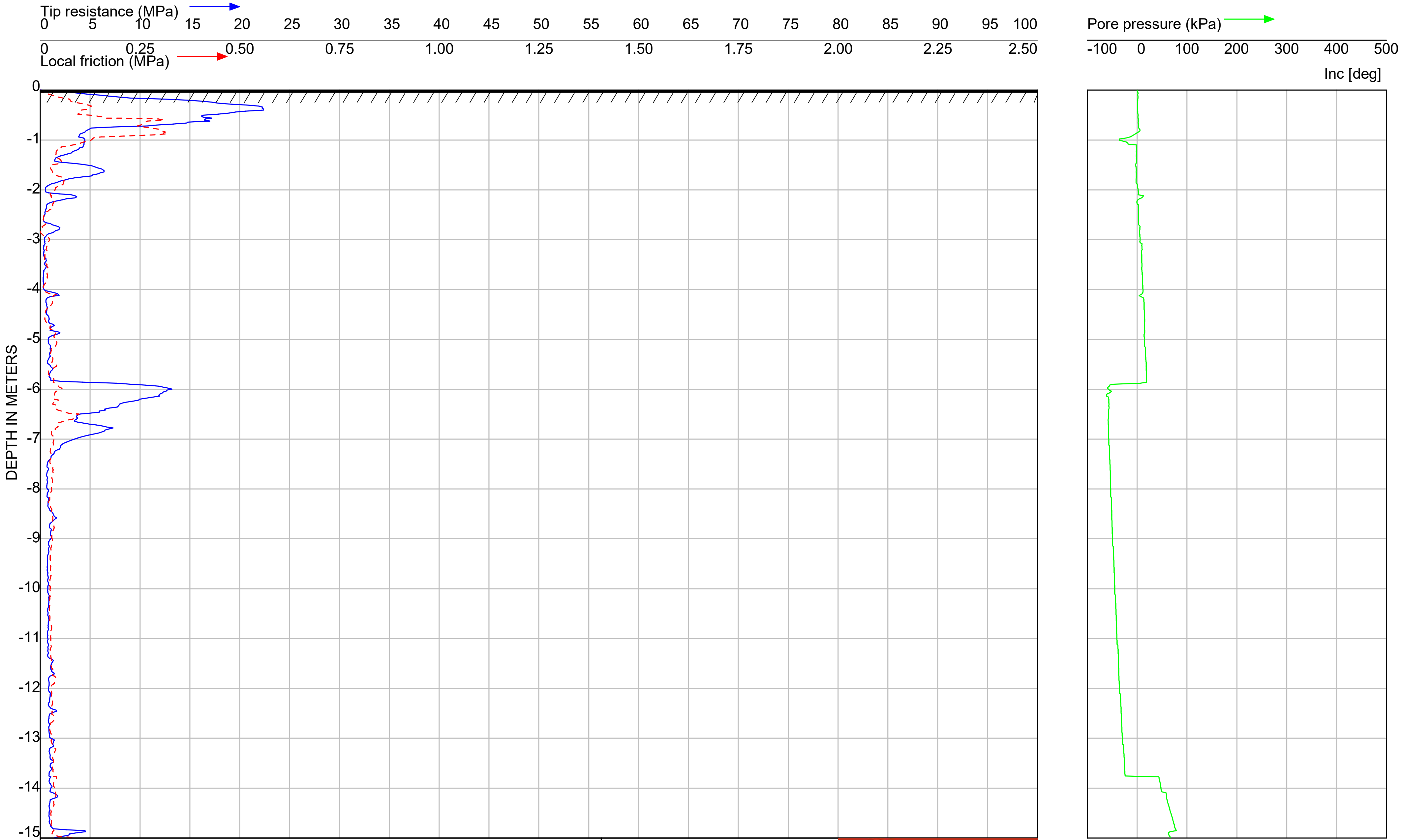
Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD3
Total depth: 20.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	2.00 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	2.00 m	Fill height:	N/A	Limit depth applied:	No
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		



Operator : JC
Date : 18-1-2017
Time : 12:42

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

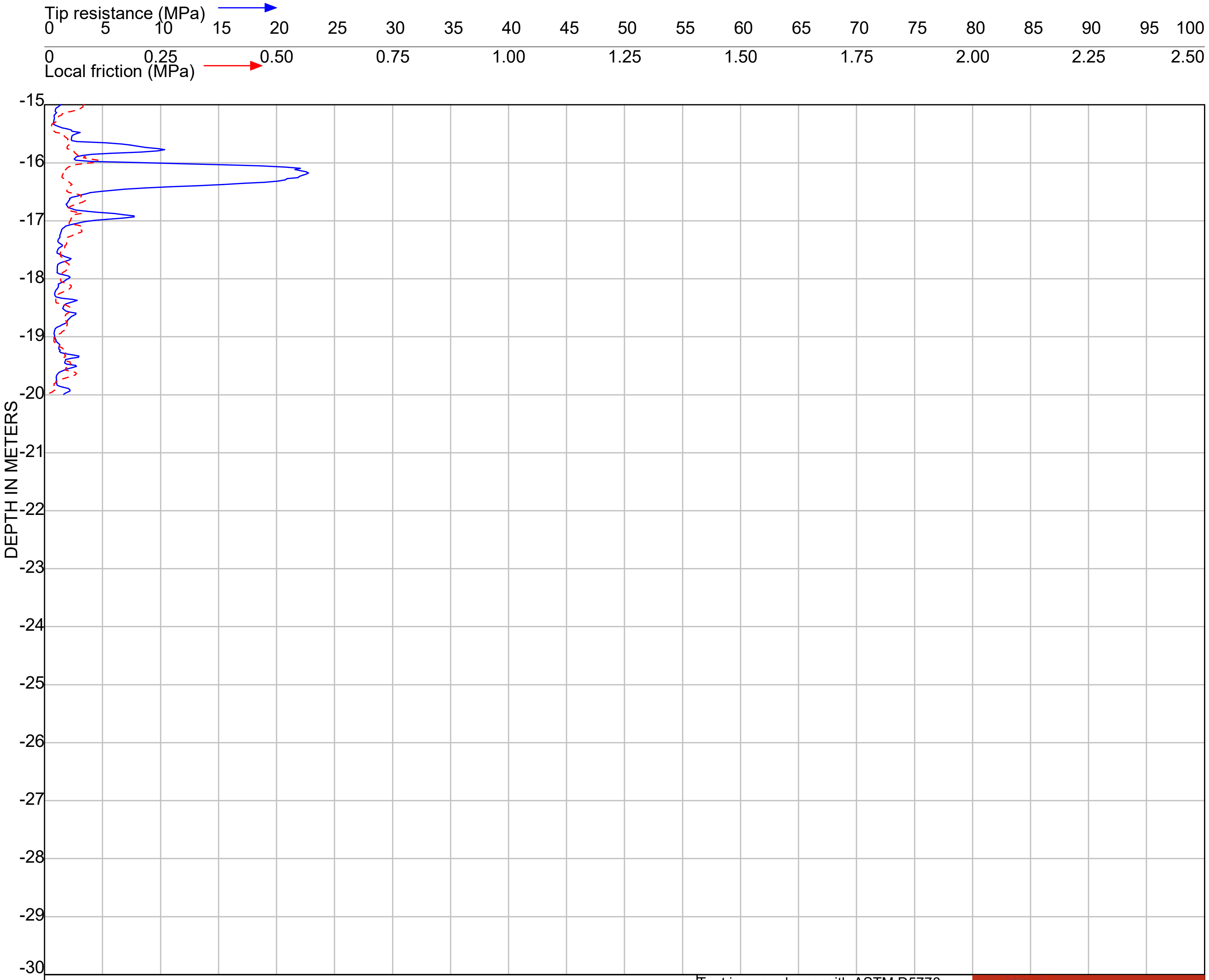
Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ^{2}
Easting [m] 1258216
Northing [m] 5005285

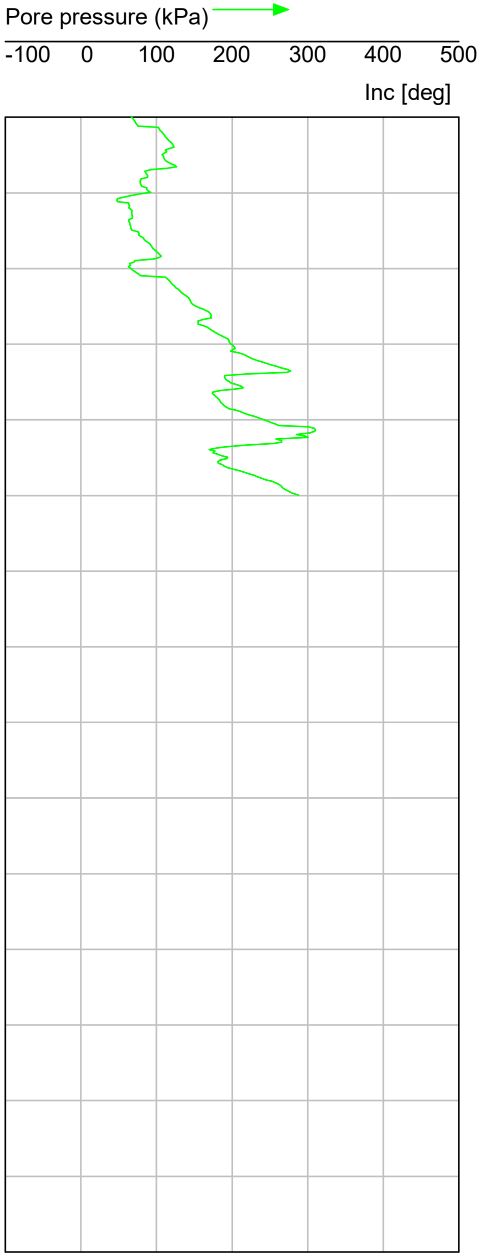
mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT4

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School





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Date :	18-1-2017	Cone Serial No :	160610
Time :	12:42	Remark :	

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ²
Easting [m] 1258216
Northing [m] 5005285

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT4

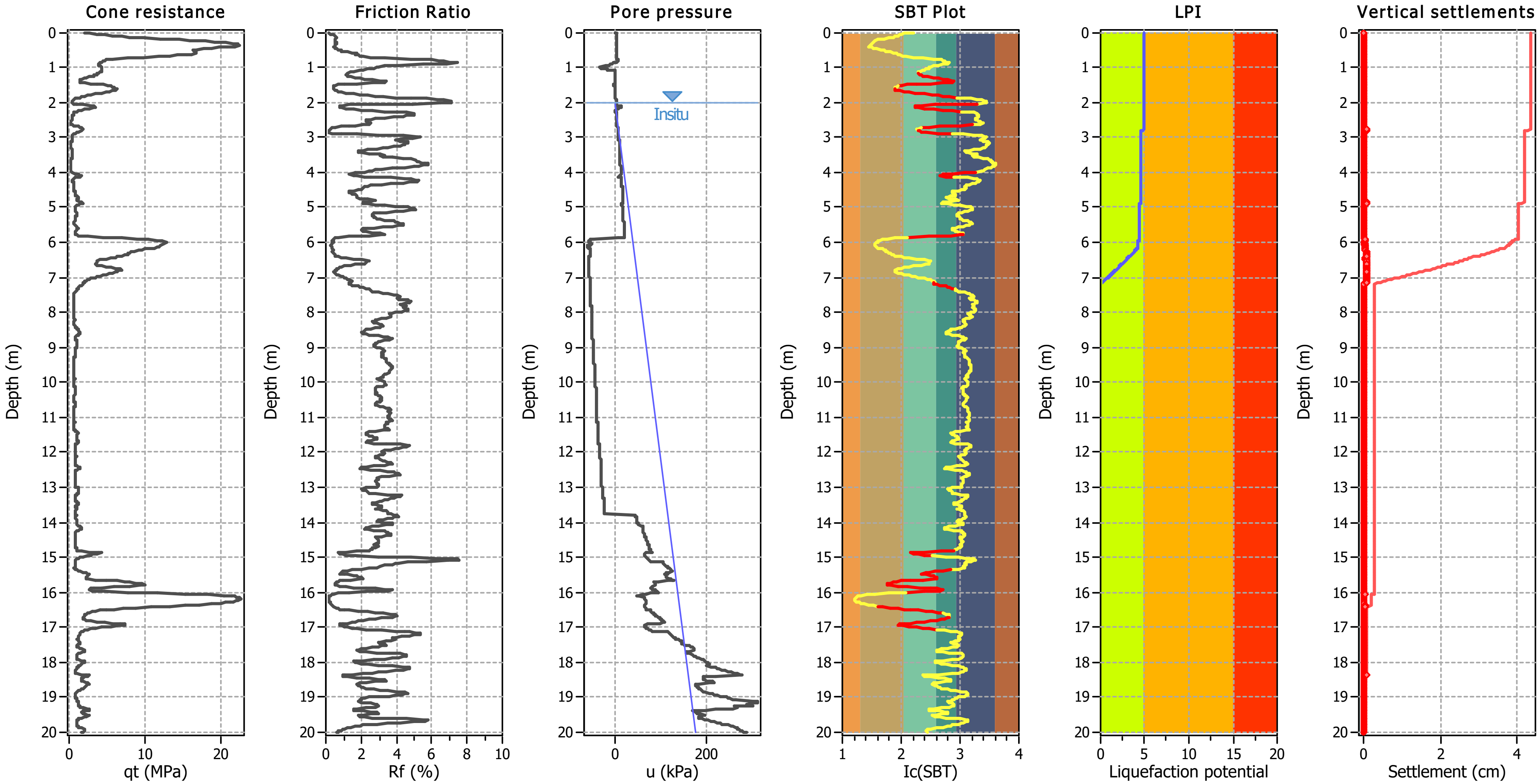
PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD CPT4
Total depth: 20.00 m



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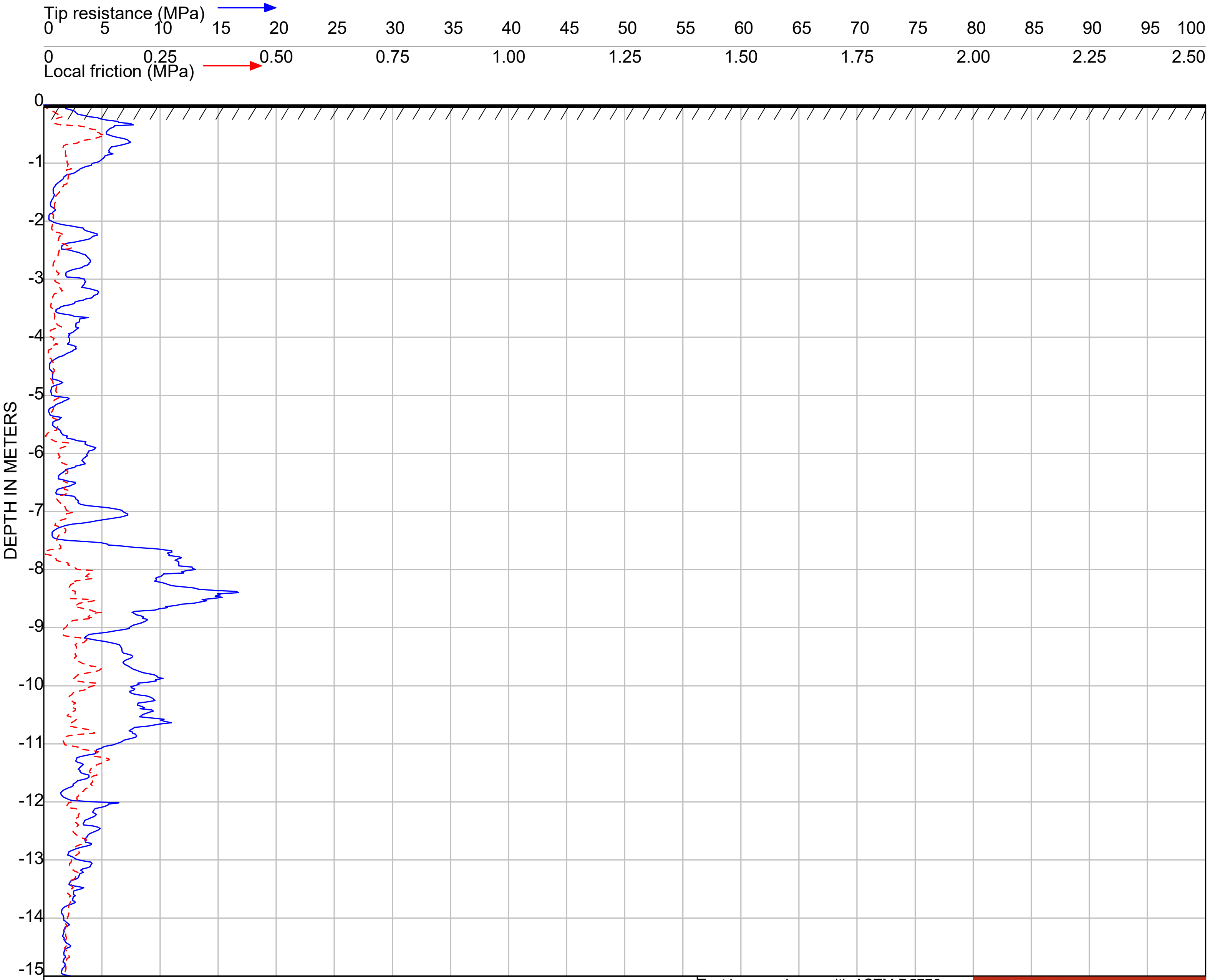
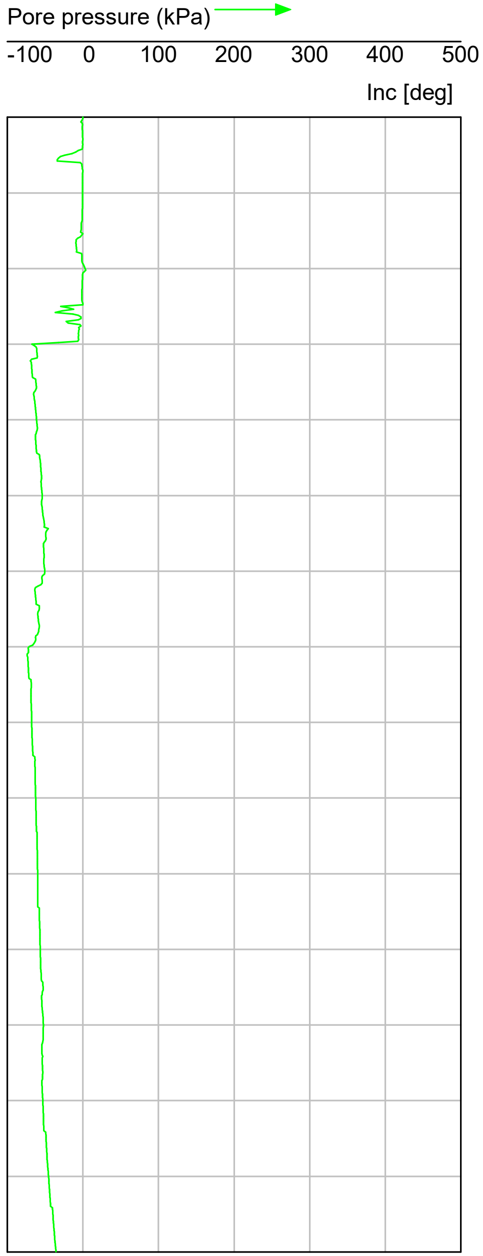
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		





Operator : JC
Date : 18-1-2017
Time : 13:50

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

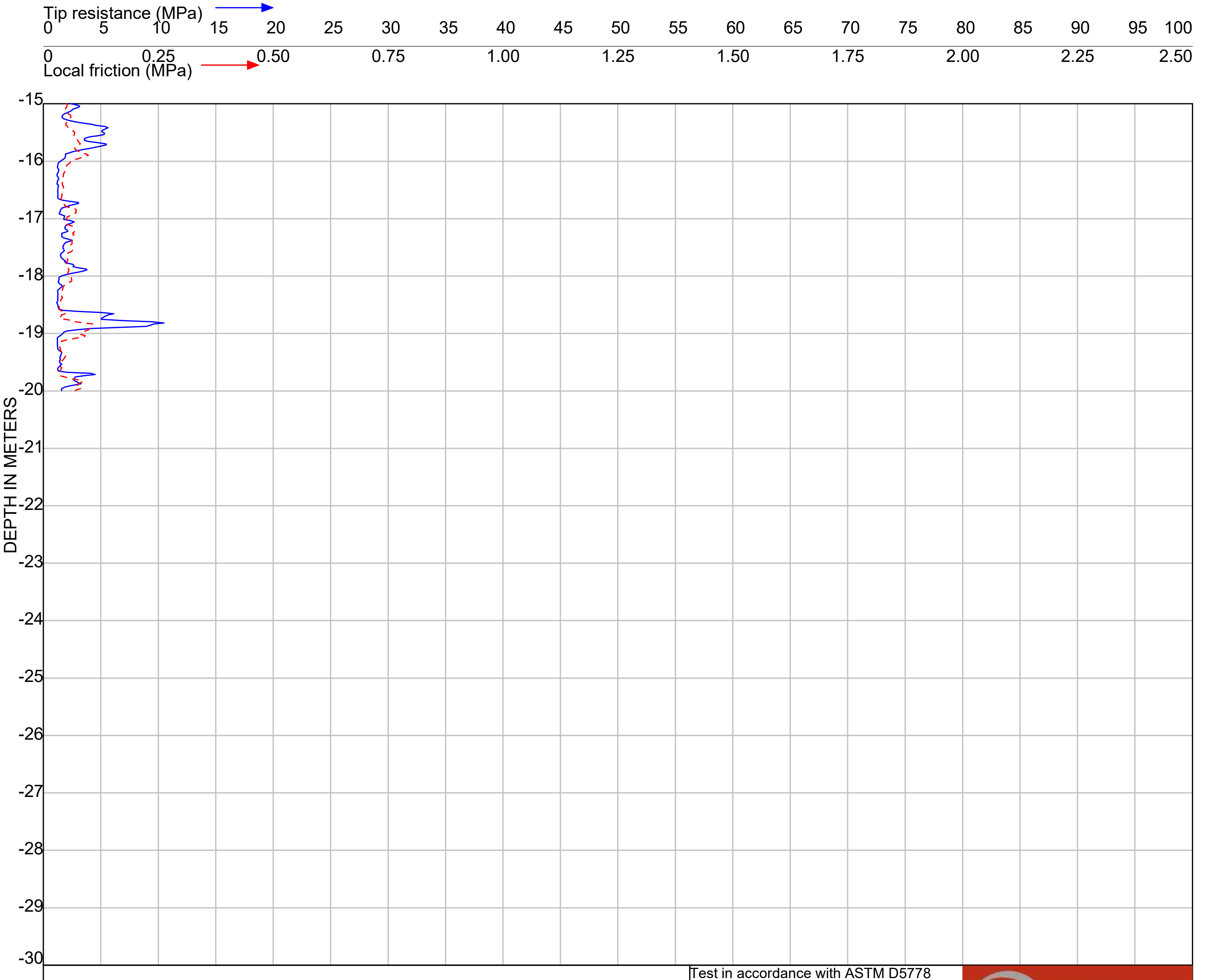
Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm [2]
Easting [m] 1258087
Northing [m] 5005335

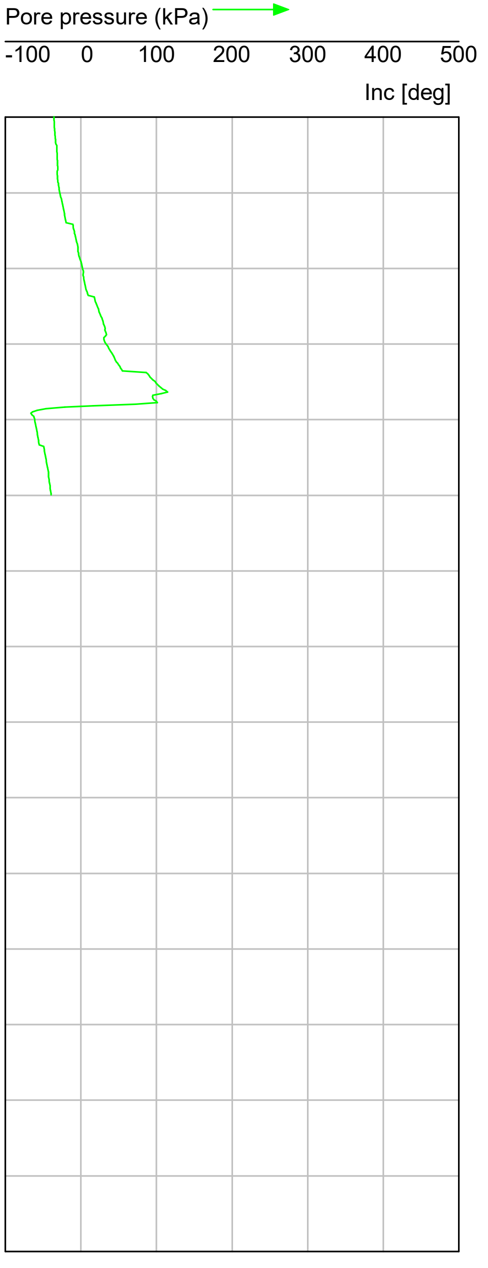
mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT5

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School





Operator : JC
Date : 18-1-2017
Time : 13:50

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ²
Easting [m] 1258087
Northing [m] 5005335

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT5

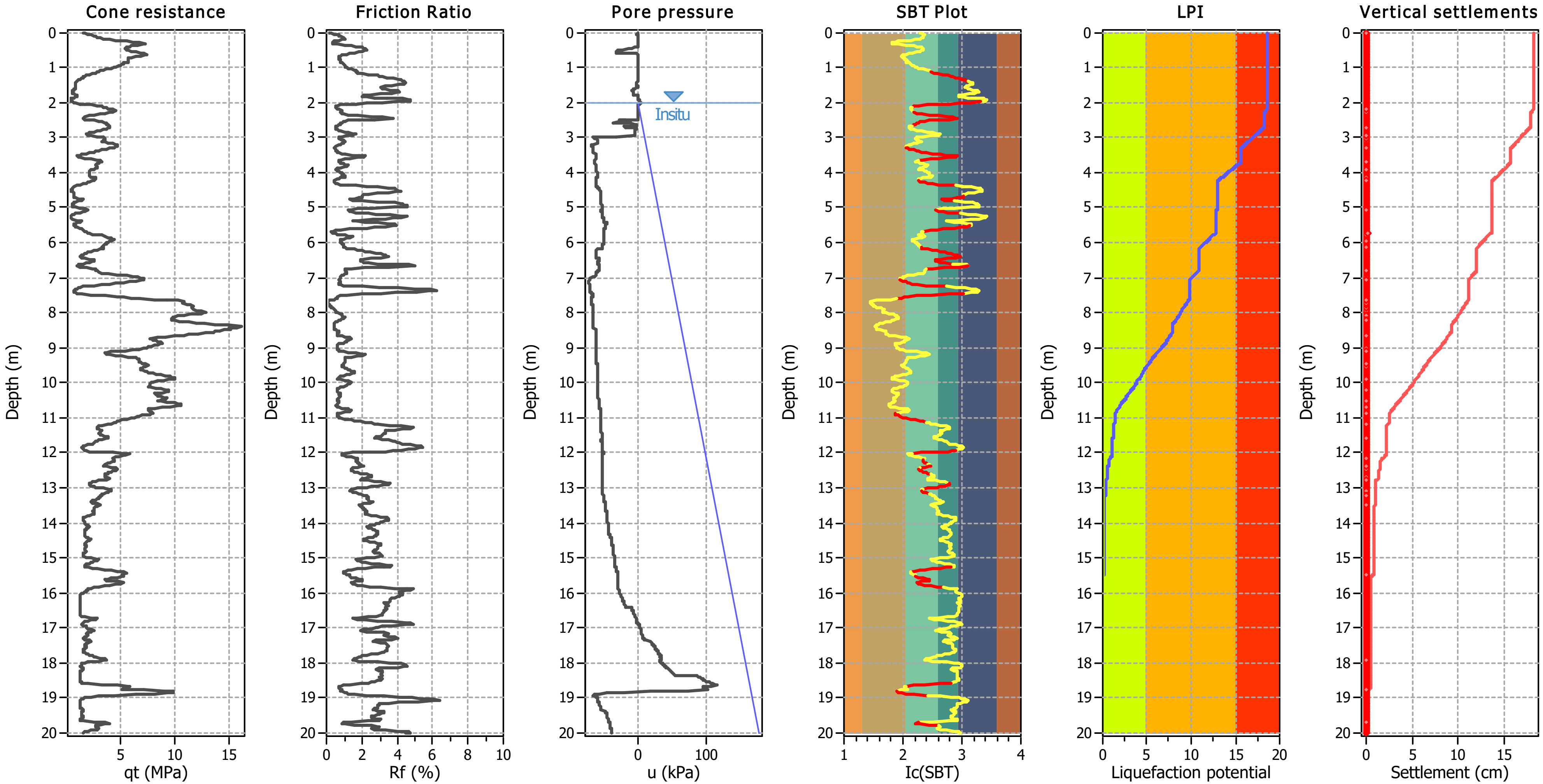
PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD 5
Total depth: 20.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	2.00 m	Use fill:	No	Clay like behavior applied:	.
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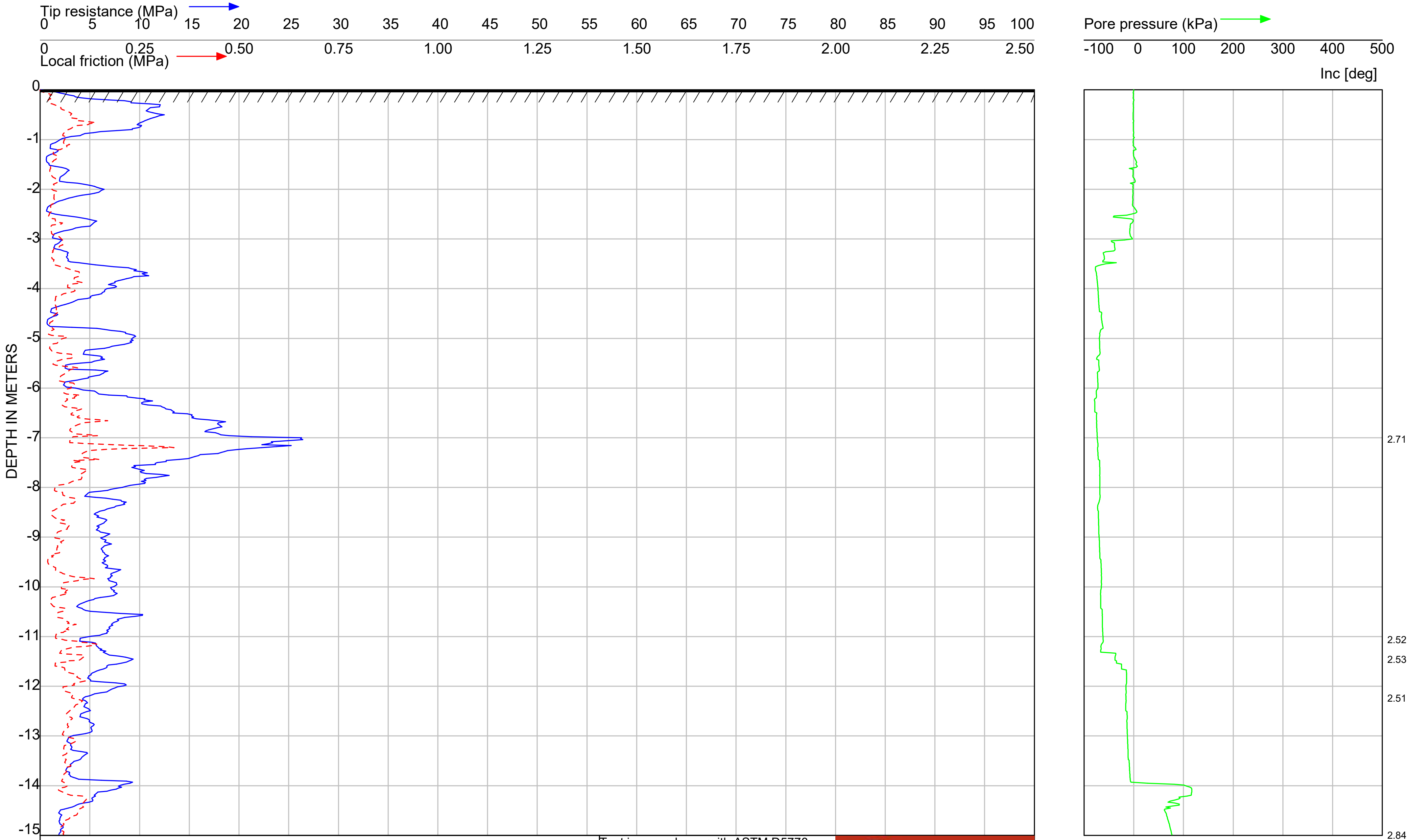
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		



Operator : JC
Date : 18-1-2017
Time : 14:48

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

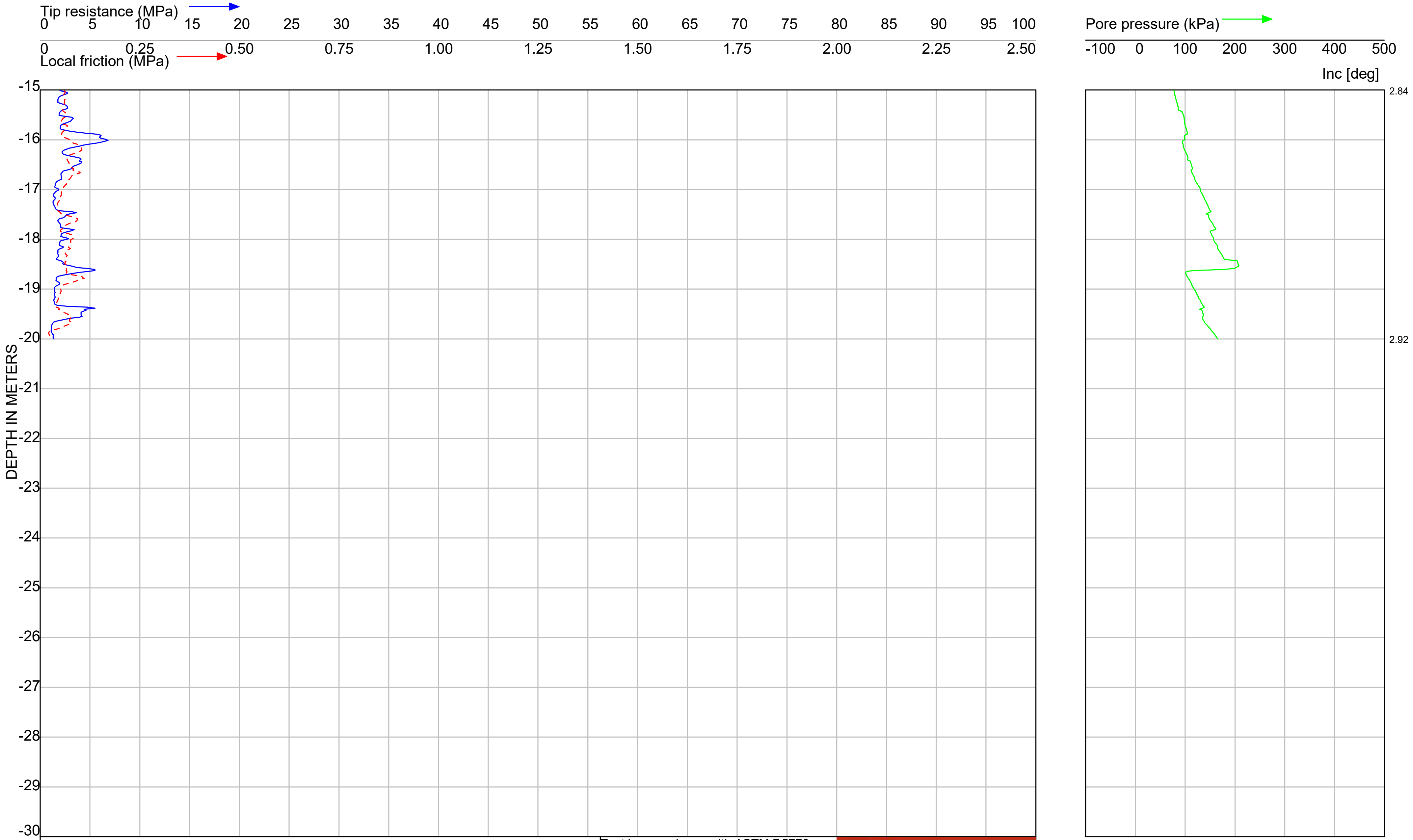
Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm 2
Easting [m] 1258123
Northing [m] 5005331

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT6

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School



Operator : JC
Date : 18-1-2017
Time : 14:48

Cone : I-CFXYP20-15
Cone Serial No : 160610
Remark :

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm²
Easting [m] 1258123
Northing [m] 5005331

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT6

PIEZO CONE PENETRATION TEST

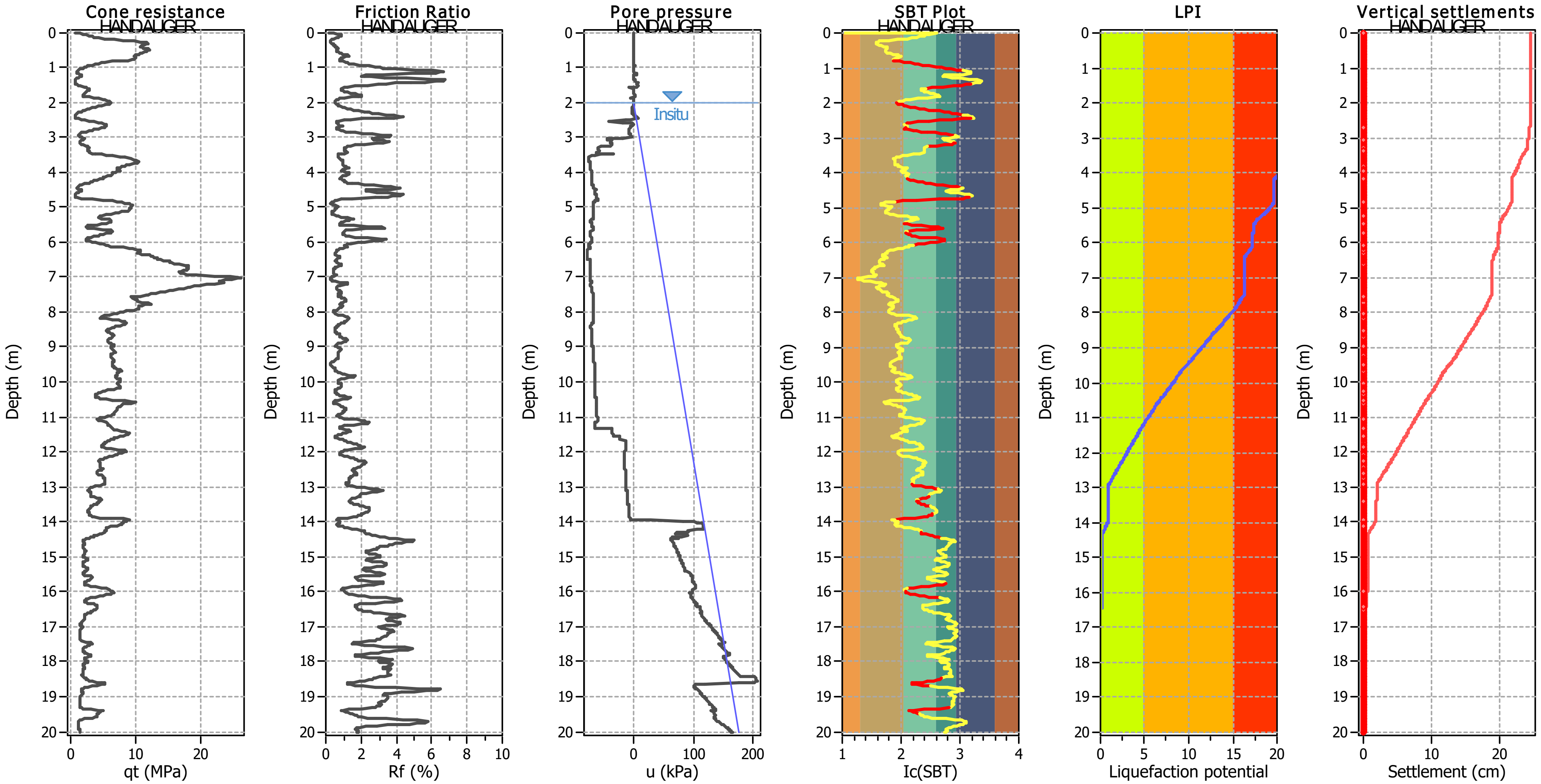
Client : GHD

Project : Wakitipu High School

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD06
Total depth: 20.02 m



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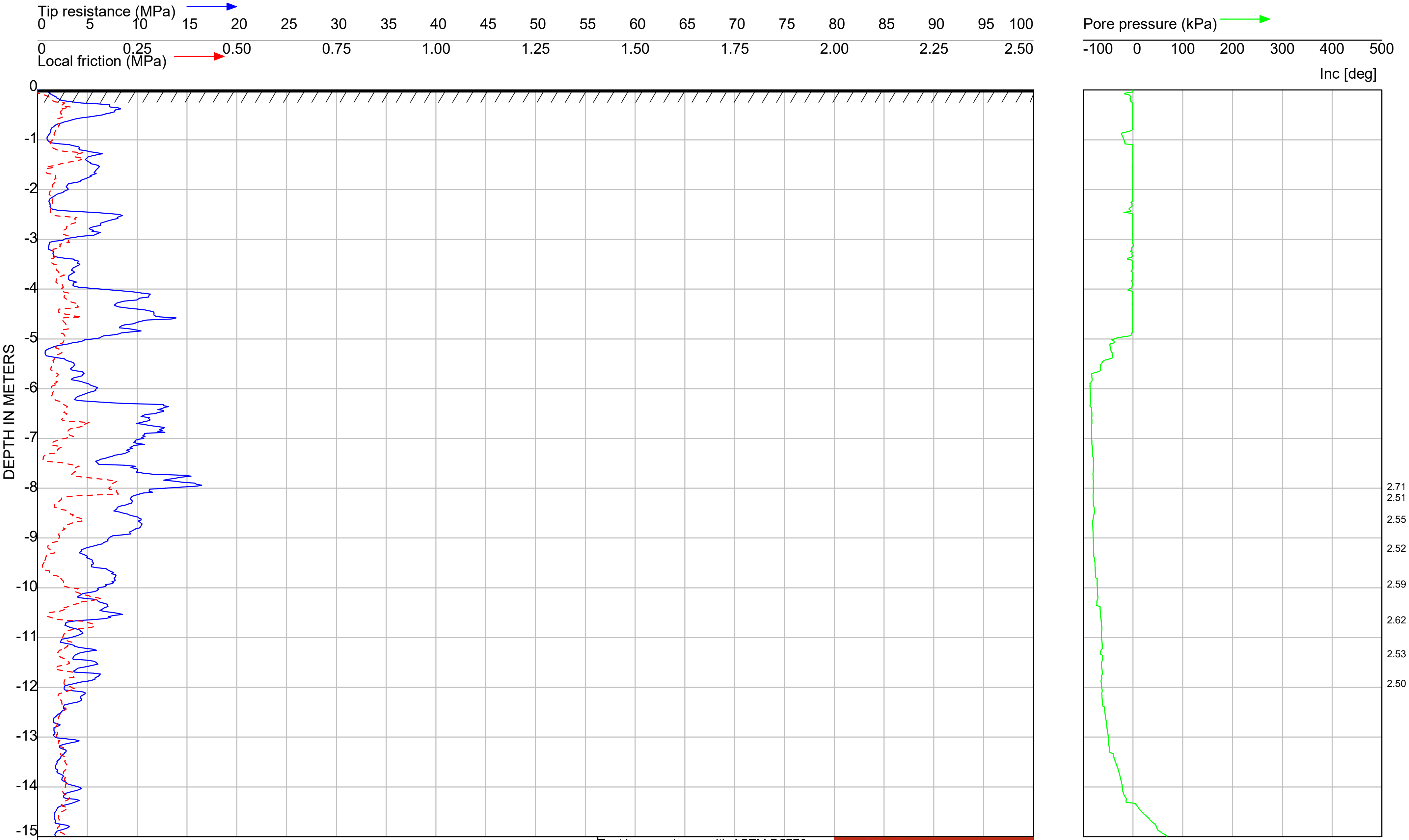
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

CLiq v.2.2.1.14 - CPTU data presentation & interpretation software - Report created on: 2/05/2019, 12:11:09 p.m.
Project file: \\Beca.net\projects\320\3209253\06 Deliverables\Appendices\Appendix K- Liquifaction\ss\Gorge Road Liquifaction.clq



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Time :	15:53	Remark :	

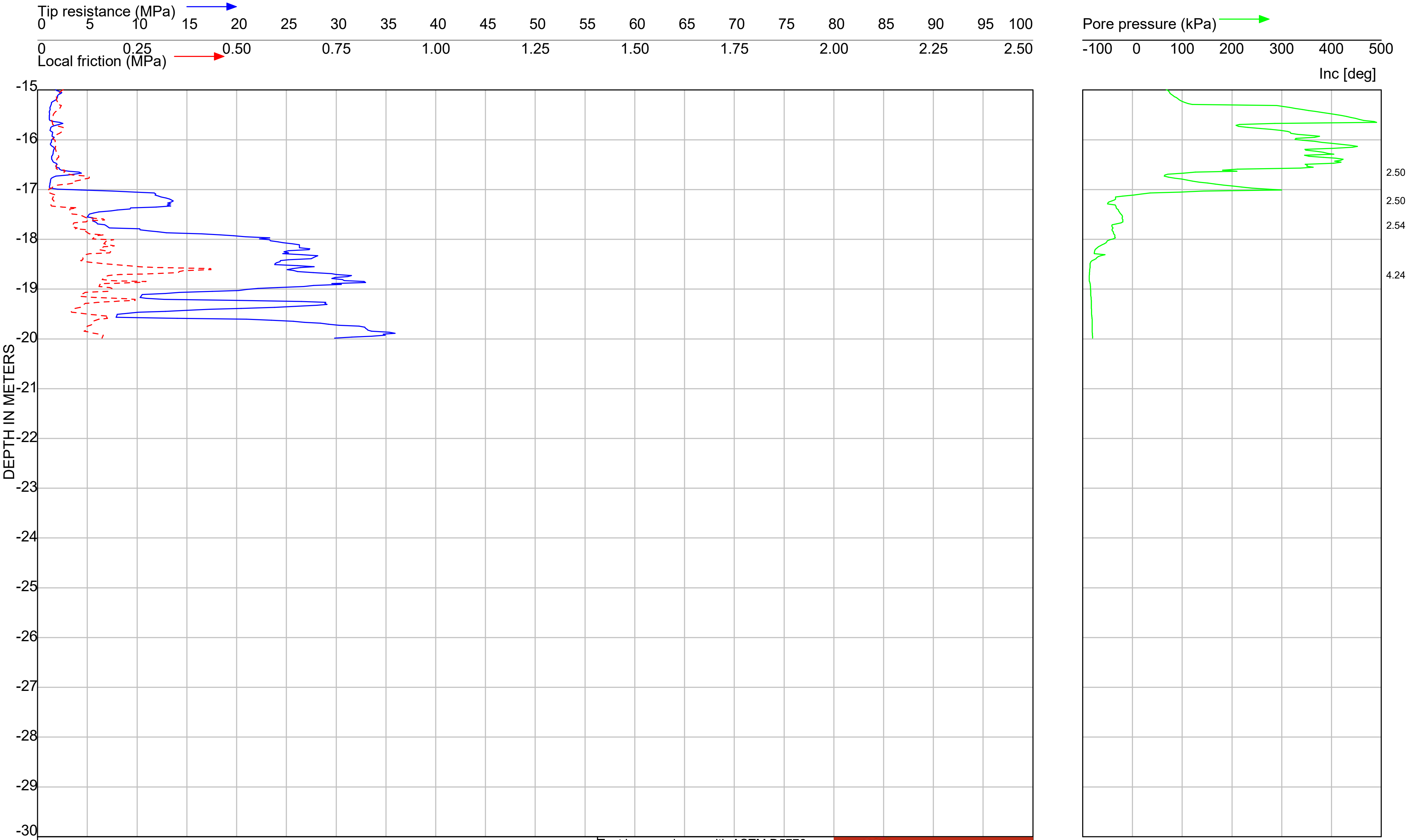
Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ²
Easting [m] 1258053
Northing [m] 5005396

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT7

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School



Operator :	JC	Cone :	I-CFXYP20-15
Date :	18-1-2017	Cone Serial No :	160610
Time :	15:53	Remark :	

Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm [2]
Easting [m] 1258053
Northing [m] 5005396

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT7

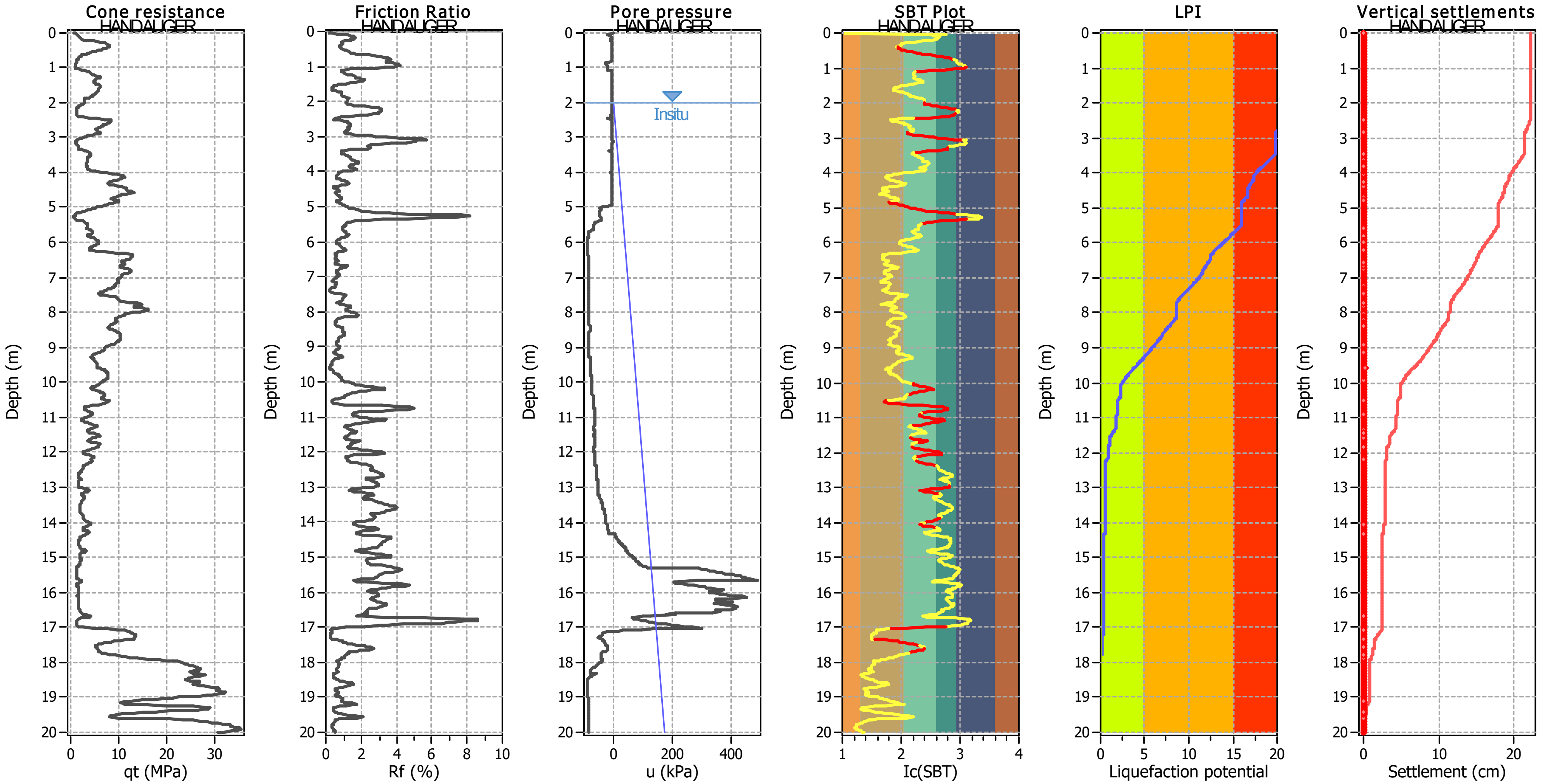
PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD CPT07
Total depth: 20.00 m



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Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
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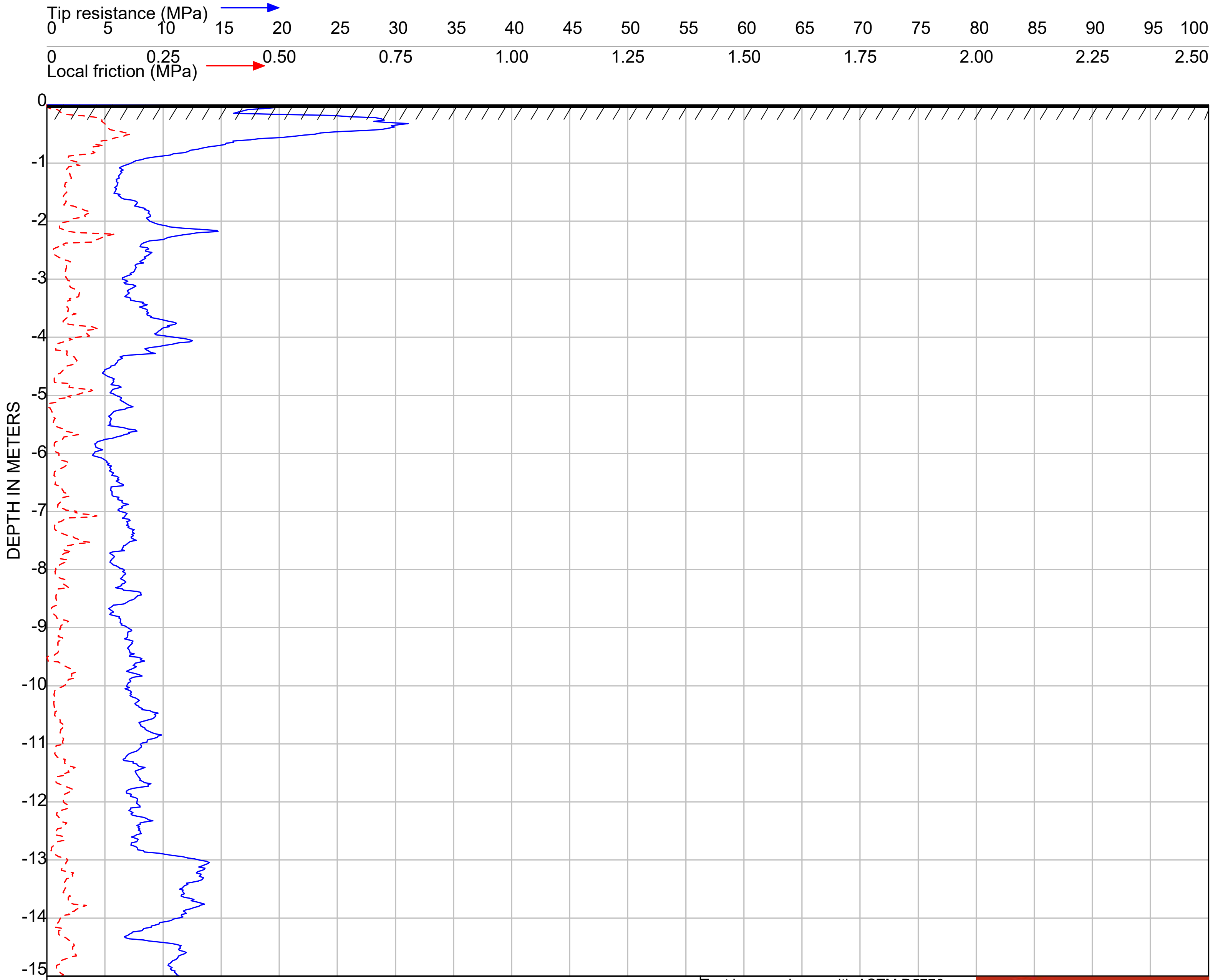
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		



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Time :	16:47	Remark :	

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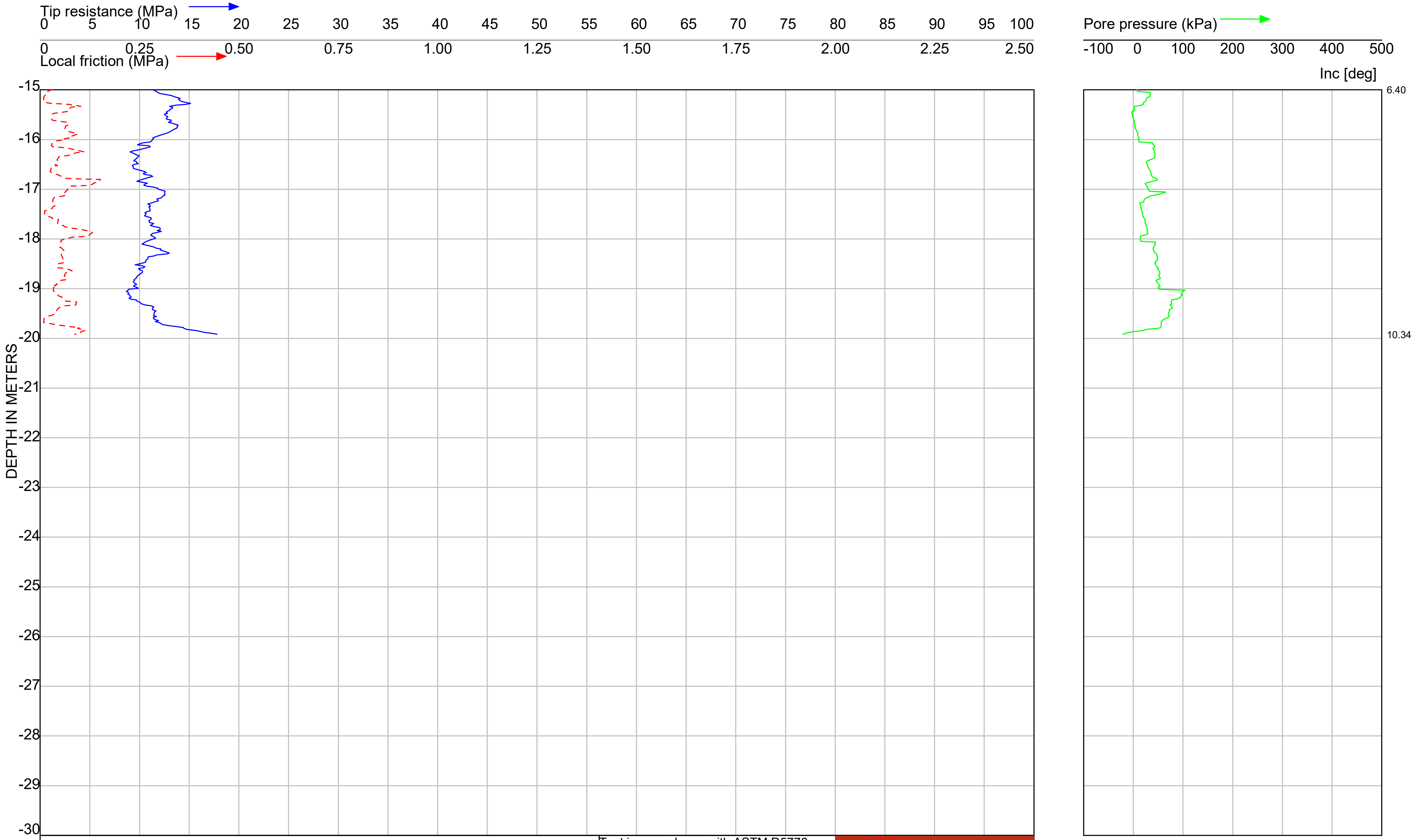
Cone type cylinrical electrical 1510 mm ²
Easting [m] 1257994
Northing [m] 5005367

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT8

PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School



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Test in accordance with ASTM D5778
Cone type cylinrical electrical 1510 mm ²
Easting [m] 1257994
Northing [m] 5005367

mcneill DRILLING ■ DISTRIBUTION ■ PUMPING SINCE 1918

Project No : 4095
Location : CPT8

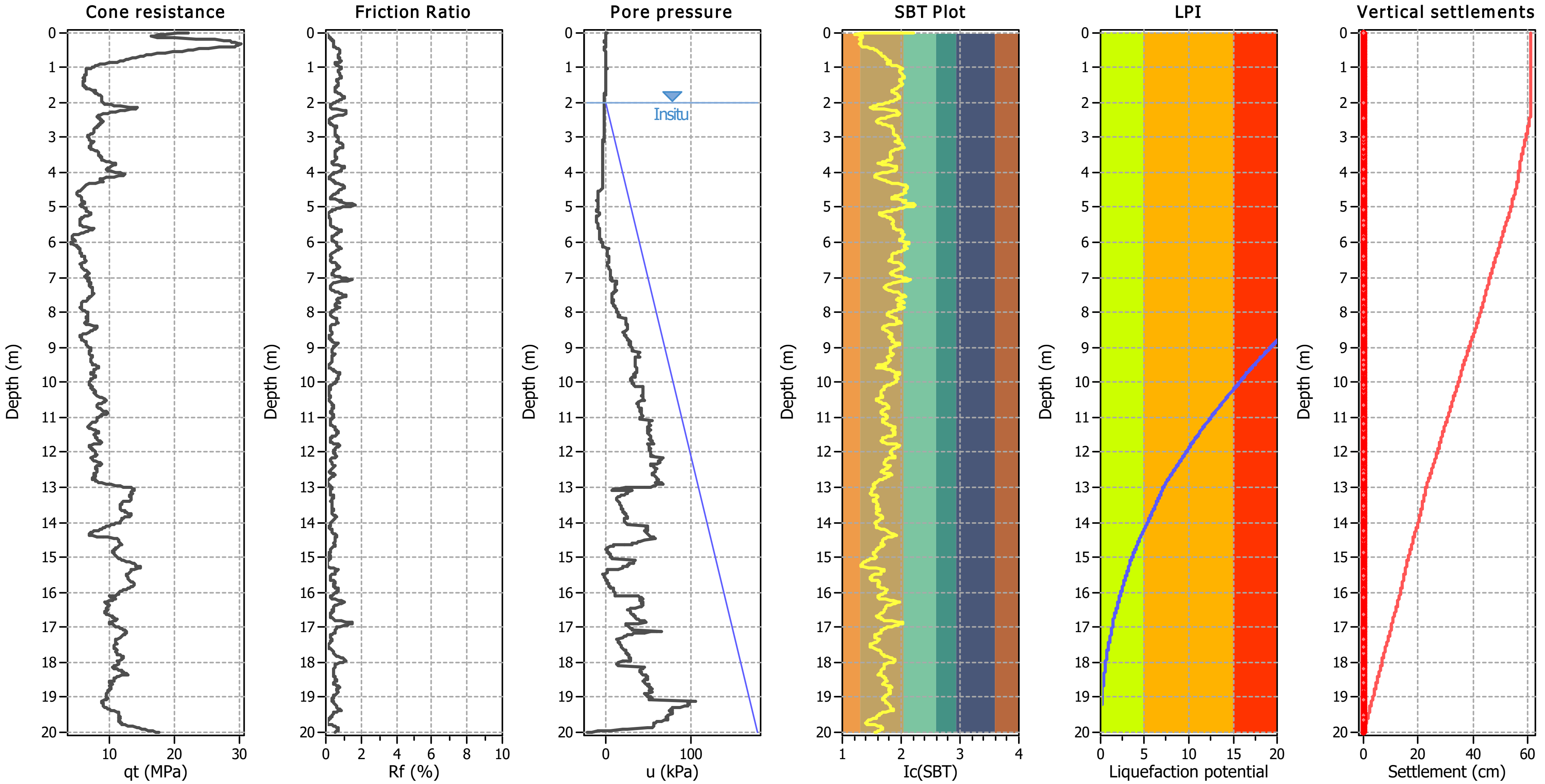
PIEZO CONE PENETRATION TEST

Client : GHD
Project : Wakitipu High School

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: GHD 8
Total depth: 20.00 m



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Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

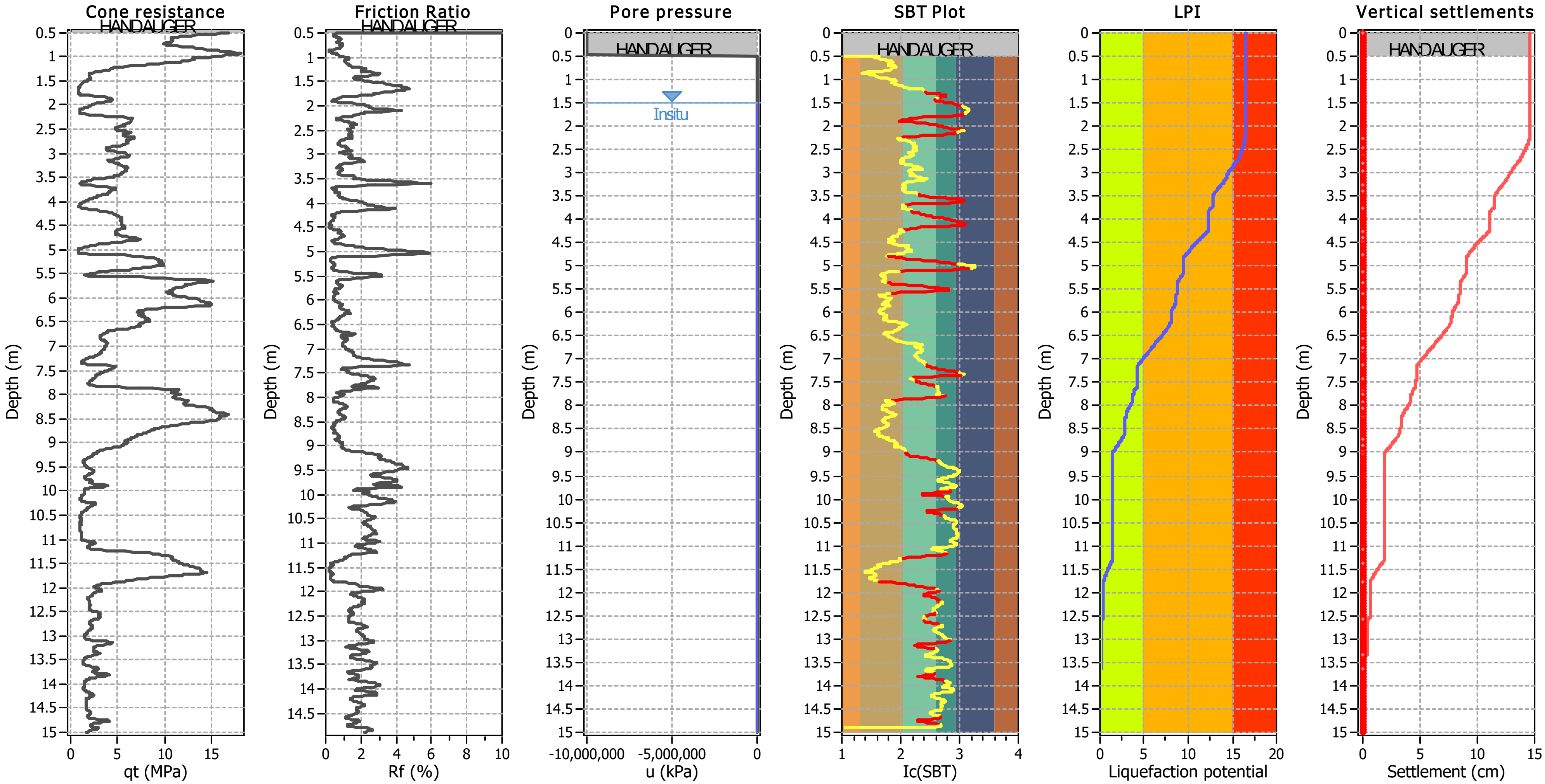
Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment

Location: Gorge Road, Queenstown

CPT: ENGEO E1

Total depth: 15.00 m



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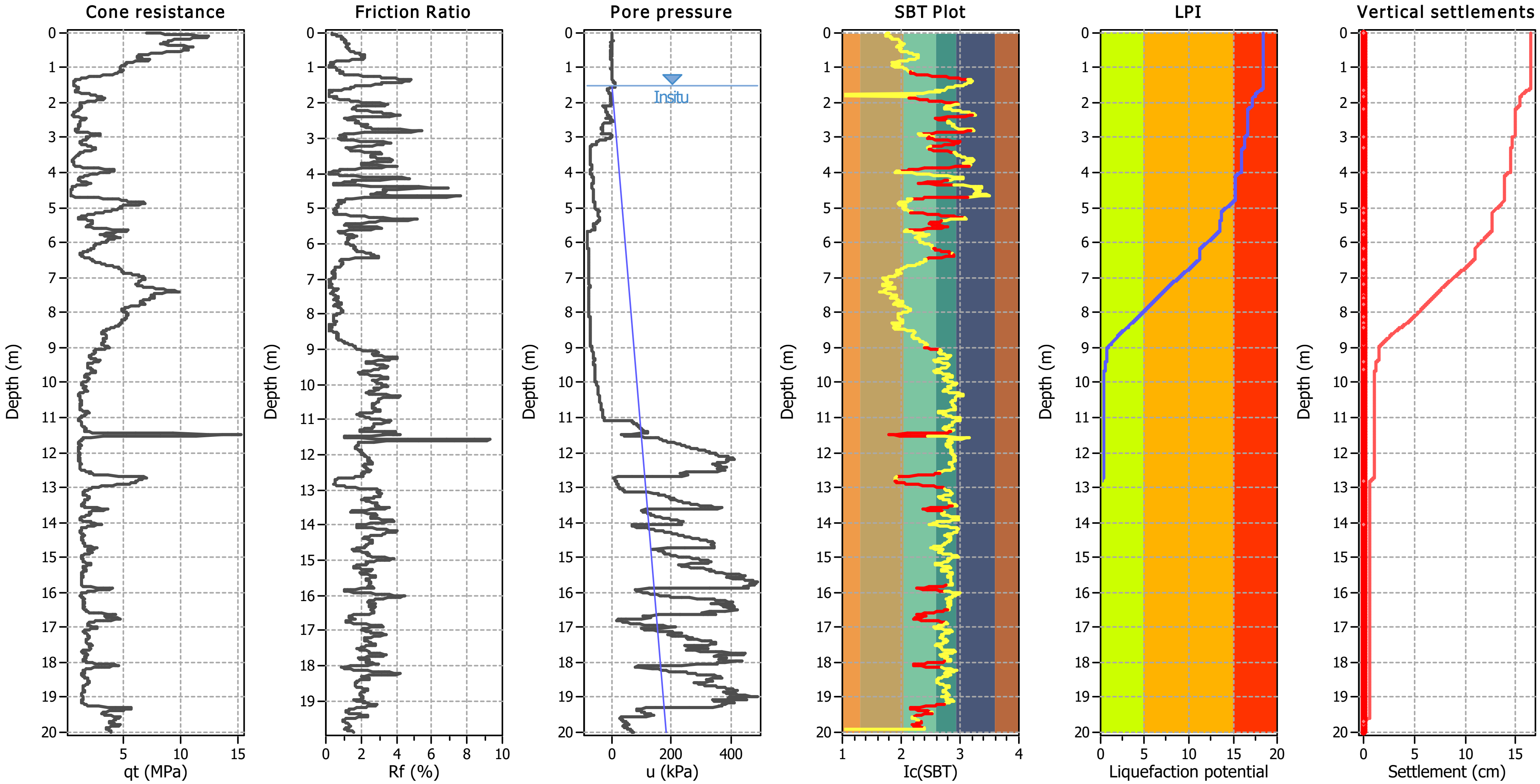
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: ENGEO E2
Total depth: 20.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	1.50 m	Use fill:	No	Clay like behavior applied:	.
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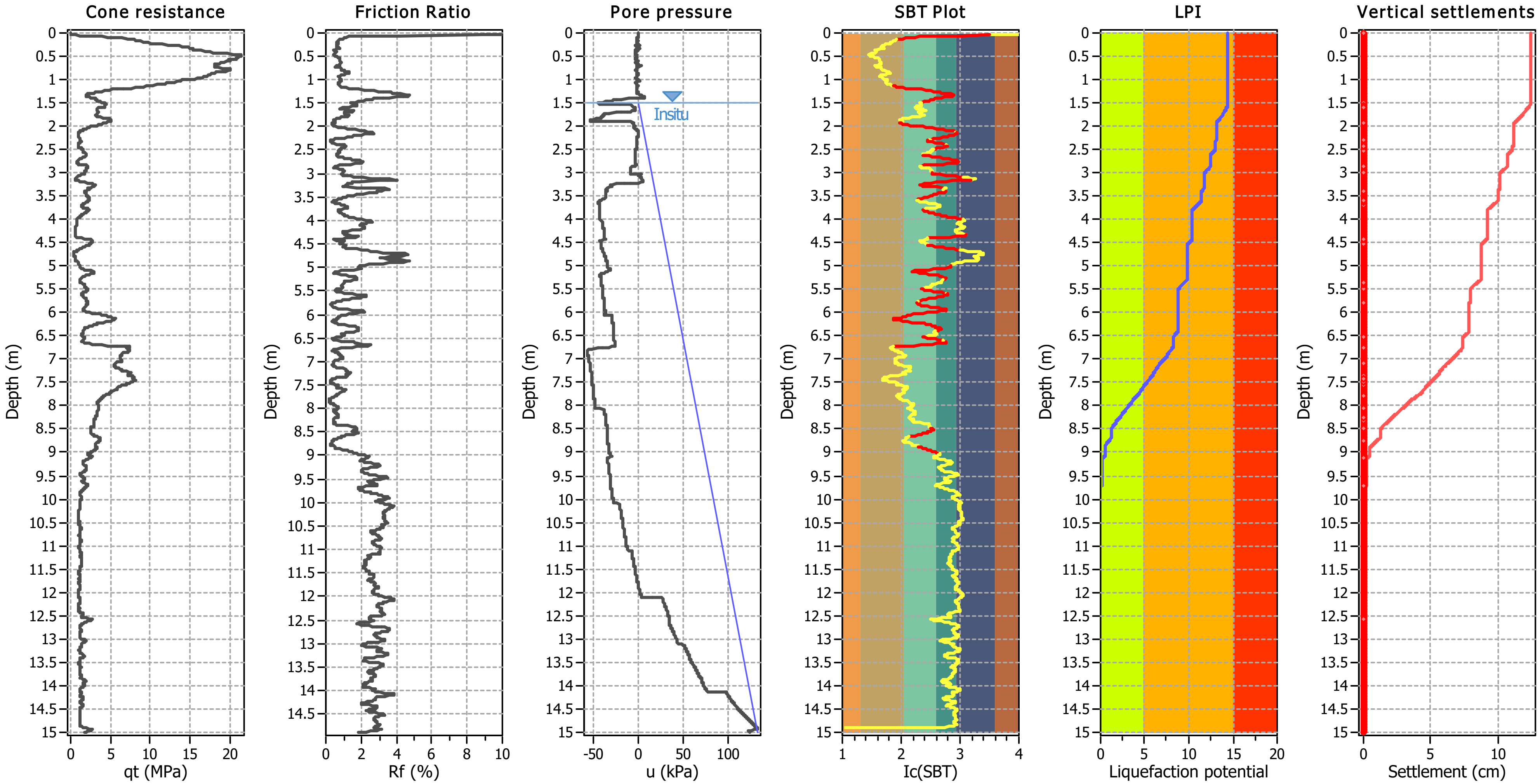
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: ENGEO E3
Total depth: 15.00 m



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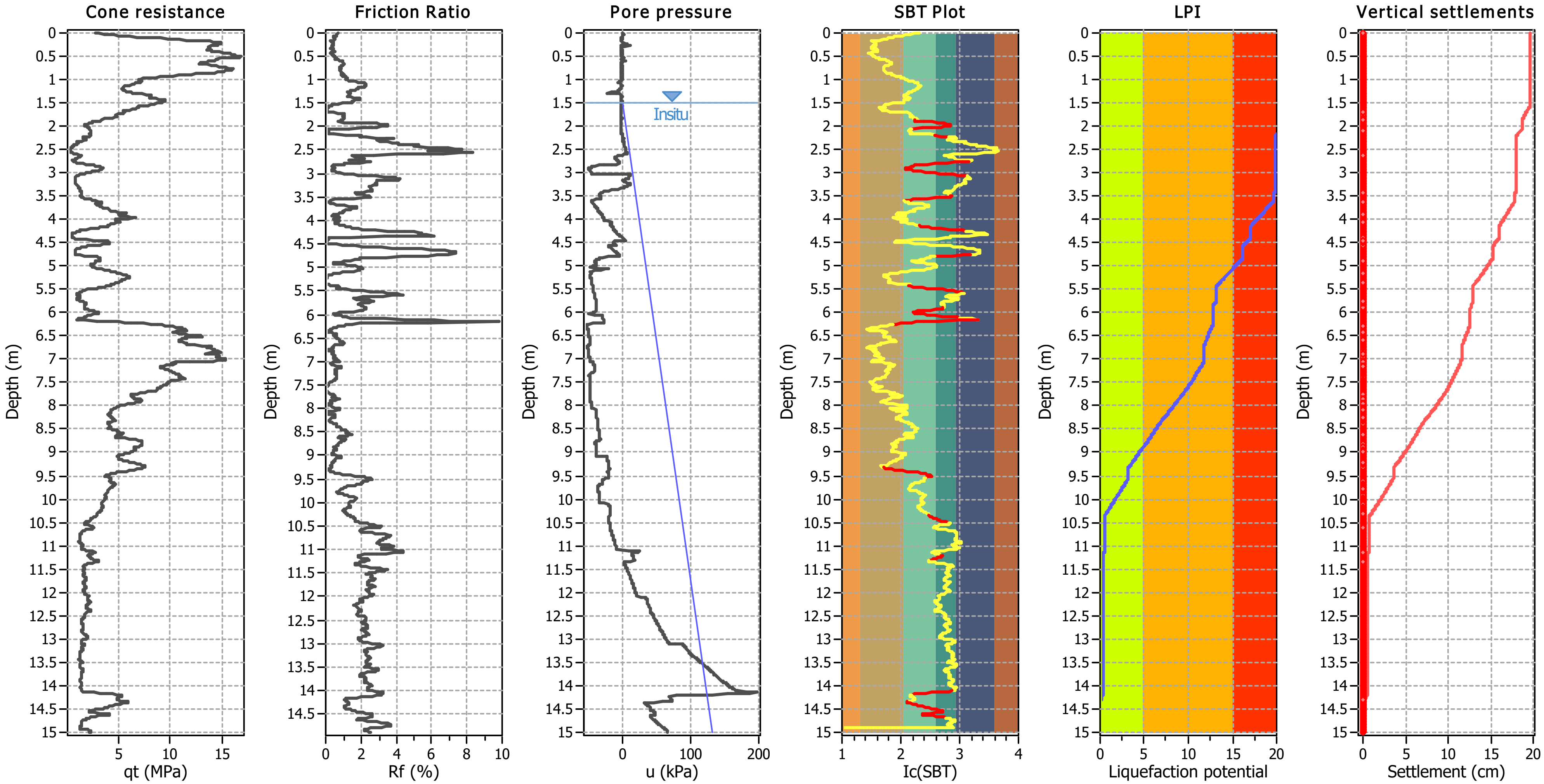
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment
Location: Gorge Road, Queenstown

CPT: ENGEO E4
Total depth: 15.00 m



Analysis method:	B&I (2014)
Fines correction method:	B&I (2014)
Points to test:	Based on Ic value
Earthquake magnitude M_w:	6.50
Peak ground acceleration:	0.41

G.W.T. (in-situ):	1.50 m
G.W.T. (earthq.):	1.50 m
Average results interval:	3
Ic cut-off value:	2.60
Unit weight calculation:	Based on SBT

Use fill:	No
Fill height:	N/A
Fill weight:	N/A
Trans. detect. applied:	Yes
K_σ applied:	Yes

Clay like behavior applied:	.
Limit depth applied:	No
Limit depth:	N/A
MSF method:	Method based

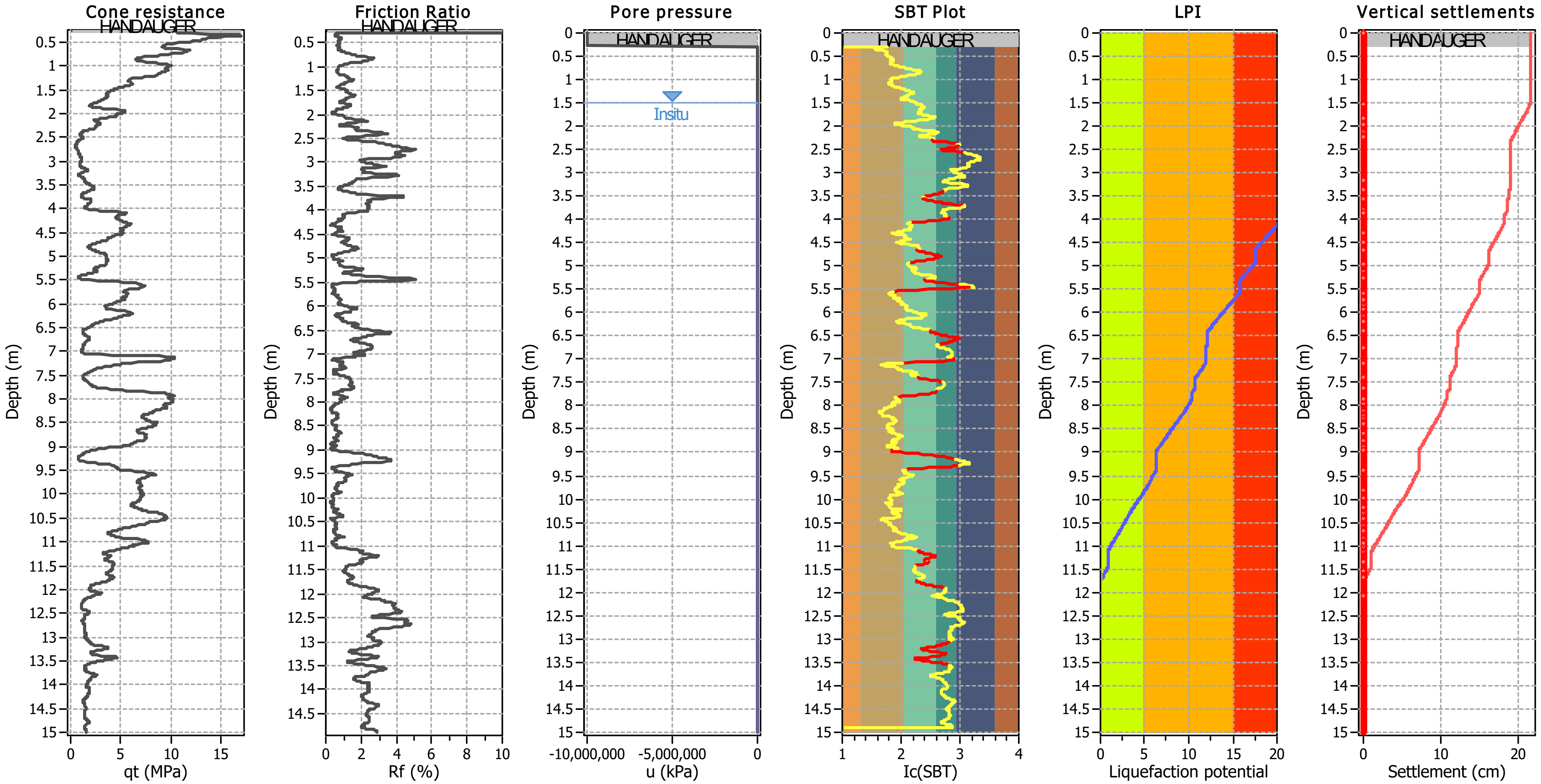
Beca Ltd.
267 High St
Christchurch
http://www.beca.com

Project: Gorge Road Natural Hazards Assessment

Location: Gorge Road, Queenstown

CPT: ENGEO E5

Total depth: 15.00 m



Analysis method:	B&I (2014)	G.W.T. (in-situ):	1.50 m	Use fill:	No	Clay like behavior applied:	.
Fines correction method:	B&I (2014)	G.W.T. (earthq.):	1.50 m	Fill height:	N/A	Limit depth applied:	No
Points to test:	Based on Ic value	Average results interval:	3	Fill weight:	N/A	Limit depth:	N/A
Earthquake magnitude M_w:	6.50	Ic cut-off value:	2.60	Trans. detect. applied:	Yes	MSF method:	Method based
Peak ground acceleration:	0.41	Unit weight calculation:	Based on SBT	K_σ applied:	Yes		

Table 2.2: Degrees of liquefaction-induced ground damage used in the land performance framework. Additional example photos of land damage are presented in Appendix A

DEGREE OF LIQUEFACTION-INDUCED GROUND DAMAGE (example photographs)	TYPICAL CONSEQUENCES AT THE GROUND SURFACE These are examples of the type of damage that would be expected, they are not intended to be criteria for calculation
None to Minor 	– ***None to Minor*** no signs of ejected liquefied material at the ground surface[1]. – No more than minor differential settlement of the ground surface (eg undulations less than 25 mm in height). – No apparent lateral spreading ground movement (eg only hairline ground cracks). – Liquefaction causes no or only cosmetic damage to buildings and infrastructure (but damage may still occur due to other earthquake effects).
Minor to Moderate 	– ***Minor to Moderate*** quantities of ejected liquefied material at the ground surface (eg less than 25 percent of a typical residential site covered[2]); and/or – Moderate differential settlement of the ground surface (eg undulations 25–100 mm in height). – No significant lateral spreading ground movement (eg ground cracks less than 50 mm wide may be present, but pattern of cracking suggests the cause is primarily ground oscillation or settlement rather than lateral spreading). – Liquefaction causes moderate but typically repairable damage to buildings and infrastructure. Damage may be substantially less where liquefaction was addressed during design (eg enhanced foundations).
Moderate to Severe 	– Large quantities of ejected liquefied material at the ground surface (eg more than 25 percent of a typical residential site covered[2]); and/or – ***Moderate to Severe*** differential settlement of the ground surface (eg undulations more than 100 mm in height); and/or – Significant lateral spreading ground movement (eg ground cracks greater than 50 mm wide, with pattern of cracking suggesting direction of movement downslope or towards a free-face). – Liquefaction causes substantial damage and disruption to buildings and infrastructure, and repair may be difficult or uneconomic in some cases. Damage may be substantially less, and more likely to be repairable, where liquefaction was addressed during design (eg enhanced foundations and robust infrastructure detailing).

Notes:

1 An absence of ejecta at the ground surface does not necessarily mean that liquefaction has not occurred. Liquefaction may still occur at depth, potentially causing ground settlement.

2 The coverage of the site with ejected liquefied material does not in itself represent ground damage in an engineering sense, however there is a strong correlation between the volume of ejecta and the severity of differential ground settlement and foundation/infrastructure damage.

G

Appendix G – Debris Flow Modelling

Site Description

The topography of the hillslope behind the study areas was assessed though a combination of field mapping and a DEM developed from 1m LiDAR, as available from the LINZ website. Landslides and slope instabilities were identified during field mapping and outline potential source areas for debris flows. Extents of the potential source regions identified during field mapping were subsequently cross-checked with the topography observed in the DEM. The DEM is assumed to be less accurate than the field survey due to the dense vegetation cover obscuring the underlying slope profile, however it provides an indication of the slope profiles in areas where access was restricted due to the steep topography and dense pine sapling cover. Debris present in the Brewery and Reavers Creek channels, and which may be mobilised during a debris flow and/or dam the channel, was additionally noted during field mapping.

Potential Debris Flow Source areas

Field mapping identified the following features of relevance to the debris flow assessment and selection of potential source areas:

Brewery Creek

- The true left hillslope is covered in pine forest with ground cover comprising fallen leaves, branches, and dead trees. Dead tree trunks and branches were noted immediately adjacent to the Brewery Creek channel and may be transported into the channel.
- Colluvium and younger trees exhibiting deformation and warping were observed on the true-left hillslope of Brewery Creek. The deformation suggests the occurrence of localised creep and slope failures and in some areas these are accompanied by tension cracks.
- The hillslope to the true right of Brewery Creek contains cliffs with localised outcrops of schist. Loose boulders up to 2000mm x 800mm x 500mm were observed at the intersection of joints in the schist and immediately downslope of the outcrops.
- The channel of Brewery Creek generally exhibited slumping of colluvial deposits along the true-left bank and outcrops of schist with loose boulders along the true-right bank. Localised colluvium deposits were observed on the true-right bank where outcrops were not present. Scarps indicating recent erosion of the colluvium deposits were locally observed along the stream channel.
- Dead trees that appear to have fallen into the channel were observed in relatively steep and narrow sections of the channel. Accumulations of dead trees partially damming the channel were observed in areas where the channel widened.

Reavers Creek

- Colluvium with localised areas of scree and debris were observed on the true-left bank suggesting recent/ongoing slope instability. Outcrops of schist and localised colluvium were observed on the true right bank of the creek.
- Localised boulders up to 500mm x 200mm x 100mm in size, broken tree branches, and leaf litter were observed on the gully floor. Boulders were generally covered in moss and no evidence of recent water flow was observed in the channel.
- Localised regions of younger trees are present within the channel and exhibit deformation/warping suggesting localised creep/slope movement.
- The channel above 430m asl varies from open (20m to 50m wide) moderately to steeply sloping sections interspersed with narrow (10m to 20m wide) steep sections.
- Localised accumulations of boulders were observed where outcrops intersect the channel. Boulders range in size from 200mm x 100mm x 50mm up to 1000mm x 800mm x 500mm.

Observations made during field mapping confirm that there is an abundance of material on the hillslope above the two study areas that could be mobilised during heavy rainfall and subsequently result in a debris flow. Logs and boulders currently present within the stream channels may locally dam water flow, and potentially create and/or exacerbate the effects of a debris flow.

High rainfall over a short duration, potentially resulting from a stalled storm cell over the catchment, is considered to be the most likely trigger mechanism for debris flows in the study area.

3D Debris Flow Modelling

3D statistical debris flow analysis has been undertaken using RAMMS: DEBRISFLOW software. Analysis aimed to better understand the paths, heights, and velocities of debris flows impacting the downslope residential and industrial areas of Brewery Creek and Reavers Fans. Input parameters were selected based on observations made during field mapping, extents of previous events affecting the Brewery Creek Fan, and in accordance with the RAMMS debris flow manual guidance. Release regions of varying sizes were selected on the hillslope above the two study areas to account for events of differing magnitudes. Model parameters were selected to consider the effects of forested and non-forested slopes on debris flow depositional zones.

Modelling utilised both hydrograph and block release mechanisms based on field observations and release mechanisms from previous events. Hydrographs simulate channelised debris flows with a release of debris in the channel and models flow discharge as a function of time. Block releases account for unchannelised release of debris where a block of debris is released at once from a hillslope, with flow defined by the spatial extent and thickness of material, and assumed internal friction parameters of the flow.

A block release area inferred to approximate that of the November 1999 debris flow in Brewery Creek was additionally selected based on post-event reports. The model outputs from this scenario were compared against known maximum extents and depths of the 1999 event and used to calibrate model parameters, in line with RAMMS recommended ranges. Models relating to the small, medium and large events were generated based on the calibrated parameters.

The 1999 event does not directly correlate to the “small” event scenarios, primarily due to changes in ground profile resulting from channel modifications since this event. It is anticipated that prior to channel modifications, debris flow or flood events would have extended further downstream (i.e. approached Gorge Road).

Input Parameters

The hillslope terrain model was created from a Digital Elevation Model generated from LiDAR with a 1m grid size, as available from the LINZ website.

Release areas were manually digitised in ArcGIS based on field observations and inferred source regions for previous events. Rationale for release area selection and specific release parameters are outlined in below.

Default release area parameters were selected for the block release models. The release areas were not subtracted from the model during analysis as the areas are upslope of the debris flow paths and therefore the change in topography is considered unlikely to impact the model outputs.

Physical friction model parameters were selected based on field observations and calibration of the model results with documented extents of the 1999 debris flow event in Brewery Creek. The dry-Coulomb type friction portion (coefficient μ) was selected based on tan (α), with α being the slope of the deposition zone; the resultant run-out distances from the models was subsequently calibrated based on the 1999 debris flow event and observed fan topography. A μ value of 0.2 was adopted for the Brewery Creek Fan, and $\mu = 0.22$ for the Reavers Fan. Areas of additional yield stresses were not considered.

The viscous-turbulent friction (coefficient ξ) was varied to simulate the effects of forested and unforested slopes. An ξ of 500m/s was adopted for forested slopes which approximates semi-muddy flows (fluid-like), and accounts for forests impacting flow velocities. The value was selected based on sensitivity analyses conducted using ξ of 200m/s, 300m/s, and 400m/s, and comparison of the modelled debris flow extents with documented debris extents and flow heights reported following the 1999 event on Brewery Creek, and maximum extents of the fan surface. The effects of unforested slopes were modelled using an ξ of 200m/s (solid-dominated) which was selected based on the sensitivity analyses and extent of the fan surface.

Erosion was incorporated downstream of the release areas through digitisation of polygons encompassing the stream channels and river banks in ArcGIS. Default parameters were adopted for analysis assuming normal erosion with an erosion density of 2,000kg/m^3, erosion rate of 0.025m/s, potential erosion depth per kPa of 0.1, and critical shear stress of 1.0kPa, at which point the model allows erosion to start occurring. Obstacles that may influence or deflect flow directions were not considered in the analysis.

A T1 value of 5 seconds was selected for the input hydrographs, being the time delay from release of material to reaching maximum initial velocity. The value was selected as it produced a hydrograph approximating that outlined in the RAMMS: Debris Flow manual. Default model parameters were selected for the remainder of the analysis. Specific input volumes and initial velocities of the hydrographs used in the modelled scenarios are outlined above.

In addition to that outlined above, the following parameters were selected when running the simulations:

- Stop parameter being the percentage of total momentum, was set at 10% based on comparison with observed extents of debris following the November 1999 event. Iterations using a stop parameter of 5% showed water with low flow velocities that continued further across the fan than that previously observed and was considered not representative.
- Simulation resolution – 1.0 m based on the grid size of input the DEM.
- End time (s) – 1000.
- Dump Step (s) – 5.0.
- Density – 2,000kg/m^3; default values were adopted as no additional information on the debris flow material was available.
- Lambda – Default of 1.0 adopted which disables the effects of Lambda as no specific effects were identified.
- Numerical System - Second order.
- Curvature – off.

Model Scenarios

All model scenarios run as part of the debris flow modelling are summarised below (Table G 1 and Table G 2). Input parameters, release areas, and release volumes were varied to test the sensitivity of the model and resultant modelled flow paths and zones of deposition. Sensitivity analysis additionally enabled the effects of forested and un-forested slopes to be accounted for through varying the viscous-turbulent friction parameter (ξ).

The full list of models was refined to include only representative scenarios to inform the AIFR calculations for forested and non-forested slopes, as summarised in Table G 3 and Table G 4.

Table G 1 - Summary of Block Release Debris Flow Model Scenarios Completed for Brewery and Reavers Creeks

Area	Release Area	Model Resolution (m)	Release Depth (m)	Erosion Depth (m)	Mu (μ)	Xi (ξ) m/s
Brewery Creek	Release Area 1	1.0	1.0	1.0	0.2	500
Brewery Creek[1]	Release Area 1	1.0	3.0	1.0	0.2	500
Brewery Creek	Release Area 1	5.0	3.0	1.0	0.2	500
Brewery Creek	Release Area 1	1.0	5.0	2.0	0.2	500
Brewery Creek	Release Area 1	1.0	3.0	2.0	0.2	500
Brewery Creek	Release Area 1	1.0	1.0	1.0	0.2	200
Brewery Creek[2]	Release Area 1	1.0 3.0	1.0	0.2	200	
Brewery Creek	Release Area 1	1.0	1.0	1.0	0.15	500
Brewery Creek	Release Area 1	1.0	4.0	2.0	0.2	500
Brewery Creek[1]	Release Area 2	1.0	1.0	1.0	0.2	500
Brewery Creek	Release Area 2	1.0	1.0	1.0	0.15	500
Brewery Creek[2]	Release Area 2	1.0 1.0	1.0	0.2	200	
Brewery Creek	Release Area 2	1.0	1.0	1.0	0.2	400
Brewery Creek	Release Area 2	1.0	2.0	2.0	0.2	300
Brewery Creek	Release Area 2	1.0	1.0	1.0	0.2	300
Brewery Creek	Release Area 2	1.0	1.0	1.0	0.2	200
Brewery Creek[1]	Release Area 3	1.0	4.0	2.0	0.2	500
Brewery Creek[2]	Release Area 3	1.0	4.0	2.0	0.2	500
Brewery Creek[1]	Release Area 4	1.0	3.0	2.0	0.2	500
Brewery Creek[2]	Release Area 4	1.0	3.0	2.0	0.2	200
Brewery Creek[1]	Release Area 5	1.0	5.0	2.0	0.2	500
Brewery Creek[2]	Release Area 5	1.0 5.0	2.0	0.2	200	
Brewery Creek[1]	Release Area 6	1.0	5.0	2.0	0.2	500

Brewery Creek[2]	Release Area 6	1.0	5.0	2.0	0.2	200	
Brewery Creek	Release Area 6	5.0		5.0	2.0	0.2	500
Brewery Creek	Large Hillslope Release Area A	5.0		5.0	1.0	0.2	500
Brewery Creek	Large Hillslope Release Area B	1.0		5.0	2.0	0.2	500
Brewery Creek	Large Hillslope Release Area C	1.0		5.0	3.0	0.2	500
Brewery Creek	Large Hillslope Release Area C	1.0		5.0	2.0	0.2	500
Reavers Creek[1]	Release Area 1	1.0		1.0	1.0	0.22	500
Reavers Creek[1]	Release Area 1	1.0		3.0	1.0	0.22	500
Reavers Creek	Release Area 1	1.0		1.0	1.0	0.2	500
Reavers Creek	Release Area 1	5.0		1.0	1.0	0.2	500
Reavers Creek[2]	Release Area 1	1.0	1.0	1.0	0.22	200	
Reavers Creek[2]	Release Area 1	1.0	3.0	1.0	0.22	200	
Reavers Creek	Release Area 1+4	1.0		1.0	1.0	0.2	500
Reavers Creek[1]	Release Area 1+4	1.0		1.0	1.0	0.22	500
Reavers Creek	Release Area 1+4	5m		1.0	1.0	0.2	500
Reavers Creek[2]	Release Area 1+4	1.0	1.0	1.0	0.22	200	
Reavers Creek[1]	Release Area 2	1.0		1.0	1.0	0.22	500
Reavers Creek	Release Area 2	1.0		1.0	1.0	0.2	500
Reavers Creek	Release Area 2	5.0		1.0	1.0	0.2	500
Reavers Creek[2]	Release Area 2	1.0	1.0	1.0	0.22	200	
Reavers Creek	Release Area 3	5.0		1.0	1.0	0.2	500
Reavers Creek	Release Area 3	1.0		1.0	1.0	0.2	500

Reavers Creek[1]	Release Area 3	1.0		1.0	1.0	0.22	500
Reavers Creek[2]	Release Area 3	1.0	1.0	1.0	0.22	200	
Reavers Creek[1]	Release Areas 2 + 3	1.0		3.0	2.0	0.22	500
Reavers Creek[2]	Release Areas 2 + 3	1.0	3.0	2.0	0.22	200	
Reavers Creek[1]	Release Area 5	1.0		5.0	2.0	0.22	500
Reavers Creek[2]	Release Area 5	1.0	5.0	2.0	0.22	200	
Reavers Creek[1]	Release Area 6	1.0		5.0	2.0	0.22	500
Reavers Creek[2]	Release Area 6	1.0		5.0	2.0	0.22	200
Reavers Creek[1]	Release Area 5 + 6	1.0	5.0	2.0	0.22	500	
Reavers Creek[2]	Release Area 5 + 6	1.0	5.0	2.0	0.22	200	
Reavers Creek	Bank Collapse	1.0		5.0	2.0	0.22	500
Reavers Creek	Large Slope Collapse - A	1.0		5.0	2.0	0.22	500
Reavers Creek	Large Slope Collapse - B	1.0		5.0	2.0	0.22	500

[1]Scenario based on forested slope used in AIFR calculation and shown in Appendix G – Debris Flow Modelling.

[2]Scenario based on non-forested slope used in AIFR calculation and shown in Appendix G – Debris Flow Modelling

Table G 2 - Summary of Hydrograph Release Debris Flow Model Scenarios Completed for Brewery Creek

Source	Model Resolution (m)	Erosion Depth (m)	Mu (μ)	Xi (ξ) m/s	Hydrograph Volume (m^3)	T1 (s)	Initial Velocity (m/s)
Hydrograph 01	1.0	1.0	0.2	500	15000	5.0	5.0
Hydrograph 01	1.0	1.0	0.2	500	17000	5.0	5.0
Hydrograph 01	1.0	1.0	0.15	500	15000	5.0	5.0
Hydrograph 01	1.0	1.0	0.15	500	17000	5.0	5.0
Hydrograph 01	1.0	1.0	0.2	200	15000	5.0	5.0
Hydrograph 01	1.0	2.0	0.2	500	40000	5.0	5.0

Hydrograph 01	1.0	2.0	0.2	200	40000	5.0	5.0
Hydrograph 02	1.0	1.0	0.2	500	10000	5.0	5.0
Hydrograph 02	1.0	2.0	0.2	500	10000	5.0	5.0
Hydrograph 02[1]	1.0	2.0	0.2	500	20000	5.0	5.0
Hydrograph 02	1.0	2.0	0.2	500	20000	10.0	5.0
Hydrograph 02	1.0	1.0	0.15	500	10000	5.0	5.0
Hydrograph 02[2]	1.0	2.0	0.2	200	20000	5.0	5.0
Hydrograph 03	1.0	2.0	0.2	500	40000	5.0	10.0
Hydrograph 03	1.0	2.0	0.2	200	40000	5.0	10.0
Hydrograph 04	1.0	2.0	0.2	500	40000	5.0	7.5
Hydrograph 04	1.0	2.0	0.2	200	40000	5.0	7.5

[1]Scenario based on forested slope used in AIFR calculation and shown in Appendix G – Debris Flow Modelling.

[2]Scenario based on non-forested slope used in AIFR calculation and shown in Appendix G – Debris Flow Modelling

The models utilised in the debris flow AIFR assessment are summarised in Table G 3 and Table G 4, with additional details in the following sections.

Table G 3 - Brewery Creek Fan scenarios considered in debris flow assessment

Return Period Range (years)	Scenario 1	Scenario 2	Scenario 3
50 - 200	Release Area 1 3m release depth 1m erosion depth 21,300m^3 release volume	Release Area 2 1m release depth 1m erosion depth 5,650m^3 release volume	Hydrograph 2 2m erosion depth 15,000m^3 volume 7.5 m/s initial velocity
200 – 2500	Release Area 3 4m release depth 2m erosion depth 74,200 m^3 release volume	Release Area 4 3m release depth 2m erosion depth 43,400 m^3 release volume	-
2,500 – 10,000	Release Area 5 5m release depth 2m erosion depth 163,000m^3 release volume	Release Area 6 5m release depth 2m erosion 171,000m^3 release volume	-

Table G 4 - Reavers Fan scenarios considered in debris flow assessment

Return Period Range (years)	Scenario 1	Scenario 2	Scenario 3
100 – 2,500	Release Area 1 1m release depth 1m erosion depth 5560m^3 release volume	Release Area 2 1m release depth 1m erosion depth 1,890m^3 release volume	Release Area 3 1m release depth 1m erosion depth 1,580m^3 release volume
2,500 – 6,700	Release Area 1 3m release depth 1m erosion depth 16,685m^3 release volume	Release Areas 2 & 3 3m release depth 2m erosion depth 10,410m^3 total release volume	Release Areas 1 & 4 1m release depth 1m erosion depth 12,140m^3 total release volume
6,700 – 20,000	Release Area 5 5m release depth 2m erosion depth 98,330m^3 release volume	Release Area 6 5m release depth 2m erosion depth 99,510m^3 total release volume	Release Areas 5 & 7 5m release depth 2m erosion 139,300m^3 release volume

Scenario Source Regions

The source region of the Brewery Creek small event scenario (Release Area 1) was selected based on the inferred source of the November 1999 event. Source regions of the other scenarios were based on evidence of erosion and slope instability observed during mapping and from aerial photography, inferring potential larger event sources from stream bank collapse and larger hillslope failure.

Model Cut Off Process

Cut-off parameters for debris flow velocity (2m/s) and depth (1m) were applied to the models, as detailed in Section 5.2.1b.i, with any areas beyond this discounted. The cut off process was followed in order to apply consistent vulnerability parameters to each modelled event, and to provide a direct link between the vulnerability parameter and the RAMMS model outputs. The cut off parameters were adopted based on a review of the following supporting information:

- Cruden and Varnes (1996) velocity scale (adopted by AGS, 2007), which links the ability of a person to avoid being hit by a landslide to velocity. Velocities of 5m/s (running speed) and approximately 1.5m/s (walking speed) were considered by Beca, with 2m/s cut off adopted.
- New Zealand council flood hazard matrices threshold for high hazard, based on flooding (Aecom, 2012).
- The United States Federal Emergency Management Agency (1979) statement that a moderate sized person begins to lose stability in water at depths of around 0.9m (3ft) and velocities of around 0.6m/s (2ft/s), as reported in Aecom (2012).

This process was followed for both forested (current situation) and non-forested cases. The resulting maps are shown in Appendix J – Slope Stability Life Risk Maps.

Debris Flow Spatial Impact Extents Summary

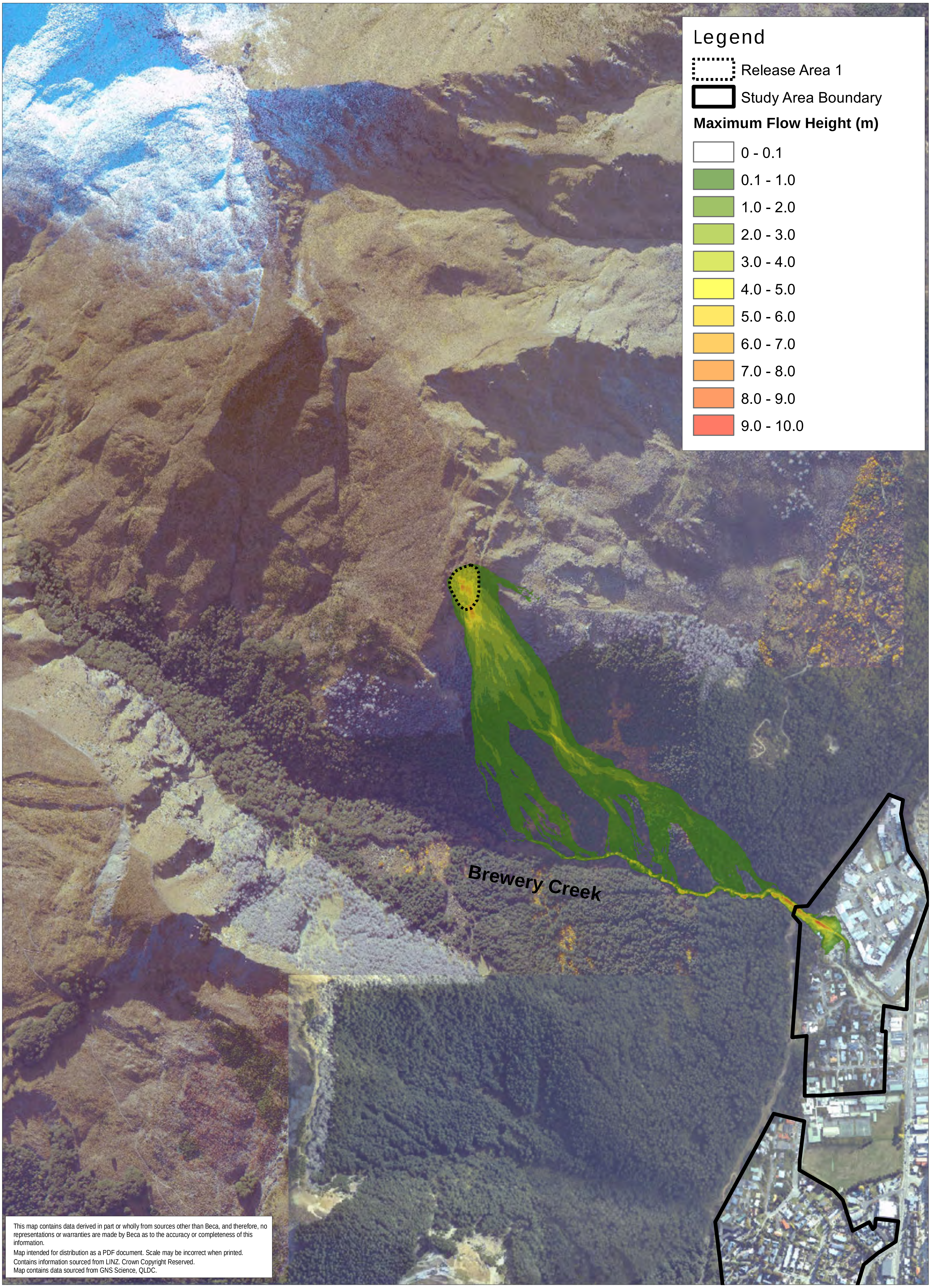
Brewery Creek Fan:

- Fan topography locally influences the flow-paths and flow heights on the fan surface. Small-scale debris flows reaching the Brewery Creek Fan generally follow the deepened channel however over-top the banks at bends in the channel causing the flow path to be diverted. Debris flows reaching the lower reaches of the fan are generally confined to the area within 20m of the channel.
- The low gradient of the Brewery Creek channel and surface roughness cause debris flow velocities and heights to decrease along the channel, resulting in confined inundation areas on the fan surface.

- Modelling of block release areas in the upper slopes of the catchment (21,300m^3) and along the creek bank (5,600m^3) that matches features observed during field mapping, show inundation areas on the fan range from 6,400m^2 to 8,300m^2. The inundation area is confined to the area immediately downslope of apex of the fan and is largely confined to the existing channel.
- Localised release of debris within the mid-section of the channel of 15,000m^3 (Hydrograph 02 in Appendix G – Debris Flow Modelling) additionally shows fan inundation is confined to the fan apex and is largely confined to the area immediately surrounding the upper-reaches of the Brewery Creek channel (inundation area of 9,900m^2).
- Modelling of large-scale block-releases on the upper slopes of the catchment and stream bed (approximately 160,000m^3 to 170,000m^3) show much of the fan within 100m of the channel as being inundated with debris. Total areas of inundation range from 26,000m^2 to 29,000m^2. Modelling indicates that the low gradient of the channel and surface roughness causes much of the debris to be deposited within the channel upstream of the fan.

Reavers Fan:

- Zones impacted by debris flow on the Reavers Fan are influenced by fan topography. Small-scale events inundate the upper slopes of the fan immediately downslope of the fan apex, while the larger scale events inundate much of the fan surface. Flow paths are not channelised on the fan due to the lack of a marked channel/ topographic depression.
- Flow heights and velocities do not decrease significantly along the length of the channel likely due to the wider channel and steeper gradient compared to the Brewery channel.
- Modelling of small-scale (1,500m^3 to 5,500m^3) block releases matching landslides observed during field mapping shows the fan inundation areas ranging from 4,600m^2 to 7,400m^2. The inundated area corresponds with the portion of the fan immediately downslope of the fan apex and culvert.
- Modelling of medium-scale block releases (16,600m^3) and events involving multiple release areas on the hillslope above the fan (10,415m^3 to 12,150m^3) indicates that inundation of the fan ranges from 12,800m^2 to 16,400m^2. The area of inundation is confined to the area immediately downslope of the culvert and fan apex and is locally influenced by the fan topography.
- Large scale block releases in the catchment (98,000m^3 to 200,000m^3) result in widespread inundation of the fan surface (40,000m^2 – 50,000m^2) covering much of the Reavers Fan surface above Fryer Street.
- No channel releases (hydrographs) were developed for Reavers Fan due to the wide nature of the channel and lack of evidence of debris or colluvium built up within the channel observed during the mapping.



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Brewery Creek
Debris Flow Modelling
Scenario 1: 50-200 yr
Forested Source Area

Client: Queenstown Lakes District Council

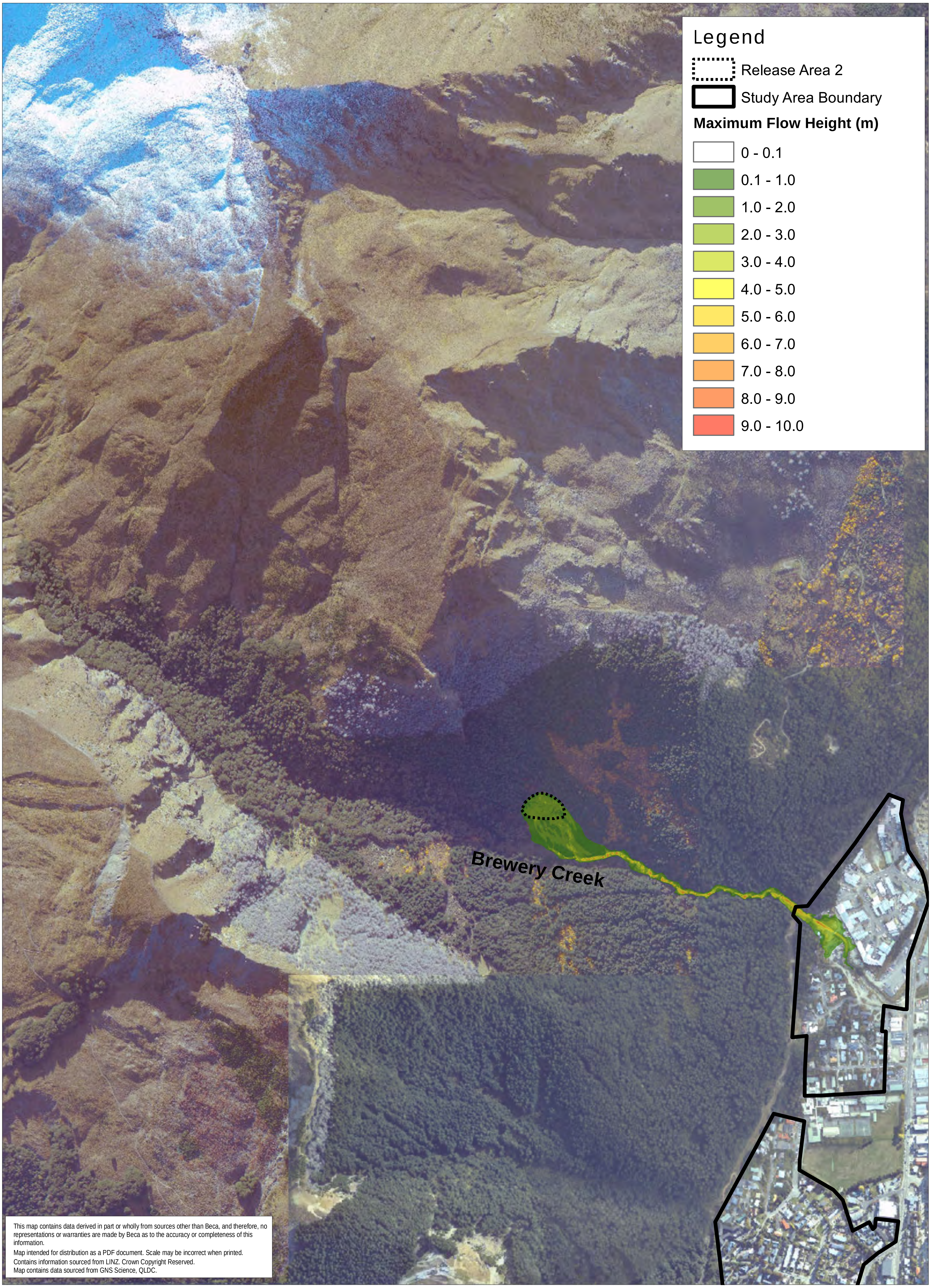
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G001



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Brewery Creek
Debris Flow Modelling
Scenario 2: 50-200 yr
Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G002

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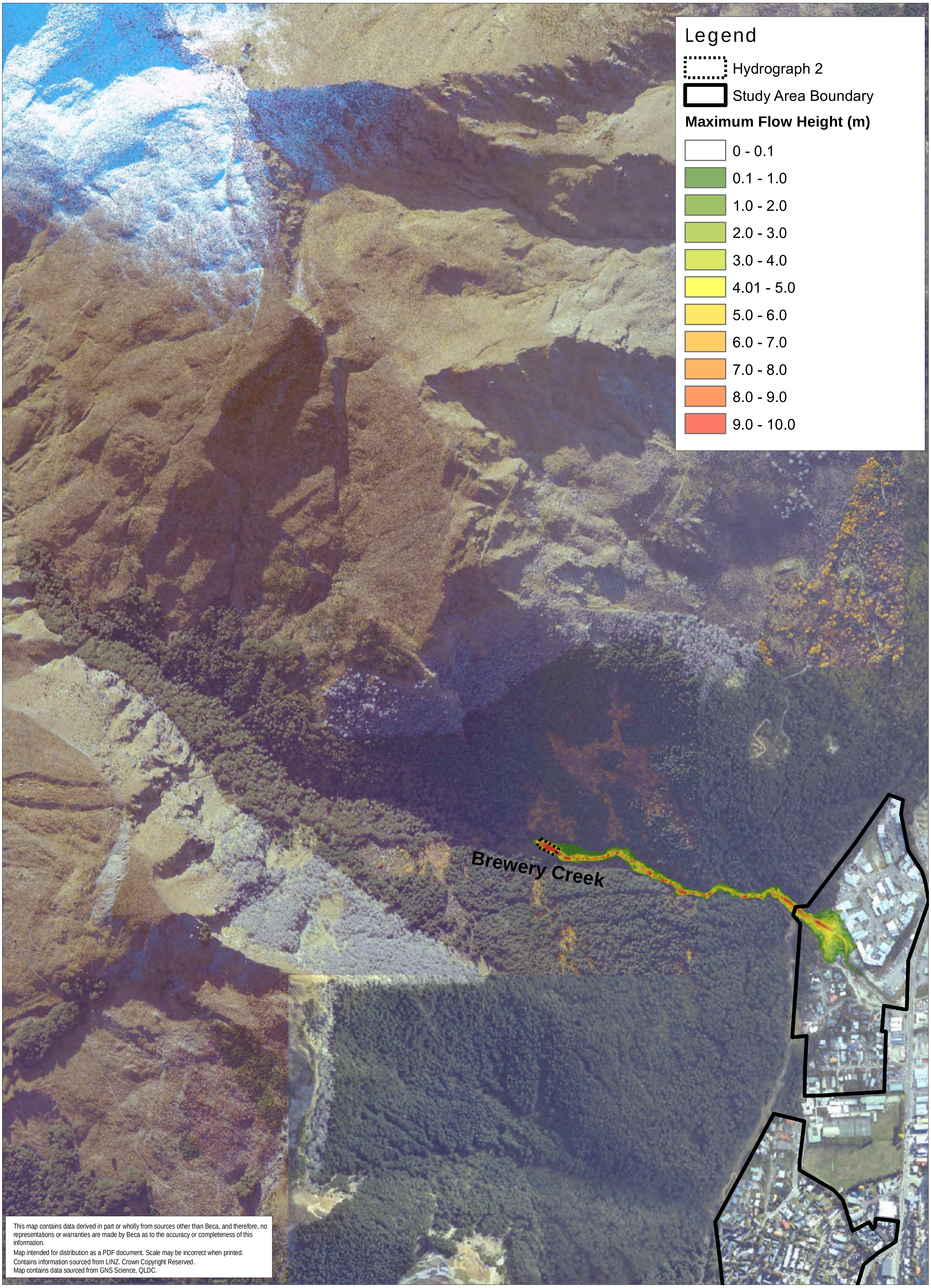

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Revision	Author	Verified	Approved	Date
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Title:
Brewery Creek
Debris Flow Modelling
Scenario 3: 50-200 yr
Forested Source Area

Client: Queenstown Lakes District Council

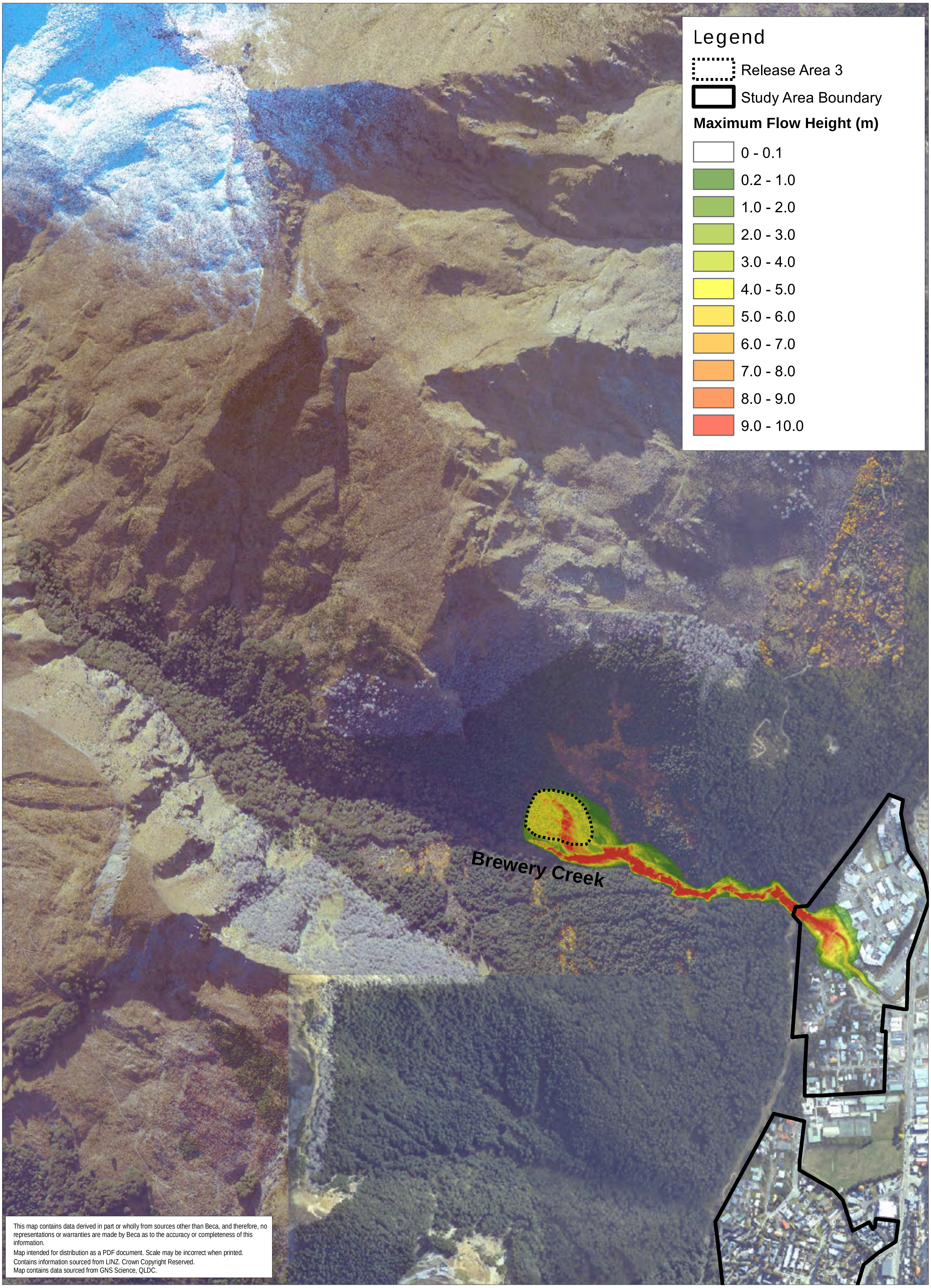
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G003



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Revision	Author	Verified	Approved	Date
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Title: Brewery Creek Debris Flow Modelling Scenario 1: 200-2,500 yr Forested Source Area

Client: Queenstown Lakes District Council

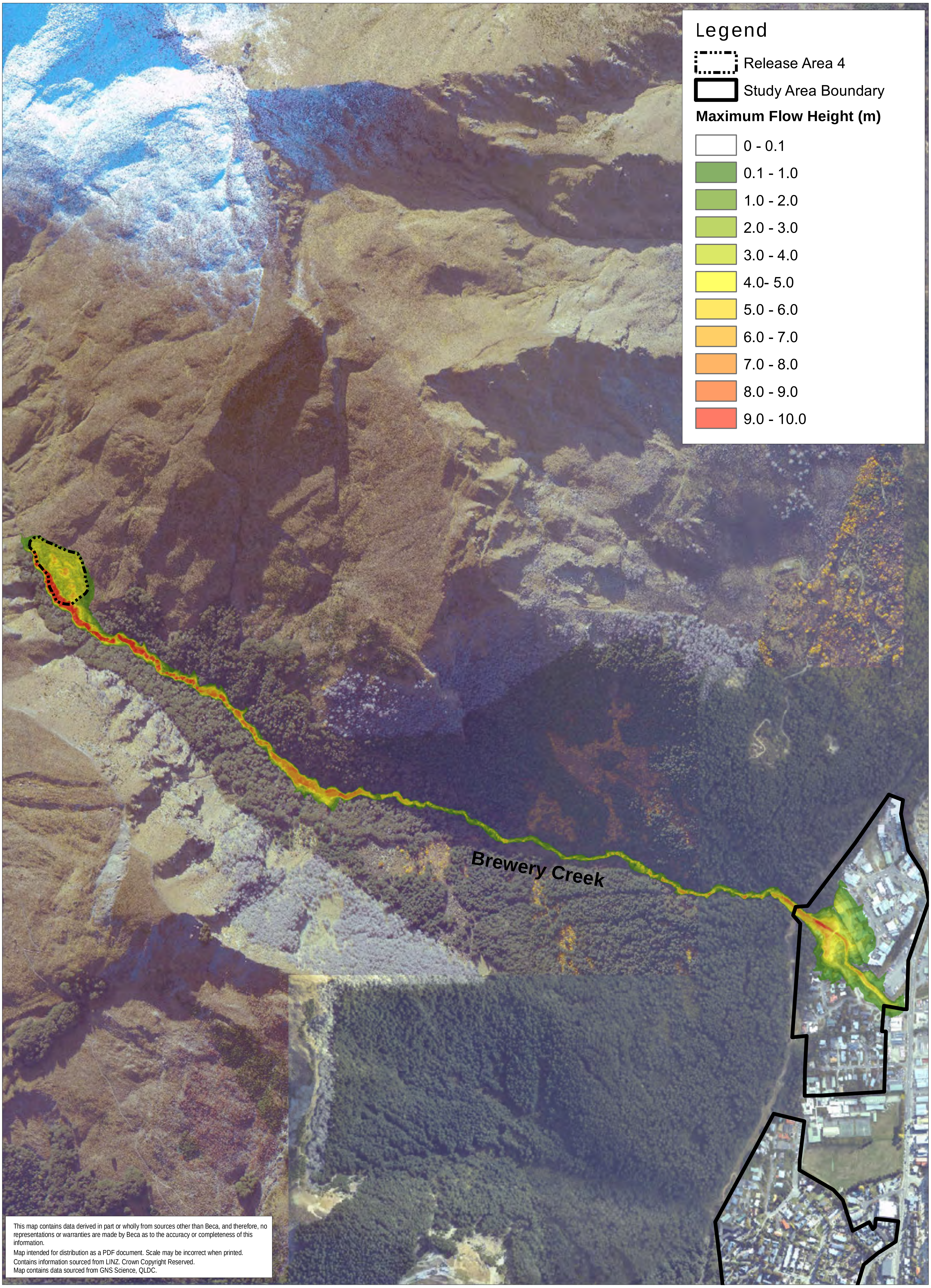
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G004



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Metres

Revision	Author	Verified	Approved	Date
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Title: Brewery Creek Debris Flow Modelling Scenario 2: 200-2,500 yr Forested Source Area

Client: Queenstown Lakes District Council

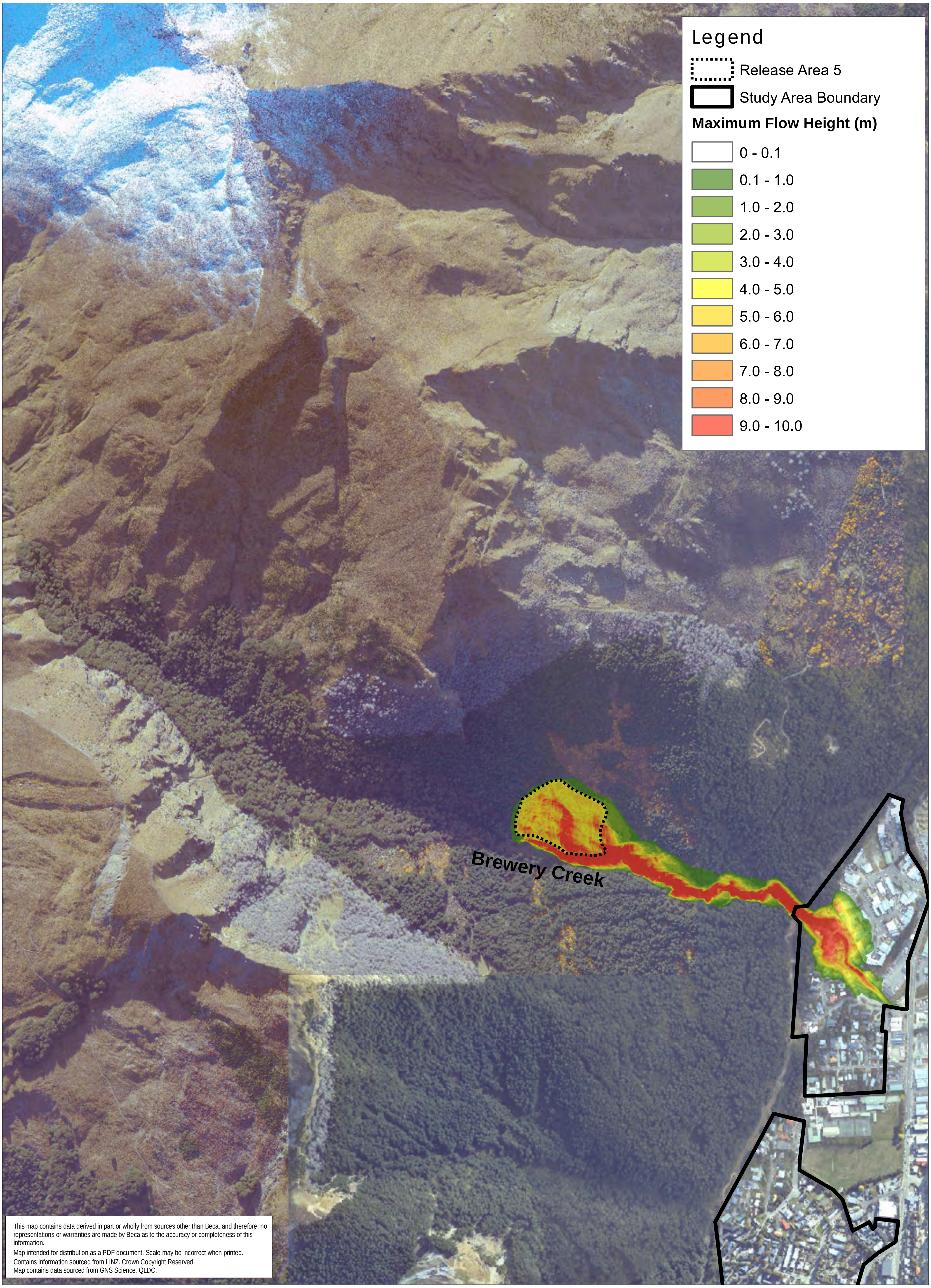
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G005



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Metres

Revision	Author	Verified	Approved	Date
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Title:
Brewery Creek
Debris Flow Modelling
Scenario1: 2,500-10,000 yr
Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

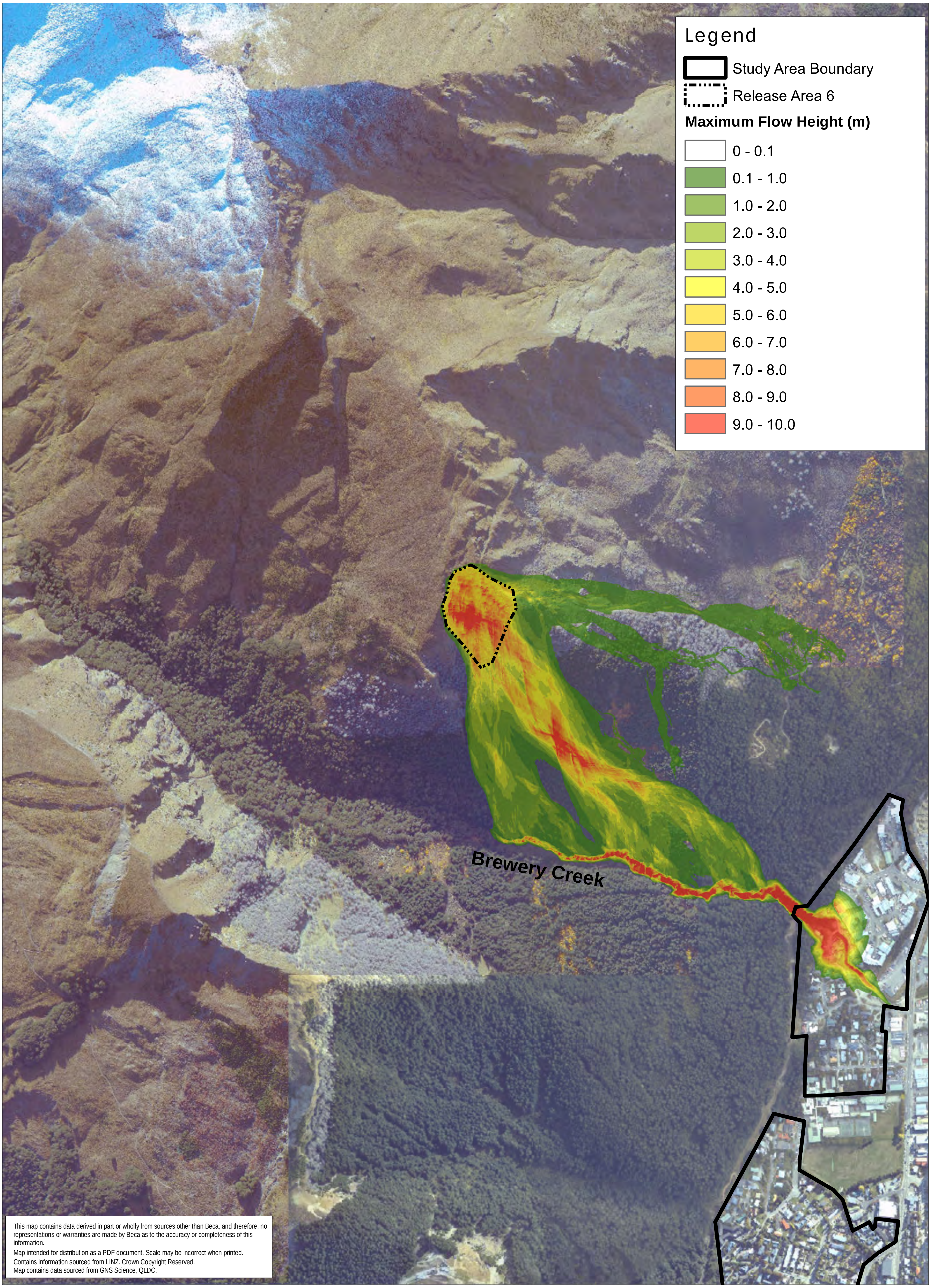
N

Beca

Discipline: GIS

Drawing No: 3209881-G006

GIS@beca.com



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Title:

Brewery Creek

Debris Flow Modelling
Scenario 2: 2,500-10,000 yr
Forested Source Area

Client: Queenstown Lakes District Council

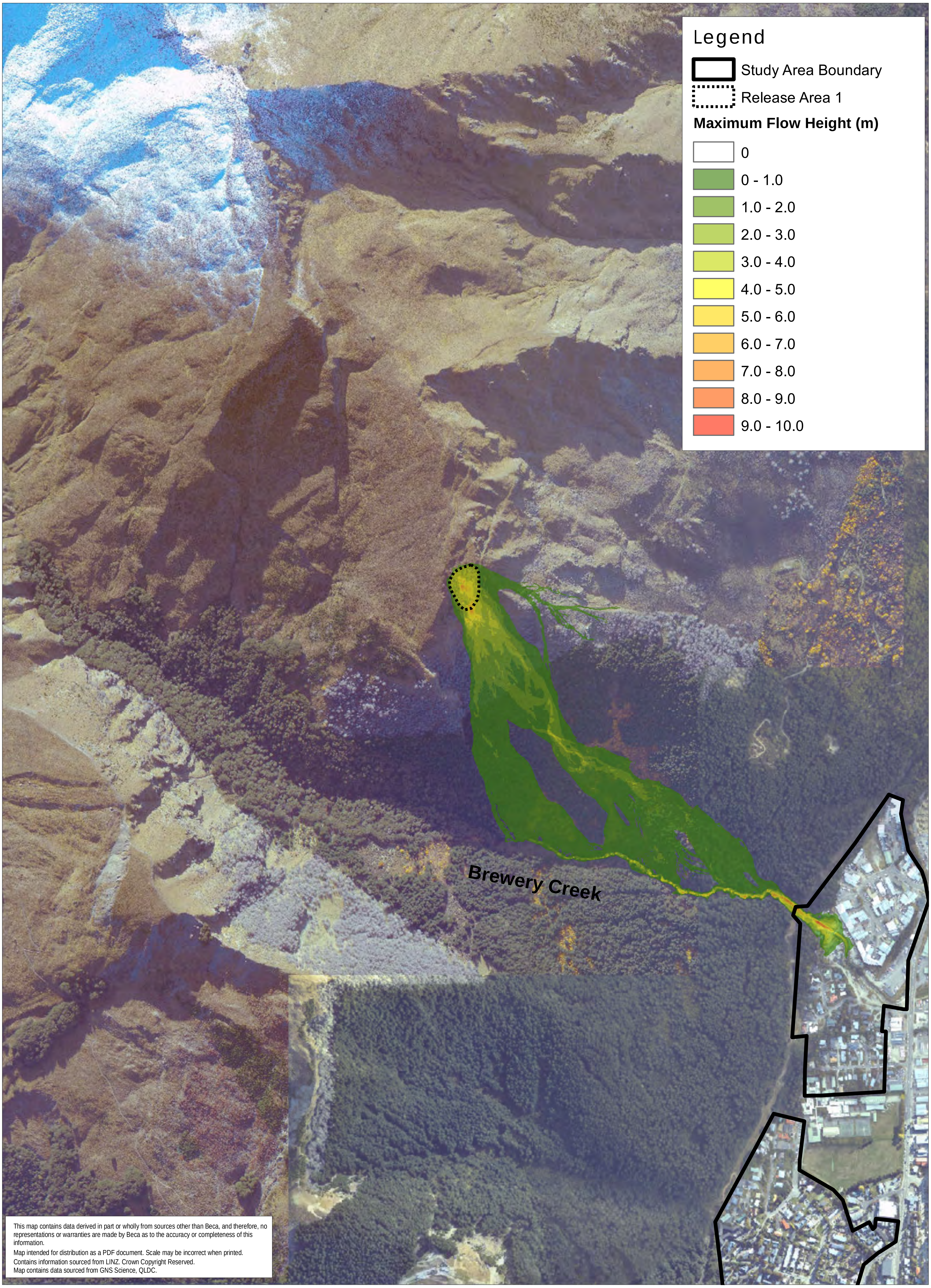
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G007



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Revision	Author	Verified	Approved	Date
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Title: Brewery Creek
Debris Flow Modelling
Scenario 1: 50-200 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

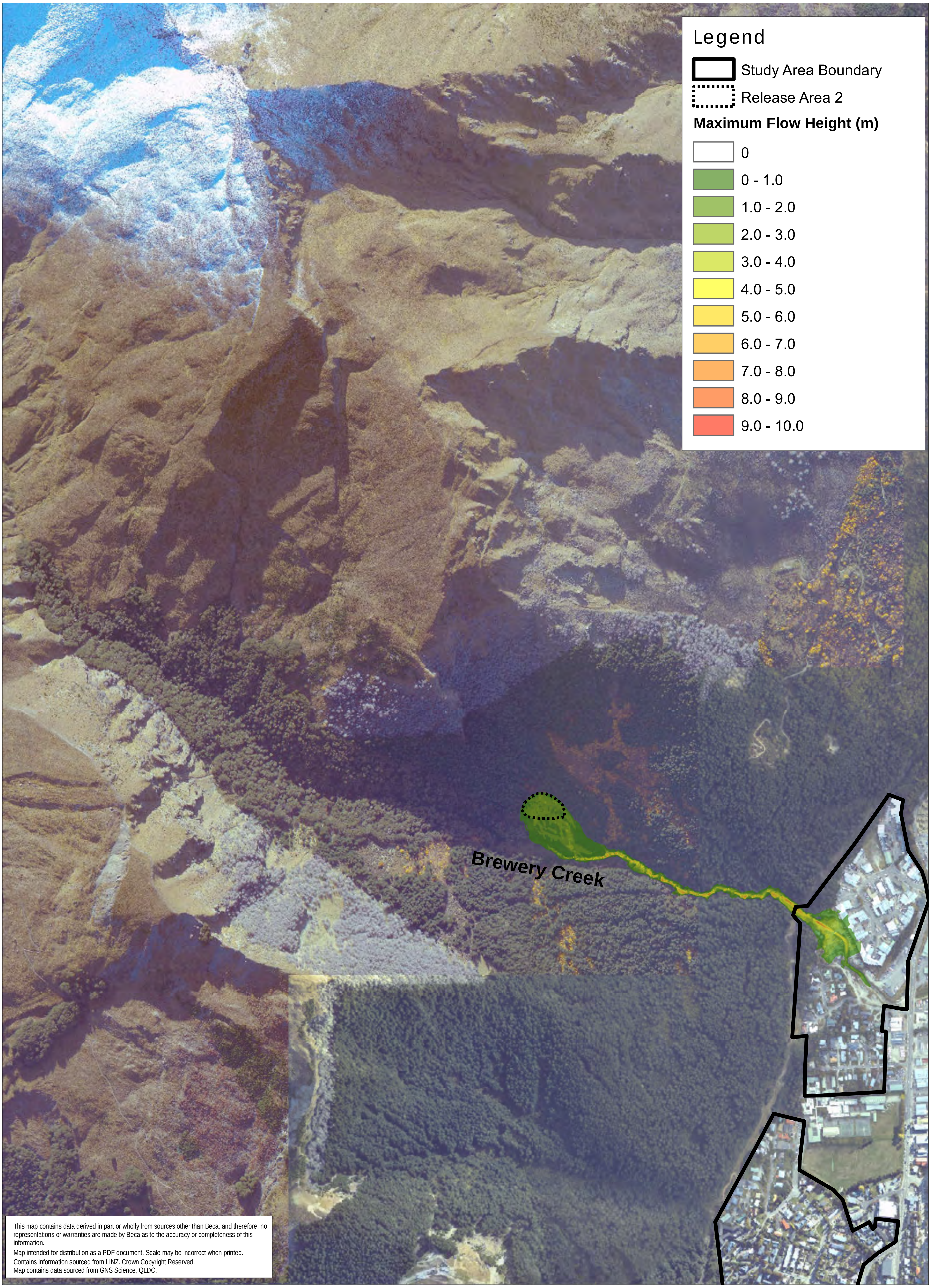
Discipline: GIS

Drawing No: 3209881-G008

File: P:\3220\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G008.mxd Author: SHB Date: 11/05/2020

GIS@beca.com

File: P:\3220\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G009.mxd Author: SHB Date: 11/05/2020 GIS@beca.com



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Map Scale @ A3: 1:8,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Brewery Creek
Debris Flow Modelling
Scenario 2: 50-200 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

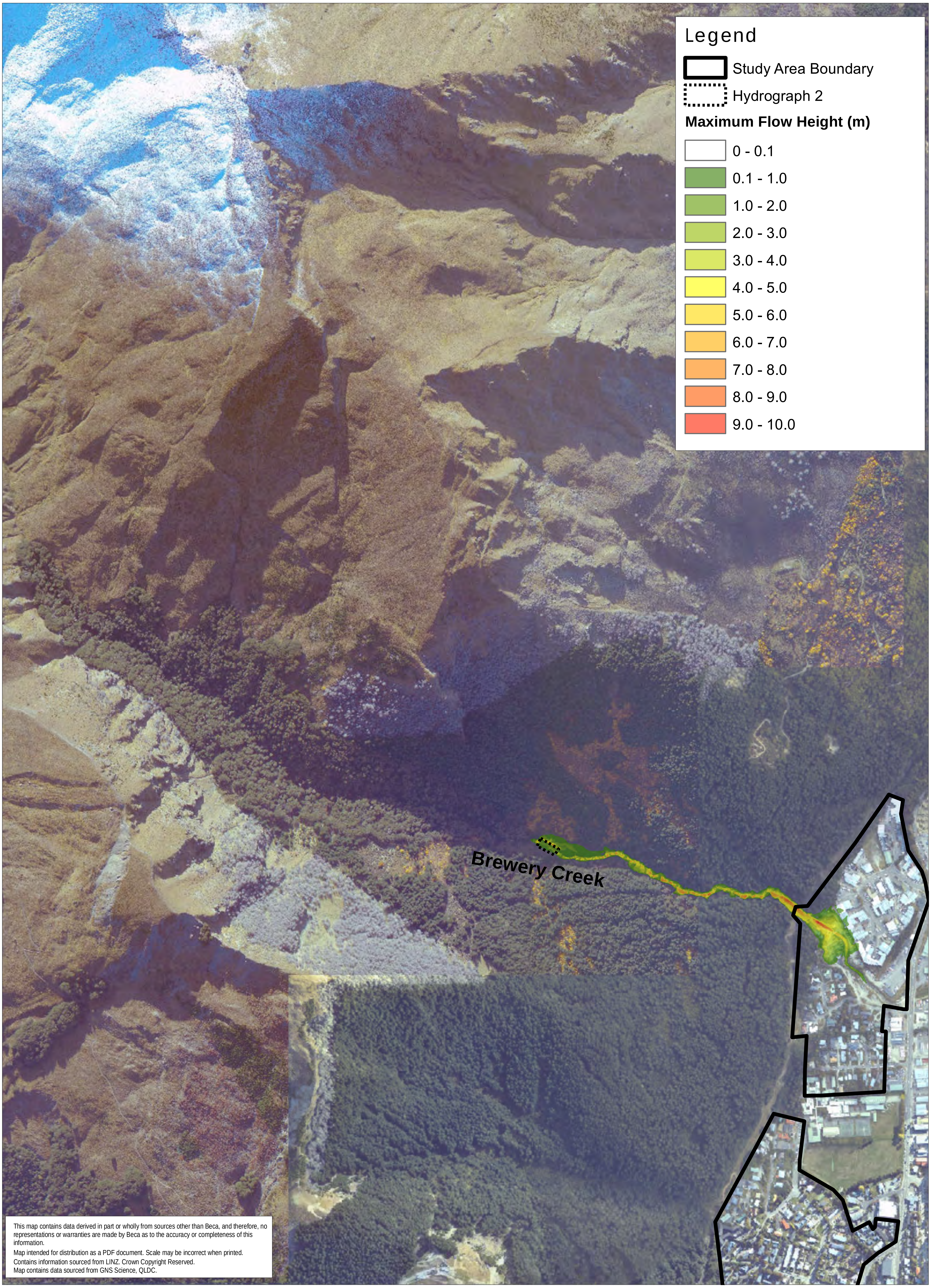
N

Beca

Discipline: GIS

Drawing No: 3209881-G009

GIS@beca.com



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title:
Brewery Creek
Debris Flow Modelling
Scenario 3: 50-200 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

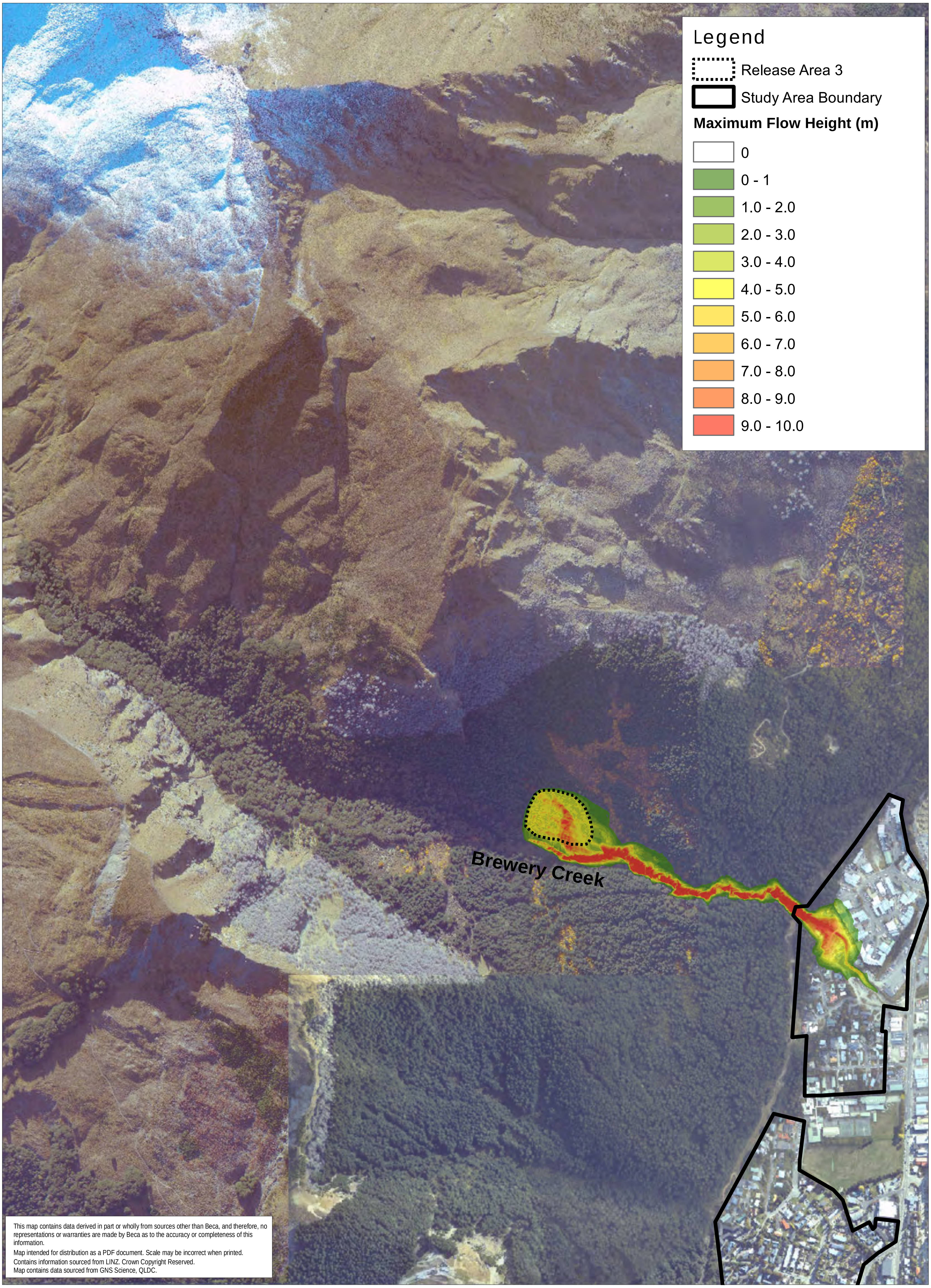
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G010



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Map Scale @ A3: 1:8,000

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Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Brewery Creek Debris Flow Modelling Scenario1: 200-2,500 yr Non-Forested Source Area

Client: Queenstown Lakes District Council

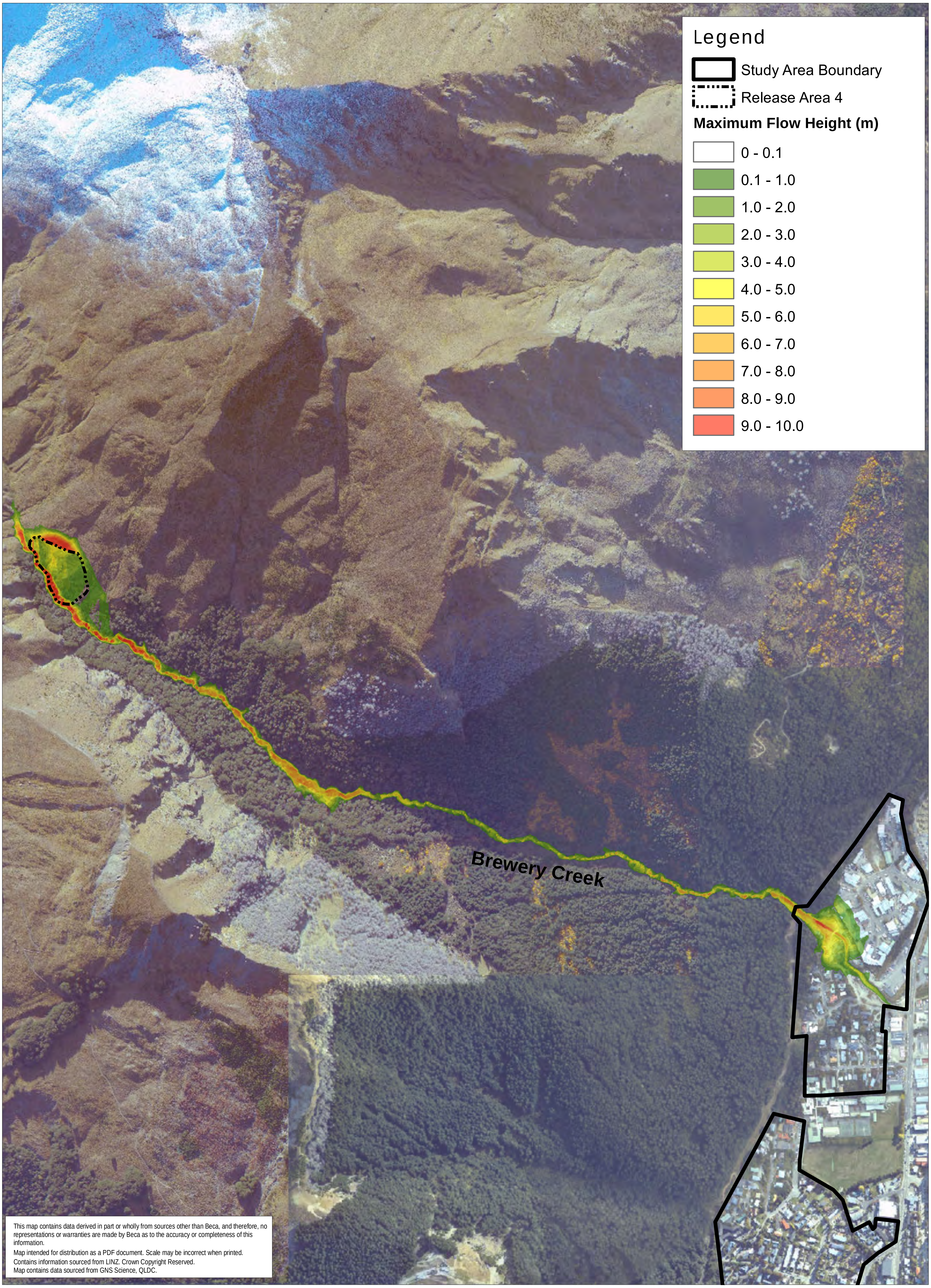
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G011



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Map Scale @ A3: 1:8,000

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Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Brewery Creek
Debris Flow Modelling
Scenario 2: 200-2,500 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G012

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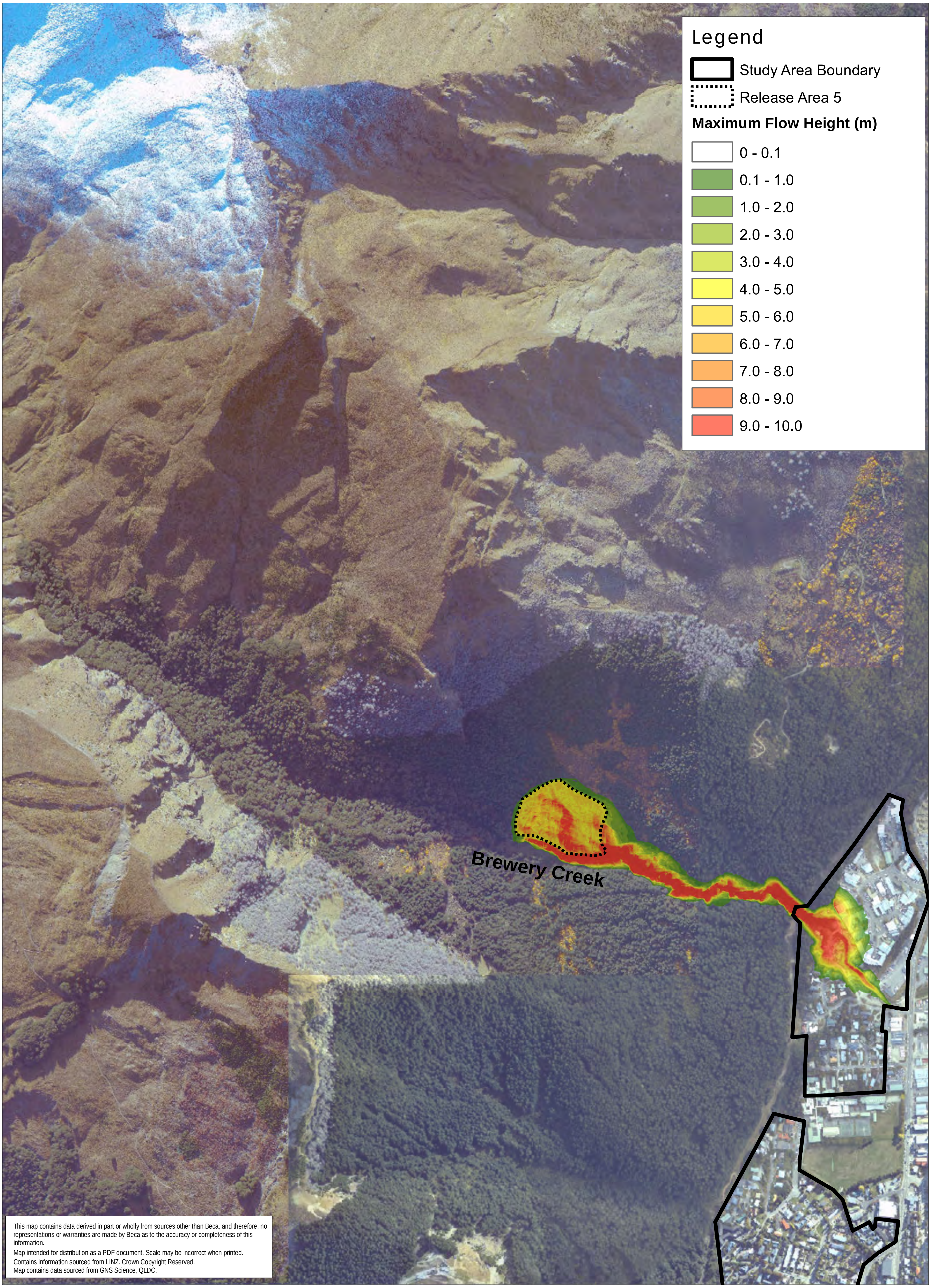

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Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Brewery Creek
Debris Flow Modelling
Scenario 1: 2,500-10,000 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

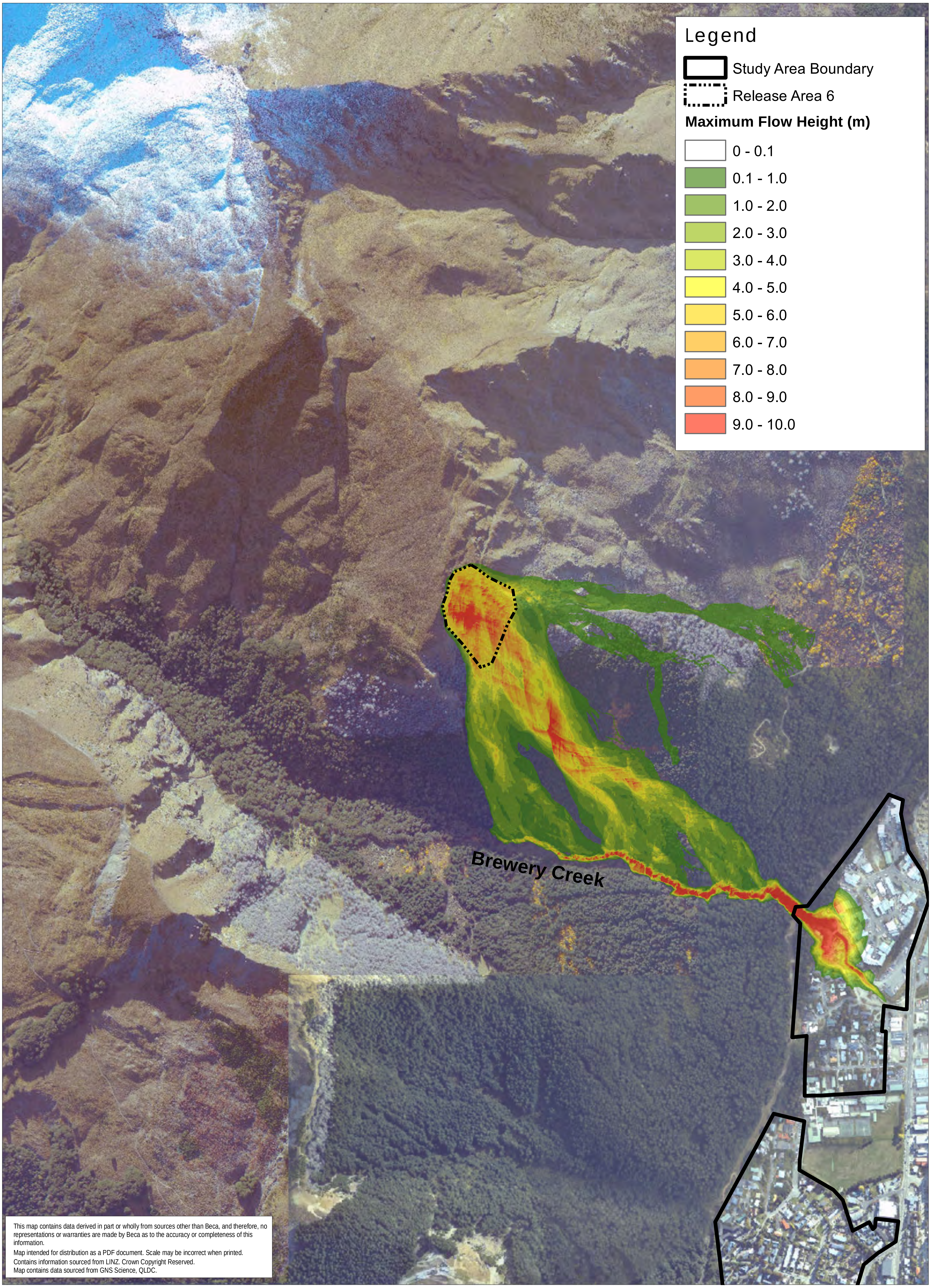
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G013



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Revision	Author	Verified	Approved	Date
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Title: Brewery Creek
Debris Flow Modelling
Scenario 2: 2,500-10,000 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

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Discipline: GIS

Drawing No: 3209881-G014

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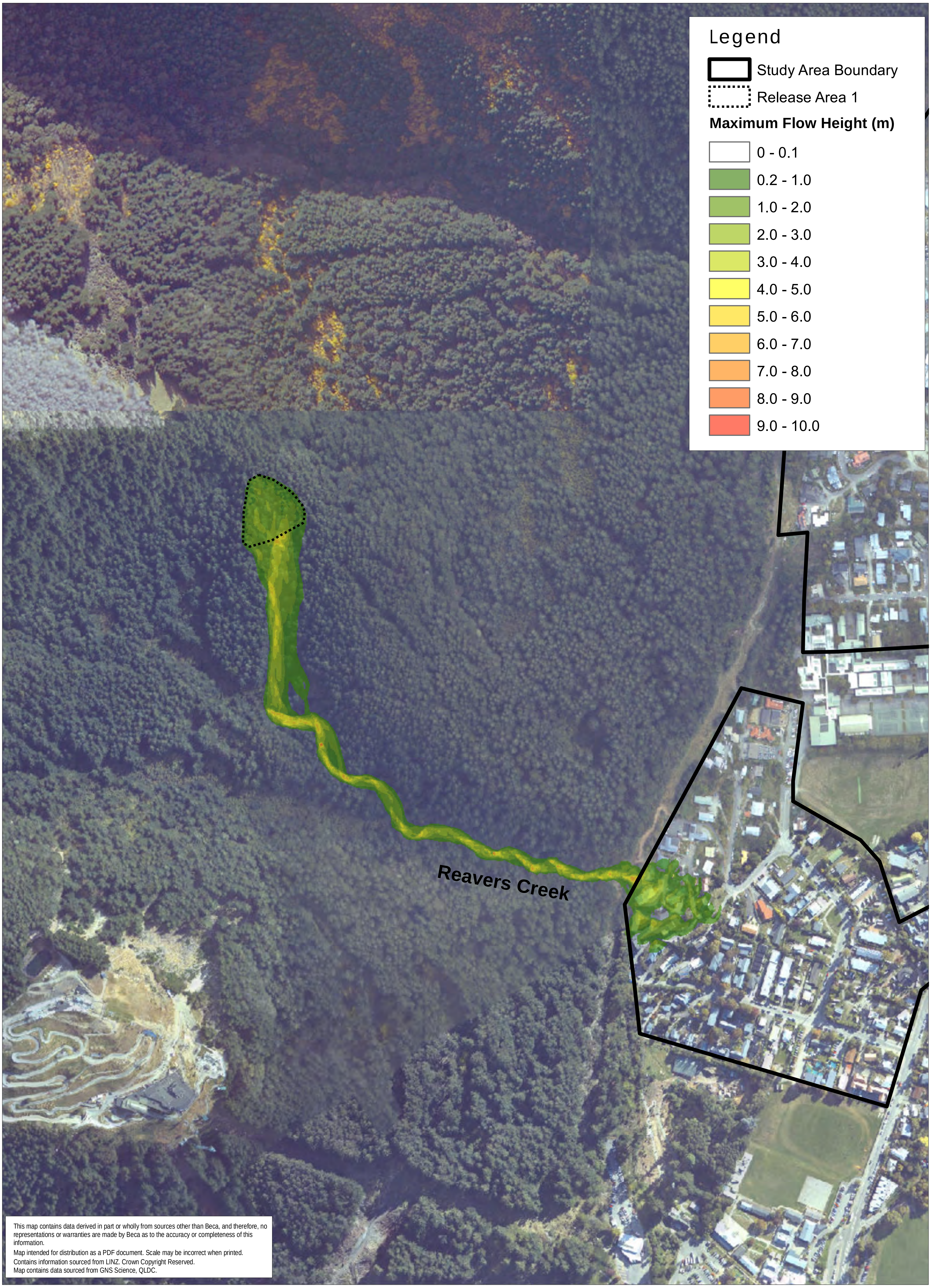

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Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 1: 100-2,500 yr
Forested Source Area

Client: Queenstown Lakes District Council

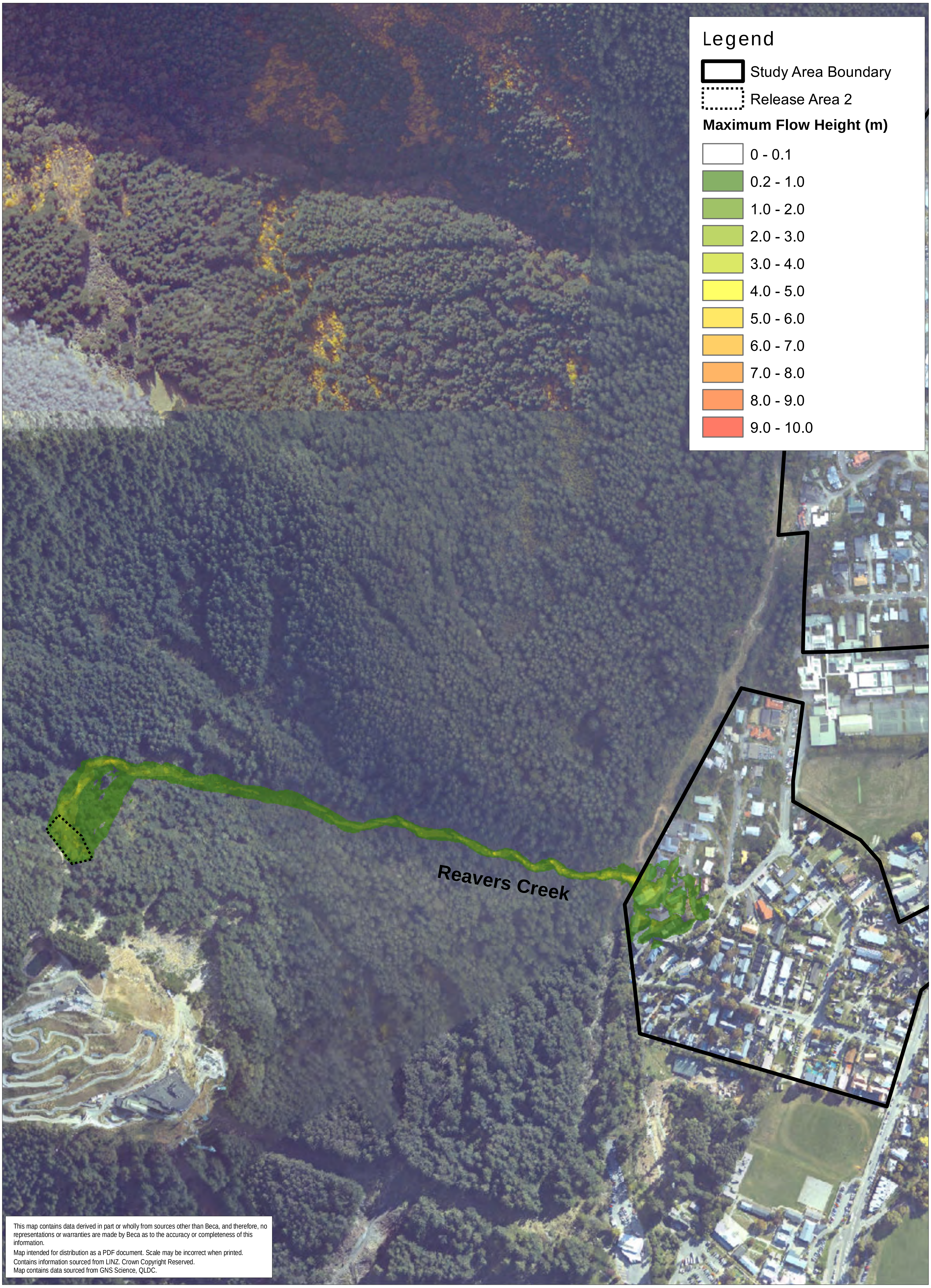
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G015



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Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title:

Reavers Creek
Debris Flow Modelling
Scenario 2: 100-2,500 yr
Forested Source Area

Client: Queenstown Lakes District Council

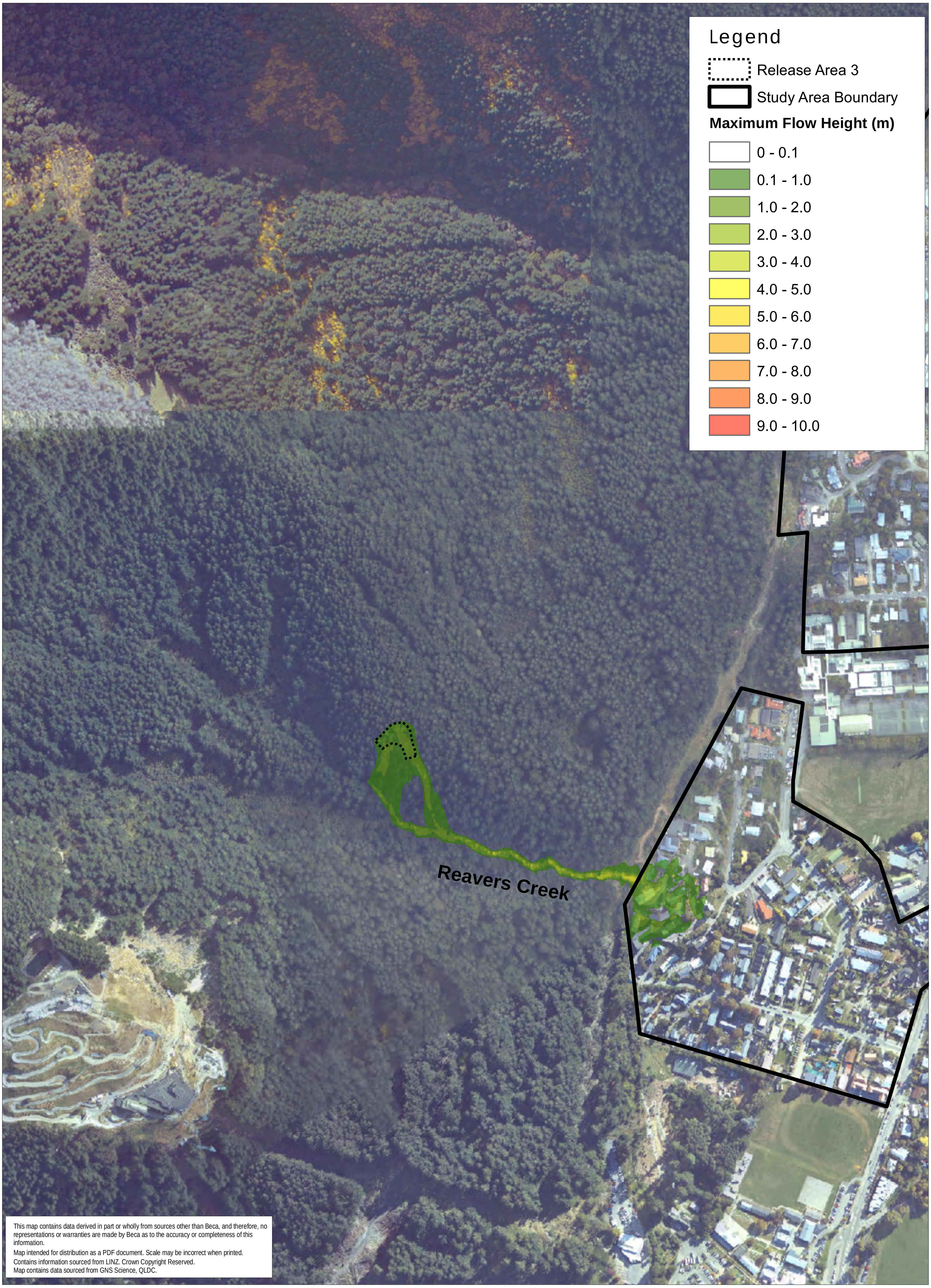
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G016



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File: P:\320\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G017.mxd Author: SHB Date: 11/05/2020

Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 3: 100-2,500 yr
Forested Source Area

Client: Queenstown Lakes District Council

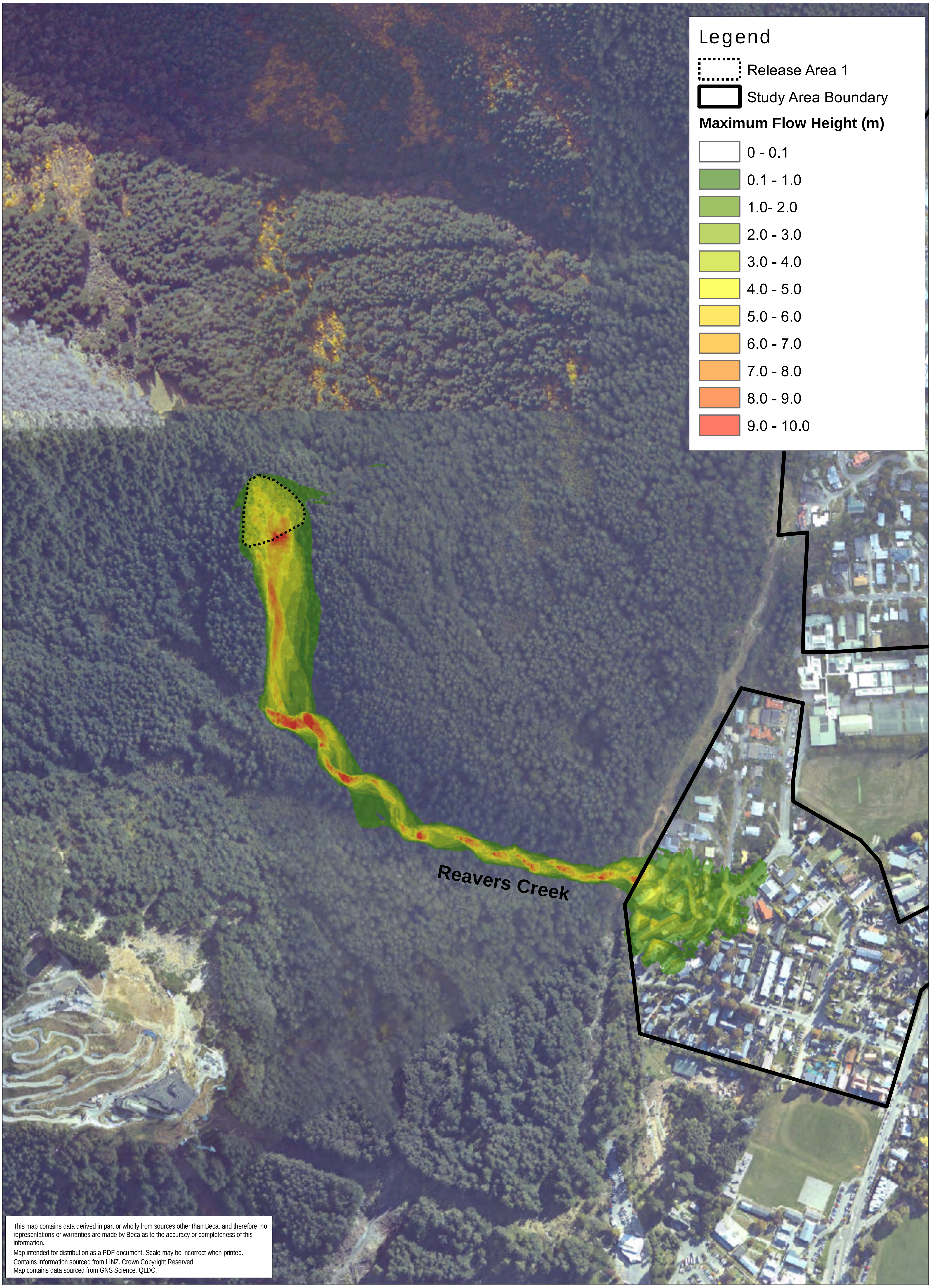
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G017



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Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 1: 2,500-6,700 yr
Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G018

File: P:\3200\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\New folder\3209881-G018.mxd Author: SHB Date: 6/05/2020

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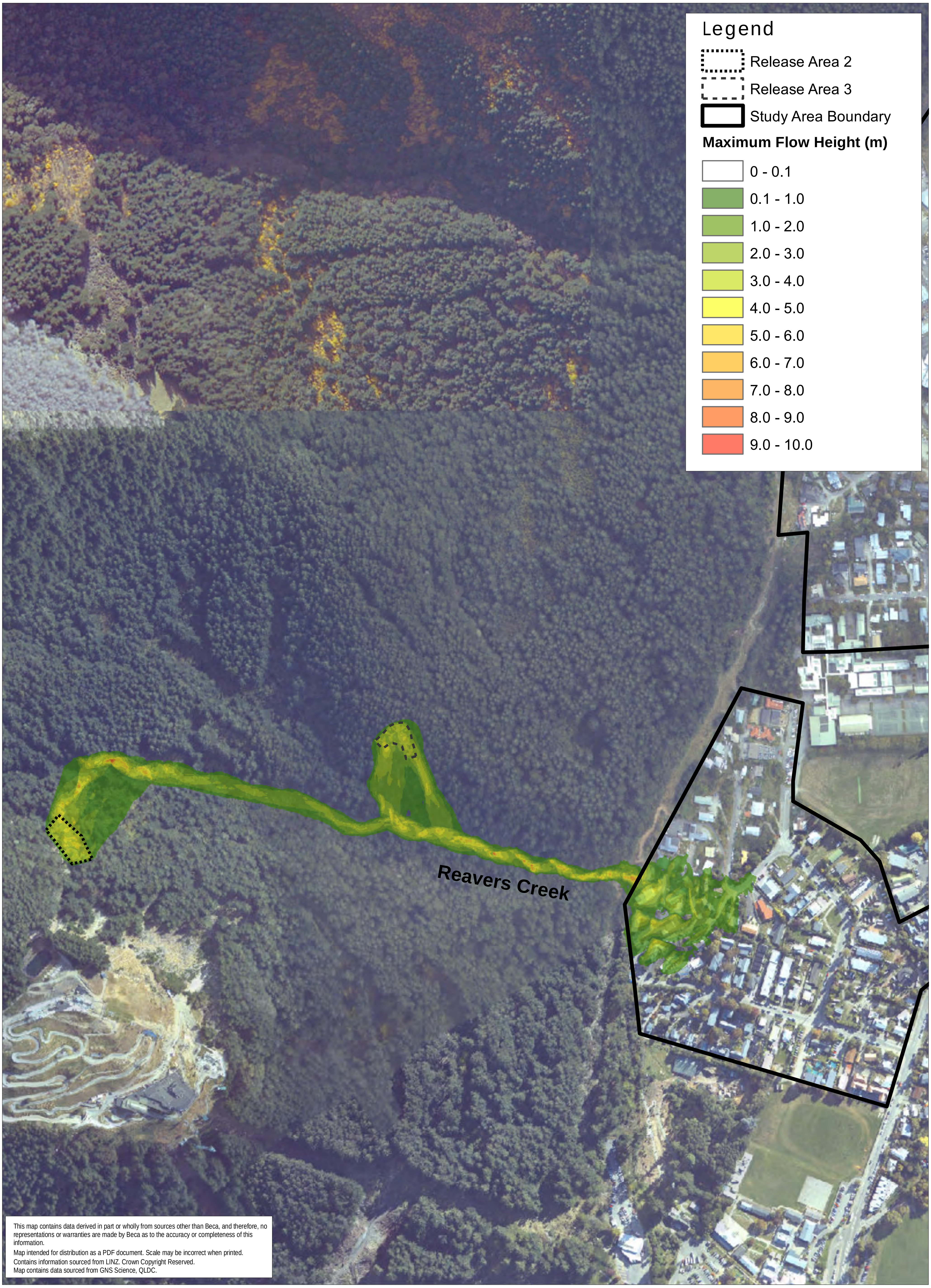

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File: P:\320\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G019.mxd Author: SHB Date: 11/05/2020

Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title:

Reavers Creek
Debris Flow Modelling
Scenario 2: 2,500-6,700 yr
Forested Source Area

Client: Queenstown Lakes District Council

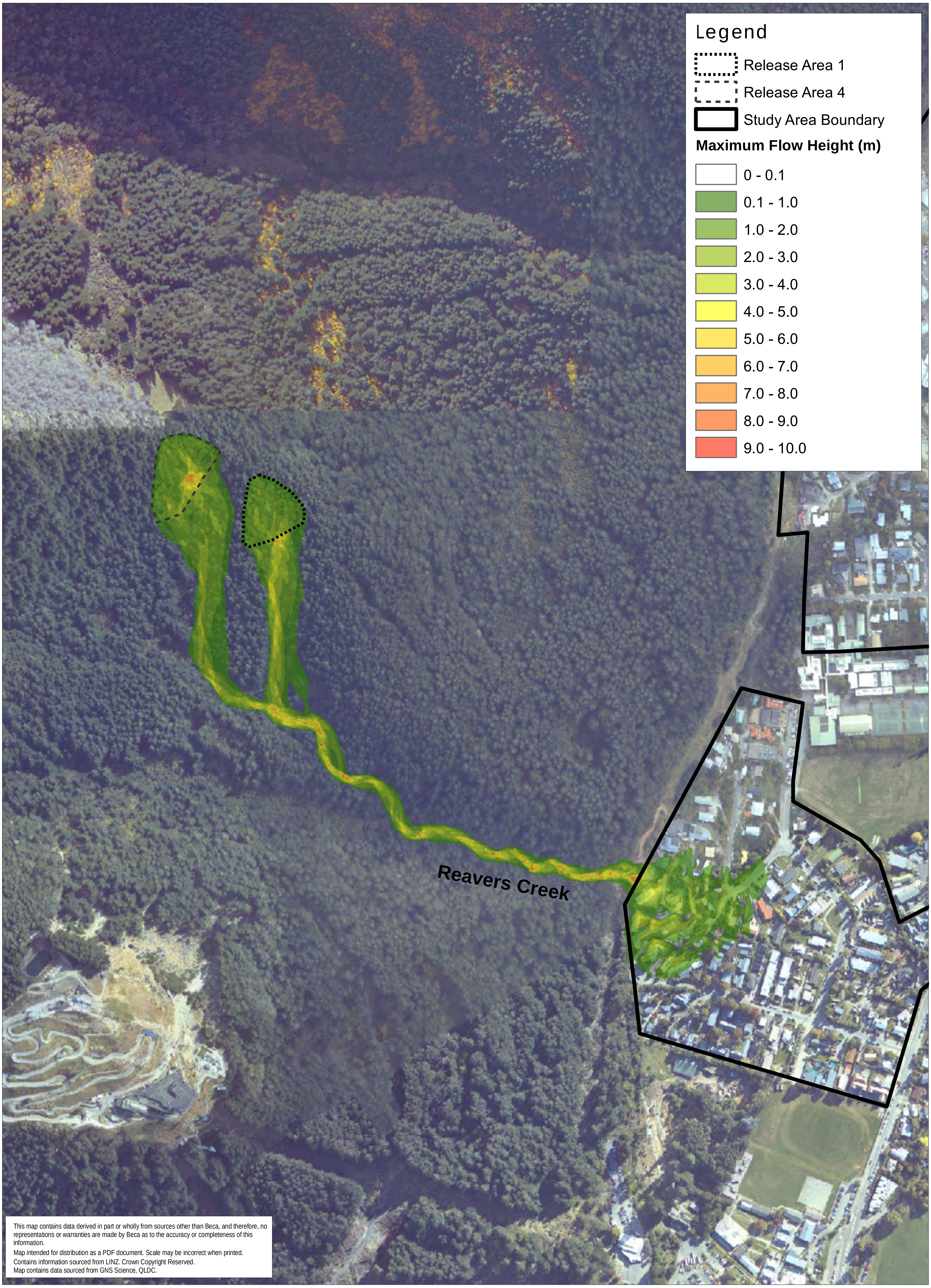
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G019



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File: P:\320\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G020.mxd Author: SHB Date: 11/05/2020

Map Scale @ A3: 1:4,000
0 80 160
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 3: 2,500-6,700 yr
Forested Source Area

Client: Queenstown Lakes District Council

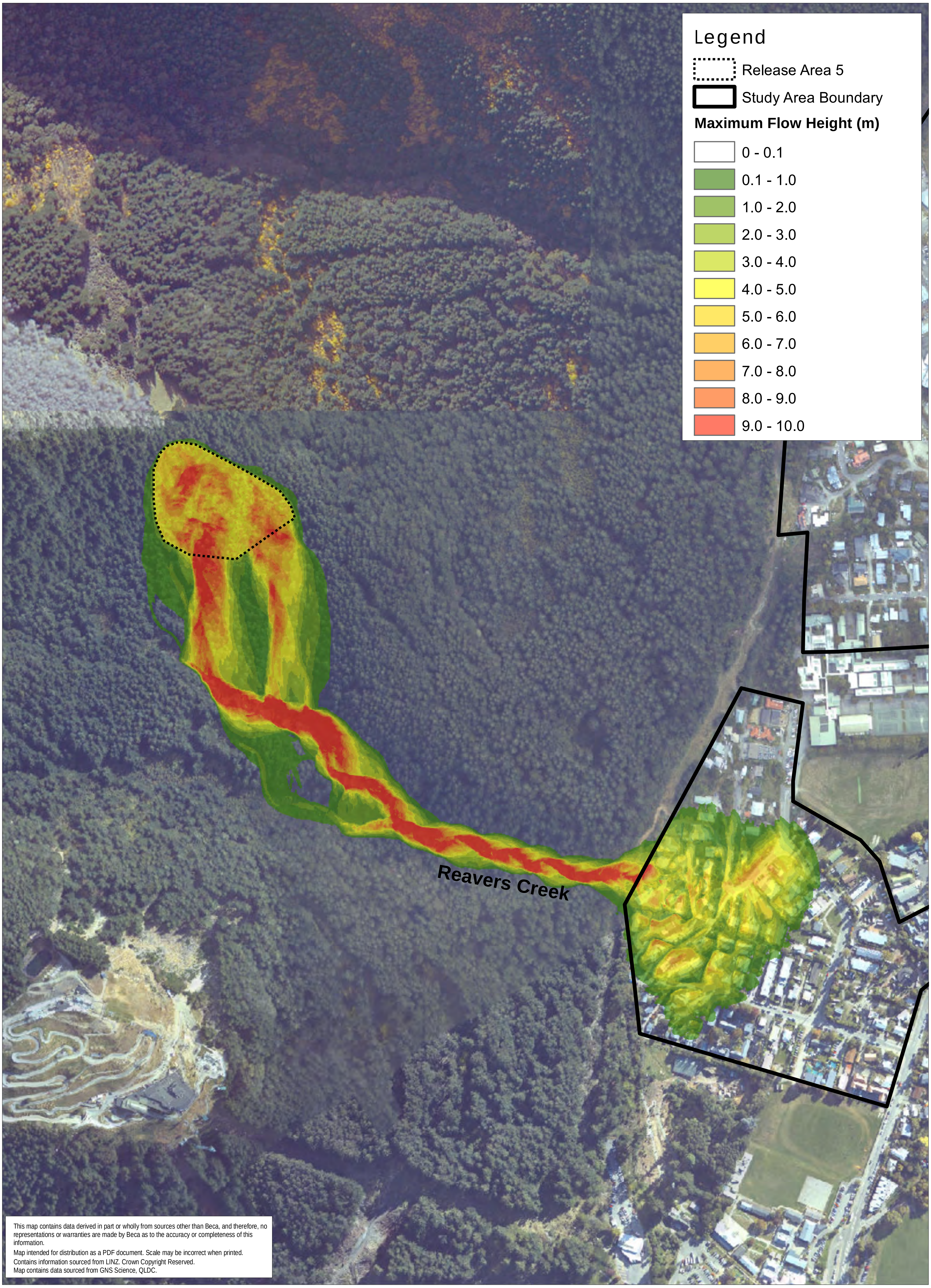
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G020



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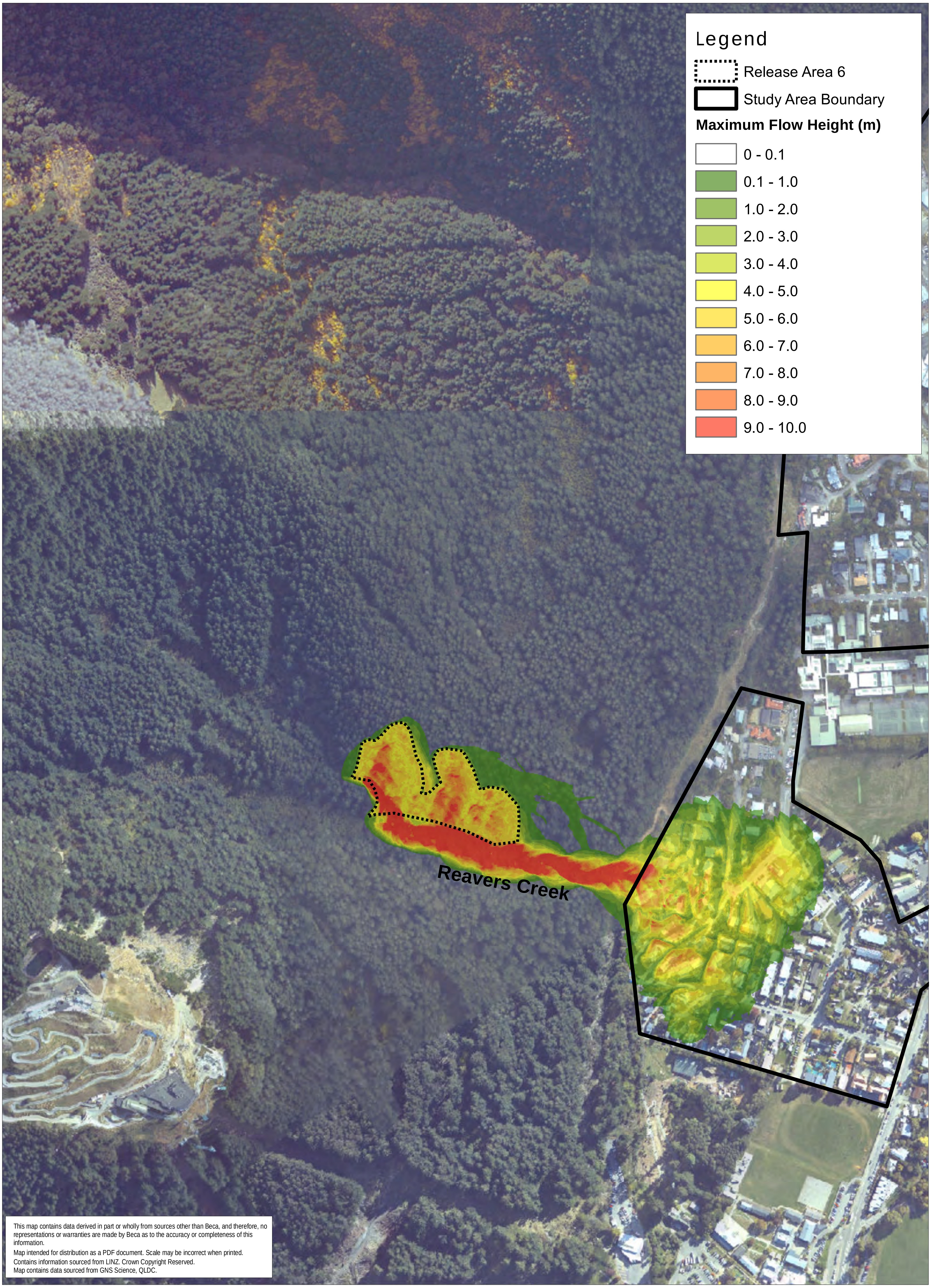
							Project: Natural Hazards Affecting Gorge Road	Beca	Drawing No: 3209881-G021



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 2: 6,700-20,000 yr
Forested Source Area

Client: Queenstown Lakes District Council

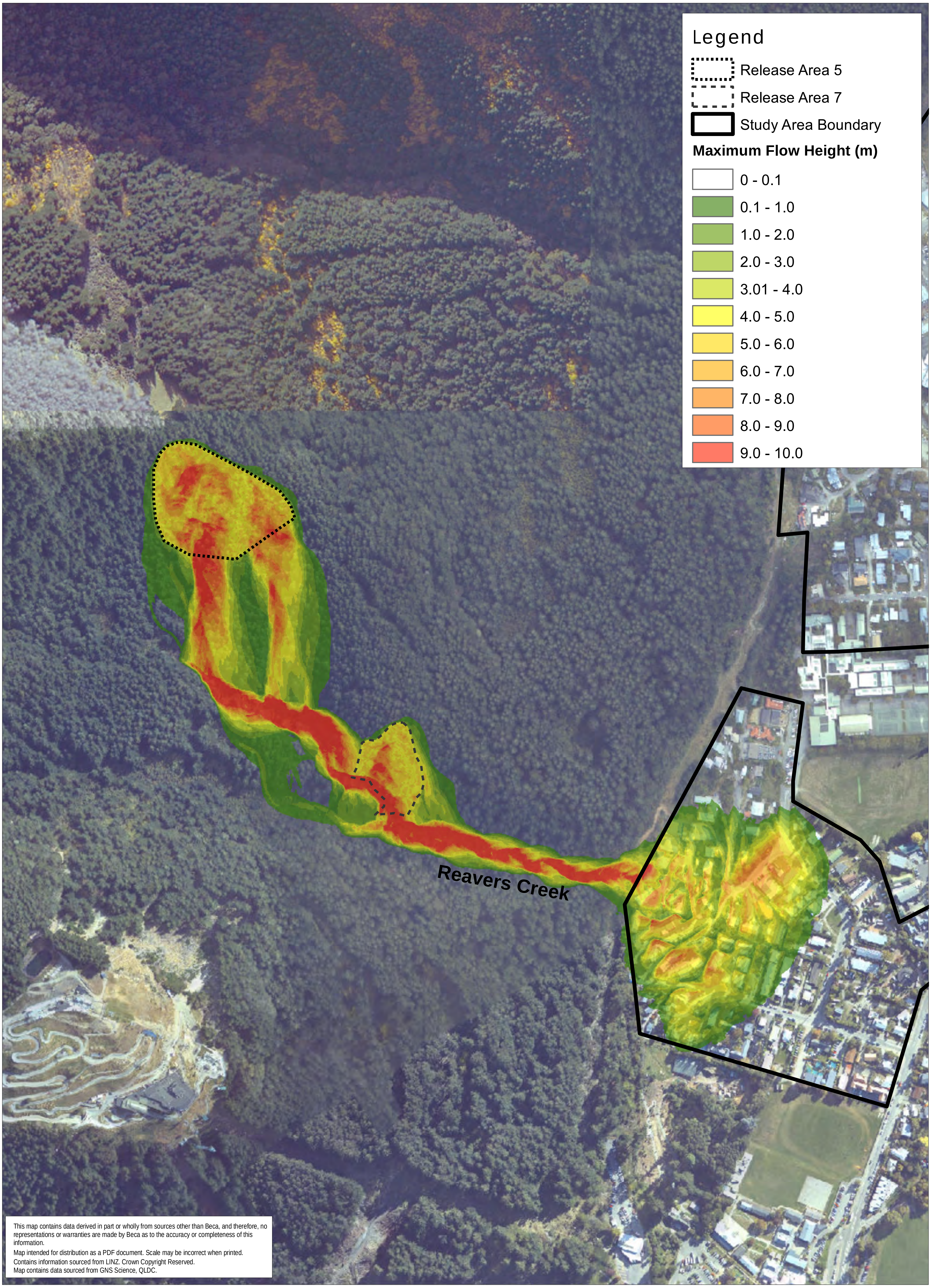
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G022



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title:

Reavers Creek

Debris Flow Modelling

Scenario 3: 6,700-20,000 yr

Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

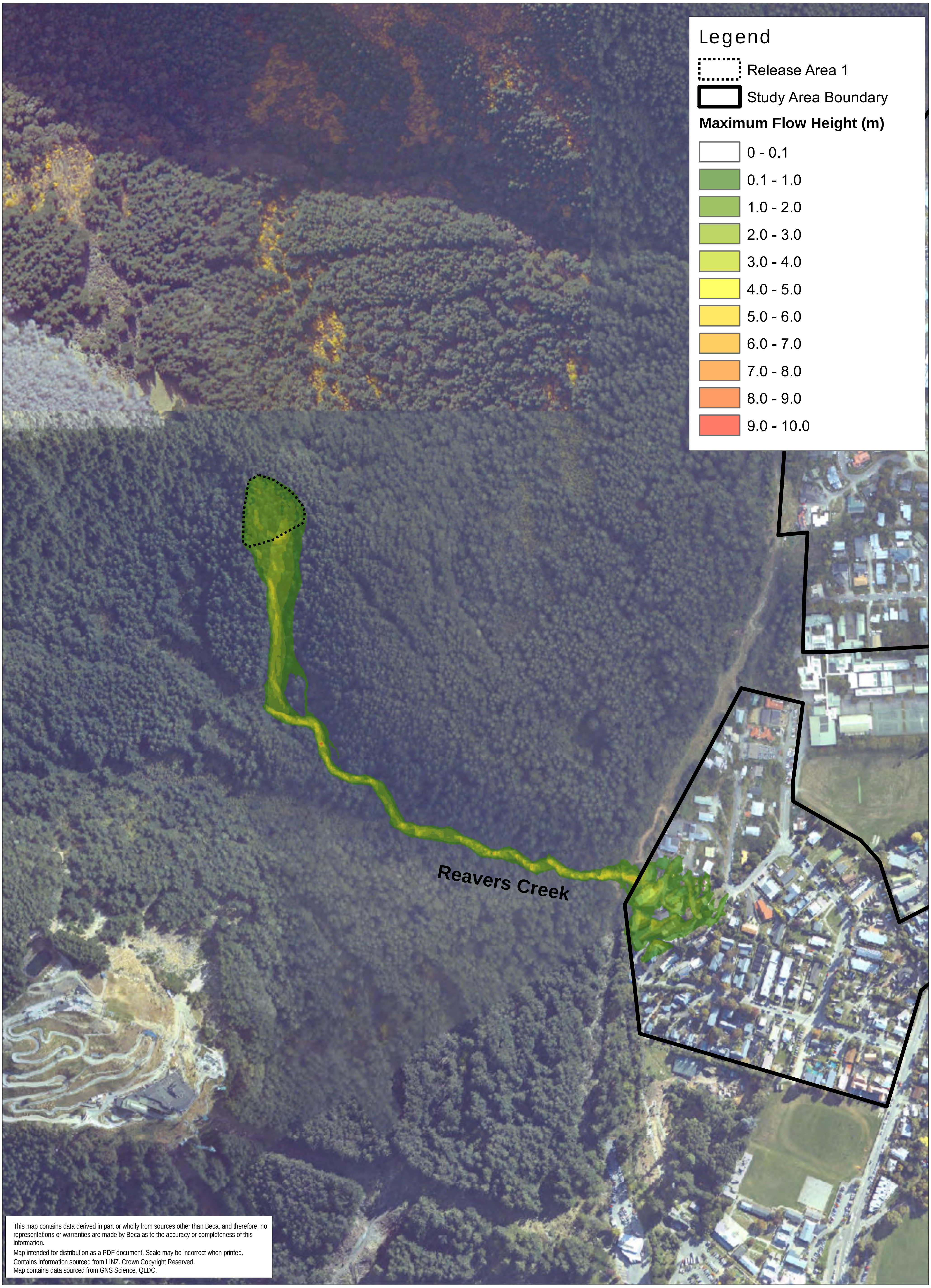
N

Beca

Discipline: GIS

Drawing No: 3209881-G023

GIS@beca.com



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Map Scale @ A3: 1:4,000

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Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 1: 100-2,500 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

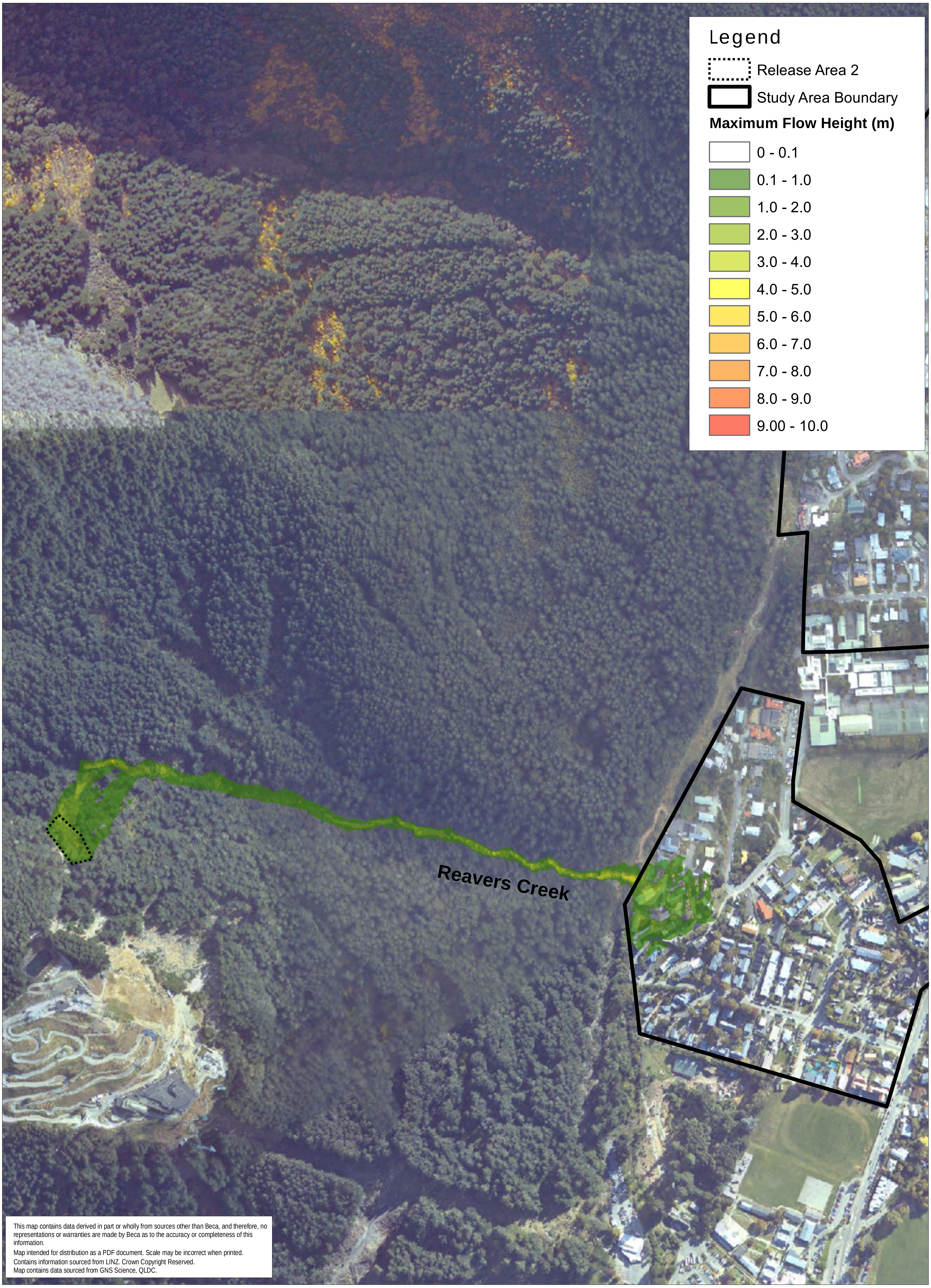
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G024



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Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 2: 100-2,500 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G025

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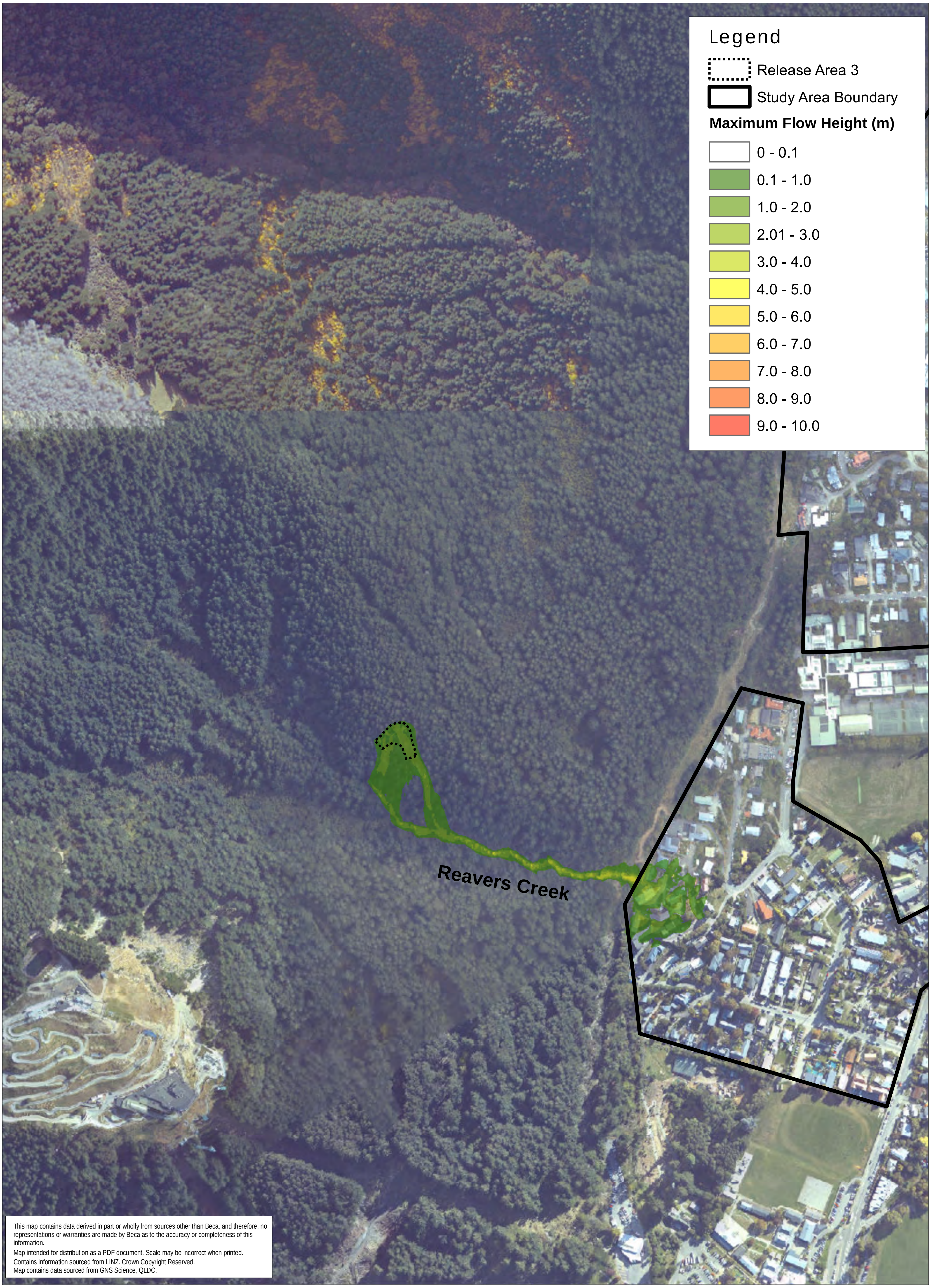
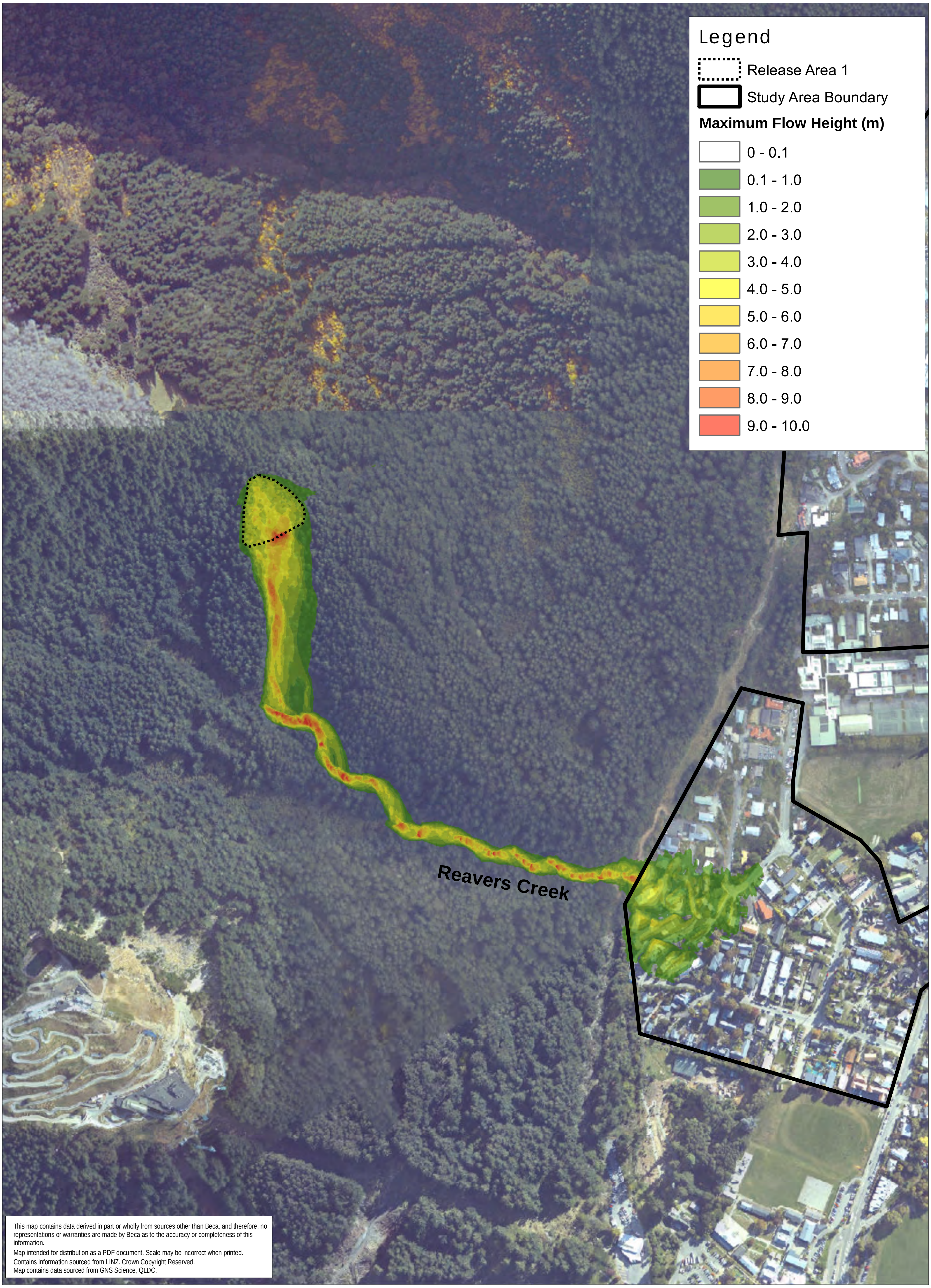


Map Scale @ A3: 1:4,000	Revision	Author	Verified	Approved	Date	Title: Reavers Creek Debris Flow Modelling Scenario 3: 100-2,500 yr Non-Forested Source Area	Client: Queenstown Lakes District Council	N	Discipline: GIS
0 80 160 Metres	1	SB	AP	PH	06/05/2020		Project: Natural Hazards Affecting Gorge Road	Beca	Drawing No: 3209881-G026



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Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 1: 2,500-6,700 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

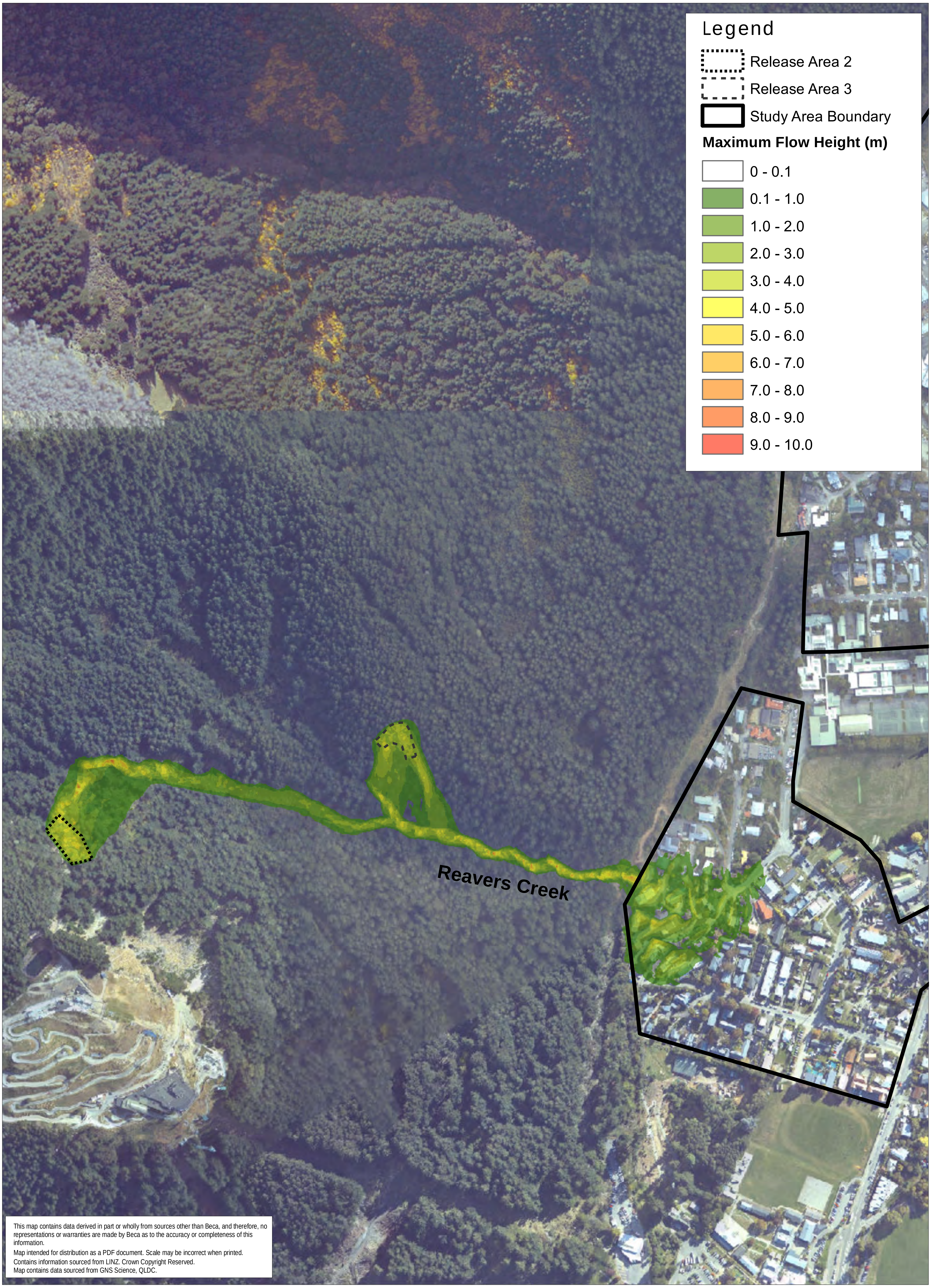
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G027



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File: P:\320\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G028.mxd Author: SHB Date: 11/05/2020

Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 2: 2,500-6,700 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

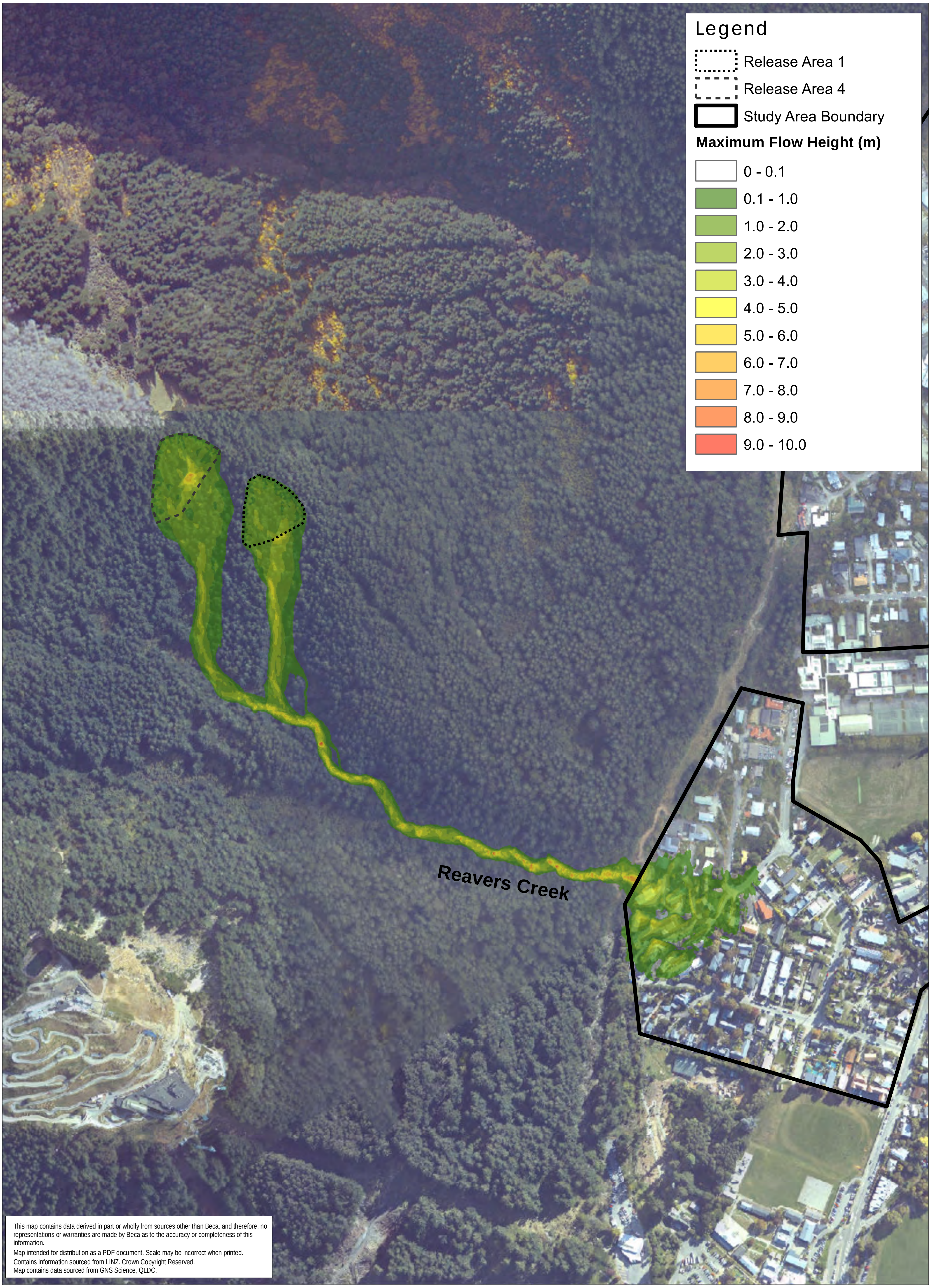
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G028



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Map Scale @ A3: 1:4,000
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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek Debris Flow Modelling Scenario 3: 2,500-6,700 yr Non-Forested Source Area

Client: Queenstown Lakes District Council

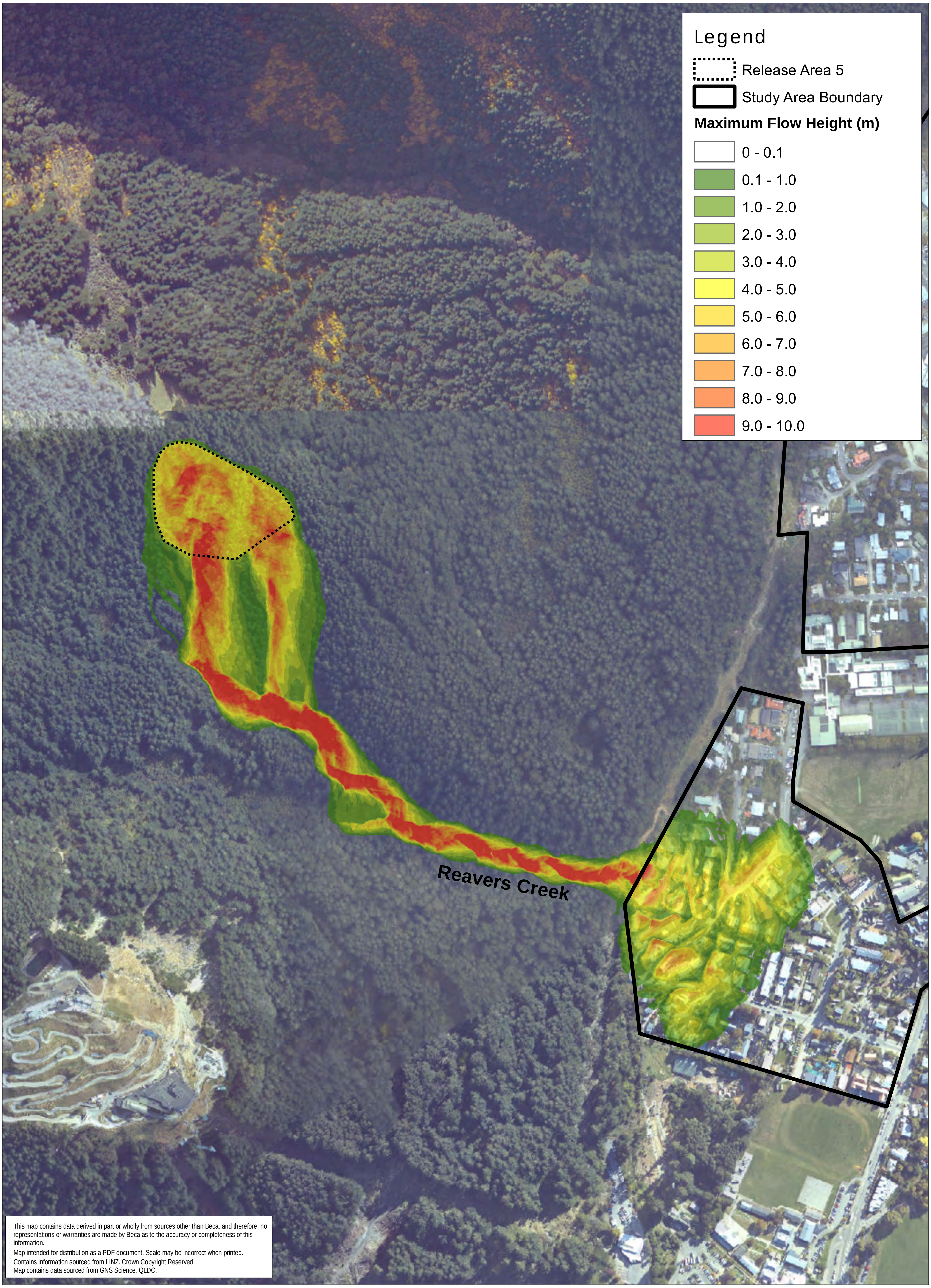
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G029



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Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 1: 6,700-20,000 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

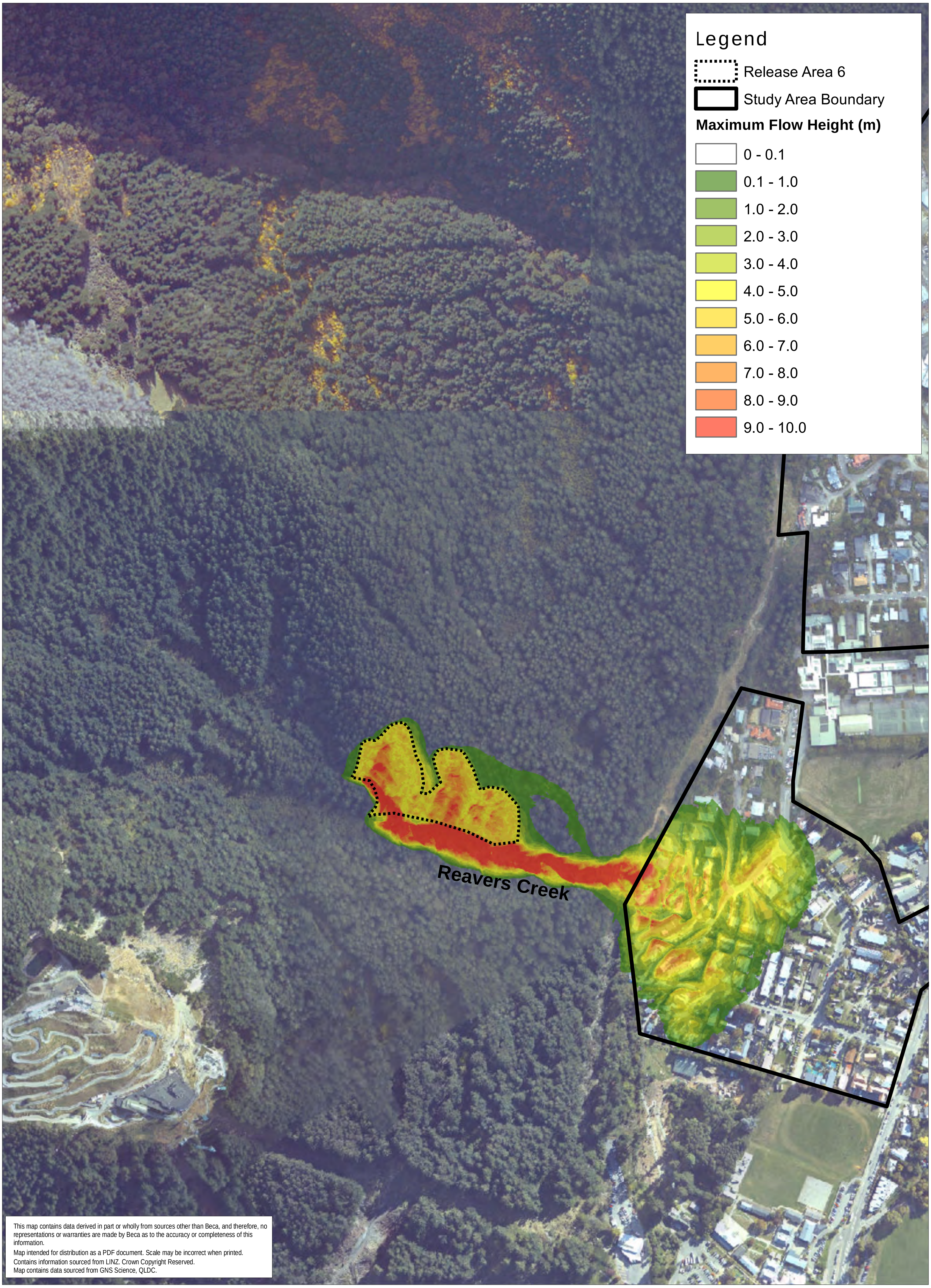
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G030



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Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title: Reavers Creek
Debris Flow Modelling
Scenario 2: 6,700-20,000 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

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Discipline: GIS

Drawing No: 3209881-G031

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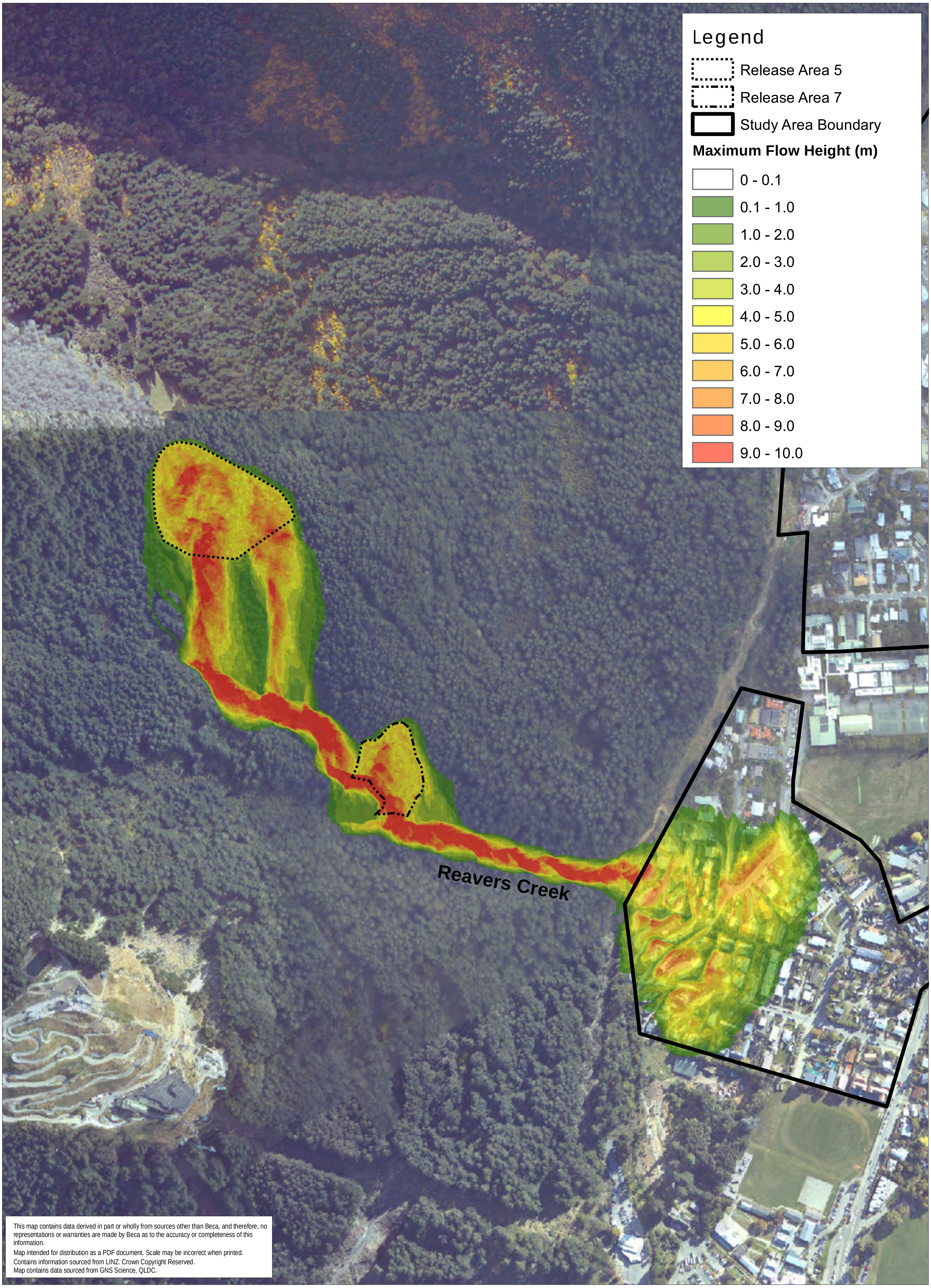
File: P:\320\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G031.mxd Author: SHB Date: 11/05/2020



Map Scale @ A3: 1:4,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	06/05/2020

Title:
Reavers Creek
Debris Flow Modelling
Scenario 3: 6,700-20,000 yr
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-G032

File: P:\3200\3209881\Technical_work_and_design\Maps\Revised Maps - Appendicies\Revised\Appendix G\3209881-G032.mxd Author: SHB Date: 11/05/2020

H

Appendix H – Rockfall Modelling

Site description

The topography of the hillslope behind the study areas, including the location and size of rock outcrops, was assessed though a combination of field mapping and a DEM developed from 1m LiDAR and available from the LINZ website. A 20m to 30m high bluff outcrop that was locally overhanging was identified from 540m to approximately 630m asl during field mapping and restricted foot assess to the upper slopes. Outcrops beneath the bluff were characterised from field mapping and cross-checked with the DEM. Upper outcrops were inferred from the DEM based on comparison of the shadings and topographic profiles of the outcrops identified on the lower slopes. The accuracy of the DEM is assumed to be less accurate than the field survey due to the dense vegetation cover obscuring the underlying slope profile.

Existing rockfall conditions

Field mapping identified the following features of relevance to the rockfall hazard assessment:

- Sub-vertical outcrops (60-90°) of in-situ schist were identified in the area from the transmission line to the bluff at 540m to 630m asl. Outcrops ranged from 3m to 20+m in height and 10m to 40m in length. No evidence for seepage was observed.
- Foliations dip 20-35° to the south/southwest in the in-situ schist.
  - Outcrops where the foliations dip into the slope generally have flat planar faces. Loose cobbles to boulders ranging from 50mm x 20mm x 5mm to 600mm x 400mm x 100mm that have broken along foliation planes were present on the outcrop face.
  - Outcrops not perpendicular to the dip-direction had irregular surfaces from shedding of material. Loose cobbles to boulders ranging in size from 100mm x 75mm x 25mm to 500mm x 500mm x 100mm were observed on, and immediately beneath, the outcrop faces and appear to have broken along foliation planes.
  - Active shedding of the loose rock debris was observed to be occurring from the outcrops. Shedding appears to occur in low volumes, and downslope transport distances appear confined (i.e. <200m).
- The schist contains two dominant joint-sets that intersect at approximately 90°. Fractured, detached, or overhanging blocks up to 2000mm x 800mm x 500mm were locally observed at the intersection of joint sets. Boulders of similar dimensions were present below some outcrops and appeared to have been sourced from the overlying outcrops.
  - A boulder field was observed in a topographic depression beneath the locally overhanging cliff outcrop and extending to approximately 500m asl. The boulders were of similar dimensions to the loose blocks observed at the intersections of joint sets and appeared to be sourced from the overlying cliff outcrop.
- The hillslope surrounding the outcrops is vegetated with mature pine trees. Ground cover includes topsoil with pine needles and vegetation debris including dead tree branches and trunks. Tree roots appeared to be causing jacking of the schist along defects and resulted in loose boulders up to 1000mm x 800mm x 500mm on the outcrop faces.
- Rock fall debris and colluvium aprons were observed below most outcrops. Cobbles to boulders of similar sizes to those observed on the outcrop surface were either embedded into the substrate immediately beneath the outcrop, or downslope from the outcrops where they appear to have been caught by trees.
  - Some boulders sitting on the ground surface exhibited fresh surfaces or a lack of weathering suggesting recent shedding of material.
  - The boulders generally exhibited varied weathering profiles and were embedded in the ground cover to differing degrees suggesting ongoing but low magnitude shedding of material.
- Localised impact damage was observed on the trees immediately beneath the outcrops, suggesting that the current tree cover provides a barrier to restrict downslope movement of boulders.

- Few boulders were observed at, and downslope of, the transmission line suggesting a low frequency of large rock fall capable of reaching this area.

Observations made during field mapping confirm that there is an abundance of loose cobbles to boulders present on the outcrops on the hillslope above the two study areas. The outcrops appear to be actively shedding low volumes material, while the release of larger blocks present at the intersections of joints appears to be relatively rare and localised.

Strong ground shaking, such as during a local seismic event, may result in large scale release of the loose material, block instabilities, and potentially structural collapse of the outcrops and is considered the most likely trigger for rockfall on the hillslope.

3D Rockfall Modelling

3D statistical rock fall analysis has been undertaken using RAMMS: Rockfall Model software. Analysis aimed to better understand predicted trajectories of rockfall debris from the outcrops above the two study areas and the residential areas at risk of rockfall impact. Input parameters were selected based on observations made during field mapping, and in line with recommendations contained within the RAMMS Rockfall Manual. Selected parameters were subsequently cross-checked with those adopted for previous studies in the wider Queenstown area.

Boulder dimensions were taken from the approximately 95^{th} percentile size of loose boulders identified on outcrop faces, and on the slope immediately behind the study area during field mapping. Patterns of boulder deposition and 95th percentile bounce heights, velocities, and kinetic energies of boulders reaching the study area were subsequently derived.

Modelling Input Parameters

The hillslope terrain model was created from a Digital Elevation Model generated from LiDAR with a 1m grid size, as available from the LINZ website. The ‘Medium’ predefined terrain category was selected for the hillslope based on field observations of ground cover and rock-fragments partially embedded in the slope. Sensitivity analyses completed based on the ‘Medium Soft’ terrain category resulted in rock run-out distances that did not match the distribution of boulders observed during field mapping.

Modelling was undertaken including and excluding the effects of forest cover. Observations made during field mapping indicate that the forest cover is consistent with the ‘Open Forest’ type implemented in RAMMS: Rockfall of $20m^2$/ha. Although the slope was forested, it was easily traversed, and the vegetation crowns were generally above the source outcrops. A polygon outlining the forest cover extents was created in ArcGIS based on field observations and aerial imagery. Discussions with QLDC indicate that long term felling or boom spraying of the hillslope has been proposed by the Department of Conservation (DoC) and the Wakatipu Wilding Control Group (WCG) which would result in the long term break down of the trees. Additionally, natural events, such as fire, may result in significant removal of trees.

Modelling adopted the predefined rock shape ‘Real_Flat_1.8’ from the Rock Builder Tool. The rock shape and dimensions were consistent with the approximate 95^{th} percentile of that observed and measured during field mapping. Model results showed boulders released from the cliff outcrop deposited in the known boulder field present in the topographic depression. Sensitivity analysis undertaken using the ‘Real_Flat_1.6’ and ‘Equitant_2.0’ rock shapes resulted in zones of deposition that did not match the concentrations and distributions of boulders observed in the boulder field. The ‘Real_Flat_1.8’ is additionally consistent with that adopted in previous studies. Field observations on the slope indicated that outcrop dimensions and resultant boulder sizes were consistent along the slope and therefore did not make a case for selecting alternative rock shape or sizes. A boulder density of $2500kg/m^3$ was adopted for the analysis.

Outcrop release areas were manually digitised in ArcGIS based on field observations, aerial imagery, and topography observed in the DEM.

In addition to that outlined above, the following parameters were selected when running the simulations:

- Dump Step – 0.2 seconds
- Stop Criterion – Automatically selected
- Stop at first contact – Not selected
- Number of random orientations per release point – 3
- Initial Velocity – 1.5 m/s (vertical)
- Initial Rotational Velocity – 0.0
- Rock Z-Offset – Automatic in that the starting of the rock is guaranteed.
- Sensitivity analysis was undertaken in the Rock Z-Offset however as the outcrop heights across the hillslope a case could not be made for manually defining the value(s).
- Number of grid points – 1

Model Scenarios

Model scenarios completed as part of the 3-D rockfall modelling are summarised in Table H 1. Input parameters were varied to test the sensitivity of the model and the resultant run-out distances in the study area.

Table H 1 - Summary of Rockfall Model Scenarios

Source Outcrops	Slope Type	Forest Cover	Rock Type	Z-Offset
All Outcrops[1]	Medium	Open	1.8 Real Flat	Automatic
True Left Brewery[1]	Medium	Open	1.8 Real Flat	Automatic
True Left Reavers[1]	Medium	Open	1.8 Real Flat	Automatic
True Right Brewery[1]	Medium	Open	1.8 Real Flat	Automatic
True Right Reavers[1]	Medium	Open	1.8 Real Flat	Automatic
Southern Outcrops[1]	Medium	Open	1.8 Real Flat	Automatic
All Outcrops[2]	Medium	None	1.8 Real Flat	Automatic
True Left Brewery[2]	Medium	None	1.8 Real Flat	Automatic
True Left Reavers[2]	Medium	None	1.8 Real Flat	Automatic
True Right Brewery[2]	Medium	None	1.8 Real Flat	Automatic
True Right Reavers[2]	Medium	None	1.8 Real Flat	Automatic
Southern Outcrops[2]	Medium	None	1.8 Real Flat	Automatic
True Left Brewery	Medium	None	1.8 Real Flat	Automatic
True Left Reavers	Medium	None	1.8 Real Flat	Automatic
True Right Brewery	Medium	None	1.8 Real Flat	Automatic
True Right Reavers	Medium	None	1.8 Real Flat	Automatic
Southern Outcrops	Medium	None	1.8 Real Flat	Automatic
All Outcrops	Medium	Medium	1.8 Real Flat	Automatic
Upper Outcrops – Whole Hillslope	Medium	None	1.8 Real Flat	Automatic
Mid Outcrops – Whole Hillslope	Medium	None	1.8 Real Flat	Automatic

Mid Outcrops – Whole Hillslope	Medium	Medium	1.8 Real Flat	Automatic
Lower Outcrops – Whole Hillslope	Medium	None	1.8 Real Flat	Automatic
Lower Outcrops – Whole Hillslope	Medium	None	1.0m³ Real Flat	Automatic
Lower Outcrops – Whole Hillslope	Medium	None	1.8 Real Flat	1.0m
Lower Outcrops – Whole Hillslope	Medium	None	1.8 Real Flat	20.0m
Lower Outcrops – Whole Hillslope	Medium	Medium	1.8 Real Flat	Automatic
Lower Outcrops – Whole Hillslope	Medium Soft	None	1.8 Real Flat	Automatic
Lower Outcrops – Whole Hillslope	Medium	None	2.9 Real Flat	Automatic
Base Outcrops – Whole Hillslope	Medium	None	1.8 Real Flat	Automatic
Base Outcrops – Whole Hillslope	Medium	Medium	1.8 Real Flat	Automatic
Reavers Trial Outcrop	Medium	Medium	1.8 Real Flat	Automatic
Reavers Trial Outcrop	Medium	None	Equant 1.2	Automatic
Reavers Trial Outcrop	Medium	None	1.6 Real Flat	Automatic

[1]Scenario used in AIFR calculation considering forest cover and shown in Appendix H – Rockfall Modelling.

[2]Scenario used in AIFR calculation considering un-forested slopes and shown in Appendix H – Rockfall Modelling.

Rock Fall Run-out and Spatial Impact Area

- Removal of tree cover results in higher boulder velocities, bounce heights, and run-out distances with more residential properties at the base of the slope incorporated within the 99th percentile boulder distributions.
- Slope topography significantly influences the trajectory, run out area, bounce height, and velocity of the rockfall. The transmission line locally appears to act as a catch bench to the true right of Brewery Creek.
- Brewery Creek Fan:
  - Model incorporating forest cover
    - Modelling of outcrops on the true-right bank of Brewery Creek shows the 99th percentile rockfall runout distance continues approximately 30m downslope of the transmission line, and approximately 20m into the residential properties. In total two residential lots are within the 99th percentile distribution.
    - Rockfall debris sourced from outcrops on the true-left of Brewery Creek is shown to accumulate at the base of the slope behind the industrial properties. The 99th percentile distribution extends approximately 5m into seven of the business zone lots.
    - Kinetic energies of boulders reaching the residential and business lots are generally less than 200kJ.

- Model excluding forest cover (non-forested slopes)
  - Modelling of outcrops on the true-right of Brewery Creek shows the 99th percentile rockfall runout distance continues approximately 40m downslope of the transmission line, and approximately 30m into the residential properties. In total four residential lots are within the 99th percentile distribution.
  - Rockfall debris sourced from outcrops on the true-left of Brewery Creek is shown to accumulate at the base of the slope behind the industrial properties. The 99th percentile distribution extends approximately 30m into 10 of the business lots.
  - Kinetic energies of boulders reaching the residential and business lots are generally less than 250kJ.
- Reavers fan:
  - Model incorporating forest cover
    - Modelling of outcrops identified on the slope to the true-left of Reavers Fan shows 99% of rockfall debris is confined to the area 30m downslope of the transmission line.
    - The 99th percentile of rockfall debris sourced from outcrops to the true-right of the Reavers Fan continues 20m downslope of the transmission line.
    - In total 16 residential lots are within the 99th percentile distribution of boulders. Kinetic energies of boulders reaching the lot are ≤400kJ, and generally ≤200kJ for the residential lots to the true-right of Reavers Creek
  - Model excluding forest cover (non-forested slopes)
    - Modelling of outcrops identified on the slope to the true-left of Reavers Fan shows 99% of rockfall debris is confined to the area 40m downslope of the transmission line.
    - The 99th percentile of rockfall debris sourced from outcrops to the true-right of the Reavers Fan continues 60m downslope of the transmission line.
    - In total 18 residential lots are within the 99th percentile distribution of boulders.
    - Kinetic energies of boulders reaching the lots are ≤750kJ, and generally ≤400kJ.

2D Rockfall Modelling

2D rockfall modelling was undertaken for eight cross-sectional profiles of the hillslope behind the study areas using version 7.003 of the RocFall modelling software by RocScience. Analysis aimed to cross-check the run-out distances of rockfall debris modelled in 3D from RAMMS: Rockfall. Slope profiles were selected to represent varied topographic profiles across the hillslope.

Modelling Input Parameters

Modelling assumed lump-mass analysis with Monte-Carlo sampling with velocity scaling. Parameters adopted in the analysis were selected from the back-analysed parameters adopted for the Port Hills, as listed in GNS Science Consultancy Report 2011/311 (GNS Science, 2012c). A velocity cut-off for rockfall extents of 0.1m/s was adopted.

Field mapping suggested seismic triggering was considered the most likely trigger for rockfall on the hillslope. Horizontal velocities of 1.5m/s and a vertical velocity of 1.0m/s were subsequently adopted, as recommended in the GNS Science Consultancy Report 2011/311 (GNS Science, 2012c).

The hillslope above the transmission line was assigned the values for ‘rock at/near surface where the rock is in part covered by talus’ based on the GNS Science Consultancy Report 2011/311 (,GNS Science, 2012c). The values were considered to best represent the outcrops and ground cover observed on the hillslope during field mapping.

Rock mass and density were adopted from the GNS Report 2011/311 (GNS Science, 2012c). It is acknowledged that these values were derived for the volcanic rocks present on the Port Hills, however these values are considered likely to be similar to the schist outcropping in the source area.

Analysis assumed that the entire slope presented a source area ('seeder') based on the presence of localised outcrops across the slope surface and occasional boulders present beneath the outcrops.

The area below the transmission line at the base of the slope was modelled using the values for the slope material 'colluvial loess with vegetation assuming a rough surface' as described in the GNS Report 2011/311 (GNS Science, 2012c). The sensitivity of the model to surface roughness at the base of the slope was evaluated using the parameters adopted for 'colluvial loess with vegetation assuming a smooth surface', as listed by GNS. Analysis yielded maximum shifts in the 99^{th} percentile run out distances of 10m therefore indicating that the model is not sensitive to changes in roughness at the base of the slope.

Specific input parameters for the project are outlined below:

Project Settings

- Lump Mass Analysis
- Sampling method = Monte-Carlo
- Number of rocks thrown = Set individually by seeder
- RN scaling = Velocity where KN = 9.144m/s
- Maximum time per rock = 5s
- Maximum steps per rock = 20000
- Stopped velocity cut off = 0.1m/s

Seeder

- Rock type
  - Rock mass = 8250kg
  - Density = 2700 kg/m^3
- Seeder conditions
  - Number of rocks thrown = 2000
  - Horizontal velocity = 1.5m/s (normal distribution)
  - Vertical velocity = 1.0m/s (normal distribution)

Slope Material type

- Top of the slope assumed 'rock and/ near surface'
  - Rn = 0.5 (+/- 0.04) with normal distribution
  - Rn = 0.85 (+/- 0.04) with normal distribution
  - Phi = 20^o (+/- 2) with normal distribution
  - Roughness = 5
- Base of the slope assumed 'colluvial loess with vegetation (rough)
  - Rn = 0.3 (+/- 0.03) with normal distribution
  - Rn = 0.85 (+/- 0.03) with normal distribution
  - Phi = 8^o (+/- 2) with normal distribution
  - Roughness = 11

2D Rockfall Run-out and Spatial Impact Area

Brewery Creek Fan:

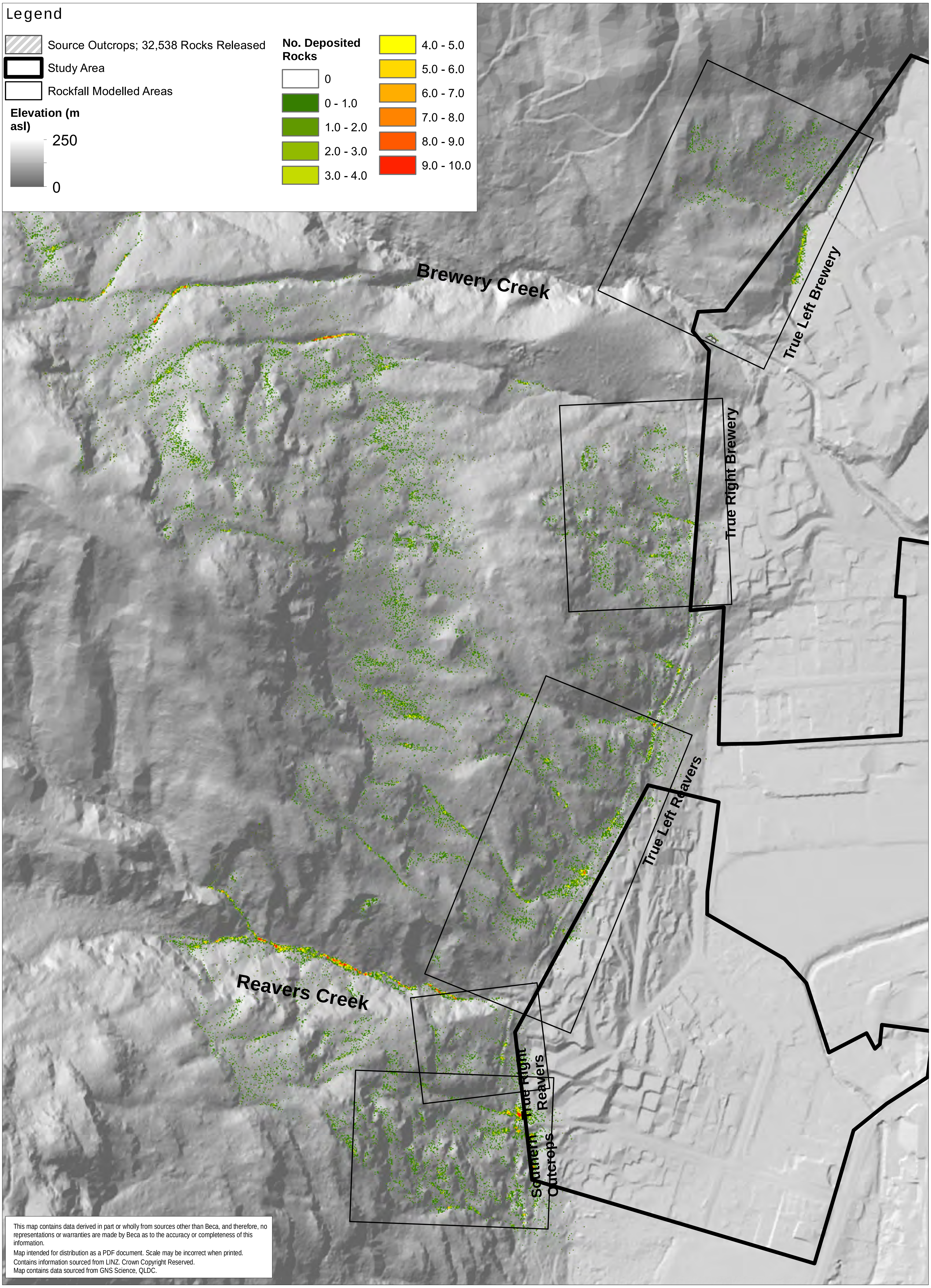
- Modelling of Sections A and B, which transect the industrial area on the true right side of the Brewery Creek Fan, shows rockfall debris extending up to 50m from the base of the slope and into the industrial properties.
- Sections C and D, which intersect the true left side of the Brewery Creek Fan, shows rockfall extending up to 100m downslope of the transmission line. Debris is shown to cover the fan surface and extend to the relatively flat ground at the base of the valley.

Reavers Fan:

- Section E is at the northern-most extent of the Reavers Fan. Modelling indicates that rockfall debris covers the fan surface and extends downslope the valley floor immediately behind the former site of Wakatipu High School.
- Section F intersects the residential area to the true right of Reavers Creek. Modelling shows rockfall debris extending approximately 10m below the transmission line, which corresponds with the grassed slope immediately behind the residential properties.
- Sections G and H extend across the hillslope on the true left side of the Reavers Creek. Modelling indicates that the rockfall debris stops between 5m to 60m downslope of the transmission line subsequently impacting the residential properties immediately at the base of the slope.

Comparison of 2D and 3D rockfall models

Rockfall run-out distances were generally higher in the 2D models than the 3D models as the 2D modelling assumed the entire slope was a ‘seeder’ or source area. The 3D modelling accounted for known outcrops which were observed during field mapping, including the presence of localised outcrops above the transmission line, and lack of source outcrops beneath the transmission line. Areas where run-out distances were influenced by topography, such as the grassed slope on Section F, show similar distributions of boulder concentrations between the 2D and 3D models.



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Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
All Outcrops
Forested

Client: Queenstown Lakes District Council

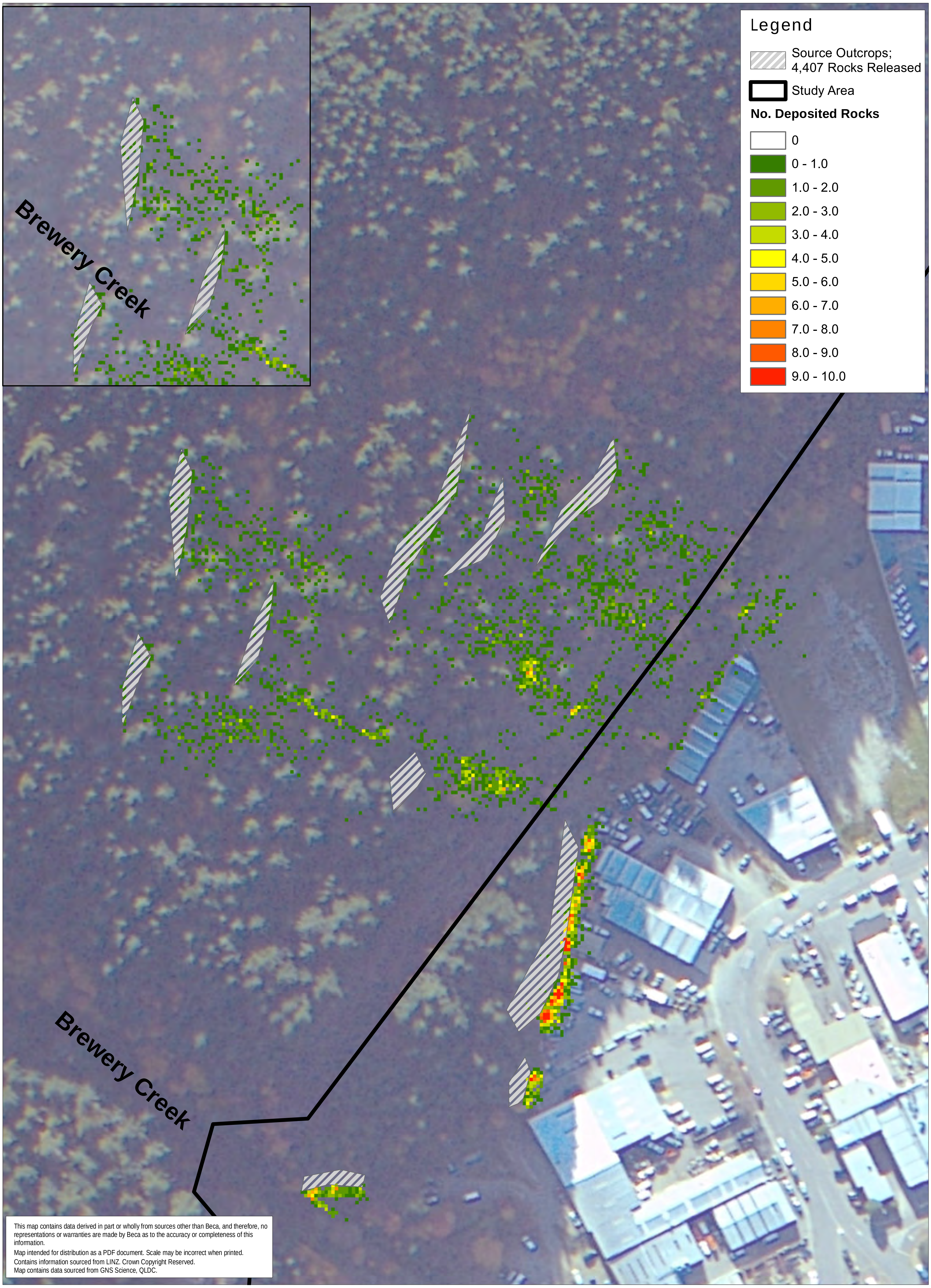
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H001



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
True Left Brewery
Forested

Client: Queenstown Lakes District Council

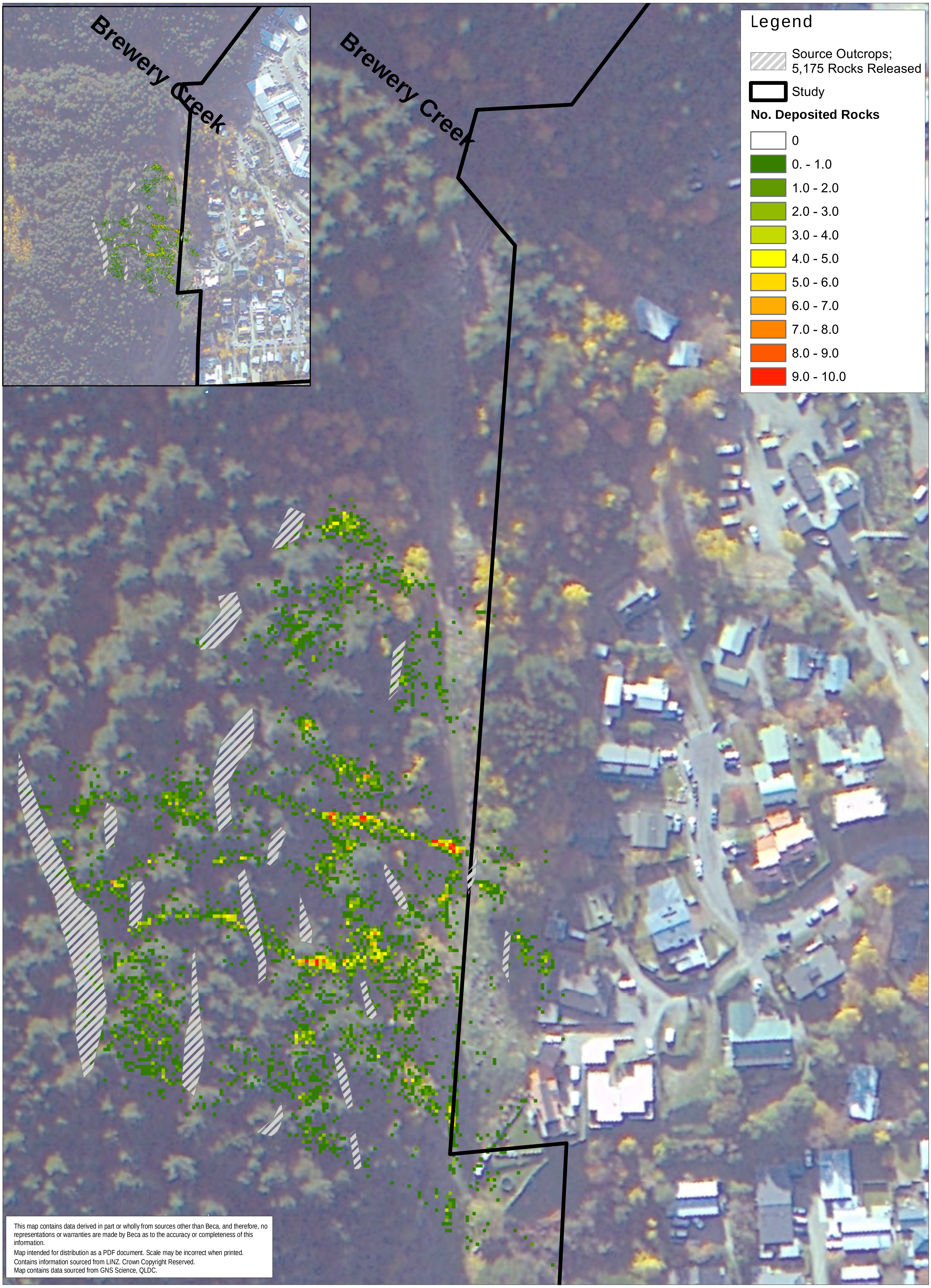
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H002



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
True Right Brewery
Forested

Client: Queenstown Lakes District Council

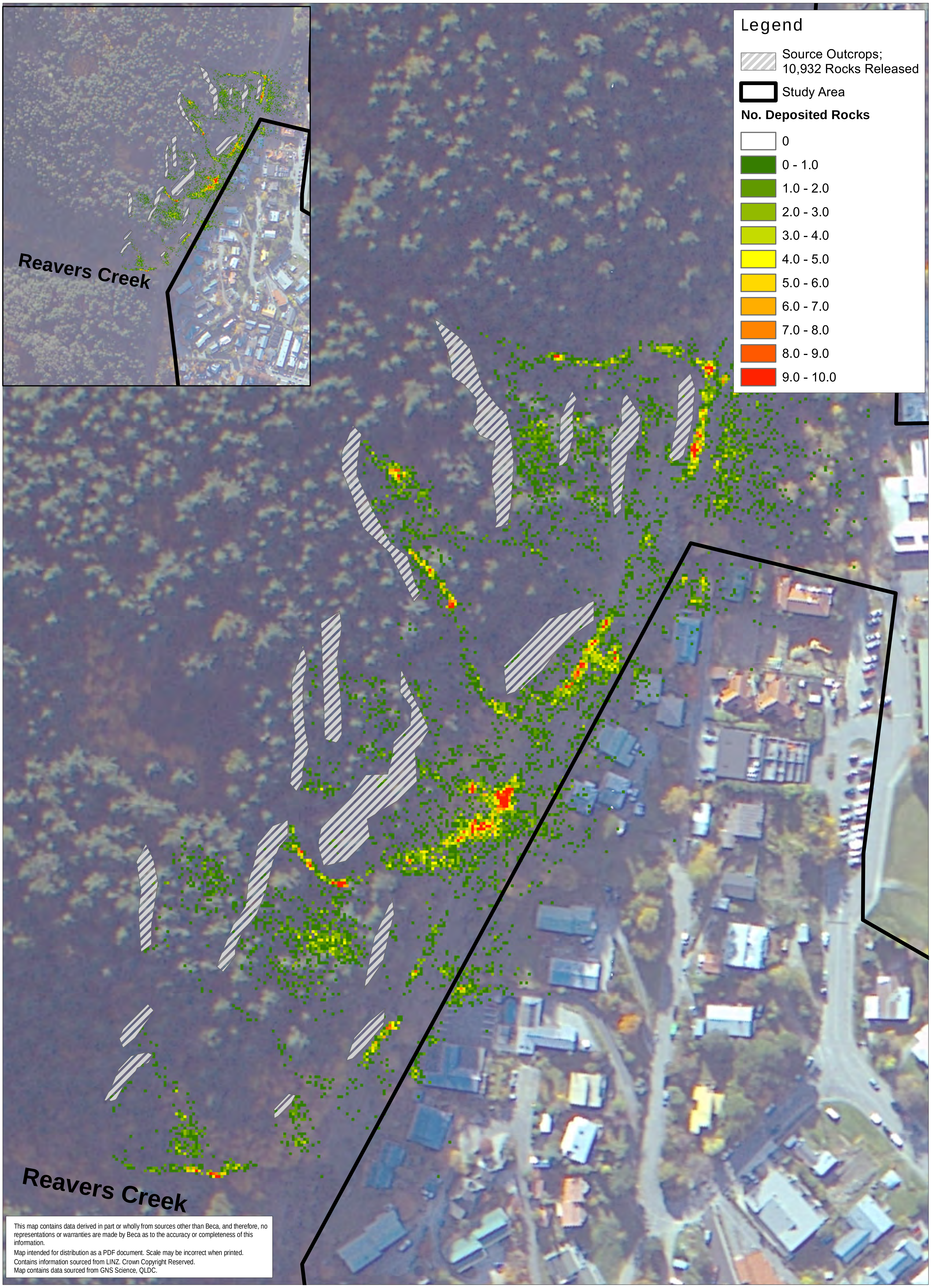
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H003



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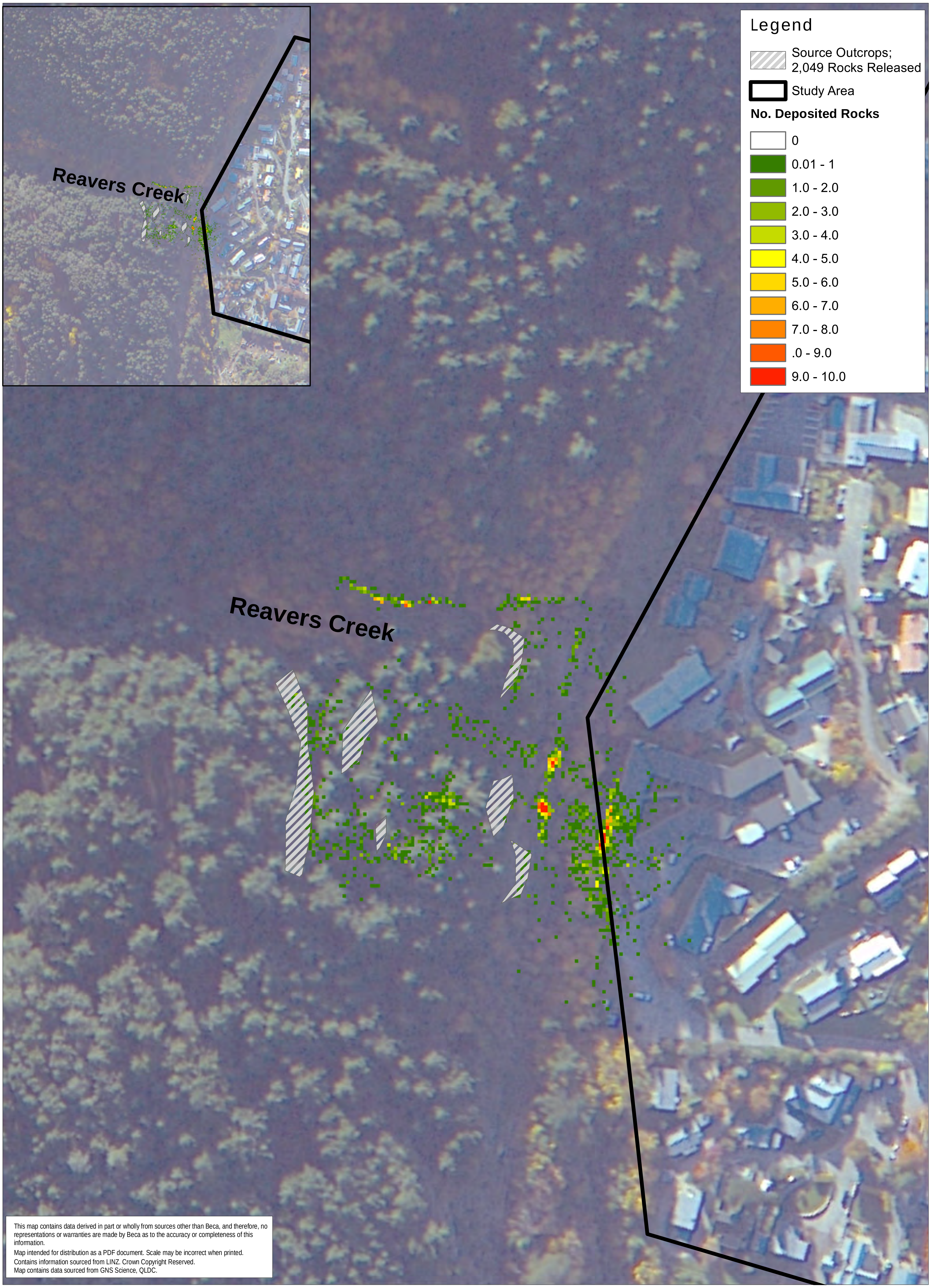

Map Scale @ A3: 1:1,000

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
True Right Reavers
Forested

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H005

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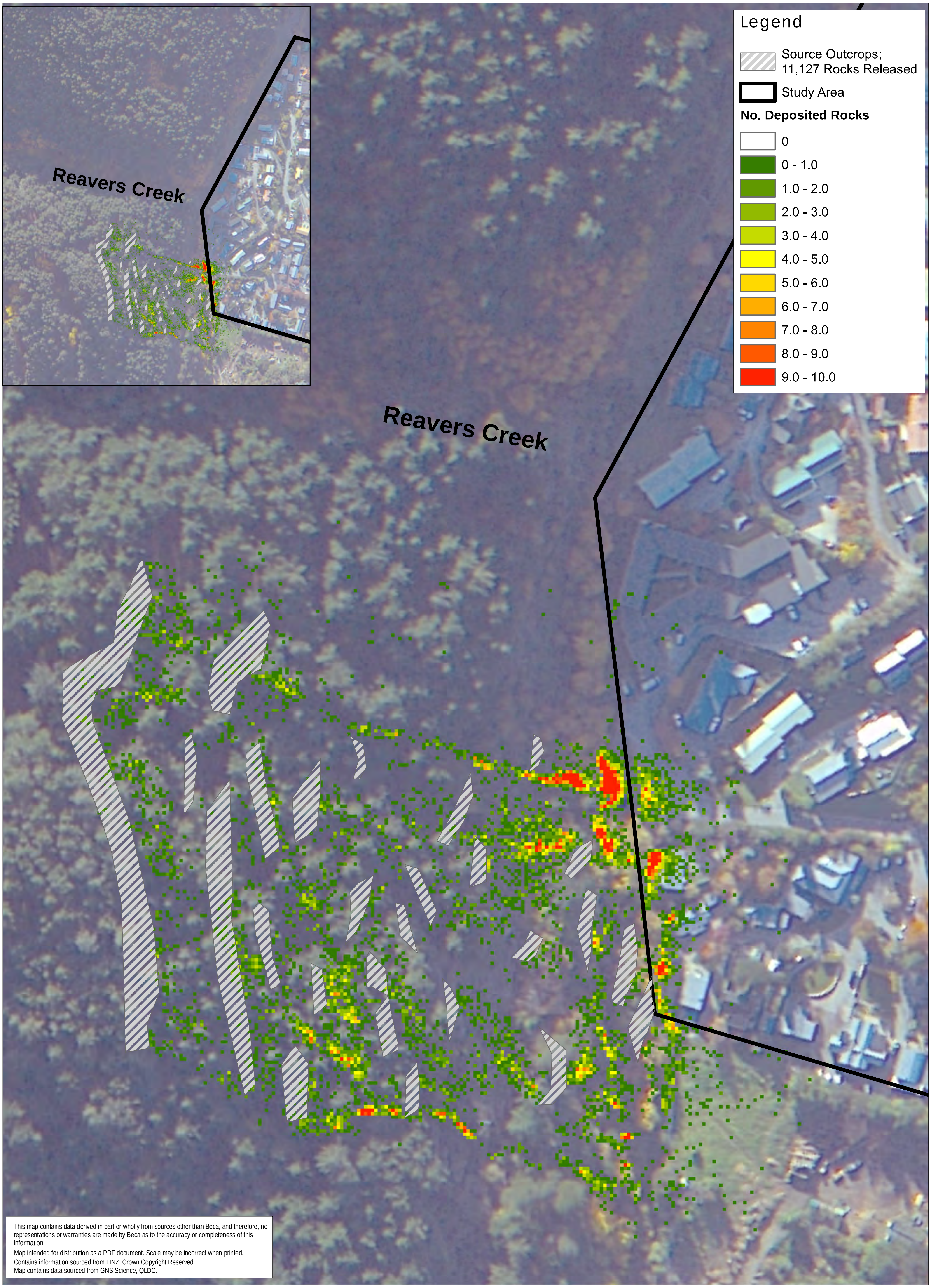

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
Southern Outcrops
Forested

Client: Queenstown Lakes District Council

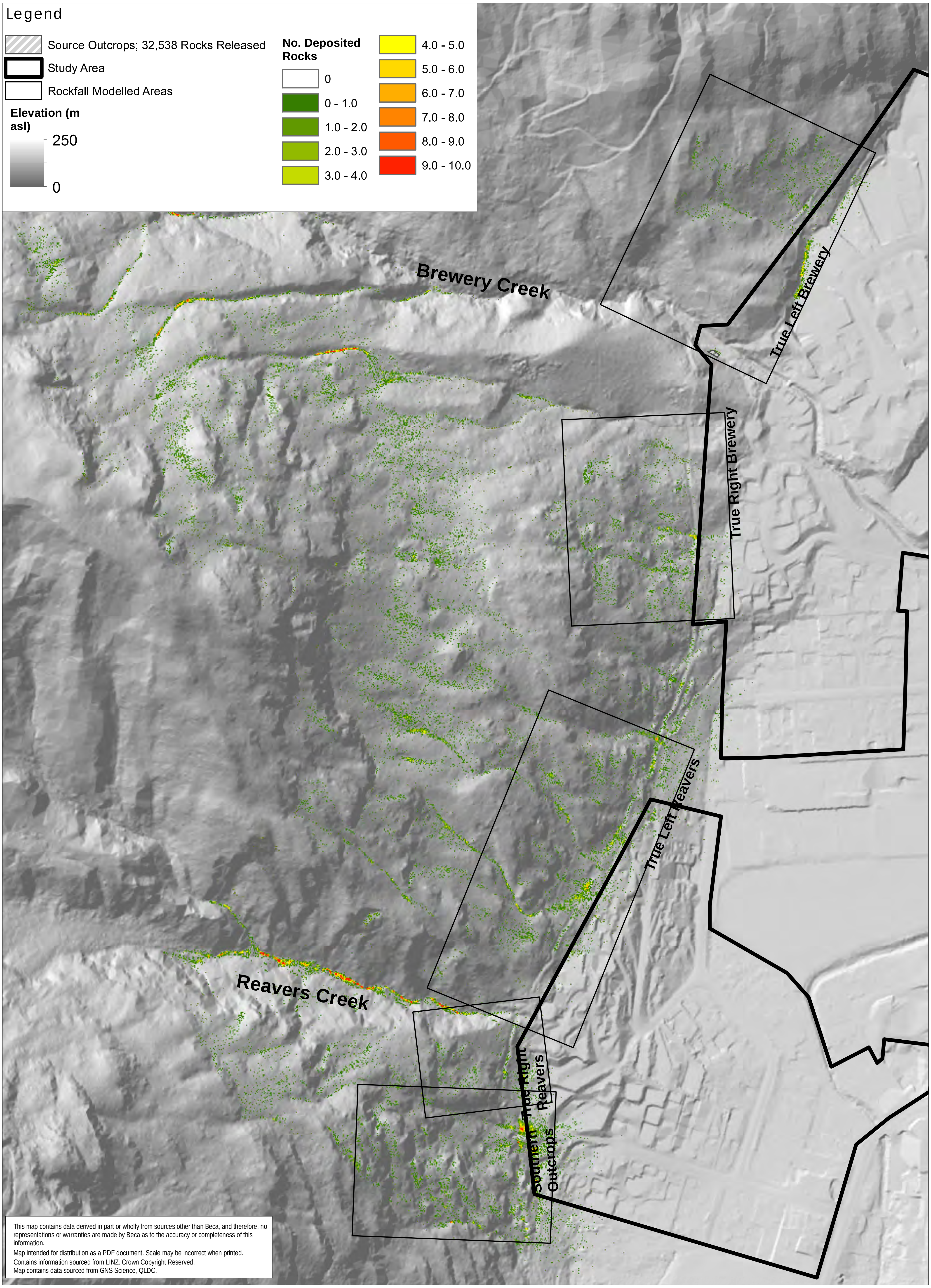
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H006



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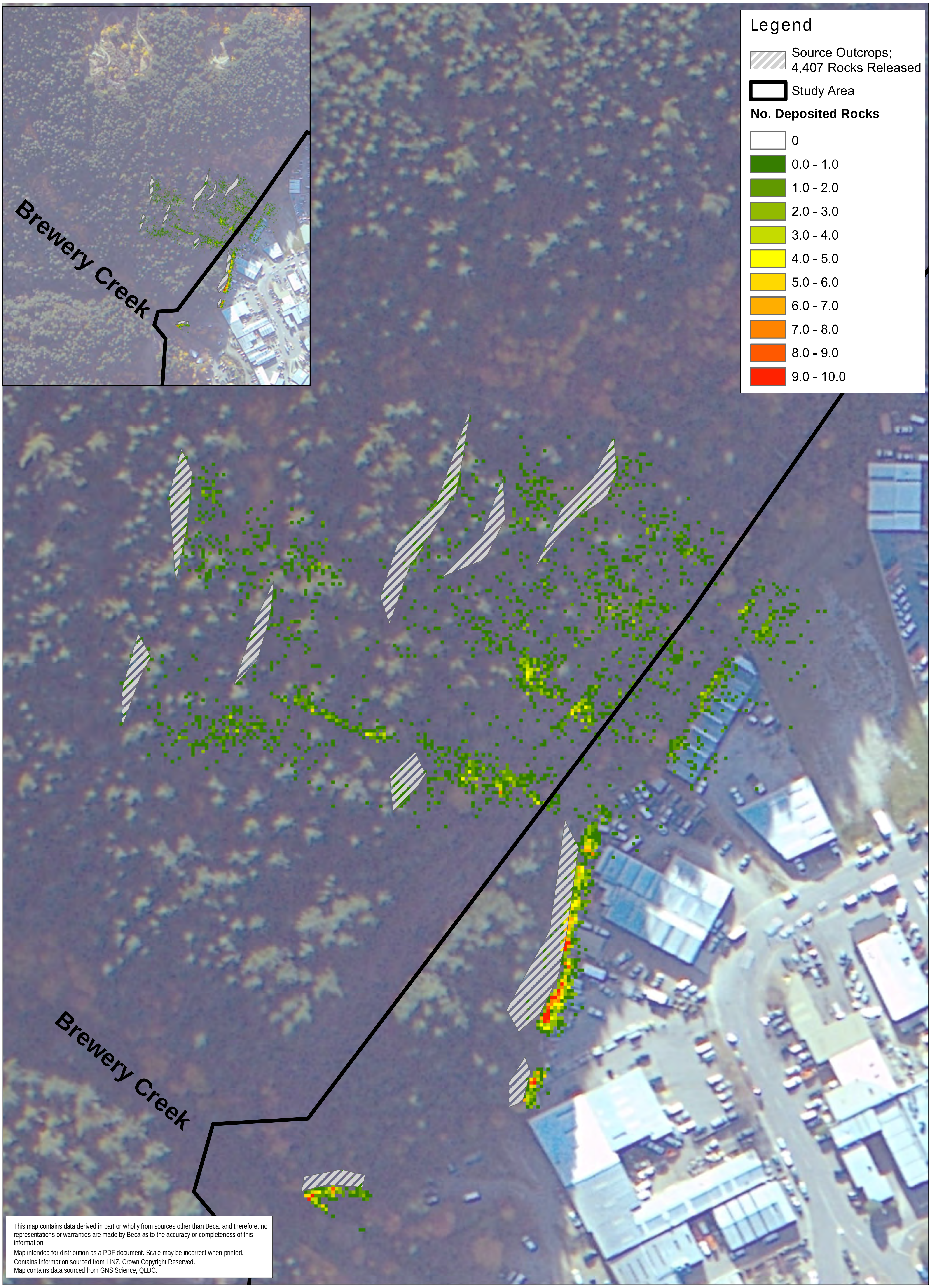

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
True Left Brewery
Non-Forested

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H008

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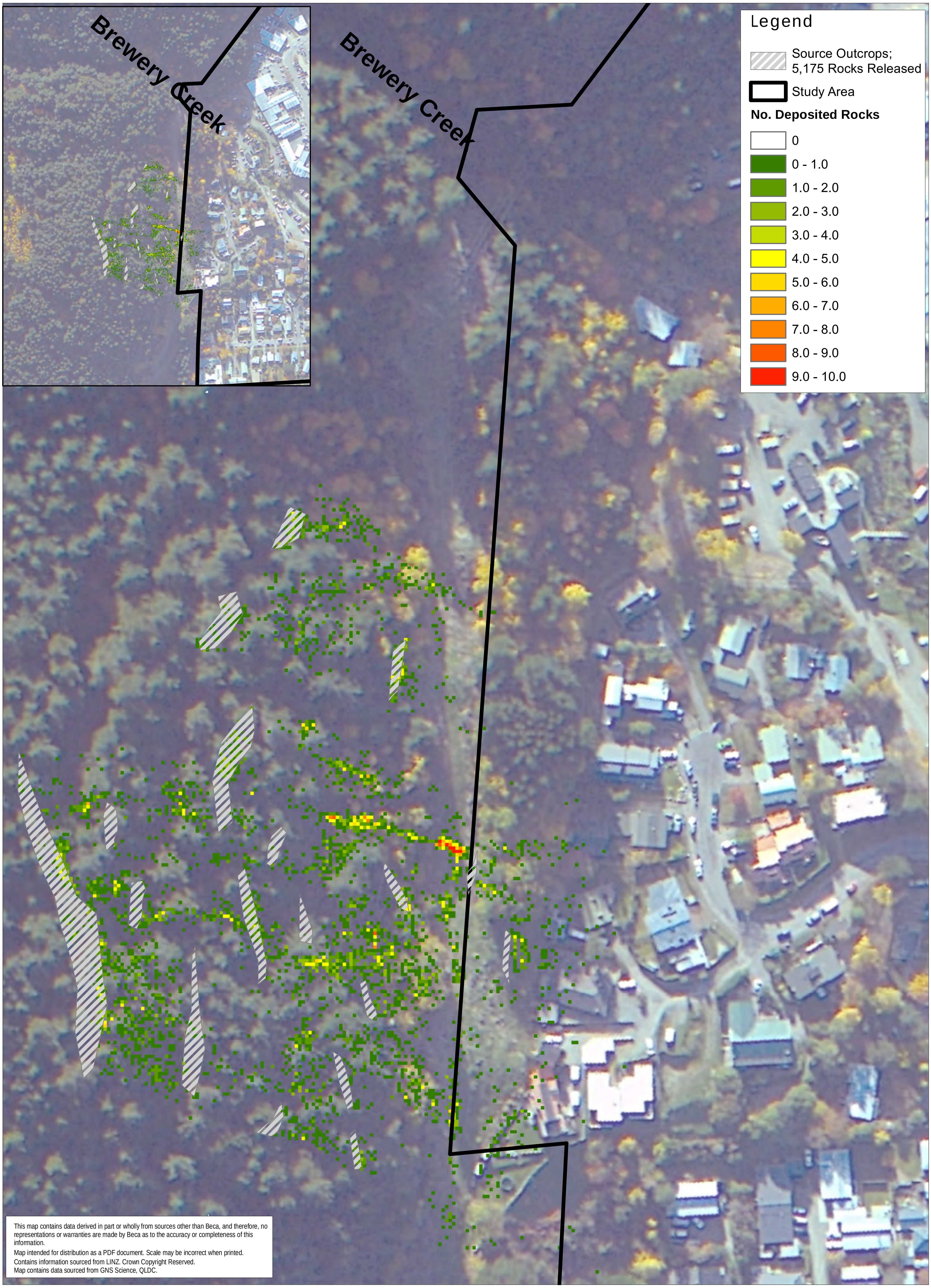

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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:
Rockfall Modelling
True Right Brewery
Non-Forested

Client: Queenstown Lakes District Council

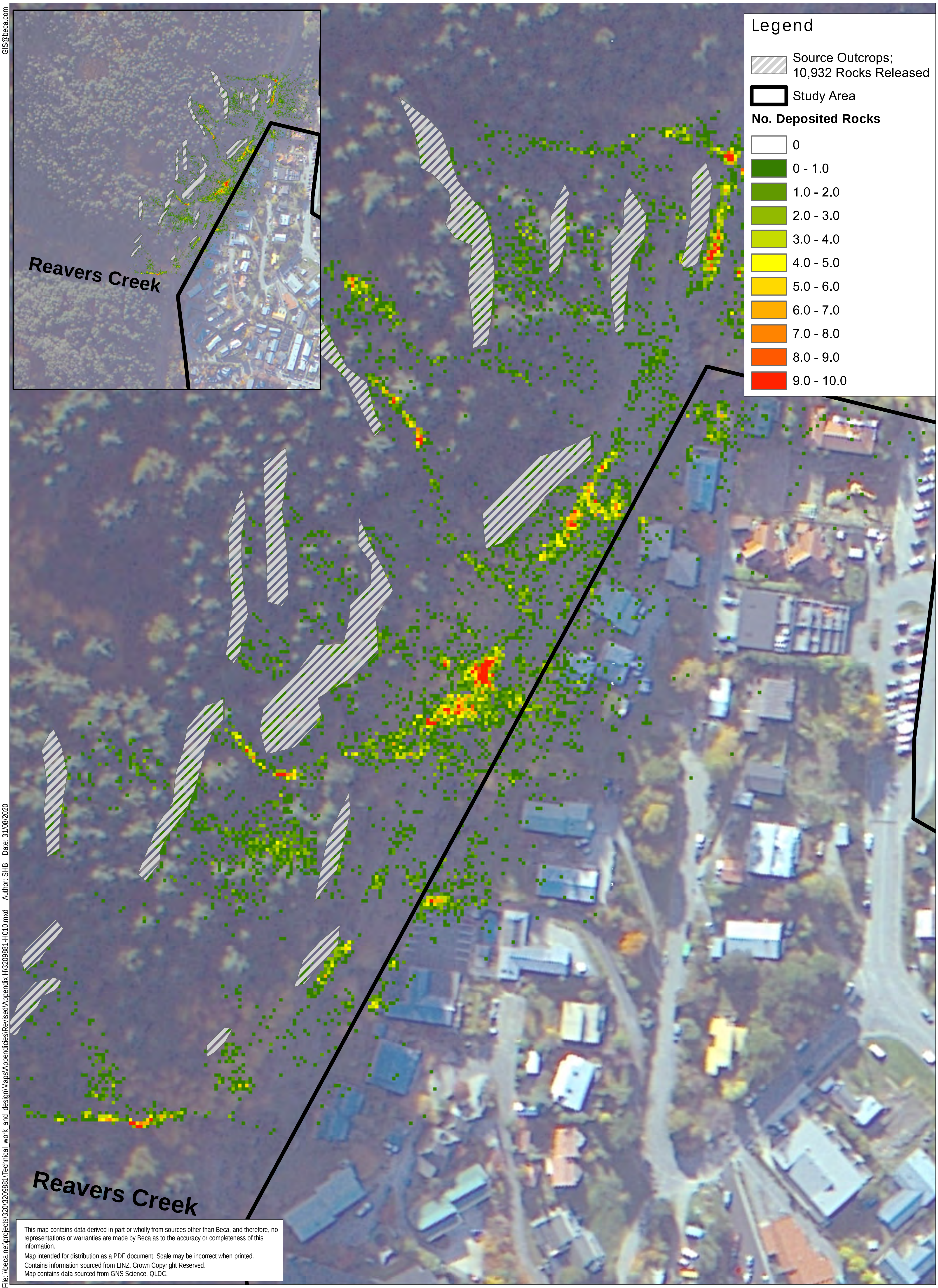
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H009



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Metres

Revision	Author	Verified	Approved	Date
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Title:

Rockfall Modelling
True Left Reavers
Non-Forested

Client: Queenstown Lakes District Council

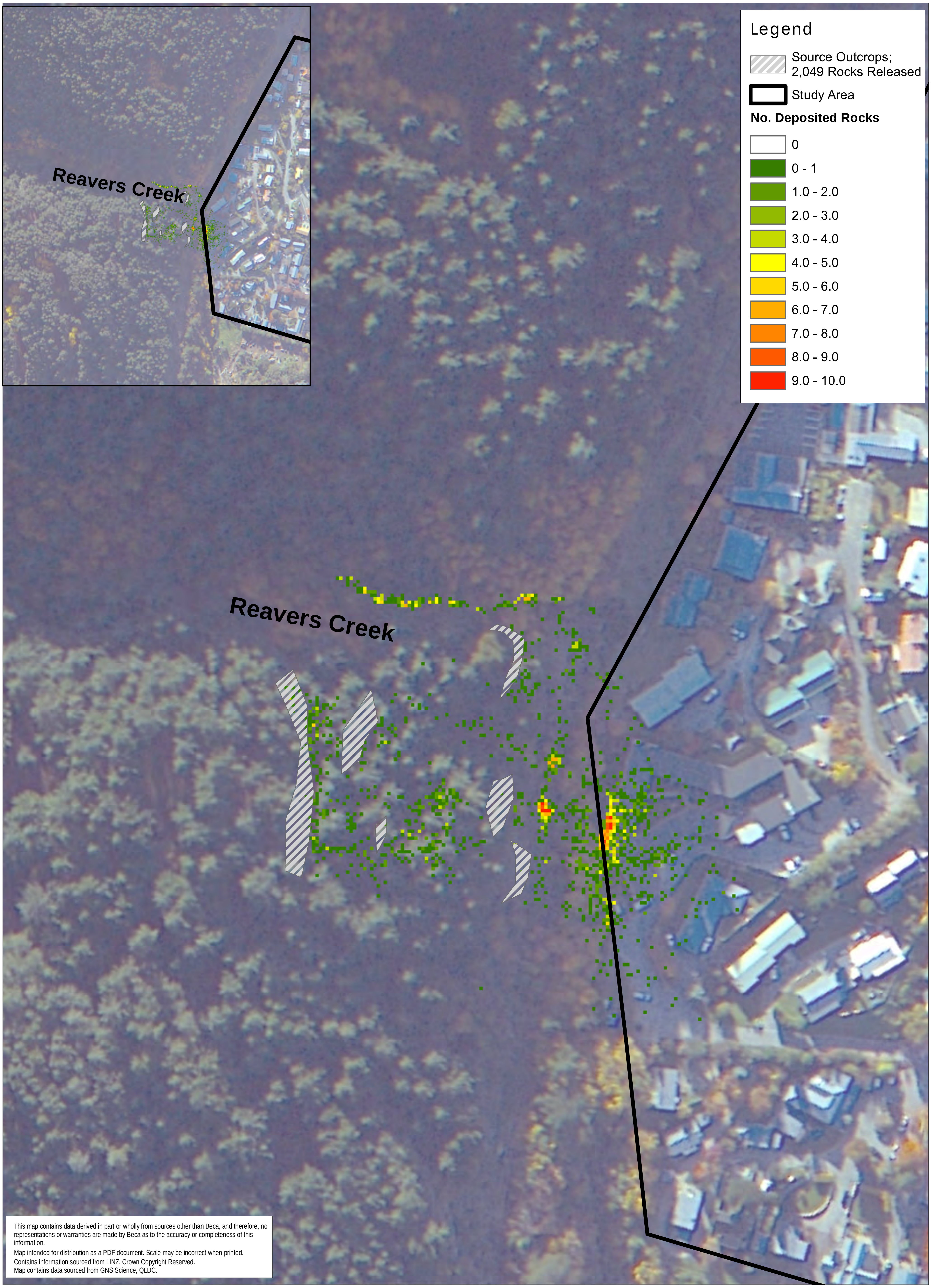
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H010



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Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/08/2020

Title:

Rockfall Modelling
True Right Reavers
Non-Forested

Client: Queenstown Lakes District Council

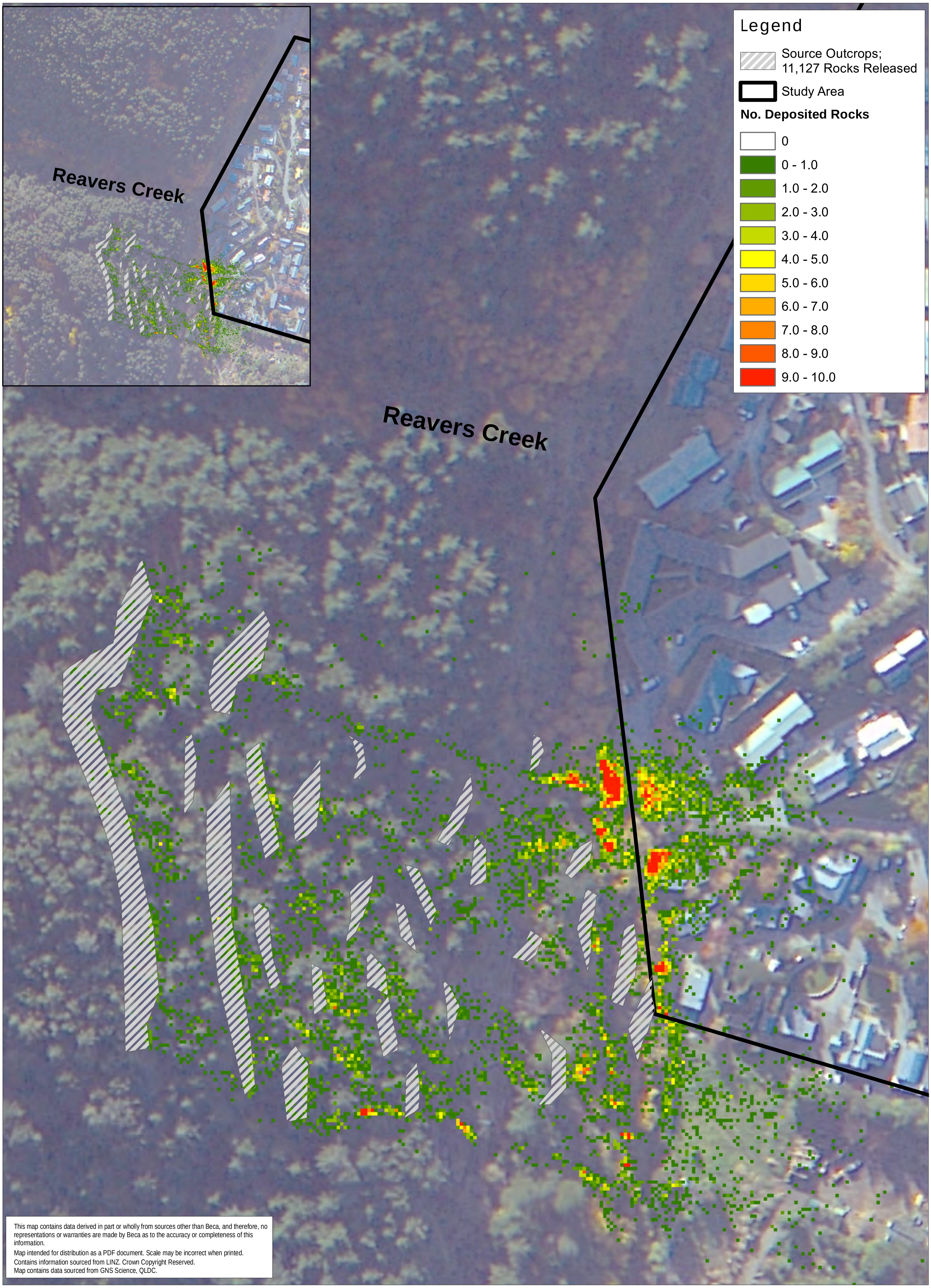
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H011



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0 20 40

Metres

Revision	Author	Verified	Approved	Date
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Title:

Rockfall Modelling
Southern Outcrops
Non-Forested

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-H012

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Appendix I – Annual Individual Fatality Risk Worksheets

Annual Individual Fatality Risk (AIFR) Assessment Worksheet

Location:	Brewery Creek Fan, Queenstown
Failure mode:	Debris flow from Brewery Creek
Consequence:	Death
Element at risk:	Individual most at risk
Date:	8-May-20
Status:	Final

Hazard	Hazard zone	Failure magnitude (refer debris flow modelling scenarios for definitions, see tab 2)	Annual probability of failure P(H) (1)				Probability of travel (P(S:H)) (2)	Temporal spatial probability (P(T:S)) (3)							Vulnerability (4)	AIFR Minimum			AIFR Average			AIFR Maximum		
			Lower		Upper			Probability of self evacuation, P(se)		Planning zone	Occupancy	Time "individual most at risk present)	Lower	Upper										
			P(H)	1 in x years	P(H)	1 in x years		Lower	Upper							AIFR	AIFR Residential	AIFR Business	AIFR	AIFR Residential	AIFR Business	AIFR	AIFR Residential	AIFR Business
Debris flow Brewery	1	Small, more frequent event	0.005	200	0.02	50	0.8	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.5	4.8E-04	5.3E-04		1.6E-03	1.8E-03		3.2E-03	3.6E-03	
			0.005	200	0.02	50	0.8	0.6	0.8	Residential	Outside	10%	0.02	0.04	0.6	4.8E-05			1.8E-04			3.8E-04		
			0.005	200	0.02	50	0.8	0.5	0.7	Business	Inside	27%	0.081	0.135	0.5	1.6E-04		2.0E-04	5.4E-04		6.7E-04	1.1E-03		1.3E-03
			0.005	200	0.02	50	0.8	0.6	0.8	Business	Outside	7%	0.014	0.028	0.6	3.4E-05			1.3E-04			2.7E-04		
		Medium	0.0004	2500	0.005	200	1.0	0.3	0.5	Residential	Inside	80%	0.4	0.56	0.8	1.3E-04	1.4E-04		1.0E-03	1.2E-03		2.2E-03	2.5E-03	
			0.0004	2500	0.005	200	1.0	0.4	0.6	Residential	Outside	10%	0.04	0.06	0.9	1.4E-05			1.2E-04			2.7E-04		
			0.0004	2500	0.005	200	1.0	0.3	0.5	Business	Inside	27%	0.135	0.189	0.8	4.3E-05		5.3E-05	3.5E-04		4.3E-04	7.6E-04		9.5E-04
			0.0004	2500	0.005	200	1.0	0.4	0.6	Business	Outside	7%	0.028	0.042	0.9	1.0E-05			8.5E-05			1.9E-04		
		Large, less frequent event	0.0001	10000	0.0004	2500	1.0	0.1	0.3	Residential	Inside	80%	0.56	0.72	0.9	5.0E-05	5.6E-05		1.4E-04	1.6E-04		2.6E-04	2.9E-04	
			0.0001	10000	0.0004	2500	1.0	0.2	0.4	Residential	Outside	10%	0.06	0.08	1.0	6.0E-06			1.8E-05			3.2E-05		
			0.0001	10000	0.0004	2500	1.0	0.1	0.3	Business	Inside	27%	0.189	0.243	0.9	1.7E-05		2.1E-05	4.9E-05		6.1E-05	8.7E-05		1.1E-04
			0.0001	10000	0.0004	2500	1.0	0.2	0.4	Business	Outside	7%	0.042	0.056	1.0	4.2E-06			1.2E-05			2.2E-05		
																AIFR	7.3E-04	2.7E-04	AIFR	3.1E-03	1.2E-03	AIFR	6.4E-03	2.4E-03
Debris flow Brewery	2	Small, more frequent event	0.005	200	0.02	50	0.0	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.5	0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00	
			0.005	200	0.02	50	0.0	0.6	0.8	Residential	Outside	10%	0.02	0.04	0.6	0.0E+00			0.0E+00			0.0E+00		
			0.005	200	0.02	50	0.0	0.5	0.7	Business	Inside	27%	0.081	0.135	0.5	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00
			0.005	200	0.02	50	0.0	0.6	0.8	Business	Outside	7%	0.014	0.028	0.6	0.0E+00			0.0E+00			0.0E+00		
		Medium	0.0004	2500	0.005	200	0.8	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.8	8.2E-05	9.1E-05		6.9E-04	7.7E-04		1.5E-03	1.7E-03	
			0.0004	2500	0.005	200	0.8	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.9	8.6E-06			7.8E-05			1.8E-04		
			0.0004	2500	0.005	200	0.8	0.4	0.6	Business	Inside	27%	0.108	0.162	0.8	2.8E-05		3.4E-05	2.3E-04		2.9E-04	5.2E-04		6.4E-04
			0.0004	2500	0.005	200	0.8	0.5	0.7	Business	Outside	7%	0.021	0.035	0.9	6.0E-06			5.4E-05			1.3E-04		
		Large, less frequent event	0.0001	10000	0.0004	2500	1.0	0.2	0.4	Residential	Inside	80%	0.48	0.64	0.9	4.3E-05	4.8E-05		1.3E-04	1.4E-04		2.3E-04	2.6E-04	
			0.0001	10000	0.0004	2500	1.0	0.3	0.5	Residential	Outside	10%	0.05	0.07	1.0	5.0E-06			1.5E-05			2.8E-05		
			0.0001	10000	0.0004	2500	1.0	0.2	0.4	Business	Inside	27%	0.162	0.216	0.9	1.5E-05		1.8E-05	4.3E-05		5.3E-05	7.8E-05		9.7E-05
			0.0001	10000	0.0004	2500	1.0	0.3	0.5	Business	Outside	7%	0.035	0.049	1.0	3.5E-06			1.1E-05			2.0E-05		
																AIFR	1.4E-04	5.2E-05	AIFR	9.1E-04	3.4E-04	AIFR	2.0E-03	7.4E-04
Debris flow Brewery	3	Small, more frequent event	0.005	200	0.02	50	0.0	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.5	0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00	
			0.005	200	0.02	50	0.0	0.6	0.8	Residential	Outside	10%	0.02	0.04	0.6	0.0E+00			0.0E+00			0.0E+00		
			0.005	200	0.02	50	0.0	0.5	0.7	Business	Inside	27%	0.081	0.135	0.5	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00
			0.005	200	0.02	50	0.0	0.6	0.8	Business	Outside	7%	0.014	0.028	0.6	0.0E+00			0.0E+00			0.0E+00		
		Medium	0.0004	2500	0.005	200	0.0	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.8	0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00	
			0.0004	2500	0.005	200	0.0	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.9	0.0E+00			0.0E+00			0.0E+00		
			0.0004	2500	0.005	200	0.0	0.4	0.6	Business	Inside	27%	0.108	0.162	0.8	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00
			0.0004	2500	0.005	200	0.0	0.5	0.7	Business	Outside	7%	0.021	0.035	0.9	0.0E+00			0.0E+00			0.0E+00		
		Large, less frequent event	0.0001	10000	0.0004	2500	0.8	0.3	0.5	Residential	Inside	80%	0.4	0.56	0.9	2.9E-05	3.2E-05		8.6E-05	9.6E-05		1.6E-04	1.8E-04	
			0.0001	10000	0.0004	2500	0.8	0.4	0.6	Residential	Outside	10%	0.04	0.06	1.0	3.2E-06			1.0E-05			1.9E-05		
			0.0001	10000	0.0004	2500	0.8	0.3	0.5	Business	Inside	27%	0.135	0.189	0.9	9.7E-06		1.2E-05	2.9E-05		3.6E-05	5.4E-05		6.8E-05
			0.0001	10000	0.0004	2500	0.8	0.4	0.6	Business	Outside	7%	0.028	0.042	1.0	2.2E-06			7.0E-06			1.3E-05		
																AIFR	3.2E-05	1.2E-05	AIFR	9.6E-05	3.6E-05	AIFR	1.8E-04	6.8E-05
Debris flow Brewery	4	Small, more frequent event	0.005	200	0.02	50	0.0	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.5	0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00	
			0.005	200	0.02	50	0.0	0.6	0.8	Residential	Outside	10%	0.02	0.04	0.6	0.0E+00			0.0E+00			0.0E+00		
			0.005	200	0.02	50	0.0	0.5	0.7	Business	Inside	27%	0.081	0.135	0.5	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00
			0.005	200	0.02	50	0.0	0.6	0.8	Business	Outside	7%	0.014	0.028	0.6	0.0E+00			0.0E+00			0.0E+00		
		Medium	0.0004	2500	0.005	200	0.0	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.8	0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00	
			0.0004	2500	0.005	200	0.0	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.9	0.0E+00			0.0E+00			0.0E+00		
			0.0004	2500	0.005	200	0.0	0.4	0.6	Business	Inside	27%	0.108	0.162	0.8	0.0E+00		0.0E+00	0.0E+00		0.0E+00	0.0E+00		0.0E+00
			0.0004	2500	0.005	200	0.0	0.5	0.7	Business	Outside	7%	0.021	0.035	0.9	0.0E+00			0.0E+00			0.0E+00		
		Large, less frequent event	0.0001	10000	0.0004	2500	0.8	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.05	1.3E-06	1.5E-06		4.0E-06	4.8E-06		7.7E-06	9.3E-06	
			0.0001	10000	0.0004	2500	0.8	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.1	2.4E-07			8.0E-07			1.6E-06		
			0.0001	10000	0.0004	2500	0.8	0.4	0.6	Business	Inside	27%	0.108	0.162	0.05	4.3E-07		6.0E-07	1.4E-06		1.9E-06	2.6E-06		3.7E-06
			0.0001	10000	0.0004	2500	0.8	0.5	0.7	Business	Outside	7%	0.021	0.035	0.1	1.7E-07			5.6E-07			1.1E-06		
																AIFR	1.5E-06	6.0E-07	AIFR	4.8E-06	1.9E-06	AIFR	9.3E-06	3.7E-06

Annual Individual Fatality Risk (AIFR) Assessment Worksheet

Location: Reavers Fan, Queenstown
Failure mode: Debris flow from Reavers Fan catchment
Consequence: Death
Element at risk: Individual most at risk
Date: 11-May-20
Status: Final

Hazard	Hazard zone	Failure magnitude (refer debris flow modelling scenarios for definitions, Tab 2)	Annual probability of failure P(H) (1)				Probability of travel (P(S:H)) (2)	Temporal spatial probability (P(T:S)) (3)							Vulnerability (4)	AIFR Lower		AIFR Average		AIFR Upper	
			Lower		Upper			Probability of self evacuation, P(se)		Planning zone	Occupancy	Time "individual most at risk present)	Lower	Upper							
			P(H)	1 in x years	P(H)	1 in x years		Lower	Upper							AIFR	AIFR Residential	AIFR	AIFR Residential	AIFR	AIFR Residential
Debris flow Reavers	1	Small, more frequent event	0.0004	2500	0.01	100	0.9	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.5	4.3E-05	4.8E-05	7.5E-04	8.3E-04	1.8E-03	2.0E-03
			0.0004	2500	0.01	100	0.9	0.6	0.8	Residential	Outside	10%	0.02	0.04	0.6	4.3E-06		8.4E-05		2.2E-04	
		Medium	0.00015	6667	0.0004	2500	1	0.3	0.5	Residential	Inside	80%	0.4	0.56	0.8	4.8E-05	5.3E-05	1.1E-04	1.2E-04	1.8E-04	2.0E-04
			0.00015	6667	0.0004	2500	1	0.4	0.6	Residential	Outside	10%	0.04	0.06	0.9	5.4E-06		1.2E-05		2.2E-05	
		Large, less frequent event	0.00005	20000	0.00015	6667	1	0.1	0.3	Residential	Inside	80%	0.56	0.72	0.9	2.5E-05	2.8E-05	5.8E-05	6.5E-05	9.7E-05	1.1E-04
			0.00005	20000	0.00015	6667	1	0.2	0.4	Residential	Outside	10%	0.06	0.08	1	3.0E-06		7.0E-06		1.2E-05	
																AIFR	**1.3E-04**	**AIFR**	**1.0E-03**	**AIFR**	**2.3E-03**
Debris flow Reavers	2	Small, more frequent event	0.0004	2500	0.01	100	0.00	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
			0.0004	2500	0.01	100	0.00	0.6	0.8	Residential	Outside	10%	0.02	0.04	0.6	0.0E+00		0.0E+00		0.0E+00	
		Medium	0.00015	6667	0.0004	2500	0.9	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.8	3.5E-05	3.8E-05	7.9E-05	8.8E-05	1.4E-04	1.5E-04
			0.00015	6667	0.0004	2500	0.9	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.9	3.6E-06		8.9E-06		1.6E-05	
		Large, less frequent event	0.00005	20000	0.00015	6667	1	0.2	0.4	Residential	Inside	80%	0.48	0.64	0.9	2.2E-05	2.4E-05	5.0E-05	5.6E-05	8.6E-05	9.7E-05
			0.00005	20000	0.00015	6667	1	0.3	0.5	Residential	Outside	10%	0.05	0.07	1	2.5E-06		6.0E-06		1.1E-05	
																AIFR	**6.2E-05**	**AIFR**	**1.4E-04**	**AIFR**	**2.5E-04**
Debris flow Reavers	3	Small, more frequent event	0.0004	2500	0.01	100	0.00	0.6	0.8	Residential	Inside	80%	0.16	0.32	0.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
			0.0004	2500	0.01	100	0.00	0.7	0.9	Residential	Outside	10%	0.01	0.03	0.6	0.0E+00		0.0E+00		0.0E+00	
		Medium	0.00015	6667	0.0004	2500	0	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.8	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
			0.00015	6667	0.0004	2500	0	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.9	0.0E+00		0.0E+00		0.0E+00	
		Large, less frequent event	0.00005	20000	0.00015	6667	0.9	0.3	0.5	Residential	Inside	80%	0.4	0.56	0.9	1.6E-05	1.8E-05	3.9E-05	4.3E-05	6.8E-05	7.6E-05
			0.00005	20000	0.00015	6667	0.9	0.4	0.6	Residential	Outside	10%	0.04	0.06	1	1.8E-06		4.5E-06		8.1E-06	
																AIFR	**1.8E-05**	**AIFR**	**4.3E-05**	**AIFR**	**7.6E-05**
Debris flow Reavers	4	Small, more frequent event	0.0004	2500	0.01	100	0.00	0.7	0.9	Residential	Inside	80%	0.08	0.24	0.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
			0.0004	2500	0.01	100	0.00	0.7	0.9	Residential	Outside	10%	0.01	0.03	0.6	0.0E+00		0.0E+00		0.0E+00	
		Medium	0.00015	6667	0.0004	2500	0	0.5	0.7	Residential	Inside	80%	0.24	0.4	0.8	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
			0.00015	6667	0.0004	2500	0	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.9	0.0E+00		0.0E+00		0.0E+00	
		Large, less frequent event	0.00005	20000	0.00015	6667	0.9	0.4	0.6	Residential	Inside	80%	0.32	0.48	0.05	7.2E-07	8.6E-07	1.8E-06	2.2E-06	3.2E-06	3.9E-06
			0.00005	20000	0.00015	6667	0.9	0.5	0.7	Residential	Outside	10%	0.03	0.05	0.1	1.4E-07		3.6E-07		6.8E-07	
																AIFR	**8.6E-07**	**AIFR**	**2.2E-06**	**AIFR**	**3.9E-06**

Annual Individual Fatality Risk (AIFR) Assessment Worksheet

Location: Brewery Creek and Reavers Fans, Queenstown
Failure mode: Individual rockfall
Consequence: Death
Element at risk: Individual most at risk
Date: 11-May-20
Status: Final

Element at risk width (m)	1
Average boulder width (m)	1
Slope width (m)	1220
P_1 (S:H)	2.5E-03

Hazard	Hazard zone	Failure magnitude class	Annual frequency of rockfall P(H)						Spatial Probability (P(S:H))			Temporal spatial probability (P(T:S))					Vulnerability	AIFR Lower			AIFR Average			AIFR Upper		
					Lower		Upper			Lower	Upper															
			Annual probability of failure	1 in x years	Number of rocks per individual rockfall (N)	Annual frequency of rockfall	Number of rocks per individual rockfall (N)	Annual frequency of rockfall	Probability of Travel (P(T))	$P(T) \times P_N(S:H)$		Probability of self evacuation	Planning zone	Occupancy	Time "individual most at risk" present	Temporal spatial probability (P(T:S))		AIFR	AIFR Residential	AIFR Business	AIFR	AIFR Residential	AIFR Business	AIFR	AIFR Residential	AIFR Business
Rockfall		Rockfall - non-seismic trigger	1	1	1	1	10	10	0.1	2.5E-04	2.4E-03	0.0	Residential	Inside	80%	8.0E-01	0.5	9.8E-05	1.2E-04		5.4E-04	6.3E-04		9.7E-04	1.1E-03	
			1	1	1	1	10	10	0.1	2.5E-04	2.4E-03	0.0	Residential	Outside	10%	1.0E-01	0.7	1.7E-05			9.4E-05			1.7E-04		
			1	1	1	1	10	10	0.1	2.5E-04	2.4E-03	0.0	Industrial	Inside	27%	2.7E-01	0.5	3.3E-05		4.5E-05	1.8E-04		2.5E-04	3.3E-04		4.5E-04
			1	1	1	1	10	10	0.1	2.5E-04	2.4E-03	0.0	Industrial	Outside	7%	7.0E-02	0.7	1.2E-05			6.6E-05			1.2E-04		
		Rockfall - far field seismic trigger - 1/100 yr	0.01	100	10	0.1	100	1	0.1	2.4E-03	2.2E-02	0.0	Residential	Inside	80%	8.0E-01	0.5	9.7E-06	1.1E-05		4.9E-05	5.6E-05		8.7E-05	1.0E-04	
	1		0.01	100	10	0.1	100	1	0.1	2.4E-03	2.2E-02	0.1	Residential	Outside	10%	9.0E-02	0.7	1.5E-06			7.6E-06			1.4E-05		
	>10%		0.01	100	10	0.1	100	1	0.1	2.4E-03	2.2E-02	0.0	Industrial	Inside	27%	2.7E-01	0.5	3.3E-06		4.4E-06	1.6E-05		2.2E-05	2.9E-05		3.9E-05
			0.01	100	10	0.1	100	1	0.1	2.4E-03	2.2E-02	0.1	Industrial	Outside	7%	6.3E-02	0.7	1.1E-06			5.3E-06			9.6E-06		
		Rockfall - near field seismic trigger 1/500 yr	0.002	500	100	0.2	1000	2	0.1	2.2E-02	9.1E-02	0.0	Residential	Inside	80%	8.0E-01	0.5	1.7E-05	2.0E-05		4.5E-05	5.2E-05		7.3E-05	8.5E-05	
			0.002	500	100	0.2	1000	2	0.1	2.2E-02	9.1E-02	0.1	Residential	Outside	10%	9.0E-02	0.7	2.7E-06			7.1E-06			1.2E-05		
			0.002	500	100	0.2	1000	2	0.1	2.2E-02	9.1E-02	0.0	Industrial	Inside	27%	2.7E-01	0.5	5.9E-06		7.8E-06	1.5E-05		2.0E-05	2.5E-05		3.3E-05
			0.002	500	100	0.2	1000	2	0.1	2.2E-02	9.1E-02	0.1	Industrial	Outside	7%	6.3E-02	0.7	1.9E-06			5.0E-06			8.1E-06		
																		AIFR	**1.5E-04**	**5.7E-05**	**AIFR**	**7.4E-04**	**2.9E-04**	**AIFR**	**1.3E-03**	**5.2E-04**
								0																		
Rockfall		Rockfall - non-seismic trigger	1	1	1	1	10	10	0.05	1.2E-04	1.2E-03	0.0	Residential	Inside	80%	8.0E-01	0.3	3.0E-05	3.6E-05		1.6E-04	1.9E-04		2.9E-04	3.5E-04	
			1	1	1	1	10	10	0.05	1.2E-04	1.2E-03	0.0	Residential	Outside	10%	1.0E-01	0.5	6.1E-06			3.3E-05			6.1E-05		
			1	1	1	1	10	10	0.05	1.2E-04	1.2E-03	0.0	Industrial	Inside	27%	2.7E-01	0.3	1.0E-05		1.4E-05	5.4E-05		7.8E-05	9.8E-05		1.4E-04
			1	1	1	1	10	10	0.05	1.2E-04	1.2E-03	0.0	Industrial	Outside	7%	7.0E-02	0.5	4.3E-06			2.3E-05			4.3E-05		
		Rockfall - far field seismic trigger - 1/100 yr	0.01	100	10	0.1	100	1	0.05	1.2E-03	1.1E-02	0.0	Residential	Inside	80%	8.0E-01	0.3	2.9E-06	3.4E-06		1.5E-05	1.7E-05		2.6E-05	3.1E-05	
	2		0.01	100	10	0.1	100	1	0.05	1.2E-03	1.1E-02	0.2	Residential	Outside	10%	8.0E-02	0.5	4.9E-07			2.4E-06			4.4E-06		
	1-10%		0.01	100	10	0.1	100	1	0.05	1.2E-03	1.1E-02	0.0	Industrial	Inside	27%	2.7E-01	0.3	9.8E-07		1.3E-06	4.9E-06		6.6E-06	8.8E-06		1.2E-05
			0.01	100	10	0.1	100	1	0.05	1.2E-03	1.1E-02	0.2	Industrial	Outside	7%	5.6E-02	0.5	3.4E-07			1.7E-06			3.1E-06		
		Rockfall - near field seismic trigger 1/500 yr	0.002	500	100	0.2	1000	2	0.05	1.1E-02	4.6E-02	0.0	Residential	Inside	80%	8.0E-01	0.3	5.2E-06	6.1E-06		1.4E-05	1.6E-05		2.2E-05	2.6E-05	
			0.002	500	100	0.2	1000	2	0.05	1.1E-02	4.6E-02	0.2	Residential	Outside	10%	8.0E-02	0.5	8.7E-07			2.3E-06			3.7E-06		
			0.002	500	100	0.2	1000	2	0.05	1.1E-02	4.6E-02	0.0	Industrial	Inside	27%	2.7E-01	0.3	1.8E-06		2.4E-06	4.6E-06		6.2E-06	7.4E-06		1.0E-05
			0.002	500	100	0.2	1000	2	0.05	1.1E-02	4.6E-02	0.2	Industrial	Outside	7%	5.6E-02	0.5	6.1E-07			1.6E-06			2.6E-06		
																		AIFR	**4.5E-05**	**1.8E-05**	**AIFR**	**2.3E-04**	**9.0E-05**	**AIFR**	**4.1E-04**	**1.6E-04**
								0																		
Rockfall		Rockfall - non-seismic trigger	1	1	1	1	10	10	0.01	2.5E-05	2.4E-04	0.0	Residential	Inside	80%	8.0E-01	0.1	2.0E-06	2.7E-06		1.1E-05	1.5E-05		1.9E-05	2.7E-05	
			1	1	1	1	10	10	0.01	2.5E-05	2.4E-04	0.0	Residential	Outside	10%	1.0E-01	0.3	7.4E-07			4.0E-06			7.3E-06		
			1	1	1	1	10	10	0.01	2.5E-05	2.4E-04	0.0	Industrial	Inside	27%	2.7E-01	0.1	6.6E-07		1.2E-06	3.6E-06		6.4E-06	6.6E-06		1.2E-05
			1	1	1	1	10	10	0.01	2.5E-05	2.4E-04	0.0	Industrial	Outside	7%	7.0E-02	0.3	5.2E-07			2.8E-06			5.1E-06		
		Rockfall - far field seismic trigger - 1/100 yr	0.01	100	10	0.1	100	1	0.01	2.4E-04	2.2E-03	0.0	Residential	Inside	80%	8.0E-01	0.1	1.9E-07	2.5E-07		9.7E-07	1.3E-06		1.7E-06	2.3E-06	
	3		0.01	100	10	0.1	100	1	0.01	2.4E-04	2.2E-03	0.2	Residential	Outside	10%	8.0E-02	0.3	5.8E-08			2.9E-07			5.2E-07		
	<1%		0.01	100	10	0.1	100	1	0.01	2.4E-04	2.2E-03	0.0	Industrial	Inside	27%	2.7E-01	0.1	6.6E-08		1.1E-07	3.3E-07		5.3E-07	5.9E-07		9.6E-07
			0.01	100	10	0.1	100	1	0.01	2.4E-04	2.2E-03	0.2	Industrial	Outside	7%	5.6E-02	0.3	4.1E-08			2.0E-07			3.7E-07		
		Rockfall - near field seismic trigger 1/500 yr	0.002	500	100	0.2	1000	2	0.01	2.2E-03	9.1E-03	0.0	Residential	Inside	80%	8.0E-01	0.1	3.5E-07	4.5E-07		9.1E-07	1.2E-06		1.5E-06	1.9E-06	
			0.002	500	100	0.2	1000	2	0.01	2.2E-03	9.1E-03	0.2	Residential	Outside	10%	8.0E-02	0.3	1.0E-07			2.7E-07			4.4E-07		
			0.002	500	100	0.2	1000	2	0.01	2.2E-03	9.1E-03	0.0	Industrial	Inside	27%	2.7E-01	0.1	1.2E-07		1.9E-07	3.1E-07		5.0E-07	4.9E-07		8.0E-07
			0.002	500	100	0.2	1000	2	0.01	2.2E-03	9.1E-03	0.2	Industrial	Outside	7%	5.6E-02	0.3	7.3E-08			1.9E-07			3.1E-07		
																		AIFR	**3.4E-06**	**1.5E-06**	**AIFR**	**1.7E-05**	**7.5E-06**	**AIFR**	**3.1E-05**	**1.3E-05**

Table I 1 - Combined Slope Stability AIFR for Brewery Creek Fan Residential Zone

				Debris Flow											
Rockfall	Zone			Zone 1			Zone 2			Zone 3			Zone 4		
				Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
				7.3×10^{-4}	3.1×10^{-3}	6.4×10^{-3}	1.4×10^{-4}	9.1×10^{-4}	2.0×10^{-3}	3.2×10^{-5}	9.6×10^{-5}	1.8×10^{-4}	1.5×10^{-6}	4.8×10^{-6}	9.3×10^{-6}
	1	Min	1.5×10^{-4}	8.7×10^{-4}			2.9×10^{-4}			1.8×10^{-4}			1.5×10^{-4}		
		Ave	7.4×10^{-4}		3.8×10^{-3}			1.6×10^{-3}			8.3×10^{-4}			7.4×10^{-4}	
		Max	1.3×10^{-3}			7.7×10^{-3}			3.3×10^{-3}			1.5×10^{-3}			1.3×10^{-3}
	2	Min	4.5×10^{-5}	7.7×10^{-4}			1.8×10^{-4}			7.7×10^{-5}			4.7×10^{-5}		
		Ave	2.3×10^{-4}		3.3×10^{-3}			1.1×10^{-3}			3.2×10^{-4}			2.3×10^{-4}	
		Max	4.1×10^{-4}			6.8×10^{-3}			2.4×10^{-3}			5.9×10^{-4}			4.2×10^{-4}
	3	Min	3.4×10^{-6}	7.3×10^{-4}			1.4×10^{-4}			3.5×10^{-5}			4.9×10^{-6}		
		Ave	1.7×10^{-5}		3.1×10^{-3}			9.3×10^{-4}			1.1×10^{-4}			2.2×10^{-5}	
		Max	3.1×10^{-5}			6.4×10^{-3}			2.0×10^{-3}			2.1×10^{-4}			4.0×10^{-5}

Table I 2 - Combined Slope Stability AIFR for Brewery Creek Fan Business Zone

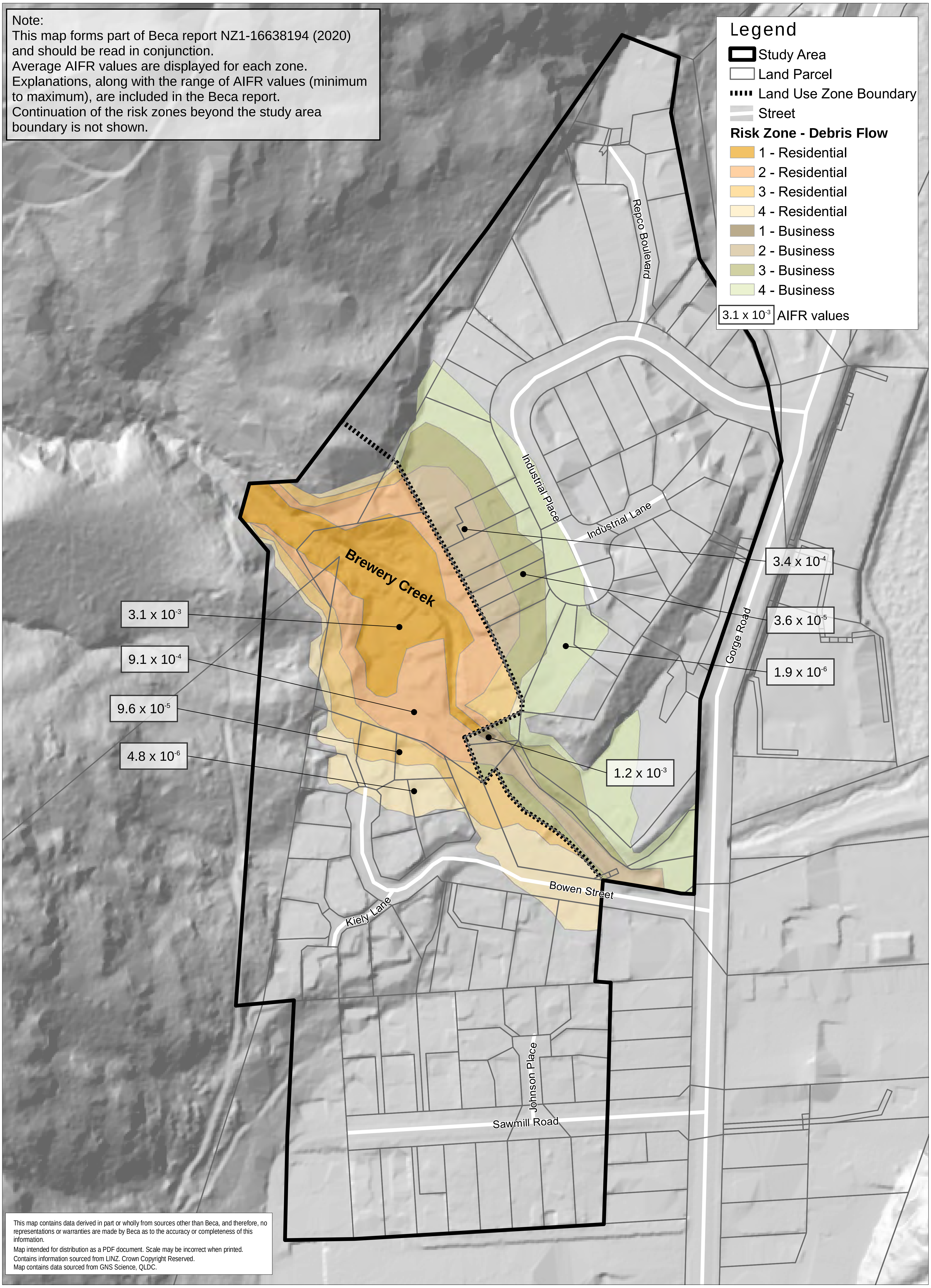
				Debris Flow											
Rockfall	Zone			Zone 1			Zone 2			Zone 3			Zone 4		
				Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
				$2.7x10^{-4}$	$1.2x10^{-3}$	$2.4x10^{-3}$	$5.2x10^{-5}$	$3.4x10^{-4}$	$7.4x10^{-4}$	$1.2x10^{-5}$	$3.6x10^{-5}$	$6.8x10^{-5}$	$6.0x10^{-7}$	$1.9x10^{-6}$	$3.7x10^{-6}$
	1	Min	$5.7x10^{-5}$							$6.9x10^{-5}$			$5.8x10^{-5}$		
		Ave	$2.9x10^{-4}$								$3.2x10^{-4}$			$2.9x10^{-4}$	
		Max	$5.2x10^{-4}$									$5.9x10^{-4}$			$5.2x10^{-4}$
	2	Min	$1.8x10^{-5}$				$7.5x10^{-5}$			$3.0x10^{-5}$			$1.9x10^{-5}$		
		Ave	$9.0x10^{-5}$					$4.3x10^{-4}$			$1.3x10^{-4}$			$9.2x10^{-5}$	
		Max	$1.6x10^{-4}$						$9.0x10^{-4}$			$2.3x10^{-4}$			$1.7x10^{-4}$
	3	Min	$1.5x10^{-6}$				$5.3x10^{-5}$			$1.3x10^{-5}$			$2.1x10^{-6}$		
		Ave	$7.5x10^{-6}$					$3.5x10^{-4}$			$4.4x10^{-5}$			$9.4x10^{-6}$	
		Max	$1.3x10^{-5}$						$7.6x10^{-4}$			$8.1x10^{-5}$			$1.7x10^{-5}$

Table I 3 - Combined Slope Stability AIFR for Reavers Fan

				Debris Flow											
	Zone			Zone 1			Zone 2			Zone 3			Zone 4		
				Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
				1.3×10^{-4}	1.0×10^{-3}	2.3×10^{-3}	6.2×10^{-5}	1.4×10^{-4}	2.5×10^{-4}	1.8×10^{-5}	4.5×10^{-5}	7.6×10^{-5}	8.6×10^{-7}	2.2×10^{-6}	3.9×10^{-6}
Rockfall	1	Min	1.5×10^{-4}	2.8×10^{-4}			2.1×10^{-4}			1.7×10^{-4}			1.5×10^{-4}		
		Ave	7.4×10^{-4}		1.8×10^{-3}			8.8×10^{-4}			7.8×10^{-4}			7.4×10^{-4}	
		Max	1.3×10^{-3}			3.7×10^{-3}			1.6×10^{-3}			1.4×10^{-3}			1.3×10^{-3}
	2	Min	4.5×10^{-5}	1.7×10^{-4}			1.1×10^{-4}			6.3×10^{-5}			4.6×10^{-5}		
		Ave	2.3×10^{-4}		1.2×10^{-3}			3.7×10^{-4}			2.7×10^{-4}			2.3×10^{-4}	
		Max	4.1×10^{-4}			2.7×10^{-3}			6.6×10^{-4}			4.8×10^{-4}			4.1×10^{-4}
	3	Min	3.4×10^{-6}	1.3×10^{-4}			6.6×10^{-5}			2.1×10^{-5}			4.3×10^{-6}		
		Ave	1.7×10^{-5}		1.0×10^{-3}			1.6×10^{-4}			6.1×10^{-5}			1.9×10^{-5}	
		Max	3.1×10^{-5}			2.3×10^{-3}			2.8×10^{-4}			1.1×10^{-4}			3.5×10^{-5}

J

Appendix J – Slope Stability Life Risk Maps



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Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:
Debris Flow Life Risk Zones
Brewery Creek Fan
Forested Source Area

Client: Queenstown Lakes District Council

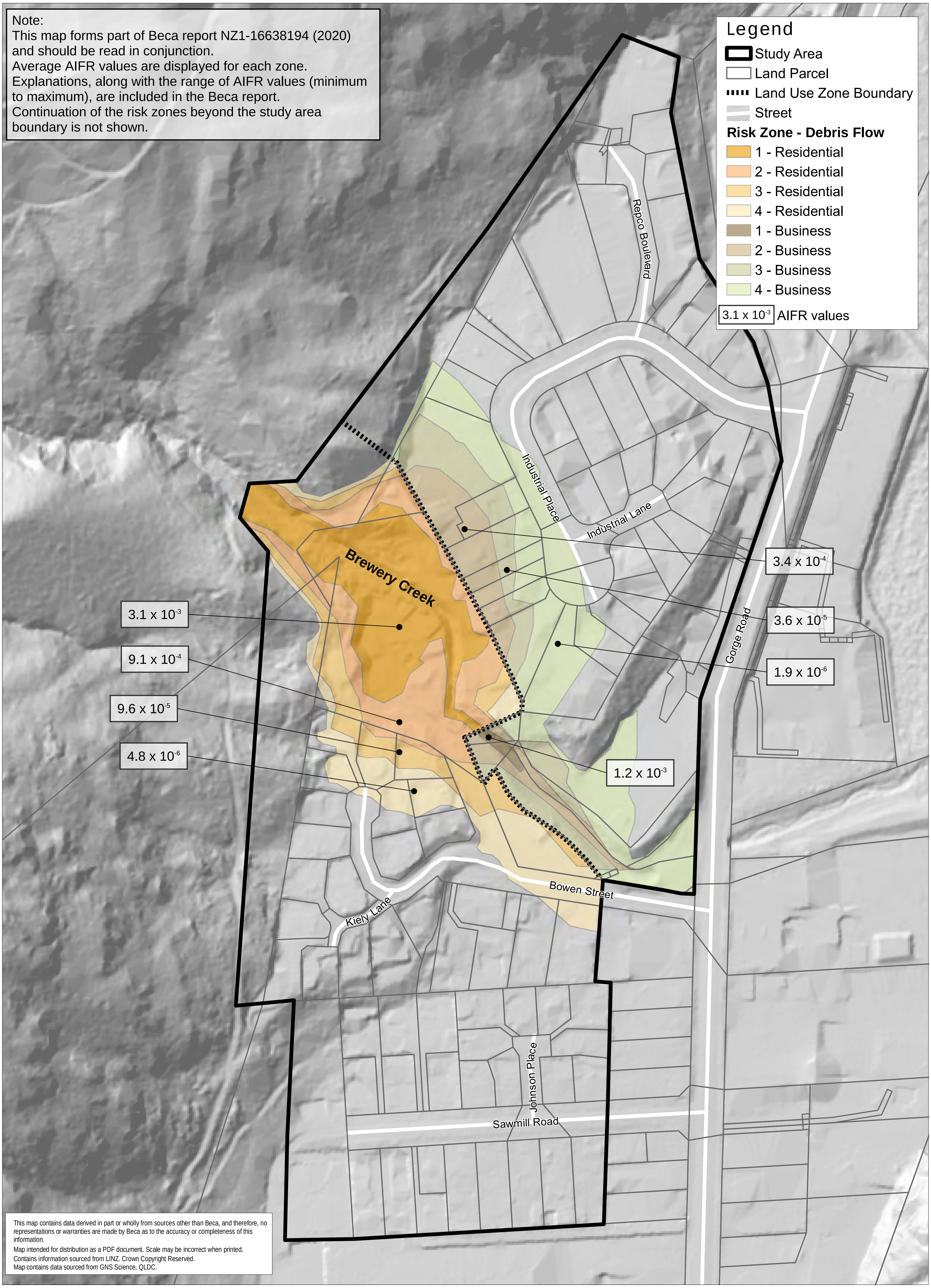
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-J001



Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:

Debris Flow Life Risk Zones

Brewery Creek Fan
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

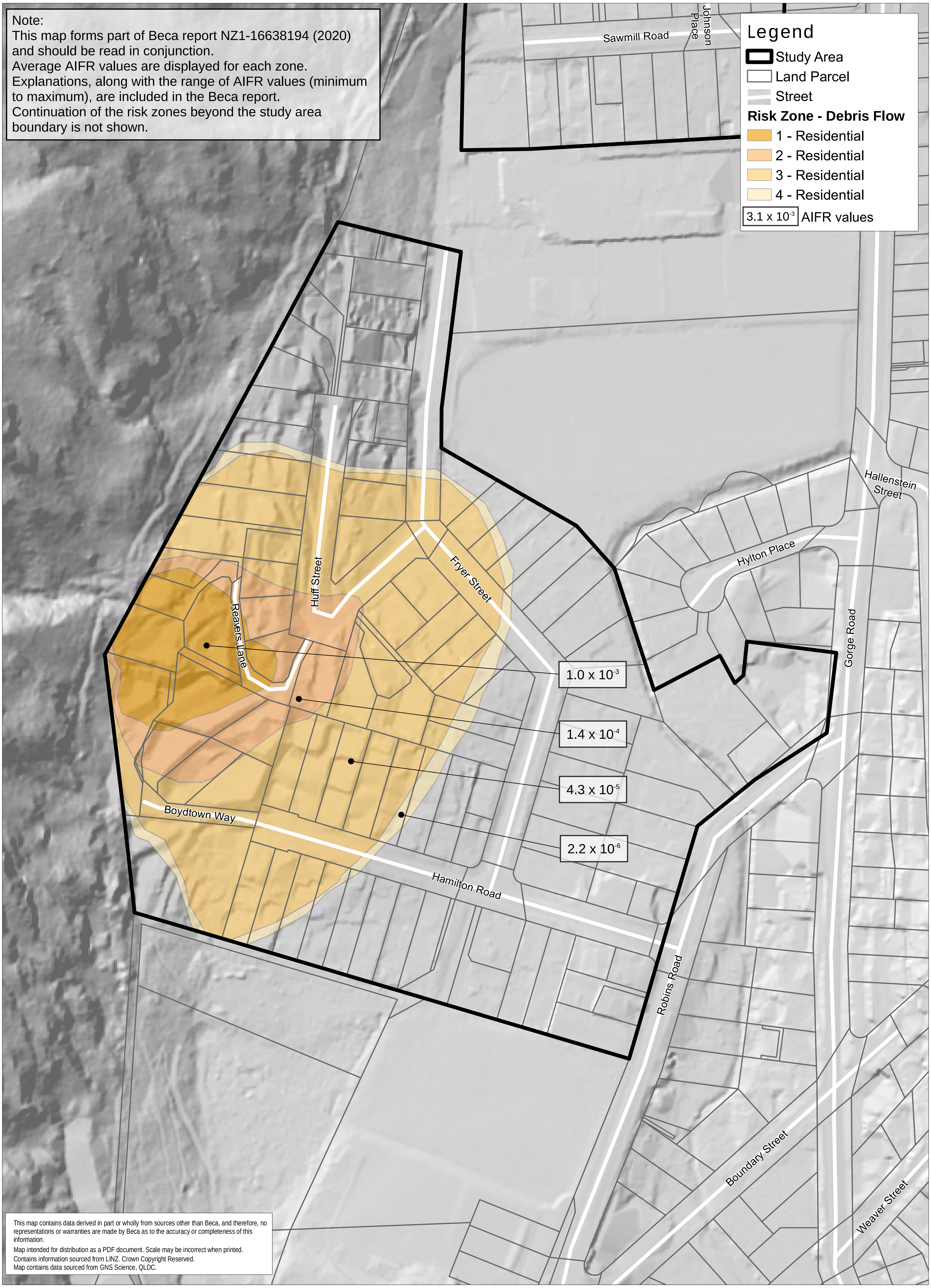
N

Beca

Discipline: GIS

Drawing No: 3209881-J002

File: \\beca.net\projects\32\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J002.mxd Author: SHB Date: 31/08/2020



Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:

Debris Flow Life Risk Zones

Reavers Fan

Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

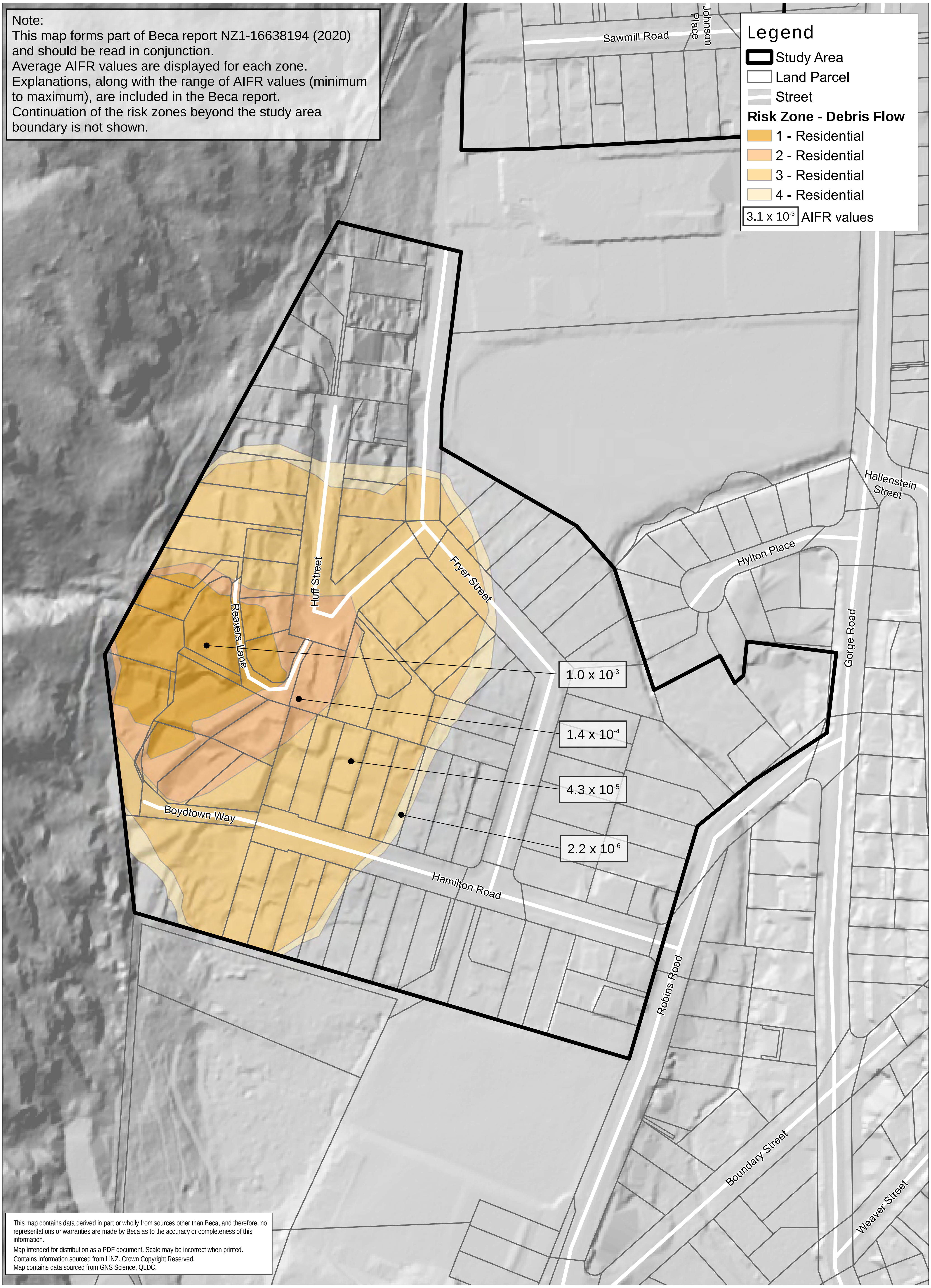
N

Beca

Discipline: GIS

Drawing No: 3209881-J003

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.



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Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:
Debris Flow Life Risk Zones
Reavers Fan
Non-Forested Source Area

Client: Queenstown Lakes District Council
Project: Natural Hazards Affecting Gorge Road
Discipline: GIS
Drawing No: 3209881-J004
Beca

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Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
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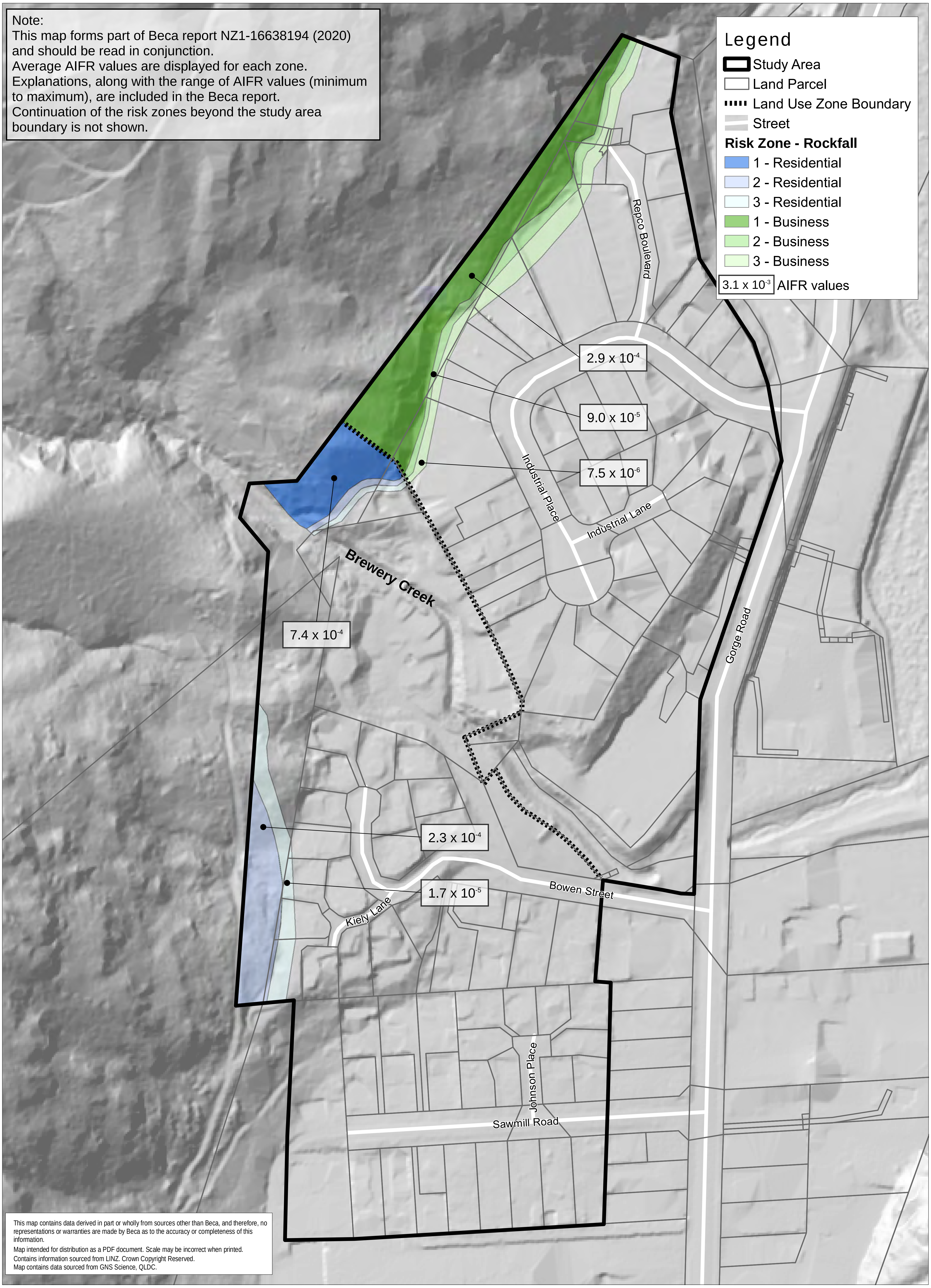
Continuation of the risk zones beyond the study area boundary is not shown.



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Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:
Rockfall Life Risk Zones
Brewery Creek Fan
Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

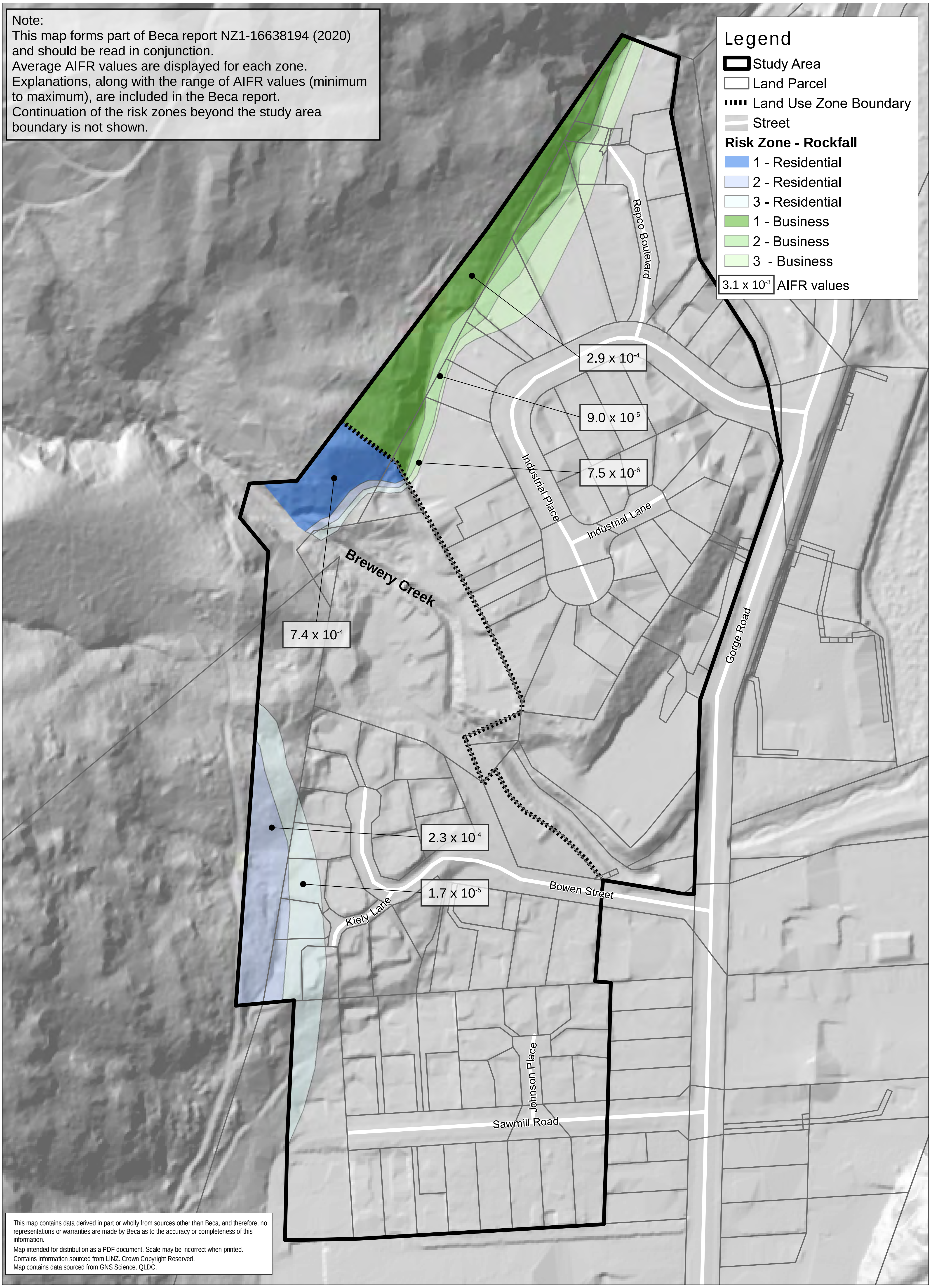
N

Beca

Discipline: GIS

Drawing No: 3209881-J005

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.



Map Scale @ A3: 1:2,000

0 40 80
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:
Rockfall Life Risk Zones
Brewery Creek Fan
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

Discipline: GIS

Drawing No: 3209881-J006

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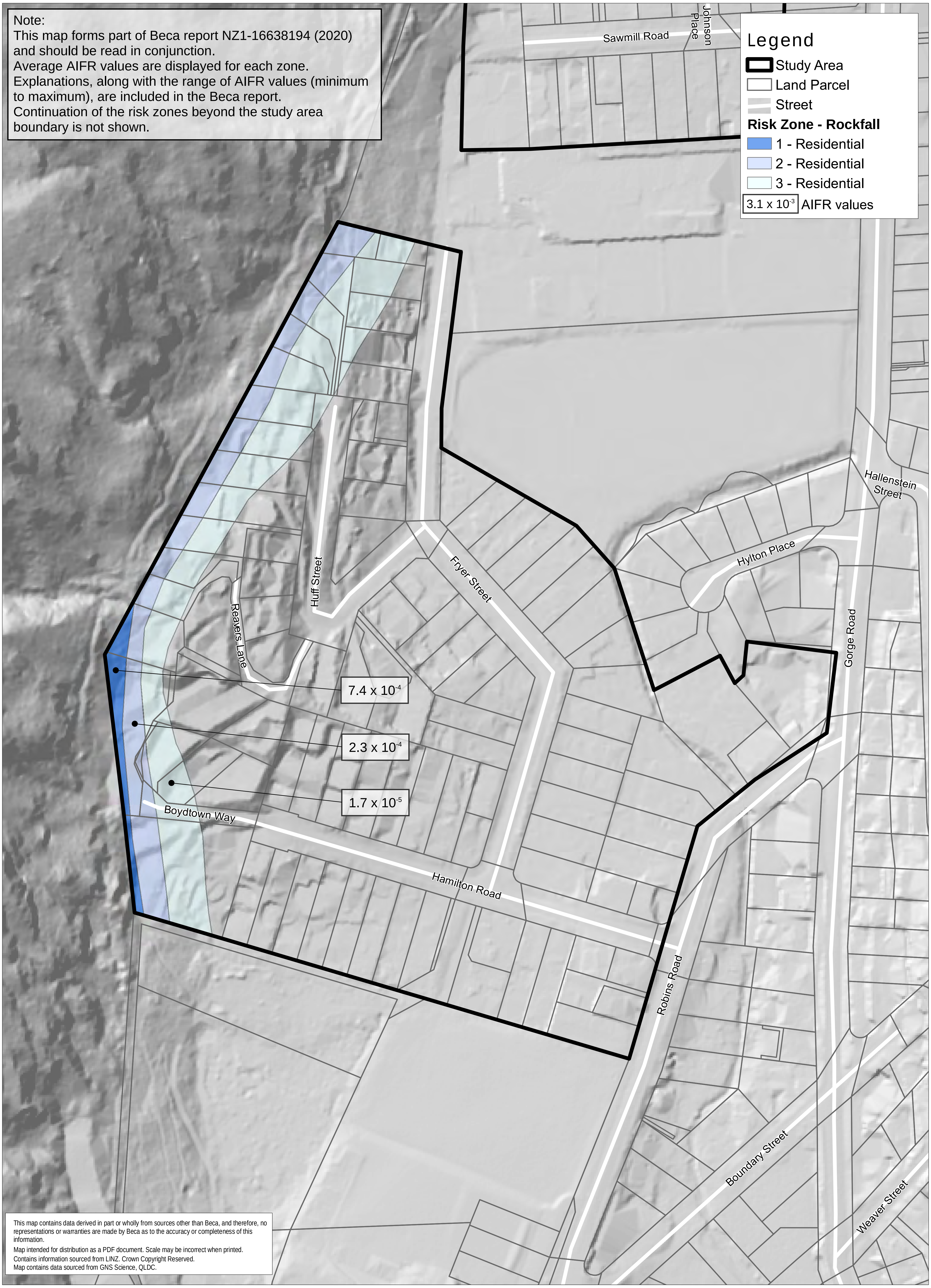
GIS@beca.com



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Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:
Rockfall Life Risk Zones
Reavers Fan
Forested Source Area

Client: Queenstown Lakes District Council

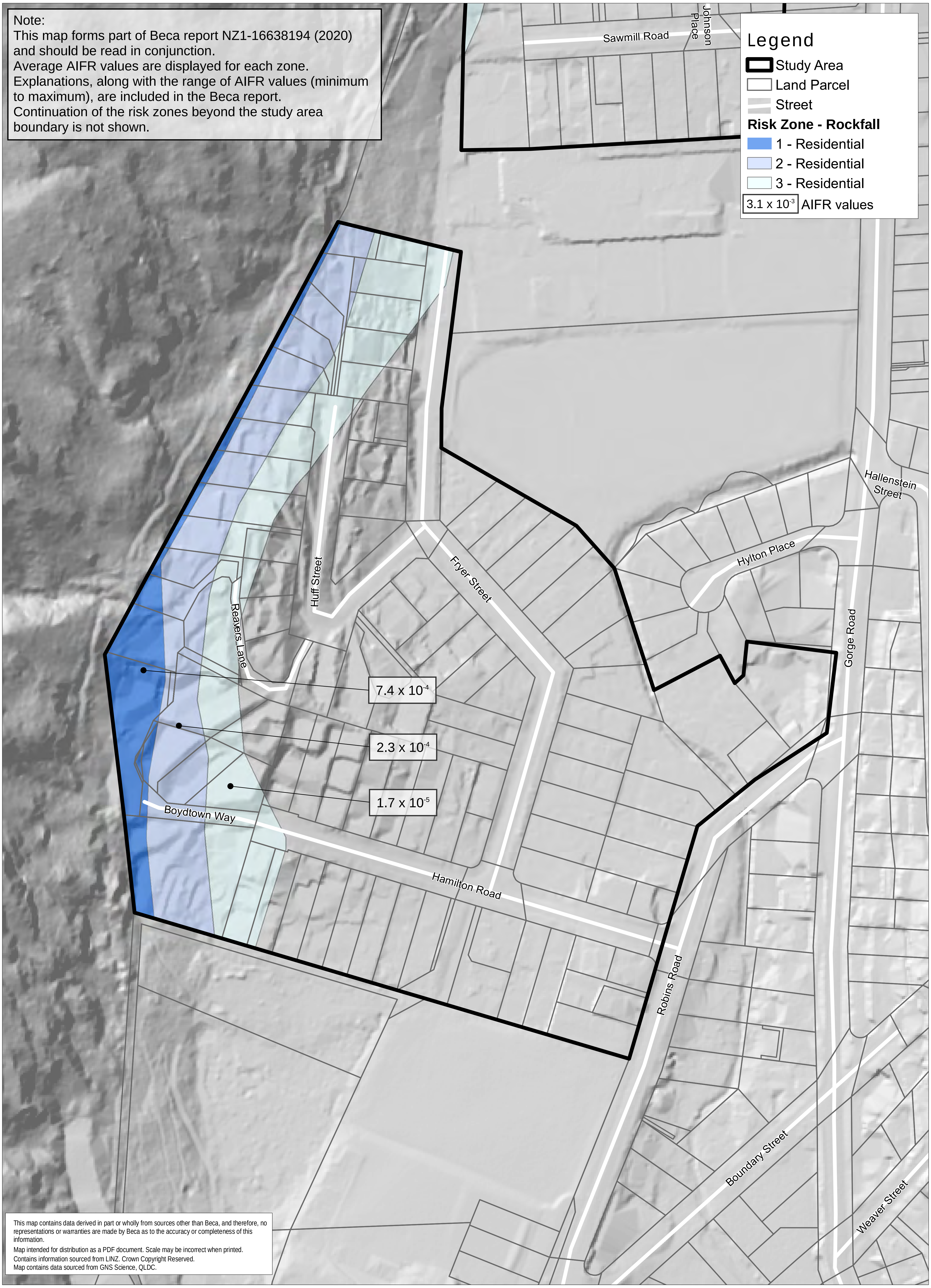
Project: Natural Hazards Affecting Gorge Road

Beca

Discipline: GIS

Drawing No: 3209881-J007

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.



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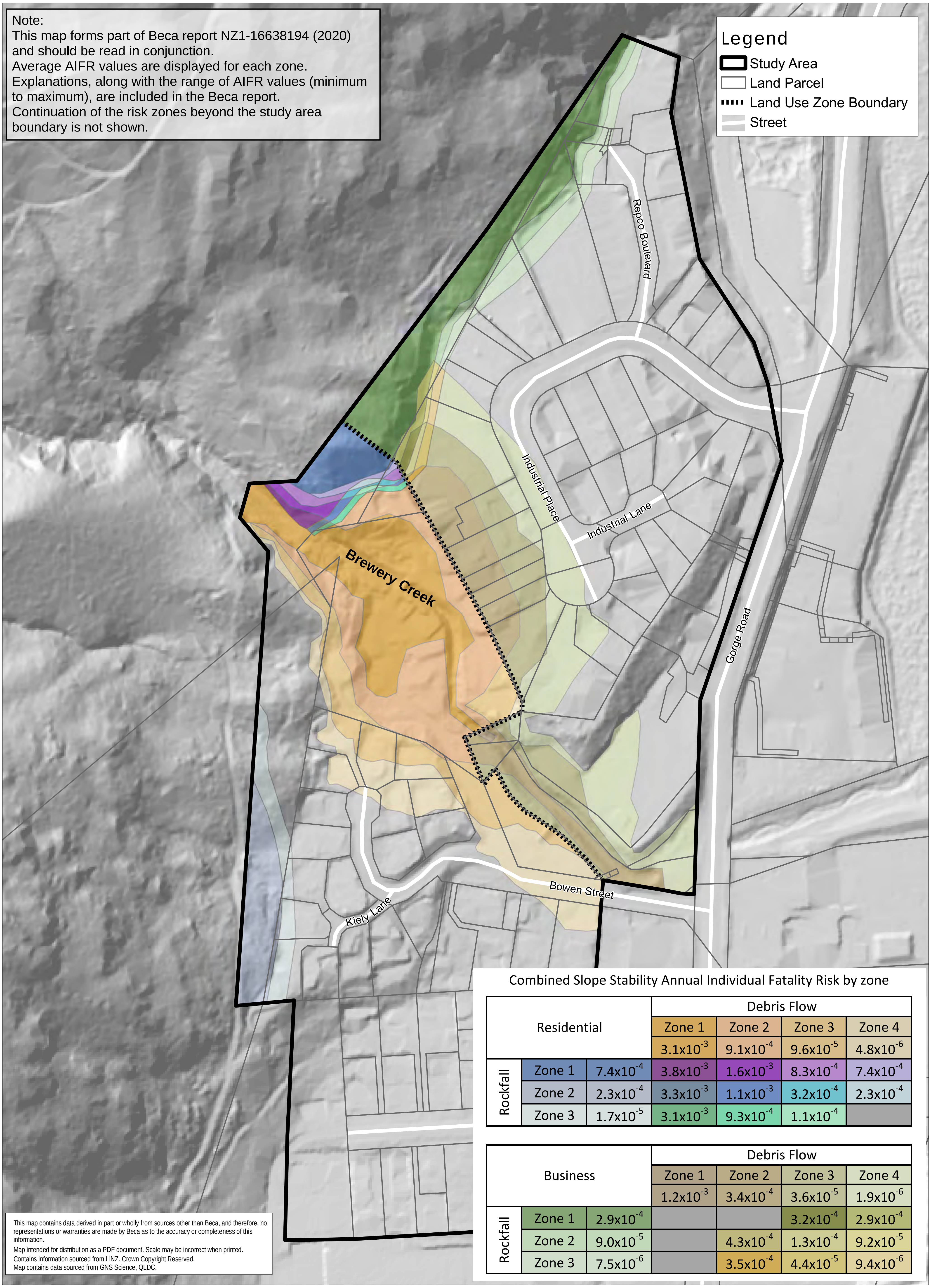
File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J008.mxd Author: SHB Date: 7/09/2020

Map Scale @ A3: 1:2,000	Revision	Author	Verified	Approved	Date	Title:	Client:		Discipline:
0 40 80 Metres	1	SB	AP	PH	04/09/2020	Rockfall Life Risk Zones Reavers Fan Non-Forested Source Area	Queenstown Lakes District Council	N	GIS
							Project: Natural Hazards Affecting Gorge Road	Beca	Drawing No: 3209881-J008



Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.

Legend
- Study Area
- Land Parcel
- Land Use Zone Boundary
- Street

Combined Slope Stability Annual Individual Fatality Risk by zone

Residential			Debris Flow Zone 1	Debris Flow Zone 2	Debris Flow Zone 3	Debris Flow Zone 4
			$3.1x10^{-3}$	$9.1x10^{-4}$	$9.6x10^{-5}$	$4.8x10^{-6}$
Rockfall	Zone 1	$7.4x10^{-4}$	$3.8x10^{-3}$	$1.6x10^{-3}$	$8.3x10^{-4}$	$7.4x10^{-4}$
Rockfall	Zone 2	$2.3x10^{-4}$	$3.3x10^{-3}$	$1.1x10^{-3}$	$3.2x10^{-4}$	$2.3x10^{-4}$
Rockfall	Zone 3	$1.7x10^{-5}$	$3.1x10^{-3}$	$9.3x10^{-4}$	$1.1x10^{-4}$	

Business			Debris Flow Zone 1	Debris Flow Zone 2	Debris Flow Zone 3	Debris Flow Zone 4
			$1.2x10^{-3}$	$3.4x10^{-4}$	$3.6x10^{-5}$	$1.9x10^{-6}$
Rockfall	Zone 1	$2.9x10^{-4}$			$3.2x10^{-4}$	$2.9x10^{-4}$
Rockfall	Zone 2	$9.0x10^{-5}$		$4.3x10^{-4}$	$1.3x10^{-4}$	$9.2x10^{-5}$
Rockfall	Zone 3	$7.5x10^{-6}$		$3.5x10^{-4}$	$4.4x10^{-5}$	$9.4x10^{-6}$

File: \\beca.net\projects\32\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J009.mxd Author: SHB Date: 7/09/2020

Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
2	SB	AP	PH	11/11/2020
1	SB	AP	PH	04/09/2020

Title: Combined Slope Stability Life Risk
Brewery Creek Fan
Forested Source Area

Client: Queenstown Lakes District Council

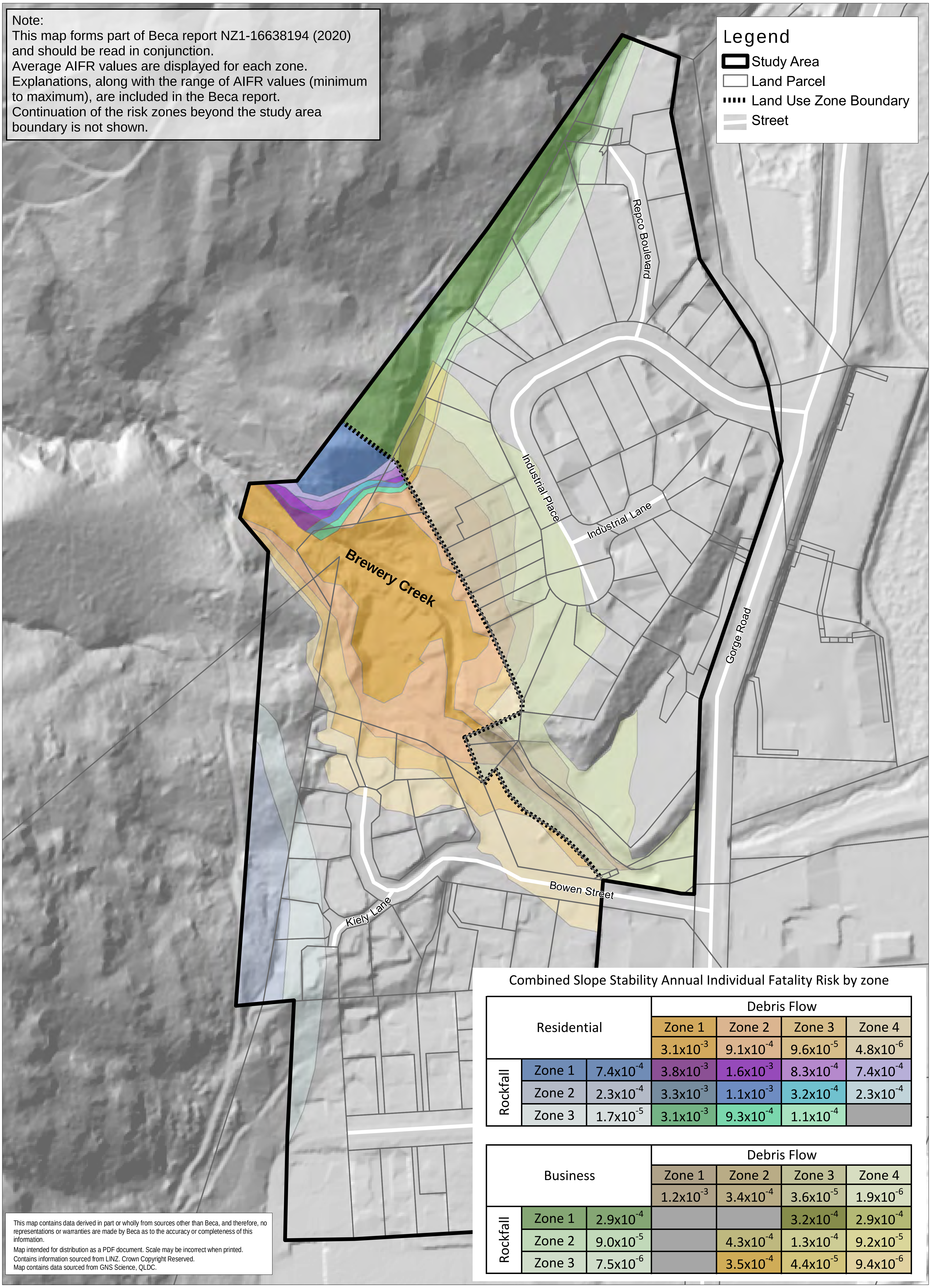
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-J009



Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.

Combined Slope Stability Annual Individual Fatality Risk by zone

Residential			Debris Flow Zone 1	Debris Flow Zone 2	Debris Flow Zone 3	Debris Flow Zone 4
			3.1×10^{-3}	9.1×10^{-4}	9.6×10^{-5}	4.8×10^{-6}
Rockfall	Zone 1	7.4×10^{-4}	3.8×10^{-3}	1.6×10^{-3}	8.3×10^{-4}	7.4×10^{-4}
Rockfall	Zone 2	2.3×10^{-4}	3.3×10^{-3}	1.1×10^{-3}	3.2×10^{-4}	2.3×10^{-4}
Rockfall	Zone 3	1.7×10^{-5}	3.1×10^{-3}	9.3×10^{-4}	1.1×10^{-4}	

Business			Debris Flow Zone 1	Debris Flow Zone 2	Debris Flow Zone 3	Debris Flow Zone 4
			1.2×10^{-3}	3.4×10^{-4}	3.6×10^{-5}	1.9×10^{-6}
Rockfall	Zone 1	2.9×10^{-4}			3.2×10^{-4}	2.9×10^{-4}
Rockfall	Zone 2	9.0×10^{-5}		4.3×10^{-4}	1.3×10^{-4}	9.2×10^{-5}
Rockfall	Zone 3	7.5×10^{-6}		3.5×10^{-4}	4.4×10^{-5}	9.4×10^{-6}

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File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J010.mxd Author: SHB Date: 7/09/2020

Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
2	SB	AP	PH	11/11/2020
1	SB	AP	PH	04/09/2020

Title: Combined Slope Stability Life Risk
Brewery Creek Fan
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

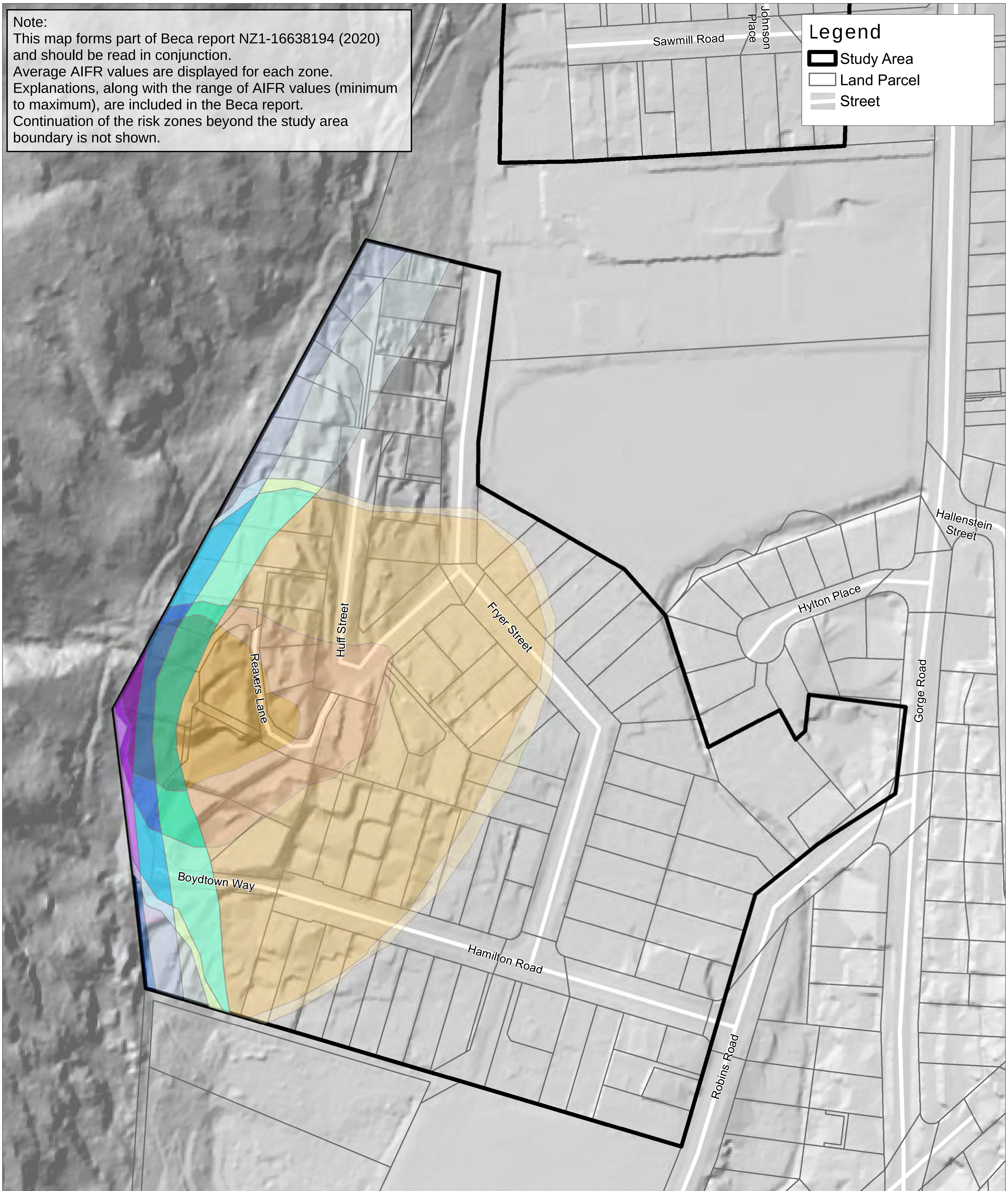
Beca

Discipline: GIS

Drawing No: 3209881-J010

GIS@beca.com

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.



Combined Slope Stability Annual Individual Fatality Risk by zone

Residential			Debris Flow Zone 1	Debris Flow Zone 2	Debris Flow Zone 3	Debris Flow Zone 4
			$1.0x10^{-3}$	$1.4x10^{-4}$	$4.3x10^{-5}$	$2.2x10^{-6}$
Rockfall	Zone 1	$7.4x10^{-4}$	$1.8x10^{-3}$	$8.8x10^{-4}$	$7.8x10^{-4}$	$7.4x10^{-4}$
Rockfall	Zone 2	$2.3x10^{-4}$	$1.2x10^{-3}$	$3.7x10^{-4}$	$2.7x10^{-4}$	$2.3x10^{-4}$
Rockfall	Zone 3	$1.7x10^{-5}$	$1.0x10^{-3}$	$1.6x10^{-4}$	$6.1x10^{-5}$	$1.9x10^{-5}$

File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J011.mxd Author: SHB Date: 7/09/2020

Map Scale @ A3: 1:2,000

0 40 80
Metres

Revision	Author	Verified	Approved	Date
2	SB	AP	PH	11/11/2020
1	SB	AP	PH	04/09/2020

Title: Combined Slope Stability Life Risk
Reavers Fan
Forested Source Area

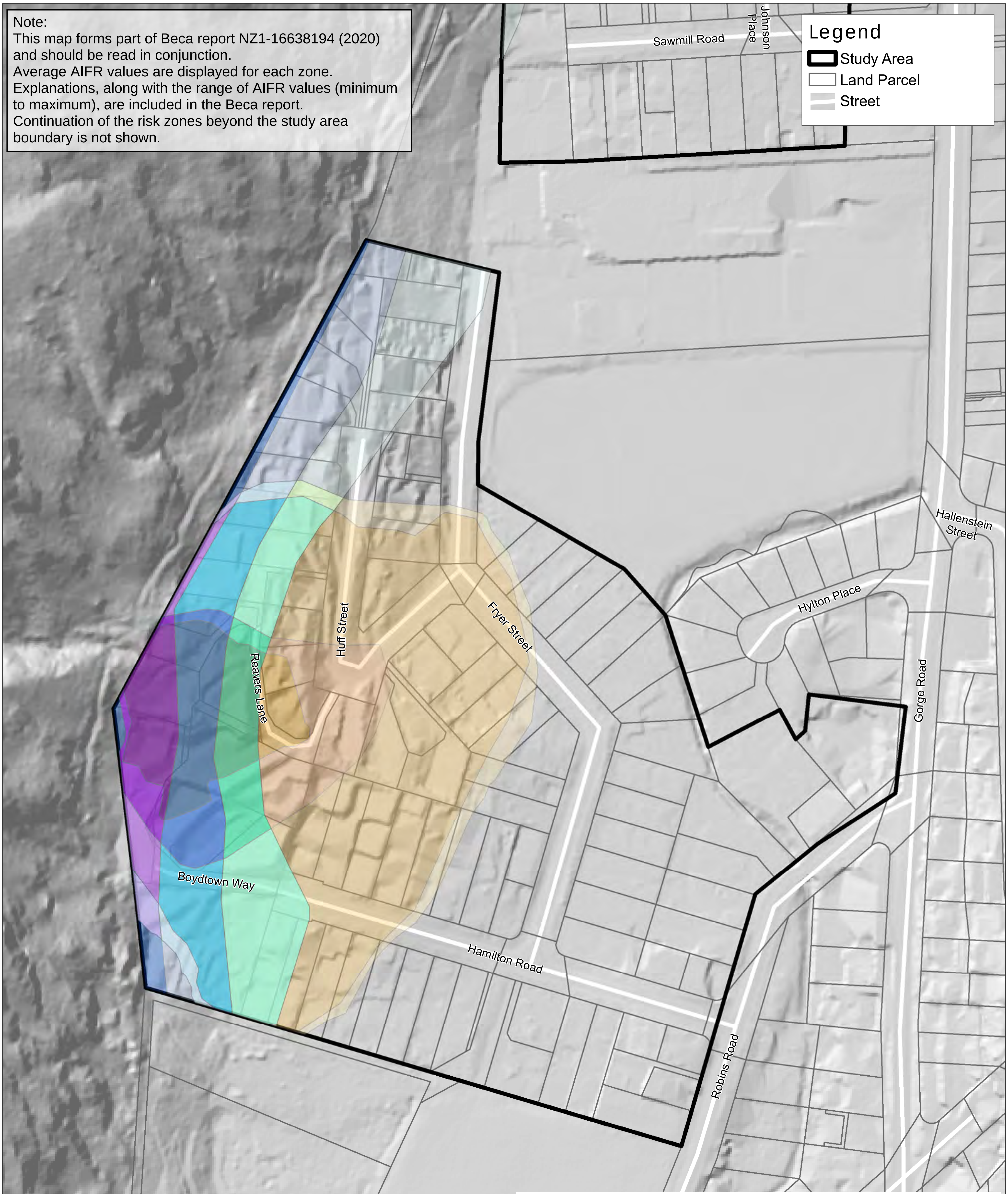
Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

Discipline: GIS

Drawing No: 3209881-J011

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR values are displayed for each zone.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.
Continuation of the risk zones beyond the study area boundary is not shown.



Combined Slope Stability Annual Individual Fatality Risk by zone

Residential			Debris Flow Zone 1	Debris Flow Zone 2	Debris Flow Zone 3	Debris Flow Zone 4
			1.0×10^{-3}	1.4×10^{-4}	4.3×10^{-5}	2.2×10^{-6}
Rockfall	Zone 1	7.4×10^{-4}	1.8×10^{-3}	8.8×10^{-4}	7.8×10^{-4}	7.4×10^{-4}
Rockfall	Zone 2	2.3×10^{-4}	1.2×10^{-3}	3.7×10^{-4}	2.7×10^{-4}	2.3×10^{-4}
Rockfall	Zone 3	1.7×10^{-5}	1.0×10^{-3}	1.6×10^{-4}	6.1×10^{-5}	1.9×10^{-5}

File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J012.mxd Author: SHB Date: 7/09/2020

Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
2	SB	AP	PH	11/11/2020
1	SB	AP	PH	04/09/2020

Title: Combined Slope Stability Life Risk
Reavers Fan
Non-Forested Source Area

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

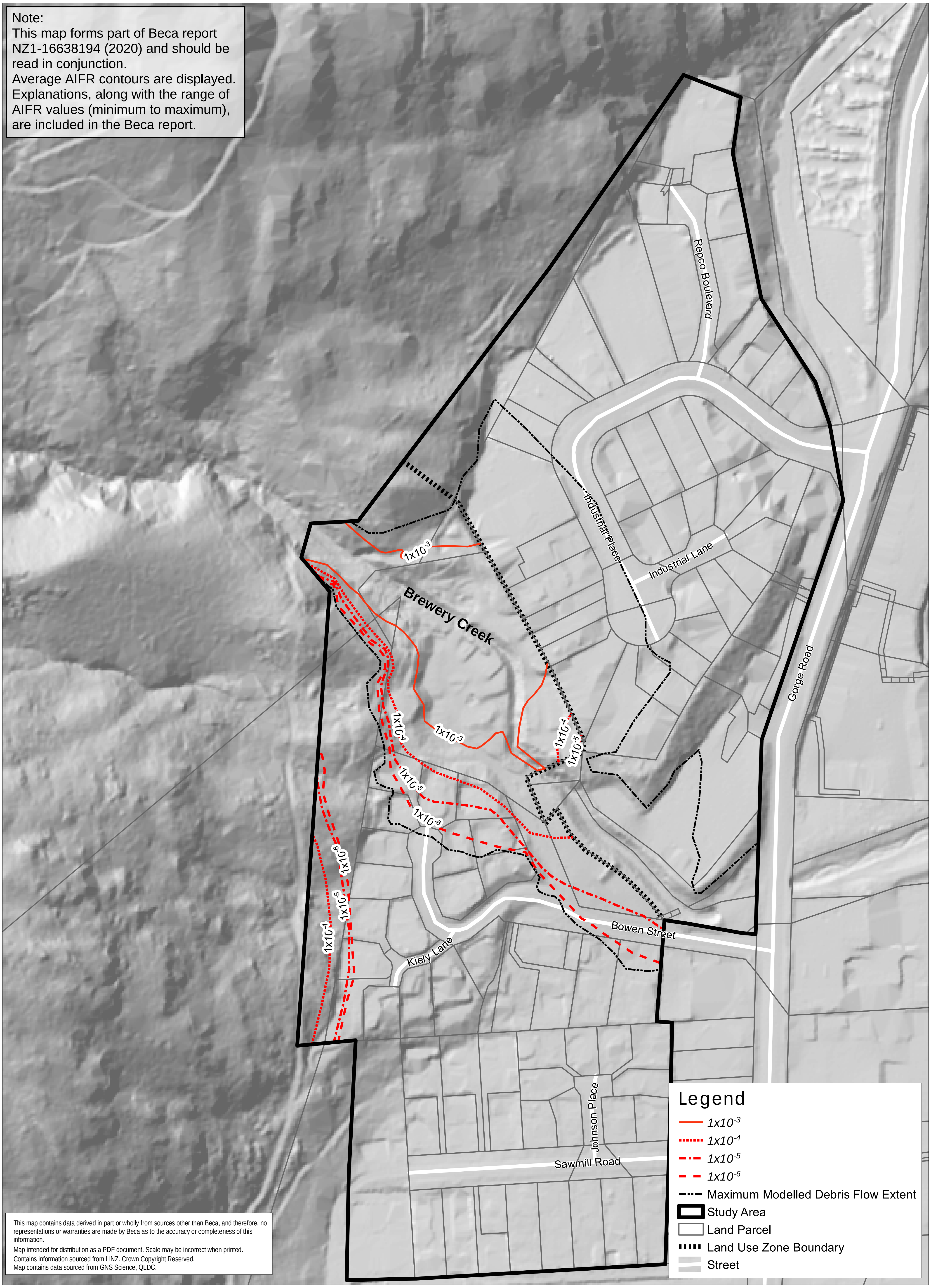
N

Beca

Discipline: GIS

Drawing No: 3209881-J012

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR contours are displayed.
Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.



Map Scale @ A3: 1:2,000

0 40 80
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:
Slope Stability Annual Individual Life Risk Contours
Brewery Creek Fan Residential Zone

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

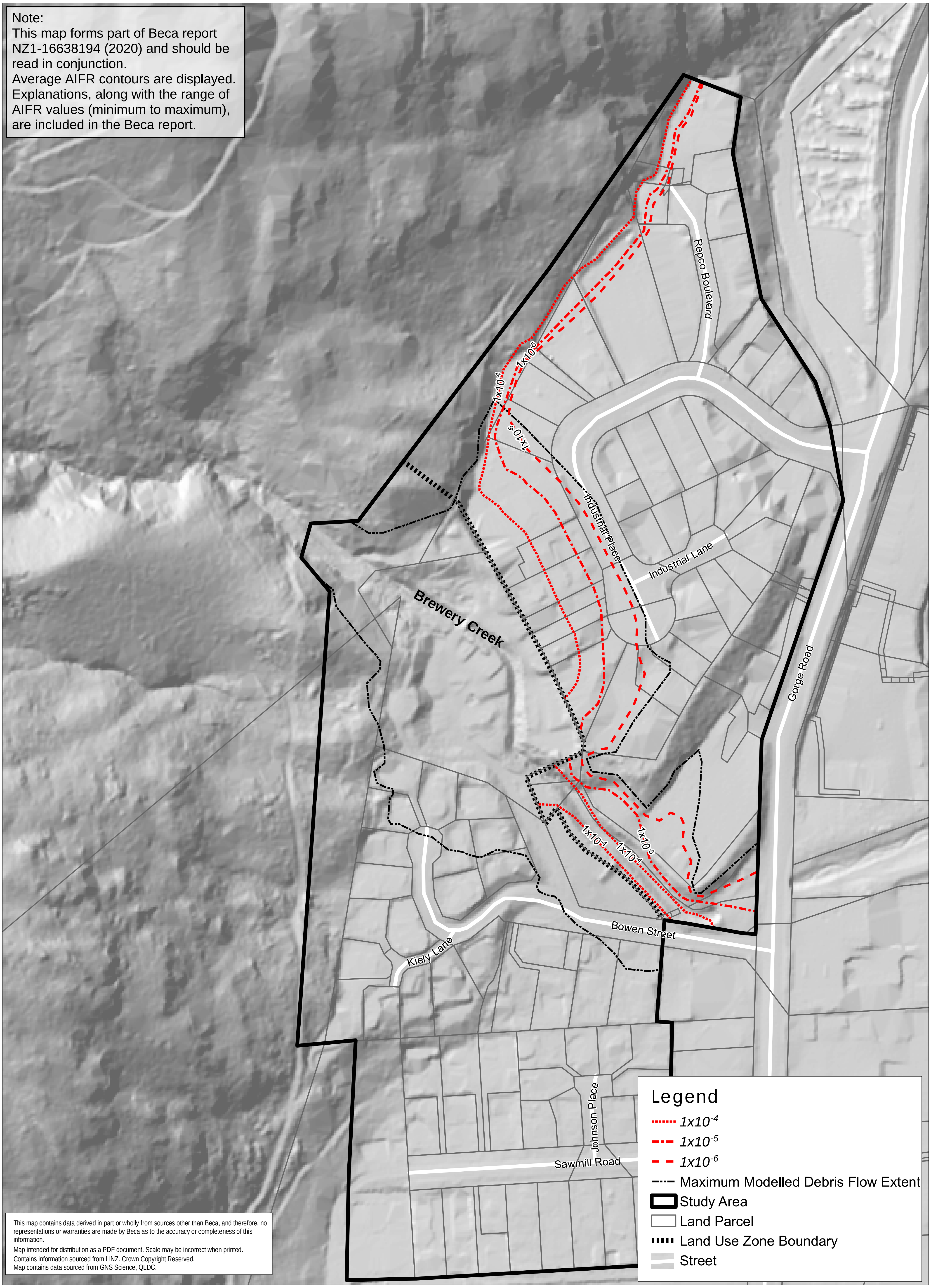
Beca

Discipline: GIS

Drawing No: 3209881-J013

File: \\beca.net\projects\32\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J013.mxd Author: SHB Date: 9/09/2020
GIS@beca.com

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR contours are displayed. Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.



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File: \\beca.net\projects\3209881\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J014.mxd Author: SHB Date: 9/09/2020

Map Scale @ A3: 1:2,000
0 40 80
Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title: Slope Stability Annual Individual Life Risk Contours
Brewery Creek Fan Business Zone

Client: Queenstown Lakes District Council

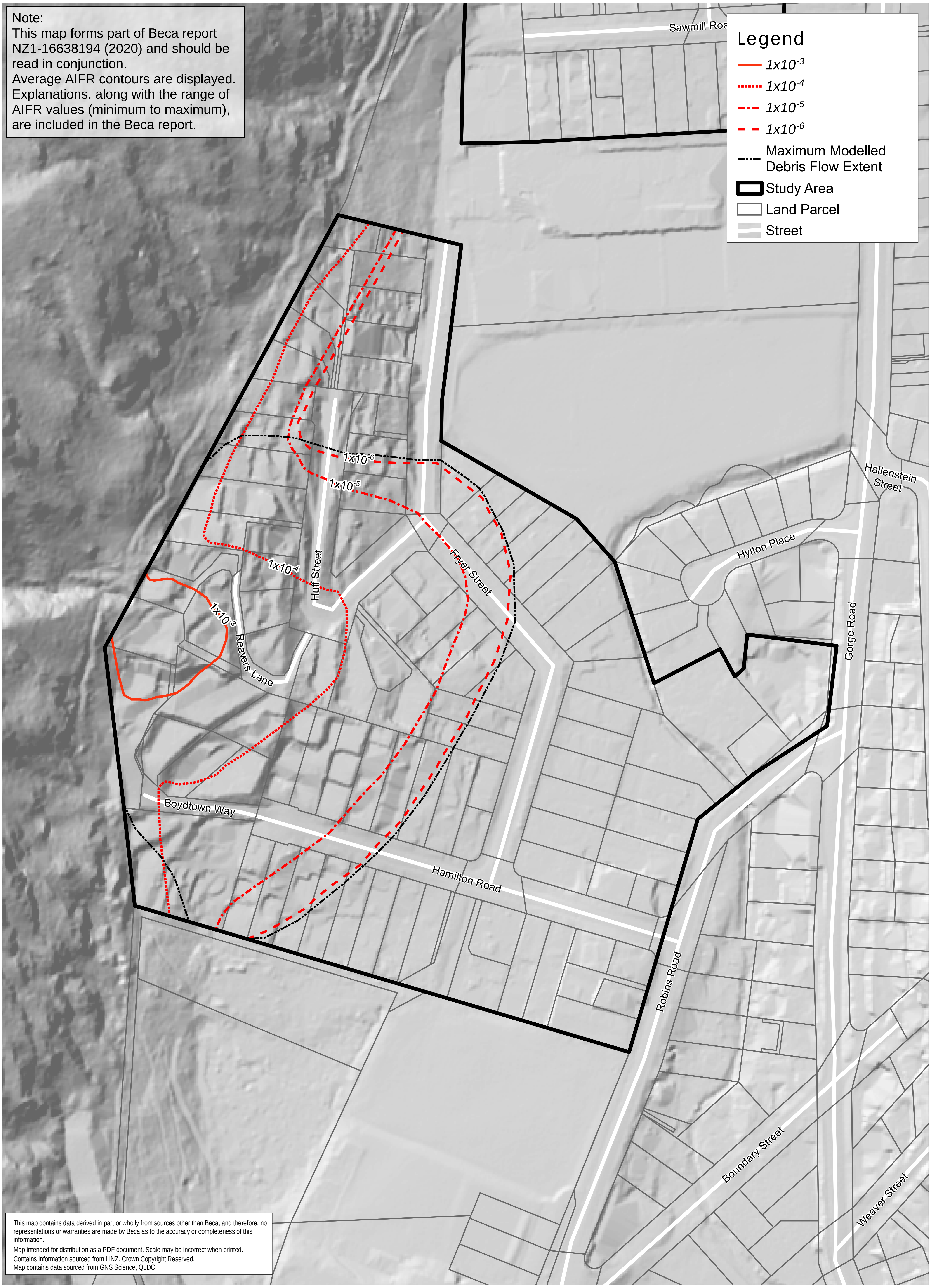
Project: Natural Hazards Affecting Gorge Road

Beca

Discipline: GIS

Drawing No: 3209881-J014

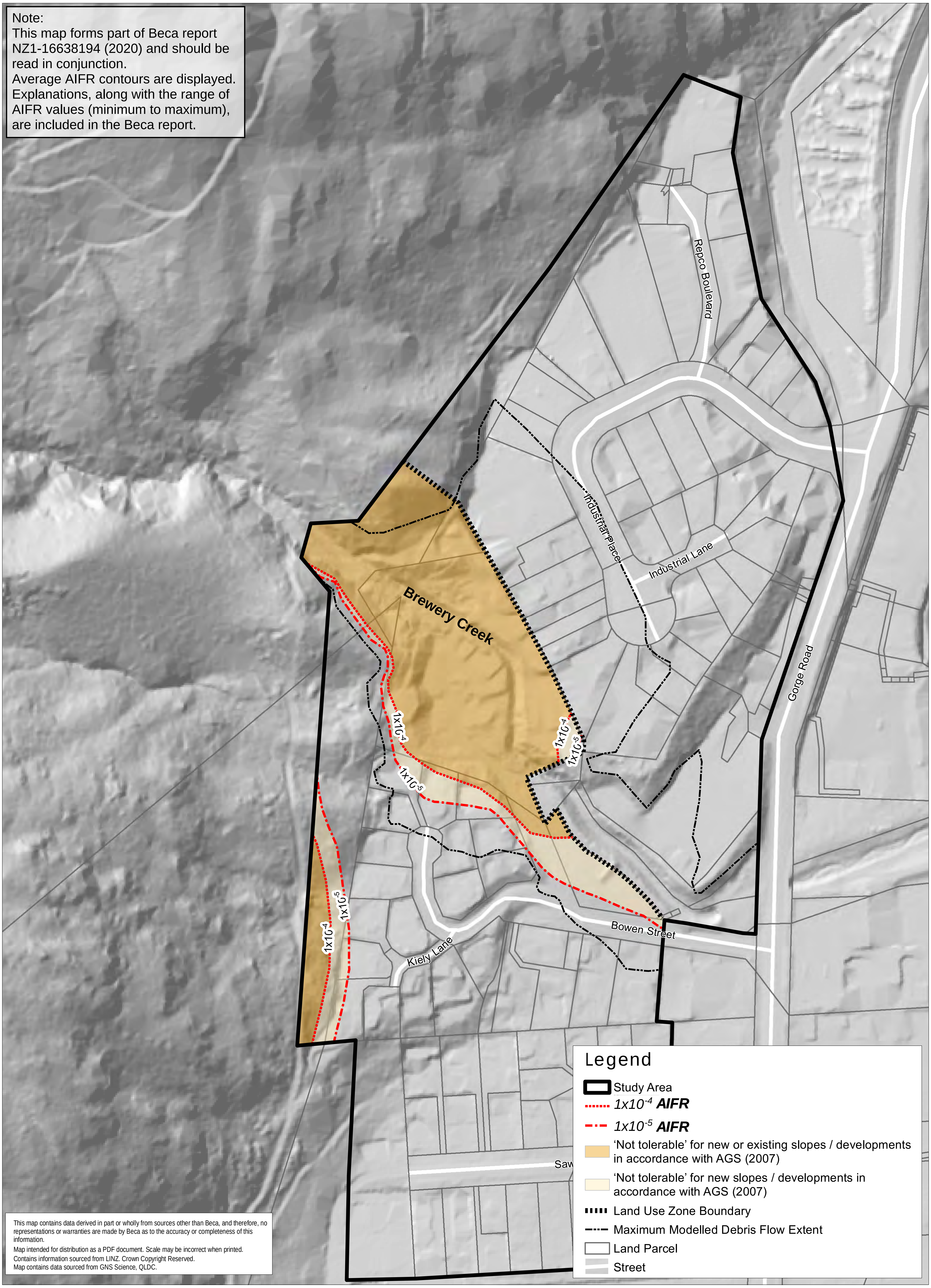
Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR contours are displayed. Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.



GIS@beca.com

File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J015.mxd Author: SHB Date: 9/09/2020

Map Scale @ A3: 1:2,000	Revision	Author	Verified	Approved	Date	Title:	Client:		Discipline:
0 40 80 Metres	1	SB	AP	PH	04/09/2020	Slope Stability Annual Individual Life Risk Contours Reavers Fan	Queenstown Lakes District Council	N	GIS
							Project: Natural Hazards Affecting Gorge Road	Beca	Drawing No: 3209881-J015



GIS@beca.com

File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J016.mxd   Author: SHB   Date: 12/11/2020

Map Scale @ A3: 1:2,000 (0 – 40 – 80 Metres)	Revision	Author	Verified	Approved	Date
	1	SB	AP	PH	12/11/2020

Title: **Slope Stability Annual Individual Fatality Risk Tolerability Brewery Creek Fan Residential Zone**

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

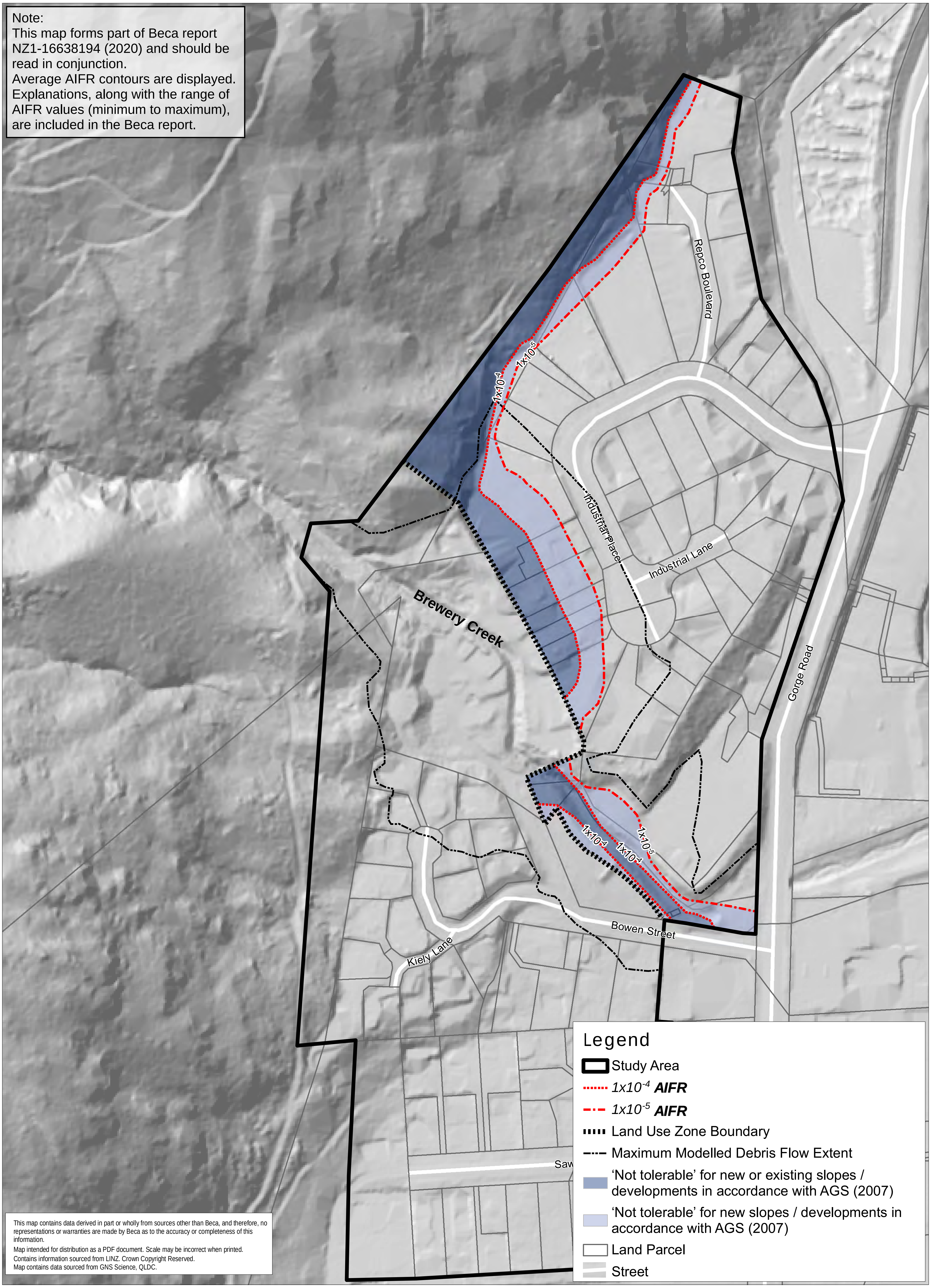
N

Beca

Discipline: GIS

Drawing No: 3209881-J016

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average AIFR contours are displayed. Explanations, along with the range of AIFR values (minimum to maximum), are included in the Beca report.



Legend

- Study Area
- $1x10^{-4}$ **AIFR**
- $1x10^{-5}$ **AIFR**
- Land Use Zone Boundary
- Maximum Modelled Debris Flow Extent
- 'Not tolerable' for new or existing slopes / developments in accordance with AGS (2007)
- 'Not tolerable' for new slopes / developments in accordance with AGS (2007)
- Land Parcel
- Street

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File: \\beca.net\projects\32\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix J\3209881-J017.mxd Author: SHB Date: 12/11/2020

Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	12/11/2020

Title:
Slope Stability Annual Individual Fatality Risk Tolerability
Brewery Creek Fan Business Zone

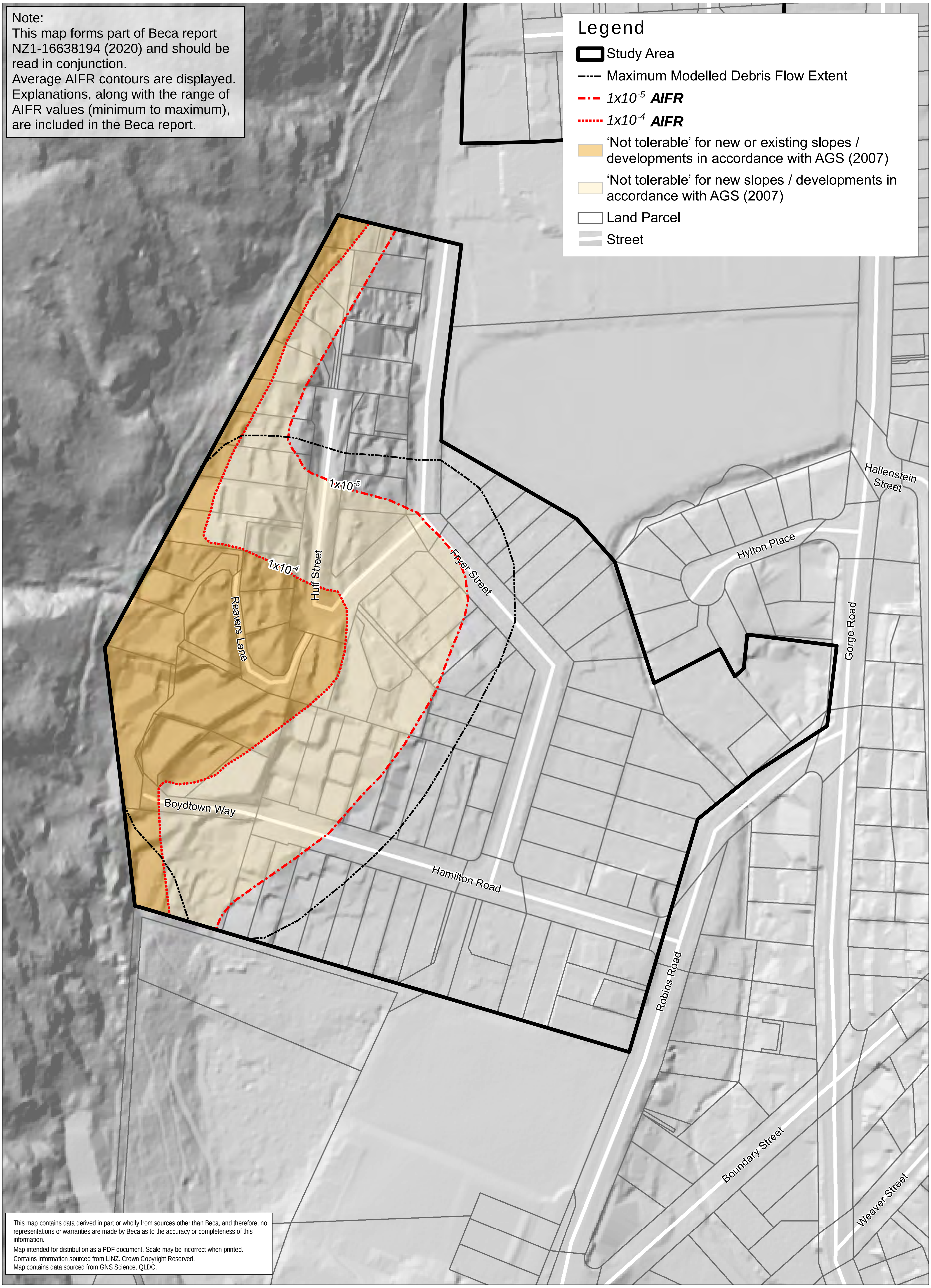
Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Discipline: GIS

Drawing No: 3209881-J017



File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendices\Revised\Appendix J\3209881-J018.mxd Author: SHB Date: 12/11/2020 GIS@beca.com

Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	12/11/2020

Title: Slope Stability Annual Individual Fatality Risk Tolerability Reavers Fan

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

Discipline: GIS

Drawing No: 3209881-J018

K

Appendix K – Property Risk Vulnerability Methodology (GNS)

Method for determining loss ratios

GNS Science used RiskScape Version 2.0 to calculate loss ratios for hypothetical buildings located on a 1 m x 1 m grid impacted by debris flow and rock fall across the Reavers and Brewery Road alluvial fans in Queenstown. The analysis used hazard layers provided by BECA to GNS Science. The loss ratio (also referred to as damage ratio) is a number between 0 and 1 inclusive that represents the ratio of repair cost to replacement cost if a building is impacted by the given hazard intensity. A value of 0 means no damage, and a value of 1.0 is complete damage. If the financial loss is required, the loss ratio is multiplied by the replacement cost of a building. The grid of loss ratios represent hypothetical buildings located in each 1 m x 1 m grid cell.

RiskScape Version 2.0 engine was used to calculate the loss ratios. Within the RiskScape engine the following process was used to create the grid of loss ratios:

1. Create a 1 m x 1 m grid across the area comprising the two alluvial fans as shown in Figure 1.
2. Select a hazard layer (either rock fall or debris flow) provided by BECA;
3. For each 1 m x 1 m grid cell extract the hazard value for this grid cell from the hazard layer provided by BECA.
4. Using the vulnerability models for rockfall and debris flow in Massey et al 2019 calculate the loss ratio for each grid cell given the hazard value from Step 3.
5. Repeat Steps 2-5 for each hazard layer.
6. The output is a 1 m x 1 m grid of loss ratios (0-1) for each hazard layer.

Figure 1. Map showing the area covered by the 1 m x 1 m grid in dark grey.

Vulnerability functions

Vulnerability functions are statistical functions that relate loss ratio to hazard intensity. Vulnerability functions for rock fall and debris flow used in this study were developed using historical insurance claim data from EQC. Fifty-seven case study buildings were selected from the EQC landslide claims database. These buildings had detailed engineering damage reports as well as retrospective modelling of landslide hazard intensity allowing losses to be correlated with hazard intensity. Statistical analysis was undertaken for different landslide intensity types (e.g. debris velocity, debris height, kinetic energy) to determine which landslide intensity type best correlates with loss. For debris flows this was found to be debris height against the building (m), and for rock fall this was maximum kinetic energy (kJ) of a given rock fall strike against the building. Given the small sample size, vulnerability models for different building characteristics were not able to be derived. The vulnerability models used in this study are shown in Figure 2 and Figure 3 and are available within the RiskScape engine. Further details on the method used to derive the vulnerability models are provided in Massey et al 2019.

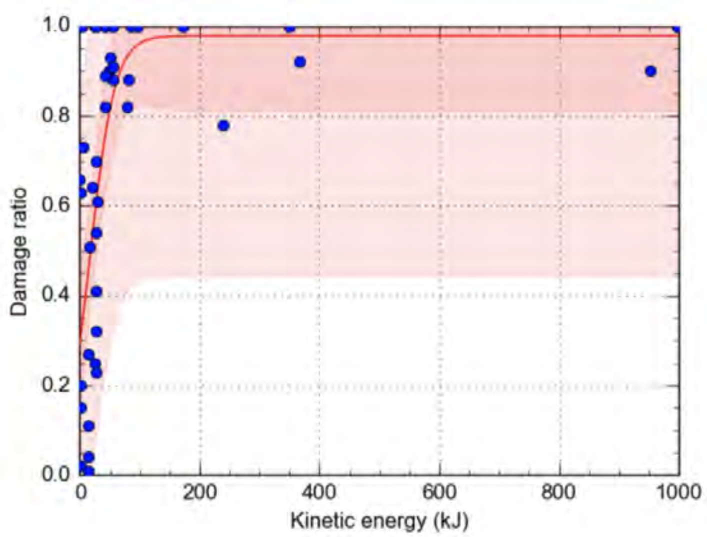


Figure 2. Vulnerability function for rock fall showing the loss (damage) ratio as a function of kinetic energy (kJ). The blue dots are observed data and red line is the fitted model. The one and two standard deviation bounds are shown as shaded dark red and light red respectively.

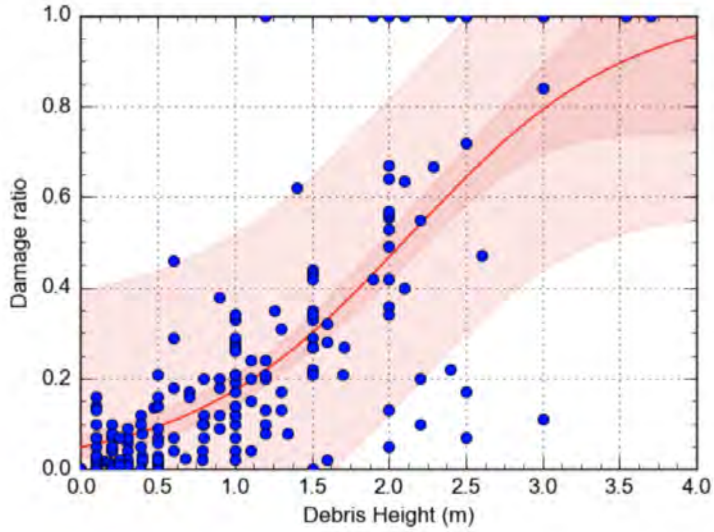


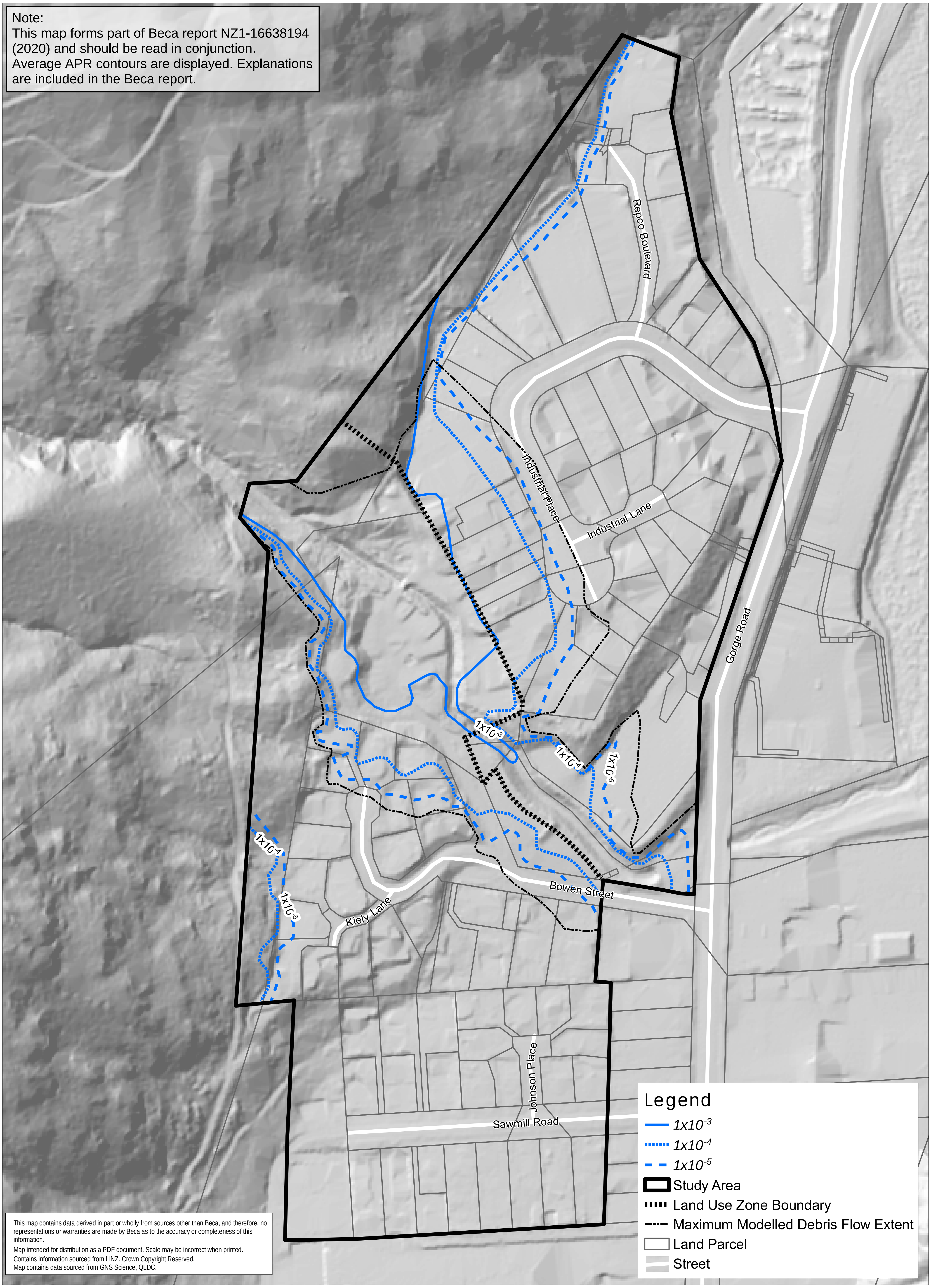
Figure 3. Vulnerability model for debris flow showing the loss (damage) ratio as a function of debris height (m). The blue dots are observed data and red line is the fitted model. The one and two standard deviation bounds are shown as shaded dark red and light red respectively.

Sources of uncertainty

The loss ratio grid results represent the mean loss ratio given a specific hazard intensity. No uncertainty is considered. However, there is uncertainty within the vulnerability functions. As shown in Figure 2 and Figure 3 there is variability in observed damage (blue dots) around the fitted vulnerability function curve (red line). This variability is quantified and shown as the shaded red bands. For example for a debris flow height of 2 m, the mean loss ratio is 0.47 and the one standard deviation bounds are 0.41 and 0.53 approximately ±13 %. The uncertainty for debris flow and rock fall increases for higher hazard intensities as there is less observational data at these intensity levels.

L

Appendix L – Slope Stability Property Risk Maps



Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title: Slope Stability Annual Property Risk Contours

Brewery Creek Fan

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

Beca

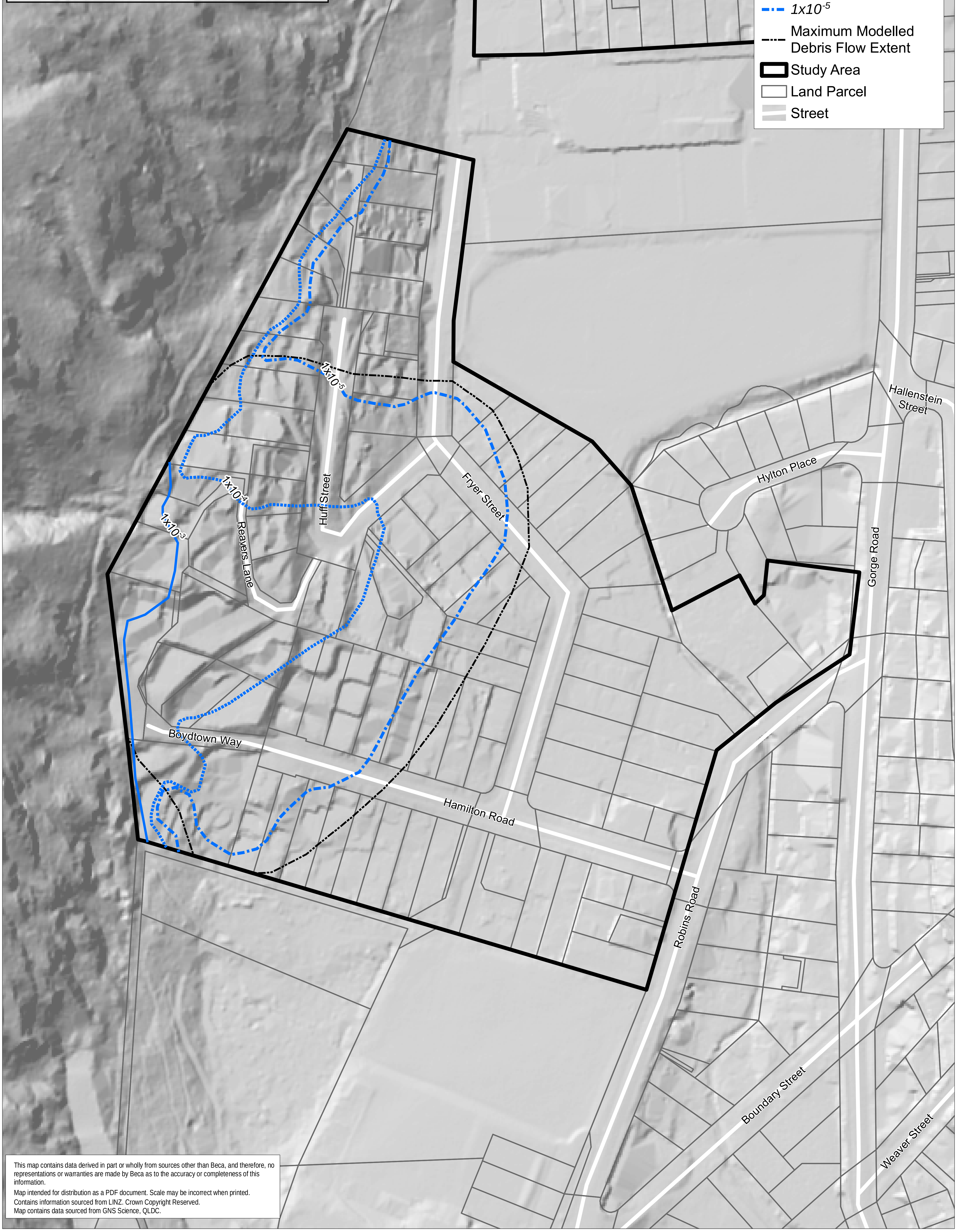
Discipline: GIS

Drawing No: 3209881-L001

File: \\beca.net\projects\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix L\3209881-L001.mxd Author: SHB Date: 7/09/2020

GIS@beca.com

Note:
This map forms part of Beca report NZ1-16638194 (2020) and should be read in conjunction.
Average APR contours are displayed. Explanations are included in the Beca report.



Map Scale @ A3: 1:2,000

0 40 80

Metres

Revision	Author	Verified	Approved	Date
1	SB	AP	PH	04/09/2020

Title:

Slope Stability Annual Property Risk Contours
Reavers Fan

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

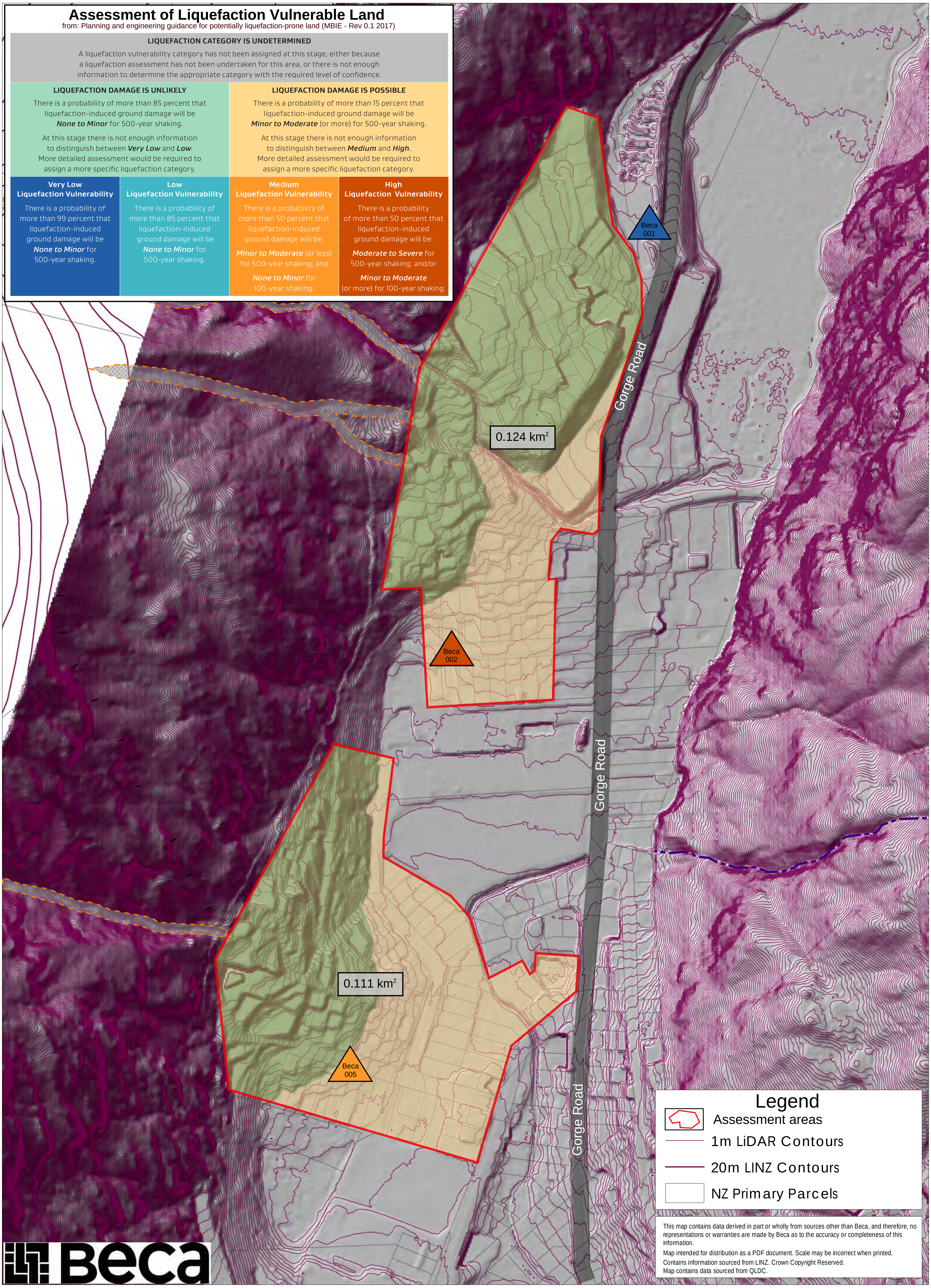
Discipline: GIS

Drawing No: 3209881-L002

GIS@beca.com
File: \\beca.net\projects\320\3209881\Technical_work_and_design\Maps\Appendicies\Revised\Appendix L\3209881-L002.mxd Author: SHB Date: 7/09/2020

M

Appendix M – Liquefaction Vulnerability



This map contains data derived in part or wholly from sources other than Beca, and therefore, no representations or warranties are made by Beca as to the accuracy or completeness of this information.

Map intended for distribution as a PDF document. Scale may be incorrect when printed.

Map contains data sourced from QLDC.

Map Scale @ A3: 1:4,000

0 50 100

Metres

Revision	Author	Verified	Approved	Date
2	SB	AP	PH	28/07/2020
1	ME	BDJ	ARP	08/11/2018

Title: Liquefaction Vulnerability

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

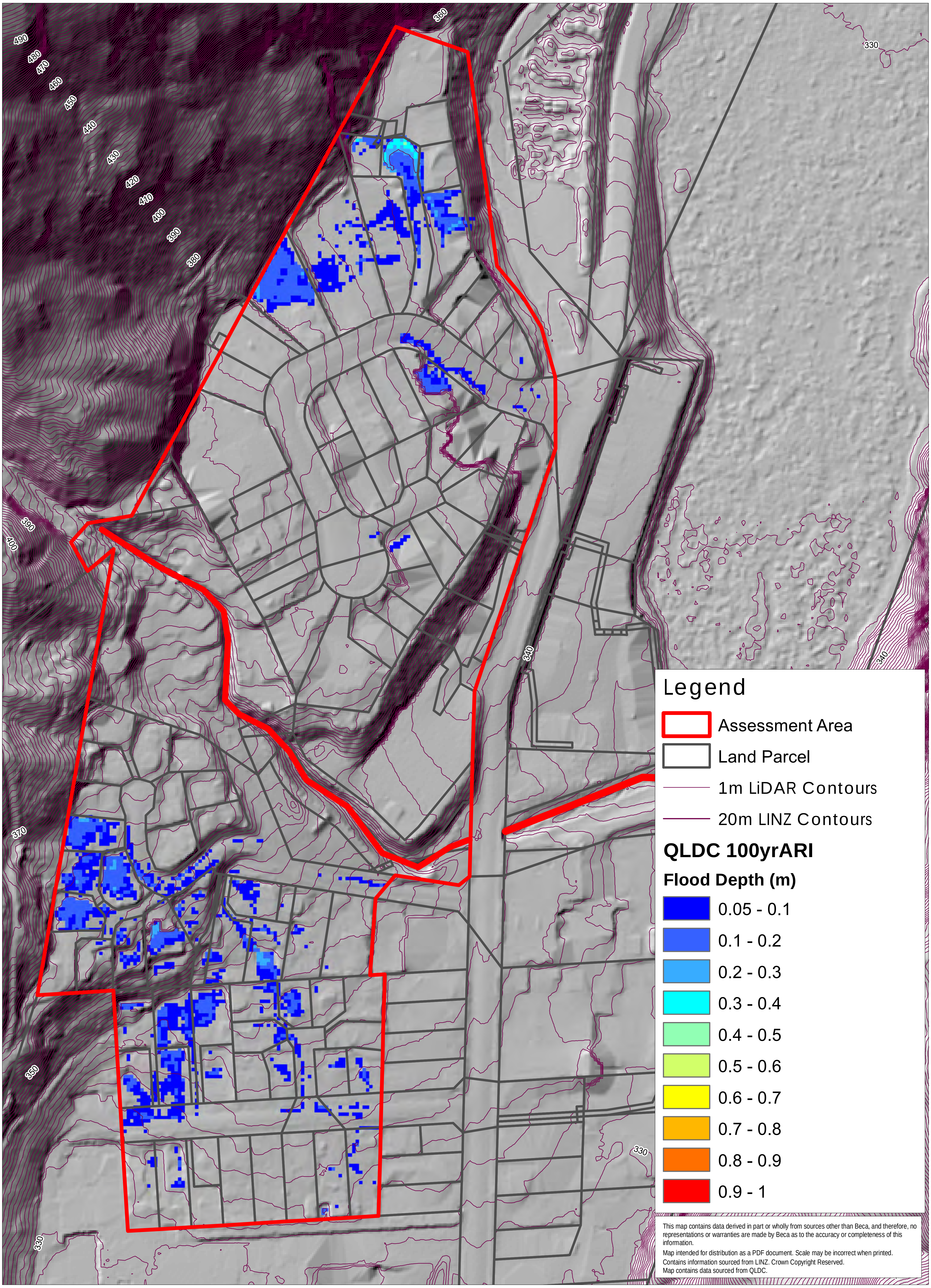
Beca

Discipline: GIS

Drawing No: 3209881-M001

N

Appendix N – Flood Maps



File: Z:\MODELS\19 Queenstown DC 1D Model\Data\20200622_Mapping\3209881-N001.mxd Author: SHB Date: 28/07/2020

GIS@beca.com

Map Scale @ A3: 1:2,000

0 25 50
Metres

Revision	Author	Verified	Approved	Date
1	NW	ET	PJH	17/08/2020

Title:

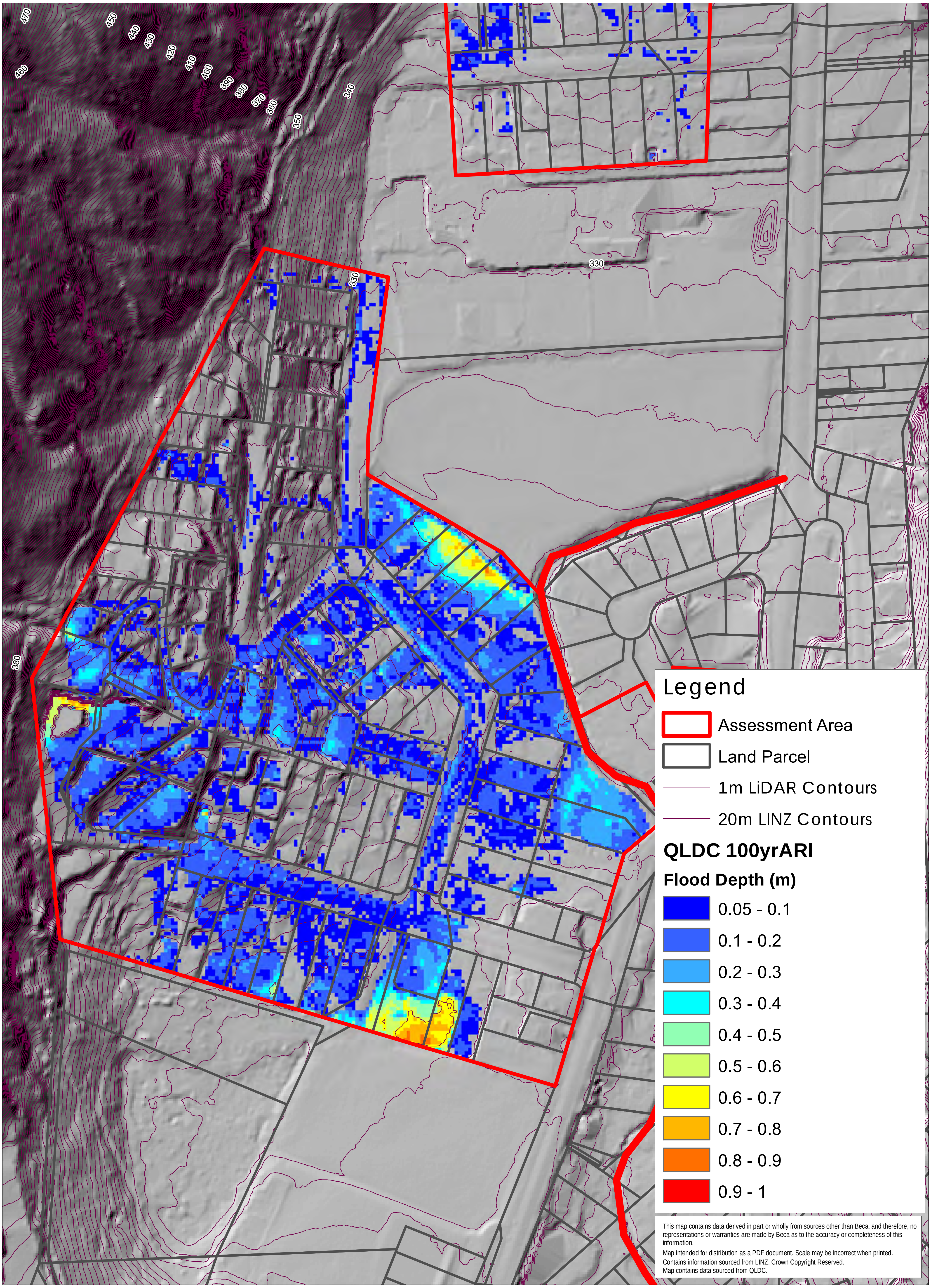
Flood Depth
100 Year ARI
Brewery Creek Fan

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

Discipline: GIS

Drawing No: 3209881-N001



GIS@beca.com

File: Z:\MODELS\19 Queenstown DC 1D Model\Data\20200622_Mapping\3209881-N002.mxd Author: SHB Date: 28/07/2020

Map Scale @ A3: 1:2,000

0 25 50

Metres

Revision	Author	Verified	Approved	Date
1	NW	ET	PJH	17/08/2020

Title:

Flood Depth
100 Year ARI
Reavers Fan

Client: Queenstown Lakes District Council

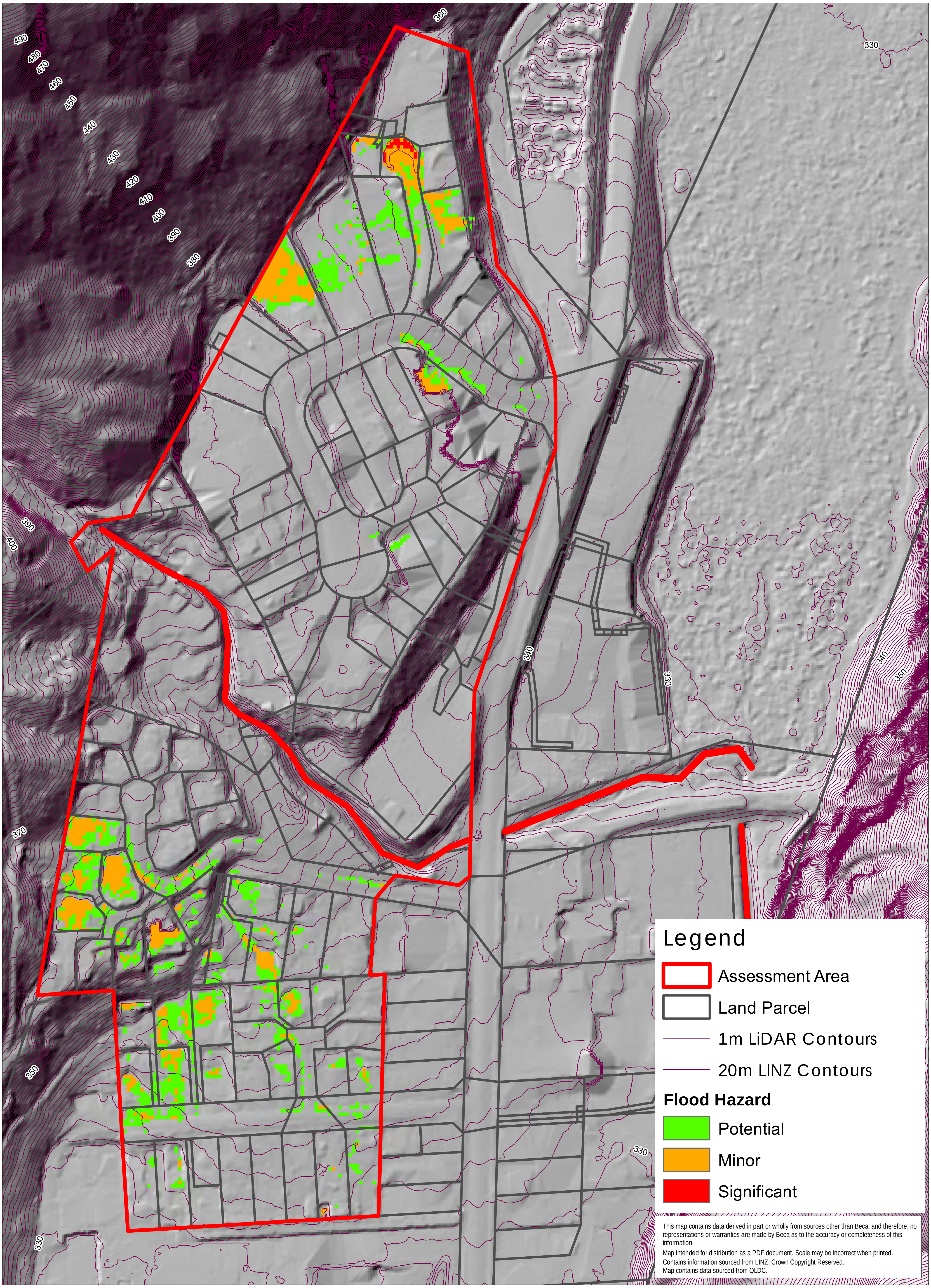
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-N002



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File: Z:\MODELS\19 Queenstown DC 1D Model\Data\20200622_Mapping\3209881-N003.mxd Author: SHB Date: 28/07/2020

Map Scale @ A3: 1:2,000
0 25 50
Metres

Revision	Author	Verified	Approved	Date
1	NW	ET	PJH	17/08/2020

Title:
Flood Hazard
100 Year ARI Flood Hazard
Brewery Creek Fan

Client: Queenstown Lakes District Council

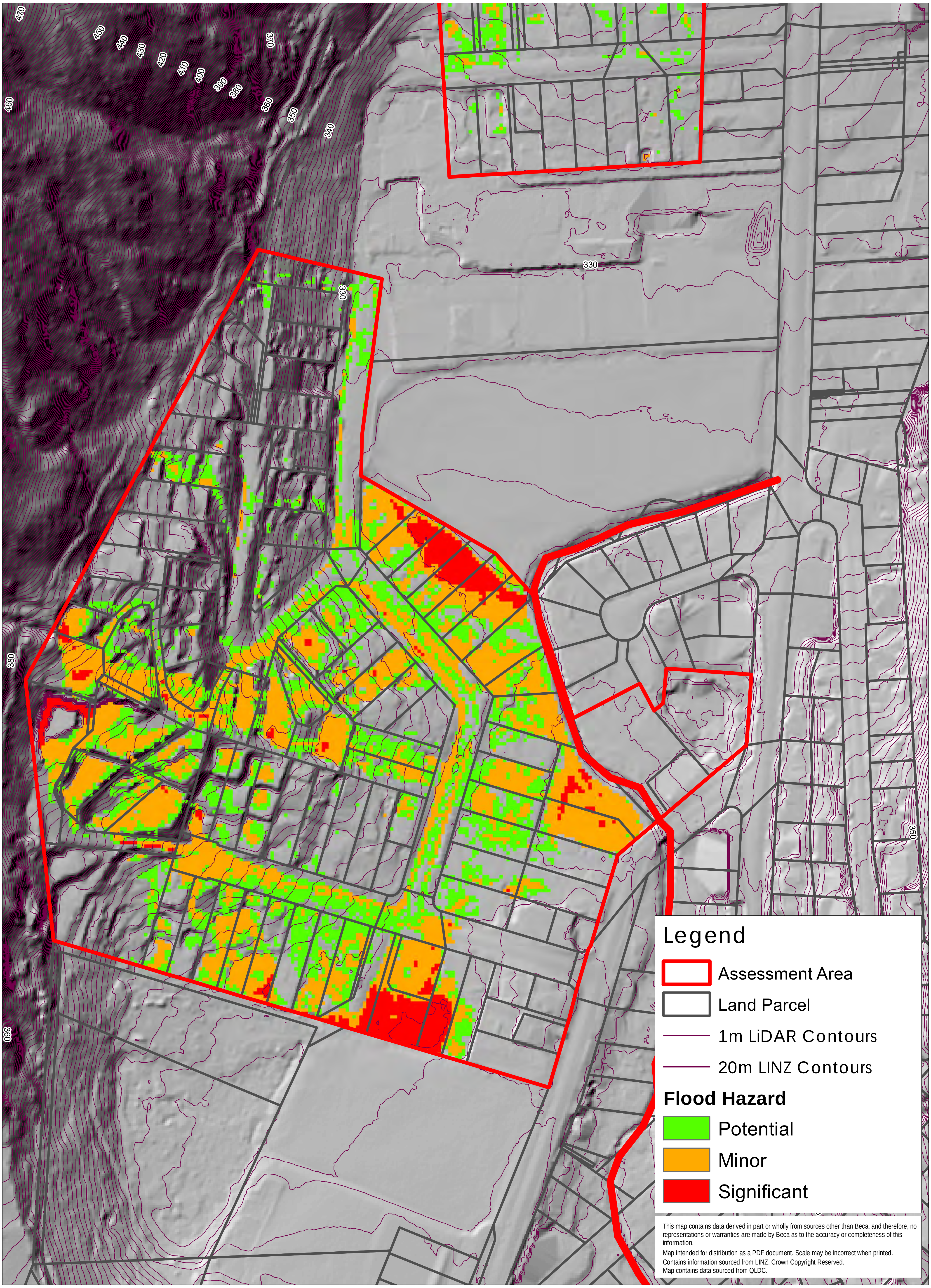
Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-N003



Map Scale @ A3: 1:2,000

0 25 50
Metres

Revision	Author	Verified	Approved	Date
1	NW	ET	PJH	17/08/2020

Title:
Flood Hazard
100 Year ARI Flood Hazard
Reavers Creek Fan

Client: Queenstown Lakes District Council

Project: Natural Hazards Affecting Gorge Road

N

Beca

Discipline: GIS

Drawing No: 3209881-N004

O

Appendix O – Flooding Technical Background

Factors affecting flood flows

There is direct correlation between flood risk (and other hazards being considered) and the rate and volume of runoff generated in the catchments upstream of the assessment area. In simple terms, runoff is a product of the catchment size, slope, geology/soil, land use and/or vegetation cover, and rainfall and climate. Of these, we would not expect the catchment size, slope or underlying geology/soils to change over the foreseeable future for the two catchments (Reavers and Brewery) feeding debris fans on the west side of the study area.

However, account should be taken of potential changes in vegetation cover and increased rainfall as a result of climate change. HEC-HMS hydrological modelling software has been used to quantify the increases in peak flow, % runoff, and flood volume of forest clearance in the catchments and increased storm rainfall due to climate change in 2040 and 2090.

Vegetation cover

The Reavers catchment is totally forested; native bush along the creek, and exotic pines on the slopes. The Brewery catchment is forested to an elevation of 900-1000 m, approximately 30% of the catchment. Exotic pines make up the majority of the forested area. Tussock predominates above the forest.

Forested catchments generally produce less runoff than those with less or lower vegetation, and runoff is anticipated to increase on land where forestry has been cleared. The effect of clearing the forested portion of the catchments has been modelled.

Climate change

The Ministry for the Environment (MfE, 2008) produced guidance on the climate change that predicted temperature increases for Otago of 0.9˚C to 2040 and 2.0˚C to 2090, with an attendant increase of 24-hour rainfall depths of 7.2% to 2040 and 16% to 2090. These adjustments for climate change were incorporated into NIWA's HIRDSv3 system for generating storm rainfall depths and intensities.

In 2018, MfE with NIWA provided updated guidance (MfE & NIWA, 2018) on climate change and temperature increases for New Zealand, which included four climate change 'representative concentration pathways' (RCP) scenarios. These RCP scenarios have been incorporated into the recently released HIRDSv4[2], but practitioners and regulators have still to decide which scenarios are to be used in design and assessment.

Figure M 1 shows the temperature increases to 2040, 2090, and 2110 (where available) for the 2008 MfE scenario, and the four scenarios from 2016 and HIRDSv4.

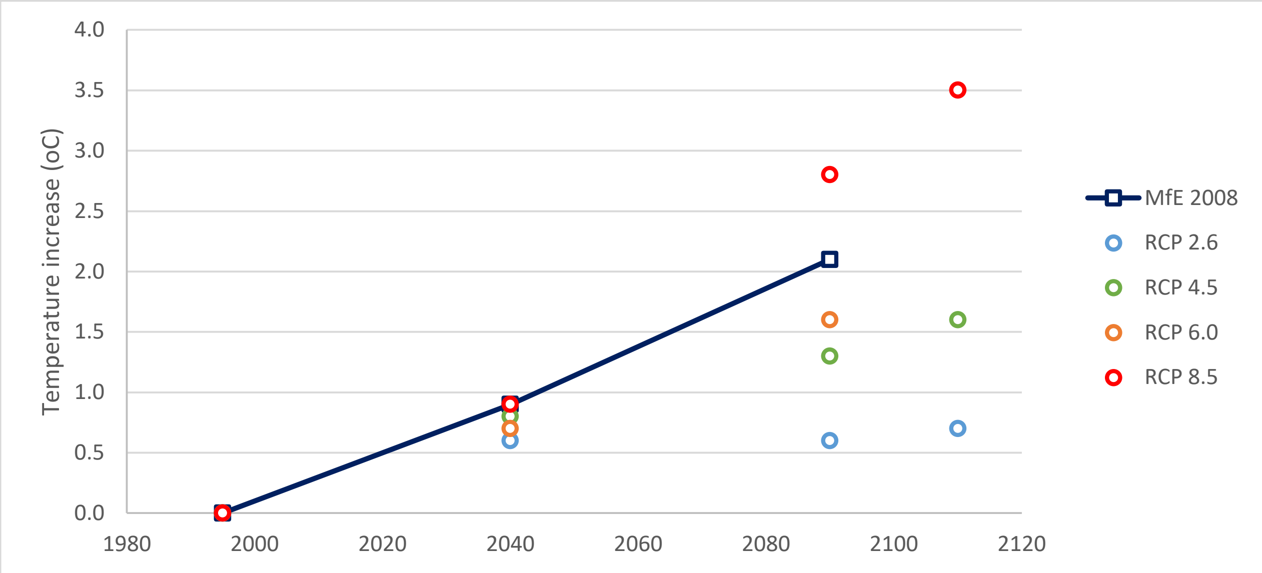


Figure M 1 - Climate change temperature increases.

Given the uncertainty as to which of the four RCP should be adopted, the hydrological response of the Reavers and Brewery catchments to climate change has been done using current climate HIRDSv4 rainfall depths adjusted using the MfE 2008 temperature increases of 0.9°C to 2040 and 2.0°C to 2090.

Hydrological modelling

A simple hydrological model of the two catchments was built using HEC-HMS. Rainfall losses were calculated using the SCS runoff curve method and the excess rainfall transformed to flow using the Clark Unit Hydrograph method.

Model parameters

The parameters are:

- SCS rainfall losses
  - Initial abstraction (Ia). An initial abstraction of 5 mm has been used for pervious areas.
  - SCS curve number (CN) used to represent land use, soil type, and hydrologic condition. Two curve numbers have been used for the Reavers and Brewery catchments:
    - 55: CN for forested areas assuming a Group B soil type and good hydrologic condition (>70% ground cover).
    - 64: CN for tussock areas assuming a Group B soil type and poor-fair hydrologic condition (30%-50% ground cover).
  - Percentage of the catchment covered in impervious surface.
- Clark Unit Hydrograph
  - Time of Concentration (ToC)
  - Storage Coefficient derived from the ToC.

Table M 1 - HEC-HMS model parameters

Catchment	Area (km²)	Land use	SCS Rainfall Losses			Clark Unit Hydrograph	
			Ia (mm)	Curve No.	% impervious	ToC (h)	Storage (h)
Reavers	0.46	Existing	5	55	0	0.49	0.16
		Future	5	61	0		
Brewery	2.85	Existing	5	64	0	1.24	0.64
		Future	5	64	0		

The 24-hour rainfall depths used in the model are shown in Table M 2. The 24-hour rainfall depths are distributed using a nested storm profile that includes the rainfall HIRDSv4 rainfall depths for all durations from 10 minutes to 24 hours, as shown in Figure M 2.

Table M 2 - HEC-HMS 24-hour rainfall depths (mm)

Time Horizon	Average Recurrence Interval (years)				
	5	10	20	50	100
Current	72.8	83.1	94.4	111.4	126.0
2040	77.9	89.2	101.4	119.8	135.8
2090	84.7	97.2	110.7	131.1	148.8

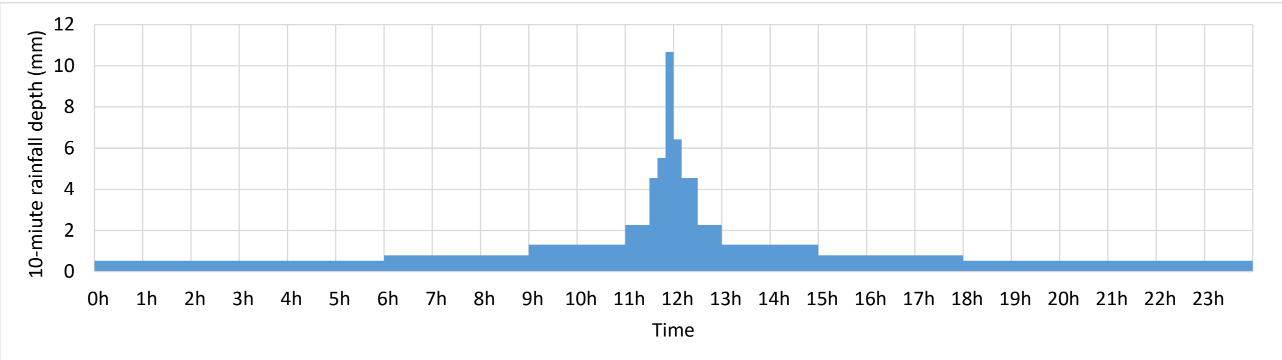


Figure M 2 - 100-year ARI rainfall for 2090 (148.8mm)

The model was run for each catchment with existing and future land use with each of the fifteen rainfall scenarios listed in Table M 2.

Sensitivity

Flow hydrographs were produced from the HEC-HMS model for sixty scenarios; two catchments, each with two land uses, for five storm events, for three climate change horizons (2*2*5*3=60). Table M 3 and Table M 4 show the peak flow and % runoff for each modelled scenario.

Table M 3 - HEC-HMS model results – peak flows (m3/s)

Catchment	Land use	Time Horizon	Average Recurrence Interval (years)				
			5	10	20	50	100
Reavers	Existing	Current	0.57	0.75	0.99	1.39	1.77
		2040	0.63	0.83	1.10	1.54	1.97
		2090	0.77	1.03	1.34	1.87	2.41
	Future	Current	0.75	0.99	1.29	1.79	2.25
		2040	0.84	1.10	1.42	1.96	2.48
		2090	1.01	1.34	1.73	2.38	3.01
Brewery	Existing	Current	2.82	3.70	4.82	6.69	8.43
		2040	3.09	4.03	5.24	7.23	9.16
		2090	3.73	4.93	6.37	8.75	11.10
	Future	Current	3.10	4.05	5.26	7.25	9.11
		2040	3.39	4.41	5.70	7.83	9.87
		2090	4.09	5.38	6.91	9.44	11.93

Table M 4 - HEC-HMS model results – % runoff

Catchment	Land use	Time Horizon	Average Recurrence Interval (years)				
			5	10	20	50	100
Reavers	Existing	Current	23%	26%	29%	33%	36%
		2040	24%	27%	30%	34%	37%
		2090	26%	29%	32%	36%	39%
	Future	Current	30%	34%	37%	42%	45%
		2040	31%	34%	38%	42%	45%
		2090	33%	37%	40%	44%	48%
Brewery	Existing	Current	26%	30%	33%	37%	40%
		2040	28%	30%	34%	38%	41%
		2090	29%	33%	36%	40%	44%
	Future	Current	29%	32%	36%	40%	43%
		2040	30%	33%	37%	41%	44%
		2090	32%	35%	39%	43%	47%

The results indicate that:

- Removing forestry from the catchments would increase peak flows by 25%-30% in the Reavers catchment and 7%-10% in the Brewery catchment. That is an increase of nine % runoff points for Reavers and three % runoff points for Brewery.
- Peak flows in 2040 will be about 10% higher than current peak flows.
- By 2090, peak flows will be 30%-35% higher than currently, with a 16% increase in flood volume.