BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

SQUAMISH-LILLOOET REGIONAL DISTRICT

EMERGENCY RESPONSE SUPPORT

JASON CREEK (REID ROAD) ASSESSMENT

FINAL

PROJECT NO.: 1358009 DATE: February 18, 2022
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February 18, 2022
Project No.: 1358009

Sarah Morgan, MA (DEM), PMP.
Director of Protective Services
Squamish-Lillooet Regional District
Box 219, Pemberton, BC V0N 2L0

Dear Sarah,

Re: Jason Creek (Reid Road) Assessment

BGC Engineering Inc. (BGC) is pleased to provide you with this desktop review of the emergency assessment at Jason Creek completed by Cordilleran Geoscience in response to the hydrogeomorphic events of November and December, 2021.

Should you have any questions, please do not hesitate to contact the undersigned.

Yours sincerely,

BGC ENGINEERING INC.
per:

Matthias Jakob, Ph.D., P.Geo., P.L.Eng.
Principal Geoscientist

EXECUTIVE SUMMARY

In late 2021, Jason Creek, 4.5 km north of Pemberton, BC, experienced three hydrogeomorphic[1] events (Nov. 14-15; 27-29; and Nov 30-Dec 1, 2021). These events impacted several properties through overland flooding and localized bank erosion along with impacts to infrastructure at road crossings. In response, an evacuation order was issued by the Squamish-Lillooet Regional District (SLRD) on December 1, 2021 for eight properties on Reid Road and an evacuation alert for other properties on Reid Road and at the intersection of Reid, Linda, and Rodgers Roads. The evacuation order for the eight affected properties remains in effect at the time of writing.

Evacuation orders were informed by field assessments completed by Cordilleran Geoscience (Cordilleran) and summarized in Cordilleran's report (December 13, 2021). At the request of the SLRD, BGC completed a desktop review of the Cordilleran report and developed preliminary risk-control concepts for Jason Creek. The objectives of this review are to inform emergency response decisions by SLRD, including decisions to issue, maintain, or rescind evacuation alerts or orders in affected areas and to assist the SLRD with risk communication.

In BGC's opinion, Cordilleran completed exemplary emergency response work during and following the sequence of hydrogeomorphic events on Jason Creek.

Cordilleran did not provide a risk estimate for individual properties, which would typically be outside the scope of a rapid emergency assessment. Based on the recommendation to issue evacuation orders for select properties, Cordilleran assessed there to be a credible risk of significant harm or life loss from debris-flow hazards on those properties. BGC agrees with the interpretations of hazard and risk level by Cordilleran that led to the decision by the SLRD to issue the December 13th, 2021 evacuation orders. While the magnitude and intensity of the potential hazards could only be hypothesized from the limited available evidence, it was of sufficient potential intensity to cause harm, and in BGC's opinion, could be reasonably considered a hazard with imminent potential to result in loss of life.

BGC completed a preliminary quantitative risk assessment (QRA) for a sample property near the fan apex and one at approximately mid-fan[2]. Using available information and pairing it with informed geoscientific judgment, total debris-flow risk near the fan apex on Jason Creek exceeds tolerable[3] life-loss risk levels (annual probability of death of an individual (PDI) of $1x10^{-4}$) by approximately one order of magnitude. At approximately mid-fan, PDI risk is estimated to approach the tolerable life-loss risk threshold. These estimates are preliminary and are subject to update following the completion of a detailed debris-flow hazard and risk assessment.

[1] Hydrogeomorphic events include floods with high sediment bedload, debris floods, and debris flows.
[2] This assessment is not for any specific individual property, but may be interpreted as a proxy of existing properties in those locations.
[3] The SLRD has not formally adopted quantitative life-loss risk tolerance criteria. However, various districts in BC and one in Alberta (Canmore) have specified 1:10,000 annual probability of death of an individual as a tolerable risk criterion for existing development.

As part of this review, BGC identified a preferred conceptual risk-control system for Jason Creek that includes:

1. A deflection berm between the fan apex and Reid Road on left (east) bank, and
2. Improvements to the Reid Road crossing to increase capacity and resilience to debris flows.

The two components of this conceptual mitigation system would work in concert to confine debris-flows to the Jason Creek channel upstream of and through the Reid Road crossing. The need for risk control measures and any potential risk transfer to areas downstream of the crossing would need to be considered as part of future phases of design. These components were identified based on desktop review only and in the absence of detailed topographic information (lidar[4]). For this reason, these recommendations should be interpreted as conceptual-level risk-control "ideas" that require field verification and detailed numerical modelling based on lidar topography to confirm their suitability, alignment, and geometry. Based on the information available to date, BGC estimates the combined cost for the system as approximately $1 million and acknowledges that this cost estimate may vary as much as -50% to >+100% given the data limitations. Determining the achievable level of risk reduction for mitigation options, and comparison of the level of risk reduction against its cost (e.g., cost-benefit analyses), would require more detailed assessment.

In addition to the preferred fan-level mitigation system, site-specific risk control options could be considered by individual property owners. Such interventions would focus on reducing the potential consequences of debris-flow impact at an individual property. Design of site-specific risk control options is outside of the scope of this assessment. However, BGC recommends that any measures of this scale be designed by third parties considering the results of a detailed debris-flow hazard and risk assessment and potential risk transfer to adjacent area(s).

Debris flows in the study area are seasonal. Debris-flow activity is accentuated in late summer and fall into early winter. Debris flows outside this time frame are possible, but much less likely. Decisions on resident occupancy in consideration of the seasonal nature of debris flows need to consider how the likelihood of debris flows in response to seasonal triggers will be evaluated along with the associated costs and limitations of available evaluation systems. At Jason Creek, BGC considered the applicability of a weather-forecast based debris-flow warning system; however, given the limitations of the forecasts, the lack of a long-enough data record of known debris flows and their corresponding hydroclimatic data, and the operational requirements of a warning system, BGC considers such system not a viable long-term solution at this location.

Longer-term resident occupancy decisions need to consider the complexity of risk management decision-making and implementation and the uncertainties associated with natural hazard risk assessment within the regional context. SLRD is a mountainous area which experiences a wide

[4] BGC engaged Apollo Mapping to develop a digital surface model (DSM) and digital terrain model (DTM)[5] of the Jason Creek watershed and fan from satellite imagery. Such data, while an improvement to standard TRIM data, is not equivalent in quality and resolution to lidar data.

range of natural hazard-types. Within the SLRD, other areas exist with debris-flow risk that exceeds generally accepted risk tolerance thresholds. BGC suggests that, in consideration of this, decisions on long-term resident occupancy on Jason Creek should be evaluated within a risk management framework that considers the unique characteristics of the site while being regionally-consistent.

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LIMITATIONS

BGC Engineering Inc. (BGC) prepared this document for the account of Squamish-Lillooet Regional District. The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

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1.0 INTRODUCTION

Jason Creek is located approximately 4.5 km northeast of Pemberton, BC. It drains the southeast facing slopes above Reid Rd (Drawing 01). In late 2021, Jason Creek, experienced three hydrogeomorphic events (November 14-15, November 27-29, and November 30-December 1, 2021). These events impacted several properties through overland flooding and localized bank erosion. The Jason Creek culvert at Reid Road was washed out twice, minor damage occurred at Portage Road, and the CN Rail line was threatened (Cordilleran, December 13, 2021).

In response to the hydrogeomorphic events, an evacuation order was issued by the Squamish-Lillooet Regional District (SLRD) on December 1, 2021 for eight properties on Reid Road. An evacuation alert was also issued for other properties on Reid Road and at the intersection of Reid Road, Linda Road, and Rodgers Road. Cordilleran Geoscience (Cordilleran) visited Jason Creek three times to complete assessments of the hazards in the watershed (December 1, 2, and 12) and support the SLRD in emergency response decision making. Cordilleran's December 13 report informed the SLRD evacuation order issued on December 14, 2021. The locations of the homes that remain on evacuation order at the time of writing are shown on Drawings 01 and 02. BGC notes that 1773 Reid Road which is at the Jason Creek fan apex is not part of the evacuation order.

At the request of the SLRD, BGC completed a desktop level review of the Cordilleran report (December 13, 2021) and developed conceptual-level risk control options for Jason Creek. The objectives of this review are to inform emergency response decisions by the SLRD, including decisions to issue, maintain, or rescind evacuation alerts or orders in affected areas and to assist the SLRD with risk communication. This report summarizes BGC's review and presents preliminary risk control options for further consideration by the District.

This work was completed as part of Services Agreement Emergency Operations Task #223901 – Jason Creek and Bear/Pete's Creek Geotechnical Assessments executed on January 13, 2022.

1.1. Scope of Work

The scope of work includes:

1. A desktop-level peer review of the information contained in the Cordilleran report (December 13, 2021).
2. An initial evaluation of geohazard mitigation options and associated costs at a conceptual level.
3. A presentation (via Web) on the findings to interested parties (e.g., SLRD, homeowners).

This scope of work is limited to desktop review of the Cordilleran report (December 13, 2021) and does not include site assessment or additional analyses, which are anticipated to be completed as part of a subsequent scope of work.

1.2. Background Information

In support of this assessment, BGC reviewed the following documents:

- Cordilleran Report to SLRD (December 13, 2021)
- SLRD Evacuation Orders (December 1 to December 14, 2021).

The Cordilleran report (December 13, 2021) includes a summary of historical reports dated from 1981 to 1997. BGC has not reviewed these reports except for material summarized in the December Cordilleran report.

At the time of writing, no bare-earth digital elevation model (DEM) of the Jason Creek watershed and fan was available. BGC engaged Apollo Mapping to develop a digital surface model (DSM) and digital terrain model (DTM)[5] of the Jason Creek watershed and fan from satellite imagery. The terrain data is shown on Drawings 01 to 02. Such data, while an improvement to standard TRIM data is not equivalent in quality and resolution to lidar data.

[5] Topographic data can be presented in different forms of terrain models. DEMs are ‘bare-earth’ indicating that all natural (e.g., trees) and built (e.g., buildings) features are removed. DEMs are often generated from lidar. DSMs contain all surface points including natural and built features (i.e., trees, buildings, etc. have not been removed). DTMs are models of the surface with natural and built features removed. DSM and DTM models are usually generated from photographs or satellite imagery through a process called ‘photogrammetry’. The terms DEM and DTM can sometimes be used interchangeably; however the quality of a DTM is influenced by the available imagery and can be lower resolution than lidar-derived DEMs.

2.0 2021 EVENTS

Cordilleran provides a timeline of events associated with the 2021 hydrogeomorphic events on Jason Creek. These are summarized in Table 2-1 and supplemented by information on the evacuations from the SLRD website (www.slrd.bc.ca).

Table 2-1. Summary of events on Jason Creek in late 2021. Atmospheric river events highlighted in grey. Information compiled from Cordilleran (December 13, 2021).

Date	Description
Nov 14-15, 2021	Atmospheric river event across southern BC.
Nov 15, 2021 (2100 hrs)	Jason Creek culvert at Reid Road washes out.
Nov 17-18, 2021	Frontera Geotechnical (Frontera) conducts site assessment (November 23, 2021). Frontera indicates the potential for debris flow activity on Jason Creek and outlines recommendations including a field review of upslope terrain and debris flow potential by a Qualified Professional.
Nov 16-25, 2021	Capilano Highways conducts emergency repairs on Jason Creek including debris clearing up the channel with a spider hoe.
Nov 27-29, 2021	Atmospheric river event across southern BC.
Nov 30-Dec 1, 2021	Atmospheric river event across southern BC.
Dec 1, 2021 (0430 hrs)	Jason Creek culvert at Reid Road washes out for second time.
Dec 1, 2021	Cordilleran completes field assessment of Jason Creek ravine.
Dec 1, 2021 (1500 hrs)	Evacuation order issued for lots 1793, 1794, 1781, 1788, 1791, 1802, 1812, 1815 Reid Road.
Dec 1, 2021 (2200 hrs)	Jason Creek washed out Reid Road. Overland flow affected multiple lots on Reid Road.
Dec 2, 2021	Cordilleran conducts review of affected fan areas and recommends further channelization above Reid Road.
Dec 3-5, 2021	Channelization work upstream of Reid Road completed.
Dec 8-9, 2021	Capilano Highways installs 1600 mm metal culvert at crossing.
Dec 9, 2021	Evacuation order rescinded. Homes on evacuation order moved to evacuation alert.
Dec 12, 2021	Cordilleran completes final channel assessment to evaluate the residual hazard and review the evacuation order.
Dec 13, 2021	SLRD issues Evacuation Order again for nine properties[1] on Reid Road. Wider community (Reid Road, Linda Road) remains on Evacuation Alert.
Dec 14, 2021	SLRD updates Evacuation Order for 1781, 1782, 1788, 1791, 1793, 1794, 1802, 1815 Reid Road.

1. BGC notes that the December 1st and December 14th orders include eight properties. BGC did not find a record on the SLRD site of which property was included in the December 13th order.

3.0 REVIEW

This section summarizes BGC's desktop-level review of the Cordilleran report (December 13, 2021). General comments are presented first, and subsequent sections are organized to follow the structure of the Cordilleran report to facilitate ease of comparison. Key conclusions from BGC's review are included within each subsection.

3.1. General Comments

In BGC's opinion, Cordilleran completed emergency response assessments following the sequence of hydrogeomorphic events on Jason Creek that are very thorough. The December 2021 report is detailed, specific, educative, and thorough with background documentation dated to 1981. Moreover, it was completed in an expedient fashion, following, and informed by three trips to site.

As expected for an emergency hazard assessment, no opportunity arose to quantify any of the hydrogeomorphic or hillslope processes beyond a rough field estimate. The level of effort in estimating hazards is hence deemed appropriate for an emergency assessment.

BGC agrees with Cordilleran's advice to the SLRD that evacuation orders for the properties on the Jason Creek upper fan in late 2021 be considered. The hazard was immediate, and while the magnitude and intensity of the potential hazards could only be hypothesized from the limited available evidence, it was of sufficient potential intensity to cause harm.

Cordilleran does not provide a life loss risk estimate for individual properties. However, based on the recommendation to issue evacuation orders for select properties, Cordilleran assessed a credible risk of significant harm or life loss from alluvial fan hazards on those properties.

Debris-flow hazards are highly seasonal in nature in southwestern BC (Jakob and Lambert, 2009; Jakob et al. 2011; Jakob and Owen, 2021). The likelihood of a debris flow occurring in the winter months except in warm coastal areas is generally reduced compared to the fall (synoptic storms) or late summer (convective storms) due to the buffering effect of snow cover that will absorb rain unless fully saturated. An exception to this can be a rapid melt and rain-on-snow event in association with a prolonged warm frontal system.

BGC acknowledges that maintaining an evacuation order over several months is a difficult decision, especially during weather conditions that are not amenable to debris-flow initiation. Any decision to modify the evacuation order would need to be informed by SLRD's life loss risk tolerance, especially in comparison with other geohazard sites with known life loss risks in the SLRD.

Cordilleran focuses on clearwater flood/debris flood/debris flow hazards. The potential for rock fall and/or rock slide hazards in the Jason Creek watershed should be acknowledged as the total hazards and risk from the watershed are cumulative. Rock slide hazards have not been quantified to date to BGC's knowledge.

3.2. Background Review

Cordilleran presents a thorough background review about the bedrock geology in the Jason Creek watershed. The highly altered[6] bedrock, and the presence of a shear zone in the watershed suggest that debris flows originating in Jason Creek may have high mobility due to a presumed high content of fines (clays, silts, and sands). Higher mobility debris flows can travel faster and farther than debris flows comprised of coarser material. The faster a debris flow the more destructive it is.

The deeply fractured bedrock bluff with evidence of slope spreading is indicative of a potential rock slope failure. At present, the relative hazards posed by different slope failure processes in the Jason Creek watershed are unknown.

BGC believes that the failure mechanism of "undrained loading" (i.e., a rock mass falling or sliding onto a saturated slope) can lead to sudden debris-flow initiation, even in absence of heavy rain (for example, at a time of rapid snowmelt). This observation should be included in a hydroclimatic debris-flow warning system, even though the frequency of such events compared to a rainfall-initiated debris flow is likely substantially lower.

Terrain mapping and a longitudinal profile of Jason Creek are presented from previous work on the creek. Point source failures, both existing and potential future sources are identified. This is an important contribution to understanding hazards in Jason Creek watershed.

<u>Conclusion(s):</u> There is sufficient evidence to suggest debris flows have historically occurred, and will continue to occur on Jason Creek. The potential hazard and risk from a rock slope failure originating in the Jason Creek watershed should be investigated further.

3.3. Cordilleran 2021 Observations

3.3.1. Watershed Characteristics

Cordilleran categorizes the Jason Creek watershed as debris-flow prone based on watershed morphometrics[7]. This is consistent with characterization of other creeks studied in the SLRD and other areas (Figure 3-1).

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[6] Hydrothermal or geomechanical alterations weakens rock and furthers disintegration of particles to clay size which in turn promotes debris-flow mobility.
[7] Morphometrics are measurable characteristics of landforms that are used to analyse them.

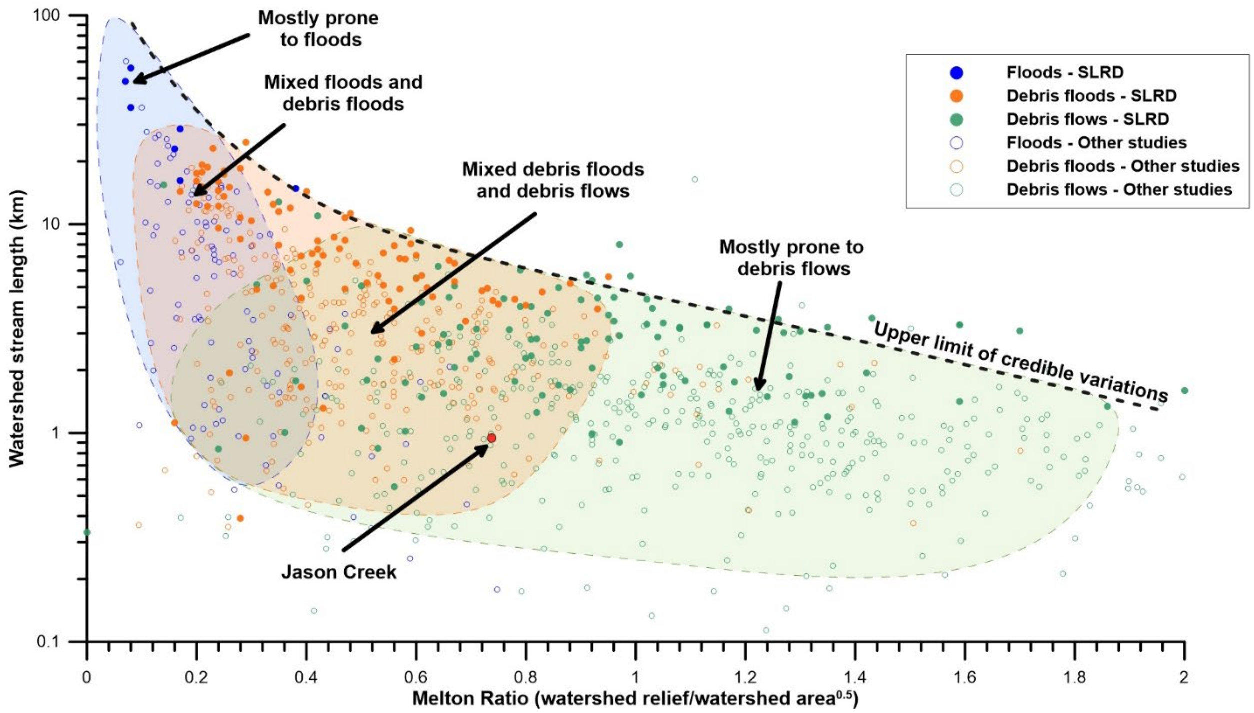

Figure 3-1. Steep creek process characterization based on watershed length and Melton Ratio. Note that this representation is simplistic because it does not include the dimension of return period. Some creeks are subject to different processes at different return periods.

Cordilleran identifies large colluvium deposits which represent potential debris-flow sediment sources. Bedrock-controlled slope failures are also identified with relatively deep failure planes, (for example: page 6 (10 m failure thickness), page 6 (2-5 m thick), page 7 (5-10 m thick), page 7 (5,000 to 50,000 m^3)). No supporting evidence is presented for the bedrock failure thicknesses and volumes. A credible range of failure depths would be preferred as it has implications for the frequency-magnitude (F-M) analysis. However, this does not affect the overall conclusions of the report.

Conclusion(s): BGC encourages additional evidence to support the selection of failure volumes or credible failure volume ranges.

3.3.1.1. Flood Frequency

The flood frequency analysis (FFA) presented used a “proprietary scaling function based on a basin area-discharge relationship developed by the author”. It would be helpful to have more information on this scaling function for review and comparison to other techniques.

BGC compared the FFA presented by Cordilleran to BGC’s application that integrates publicly available hydrometric data with GIS-based analytical tools (River Network Tools™). BGC’s FFA utilized historical data from six suitable[8] river gauges in southwestern British Columbia and northwestern Washington State. The two FFAs differ by 5 to 17% for the return periods presented by Cordilleran. BGC notes that FFAs for small, ungauged catchments typically have higher uncertainty than large catchments, as hydrometric gauge stations operated by data collection agencies are predominantly installed on watercourses with large upstream catchments. As a result, flow records collected at these gauge stations may not be representative of flow conditions in smaller catchments. For example, peak flows in small catchments can be triggered by localized storms that may not be reflected in nearby hydrometric gauge flow readings. Neither FFA considers the impacts of climate change on future flood frequencies.

With recognition of these uncertainties, BGC believes Cordilleran's estimate to be reasonable. While neither FFA compared above considers the impacts of climate change on future flood frequencies, clear water flooding is not governing hazards and risks on Jason Creek fan.

Cordilleran comments on the opening size of the main culvert on Reid Road and estimates flow velocities, quoting 2 m/s. In BGC's experience, flow velocities at rarer (higher) flows may exceed this value, especially with high sediment concentration that can reduce turbulence and can break up the step-pool morphology by mobilizing large (D_{84} and greater) particles.

Conclusion(s): The FFA presented by Cordilleran appears to be a reasonable approximation for an emergency assessment of flow reaching Reid Road during a flood. It does not include climate change impacts, nor does it account for organic or mineral debris mobilized in a debris flood or debris flow. For this reason, it should not be relied upon for detailed hazard and risk assessment or mitigation design.

3.3.2. Reid Road Stream Crossing Structure

BGC agrees that the culvert at Reid Road is likely undersized. Culverts conveying steep mountain streams commonly do not have sufficient capacity to convey both water and debris during high return period runoff events, as was observed in December 2021 at Jason Creek. Bridge crossings are much more resilient if enough conveyance is ascertained, and if the abutments sufficiently protected to avoid outflanking or direct abutment damage. However, bridge crossings have a significantly higher capital cost than culverts. For this reason, selection of the preferred crossing infrastructure should consider the process type, estimated flows, erosion control requirements, and economics.

Conclusion(s): The Reid Road culvert is likely insufficient to convey debris floods and definitely insufficient to convey debris flows.

3.3.3. Alluvial Fan Areas

Cordilleran estimates a "high probability" that Reid Road would convey flow towards the east in the event of a culvert blockage or discharge exceeding the culvert capacity. This can be attributed

[8] Suitable gauges are those with similar watershed size and Strahler order, with sufficient years of historical records, and prioritized by proximity to the watercourse segment.

to Reid Road ascending the fan from east to west towards the crossing and there not being a swale preventing avulsions from following the road. BGC agrees with this assessment and notes that in such an event it is very likely that the road ditch would erode and potentially lead to road washout where water overtops the road and flow being directed towards property(ies) to the south and east. Predictions of where the water would overtop along the road is difficult in absence of detailed numerical modeling.

Cordilleran describes a debris berm on the upper fan, and an "ad hoc"[9] dike on the lower fan. The potential risk transfer implications of these structures are not discussed.

Conclusion(s): The alignment of Reid Road increases the likelihood of flow along the road and associated impacts to the road and properties to the south and east in the event of a culvert blockage or flow exceeding the culvert capacity. Risk transfer resulting from the debris berm and ad hoc dike should be assessed.

3.3.4. Damages Resulting from the November 14 through December 1, 2021 storms

Cordilleran provides an informative summary of the 2021 events and photographic record of post-event conditions.

3.4. Hazard and Risk Assessment

3.4.1. Hazard and Risk Concepts

Cordilleran presents qualitative hazard and consequence assessment in Table 4 and 5 of their report. These are appropriate for this level of assessment and are helpful in communicating hazards and their respective consequences.

3.4.2. Hazard and Risk Evaluation Criteria

Cordilleran asserts that the SLRD currently has not adopted formal (council-approved) quantitative life-loss risk tolerance thresholds. However, it should be noted that the SLRD does have substantial experience with quantitative life loss risk assessments (QRAs) that have been conducted by consultants and academics (for example, Cataline Creek and Bear Creek/Pete's Creek debris flows, Mount Currie rock avalanches, lahars from the Mount Meager volcanic complex), and risk management decisions have been made based such assessments. On the Jason Creek fan, a similar QRA could be executed to support SLRD's risk management decisions including engineered and non-engineered mitigation.

Conclusion(s): SLRD has experience with QRAs and risk-informed decision making. These practices could be applied to inform decisions at Jason Creek which would also allow direct comparison with other sites were risk has been estimated.

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[9] The term "ad-hoc" is not defined in the Cordilleran report. BGC interprets this to mean an orphaned, non-standard dike.

3.4.3. Hazard Assessment

The hazards affecting the upper, middle, and lower Jason Creek fans are described. BGC agrees that the upper fan is most vulnerable to alluvial fan hazards. Cordilleran states that the middle and lower fan of Jason Creek are "likely only vulnerable to overland flow and debris flooding". At this stage, this should be regarded as a preliminary hypothesis and examined during a detailed assessment as Cordilleran describes in their concluding section.

Cordilleran provides a preliminary frequency-magnitude (F-M) curve which is an advanced technique for an emergency risk assessment. As expected for the scope of work, it is based on limited information informing expert judgment. The estimates of 1000 m^3 for the 25-year return period and the 100,000 m^3 for a 5000-year return period could be better justified. It would also be helpful to plot the December 2021 events on this graph and hence understand their respective estimated frequencies.

BGC compared the F-M curve presented by Cordilleran to a statistically based, F-M relationship derived from fan-area relationships in British Columbia and Alberta (Jakob et al., 2019). The two curves are shown on Figure 3-2. The BGC regional analysis likely overestimates potential sediment volumes at lower return periods (<100 years) due to the nature of the fan-area relationship fit. This relationship can be better constrained with additional analyses including airphoto interpretation, supplemented with dendrogeomorphological analysis, and test pitting and radiocarbon dating.

Figure 3-2. Estimated simplified frequency-magnitude (F-M) curves for Jason Creek. F-M curve from Cordilleran (December 13, 2021) is shown in orange, with a power fit shown by the orange dashed line. BGC regional F-M curve shown in blue

In BGC's opinion, the F-M curves presented in Figure 3-2 should not form the basis for debris-flow modeling or risk assessment as more work would be required improve their reliability.

Specifically, one would need to split up the different triggering events (rainfall triggered, vs. rock slide triggered), which would likely create break points in the F-M curve. This is consistent with Cordilleran's intention as described in their conclusions. The confidence bounds presented on the Cordilleran F-M curve are helpful as they convey uncertainty in the F-M estimates. However, Cordilleran does not explain the width of the confidence bounds.

Cordilleran does not address any post-fire debris flow hazards as this was outside of their scope. BGC notes that the area is in a region susceptible to wildfires and a post-wildfire debris flow scenario should be included in a comprehensive risk assessment.

Cordilleran does not provide a risk estimate for individual properties which again, would be unusual for an emergency assessment. Based on the recommendation to issue evacuation orders for select properties, Cordilleran assessed a credible risk of significant harm or life loss from alluvial fan hazards on those properties. To test these conclusions, BGC conducted a preliminary quantitative life loss risk assessment that considers total annual debris-flow risk at two locations on the fan: near the fan apex, and at approximately mid-fan. The assessment is not specific to individual properties, but was completed to develop an approximate range of individual life loss risk levels on the upper and middle portions of Jason Creek fan.

BGC's preliminary individual risk assessment is based on the Cordilleran F-M curve, assumptions about debris-flow runout and flow depths informed by Cordilleran's photographs and expert judgement, and vulnerability criteria for individuals in buildings (Appendix A). Given the level of uncertainty associated with the risk assessment inputs, range and best estimates are presented for both scenarios[10]. This preliminary assessment suggests that total debris-flow risk near the fan apex on Jason Creek exceeds life-loss risk levels considered tolerable by various jurisdictions in BC (annual probability of death of an individual (PDI) of $1x10^{-4}$). Debris-flow life-loss risk is exceeded by approximately one order of magnitude near the fan apex decreasing to near the tolerable threshold in mid fan. This also implies that the properties on the lower Jason Creek fan are likely at tolerable risk. These landslide risk thresholds can be contextualized in relation to other causes of death as shown in Figure 3-3.

[10] The risk calculations considered minimum and maximum spatial impact and temporal impact probabilities and use a range of flow depths and channel slope measurements to derive flow velocities and life loss vulnerability for individuals in buildings. These inputs represent the minimum and maximum range for PDI. The best estimate is an average of the minimum and maximum PDI estimates.

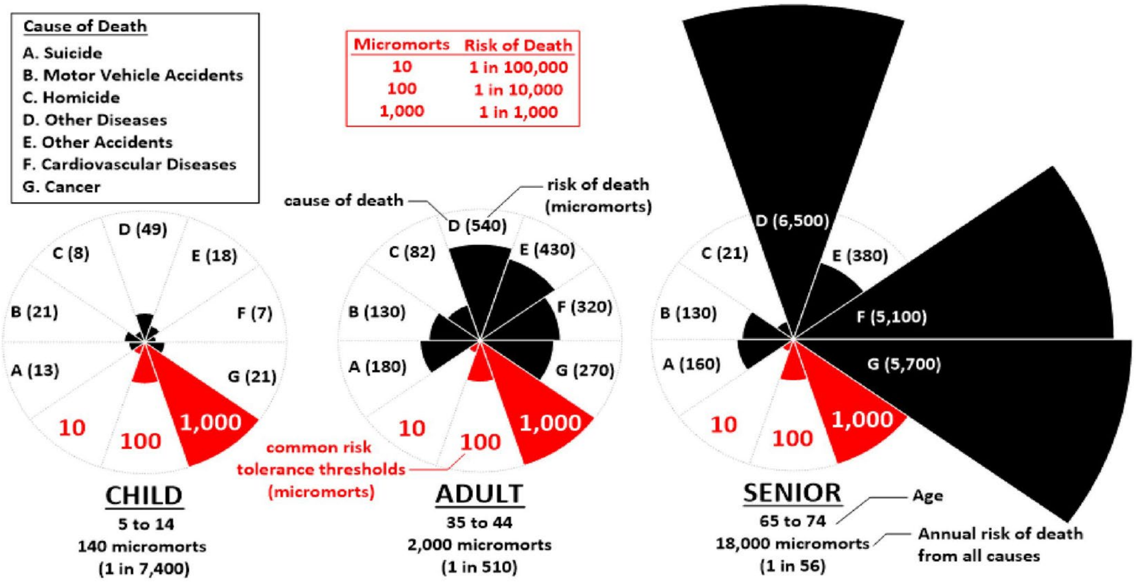

Figure 3-3. Comparison of common risk tolerance thresholds (red) with risk of death per year in the USA from other causes for three different age groups (Strouth & McDougall, 2022). The area of each triangle is proportional to the risk in micromorts; it is neither a traditional pie chart nor polar bar chart.

BCG's preliminary risk estimates should not be relied upon beyond the scope of this report as they are based on broad assumptions rather than numerical modeling. They also exclude risk associated with rock slides or rock fall, which would have to be considered alongside debris flow risks for properties affected by more than one geohazard process. As a comparative estimate, BGC's risk estimates support Cordilleran's recommendation to issue evacuation orders for properties near the fan apex on the upper Jason Creek fan during a period of heavy rainfall or rain-on-snow. The SLRD may wish to review life loss risk on the Jason Creek fan in relation to risks quantified on other alluvial fans in the District in support of risk management.

Conclusion(s): Properties on the upper, middle, and lower Jason Creek are vulnerable to a range of alluvial fan hazards, and potentially rock slope failure(s) originating in the Jason Creek watershed. Detailed assessment is required to better quantify these hazards, and should consider climate change, and wildfire impacts to debris-flow frequency and magnitude. A preliminary estimate of life-loss risk from debris flows on Jason Creek fan supports Cordilleran's recommendation to issue evacuation orders for properties near the fan apex in late 2021. Life-loss risk from debris flows decreases with distance from the fan apex, the extent of reduction can only be approximated with the information presently available.

3.5. Residential Development on Alluvial Fans in BC

Cordilleran presents a short summary of professional guidance documents that govern assessment of hazards and risk and construction on alluvial fans. BGC has no review comments, and finds such summary helpful to decision makers.

3.6. Emergency Repairs on Reid Road

BGC agrees that safe working conditions are very important and for all future emergency works in inclement weather. Spotters must be used when workers are in harm's way and an emergency egress plan for the workers developed ahead of time

3.7. Conclusions

The Cordilleran emergency assessment report (December 13, 2021) is comprehensive and fulfilled the needs of the SLRD. BGC expects that, given the same evidence, we would have very likely come to a similar conclusion, i.e., that the hazard is imminent and that there is a high risk to people and structures.

BGC supports most of Cordilleran's assessment but notes (as understood by Cordilleran) that the frequency-magnitude analysis should not be relied upon for a detailed quantitative risk assessment nor for mitigation design.

A preliminary judgement-based quantitative risk assessment was completed which suggests that existing risk is likely above thresholds generally considered tolerable by some jurisdictions in BC. This supports the conclusion that at least some residences are exposed to unacceptably high risk.

3.8. Recommendations

BGC agrees with Cordilleran's recommendation to complete additional multi-hazard (landslide and alluvial fan hazards) geotechnical assessments to inform risk control options as well as the recommended components of such an assessment.

Cordilleran recommends that "the homes on lots 1781, 1791, 1793, 1815, 1782, 1788, 1794 & 1802 Reid Road must remain on evacuation order" until more detailed analyses are completed. BGC agrees that there sufficient evidence to suggest that debris-flow hazard is imminent and that there is a high risk to people and structures.

BGC acknowledges that the preliminary risk assessment suggests that at some locations on the Jason Creek upper fan, the risk from debris flows may be tolerable in comparison with generally accepted thresholds (PDI less than 1:10,000) but given the limited information available, additional analyses are required before this can be confirmed.

Cordilleran recommends improvements to the Reid Road, Portage Road, and CN Rail track crossings. BGC acknowledges that improvements at the CN Rail crossing will need to align with CN's internal risk tolerance criteria.

<u>Conclusion(s):</u> Multi-hazard and risk assessments are recommended to support risk management by SLRD.

4.0 RISK-CONTROL OPTIONS

There are a wide range of debris flow risk control options that can be considered to reduce risk to a particular area. Table 4-1 summarizes a comprehensive set of mitigation (risk-control) techniques based on international professional practice and literature. These mitigation techniques include active measures, which are constructed in the upper catchment, watershed, or on the fan, and passive measures, which reduce risk without construction of new mitigation structures. The suite of techniques that will be suitable for a particular site varies based on the site conditions, access, and available resources.

At Jason Creek, microtopography is very important in deciding on the type, scale, and geometry of risk-control techniques. In absence of detailed lidar, the recommendations provided herein are conceptual and need to be confirmed with a field assessment when the ground is snow-free and lidar topography. The improved topographic information is important to facilitate numerical modelling of debris flows on Jason Creek without mitigation in place, and then with the proposed mitigation in place to test the efficacy in reducing risk to the properties and infrastructure on the fan.

As shown in Table 4-1, BGC recommends a combination of active measures on the fan to divert the flow away from the at-risk properties, and improve conveyance at Reid Road. Review of the need to improve conveyance downstream of the Reid Road crossing will require field reconnaissance. A passive measure, in the form of evacuation orders and alerts, is already in effect. Implementation of a weather forecast-based warning system was considered but deemed to be a last resort option to manage risk at Jason Creek due to the lack of previous debris-flow dates and limitations of the forecast data as well as operational constraints associated with system implementation.

Active measures in the upper catchment and watershed channel were not considered as these require access for construction, and are very costly to build and maintain. Similarly, on Jason Creek fan, BGC favours techniques with lower anticipated capital and operational and maintenance costs. For example, a debris basin would require regular maintenance to ensure that the design storage is available when an event occurs. This would incur long-term maintenance costs and is therefore less desirable.

Risk-control options at individual properties can also be implemented to reduce the vulnerability of individual properties or structures. As with all techniques, the limitations of measures to reduce risk at this scale need to balanced with the associated benefits. Based on the information available to date, BGC cannot confirm if such measures can reduce risk to tolerable levels. BGC recommends that improvements to Reid Road crossing at Jason Creek be completed whether or not property- or building-level measures are implemented to minimize the potential for localized erosion, overland flooding, and road closure.

Following additional hazard and risk assessment, the preferred mitigation techniques may be refined.

Table 4-1. Mitigation functions and techniques. Those measures considered for Jason Creek are highlighted in grey (modified after Mark, 2018).

Type	Location	Function	Description	Techniques
Active	Upper catchment	Source zone stabilization	Limit erosion, debris entrainment or runoff in the watershed to prevent or limit event initiation	Forestry management; bioengineering; stabilization of specific instabilities; mulching; seeding; tree planting; drainage; diversion of runoff
	Watershed channel	Channel stabilization	Reduce entrained sediment volume by limiting incision and channel widening	Longitudinal structures (berms, riprap); transverse structures (low check dams, ground sills)
		Channel consolidation	Elevate the channel bed to stabilize side slopes	Closed check dams
		Debris retention	Permanent or temporary storage of debris	Closed check dams; some open check dams
		Debris regulation	Attenuate or reduce peak discharges; temporary storage of debris; dosing and filtering	Open check dams; some closed check dams; debris deflection berms
		Energy dissipation	Attenuate; decrease peak discharge and velocity	Debris breakers; open check dams; dewatering grills; closed check dams that create alluvial reaches
	Fan	Channel stabilization	Reduces sediment entrainment; protects infrastructure below or adjacent to the channel	Longitudinal structures; transverse structures; armouring the channel
		Debris retention	Permanent or temporary storage of debris	Closed check dams; some open check dams
		Debris regulation	Temporary storage of debris; dosing and filtering	Open check dams
		Energy dissipation	Attenuate; decrease peak discharge and velocity	Debris breakers; open check dams; dewatering grills; increased channel capacity
		Diversion	Redirect flows away from elements at risk	Diversion berms; overflow channels or weirs
		Improved conveyance	Straighten the channel and increase the cross-section to reduce avulsion potential	Remove or reconstruct bridges; add berms to contain super-elevating flows around corners
Passive	Community	Local protection of infrastructure	Use of damage-resistant construction methods	Reinforcing upslope walls; tunneling of highways or rail lines; raising the construction level
		Warning System	Weather-forecast based warning system to alert or evacuate residents	Evaluation of storms in the area that have and have not triggered post-wildfire debris flows
		Relocation of elements at risk	Permanent or temporary relocation of people and infrastructure	Zoning or bylaws to manage or limit development; warning or alert systems to evacuate residents; permanent relocation if risks cannot be managed
		Emergency response planning	Protocols to manage and limit risks if a disaster occurs	Trained emergency services; education; disaster response drills
		Risk sharing	Transfer financial risks to insurance agencies or other parties	State-sponsored or private insurance, government disaster financial assistance funds

4.1. Flow Deflection on Jason Creek Fan

Flow deflection on Jason Creek fan could be achieved through construction of an erosion-protected berm on the left (east) bank of Jason Creek from the fan apex downstream to the Reid Road crossing. The approximate location of such a berm is shown on Figure 4-1. The need for a berm and/or erosion protection on the right (west) bank from the fan apex downstream to the crossing would need to be reviewed as part of a site visit. Similarly, the need for erosion protection downstream of the Reid Road crossing would need to be reviewed as part of a site visit supplemented with numerical modelling. A schematic of a deflection berm is shown in Figure 4-2. In contrast to the schematic, BGC does not propose to reroute Jason Creek to a new channel, but instead the purpose of the berm would be to divert flow back into the channel and away from inhabited areas on the east side of the creek.

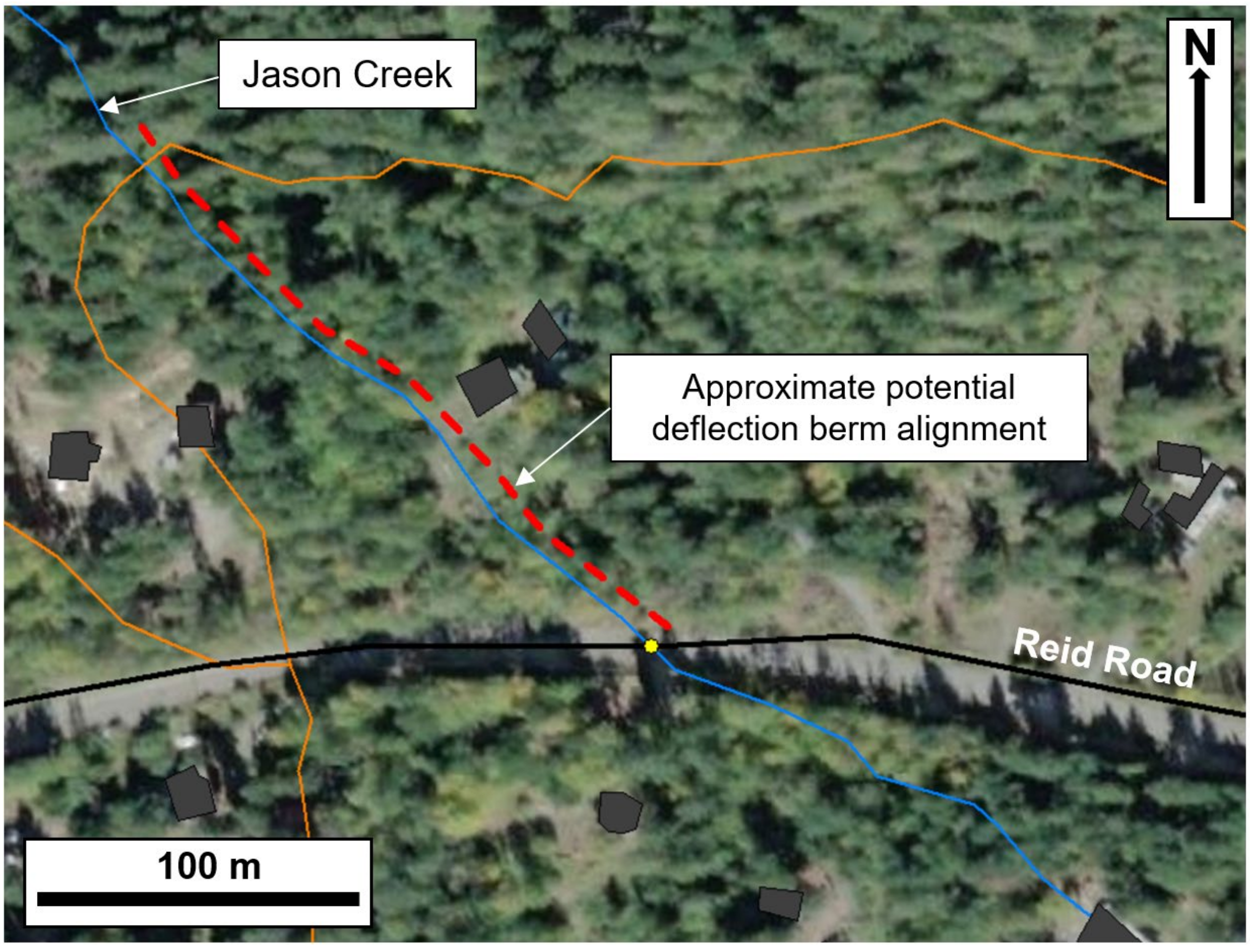

Figure 4-1. Approximate alignment of potential flow deflection berm (red). Jason Creek (blue line), fan boundary (orange line), building footprints (grey polygons), and Reid Road (black line) also shown. Base map is WorldImagery from Global Mapper.

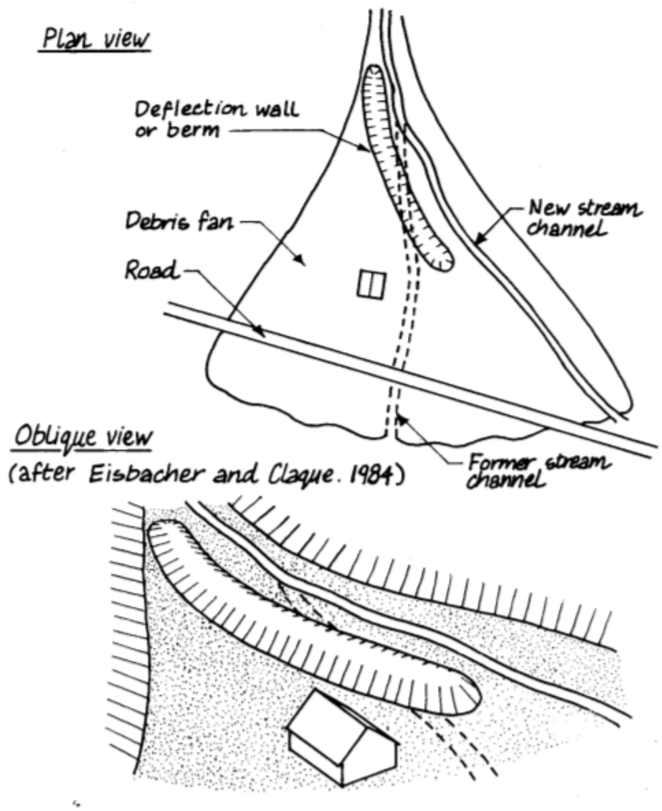

Figure 4-2. Plan and oblique view of deflection wall or berm (BC Ministry of Forests Research Program, 1996).

The distance from the fan apex to the Reid Road crossing along the left (east) bank is approximately 230 m. The required height of a berm should be informed by modelling. BGC estimated a material cost for two potential berm heights of 1.5 m and 2 m, each with side slopes of 1.5H:1V, and a crest width of 4 m. The side of the berm that parallels the creek would be protected with riprap. For the purposes of cost approximation, BGC assumed Class 3 riprap (D_{100} of 1100 mm) for erosion protection. Table 4-2 outlines the estimated capital costs for the two berm heights, with additional detail in Appendix B. BGC has not estimated the anticipated operations and maintenance costs over the life-cycle of the berm.

Table 4-2. Estimated capital cost of berm on Jason Creek

Berm Height	Estimated Capital Cost
1.5 m	$500,000
2 m	$600,000

Note: Costs are estimated based on unit costs from mitigation construction bid on Heart Creek, AB in April 2020. Costs rounded to nearest $100,000.

The design height of the berm would need to be confirmed with numerical modelling to achieve sufficient protection including adequate freeboard. The amount of freeboard will depend, in part, on whether superelevation of the debris flow around a curve needs to be designed for.

Design of the berm will also need to consider risk transfer to downstream infrastructure and properties. This can be evaluated with numerical modelling.

4.2. Improve Conveyance at Reid Road Crossing

The Reid Road culvert is insufficient to convey debris flows on Jason Creek. The crossing could be improved through replacement of the circular corrugated steel culvert with a large box culvert or a bridge with sufficient capacity to convey the design event. BGC estimates that a sufficiently sized box culvert could cost approximately $1.3 to $1.5 M based on cost estimates from similar sites in BC and Alberta. A challenge with any water conveyance structure, is the potential for avulsions in the event of a blockage or event exceeding the capacity of the structure. At Reid Road, the alignment of the road across the fan encourages flow along the road and east in case the crossing is overtopped. A bridge or box culvert constructed in isolation would remain vulnerable to such avulsions. BGC acknowledges that the Ministry of Transportation and Infrastructure (MoTI) of BC is the responsible authority for Reid Road.

An alternative option to improve the conveyance at the crossing and reduce the avulsion potential is to install an armoured ford at Reid Road. A conceptual diagram of an armoured ford is shown in Figure 4-3. Armoured fords have been used on Mud (Turbid) Creek in the upper Squamish Valley and also in Washington State on the Mt Baker Hwy.

An armoured ford would involve regrading the road so that the crossing is a local depression that encourages flow to re-enter the channel on the downstream side if the culvert is overtopped. The road surface through the ford could be concrete or grouted competent flat rock to increase the erosion resistance. The culvert at Reid Road could be twinned (two 1600 mm corrugated steel pipe culverts) to increase the capacity to convey clearwater flow while a grizzly rack[11] could be constructed across the channel upstream of the crossing to retain woody debris and larger particles. The dimensions of the culvert(s) and grizzly rack should be refined with detailed assessment. The channel would be protected from erosion on the up- and downstream sides of the crossing with grouted riprap.

BGC estimates that an armoured ford crossing at Jason Creek would cost approximately $400,000 including the grizzly rack (Appendix B). Field verification and additional analyses are required to determine the design dimensions for Jason Creek and therefore, BGC acknowledges that this cost estimate is approximate and subject to change.

[11] A grizzly rack is constructed across a channel upstream of a culvert or other water conveyance structure to retain large woody debris and reduce the likelihood of blockage.

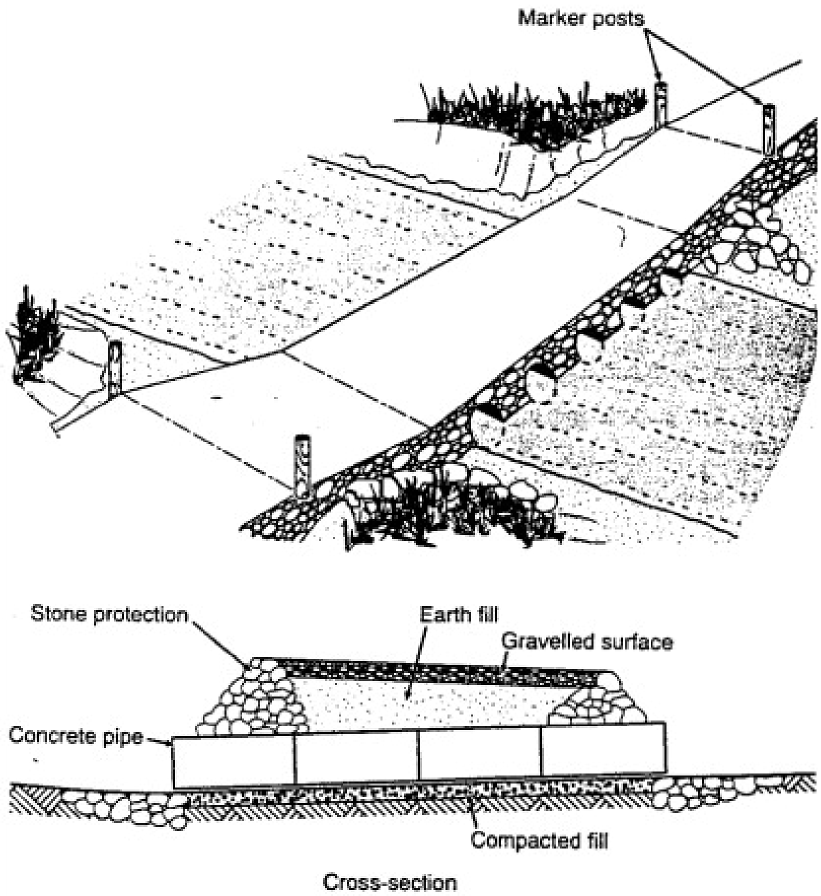

Figure 4-3. Schematic of armoured ford (Hazeltine & Bull, 2003). At Jason Creek, twin culverts with a concrete road surface and a grizzly rack upstream of the crossing could be used.

Regular debris removal and maintenance would be required on the grizzly rack; however, in comparison with risk-control measures installed further upstream on the fan or in the watershed, access to the grizzly would be simpler and more cost effective. BGC has not estimated the operations and maintenance costs over the life cycle of the ford or grizzly rack.

As with the berm, design of the Reid Road crossing will need to consider risk transfer to downstream infrastructure and properties. This can be evaluated with numerical modelling.

4.3. Evacuation Alert(s) /Order(s)

The evacuation order and alert currently implemented are examples of passive risk-control techniques. Cordilleran identified some of the challenges associated with managing risk through evacuation alerts and/or orders over the long term. BGC considered the implementation of a weather forecast-based warning system to supplement the current alert and order in consideration of the seasonal nature of debris flows. Such systems require a number of key components in order to be successful. These are:

1. known dates of previous debris flows (at least 3) and their weather conditions
2. weather forecast[12] data of sufficient quality and reliability and with sufficient granularity to apply to the study area and/or system to reliably downscale regional data to the study area
3. operational framework to ingest weather forecast, determine threshold conditions to issue warnings, disseminate warning information, and implement evacuations
4. sustainable funding structure to support system operational and risk response costs
5. an enforcement mechanism in case evacuations orders are not heeded.

In absence of any of the above components, a weather forecast-based warning system does not appear to be an effective risk-control option. For this reason, at Jason Creek, a warning system is not recommended and BGC has not estimated the costs of developing or implementing a weather forecast-based warning system.

BGC has assessed that outside of the Jason Creek and adjacent fans, debris-flow hazards originating in the Jason Creek watershed are likely to result in intensities lower than those that could credibly result in loss of life for people within buildings. BGC has not reviewed the conditions on Mungye fan or the small west tributary fan (Drawing 01). A field visit possibly assisted by numerical modeling would be required to comment on hazards originating in nearby watersheds and fans.

4.4. Risk Control on Individual Properties

Risk-control options at individual properties can be implemented to reduce the vulnerability of individual properties or structures. Various risk-control measures at this scale are available. Selection of appropriate measures needs to consider the hazard exposure of the site, impact forces, the building location(s), micro-topography, available materials, material and construction costs, site aesthetics, and risk transfer to adjacent area(s). Figure 4-4 shows an example schematic of multiple risk-control components applied to a single building.

Various important limitations to site-specific risk-control measures apply. Design of such measures should be completed under the supervision of a Qualified Professional (QP); however, the scope of a debris-flow hazard and risk assessment is outside of the typical scope of site-specific assessments completed by QPs. The cost to design and implement such measures also needs to be considered. Finally risk transfer to adjacent area(s) and property(ies) must be evaluated. The SLRD advised BGC that structural modifications of residences are not considered feasible, but that mitigation works that aim to protect against debris flows on individual properties could be considered, if appropriately designed.

[12] Debris-flow warning systems on small watersheds must be based on weather forecasts and not weather monitoring data in order to allow sufficient lead time for data collection, analysis, decision-making, and implementation in advance of hazard occurrence.

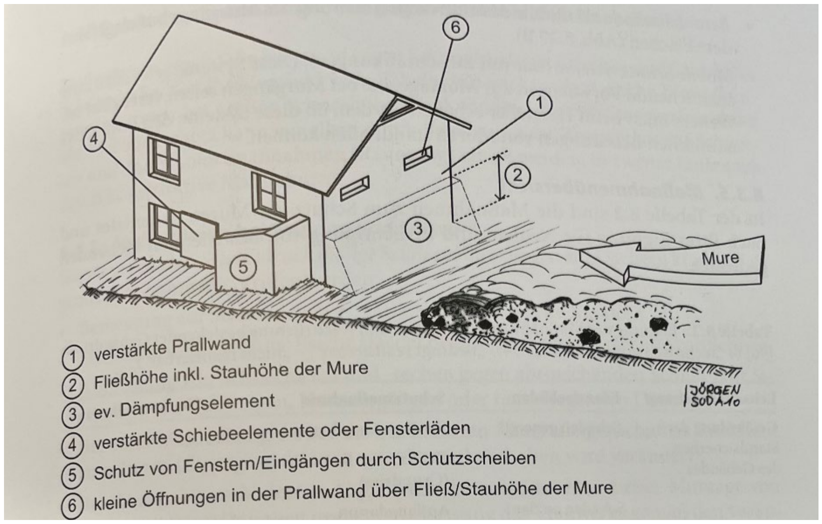

Figure 4-4. Example schematic of building-level risk control options. Annotations are in German and read 1) reinforced baffle, 2) flow height including the accumulation height of the mudflow, 3) buffer element, 4) reinforced sliding elements or shutters, 5) protection of windows/entrances with protective panes, 6) small openings in the impact wall above the flow/level of the debris flow. (Suda & Rudolf-Miklau, 2012). Other configurations are certainly possible.

If risk control on individual properties is pursued as the preferred option, BGC re-iterates the importance of also including improvements to the Reid Road crossing at Jason Creek. This is due to the need to improve the conveyance at Reid Road as well as the accompanying benefits of minimizing the risk of overland flow outside of the Jason Creek channel.

BGC has not estimated the costs of property- or building-level risk-control options as this requires a site-specific assessment and review of the overall objectives of the landowner.

4.5. Risk Transfer Considerations

Risk transfer can occur when a mitigation structure redirects the hazard, in this case a debris flow, and increases the risk at another location. Selection of the preferred mitigation option(s) at Jason Creek should consider risk transfer from any existing protection works (ad hoc dike and debris berm identified by Cordilleran (December 13, 2021)) and proposed mitigation. The existing protection works should be surveyed to collect information on their dimensions, construction methods/materials, and geotechnical condition. These works could be integrated into numerical modelling at the site.

As outlined, the impact of proposed mitigation works on downstream properties and infrastructure should be considered and can be evaluated through a comparison of pre- and post-mitigation conditions using numerical modelling.

5.0 RECOMMENDATIONS FOR FUTURE WORK

Future work to understand the hazard and risk on Jason Creek should include:

- Acquisition of lidar for the watershed and fan areas
- Acquisition and review of the geotechnical reports completed in advance of construction of the properties along Reid Road.
- Field visit to confirm:
  - Alignment of Jason Creek on the fan
  - Location and dimensions of all building footprints to supplement the aerial mapping completed by BGC
  - Conditions of Jason Creek right (west) bank from the fan apex downstream to the Reid Road crossing to evaluate the need for erosion protection or a berm
  - Alignment, dimensions, construction materials, and condition of existing protection works (ad hoc dike, debris berm, and others, if applicable)
  - Estimation of sediment yield rates along the channel
  - Refinement of volume estimates of landslides that could trigger debris flows
  - Structural measurements to inform kinematic analysis for rock slope failures in the Jason Creek watershed
  - Dendrochronological investigations to constrain past debris-flow frequency
  - Test trenching to measure former debris-flow depths and radiocarbon dating of organic materials to refine a frequency-magnitude relationship
- Detailed hazard assessment of alluvial fan and rock slope hazards from the Jason Creek watershed including numerical modeling for a variety of return periods (up to 1,000 to 3,000 year return periods as per the draft EGBC Guidelines for Landslide Assessments anticipated for 2022 (EGBC, n.d.)
- Quantitative life-loss risk assessment for the properties on Jason Creek upper, middle, and lower fans, and if life loss potential is considered to be unacceptable:
- Preliminary to detailed design of risk-control measures on Jason Creek and subsequent implementation of the preferred system should funding be secured.
- Preparation of a composite hazard map that informs future development decisions and which is in accordance with EGBC, 2022.
- Given that all risk management decisions imply evaluation of risk, whether or not formally established as policy or regulation, the development of risk evaluation criteria by SLRD to support objective and transparent decisions about risk tolerance within the District.

6.0 CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

BGC ENGINEERING INC.
per:

[redacted]

[redacted]

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LCH/KH/sf/mm

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APPENDIX A
PRELIMINARY RISK ASSESSMENT

Preliminary Individual Risk Assessment: Jason Creek

Hypothetical home near fan apex

Debris Flow Scenario		Return Period		Annual Probability of occurrence	Spatial Impact Probability				Life-Loss Vulnerability										Temporal Impact Probability		Annual PDI					
Volume Class	Volume	From	To	H	S_1		S_2		Flow depth (m)		Slope (deg)		Flow velocity (m/s)		Flow Intensity, I		V		T		Annual PDI $R = H*S_1*S_2*T*V$			micromorts		
					Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Best Estimate	Max	Min	Best Estimate	Max
1	1,000	10	30	0.0667	0.6	0.8	0.4	0.5	0.3	0.5	14	18	2	2	1.0	2.8	0	0.02	0.5	0.9	0.0E+00	2.4E-04	4.8E-04	0	240	480
2	2,000	30	100	0.0233	0.7	0.9	0.5	0.6	0.4	0.6	14	18	2	3	1.7	4.0	0.02	0.2	0.5	0.9	8.2E-05	1.2E-03	2.3E-03	82	1175	2268
3	6,000	100	300	0.0067	0.8	0.95	0.6	0.7	0.6	1	14	18	2	3	3.7	11.1	0.2	0.4	0.5	0.9	3.2E-04	9.6E-04	1.6E-03	320	958	1596
4	13,000	300	1,000	0.0023	0.9	0.99	0.7	0.8	0.8	1.2	14	18	3	4	6.5	16.1	0.2	0.4	0.5	0.9	1.5E-04	4.1E-04	6.7E-04	147	406	665
5	44,000	1,000	3,000	0.0007	0.99	0.95	0.8	0.9	1	1.5	14	18	3	4	10.2	25.7	0.4	0.4	0.5	0.9	1.1E-04	1.6E-04	2.1E-04	106	155	205
6	98,000	3,000	10,000	0.0002	1	1	0.9	0.99	1.5	2.5	14	18	4	6	23.7	76.6	0.4	0.6	0.5	0.9	4.2E-05	8.3E-05	1.2E-04	42	83	125
7	180,000	10,000		0.0001	1	1	0.95	0.99	2.5	4	14	18	5	7	70.3	214.0	0.6	0.9	0.5	0.9	2.9E-05	5.4E-05	8.0E-05	29	54	80
																				Annual Probability of Death to the Individual (PDI):	**7.0E-04**	**3.0E-03**	**5.3E-03**	**696**	**3018**	**5339**

Hypothetical home at approximately mid-fan

Debris Flow Scenario		Return Period		Annual Probability of occurrence	Spatial Impact Probability				Life-Loss Vulnerability										Temporal Impact Probability		Annual PDI					
Volume Class	Volume	From	To	H	S_1		S_2		Flow depth (m)		Slope (deg)		Flow velocity (m/s)		Flow Intensity, I		V		T		Annual PDI $R = H*S_1*S_2*T*V$			micromorts		
					Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Best Estimate	Max	Min	Best Estimate	Max
1	1,000	10	30	0.066667	0.3	0.5	0.01	0.1	0	0.1	4	8	1	1	0.0	0.1	0	0	0.5	0.9	0.0E+00	0E+00	0.0E+00	0	0	0
2	2,000	30	100	0.023333	0.4	0.6	0.05	0.2	0.1	0.3	4	8	1	2	0.1	0.9	0	0	0.5	0.9	0.0E+00	0E+00	0.0E+00	0	0	0
3	6,000	100	300	0.006667	0.5	0.7	0.1	0.3	0.2	0.5	4	8	1	2	0.4	2.2	0	0.02	0.5	0.9	0.0E+00	1E-05	2.5E-05	0	13	25
4	13,000	300	1,000	0.002333	0.6	0.8	0.2	0.4	0.4	0.6	4	8	2	2	1.2	3.2	0.02	0.2	0.5	0.9	2.8E-06	7E-05	1.3E-04	3	69	134
5	44,000	1,000	3,000	0.000667	0.7	0.9	0.3	0.5	0.5	0.7	4	8	2	2	1.9	4.3	0.02	0.2	0.5	0.9	1.4E-06	3E-05	5.4E-05	1	28	54
6	98,000	3,000	10,000	0.000233	0.8	0.95	0.4	0.9	0.6	1.5	4	8	2	4	2.6	19.8	0.02	0.4	0.5	0.9	7.5E-07	4E-05	7.2E-05	1	36	72
7	180,000	10,000		0.000100	1	1	0.6	0.95	1	2	4	8	3	4	7.0	36.2	0.2	0.6	0.5	0.9	6.0E-06	3E-05	5.1E-05	6	29	51
																				Annual Probability of Death to the Individual (PDI):	**4.9E-06**	**1.5E-04**	**2.9E-04**	**5**	**145**	**285**

Notes:

1. Debris flow volumes derived from F-M relationship presented in Cordilleran (December 13, 2021) interpolated between 25- and 5,000-year and extrapolated to a 10,000-year event using a power fit.
2. Spatial impact probability, life-loss vulnerability, and temporal impact probability sources shown in tables bellow.
2. Flow depth estimated from photographs provided by Cordilleran (December 13, 2021) and informed by expert judgement.
3. Fan slope at fan apex and mid-fan measured from satellite imagery-derived DTM. The quality of the DTM is a function of the processing techniques applied to remove natural (e.g., trees) and built (e.g., building) surfaces. Higher resolution DTM sources (e.g., lidar) increase the accuracy.
4.. Flow velocity calculated as a function of flow depth and fan slope using empirical relations presented in Prochaska et al. (2008). The best-fit regression from Lo (2000) was determined to be the best fit for Jason Creek where debris flow would be a combination of channelized and overland flow.
5. Best estimate for annual PDI is an average of the minimum and maximum values.
6. PDI estimates are for hypothetical properties based on the relative location to the fan apex. These estimates should not be relied upon for any individual properties on Reid Road.

Risk Components

Risk Components		Notes
Geohazard probability	H	Annual probability of hazard occurrence (based on return period).
Spatial probability	S_1	Probability that debris flow reaches the fan (based on expert judgement).
	S_2	Probability that building is hit by debris flow (based on expert judgement).
Life-loss vulnerability	V	Function of debris flow intensity (see table)
Temporal impact probability	T	Probability that elements at risk are in impact zone (based on residential for minimum and individual most at risk

Temporal Probability

	P(T:H)
Residential	0.5
Non-Residential or Hotel	0.25
Individual Most at Risk	0.9

For residential assumes that the property is occupied about 50% of the time on average. A more conservative value of 90% is used for the maximum range and corresponds to a person spending the greatest proportion of time at home, such as a young child, stay-at-home person, or an elderly person.

Life-Loss Vulnerability for People in Buildings

Flow Intensity Index (m^3/s^2)		Building Impact	Life loss Vulnerability
From	To		
0	1	Minor damage	0
1	3	Moderate damage	0.02
3	10	Major damage	0.2
10	30	Extensive damage	0.4
30	100	Severe damage	0.6
100	n/a	Complete destruction	0.9

Developed from judgement based on Jakob et al. (2011), and corresponds to best estimate values applied in previous BGC quantitative risk assessments to estimate debris-flow vulnerability of persons within buildings.

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APPENDIX B
RISK-CONTROL COST ESTIMATES

B.1. COST ESTIMATE INTRODUCTION

This appendix contains the cost estimates of the engineered risk-control options considered at Jason Creek. Unit costs are sourced from the following sources:

- Heart Creek, Alberta average mitigation construction bid from April 2020
- Alberta Transportation unit price averages report from 2015-2017
- Construction bids from creek crossings in North Vancouver, BC (various contractors),

Option total costs are rounded to the nearest $100,000 so as to not give a sense of exactness. These cost estimates should be considered as order-of-magnitude and may vary -50% to >+100% as they are developed without the benefit of detailed topography, numerical modelling, or field verification. Volumes, areas and lengths are estimated using approximate geometries and layouts and are subject to change as part of future phases of design.

Table B-1. Cost estimate for 1.5 m high flow diversion berm.

Item	Quantity	Unit	Unit Cost	Item Total Cost
Access construction	230	m	$ 100	$23,000
Clearing, grubbing, & disposal	2,900	m2	$ 6	$ 17,000
Excavation	1,200	m3	$ 6	$ 7,000
Off-site sediment disposal	1,200	m3	$ 16	$ 19,000
Berm fill (supply & placement)	1,800	m3	$ 34	$ 61,000
Class 3 riprap (supply & placement)	1,600	m3	$ 137	$ 219,000
Seeding, planting, site restoration	1,600	m2	$ 5	$ 8,000
			Direct Costs Subtotal:	**$ 350,000**
Contractor general		Lump sum	15%	$ 53,000
Contingency (unlisted items)		Lump sum	10%	$ 35,000
Engineering and permitting		Lump sum	15%	$ 53,000
			Indirect Costs Subtotal:	**$ 140,000**
			Total	**$ 500,000**

Table B-2. Cost estimate for 2.0 m high flow diversion berm.

Item	Quantity	Unit	Unit Cost	Item Total Cost
Access construction	230	m	$ 100	$23,000
Clearing, grubbing, & disposal	3,200	m2	$ 6	$ 19,000
Excavation	1,200	m3	$ 6	$ 7,000
Off-site sediment disposal	1,200	m3	$ 16	$ 19,000
Berm fill (supply & placement)	2,600	m3	$ 34	$ 88,000
Class 3 riprap (supply & placement)	1,800	m3	$ 137	$ 247,000
Seeding, planting, site restoration	1,800	m2	$ 5	$ 9,000
Direct Costs Subtotal:				**$ 410,000**
Contractor general		Lump sum	15%	$ 62,000
Contingency (unlisted items)		Lump sum	10%	$ 41,000
Engineering and permitting		Lump sum	15%	$ 62,000
Indirect Costs Subtotal:				**$ 170,000**
Total				**$ 600,000**

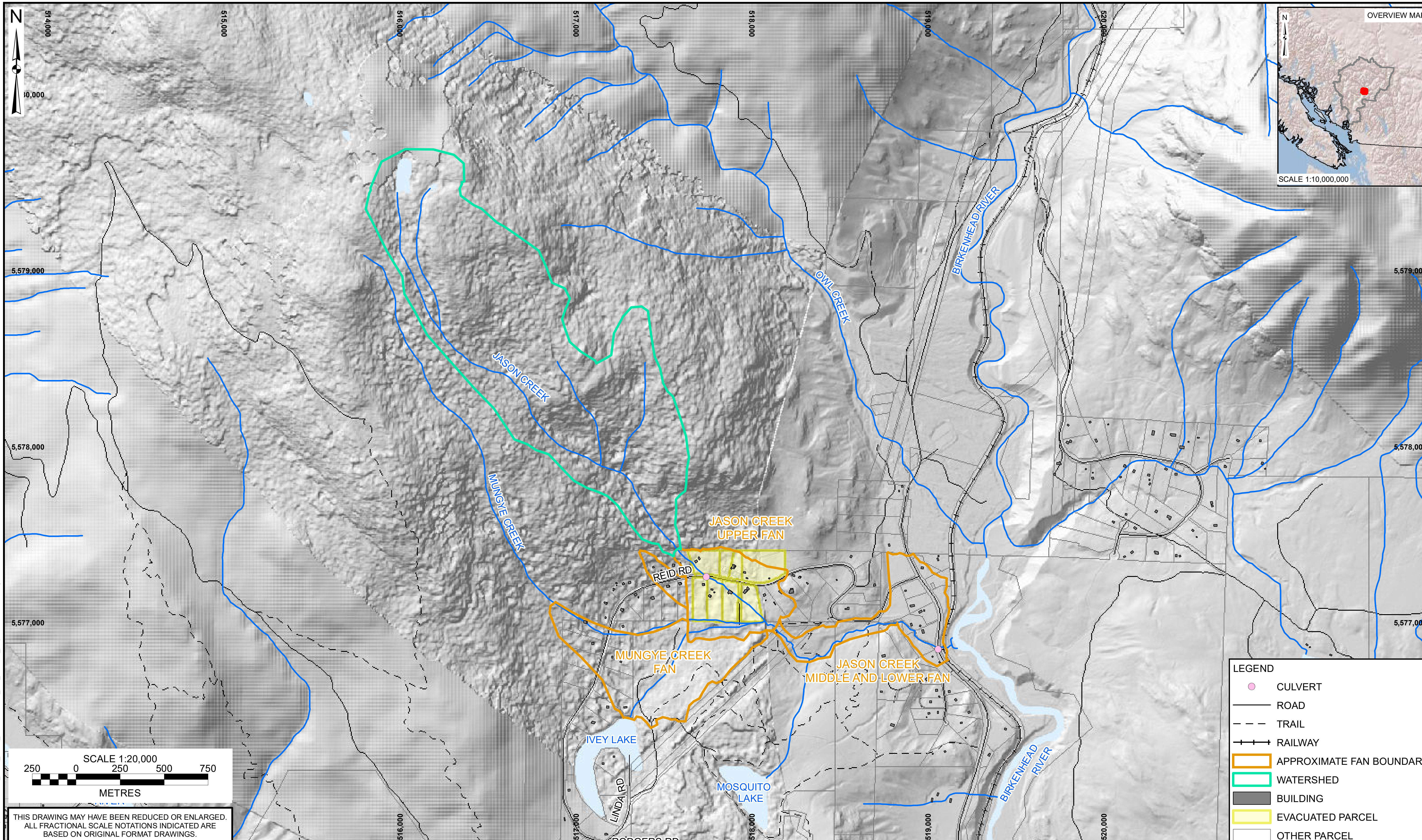
Table B-3. Cost estimate to replace Reid Road culvert with concrete box culvert.

Item	Quantity	Unit	Unit Cost	Item Total Cost
Concrete box culvert	1	each	900,000	$900,000
Seeding, planting, site restoration	2,000	m2	$ 5	$ 10,000
Direct Costs Subtotal:				**$ 910,000**
Contractor general		Lump sum	15%	$ 137,000
Contingency (unlisted items)		Lump sum	10%	$ 91,000
Engineering and permitting		Lump sum	15%	$ 137,000
Indirect Costs Subtotal:				**$ 360,000**
Total				**$ 1,300,000**

Table B-4. Cost estimate to replace Reid Road culvert with armoured ford.

Item	Quantity	Unit	Unit Cost	Item Total Cost
Access construction	25	m	$ 100	$2,500
Clearing, grubbing, & disposal	2,000	m2	$ 6	$ 12,000
Road subgrade excavation	100	m3	$ 19	$ 1,900
Off-site sediment disposal	100	m3	$ 16	$ 1,600
Regrade road	200	m2	$ 2	$ 300
Concrete road surface	60	m3	$ 1,500	$ 90,000
Grizzly rack	10	m	$ 3,000	$ 30,000
Culvert	10	m	$ 3,000	$ 30,000
Grouted riprap	400	m2	$ 300	$ 120,000
Seeding, planting, site restoration	2,000	m2	$ 5	$ 10,000
			Direct Costs Subtotal:	**$ 300,000**
Contractor general		Lump sum	15%	$ 45,000
Contingency (unlisted items)		Lump sum	10%	$ 30,000
Engineering and permitting		Lump sum	15%	$ 45,000
			Indirect Costs Subtotal:	**$ 120,000**
			Total	**$ 400,000**

DRAWINGS



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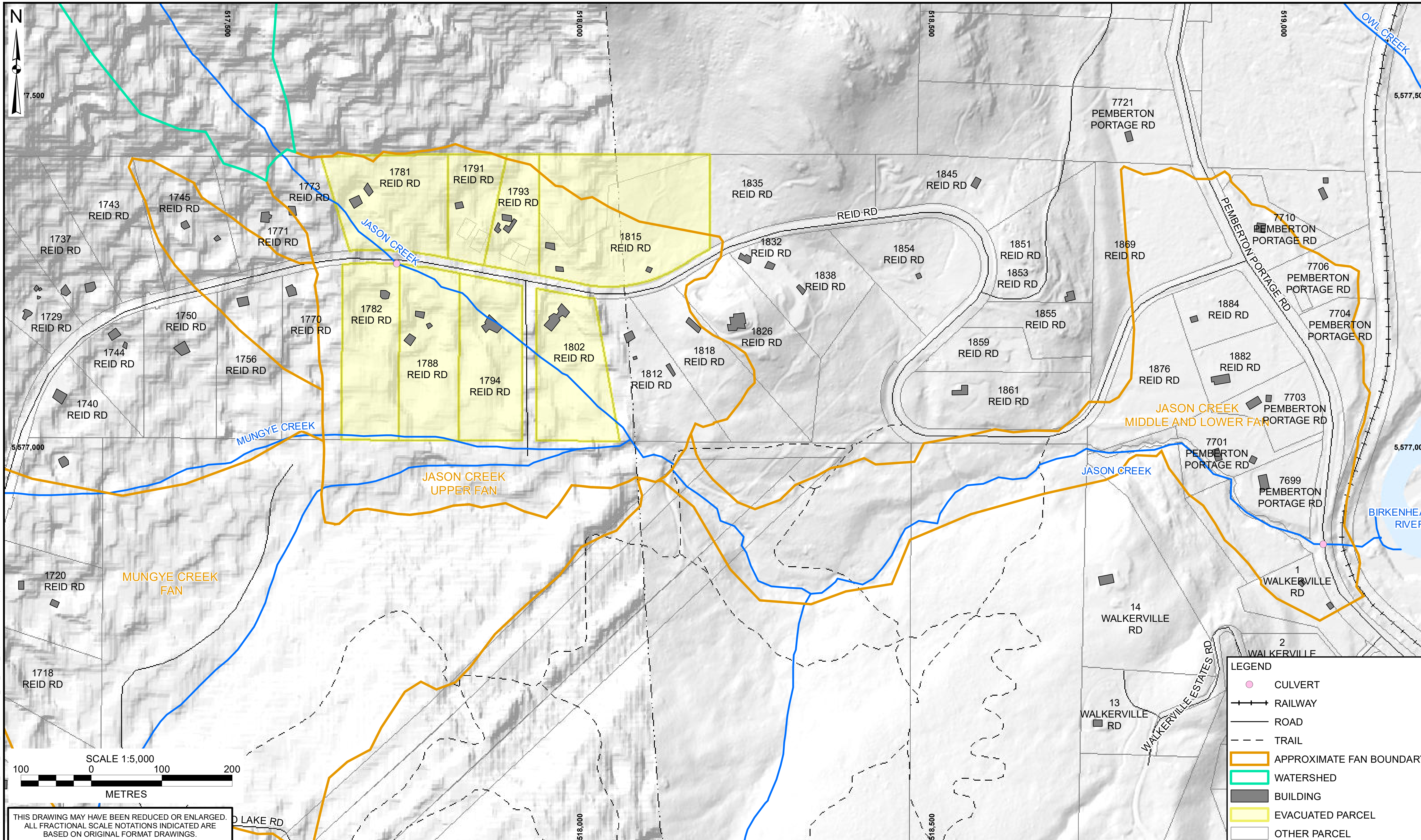

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TITLE: FAN AREAS MAP

PROJECT No.: 1358009

DWG No: 02