ZEBALLOS SLOPE HAZARDS RISK ASSESSMENT UPDATE

PROJECT NO.: 1849-002

April 22, 2019
Meredith Starkey, Chief Administrative Officer  
Village of Zeballos  
157 Maquinna Avenue  
Zeballos, BC V0P 2A0

Dear Ms. Starkey,

Re: Zeballos Slope Hazards Risk Assessment Update – FINAL

Please find enclosed a FINAL version of our above referenced report. We appreciate the opportunity to work with the Village on this assignment. We trust this report meets your current requirements.

Yours sincerely,

BGC ENGINEERING INC.
per:

Hamish Weatherly, M.Sc., P.Geo.
Principal Hydrologist
EXECUTIVE SUMMARY

Portions of the Village of Zeballos (the Village) are located below steep rocky slopes that rise to almost 800 m elevation. In 2018, the Village awarded BGC Engineering Inc. (BGC) a detailed assessment and comparison of flood and slope hazards for the Village of Zeballos (BGC, December 21, 2018). BGC concluded the slopes east of the Village are prone to rock fall, rock slides and debris flows.

In August 2018, a wildfire burned 128 hectares (ha) of forest on the eastern hillsides above the Village. This fire was perceived to increase the probability of rock fall, rock slide, and debris flow risk. Accordingly, the Village evacuated 17 properties. The Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) retained BGC for a post-fire hazard assessment, the results of which were integrated into the original detailed geohazard risk assessment (BGC, October 15, 2018).

FLNRORD and BGC's primary concerns revolved around the perceived increase in the activity of rock fall and debris flows following the fire. BGC quantified risks from rock fall, rock slides and debris flows potentially affecting the eastern portions of the town and found that 12 properties had an individual risk of greater than 1:10,000, a risk tolerance threshold used in Canada by the District of North Vancouver and the Town of Canmore to guide their land use policies for steep creek and landslide hazards. This finding prompted the Village to maintain the evacuation orders. BGC interpreted that the fire had increased the likelihood of a post-fire debris flows and rock fall by a factor of 10 which appeared reasonable given the experience of post-fire geomorphic activity observed elsewhere in North America.

The assessment for FLNRORD included reconnaissance along the bottom of the slope and a helicopter inspection of the burned slopes. At the time the burned slopes and creeks were not hiked for safety reasons. A follow up visit was conducted on March 7 and 8, 2019 by Hamish Weatherly and Matthias Jakob of BGC. This time, Mr. Weatherly and Dr. Jakob ascended the three study creeks as far as was practical and crisscrossed the burned slopes above the Village. Sedimentation volumes were noted in the creek channels and the geomorphic stability of the watershed examined. Soil depth was probed in various locations and the burn severity noted.

During the unusually dry fall and winter of 2018/2019, storms did not exceed a return period of 2 years for durations of 1 hour to 24 hours. None of those storms was sufficiently large to trigger rock fall reaching the Village boundaries nor did it trigger debris flows.

Based on the March 2019 field review, BGC concluded that, in the case of the August 2018 wildfire, a factor of 10 increase of debris flow and rock fall activity appears over-conservative. Subsequent to the field review, the factor increase was lowered to two for both A Creek and B Creek (which were affected by the wildfire), still reflecting a somewhat higher susceptibility of the slopes to produce rock fall and debris flows due to the wildfire. In addition, BGC reviewed the potential volumes of debris flows on A, B and C creeks and adjusted volumes from previous estimates. In addition, a second return period class was added as a sensitivity analysis to reflect
a deeper understanding of debris flow supply mechanisms and watershed stability even though the return period class from 1000 to 3000 is not mandated by the EGBC professional practice guidelines for legislated landslide assessments (EGBC, 2010). Debris flows were modeled with the new parameters, and the quantitative risk assessment adjusted given the new modeling results and the post-fire frequency adjustment factor.

BGC found that only 5 (compared to previously 12) properties exceeded the critical 1:10,000 individual risk threshold given present occupancy. BGC also estimated risk given full-time occupancy as it is possible that occupancy changes with changes in ownership or the personal situation of the property owner. A change in occupancy could primarily influence the time that is being spent in a home, which in turn increases the risk to residents. Under the assumption of full-time occupancy, 11 properties exceed the 1:10,000 life loss risk threshold.

Based on these findings, the Village may wish to review the evacuation orders for those properties whose individual risk has dropped below the 1:10,000 life loss risk threshold.

While this study has suggested an individual risk relaxation based on the field findings and accompanying analyses, the reader is reminded that there is no absolute safety for residents in the designated hazard zones. A residual risk persists even for those properties whose risk has now been re-classified as below 1:10,000. In line with the ALARP principle that posits that risk should be reduced where practical and affordable, residents in the hazard zones are able to reduce their risk by avoiding using their property during inclement weather should they choose to return to their properties after lifting the evacuation order for those properties. Lastly, BGC reviewed previous structural (engineered) mitigation concepts and refined those with the objective of examining their effectiveness and approximate cost for their construction. Technically viable mitigation options include debris basins, constructed channels, deflection berms and barriers.

BGC also visited two potentially suitable sites, one within the Village boundaries, that are not subject to slope or river geohazards and which could be zoned residential should the Village wish to resettle properties subject to intolerable risk and/or provide additional lands for future development in Zeballos. Given the long-term projected worsening geohazards and associated risks faced by Zeballos from rising sea levels, predicted higher flood levels and intensification of extreme storms, it may be prudent to consider beginning a subdivision approval process as an option to facilitate resettling of those willing to relocate to safer locations within the Village of Zeballos.
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LIMITATIONS

BGC Engineering Inc. (BGC) prepared this document for the account of the Village of Zeballos. 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 of 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 of actions based on this document.

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1.0 INTRODUCTION
1.1. Background

The Village of Zeballos (the Village) is located on the fan-delta of the Zeballos River where it discharges into the Pacific Ocean through the Zeballos Inlet. Steep mountains rise to the east from sea level to approximately 800 m. Three small tributaries (Creeks A, B, and C) enter the Village from the steep hillslopes toward the portion of the Village located to the east of the Zeballos River (Drawing 01). The Village is exposed to hazards originating from the Zeballos River (flooding, bank erosion) and the ocean (storm surges, inundation, wave runup, tsunamis). Buildings on the east side of the river are also potentially subject to rock fall, rock slides, and debris flows from the three small tributary creeks. Rock fall and rock slides can originate from numerous cliffs and bluffs of the steep slopes east of the Village.

In light of these geohazards, the Village was awarded a grant from the provincial Community Emergency Preparedness Fund (CEPF) to seek consulting services with the objective of characterizing flood and slope hazards, as well as the associated risks posed to their community, and to assess mitigation options. While Golder (January 23, 1997) had previously identified slope hazards (rockfall and rock slides) on the east side of Zeballos and assigned probabilities to their occurrence, the grant application noted that those findings needed to be updated and affirmed. The Village retained BGC Engineering Inc. (BGC) to conduct this work. The overall objective of the risk assessment was to estimate the frequency and magnitude of hydrogeomorphic hazards at the Village and to identify conceptual mitigation options that could reduce risk to a tolerable risk level.

BGC’s original scope of work included a semi-quantitative risk assessment (SQRA) approach for the geohazards under consideration, using risk matrices for flooding and slope hazards. This work was done with the ultimate goal of homogenizing and prioritizing risks from disparate geohazards.

Following a wildfire in August of 2018 on the east slopes above the Village, BGC’s scope was expanded through collaboration with the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD). The scope expansion included a quantitative risk assessment (QRA) for safety risk specifically for 17 residences that were evacuated via an evacuation order issued by the Village and informed by FLNRORD staff recommendation in September 2018 near the three tributary creeks on the east side of the Village. The concern was that the recent wildfire had increased the rate of rock fall, rock slides and debris flow beyond background levels. BGC’s QRA (BGC, October 15, 2018) was meant to help inform the Village in deciding if and when the property owners of the currently evacuated houses can return to their homes.

The QRA quantified the hazard and risk from debris flows, rock slides and rock fall. For pre-fire conditions, BGC found that 7 properties exceeded a risk threshold of $1 \times 10^{-4}$ (1 in 10,000), which is a safety risk tolerance threshold adopted by the Town of Canmore and District of North Vancouver (DNV) for existing development. For post-fire conditions, an additional five homes were found to exceed a risk threshold of $1 \times 10^{-4}$. This increase in risk was based on BGC’s experience and literature review that the post-fire conditions had increased the frequency of
debris flows by an order of magnitude (i.e., 10 times). In other words, debris flows that used to occur at a 300 to 1000-year return period would now occur during a 30 to 100-year return period.

BGC’s findings were based on a limited traverse at the base of the fire-affected slopes (a foot traverse of the affected slopes was considered too dangerous as the fire had occurred only within a few weeks of BGC’s site visit), a helicopter overflight, and a literature review of the impacts of fire on debris flow frequency and intensity (although there were no analogs for the impact of forest fires in a temperate maritime climate). The fire-affected slopes are now safe to traverse, and early in 2019 BGC (February 1, 2019) proposed to the Village that the QRA be updated based on field observations. The Village was interested in such an update, as affected homeowners remained under an evacuation order. Funding for the hazard and risk update was provided to the Village by Emergency Management British Columbia (EMBC).

The overall objective of the risk update is to determine for which properties (if any) the individual risk value would be below 1:10,000, given the current conditions on the east slopes. The risk value of 1:10,000 was the threshold that guided a FLNRORD recommendation and the Village’s decision on property evacuations. This risk relaxation could be ascertained if BGC, upon a field visit without access limitations, would decide that the 10x multiplier for post-fire risk is overly conservative.

1.2. Scope of Work

The proposed scope of work included the following elements:

1. A site visit to:
   - Conduct a full traverse of the accessible portions of A, B and C Creeks and some of the accessible adjacent side slopes to assess tree mortality by the fire which influences root strength, estimate the volume of sediment stored in the creeks, estimate the potential volume of side slope failures and observe any existing side slope instabilities such as tension cracks, bulging or lateral spreading. This assessment could allow BGC to change the post-fire hazard multiplier.
   - Identify rock falls or debris movements that have occurred since the August 2018 wildfire, measure their locations (initiation and runout) by hand-held GPS and record boulder dimensions.

2. Following the site visit, BGC would:
   - Conduct an analysis of rock falls or debris movements that have occurred since the August 2018 wildfire. This analysis may allow a fine-tuning of rock fall runout and frequency estimates. It would be supplemented with information by BC Ministry of Transportation and Infrastructure (MOTI) on rock fall observed along the access road, which is currently still closed to traffic.
   - Analyze all storms that have occurred since the August 2018 wildfire with respect to return periods for different rainfall durations. The rationale for this work is to determine if any of the 2018 storm durations have been particularly rare, which, in
absence of debris flows, may allow a reduction of the post wildfire hazard multiplier of 10.

- If found necessary, re-analyze debris flow hazard via numerical modelling given the findings from the site visit to examine changes in modelling results and thus hazard exposure.
- Provide preliminary design ideas and concepts for mitigation works. Those will be limited to sketches and rough dimensions.

Results of the updated hazard and risk assessment are to be documented in a draft report for review by the Village. The report will also provide direction as to whether risks currently deemed as unacceptable by the Village could be reduced to a tolerable or even acceptable level through affordable structural mitigation efforts.

The reader should reference BGC’s original hazard and risk assessment (BGC, October 15, 2018) for background information and details on the original analysis. Much of that information is not presented in this report.
2.0 HAZARD ASSESSMENT UPDATE
This chapter provides a hazard assessment update for the identified slope hazards on the east side of Zeballos.

### 2.1. Site Visit

On March 7 and 8, 2019, Hamish Weatherly, M.Sc., P.Geo. and Dr. Matthias Jakob, P.Geo. of BGC hiked A, B and C creeks to as high as practical, either within the creek bed, or on side slopes for those sections where the creek descended over bedrock waterfalls. Several observation waypoints were established along the creeks, the locations of which are shown on Drawing 01. The following observations were made:

- Reach length and gradient
- Channel debris yield rate\(^1\)
- Reaches burned/unburned and burn severity
- Hillslope stability and sediment connectivity to the creeks
- Potential debris flow initiation mechanisms
- Rock fall sources and recent rock fall
- Soil thickness and degree of burning
- Blowdown and toppled trees.

The following key observations were made:

- No fresh (< 1 year) debris slides were encountered
- No large detached rocks were encountered
- Abundant loose angular colluvium was noted on all burned slopes (Figure 2-1)
- Extensive blowdown and fallen trees with their root collars burned (Figure 2-2).

In conclusion, the August 2018 wildfire affected different portions of the watersheds of A and B creeks. No fire effects were noted on C creek. While the forest floor has been burned for large portions of the A and B creek watersheds exposing colluvial sediment (Figure 2-1), only a thin veneer of soil mantles many of the bedrock underlain slopes. This implies that even in the case of a debris avalanche or debris slides, a limited amount of debris can be entrained. Similarly, and unlike for watersheds with deeper soils consisting of till or other glacial sediments, or weathered bedrock, the A and B creek watersheds cannot produce large quantities of sediment due to thin and incoherent soil coverage. This characteristic is important as it suggests a marked difference to watersheds in the Interior of BC where rilling and gullying of deeper soils or weathered bedrock after wildfires may produce significant volumes of sediment.

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\(^1\) That is, how much debris could be entrained from the channel given the occurrence of a debris flow. This variable has units of m\(^3\)/m.
Figure 2-1. Exposed colluvial soils on the south side of A creek. BGC photograph of March 7, 2019.

Figure 2-2. Exposed colluvium from a windthrown burned tree on the south side of A creek. BGC photograph of March 7, 2019.
2.2. Hydrological Analysis

2.2.1. Introduction

Part of BGC’s scope was to analyze the recorded rain storms that have occurred since the August 2018 wildfire with respect to return periods for different rainfall durations. The rationale for this work was to determine if any of the 2018 storm durations have been particularly rare. In absence of debris flows, this may allow a reduction of the post-wildfire hazard multiplier of 10 that was applied by BGC immediately after the wildfire to reflect the potential effect of the wildfire on debris-flow susceptibility. For example, if a storm in the winter of 2019 had a < 1 hour duration return period of > 5 years (a storm that has been observed elsewhere to result in a post-fire debris flow), one could argue that the factor of 10 is overly conservative. The factor of 10 was initially chosen purposely conservatively as the on-ground conditions could not be observed by BGC immediately after the fire due to slope stability concerns and tree fall hazards.

Neither Environment and Climate Change Canada (ECCC) nor the provincial government maintain a climate station in Zeballos. ECCC does operate a climate station in the upper watershed – Zeballos Muraude Creek (# 1039035). This station was commissioned in July 2010, but only daily precipitation data are collected. For the slopes above Zeballos, much shorter duration rainfall data (i.e., < 1 hour) are of interest, as observations in the western US and Canada have shown that these short duration intensities are most likely responsible for triggering debris flows in watersheds similar to A, B, and C creeks. The Village installed their own climate station at the municipal hall, which became operable on November 28, 2018. The Zeballos station collects the following data at 5-minute intervals:

- Temperature
- Dew point temperature
- Rainfall
- Wind speed/direction
- Relative humidity
- Barometric pressure.

The station can be accessed at the following link:

2.2.2. Results

Daily rainfall data from the Zeballos station are summarized in Figure 2-3 for the period December 1, 2018 to March 16, 2019. The highest daily rainfall during that period was 111 mm on January 2, 2019. Maximum shorter duration rainfall (5 minutes to 1 hour) during that period are summarized in Table 2-1. These data were then compared to rainfall intensity-duration-frequency (IDF) data, as estimated by ECCC at Tofino A (#1038205) since no IDF curve has been developed for Zeballos. Tofino A is the closest climate station to Zeballos with a relatively long record of published IDF data. Table 2-1 demonstrates that there were no storms with a return period greater than 2 years between December 1, 2018 and March 16, 2019 for durations less
than 1 hour. There was one 24-hour storm (January 2-3, 2019) with a return period between 2
and 5 years.

**Table 2-1. Maximum rainfall intensities at Zeballos for durations of 5 minutes to 24 hours and return periods using Tofino A IDF data.**

<table>
<thead>
<tr>
<th>Duration</th>
<th>Zeballos (mm)</th>
<th>Tofino A (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-year</td>
<td>5-year</td>
</tr>
<tr>
<td>5-min</td>
<td>2.8</td>
<td>3.8</td>
</tr>
<tr>
<td>10-min</td>
<td>4.6</td>
<td>5.9</td>
</tr>
<tr>
<td>15-min</td>
<td>5.8</td>
<td>7.7</td>
</tr>
<tr>
<td>30-min</td>
<td>9.4</td>
<td>11.4</td>
</tr>
<tr>
<td>1-hr</td>
<td>15.2</td>
<td>17.8</td>
</tr>
<tr>
<td>24-hr</td>
<td>150</td>
<td>128</td>
</tr>
</tbody>
</table>

![Daily rainfall at Zeballos from December 1, 2018 to March 16, 2019. The 2-5 year storm is circled in red.](image)

In summary, rainfall intensities between December 1, 2018 and March 16, 2019 were all less than
a 2-year return period event, except for one storm on January 2-3 that was a 2 to 5-year return
period storm for a 24-hour period. Given that post-fire debris flows are primarily triggered by
rainfall durations of less than one hour and that no “rare” (> 2-year rain storm) occurred, it is not possible to conclude that the factor 10 post-fire adjustment can be lowered based on the hydrological analysis alone.

2.3. Debris Flow Frequency-Magnitude Update

Based on the fieldwork conducted by Mr. Weatherly and Dr. Jakob of BGC, as well as examination of other analytical techniques, the previous frequency-magnitude (F-M) work (BGC, October 15, 2018) was expanded and refined. Three principal techniques for F-M analysis were applied, as summarized in Table 2-2.

Table 2-2. Techniques used for frequency-magnitude analysis

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Regional Analysis</td>
<td>A regionally (southwestern BC) developed relationship between debris flow fan areas and volumes.</td>
</tr>
<tr>
<td>(B) Post-Fire Debris Flow Analysis</td>
<td>Multiple regression analysis relating debris flow volumes to watershed and burn characteristics of recently burned watersheds in the western United States.</td>
</tr>
<tr>
<td>(C) Yield Rate Analysis</td>
<td>Summing potentially erodible sediments in creek channels as observed in the field and adding potential point sediment source volumes to arrive at a total debris flow volume.</td>
</tr>
</tbody>
</table>

The rationale for using three rather than one method was to decrease the uncertainty associated with use of only one method. This strategy is akin to multi-model weather forecast models, hurricane predictions and climate change prediction.

2.3.1. Method A – Regional Analysis

Details on the development of the F-M relationship for debris flows based on regional analysis are provided in BGC (October 15, 2018). Results for this analytical technique are provided in Table 2-3. Peak discharge was estimated by using an average of three empirical volume-discharge relationships, as discussed in BGC (October 15, 2018).

Of note is that debris flows are not expected on any of the three creeks for return periods less than 300 years based on analyses of past events and observed channel conditions. While climate change will increase the intensity and frequency of future storms in coastal BC, without sufficient sediment supply, neither debris flow frequency nor magnitude will increase. The only unknown is if climate change will be associated with an increase in the frequency of coastal fires. If so, then debris flow frequency may increase with an associated likely decrease in magnitude as recharge rates at A and B creeks are likely to be very slow. These considerations are presently speculative and are thus not included in this hazard and risk assessment.
Table 2-3. Debris flow magnitude estimates for Method A (Regional Analysis).

<table>
<thead>
<tr>
<th>Return Period (T) (years)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris-Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris-Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris-Flow Peak Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A Creek</td>
<td></td>
<td>B Creek</td>
<td></td>
<td>C Creek</td>
<td></td>
</tr>
<tr>
<td>300 to 1000</td>
<td>4,200</td>
<td>100</td>
<td>3,900</td>
<td>100</td>
<td>2,300</td>
<td>60</td>
</tr>
<tr>
<td>1000 to 3000</td>
<td>6,000</td>
<td>140</td>
<td>5,500</td>
<td>130</td>
<td>3,200</td>
<td>80</td>
</tr>
</tbody>
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2.3.2. Method B – Post-Fire Debris Flow Analysis

After wildfires, both debris flow and rock fall frequency and magnitude can change. Post-fire landscapes are subject to two primary debris flow initiation processes, as summarized by Cannon and Gartner (2005):

1. Runoff-dominated erosion by surface overland flow.
2. Infiltration-triggered failure and mobilization of soil/rock mass.

Empirical models for predicting post-fire debris flow volumes (e.g., Cannon et al., 2010; Gartner et al., 2009; 2014) can be used to assess hazards posed by debris flows following wildfires. These models predict volumes of material that may flow past a given point along a debris flow channel. For this assessment, the "emergency assessment model" for post-wildfire debris flow volumes in Gartner et al. (2014) was calculated for the watershed outlets. This model is currently used by the U.S. Geological Survey for emergency assessments of post-fire debris flow hazards (available online at https://landslides.usgs.gov/hazards/postfire_debrisflow/). The inputs for the model include the contributing area burned at moderate and high severity, the relief of the contributing area and the storm rainfall intensity measured over a 15-minute duration. The model is applicable for up to two years following the wildfire, after which plant re-growth and/or source area sediment depletion render it unreliable.

Model inputs were based on GIS analyses of the LiDAR DEM data, burn severity data provided by FLNRORD (Drawing 01) and rainfall IDF data collected at the Tofino A (#1038205) climate station. The Tofino climate station data were used as a reasonable proxy to Zeballos.

Post-wildfire debris flow volumes were calculated for storms with return periods from 2 to 100 years. Each return period is associated with an annual probability and, since the “emergency assessment model” from Gartner et al. (2014) is applicable for two years, an annual probability of occurring within the next two years. For example, a storm with a 25-year return period has an annual probability of 0.04 and an annual probability of occurring within the next two years of 0.08. Therefore, the volume calculated with the 15-minute rainfall intensity of a storm with a 25-year return period has an annual probability of occurrence of 0.08 assuming that the 25-year return period storm initiates a debris flow.

Volume predictions are rounded to the nearest 1000 m³ because the prediction intervals for the volume estimates range by about one order of magnitude plus or minus the volume estimate.
Given these broad prediction intervals, the volume estimates cannot be considered precise. Table 2-4 presents the estimated post-wildfire debris flow volumes estimated based on storms with various return periods.

Table 2-4. Storm rainfall data and estimated post-wildfire debris flow volumes for the burned watersheds at Zeballos.

<table>
<thead>
<tr>
<th>Storm Return Period (years)</th>
<th>Annual Probability</th>
<th>Annual Probability of Storm within 2 Years of the Fire</th>
<th>Tofino A 15-min Rainfall Intensity (mm/h)</th>
<th>Post-wildfire Debris Flow Volume (m$^3$) A Creek</th>
<th>Post-wildfire Debris Flow Volume (m$^3$) B Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.8</td>
<td>30.9</td>
<td>3,000</td>
<td>4,000</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>0.4</td>
<td>40.9</td>
<td>5,000</td>
<td>6,000</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>0.2</td>
<td>47.5</td>
<td>6,000</td>
<td>7,000</td>
</tr>
<tr>
<td>15</td>
<td>0.07</td>
<td>0.1</td>
<td>50.8</td>
<td>6,000</td>
<td>8,000</td>
</tr>
<tr>
<td>25</td>
<td>0.04</td>
<td>0.08</td>
<td>55.9</td>
<td>7,000</td>
<td>9,000</td>
</tr>
<tr>
<td>50</td>
<td>0.02</td>
<td>0.04</td>
<td>62.1</td>
<td>8,000</td>
<td>10,000</td>
</tr>
<tr>
<td>100</td>
<td>0.01</td>
<td>0.02</td>
<td>68.3</td>
<td>10,000</td>
<td>12,000</td>
</tr>
</tbody>
</table>

Two questions can be asked when examining the frequency of post-fire debris flows:

1. What is the probability of a debris flow given that the wildfire has occurred?
2. What is the probability of a post-fire debris flow in general?

The first question applies directly to the slopes above Zeballos because the wildfire did occur. In this instance one wishes to know what return period storm is likely to trigger a debris flow. Previous research in drier areas of western North America has demonstrated that even a 2-year return period storm, which has a 50% chance of occurring in any given year, can trigger a debris flow (Cannon et al., 2008). If past research is applicable to the present situation at Zeballos, then the chance of a debris flow occurring on A or B creeks is 0.5 (50%).

The second question needs to be asked to compare the previous frequency estimates for Method A and B. In this instance one would need to combine the probability of a wildfire occurring with that of a potential debris flow triggering storm occurring in the critical post-fire period. Wildfire frequency on the slopes above east Zeballos is unknown. However, judging from the tree ages and lack of fire scars observed by BGC, wildfire frequency is likely in excess of 200 years.

Given that the soils in the A and B creek watersheds are relatively coarse-grained, it can be argued that a 2-year storm may not suffice to trigger a debris flow (i.e., coarse-grained soils drain more rapidly and thus do not allow pore water pressure build-up as readily as in finer-grained soils). Therefore, BGC assumed that a 5-year return period storm would be needed to potentially trigger a debris flow. The combination of a 5-year return period storm and a 200-year wildfire cycle was used a representing the 300 to 1000-year return period class, while a 25-year return period
storm was used with a 200-year wildfire cycle to represent the 1000 to 3000-year return period class.

Debris flow F-M estimates based on the methodology of Gartner et al. (2014) are provided in Table 2-5. No results are presented for C Creek in this section, as the 2018 wildfire did not affect this watershed (Drawing 01). The association of debris flow volumes with return periods as attempted here is clearly associated with substantial error and relies on judgment. Hence the sediment volume estimates presented in Table 2-5 are to be interpreted as approximations rather than precise estimates.

Table 2-5. Debris flow magnitude estimates for Method B (Post-Fire Analysis).

<table>
<thead>
<tr>
<th>Return Period (T) (years)*</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Creek</td>
<td>5,000</td>
<td>110</td>
<td>6,000</td>
<td>140</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>B Creek</td>
<td>6,000</td>
<td>140</td>
<td>8,000</td>
<td>170</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>C Creek</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Note: * refers to a 15-minute storm occurring in the next 2 years (the period in which debris flows are likely to be affected by the effects of the August 2018 wildfire). The return periods are approximations as the fire frequency is unknown in the A and B creek watersheds.

2.3.3. Method C - Yield Rate Analysis

One can estimate the total volume of a potential debris flow recruited by a debris flow by determining the volume of debris stored in a channel. This is done by choosing reaches with relatively homogenous channel and debris fill characteristics and noting their segmental debris volumes expressed as cubic meters per metre channel length (m³/m). By summing all channel reaches one can arrive at the total potential debris volume. This method is strongly dependent on the time since the last debris flow or major flood capable of transporting sediment out of a given reach.

The maximum volume of debris potentially recruited needs to be added to a potential source volume as in-channel debris flow initiation is rare, particularly when the channel is at least partially obstructed by coarse granular debris (such as rock fall) or large organic debris, both of which are the case at A and B creeks (Figure 2-4, Figure 2-5). Source volumes were approximated by delineating potential debris avalanche areas given the topographic constraints and multiplying that area by 0.5 m, which is considered an upper limit of soil thickness in the upper watersheds of A and B creeks.
In general, BGC observed that yield rates in the channels were low (< 2 m³/m), with bedrock frequently observed on the channel substrate. The in-channel yield rates were used by BGC to arrive at volume estimates for the 300 to 1000-year return period class. Higher yield rates were used for the 1000 to 3000-year return period class, acknowledging the potential for extremely large debris flows to entrain debris along the sides of the channel. This situation was recently observed by BGC in a small watershed in North Vancouver, where a 0.3 km² watershed produced a debris flow with an approximate volume of 15,000 m³.
Debris flow F-M estimates based on yield rates are provided in Table 2-6. This method does not allow a direct designation of the debris volumes estimated to a specific return period, and hence the return period values reported in Table 2-6 are based on experience and judgement.

Table 2-6. Debris flow magnitude estimates for Method C (Yield Rate Analysis).

<table>
<thead>
<tr>
<th>Return Period (T) (years)*</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Creek</td>
<td>2,200</td>
<td>60</td>
<td>2,300</td>
<td>60</td>
<td>900</td>
<td>29</td>
</tr>
<tr>
<td>B Creek</td>
<td>5,500</td>
<td>130</td>
<td>6,300</td>
<td>140</td>
<td>1,200</td>
<td>36</td>
</tr>
<tr>
<td>C Creek</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3.4. Discussion

Of interest in this analysis is the time required for sediment to accumulate along the channel substrate of A and B creeks, which is a pre-requisite for debris flow initiation. For relatively small watersheds in coastal areas of BC, channel recharge typically occurs over a long period (decadal to century scale) through raveling and sloughing from side slopes and minor landsliding from adjacent valley slopes (Jakob, Bovis & Oden, 2005). When debris flows occur, a majority of this in-channel sediment is transported onto the fan. Previous large debris flows on A and B creeks appear to have largely depleted the available debris stored in the channel, as evidenced by the channel being scoured to bedrock in many of the observed sections.

Channel recharge rates can be estimated by the research of Jakob et al. (2005). In that work, the authors provided predictive equations for time-normalized channel recharge rates from southwestern BC and Haida Gwaii (formerly the Queen Charlotte Islands). The southwestern BC dataset is heavily biased by creeks in volcanic rocks that recharge very quickly. However, the Haida Gwaii non-logged dataset may be a suitable analog for Zeballos:

\[ R_t = 0.2t_e^{-0.49} \]  

where \( R_t \) is the normalized recharge rate and \( t_e \) is the time since the last debris flow on A and B creeks.

Assuming Equation 2-1 is applicable to the Zeballos area, one can calculate how long it would take to accumulate the estimated average debris flow volume from all three methods. The average estimated sediment volume for A and B creeks for the 300-1000-year return period is 3,800 and 4,100 m³, respectively. Using Equation 2-1, the approximate time to recharge A Creek to the 3,800 m³ debris volume is 130 years, while for B Creek it is approximately 180 years. For the 1000 to 3000-year return periods, the time to recharge A Creek is approximately 300 years, and approximately 500 years for B Creek.

These estimates suggest that the time to recharge to the estimate volumes is lower than the return periods estimated. However, return periods and time to recharge are not interchangeable terms. The former indicates that both a sufficient volume of sediment and an extreme hydroclimatic event need to prevail. Also, some sediment is likely eroded and transported in the very steep channels of A and B creeks (on average >60%) during floods. This means that the true recharge time is likely considerably longer than suggested by the Jakob et al. (2005) method.

Further, it needs to be recognized that the cumulative debris volume estimates as per Equation 2-1 are highly sensitive to the exponent of that equation which may not apply to recharge rates of A and B creeks. They should therefore be interpreted as rough approximations.

2.3.5. Conclusion

Three different methodologies have been presented to estimate the magnitude of debris flows in A, B, and C creeks. The results from the methods need to be amalgamated into a set of debris flow volume and peak discharge estimates that can then be applied to numerical modelling and the risk assessment. One approach would be to take the average of each method, a second would
be to weigh each volume and peak discharge estimate based on judgment, while a third would be to use the most conservative value from each method. BGC chose to average the methods for A and B creeks. The rationale is that the highest estimates yielded by the post-fire debris flow method (Method B) are highly uncertain and likely overly conservative, as the conditions on which the Gartner et al. (2014) method was developed are dissimilar (more debris availability) to those observed on the slopes above east Zeballos (less debris availability). Moreover, if one were to rely on the post-fire method for estimating debris flow volumes of A and B creeks, the post-fire risk multiplier adopted for the risk assessment (see Section 3) would have to be deleted as the method is already based on post-fire conditions. Similarly, the lower end estimate based on the observed channel yield rates is associated with uncertainty in that a future debris flow may entrain material from the side of the channel.

For C creek, neither the post-fire method or regional assessment are considered valid. The post-fire method does not apply as the August 2018 fire did not affect that watershed. The regional method relies on accurate fan area mapping. However, at C creek the “fan” is at least partially a colluvial cone, hence affected by both rock fall and debris flow processes which may yield a false fan area estimate which in turn results in an unreasonably high magnitude estimate. For this reason, the yield rate method only was used for C Creek volume and peak discharge estimates. The final volumes and peak discharges that were carried forward to numerical modelling are summarized in Table 2-7.

**Table 2-7. Debris flow magnitude estimates carried forward to numerical modelling.**

<table>
<thead>
<tr>
<th>Return Period (T) (years)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
<th>Sediment Volume Best Estimate (m³)</th>
<th>Debris Flow Peak Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Creek</td>
<td></td>
<td></td>
<td>B Creek</td>
<td></td>
<td>C Creek</td>
<td></td>
</tr>
<tr>
<td>300 to 1000</td>
<td>3,800</td>
<td>90</td>
<td>4,100</td>
<td>100</td>
<td>900</td>
<td>30</td>
</tr>
<tr>
<td>1000 to 3000</td>
<td>5,800</td>
<td>130</td>
<td>6,600</td>
<td>150</td>
<td>1,200</td>
<td>36</td>
</tr>
</tbody>
</table>

The magnitude estimates presented in Table 2-7 for A and B creeks are very similar to those published in the initial assessment (BGC, October 15, 2018). However, the volume estimates are substantially higher for C Creek compared to the 2018 assessment. The reason for the increase is that fieldwork identified a steep erodible channel downstream of a bedrock bluff. Given its steepness, BGC considers it possible that during an extreme rainstorm (> 300-year return period) substantial debris could be entrained along the steep channel sections of C creek. Such sudden erosion in a colluvial channel has been observed by the authors elsewhere.

The following key observations are amended from BGC (October 15, 2018):

- Debris flows on A, B and C creeks occur at return periods greater than 300 years based on interpretation of air photographs, field observations, archival information, dendro-geomorphology and radiocarbon dating.
• Debris flow volumes are limited by sediment supply limitations in the upper watersheds that are characterized by sporadic bedrock outcrops and intermittent, shallow soils. This implies that once a debris flow has occurred, it requires substantial time before another debris flow of similar magnitude can occur. The key sediment supply mechanisms are rock fall and sediment ravelling into the channel. The expected dominant debris flow triggering mechanism are interpreted debris avalanches or debris slides, none of which were identified on historical air photographs. This corroborates the findings from radiocarbon analysis of fan sediments indicating that debris flows are rare (i.e., greater than 300-year return period).

• At C creek, the main debris-supply mechanism to a debris flow is entrainment on the steep talus slopes flanking the hillside downslope of near-vertical bedrock cliffs.

The only way to further refine F-M estimates would be to execute a rigorous test trenching program on various locations on the three fans, combined with additional radiocarbon dating. Such a study could lead to an upward or downward revision of the magnitude estimates presented in Table 2-7.

2.4. Rock Fall Frequency-Magnitude Update

For rock fall, extreme heating of loose boulders and jointed rock masses due to a forest fire can further dilate discontinuities, stress cohesion-providing characteristics like rock bridges, and remove or weaken buttressing trees. Dry raveling can further undermine rocks close to their pivot point. The March 2019 field traverse as conducted by Hamish Weatherly and Matthias Jakob of BGC did not show any indications that the pre-fire frequency or magnitude of rock fall requires adjustment of the values previously used by BGC.

For the post-fire frequency, BGC (October 15, 2018) had also adjusted the frequency by a factor of 10. During the field traverse no large (i.e., large enough to travel into the inhabited portions on the lower slope) boulders were identified. This observation is at odds with the observations by BGC in the fall of 2018 when several fresh boulders were found along Zeballos Main Road north of East Zeballos and observations by MOTI that 12 boulders have reached Zeballos Main Road in 2019. Several explanations are possible to explain the discrepancy.

First, cliff faces are within tens of metres of the road at Maquinna Avenue north of Zeballos, whereas cliffs are more set back (100 and more metres) in Zeballos East. This implies that boulders with a minimum diameter of 0.3 m could reach the road north of the Village, whereas boulders of this diameter would not reach East Zeballos. Second, portions of Zeballos Main Road north of Zeballos have been cut into the slopes, thus oversteepening them and allowing loose debris to fall into the road ditch or onto the road. Third, it is possible that at least some of the boulders observed by BGC in the road ditches or near the road may have been dislodged by the release of water from helicopters fighting the fire.

Given the lack of large, freshly released (i.e., in the 6 months since the fire) boulders in or near the eastern slopes above the Village, BGC considers the previously estimated frequency
adjustment of a factor of 10 overly conservative. It was thus lowered to two for consistency with the debris flow adjustment factor (see Section 3.2.3).

2.5. Debris Flow Modelling

Debris flow modelling was completed using FLO-2D, a two-dimensional, volume conservation hydrodynamic model. FLO-2D can be used to model clearwater flows, sediment transport, and debris flows, which allows its application for A, B, and C creeks, because they are subject to this process continuity. Details of the modelling can be referenced in BGC (October 15, 2018).

Updated modelling was not required for 300 to 1000-year return period debris flows on A and B creeks as the updated magnitude estimates for these two creeks are very similar to those estimated in the 2018 report (BGC, October 15, 2018). However, updated modelling was completed for C Creek. BGC also modelled the 1000 to 3000-year return period class, as a sensitivity analysis. This sensitivity analysis answers the question if an additional return period class were added with corresponding higher debris flow magnitudes, how this would manifest itself in risk and how many properties would exceed the $10^{-4}$ individual risk threshold.

The Engineers & Geoscientists British Columbia (EGBC) Guidelines for Legislated Flood Assessments in a Changing Climate (2018) suggest that, where appropriate, up to a 500-year return period class be applied for subdivisions of 10 to 100 buildings. For subdivisions over 100 buildings, an additional return period class up to 2500 years is recommended. At Zeballos the number of buildings potentially at risk from debris flows and rock fall (i.e., within the consultation zone) is approximately 25 and hence the 500-year return period applies. BGC chose to bracket this return period within the 300 to 1000-year return period class as the use of a single return period has shown to be too limiting given the uncertainties inherent in the F-M analyses.

Debris flow model results for the 300 to 1000-year return period class are provided in Drawing 02. This drawing uses a flow intensity index ($I_{DF}$) to characterize the potential destructiveness of debris flows. This flow intensity was defined based on flow depth and velocity squared ($I_{DF} = d \times v^2$). For example, an $I_{DF}$ of 50 corresponds to a 2 m diameter boulder traveling at 5 m/s (faster than most persons can run on uneven ground) and would likely inflict major structural damage on a timber-frame home. Hazard intensity ranges can be associated with the degree of damage they produce by comparing historical events with the damage they inflicted on buildings in their travel path, as summarized in Table 2-8. Of note is that this table has been refined by adding a new intensity category since the original hazard and risk assessment report (BGC, October 15, 2018).

Drawing 02 also includes the potentially impacted portions of the Village due to rock fall and rock slides. These hazards are shown as runout exceedance percent lines. For all identified hazards, the key assumption is the indicated hazard severity requires both the hazard to occur and to reach the location.
Table 2-8. Hazard intensity descriptions and vulnerability of persons in homes when impacted by debris flows or rock fall.

<table>
<thead>
<tr>
<th>Impact Intensity</th>
<th>Colour</th>
<th>Building Damage Potential</th>
<th>Description</th>
<th>Human Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>Pale Yellow</td>
<td>Minor</td>
<td>Slow flowing shallow and deep water with little or no debris. High likelihood of water damage. Potentially dangerous to people in buildings, on foot or in vehicles in areas with higher water depths.</td>
<td>0.001</td>
</tr>
<tr>
<td>1 to 3</td>
<td>Yellow</td>
<td>Moderate</td>
<td>Slow flowing shallow and deep flow with minor debris. High likelihood of sedimentation and water damage. May include small rock falls or slow-moving rock slides. Potentially dangerous to people in buildings, on foot or in vehicles in areas with higher water depths.</td>
<td>0.02</td>
</tr>
<tr>
<td>3 to 10</td>
<td>Orange</td>
<td>Major</td>
<td>Potentially fast flowing but mostly shallow water with debris, or fast-moving small rock falls or rock slides. High likelihood of building structure damage and high likelihood of major sediment and/or water damage. Potentially dangerous to people on the first floor or in the basement of buildings, on foot or in vehicles.</td>
<td>0.2</td>
</tr>
<tr>
<td>10 to 30</td>
<td>Dark Orange</td>
<td>Extensive</td>
<td>Fast flowing and deep water, debris or rock falls. High likelihood of extensive building structure damage and severe sediment and water damage. Very dangerous to people in buildings, on foot or in vehicles.</td>
<td>0.4</td>
</tr>
<tr>
<td>30 to 100</td>
<td>Red</td>
<td>Severe</td>
<td>Very fast flowing and deep water, debris or rock falls. High likelihood of severe building structure damage and sever sediment and water damage. Extremely dangerous to people in buildings, on foot or in vehicles.</td>
<td>0.6</td>
</tr>
<tr>
<td>&gt;100</td>
<td>Brown</td>
<td>Total Destruction</td>
<td>Very fast flowing and deep water, debris or rock falls. Very high likelihood of total building destruction. Extremely dangerous to people in buildings, on foot or in vehicles.</td>
<td>0.9</td>
</tr>
</tbody>
</table>
3.0 RISK ASSESSMENT UPDATE
3.1. Introduction

Risk was assessed using the same methodology as described in BGC (October 15, 2018), but with some notable refinements:

- A 6th intensity category was added.
- A second debris flow frequency scenario (1000 to 3000-year return period) scenario was added to the numerical model and the risk assessment as a sensitivity check but is not recommended for the size of subdivision in the study area at Zeballos East as per guidance in the EGBC professional practice guidelines for Legislated Flood Assessments in a Changing Climate (EGBC, 2018).

3.2. Risk Update

The following sections provide a discussion on the updated risk assessment.

3.2.1. Elements at Risk

Buildings in the Village are concentrated on the valley bottom, on the east side of the Zeballos River. Zeballos has a population of 107 full-time residents, with seasonal variation from 85 in the winter to 185 people in the summer (Village of Zeballos, pers. comm). The additional summer population is primarily forestry workers, vacation property occupancy, and tourists staying in hotels and camp housing.

Table 3-1 lists the dwellings and occupancy information provided by residents to the Village. The risk assessment in this report assumes current conditions, including current building locations and occupancy. A second assessment assuming full-time occupancy in all habitable buildings is also presented to illustrate how future changes in occupancy or land use would change the level of risk. This ought to be realized by residents who, for example, wish to change from weekend use to full-time use. It is also pertinent information for future prospective buyers who may not be aware of the specific risk rating of the property of interest or how it may change with a switch to full-time occupancy.

Table 3-1 does not include all elements that could suffer direct or indirect consequences due to a geohazard event, but focuses on those that can be reasonably assessed, based on the information available. BGC did not attempt to quantify risk to persons on foot or in cars as their location and number cannot be estimated with any confidence especially since the time of a future debris flow is unknown.
Table 3-1. List of elements at risk considered in the risk assessment.

<table>
<thead>
<tr>
<th>Lot</th>
<th>Number of People</th>
<th>Occupancy Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>2</td>
<td>Second home</td>
</tr>
<tr>
<td>103</td>
<td>1</td>
<td>Principal residence, stay-at-home adult</td>
</tr>
<tr>
<td>102, 104 and 106</td>
<td>4</td>
<td>Principal residence, 1 working adult, 1 stay-at-home adult and child, 1 child attending school</td>
</tr>
<tr>
<td>108</td>
<td>4</td>
<td>Year-round residence, 1 teen attending school out of Zeballos October through April, 1 adult working from home, 2 adults working outside the home</td>
</tr>
<tr>
<td>109</td>
<td>2</td>
<td>Fishing business, occupied business hours</td>
</tr>
<tr>
<td>110</td>
<td>5</td>
<td>Principal residence, 2 working adults with 1 working at home, 1 stay-at-home adult, 2 teenagers attending school</td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td>Vacation property, currently vacant</td>
</tr>
<tr>
<td>112</td>
<td>3</td>
<td>Principal residence, 1 working adult, 1 stay-at-home adult, 1 stay-at-home child</td>
</tr>
<tr>
<td>118</td>
<td>0</td>
<td>Vacant</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>Principal residence, stay-at-home adult</td>
</tr>
<tr>
<td>122 and 126</td>
<td>1</td>
<td>Museum, occupied business hours between June and August</td>
</tr>
<tr>
<td>128</td>
<td>2</td>
<td>Principal residence, 2 working adults</td>
</tr>
<tr>
<td>130</td>
<td>1</td>
<td>Principal residence, working adult</td>
</tr>
<tr>
<td>132</td>
<td>0</td>
<td>Uninhabitable lot owned by school district #84</td>
</tr>
<tr>
<td>202 and 204</td>
<td>1</td>
<td>Principal residence, stay-at-home adult</td>
</tr>
<tr>
<td>203</td>
<td>Variable</td>
<td>Hotel, occasionally fully occupied with approximately 30 people (about 4 times per year). Seasonal variation in occupancy. May to September is peak period, closed from November to February.</td>
</tr>
<tr>
<td>205</td>
<td>1</td>
<td>Vacation property</td>
</tr>
<tr>
<td>206</td>
<td>2</td>
<td>Vacation property. Planned to be retirement home within 2 years</td>
</tr>
<tr>
<td>207</td>
<td>1</td>
<td>Vacation property</td>
</tr>
<tr>
<td>214</td>
<td>0</td>
<td>Vacant lot; no full-time residents</td>
</tr>
<tr>
<td>402 A</td>
<td>2</td>
<td>Vacation property</td>
</tr>
<tr>
<td>402 B</td>
<td>5</td>
<td>Principal residence, 2 working adult, 1 stay-at-home adult, 2 teenagers attending school</td>
</tr>
<tr>
<td>404</td>
<td>1</td>
<td>Principal residence, working adult</td>
</tr>
<tr>
<td>406</td>
<td>2</td>
<td>Principal residence, 2 working adults</td>
</tr>
</tbody>
</table>

Buildings in lots 107, 132 and 216 are not habitable (Village of Zeballos, pers. comm) and are excluded from the risk assessment.
Table 3-2 lists factors affecting confidence in these estimates. The level of confidence in population estimates is consistent with that used by other jurisdictions, in BGC’s experience, to make risk management decisions.

### Table 3-2. Uncertainties associated with estimating the number of occupants of a building.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average occupancy rates may not correspond to actual occupancy rates for a given dwelling unit.</td>
<td>Over- or underestimation of occupant numbers</td>
</tr>
<tr>
<td>Seasonal population fluctuations (including tourists) exist that were not accounted for.</td>
<td></td>
</tr>
<tr>
<td>Occupancy rates for the hotel differ from the estimate.</td>
<td></td>
</tr>
<tr>
<td>Distribution of persons within a building are unknown. As such, the number of persons most vulnerable to geohazard impact on the first floor or basement is unknown.</td>
<td></td>
</tr>
<tr>
<td>Seasonal visitors may occupy private residences, and additional visitors temporarily occupy service businesses.</td>
<td>Uncertainty in estimation of human vulnerability to geohazard impact</td>
</tr>
</tbody>
</table>

#### 3.2.2. Individual Life Loss Estimation

Individual risk of loss of life \( (P_i) \) was estimated using the following equation:

\[
P_E = \sum_{i=1}^{n} P(H)_i P(S:H)_i P(T:S)_i N
\]

[Eq. 3-1]

where:

- \( P(H)_i \) is the annual hazard probability defined as annual frequency range.
- \( P(S:H)_i \) is the probability that the scenario would reach the element at risk, given that it occurs.
- \( P(T:S)_i \) is the probability that the element at risk (e.g., persons within buildings) is in the impact zone, given that the scenario reaches the location of the element at risk.

\[
N = V_i E_i
\]

[Eq. 3-2]

where:

- \( V_i \) is the vulnerability, which is the probability elements at risk will suffer consequences given hazard impact with a certain severity. For persons, vulnerability is defined as the likelihood of fatality given impact.
- \( E_i \) is a measure of the elements at risk, quantifying the value of the elements that could potentially suffer damage or loss. For persons, it is the number of persons exposed to hazard, equal to 1 in the case of individual risk assessment.

Individual risk is reported as the annual Probability of Death of an Individual (PDI). Individual risk levels are independent of the number of persons exposed to risk. The following sections describe how each parameter in Equation 3-2 was estimated.
3.2.3. Hazard Probability

Hazard probability, \( P(H_i) \), corresponds to the annual probability of occurrence of each hazard scenario, which are defined as annual frequency ranges. Hazard frequency was estimated using methods described in BGC (October 15, 2018). In BGC (October 15, 2018), a tenfold increase from the background conditions was estimated for debris flow and rock fall hazards.

This factor 10 increase was an estimate based on the burn severity and the quantity of rock fall that reached Zeballos Main Road during the wildfire. The factor 10 increase was purposely conservative as few details were known about the post-fire channel conditions and detailed field observations were not possible as it was considered too dangerous to hike the creeks in the immediate post-fire period. In March 2019, Hamish Weatherly and Matthias Jakob of BGC hiked all three creeks during dry weather following a prolonged period of little rain which allowed a safe ascent. Detailed observations were made at multiple waypoints on the geomorphological characteristics of the creeks, side slopes and tree mortality.

The following key findings were made:

- Burns were patchy and mostly concentrated in the A Creek watershed at low elevation, and B Creek at high elevation (> 500 m).
- The August 2018 wildfire did not affect the C Creek watershed.
- Heat penetrated several tens of centimeters as judged from charred roots and reddened soils at depth.
- Soils in the A and B creek watersheds were generally thin (< 0.5 m) and frequently interrupted by bedrock outcrops.
- No rill or gully formation was observed anywhere in the watersheds except where it appeared that water had been dumped from helicopter during the fire-fighting efforts.
- No shallow or deep-seated landslides or tension cracks were observed anywhere along the traverse.
- Little sediment transfer from the hillslopes to the creek system had occurred since the wildfire.

In combination, these factors suggest that the hazard probability increase by a factor of 10 is overly conservative and requires adjustment. Specifically, the fact that no rilling, nor gully formation has occurred and would be hindered by sporadic bedrock outcrops suggests that even during severe rainstorms limited amounts of debris can be transferred to the creek. In absence of sudden and sustained debris transfer to the creek system, only a landslide (debris avalanche, rock fall) appears able to trigger a debris flow. Moreover, large organic debris aligned with, and aligned perpendicular to, the channels of A and B creeks suggest that debris flow triggering is hampered by such woody debris. Figure 3-1 juxtaposes: (a) a watershed in southern California where rilling and gullying can occur unencumbered due to thick (previously unglaciated) soils and complete lack of root cohesion with (b) the A creek watershed with shallower soils, remaining vegetation and sporadic bedrock outcrops.
While it is still not possible to “calculate” the factor increase in the probability of debris flows at A and B creeks, BGC assumes that a factor of 2, instead of 10, is more reasonable and justifiable based on our field findings and comparisons with post-fire conditions encountered elsewhere.

3.2.4. Spatial Probability of Impact

Spatial probability, $P_{S:H}$, is defined as the chance that the hazard, should it occur, reaches the element at risk. A wide range of inundation areas are possible for a given event magnitude. Specifically, more watery debris flows are expected to run out further than those with higher sediment concentration. Moreover, flow avulsions near the fan apex can result in flow trajectories primarily towards a certain sector of the fan. For a given hazard scenario, these factors influence the spatial probability of geohazard impact.

Spatial probability estimates for a given lot were based on “lateral impact” probability. This factor addresses the question, “what is the chance that a flow or rock will follow a particular trajectory that results in impact to a building (as opposed to travelling past but missing a dwelling)?” Values used in the analysis are based on the results of modelling and judgement. Debris flow and rock slides are sufficiently wide it is assumed an impact will impact the entire width of the building, which was conservatively assumed for the purposes of this analysis. For these hazards the lateral component of the spatial probability was assumed to be 1.0. Spatial probabilities for rock falls are the product of the runout exceedance and the proportion of the building impacted by the boulder. The median boulder size (2 m diameter) and an average building width of 10 m are assigned to each rock fall $P_{S:H}$ calculation.

3.2.5. Temporal Probability

Temporal probability considers the proportion of time residents spend within their dwelling. All else being equal, safety risk is directly proportional to the time residents spend at home (e.g., a
resident who is rarely home has less chance of being impacted by a slope hazard). The proportion of time residents spend in dwellings varies annually, seasonally and from occasional to full time occupants. Temporal probability is estimated using the following assumptions:

- Retired people spend 75% of day in their home, 95% of days in the year
- Children attending school spend 75% of their day at home during school year
- Working adults spend 66% of their day at home (8 hours out per day)
- Stay-at-home adults spend 90% of their day at home
- Elderly and infants spend 90% of day in their home
- Teenagers spend 50% of day at home (e.g., school and part time job, recreation)
- Vacation residents spend 4 weeks per year, occupy house 50% of their day
- "A few weekends a year" vacation residents spend 20 days per year, occupy house 50% of day.

3.2.6. Vulnerability

Section 2.5 shows the criteria used to estimate the vulnerability of persons within buildings to slope hazard impact, where vulnerability is primarily an indirect outcome of building damage or collapse. Assigned IDF values at lot 205 and 406 were increased one category to account for flow likely to superelevate out of the creek channel and divert toward the houses, that cannot be simulated by FLO-2D.

3.3. Results

PDI for each lot in the study area are plotted in Figure 3-2 and colour-coded on Drawing 02 based on the occupancy information provided by the Village. High and low estimates of $P_H$ and $P_{S:H}$ are carried through the analysis and are represented as the vertical lines representing the credible PDI range, with our best estimate of PDI represented as the green dot. Our best estimate of PDI without the 2x post-fire multiplier are represented as the blue square, which may be illustrative of the $P_H$ without the influence of the wildfire. This would be representative of the site prior to the Zeballos fire or after a sufficient period has passed following the fire where the vegetative canopy, understory and duff have regrown and the physical changes to the soil by the fire have returned to pre-fire conditions, which in this case is currently estimated at approximately 10 years. Figure 3-2 also show safety risk tolerance thresholds adopted by the Town of Canmore (2016) and District of North Vancouver (2009) as solid red and dashed orange lines. Solid red and dashed orange lines show risk tolerance thresholds for existing and proposed development, respectively.

The results present the combined annual risk from debris flow, rock fall and rock slide scenarios, given that some parcels may be impacted by more than one scenario. Debris flows are the dominant risk for all lots except 101 through 106, where rock fall governs the risk to individuals in homes.
BGC also conducted a sensitivity analysis where debris flow volumes and peak discharges were calculated with an average of methods A and C only, discarding the results of the post-fire debris flow assessment (i.e., Method B). The end result is a reduction in peak flow for a 300 to 1000-year debris flow on A and B creeks. However, debris flow modelling results were not substantially different from the base case scenario, resulting in similar risk estimates as shown in Figure 3-2.

![Figure 3-2](image-url)

**Figure 3-2.** PDI for lots in the study area using current occupancy as reported by Zeballos. Solid red and dashed orange lines are the District of North Vancouver and Town of Canmore PDI thresholds for existing and new developments, respectively.

Five dwellings remain in excess of the $10^{-4}$ risk tolerance criterion, even with removal of the 2x post-fire multiplier. BGC repeated the risk assessment assuming full-time ($P_{T:S} = 0.9$) occupancy in all dwellings to provide context for long-term land-use and policy development (Drawing 02; Figure 3-3). This analysis shows that 11 properties exceed the $10^{-4}$ risk tolerance criterion which emphasizes that changes in the occupancy (i.e., temporal probability) will lead to 6 additional properties potentially exceeding the risk tolerance criterion. Both residents and prospective buyers should be made aware of this potential change in risk.
The results presented on Drawing 02 provide a similar conclusion to the hazard zoning developed by Golder (1997). That is, some of the habitable structures to the area east of Maquinna Avenue are exposed to hazard and risk levels greater than what is generally considered acceptable by society.

3.4. Risk Assessment Limitations and Uncertainties

This assessment is based on a combination of quantitative likelihood estimates paired with geoscience judgement and field observations. BGC allowed for variations in the numerical values entered in the analysis to reflect the inherent uncertainty underlying various assumptions. We also conducted a sensitivity study if a second return period class were included. This analysis showed that if a 1000-3000-year return period class were included, three additional properties for existing occupancy would exceed the risk tolerance threshold, while four additional properties for full-time occupancy would exceed the risk tolerance threshold. Given EGBC guidance, addition of the second return period class is not required.
Hazard maps represent a snapshot in time; conditions will change after each subsequent event, or with the construction of mitigation measures and other substantial fan topography alterations. Modelling and maps will therefore need to be updated either after significant sedimentation events, or significant topography alterations on the fan or along the creek channels.