BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY
Suite 500 - 980 Howe Street
Vancouver, BC Canada V6Z 0C8
Telephone (604) 684-5900
Fax (604) 684-5909

October 15, 2018
Project No.: 1114014

Ken Taekema
Coastal Fire Centre
665 Allsbrook Road
Parkville, BC V9P 2T3

Dear Mr. Taekema,

Re: Village of Zeballos Post-Fire Geohazard Assessment

BGC Engineering Inc. (BGC) is pleased to provide the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) this post-fire hazard and risk assessment for rock fall, rock slide, debris flows and related geohazards on the eastern hillside flanking the Village of Zeballos. This letter report is prepared for FLNRORD. Concurrent with this assignment is an integrated flood and slope geohazard and risk assessment currently underway for the Village of Zeballos. For added clarity this letter report provides some context on the hazard assessments conducted under the other scope of work. It fulfills the terms of the contract with British Columbia Wildfire Service (BCWS) to provide a detailed post wildfire hazard assessment of Fire V82411 and characterize risks to evacuated homes, other properties within the defined assessment area, and the defined assessment section of Zeballos Main Road.

1.0 INTRODUCTION

The Village of Zeballos (the Village) is located on the banks of the Zeballos River where it discharges into Zeballos Inlet on northwestern Vancouver Island, British Columbia. Homes and businesses are built on the deposits of an alluvial fan of river-transported sediment overlain by an unknown thickness of waste rock from historical mining. The eastern extent of Zeballos is a hillside that rises from sea level to nearly 800 m elevation, featuring three steep ephemeral creeks named A, B and C for the purposes of this assignment.

In spring of 2018 the Village retained BGC Engineering Inc. (BGC) to characterize flood and slope hazards and risks posed to their community. The overall objective of the risk assessment was to estimate the frequency and magnitude of various geohazards and provide the Village a consistent and transparent method to compare flooding and slope geohazard risks. This risk comparison provides a basis for the Village to guide future funding applications for mitigation, to increase safety and decrease economic losses by geohazards in the future.

On August 16, 2018 Fire no. V82441 Gold Valley Main started north of Zeballos along Zeballos Main Road and eventually engulfed approximately 128 hectares east and above the Village (Figure 1-1). FLNRORD flew the watershed on September 5, 2018 and facilitated a call with

Emergency Management British Columbia (EMBC) on September 7, 2018. At this call FLNRORD informed the Village that post-fire natural hazards developed and with the coming rains, advised an evacuation warning. Discussions followed during and after the call with EMBC and FLNRORD weighing the benefits and risks of an evacuation warning versus an evacuation order. These discussions ultimately led the Village to expand the evacuation order previously implemented due to fire risk on September 8, 2018 to 17 residences in the red polygon shown in Figure 1-2. BGC contacted FLNRORD on the Village's behalf to discuss a complementary scope of work updating the hazard and risk assessment to include the conditions resulting from the fire. FLNRORD accepted BGC's scope of work on September 11, 2018 via email.

The scope of work for this assignment was agreed upon between FLNRORD and BGC via email on September 10, 2018 to include the following:

- Assessment of increased geohazard safety risk due to the wildfire for all properties shown in a Google Earth polygon provided by FLNRO (Figure 1-1)
- Assessment of increased geohazard risk due to wildfire for the road leading into town, delineated in Google Earth by FLNRO (Figure 1-2)
- If needed, brief descriptions of possible mitigation works with order of magnitude costs
- Reporting.

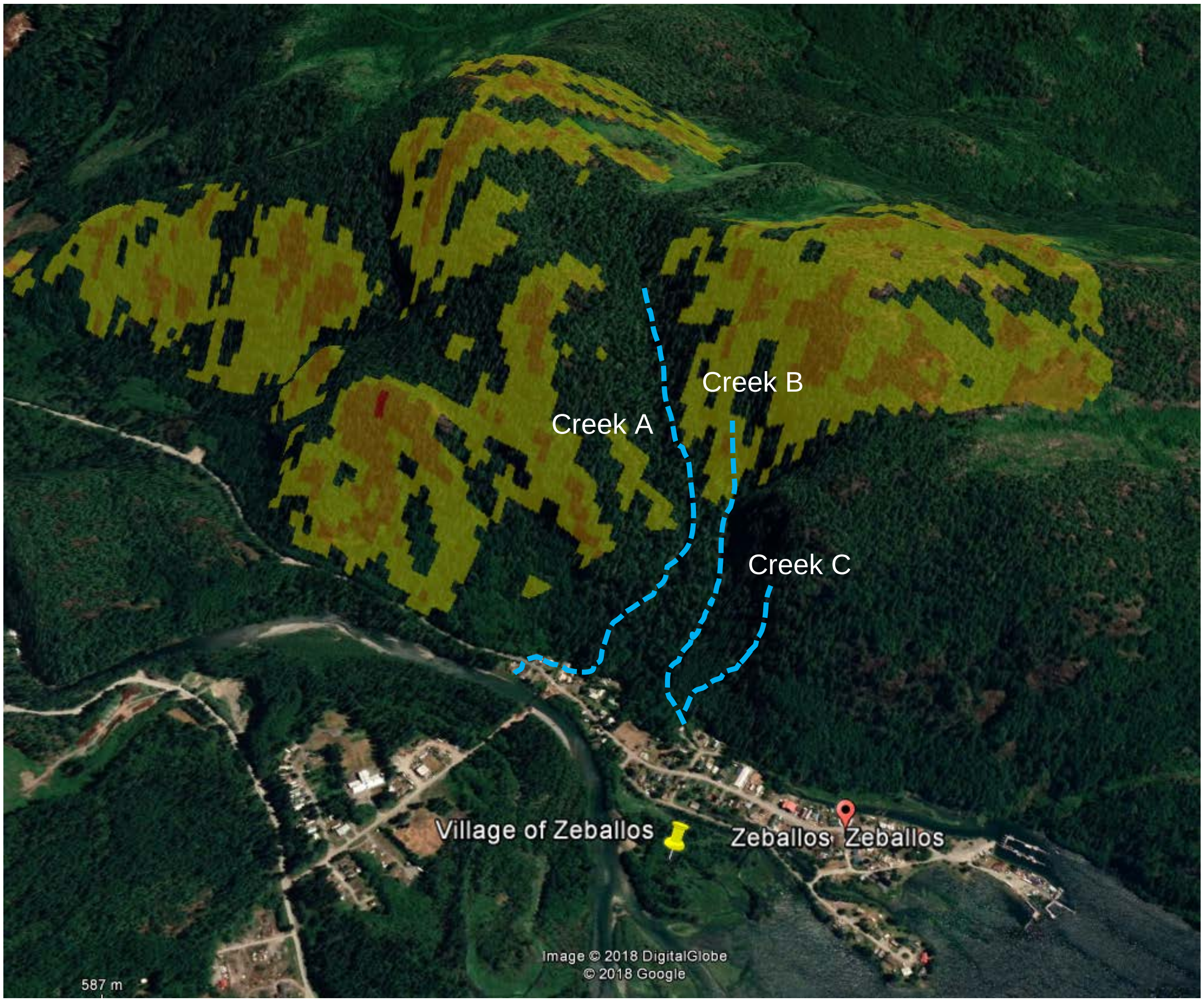

Figure 1-1. **Preliminary burn severity map for Fire V82441 (FLNRORD, 2018). Creeks A, B and C are added for reference.**

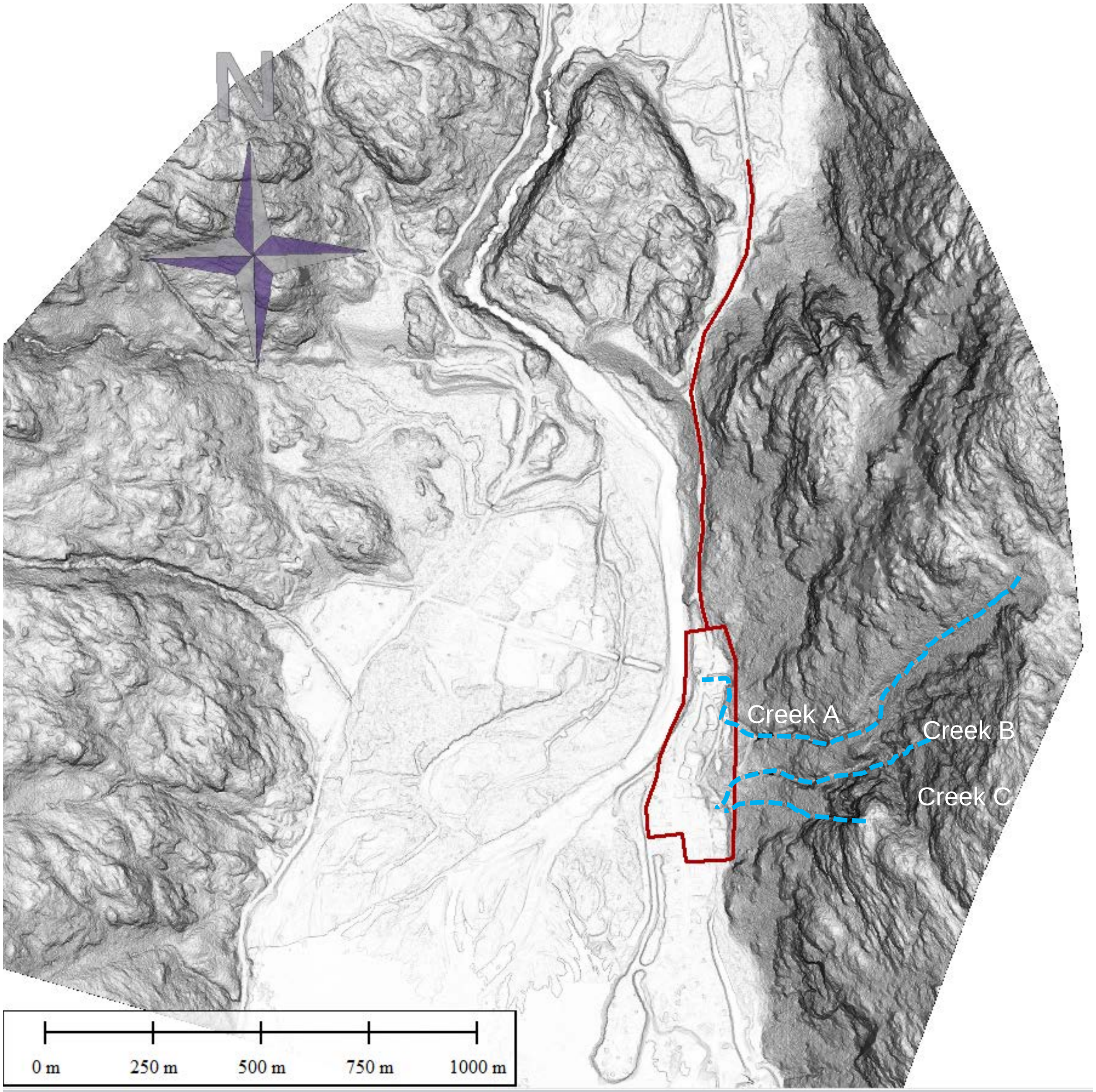

Figure 1-2. Hazard and risk assessment locations (in red) requested by FLNRO overlain on LiDAR topography.

2.0 WILDFIRE EFFECT ON SLOPE HAZARD MECHANISM AND FREQUENCY

After wildfires, both debris flow and rock fall frequency and magnitude are likely to change for a certain period. Appendix A provides a summary of the literature on this subject. While not an exhaustive review of the substantial literature on the subject, it distills key issues.

Post-fire landscapes are subject to two primary debris flow initiation processes, summarized by Cannon and Gartner (2005) as runoff-dominated erosion by surface overland flow, and infiltration-triggered failure and mobilization of soil/rock mass.

For rock fall, extreme heating of loose boulders and jointed rock masses further dilates discontinuities, stresses cohesion-providing characteristics like rock bridges, and removes or weakens buttressing trees. Dry raveling can further undermine rocks close to their pivot point.

3.0 PRE-FIRE HAZARD ASSESSMENT SUMMARY

3.1. General

The following text is a summary of pre-fire hazard assessments conducted as part of the scope with the Village of Zeballos. It is included to provide the reader with the context of this study and how it is embedded into the more comprehensive hazard and risk assessment. A full description, including design basis and methodology, will be provided in the detailed hazard and risk report. The pre-fire slope hazard assessment was based on the following data sources:

- A field reconnaissance on May 10 and 11, 2018, including:
    - Deposit mapping
    - Creek bed and side wall inspections
    - Test trenching
    - Dendrochronology
    - Resident interviews
    - Museum archive review
- Watershed-scale air photo analysis
- Radiocarbon dating.

Slope hazards are assessed in terms of how likely they are to occur and, if they occur, how likely the hazard is to reach the limits of the Village in general and specific properties. As previous studies have concluded (e.g. Golder, 1997), slope hazards exist throughout the entire length of the slope east of the Village. Over the very long term, it is a statistical certainty a slope hazard could occur and reach the Village. Hence, BGC assessed the hazard’s effect on the Village as the combined analysis of the hazard occurring, reaching the Village and resulting in some damage.

Snow avalanches were excluded from the scope as no signs of snow avalanche paths were identified. Note that extensive tree mortality on a slope potentially prone to snow avalanche formation associated with the wildfire could, under certain circumstances, result in the formation of new snow avalanche paths.

Debris avalanches and debris slides from the slopes flanking the Village to the east were not considered because air photograph interpretation demonstrated no signs of debris slides during the past 70 years, and probably much longer given that BGC did not identify longitudinal swath of substantially younger trees indicative for old debris avalanches. Widespread tree mortality above or within the main gullies (creeks A and B), could result in debris slides that have not been documented in the air photograph record. Debris slides may thus result from the effects of the wildfire but are believed to likely transition into debris flows.

BGC grouped the geohazards under consideration into three categories: debris flow, rock fall and rock slides. Each geohazard type included the following analyses:

- Return period estimate
- Estimation of plausible event magnitudes
- Two-dimensional runout analysis (for rock fall and debris flow)
- Hazard intensity mapping (for debris flow).

These analyses were used to produce hazard intensity zones and probabilistic runout length estimates, which informed an estimate of the likelihood of a geohazard impacting a building at various locations in the Village.

3.2. Geohazard Scenarios

This assessment is based on debris flow, rock fall and rock slide scenarios, which are defined as events with particular volumes and likelihoods of occurrence. Geohazard scenarios were chosen to represent the spectrum of possible event magnitudes. Along with their probability of occurrence, these scenarios are the primary outcome of the hazard assessment that is carried forward into the risk analysis. The following scenarios were assessed:

- Debris Flow – 300 to 1000-year pre-fire and 30 to 100-year return period post-fire corresponding to approximate event magnitude of 4000 m^3 for creeks A and B and 230 m^3 for Creek C. Pre-fire debris flows are considered unlikely for return periods less than 300 years under historical climate conditions.
- Rock Fall – median boulder size of 2 m diameter observed during site visit.
- Rock Slide – 90th and 99th event magnitudes, corresponding to approximate 6000 m^3 and 30,000 m^3.

While the possibility of larger, rarer scenarios cannot be ruled out, the incremental increase in risk due to these scenarios is small because the next higher return period class (1000 to 3000 years) is expected to be of marginally higher (+40%) volume. This implies similar impact intensities and extent, within the precision of this analysis. For group risk assessments (not conducted herein), the higher return period class should be considered.

3.2.1. Debris Flow

The pre-fire probability of debris flows occurring (P_H) was estimated by radiocarbon dating of organic materials found on the fan of A and B creeks and by application of a regional frequency-magnitude relationship based on fan area developed by Jakob et al. (2016).

For debris flow, an event large enough to reach the Village is likely to spread to anywhere on the fan and have sufficient width to impact the entirety of an intersecting building. BGC modelled the 300-1000-year debris flow scenario numerically to estimate the spatial probability, $P_{S:H}$, described in Section 4.3.1.

3.2.2. Rock Fall and Rock Slides

BGC estimated the pre-fire frequency of rock fall and rock slides to be the lesser of the historical record (i.e., they occur at an interval at least as long as the historical record) or the number of observed events since the last glaciation. Both are approximately equal to 100 years (e.g., 109 rock slide events in 10,000 years), and therefore the annual probability of rock fall and rock slides is at least 1 in 100 years, or 0.01.

Rock fall sizes were mapped for each boulder BGC observed reaching the Village. Boulder diameters ranged from 1 to 7 m, with a median of 2 m. Rock slide source volumes were estimated by measuring the scarp crest length from the October 2015 LiDAR topography and then scaling the value to the published best fit regressions. This was then calibrated to the two known historical event volumes estimated by Golder (1997). Representative source volume ranges used in the analyses are 5,000 to 6,000 m^3 (90%) and 25,000 to 30,000 m^3 (99%).

BGC modelled rock slide and rock fall runout on 100 m spaced cross-sections throughout the Village using Dan-W and Pierre2 software packages, respectively, to produce the probability of runout exceedance lines on Drawing 2 and estimate the longitudinal component of the spatial probability $P_{S:H}$. The spatial probability of rock falls is reduced by a factor of one fifth (0.2), representing the median boulder diameter observed (2 m) divided by a typical width of building (10 m), to represent a boulder damaging a portion of the building thus reflecting that boulder impact does not necessarily lead to total building destruction.

4.0 POST-FIRE ASSESSMENT

4.1. General

BGC's scope with the Village of Zeballos initially proposed a semi-quantitative risk assessment to compare risk associated with slope, river and coastal hazards. The results of such an assessment would include qualitative estimates of risk (e.g. Low, Moderate, High). In consultation with the Village on September 13, 2018, and FLNRORD on September 14, 2018, BGC is complementing the *semi-quantitative* approach with a *quantitative* safety risk assessment (QRA) in the portion of the Village evacuated following the wild fire. The results of QRA provide a numerical estimate of the annual probability of loss of life due to the geohazards assessed. The addition of quantitative assessment to the scope of work supports decision making through comparison to safety risk tolerance thresholds applied in other jurisdictions, including the District of North Vancouver and Canmore, Alberta.

Geohazard risk assessment involves estimation of chance that geohazards occur, impact elements at risk, and result in undesirable consequences. In this study, the assessment involves estimating the risk that debris flows, rock fall, or rock slides occur on the slope east of the Village, impact buildings within the evacuation zone or vehicles on Zeballos Main Road, and cause loss of life.

This risk assessment considers key risks that were estimated and compared to risk tolerance standards applied elsewhere and focuses on individual risk from rock fall, rock slide and debris flow hazards. Individual risk estimates the chance that a specific individual will be affected by the hazard. For example, an assessment of individual risk estimates the chance that a specific person living in a dwelling would be affected by the hazard. Individual risk is independent of the number of people exposed to the hazard, as it focusses on a single individual.

This assessment is completed for each building and assumes current occupancy and full-time occupancy. BGC conservatively assumes that no evacuation of persons occurs during the event. Future changes to building location or occupancy would change the results of the assessment.

For the purposes of land use planning, lots containing habitable buildings within the evacuation area were identified on risk maps (Drawing 2).

The risk assessment included the following estimates:

- Geohazard probability pre- and post-fire (the former was completed previously as part of the comprehensive geohazard assessment)
- Chance of the hazard reaching an element at risk (building or vehicle)
- Chance of people being in their homes or vehicle when the geohazard occurs
- A person's vulnerability or the chance of someone dying should the home or vehicle be impacted by the geohazard. It is necessary to estimate intensities (destructive potential) of expected debris flows, defined by speed and flow depth. This can be achieved by numerical modelling which is described in the following section.

4.2. Site Visit

Dr. Matthias Jakob, P.Geo. and Mr. John Whittall, P.Eng. of BGC revisited the Village on September 13, 2018 to assess post-fire hazards and present preliminary findings to the Village council. Reconnaissance goals were to estimate the change (increase) in hazard likelihood and assess how the fire might have changed the initiation mechanism(s) of geohazards. Given that the fire has occurred within a few weeks of the field visit, a traverse of the watershed and slopes was considered too dangerous. Hence, most observations were conducted from roads and helicopter during several slow fly-bys. Key observations include:

- Tree mortality on slopes feeding towards the three creeks is very high and most tree roots appear to have burned (Figure 4-1). This indicates tree mortality even if the tree's crowns are still green. It also indicates a loss of the strength afforded by tree roots on steep slopes. Root strength is an important agent of slope stability on steep forested slopes.
- Dilated bedrock discontinuities (i.e. cracks in rocks) are visible (for example Figure 4-2), although there is uncertainty whether this is because of temperature fluctuations, removal of buttressing trees/roots, or simply the removal of vegetation that obstructed the view during BGC's field visit in May 2018.
- A previously vegetated outcrop exposed by the fire at the north extent of the Village show overhanging rock blocks with potential release planes (orange circle in Figure 4-3).
- Approximately 20 fresh (since the fire) rock fall deposits are present in the ditches along Zeballos Main Road (Drawing 1), including impact scars in the pavement and vegetation damage delineating the travel path (Figure 4-4). This evidence strongly suggests an increase in rock fall frequency associated with the recent wildfire. Additional/new rock fall deposits were not observed in the Village.

Figure 4-1. Photograph of typical forest floor and surface conditions post-fire. Note person for scale in mid photograph.

Figure 4-2. Photograph of a dilated bedrock discontinuity upslope of Ferris Road exposed by fire.

Figure 4-3. Photograph of previously concealed (fully tree-covered) outcrop with overhanging blocks. Photograph by BGC, September 13, 2018.

Figure 4-4. Fresh (charred) boulders observed in downslope ditch of Zeballos Main Road. Photographs by BGC, September 13, 2018.

4.3. Hazard Assessment

4.3.1. Debris Flow Modelling

BGC computer-modelled debris flows to estimate the spatial extent associated with these hazards and estimate their intensities. Rock fall and rock slide runout modelling were included in the original scope with the Village. The model outputs are used to develop interpreted hazard intensity maps, which form the basis for risk assessment.

Model Selection

Modelling was completed using FLO-2D, a two-dimensional, volume conservation hydrodynamic model. FLO-2D can be used to model clearwater floods, debris floods and debris flows. FLO-2D is also a model approved by the U.S. Federal Emergency Management Agency (FEMA).

Model Setup and Input Parameters

The models are run on a 2 m spaced grid created from a digital elevation model (DEM) constructed from 2015 LiDAR. Elevation is averaged for each cell from the DEM.

Boundaries were selected for each creek to best represent how the flows would interact with the topography and development. Manning’s n values (a measure of flow roughness or flow resistance) were varied depending whether the cell was in the built environment or on the undeveloped parts of the fan. A hydrograph for the inflow cell at the apex of the fan was specified for each fan based on the peak flow and sediment volume estimated for a 300 to 1000-year return period for each watershed. For the post-fire debris flows, it was assumed that only the frequency would change by an order of magnitude (namely from a 300 to 1000-year return period to a 30 to 100-year return period). The magnitude, as discussed in Section 3.2, would only increase by approximately 40%. A 40% increase in debris volume is not believed to result in substantially different impact forces (i.e. increases in the impact intensity index by one order of magnitude). Should several debris slides develop in burned areas, it is conceivable that the magnitude of debris flows may also increase. However, given the lack of any quantitative methods to test this hypothesis, it was not included in BGC's analysis.

Supercritical flow (faster velocities typical for shallow flows) was assumed as it represents a natural debris flow. Table 4-1 summarizes the input parameters that were used to set up the models.

Table 4-1. FLO-2D input parameters.

Parameter		Value
Manning's n	Undeveloped areas	0.075
	Streets	0.025
Floodplain limiting Froude number		1.3
Sediment concentration		50%
Surface detention		0.03 m

The effects of infiltration were not modelled. Infiltration during a debris flow (unlike debris floods or floods) is considered of minor importance due to the high sediment concentration of the flow.

In addition to modelling fluid debris, FLO-2D also has several features that facilitate modelling flows through urban environments, such as the Village of Zeballos development on the edge of the A, B, and C creek fans. Area reduction factors (ARFs) were used to represent buildings and block flow through grid cells. ARFs were applied to grid cells that are entirely occupied by buildings on the A, B, and C creek fans. The use of ARFs allows for flows to be routed around and between buildings which is particularly important for debris-flow intensities (as applicable to A, B, and C creeks) that are unlikely to inflict major structural damage to a building.

Sediment and water inputs are defined using inflow hydrographs assigned to a grid cell at the fan apex. The peak discharge of the hydrograph differs for the three creeks. The sediment volumes are estimated using regional F-M relationships for each creek (Jakob, McDougall, Bale & Friele, 2016). The debris flow input hydrographs use a constant length of hydrograph and sediment concentration (50%), and the shape of the hydrograph is adjusted to match the estimated sediment volume and peak discharge. The inflow hydrograph parameters are summarized in Table 4-2.

Table 4-2. Simulated debris flow scenarios for a 300 to 1000-year event on A, B and C creeks.

	A Creek	B Creek	C Creek
Sediment volume (m^3)	4,200	3,900	200
Peak discharge (m^3/s)	102	98	9

Debris flow modelling also requires the definition of rheological parameters, which inform the flow behaviour of the water and debris slurry. The main rheological parameters are viscosity and yield stress, which are modified during model calibration to best match the deposit extent and thickness of events that have been determined through test trenching conducted by BGC in May of 2018. Neither variable is directly measured from observed events.

There were no previously recorded debris flow with known runout or flow depth for A, B or C creeks. This meant that a direct calibration from a previous deposit was not possible. Rheological parameters were chosen based on the anticipated runout distance judged by observed and interpolated fan boundaries and deposit thickness as inferred from test pitting. Deposit thickness is a minimum estimate for flow thickness. The final rheological parameters that are considered as reasonably approximation of a true debris flow are presented in Table 4-3.

Other variable combinations are certainly possible that would result in somewhat different model outcomes. In absence of a known debris flow suitable for model calibration, it is not possible to further constrain these variables. Given that BGC varied most input parameters for the risk assessment, it is reasonable to assume that minor variations in debris flow runout have been captured adequately.

Table 4-3. Rheological parameters used for A, B and C creek debris flow models.

Viscosity Coefficient	Viscosity Exponent	Yield Stress Coefficient	Yield Stress Exponent
0.0075	14.4	2.6	17.5

4.3.2. Hazard Mapping

FLO-2D model outputs include grid cells showing the velocity, depth, and extent of debris flow inundation. Hazard mapping is used to translate these results into inputs that can be used for the risk assessment. This is done using the flow intensity index ($\mathrm{I_{DF}}$), which is a measure of the potential destructiveness of the modelled events, at all locations within the study area. Flow intensity was defined as an index according to Jakob, Stein, and Ulmi (2012) as:

$$\mathrm{I_{DF}} = \mathrm{d} \times \mathrm{v}^2 \qquad \text{[Equation 4-1]}$$

where d is flow depth (m) and v is flow velocity (m/s). $\mathrm{I_{DF}}$ values in certain ranges have implications for potential building damage, as shown in Table 4-4. The paper's methods were further refined by subdividing the 1 to 10 $\mathrm{I_{DF}}$ class into a 1 to 3 and 3 to 10 classes for added granularity. This is believed to result in a more realistic outcome.

Table 4-4. Definitions and colour coding for debris flow intensity.

Impact Intensity	Colour	Building Damage Potential	Description
< 1	Yellow	Minor	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.
1 to 3	Dark Yellow	Moderate	Slow flowing shallow and deep flow with minor debris. High likelihood of sedimentation and water damage. Potentially dangerous to people in buildings, on foot or in vehicles in areas with higher water depths.
3 to 10	Orange	Major	Potentially fast flowing but mostly shallow water with debris. Moderate 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.
10 to 100	Red	Severe	Fast flowing and deep water and debris. High likelihood of moderate to major building structure damage and severe sediment and water damage. Very dangerous to people in buildings, on foot or in vehicles.
>100	Brown	Destruction	Very fast flowing and deep water and debris. High likelihood of severe building structure damage and severe sediment and water damage. Extremely dangerous to people in buildings, on foot or in vehicles.

Interpreted hazard maps showing I_{DF} values at all locations within the study area were developed for A, B and C creeks, for a 300- to 1000-year return period pre-fire debris flows which are subjectively thought to be equivalent to 100- to 300-year return period post-fire debris flows (Drawing 2). BGC used the smoothed fan debris flow intensities to estimate the intensities as they apply to specific buildings.

4.4. Risk Assessment for Buildings

4.4.1. 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 and tourists staying in hotels and camp housing. Hotel capacity is approximately 41 people spread over 13 rooms and 2 cottages. In total, the 1,360 m^2 evacuated area (Drawing 2) includes 17 buildings that could house people.

Table 4-5 lists the dwellings and occupancy information provided by the Village. The risk assessment in this letter 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. Table 4-5 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.

Table 4-5. List of elements at risk considered in the risk assessment.

Lot	Number of People	Occupancy Description
101	1	Some weekends, vacation property
103	1	Principal residence, stay-at-home adult
102, 104 and 106	4	Principal residence, 1 working adult, 1 stay-at-home adult and child, 1 child attending school
108	5	Year-round residence, 3 teens attending school, 2 working adults
202	1	Every second weekend, vacation property
204	1	Vacation property
205	1	Vacation property
206	1	Currently vacant. Planned to be retirement home within 2 years
203	Variable	Hotel, occasionally fully occupied
110	2	Principal residence, 1 working adult, 1 stay-at-home adult
112	3	Principal residence, 1 year old, 2 working adults
214	0	No full-time residents
402	4	Working adult and 3 school-aged kids
404	1	Principal residence, working adult
406	2	Principal residence, 2 working adults
120	1	Principal residence, stay-at-home adult
109	2	Fishing business, occupied business hours
122	2	Museum, occupied business hours

Based on Table 4-5, the evacuated area is home to a permanent population of approximately 17 permanent residents, 6 non-permanent residents and at least 4 business occupants. Population estimates for hotel occupants are based on the number and type of beds (i.e. a double bed can accommodate 2 people, a twin bed can accommodate 1) posted on the hotel's website. Buildings in lots 107, 118, 126, 207, and 216 are not habitable (Village of Zeballos, pers. comm) and are excluded from the risk assessment.

Table 4-6 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 4-6. Uncertainties associated with estimating the number of occupants of a building.

Uncertainty	Implication
Average occupancy rates may not correspond to actual occupancy rates for a given dwelling unit.	Over- or underestimation of occupant numbers
Seasonal population fluctuations (including tourists) exist that were not accounted for.	
Occupancy rates for the hotel differ from BGC's estimate.	
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.	
Seasonal visitors may occupy private residences, and additional visitors temporarily occupy service businesses.	Uncertainty in estimation of human vulnerability to geohazard impact

4.4.2. Risk Analysis

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

$$P_E = \sum_{i=1}^{n} P(H)_i P(S{:}H)_i P(T{:}S)_i \, N \qquad \text{[Equation 4-2]}$$

where:

$P(H)_i$ is the annual hazard probability defined as annual frequency ranges.

$P(S{:}H)_i$ 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.

$N = V_i E_i$ describes the consequences. [Equation 4-3]

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 4-2 was estimated.

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 (Section 3.2). The upper and lower bounds of each range were used in the risk analysis as approximate upper and lower uncertainty bounds for each frequency range.

BGC estimated a tenfold increase in debris flow and rock fall P_H based on the burn severity observed on the forest floor and the quantity of rock falls that reached Zeballos Main Road during the fire. A fivefold increase was applied to P_H as well to test the ultimate PDI estimate's sensitivity to this estimation. The results present the combined annual risk from all debris flow, rock fall and rock slide scenarios, given that some parcels may be impacted by more than one scenario.

Spatial Probability

A wide range of inundation areas are possible for a given event magnitude. Specifically, more fluid (i.e. higher water content) debris flows are expected to runout 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 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 for each creek are shown in Drawing 2. They are based on the results of modelling and judgement. Debris flow and rock slides are sufficiently wide to impact the entire width of the building, which was conservatively assumed for the purposes of this analysis. For individual risk, 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.

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 within the evacuated area varies annually, seasonally and from occasional to full time occupants. There is strong variation in the proportion of time residents spend on in the dwellings, from occasional vacation users to full-time occupants. There is also seasonal variation and likely variations from year to year.

BGC used the occupancy information provided by Village of Zeballos to estimate the average proportion of the year the person spending the greatest proportion of time at home, such as a young child, stay-at-home person, or an elderly person, is occupying the home. The assessment was then repeated assuming full-time occupancy to assess baseline risk for land use planning and permitting. "Full-time" is defined in this report as occupying the dwelling 90% of the year. This definition is consistent, in BGC's experience, with that used in jurisdictions where QRAs have informed risk reduction decision making for residential development (e.g. Canmore, District of