North Vancouver, District of Squamish). BGC assumed businesses are occupied during business hours and the hotel is at full capacity one weekend per month during spring/summer months.

Vulnerability

Table 4-7 shows the criteria used to estimate the vulnerability of persons within buildings to debris-flow or debris-flood impact, where vulnerability is primarily an indirect outcome of building damage or collapse. Building impact by flow depths < 30 cm were assumed to pose negligible risk to life for persons within buildings and were excluded from the analysis. Two different vulnerability classes are shown. Estimates for individual risk correspond to an individual most at risk, who may be located on the building ground floor. The vulnerability criteria were developed based on Jakob, Stein, and Ulmi (2012) and calibrated from known events.

Table 4-7. Vulnerability criteria for persons within buildings.

Hazard Intensity Index Range	Individual Risk
<1	0.001
1-3	0.02
1-10	0.2
10-100	0.6
>100	0.9

Note: Values indicate estimated probability of loss of life given impact

4.4.3. Results

Pre and post-fire PDI for each lot are plotted in Figure 4-5 and Figure 4-6 and colour-coded on Drawing 2 based on September 2018 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. Figure 4-5 and Figure 4-6 also show safety risk tolerance thresholds adopted by the Town of Canmore and District of North Vancouver as solid red and dashed orange lines (Town of Canmore, 2016, DNV, 2009). Solid red and dashed orange lines show risk tolerance thresholds for existing and proposed development, respectively.

Debris flow are the dominant risk for all lots except 101 through 106, where rock fall governs the risk. Lots 120 and 122, and other dwellings south of Ferris Road along Maquinna Avenue, are situated beyond the debris flow intensity contours (Drawing 2) and are unquantifiable risk, but are interpreted to be associated with risk lower than the 10^{-5} criterion.

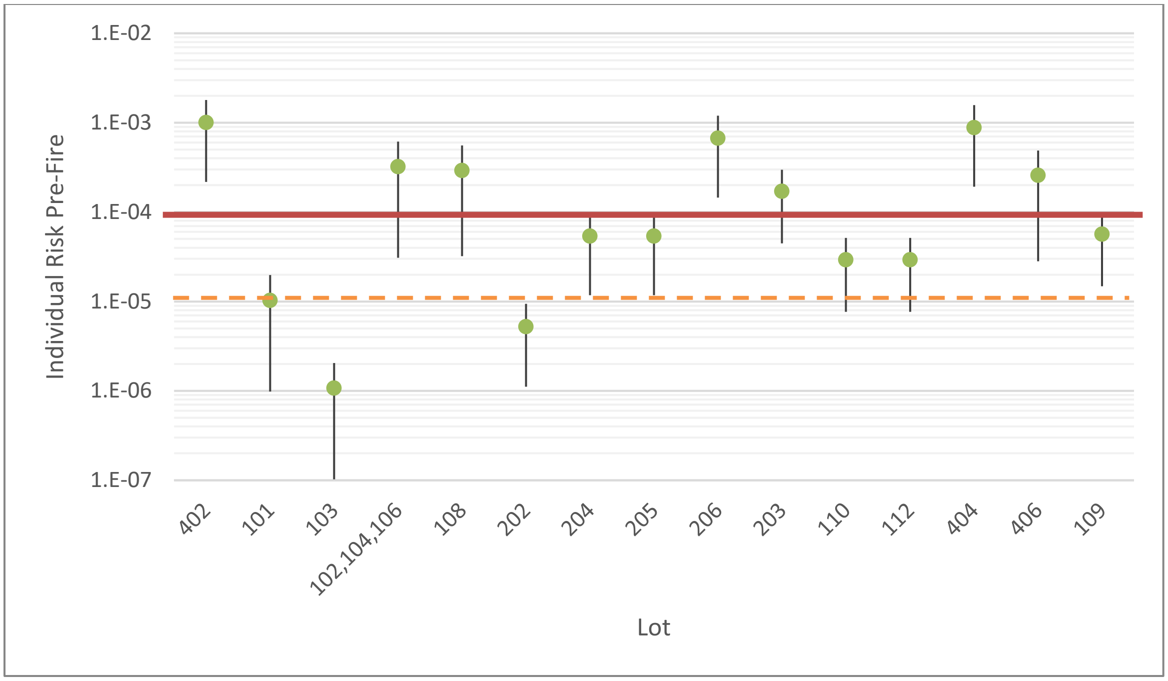

Figure 4-5. **<u>Pre-fire</u> PDI for lots in the evacuation zone using current occupancy as reported by Zeballos. Solid red and dashed orange lines are the District of North Vancouver and Town of Canmore PDI thresholds for existing and new developments, respectively.**

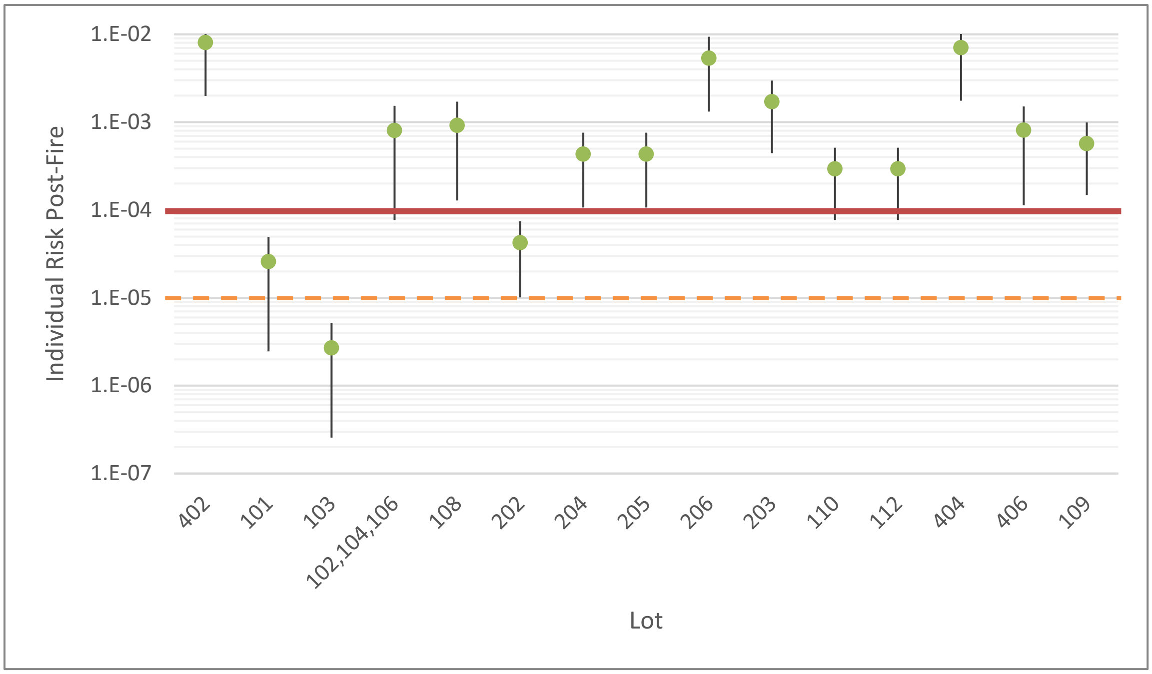

Figure 4-6. **<u>Post-fire</u> PDI for lots in the evacuation zone using current occupancy as reported by Zeballos. Solid red and dashed orange lines are the District of North Vancouver and Town of Canmore PDI thresholds for existing and new developments, respectively.**

The same twelve dwellings remain in excess of the 10^{-4} criteria if post-fire P_H is increased only fivefold. BGC repeated the risk assessment assuming full-time occupancy in all dwellings to provide context for long-term land-use and policy development (Figure 4-7 and Figure 4-8).

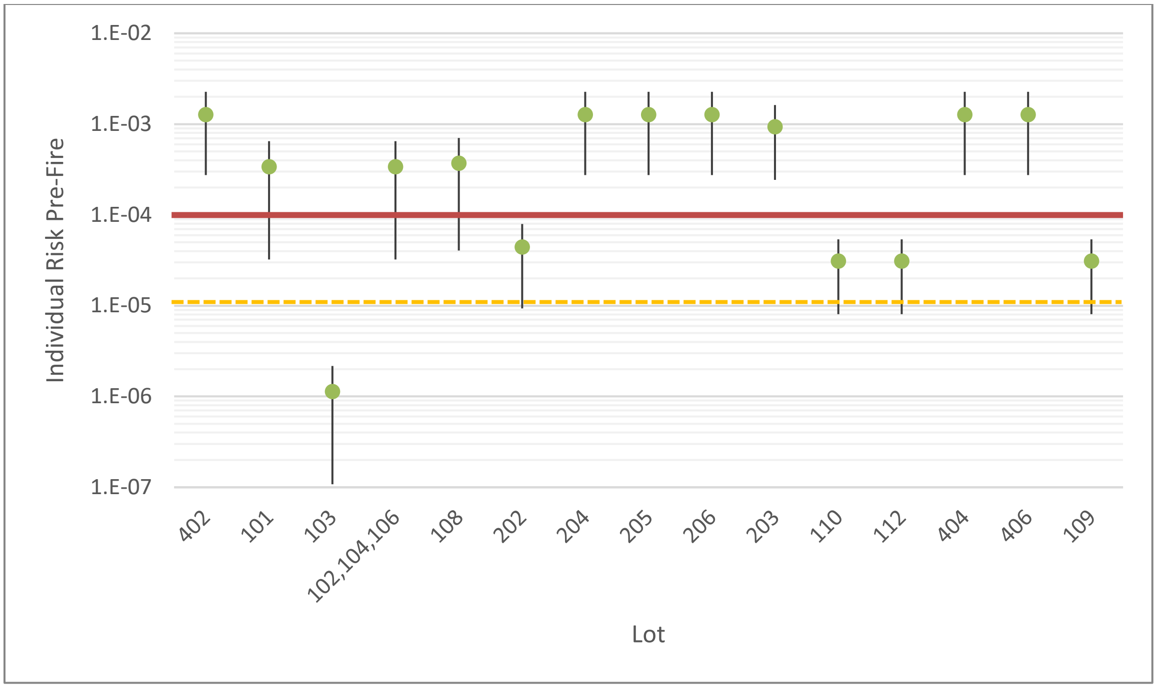

Figure 4-7. **<u>Pre-fire</u> PDI for lots in the evacuation zone assuming <u>full-time occupancy</u>. Solid red and dashed orange lines are the District of North Vancouver and Town of Canmore PDI thresholds for existing and new developments, respectively.**

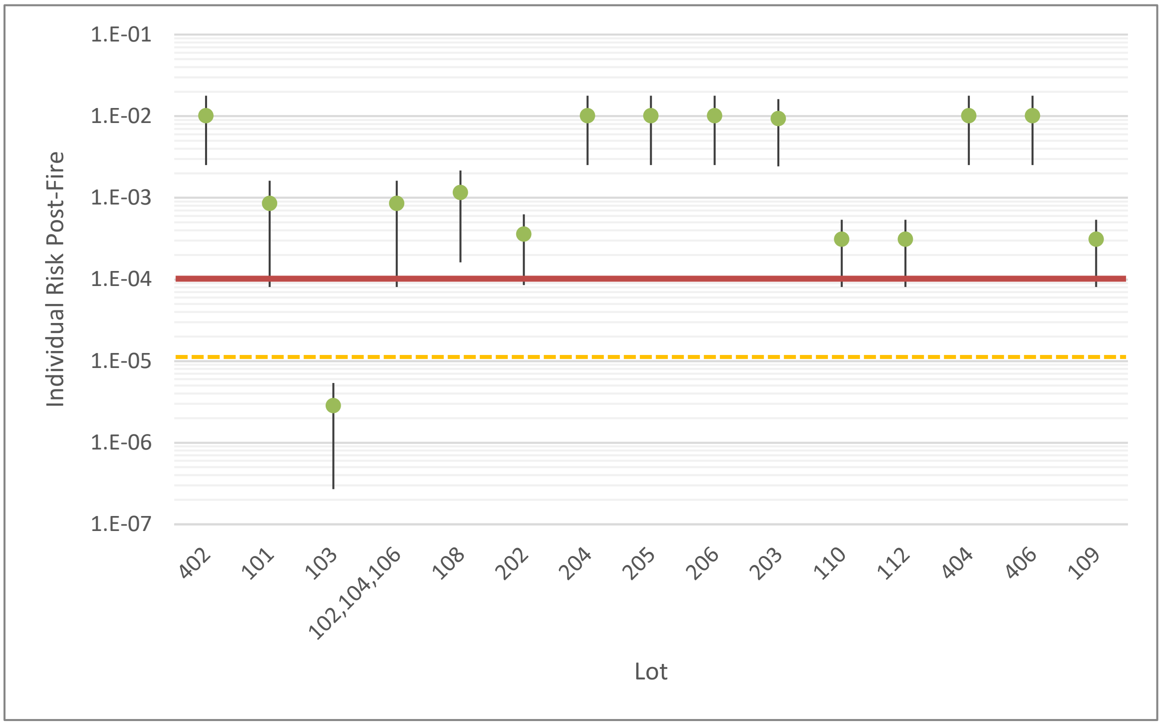

Figure 4-8. **<u>Post-fire</u> PDI for lots in the evacuation zone assuming <u>full-time occupancy</u>. Solid red and dashed orange lines are the District of North Vancouver and Town of Canmore PDI thresholds for existing and new developments, respectively.**

4.5. Risk Assessment to Zeballos Main Road

4.5.1. Introduction

BGC estimated risk of loss of life due to rock fall impacting a moving vehicle along a 1.05 km section of Zeballos Main Road, from the northern boundary of the Village to the tsunami evacuation site (Figure 1-2). Village works personnel indicated to BGC during the September 2018 site visit that there is no record of rock fall or other slope hazards reaching the road prior to the fire. During the May 2018 site visit, BGC identified one rock fall boulder on the southern extent of the tsunami evacuation clearing but the time of occurrence is not known. As stated in Section 4.2, BGC identified approximately 20 fresh boulders in the road ditches that occurred during the fire.

BGC did not consider scenarios of rock fall impacting a stopped vehicle or a vehicle impacting a previously deposited rock fall relevant to this assessment as traffic is sparse (Village of Zeballos, pers. comm), sight lines are long, and the posted speed limit is low.

4.5.2. Elements at Risk

Elements at risk considered in this assessment include individuals travelling the road in light vehicles (i.e. cars and light trucks).

4.5.3. Risk Analysis – Impact to Moving Vehicles

Risk of loss of life due to rock fall for moving vehicles is the probability that rock fall occurs and reaches a vehicle when it is present within the hazard zone, with enough destructive potential to result in loss of life. BGC applied Equation 4-2 to estimate the PDI. The risk analysis follows the same principles as for fixed infrastructure (i.e. buildings) but uses different methods to estimate probability of impact.

Estimates of rock fall probability and vulnerability to loss of life given impact are highly uncertain given the available information. As a sensitivity analysis to determine whether rock fall risk could credibly reach or exceed risk tolerance thresholds normally applied to residential development (i.e. Canmore and DNV risk tolerance criteria), BGC made several assumptions.

The probability a vehicle driver is present in the hazard zone at the time of impact depends on vehicle speed and how frequently they travel the road. BGC estimated the level of individual risk for a driver travelling the road an average of twice per day, 230 days per year, at 50 to 80 km/hr. The upper and lower speeds defined an upper and lower proportion of time spent within the hazard zone. Rock fall was assumed to occur anywhere in the road section, where the chance of the moving vehicle being struck depends on the timing and location of the boulder. Given impact, BGC applied a 0.6 likelihood of fatality, according to Table 4-7.

Based on the above assumptions, BGC estimated the rock fall frequency that would be required for annual risk of loss of life to exceed 1:10,000. For this value to be exceeded rock fall would have to impact the studied road reaches with a frequency of 24 to 38 boulders per year and have sufficient energy to result in a 60% chance of fatality given impact. This frequency is higher than that observed in the historical record and higher than observed post-fire rockfall frequency to date. Risk to a hypothetical road user traveling the road 460 times a year ranges from 1:18,000 to 1:29,000 for post-fire conditions, and is thus considered tolerable according to DNV and Canmore risk tolerance thresholds.

In summary, BGC estimates that the risk of loss of life due to rock fall impact to moving vehicles is likely in the tolerable (PDI<1:10,000) to broadly acceptable (PDI<1:100,000) range.

5.0 POST-FIRE RECOVERY

The period of increased geohazard activity following fire is most pronounced within the first three to five years after the fire (Cannon and Gartner, 2005; DeGraff et al., 2015). After about three to five years following fire, vegetation can re-establish on hillslopes and loose, unconsolidated sediment mantling hillslopes and channels may have been eroded and deposited downstream. A second period of post-fire debris flow activity is possible about ten years following a fire, when long duration storms with high rainfall totals or rain-on-snow events cause landslides that more easily mobilize due to a loss of cohesion caused by tree root decay (Degraff et al., 2015; Klock and Helvey, 1976; Sidle, 1991; 2005). This second period of heightened debris flow activity is rare. Degraff and Gallegos (2012) estimate rock fall frequency returns to pre-fire levels after a year or two.

6.0 MITIGATION MEASURES

A variety of measures can be contemplated to reduce the existing risk. They include active (structural mitigation, warning systems) and passive measures (land sterilization and land use zoning). A selection of such measures are summarized in Appendix C.

7.0 LIMITATIONS

This assessment is based on a combination of quantitative methods paired with expert judgement and field observations. An effort was made to allow for variations in the numerical values entered in the analysis to reflect the inherent uncertainty underlying various assumptions. The most significant uncertainty lies in the estimate of return period (frequency) of the geohazards considered, as no historical observations are available.

The work presented herein had to be produced rapidly to facilitate risk-informed decisions. The short timeline required simplification in the number of scenarios assessed and precluded the use of more sophisticated approaches to estimate geohazard event frequency, magnitude, runout and intensity, such as dendrochronological investigations and individual boulder runout modelling. Such work could result in somewhat different outcomes. Nonetheless, BGC believes the outcome to be a reasonable representation of safety risk posed by rock fall, rock slides and debris flows.

As additional information on geohazards (timing, location and size) becomes available in the coming months, aspects of the quantitative risk assessment can (and should) be refined. Such refinement could change the outcome of the present risk assessment.

8.0 CONCLUSIONS AND RECOMMENDATIONS

This assessment aimed to quantify risk from rock fall, rock slides and debris flows for the properties within a defined assessment area following the V82441 wildfire that burned the eastern slopes above the Village beginning August 16, 2018. The motivation of the quantitative risk assessments was to provide information to the Village that may help in the decision to extend or lift the existing evacuation order, or at least lift it for selective properties.

BGC estimated that the V82441 wildfire has increased debris flow and rock fall probability and hence risk by approximately one order of magnitude (tenfold). This estimate was based on a review of literature pertaining to the subject, and a subjective evaluation based on visual post-fire landslide observations. It is also the variable associated with most uncertainty given that little research has been conducted in the wet areas of the Pacific Northwest.

Hazard and risks are presented for the 2018 occupancy of the evacuated residences and businesses and compared to international and risk tolerance criteria applied by two Canadian municipalities (Appendix B). Of the seventeen properties that were affected by the evacuation order, seven exceeded the 1:10,000 life loss risk criterion that is being used by the District of North Vancouver and Canmore in Canada and elsewhere. After the wildfire of August of 2018, the risk increased to twelve properties exceeding the 1:10,000 life loss risk criterion. Three additional properties are close to the criterion but did not exceed BGC's best risk estimate.

The analysis was repeated with the assumption of full-time residency of all habitable buildings. In that case, the pre-fire risk would be similar to the current occupancy levels with ten properties exceeding the 1:10,000 life loss risk criterion. For the post-fire situation fourteen evacuated properties would exceed the 1:10,000 life loss risk criterion. Of these properties, eight exceed 1:1,000 annual risk of loss of life.

BGC also estimated the risk to the road users most at risk, namely someone driving by the investigated slopes 460 times per year. Risk to this hypothetical road user ranges from 1:18,000 to 1:29,000 for post-fire conditions. This implies risk being tolerable using the 1:10,000 life loss risk criterion that is being used by the District of North Vancouver and Canmore in Canada and elsewhere.

BGC recommends that detailed records be kept by the Village on any rock fall that enters the Village (time, date, location, boulder size), or any changes in the behaviour of A, B, or C creeks (changes in flow direction, flow magnitude, coloration, debris movements). Furthermore, weather records from the Village's weather station should be digitized and made available so that the geomorphic response to major rainstorms and wind storms can be analyzed. A monitoring program involving measurement of debris in A, B and C creek at particular locations over time could also help to adjust especially the frequency of the post-fire geohazards and further adjust the risk assessment.

Mitigation measures that can be considered are summarized in Appendix C.

9.0 CLOSURE

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

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Attachment(s): Appendix A – Wildfire Influences on Geohazards
Appendix B – Individual Risk Tolerance Criteria
Appendix C – Conceptual Mitigations
Drawings

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APPENDIX A
WILDFIRE INFLUENCES ON GEOHAZARDS

A.1. WILDFIRE EFFECTS ON GEOHAZARDS

This appendix describes the influence of wildfire on the likelihood and severity of geohazards in mountainous terrain.

Wildfires in steep mountainous terrain are often followed by a temporary period of increased geohazard activity. The intense heat of a wildfire can cause a variety of changes to the overall hydrologic response of a watershed to rainfall resulting in destructive debris slides, debris flows and debris floods.

Erosion in recently burned areas has been well documented. Changes to the hydrologic response of a drainage basin to rainfall have been attributed to the intense heat of a wildfire removing vegetation and causing changes to the ability of the soil to infiltrate water (Ebel et al., 2012; Moody and Martin, 2001). Ash on the soil surface can absorb water, seal off pore spaces in the soil and reduce the amount of water that can infiltrate the soil (Balfour and Woods, 2007). Hydrophobic compounds in vegetation are combusted during fire and can travel downwards into the soil column and precipitate on a layer 5 to 10 cm deep, creating a water-repellant layer (DeBano, 1981; Doerr et al., 2000). The removal of the vegetative canopy, litter and duff by fire exposes bare ground to rainfall (Moody and Martin, 2001). The combustion of vegetation and shallow rootlets that anchors soil at the surface leads to dry raveling of material that accumulates in channels and provides easily eroded material for erosion by debris flows and debris floods (Lamb et al., 2011; Wells, 1987). The combination of these changes to the soil surface by wildfire results in increased overland flow of rainfall that erodes material and concentrates in gullies and channels to form hazardous debris flows and debris floods (Cannon and Gartner, 2005; Moody and Martin, 2001; Wells, 1987).

A range of erosive processes are possible in burned areas due to rainfall. Rills are small channels (less than 20 cm wide and 30 cm deep) that may erode hillslope material (Figure A-1). Progressive bulking of sediment (Cannon et al., 2003) in channels may form debris flows that can transport large volumes of material (greater than about 1000 m^3), impart force sufficient to scar or snap trees (Figure A-2), and deposit enough material to bury cars, homes and roads. Debris-flow material deposited in flooded creeks with larger contributing drainage areas can result in debris floods that are highly erosive and capable of transporting significant volumes of sediment and woody debris (Figure A-3). These erosive responses of a burned area to rainfall may be the result of relatively normal rainfall events with frequent recurrence intervals (Cannon et al., 2008).

Increases to rock fall activity during and following fire have been observed and are evidenced by colluvial cones of material deposited on roads that traverse steep, burned hillslopes (e.g., DeGraff and Gallegos, 2012; Shakesby and Doerr, 2006). Increased rock fall activity has been attributed to intense drying of the soil that reduces cohesion (Swanson, 1981), the removal of vegetative anchors for rock and soil (Floresheim et al., 1991), and rock spalling (Birkeland, 1984; DeGraff and Gallegos, 2012).

The period of increased geohazard activity following fire is most pronounced within the first three to five years after the fire (Cannon and Gartner, 2005; DeGraff et al., 2015). After about three to five years following fire, vegetation can reestablish on hillslopes and loose, unconsolidated sediment mantling hillslopes and channels may have been eroded and deposited downstream. A second period of post-fire debris-flow activity is possible about ten years following a fire, when long duration storms with high rainfall totals or rain-on-snow events cause landslides that more easily mobilize due to a loss of cohesion caused by tree root decay (Degraff et al., 2015; Klock and Helvey, 1976; Sidle, 1991; 2005). This second period of heightened debris-flow activity is rare and post-wildfire debris flows are most predominant immediately following the fire and continuing for up to about three to five years.

Geohazards are exacerbated by hydrologic changes to the burned watersheds. The removal of vegetative canopy, understory, litter and duff results in less attenuation of water during a rainfall event that is a result of fewer obstructions to flow and reduced evapotranspiration. As a result of the fire, more rainfall is able to concentrate in creeks at a faster rate and rainstorms can produce higher peak flows in creeks than before the fire. Furthermore, overland flow of water, which would normally infiltrate the soil, can cause excessive erosion of hillslopes and rocky terrain where overland flow of water is not common (e.g. rilling on hilllslopes visible in Figure A-1).

Specifically, with respect to wildfire impacts in the wet portions of the Pacific Northwest, Jackson and Roering (2007) reported the development of water repellent soils. However, these did not appear to lead to rilling and overland flow as typical for dry-area soils, but did allow for infiltration though soil discontinuities. Dry raveling was observed in the authors’ study site of the Oregon Coast range similar to the better-studied drier areas. Notably, the authors discovered a more rapid decay in root strength compared to timber harvesting which suggested that root strength was compromised prior to the fire or that intense heat damaged roots in the shallow subsurface.

Jackson and Roering (2007) also suggested that the high infiltration rates of the Oregon Coast Range soils appear to disfavor debris flow initiation via entrainment of ash, soil, and debris along valley axes that is commonly observed in other landscapes. Instead, their findings appear to highlight the role of shallow landslide-initiated debris flows in sculpting the landscape. Irrespective of the debris-flow initiation mechanisms, the authors concede that the frequency of debris flows is likely to increase in the post-fire era. This finding was further corroborated by Wondzell and King (2009) who noted that in the Pacific Northwest region, debris flows are typically initiated as debris slides, cause by soil saturation and loss of soil cohesion as roots decay following fire.

A study of sediment residence time in Oregon Coast Range headwater catchments suggests that headwater debris deposits are preferentially stored (rather than evacuated) such that the signature of debris flow transport following fire may be muted to downstream areas (Lancaster and Casebeer, 2007). This is relevant for creeks A and B at Zeballos as temporary storage could delay the debris-flow response by years or even decades, depending on the type (log jams, large boulder jams) and their present state (stable, unstable, decayed), as well as the recharge mechanism acting in the watersheds.

01/11/2004

Figure A-1. Steep hillslopes and channels in the San Bernardino Mountains of southern California demonstrate how recently burned areas are prone to erosion following fire. Photo: Susan Cannon, USGS.

01/25/2004

Figure A-2. A debris-flow deposit in Day Canyon, California consisting of large boulders embedded in a fine-grained matrix that scarred and broke full grown trees. Photo: Susan Cannon, USGS.

Figure A-3. Woody debris deposited by a debris flood in the San Bernardino Mountains, southern California. Photo: Susan Cannon, USGS.

APPENDIX B
INDIVIDUAL RISK TOLERANCE CRITERIA

B.1. DEVELOPMENT OF STANDARDS INTERNATIONALLY

B.1.1. Hong Kong

The Hong Kong Geotechnical Engineering Office (GEO) developed criteria for societal and individual risk for developments potentially affected by landslides in 1998. The criteria have been widely used in Hong Kong, and have been used or adapted by many other jurisdictions since. As examples, the Hong Kong criteria have been recommended by eminent review boards for development on the Cheekeye River Fan near Squamish in southern BC (Clauge, J., Hungr, O., VanDine, D. 2014) and for development on steep creek fans in Alberta (Alberta, Environment and Parks, AEP, 2015).

Individual risk tolerance criteria were set at 1:10,000 chance of fatality per year for existing construction and 1:100,000 for new construction (GEO, 1998). The societal risk tolerance criteria can be summarized by an F-N curve, which defines four “zones” of risk: unacceptable, as low as reasonable practicable (ALARP), intense scrutiny, and broadly acceptable. The zones are defined by the expected number of fatalities, N, and the annual frequency of the event causing N or more fatalities. The 1:1 slope in log-log space signifies society’s aversion to an increasing number of fatalities.

The use of risk of loss of life tolerance criteria originated in the United Kingdom and the Netherlands during the 1970’s and 80’s in response to the need to manage risks from major industrial accidents (Ale 2005). Hong Kong adapted the United Kingdom criteria for the management of landslide hazards, and similar approaches have been applied in Australia, Switzerland and Austria. While risk tolerance levels vary amongst jurisdictions and the evaluation criteria for individual and societal risk are different, some common general principles apply (Leroi et al. 2005):

- The incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life.
- The incremental risk from a hazard should be reduced wherever reasonably practicable, i.e., The ALARP principle should apply.
- If the possible number of lives lost from an incident is high, the likelihood that the incident might occur should be low. This accounts for society’s particular intolerance to many simultaneous casualties, and is embodied in societal tolerable risk criteria.
- Higher risks are likely to be tolerated for existing developments than for new proposed developments.