The Meager and Pebble Creek Hotsprings near Pemberton, British Columbia: Guidance towards a Landslide Risk Management Plan

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1.0 Introduction

This report provides guidance for the development of an operation safety plan for Meager Creek and Pebble Creek hotsprings, Mount Meager Volcanic Complex, upper Lillooet River, BC (Figure 1). Since forestry road access in the late 1970s, these hotsprings sites have been popular. Meager Creek more so, as there are more pools and easier access.

Due to the recognition of the seriousness of the landslide risk, in 1999 MoF commissioned a landslide risk management plan for Meager Creek (Baumann Engineering/EBA 1999). At that time the Meager Creek hotsprings were being rejuvinated, and the management plan was initiated, with overnight camping at 36 km on the Lillooet FSR and day use only at the hotsprings, with shutdown governed by daily monitored weather thresholds. Almost as soon as the hotsprings were operational, the old Meager Creek bridge was washed out by bank erosion during the 2003 flood. It was not until spring 2008 that the bridge was replaced and access reestablished. Then in fall 2009 a large debris flow (0.5 M m^3) took out access at Capricorn Creek (Cordilleran 2009). In early summer 2010, work to reestablish the Capricorn Creek crossing and the lower 3 km of Br 3 accessing Meager Creek valley was being conducted when the August 6, 2010, Mount Meager landslide occurred (Guthrie et al., 2012). Since then there has been significantly reduced use of the Meager Creek hotsprings.

As of August 2010, Meager Creek hotsprings users have had to walk in, either 7 km up the Meager Creek valley across the landslide surface, or via the VOC trailhead off Perkins Main on the South Lillooet mainline (Figure 1). Either way takes 3-4 hours, and only determined persons make the hike. Alternately, the site may be accessed by helicopter. In 2011 a quantitative risk assessment of the former 36 km campground was conducted (Cordilleran 2011), and subsequently that site was decommissioned.

In 2013, the timber licencee Squamish Mills, determined that it would develop a new access into Meager Creek via the South Meager FSR (Cordilleran 2013). Construction was started in 2014, and to date the road heading has advanced almost 6 km, and is within a few kilometers of joining with an existing FSR on the hotsprings side (Figure 1). It is anticipated that the new road access will be completed in 2017 or 2018.

Meanwhile, Pebble Creek languished as the more difficult to access site until the development of Innergex's upper Lillooet and Pebble Creek HEF. As part of an amenity package, in 2014 Innergex located and built a new trail into the Pebble Creek site, following a low route along river level from downstream access point, rather than the old route from a parking spot just past Truckwash Creek and a trail down the escarpment slope. Since the new trail was completed, use of Pebble Creek hotsprings has dramatically increased.

In light of the popularity of the Meager and Pebble Creek hotsprings sites, with the soon to be renewed and recently improved access, MoFLNO seeks to review and revise its management plan for these sites. Due to wildlife management and public safety concerns, it is understood that gates will be placed at a strategic locations, thereby blocking unrestricted public vehicle access into Meager Creek and upper Lillooet River. This report compiles all background data pertaining to hazards affecting Meager and Pebble Creek Hotsprings sites, proposed overnight camping/staging areas and road/trail access. A landslide risk management plan is presented, extending that presented by

Cordilleran (2012). This management plan comprises a 'model' for managing landslide risk consistent with the guidelines of APEGBC & ABCFP, 2008.

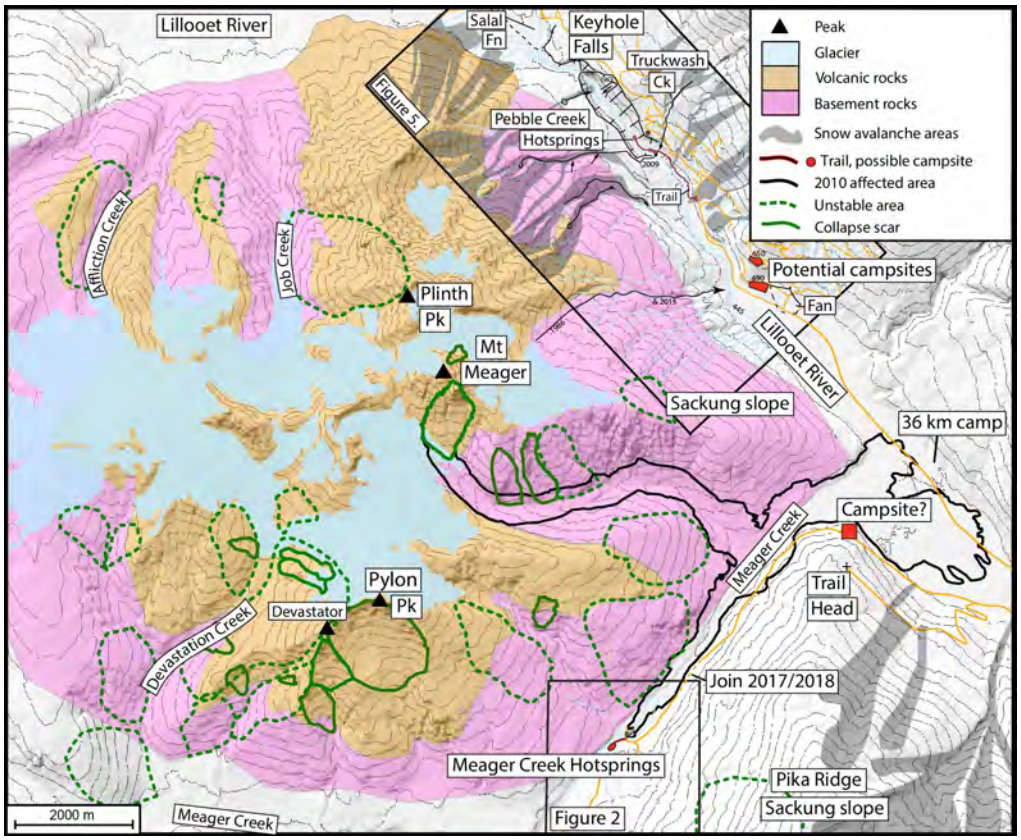


Figure 1. Location map, geology and large scale instabilities of the Meager Creek volcanic complex (after G. Roberti et al., in press).

2.0 Study Area

The Mount Meager Volcanic Complex (MMVC) is a Pliocene to Pleistocene volcanic centre covering an area of about 80 km^2 located between Meager Creek and upper Lillooet River (Figure 1), southwestern BC. It is the northernmost volcano in the Garibaldi Volcanic Belt (Green 1988), and is related to convergent margin plate tectonics on the Cascadia subduction zone. The Meager Creek and Pebble Creek hotsprings are located where geothermal waters emerge from toe of slope on the periphery of deep magma chambers located more directly beneath the volcanic massif.

Relief ranges from 400 m at the confluence of Meager Creek and upper Lillooet River to just over 2600 m on the summits of Mount Meager and Plinth Peak. The headwater valleys are steep sided and the massif is covered by alpine glacier fields. Since the end of the Pleistocene glaciation 10,000 years ago, alpine glacier coverage has fluctuated in extent in the Coast Mountains (Menounos et al., 2009), with the greatest extent reached during the peak of the Little Ice Age ca 200-300 years ago. Since the early 20th century there has been rapid retreat (Koch et al., 2009; Bolch et al., 2010), with ice cover expected to be largely gone by late this 21st century (Clarke et al., 2015).

The most recent eruption occurred 2400 years ago (Clague et al., 1995), a highly explosive event from the north side of Plinth Peak, directed northwesterly, sending a plume of tephra high into the stratosphere that then spread by the jet stream as far east as Alberta. Materials from the eruption filled upper Lillooet River below the Plinth crater, with a 275 m thick deposit of syneruptive debris, forming what is known as the Pebble Creek formation (Stasiuk et al., 1996), a chronologic/bottom-up sequence of tephra, pyroclastic flows, edifice collapse landslide deposits and outburst flood deposits (Stewart 2002; Stewart et al., 2008). The tephra, pyroclastic flows and landslide deposits blocked upper Lillooet River forming lahar-dammed Salal Lake, so-named because Salal Creek immediately upstream formed a delta into the lake. The soon thereafter, the lake breached catstrophically resulting in an outburst flood that affected the length of Lillooet River as far as Pemberton (Friele et al 2005). The flood eroded the canyon with Keyhole Falls marking the canyon head. Pebble Creek Hotsprings are found in the canyon floor.

In the Mount Meager volcanic complex, volcanic rocks overlie stronger granitic, or basement rocks mainly above 1500 m asl, but they extend down to 900 m asl south of Pylon Peak in what may be an exhumed volcanic vent (Read 1978). The most unstable areas are underlain by hydrothermally altered rocks typically associated with ancient vents. These rocks were implicated in two flank collapses of Pylon Peak, 4400 and 8000 years ago, spawning debris flows that reached Pemberton Meadows (Friele and Clague 2004; Friele et al 2005; Simpson et al 2006). Especially unstable are the headwaters of Devastation Creek and the SE ridge and flanks of the Devastator (Figure 1)(Read 1978; Van der Kooij and Lambert, 2002; Roberti et al., in press). Historic events from this area include the 1931 debris flow that reached Lillooet River (Carter 1932; Decker et al 1977), and the 1975 rockslide that killed four BC Hydro geologists (Mokievsky-Zubok, 1977). The August 6, 2010 Mount Meager landslide (Guthrie et al., 2012; Allstadt, 2013; Moretti et al., 2014; Roberti et al., 2015, 2017, in press) also involved altered rocks, which made up about 12% of the failed 50 M m^3 mass (Roberti et al. 2017).

At Meager Creek, landslides typically occur during the wet season or during the hottest part of summer when snow melt rates are high (Jordan 1994; Bovis and Jakob, 1998; Roberti et al., in press). The types of events that may directly affect the hotsprings sites are rock avalanches and debris flows from adjacent basins; debris flows initiated from basins upstream; debris or hyperconcentrated flows caused by sediment bulking or from outburst following temporary landslide damming; or hydrologic floods. Potential hazards affecting the hotsprings sites are reviewed in Section 4.0.

Climate in the area is transitional from coastal to interior, with warm relatively dry summers, with the peak of the summer heat occurring in July/August, and cool wet winters. The precipitation peaks in October through March, with a maximum rainfall intensities in October. The flood regime is mixed, with a sustained snowmelt freshet occurring between May and July and flashy storm-generated floods caused by fall rain or winter rain-on-snow events. On average, fall/winter floods are 1-2 times larger than freshet floods, with the largest regionally significant floods in the last 30 years occurring in the falls of 1984, 1991 and 2003.

There are no long term climate records for Mount Meager. Pemberton or Whistler climate stations have traditionally been used as proxy sites. In spring 2010 an automated station was installed at the mouth of Meager Creek. This station in conjunction with Pemberton station may be used for forecasting.

3.0 Landslide Hazard, Frequency, Magnitude and Consequence

Table 1 provides qualitative landslide hazard categories and general descriptions of hazard frequency in terms relevant to the human perspective.

Table 1. Qualitative landslide hazard frequency categories (MoE 1999).

Qualitative frequency	Annual return frequency	Comments
Very high	>1/20	Hazard is well within the lifetime of a person or typical structure. Clear and relatively fresh signs of hazard activity are present.
High	1/100 to 1/20	Hazard could happen within the lifetime of a person or typical structure. Landslides are clearly identifiable from deposits and vegetation, but may not appear fresh.
Moderate	1/500 to 1/100	Hazard within a given lifetime is possible, but not likely. Signs of previous events may not be easily noted.
Low	1/2500 to 1/500	The hazard is of uncertain significance.
Very low	<1/2500	The occurrence of the hazard is remote.

The consequences of large volcanic landslides are extremely severe (Table 2).

Table 2. Landslide size and related consequence (Jakob 2005).

Class	Volume (m^3)	Potential consequences
1	$<10^2$	Very localized damage, known to have killed forestry workers in small gullies and damaged small buildings.
2	10^2-10^3	Bury cars, destroy small wooden buildings, break trees, block culverts, and damage heavy machinery.
3	10^3-10^4	Destroy larger buildings, damage concrete structures, damage roads and pipelines, and block creeks.
4	10^4-10^5	Destroy camps, destroy sections of infrastructure corridor, damage bridges and block creeks. The 1984 debris on Hotsprings Creek affected the former camping area and stranded vehicles.
5	10^5-10^6	Destroy camps and forest up to 2km^2 in area, block creeks and small rivers. Identified instabilities of this volume in Hotsprings Creek basin.
6	10^6 - 10^7	Could obliterate valleys or fans up to several tens of km^2 in size, and dam large rivers with the potential for destructive outburst floods and hyperconcentrated flows. Modeling indicates debris flows travel up to 5 km downstream from the Meager-Lillooet river confluence. The 1931 Devastation debris flow reached Lillooet River and caused muddy surges 15 km downstream.
7	10^7 - 10^8	Could inundate large valleys up to 100 km^2 in size, and dam large rivers with the potential for destructive outburst floods and hyperconcentrated flows. Modeling indicates debris flows may reach upstream limits of settlement in Pemberton Valley, 32 km downstream from MMVC. The 2010 event was a Class 7 landslide.
8	10^8 - 10^9	Vast and complete destruction over hundreds of km^2. Modeling indicates debris flows would inundate the entire Lillooet River valley, traveling 20-75 km downstream from Mount Meager to Lillooet Lake. Field evidence documents three debris flow deposits 32-50 km downstream from the volcano.
9+	$>10^9$	No known events.

4.0 Hazards Affecting Mount Meager Volcanic Complex

4.1 Non-eruption Related Landslide Hazard Overview

The first documented instability at Mount Meager was the 1931 landslide from Devastation Creek (Carter 1932). To support BC Hydro geothermal exploration, geological mapping was conducted by Read (1978), who first identified many of the unstable areas. In July 1975 four BC Hydro geologists were killed by another Devastation Creek landslide (Mokievesky-Zubok 1977). In the 1980s, Dr Mike Bovis (UBC) began his research on landslide processes at Meager with monitoring of the Affliction Creek sackung slope (Bovis 1989), and he first related the progressive slope distress to glacier retreat. Evans (1987) described a 500,000 m^3 rock avalanche that initiated in 1986 on the north flank of Mount Meager and reached upper Lillooet River, forming a temporary blockage. Evans highlighted the landslide risk to human activities. Jordan (1987) mapped, differentiated and dated several valley bottom landslide deposits in Meager Creek and upper Lillooet River valleys in his study of landslide-river interaction in Squamish Lillooet Regonal District. Read (1990), in a summary of Meager geology, commented that the massif was likely the most unstable region in Canada. In the 1990s two significant PhD studies supervised by Bovis focussed on volcanic landslide processes: Jordan's (1994) study of debris flow mobility; and Jakob's (1996) reconstruction of the 200 year long debris flow record for tributary basins based on dendrochronology. Bovis and Evans (1996) mapped numerous sites of gravitional slope distress in an about Mount Meager. A large landslide from Capricorn Creek in July 1998 was documented by Bovis and Jakob (1998). Baumann Engineering/EBA (1999) compiled and summarized all previous work as background for the landslide risk Management Plan for Meager Creek Hotsprings. Van der Kooij and Lambert (2002) used InSar to document settlement rates of 1.0 cm/yr of a 1km by 1km area on the east side of Devastation Creek. The last student of Bovis to work at Meager, Holm et al (2004) completed a detailed analyses of landslide response to glacier retreat from Little Ice Age moraines. First recognition that large edifice collapse at Pylon Peak had spawned debris flows large enough to travel 10s of kilometers downstream to Pemberton Meadows was reported by Friele and Clague (2004) and confirmed by a subsurface drilling program in Pemberton Meadows 30-50 km downstream from the massif (Friele et al 2005). Simpson et al (2006) conducted debris flow runout modeling (LaHarz) to investigate the potential impacts of future large clay-rich debris flows on Pemberton Meadows; while Friele et al., (2008) conducted a Quantitative Risk Assessment (QRA) concluding that the non-eruptive volcanic landslide risk affecting Pemberton Meadows was unnacceptable by international safety standards.

Since the occurrence of the August 6, 2010 Mount Meager Landslide at Capricorn Creek, there has been considerable research paid to that event (Guthrie et al 2012; Allstadt 2013; Moretti 2014; Roberti et al., 2017, in press), and Mount Meager has again become the focus for graduate research. Hetherington (2014) conducted numerical analysis of slope stability across a North-South transect of the massif from Meager Creek to Lillooet River. She demonstrated that large edifice collapses (10^8 m^3) are still possible, with five main areas currently having a greater likelihood of failure: West Devastation Creek, the southern flank of Pylon Peak, the bulge at Job Creek, Affliction Creek and the eastern flank of Plinth Peak (Figure 1). The first four of these locations have clearly visible unstable features and the fifth is a steep cliff, which failed during the last volcanic

eruption. Hetherington noted that instability was sensitive to annual water infiltration, and minor changes could trigger failure. If failure occurred along a deep failure plane, volumes greater than 10^8 m^3 could be delivered to Lillooet River, which would inundate the entire valley, and could reach Pemberton. As part of initial stages of a Ph.D. program, Giochino Roberti has been conducting slope movement monitoring using sequential air photo and satellite imagery (Roberti et al., 2015), and has confirmed several areas of movement and identified others. In summer of 2016, gas vents, or fumaroles, were noted for the first time, and GSC issued a situation report on the status of Mount Meager volcanic activity, suggesting that at this time there was no concern about an explosive eruption (NRCan 2016).

The main conclusions regarding future slope hazards are summarized nicely in the abstract to Holm et al (2004), cited below:

> "The bedrock landslide response to glacial retreat varies appreciably according to rock type and the extent of glacial scour below the Little Ice Age (LIA) trimline. Valleys carved in weak Quaternary volcanics show significant erosional oversteepening and contain deep-seated slope movement features, active rock fall, rock slides, and rock avalanches near glacial trimlines. Basins in stronger granitic rock rarely show increased bedrock instability resulting from post-LIA retreat, except for shallow-seated rock slides along some trimlines and failures on previously unstable slopes. In surficial materials, landslides associated with post-LIA retreat originate in till or colluvium, as debris slides or debris avalanches, and are concentrated along lateral moraines or glacial trimlines.
>
> Significant spatial association was also observed between recent catastrophic failures, gravitational slope deformation, and slopes that were oversteepened then debuttressed by glacial erosion. Eight out of nine catastrophic rock slope failures occurred just above glacial trimlines and all occurred in areas with a previous history of deep-seated gravitational slope movement, implying that this type of deformation is a precursor to catastrophic detachment."

Holm's latter statement was borne out by the August 6, 2010 Mount Meager landslide which has been shown to be directly related to progressive slope distress resulting from glacier retreat and debuttressing (Roberti et al., in press).

4.2 Incidents Involving Risk to Human Life

Due to the high frequency of large destructive landslides, there is a high landslide risk to infrastructure and user groups at Meager Creek and upper Lillooet River, including both industrial users and recreationists. Local history includes such recorded events as the 1931 Devastation debris flow nearly washing Bert Perkins away while at his trappers cabin at South Creek (Decker et al., 1977). In July 1975, four geologists lives were lost while waiting for a helicopter pickup at Devastation Creek (Mokievsky-Zubok, 1977). A debris flow on Hotsprings Creek in 1984 stranded vehicles and recreationists; while the CRB watchman's camp and repair shop at Canyon Creek were partly buried a couple of times in the late 1980s and early 1990s. After the 2003 regional flood, the Meager Creek

bridge to the Hotsprings was washed out. The site remained inaccessible till the bridge was finally replaced in 2008. With the upgraded Hotsprings Recreation site open for business, a recreation site manager set up camp for the summer season. The task was to open and close the Br 3 gate daily and to monitor weather. The camp location for two seasons was at the mouth of Meager Creek on the floodplain, and was eventually deemed unsafe (Cordilleran 2009), and for the 2010 season was relocated to the 36 km campsite. Had the operator been in camp at the time, the move would have saved his life, as the previous seasons camp was completely destroyed by the 2010 Meager landslide. The 2010 Meager landslide resulted in two other close calls. Weather shutdown employed by Squamish Mills (Cordilleran, 2010), who were rebuilding the Capricorn Creek crossing after the 2009 landslide resulted in a heatwave triggered shutdown, such that on the day of the 2010 landslide there was no work occurring at the Capricorn Creek crossing. Again, had the landslide occurred during working hours, this would have spared lives. Finally, the 36 km public campsite was occupied on the night of August 6, 2010, and one group was just arriving at 3am; they were in the midst of setting up camp when they heard the loud reports of the initial release, and as they attempted to flee northward in their vehicle they were turned around and nearly overwhelmed by the wet front of the debris that had overtopped the river terrace (Guthrie et al. 2012).

4.3 Hazards Affecting the Meager Creek Hotsprings Recreation Site

The contributing basin area upstream of the Meager Creek Hotsprings Recreation site is 215 km^2 and extends from Canyon Creek to Devastation Creek, including the watersheds of Devastation, Boundary, No Good, Angel, Pylon, Canyon, and Hotsprings Creeks, and the lower reaches of Barr and South Meager Creeks.

In the study area, Meager Creek is narrowly confined with 2000 m of relief to glaciated summits. Upstream of Angel Creek, large debris fans from the north force the river against the south valley wall. Between Angel and Canyon creek, Meager Creek is incised 60-140 m in rock avalanche deposits from Pylon Peak. Downstream of these rock avalanche deposits the creek is confined between alluvial fans on Hotsprings and Canyon creeks. Capricorn Creek is 4 km downstream of the Hotsprings and landslides from this basin would likely not directly impact the site, although 2010 was close call reaching with 300 m of the site, but landslides from Capricorn Creek do sever access and/or cause upstream inundation.

4.3.1 Hydrologic Clear Water Floods

Based on a basin size of 215 km^2 for the Hotpsrings site, the 100-year peak discharge was estimated to be 275 m^3/s (DWB Forestry Services Ltd., 2005). Using Creager's equation, applied to Lillooet and Bridge river records, Baumann Engineering/EBA (1999) suggested a value of 290 m^3/s. Based on a Gumbel distribution applied to data from Cheakamus River at Millar Creek (1982-2004), the 10-year and 50-year floods would be on the order of 165 m^3/s and 250 m^3/s, respectively. Hydrologic floods in the range up to about 50-year return appear not to affect the Hotsprings pools (Photo 1).

4.3.2 Coarse Woody Debris and Sediment Loading

Upstream of the Hotsprings site, Meager Creek is incised up to 60-140 m in landslide deposits (Photo 2). The steep slopes to the creek are mostly forested, but local slumping is common. Slumps may be tens of metres wide and extend the full height of the scarp, and may introduce abundant coarse woody debris and sediment into the channel. Sediment introduced by bank slumps and from debris flows from tributary basins results in high sediment loads that may lead to cycles of bed aggradation and degradation, which could make the pools more or less vulnerable to flooding.

4.3.3 Outburst floods

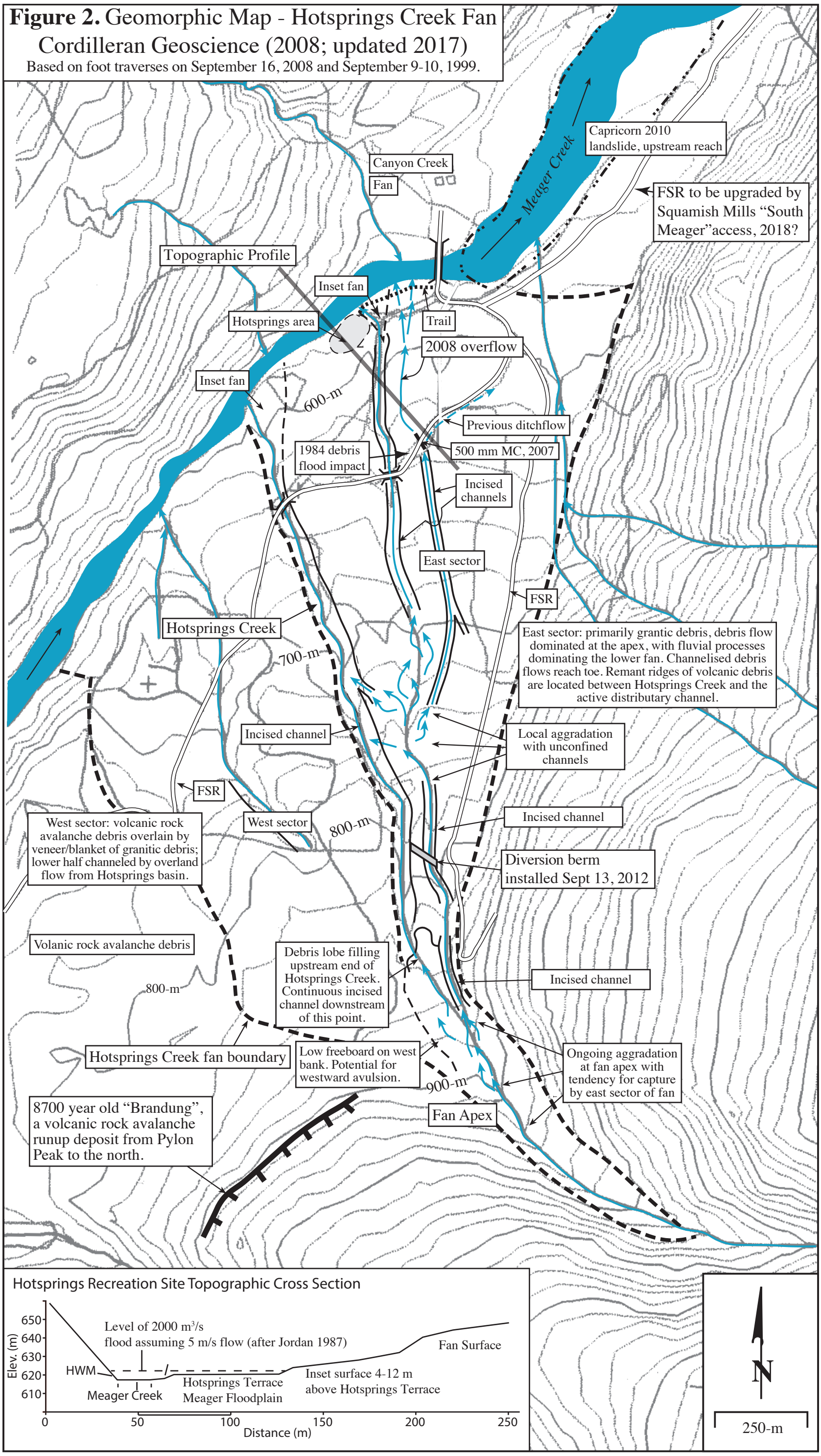
Debris flows, rockslides from tributary basins, or bank collapses could all lead to blockage along Meager Creek, and potential dam break flooding. Impoundment volumes and potential instantaneous discharges from blockages at No Good Creek were calculated by Jordan (1987). The calculated outburst flood discharges ranged from 130-6000 m^3/s, with the largest likely debris flow producing an outburst flood with a discharge of 360-1800 m^3/s, for most-likely and maximum cases, respectively. Given an instantaneous discharge of 2000 m^3/s with a velocity of 5 m/s the flood wave would occupy an area of about 400 m^2. This would inundate the Meager Creek hotsprings terrace (Figure 2).

According to former CRB woods boss, Terry Ross (personal communication), the original Meager Creek bridge was destroyed by a small outburst flood due to damming of Meager Creek by a small debris flow on Canyon Creek in 1984. Further, Jordan (1987) described a potential outburst flood resulting from a blockage of Meager Creek by a debris flow on Hotsprings Creek in the mid 1950s. This event washed out the Hotsprings site to a level at least 3-m higher than low water level. The blockage from the 1975 Devastation Creek event persists to this day, with the lake completely infilled by sand; while the blockage of Meager Creek by landslides on Capricorn Creek in 1998 & 2009 drained slowly over the course of one year. In contrast, the Meager Creek blockage caused by the 2010 Mount Meager landslide drained catastrophically after 18 hours (Guthrie et al 2012). The stability and outburst potential of a landslide dam is a function of its geometry and composition. Since there is no lengthy record of historic outburst flooding in the study area, a magnitude-frequency distribution is not possible, but the potential for flood surges on the order of 10^2 m^3/s to 10^3 m^3/s is likely high (Table 1).

4.3.4 Volcanic debris flows along Meager Creek

Volcanic debris flows are probably the most significant hazard affecting the Meager Creek Hotsprings site. Not all landslides will evolve into debris flows, as illustrated by the difference in behaviour between the 1931 and 1975 events: both initiated in the same general area with similar magnitudes (10^6-10^7 m^3); however, the 1975 event stopped at the mouth of Devastation Creek, forming a dam on Meager Creek; while the 1931 event, transformed into a debris flow that traveled the length of Meager Creek, and caused surging on Lillooet River as far as South Creek (Decker et al 1977). Landslides from downstream sources may affect the site as well, as indicated by the near miss of the upstream surge of the 2010 Mount Meager landslide.

Figure 2. Geomorphic Map - Hotsprings Creek Fan
Cordilleran Geoscience (2008; updated 2017)
Based on foot traverses on September 16, 2008 and September 9-10, 1999.



Typical landslides in Devastation Creek have magnitudes of 10^6-10^7 m^3 with recurrence interval of about 20-40 years in the historic period. However, only one of three events evolved into a debris flow. Thus, the recurrence interval of large volcanic debris flows issuing from Devastation Creek may be on the order of 100-years. With respect to future hazards, Dr. Steve Evans' (personal communication, 1998) opinion was that major events were imminent; while detailed measurement from satellite imaging (Van der Kooij and Lambert, 2002), indicate ongoing, deep-seated settlement, with average rates of 1 cm/yr between 1992-1998, over an area 1km wide by 1 km long on the east side of the valley. More recent InSAR work confirms active instability on the north side of Plinth Peak in Job Creek (Roberti 2016). While Hetherington (2014) showed that factors of safety at these sites are low, and edifice collapse is feasible. This observation, and the observation that ongoing glacier retreat leads to gravitational distress (Bovis 1990; Holm et al 2004; Roberti et al, in press), suggest that large (10^6-10^8 m^3) volcanic debris flows along Meager Creek should be regarded as having a moderate to high (Table 1) potential.

Figure 3 shows modeling results for volcanic debris flow of various magnitudes initiated from Devastation Creek (Simpson et al 2006). The results indicate that 10^8-10^9 m^3 events inundate fans and high terraces; whereas, 10^6-10^7 m^3 events remain confined along Meager Creek as far as Lillooet River. The 1931 event provides an historic analog; it was described by Carter (1932):

> "The slide had apparently impounded the surface drainage of the glacier, then giving way, had swept downstream. At each sharp bend in the valley, great sections of the bank had been washed away and the amount of material deposited was enormous. Even the location and nature of the Hotsprings had been altered."

At the mouth of Devastation Creek this event had a velocity of 30 m/s and a peak discharge of 70,000 m^3/s (Jordan 1994). Between Boundary Creek and No Good Creek, Jordan (1994) mapped the side-to-side washing of the 1931 event from 1981 air photos. Field measured runup of 15-30 m on the outside of bends was documented, with the amount of runup diminishing downstream. No Good Creek fan pinches the river; just upstream from No Good Creek, where the channel was about 150 m wide, the trimlines reached to about 25 m height. It is likely that the peak discharge was significantly attenuated in the confined reach between No Good and South Meager Creek confluence. Just downstream from the confluence of South Meager Creek the channel is 120-m wide. In this reach remnant terraces of the 1931 event are 3-m tall (Friele, personal observation). Immediately downstream from Canyon Creek fan, the debris flow did not overtop 4400 year old debris flow terraces 25-m in height (Friele and Clague 2005). Here the incised channel is about 200-m wide, implying a maximum cross sectional area of < 5000 m^2. Assuming a velocity of about 10 m/s at this location, the peak discharge was likely still the same order of magnitude (i.e., 10^4 m^3/s) as calculated at the mouth of Devastation Creek.

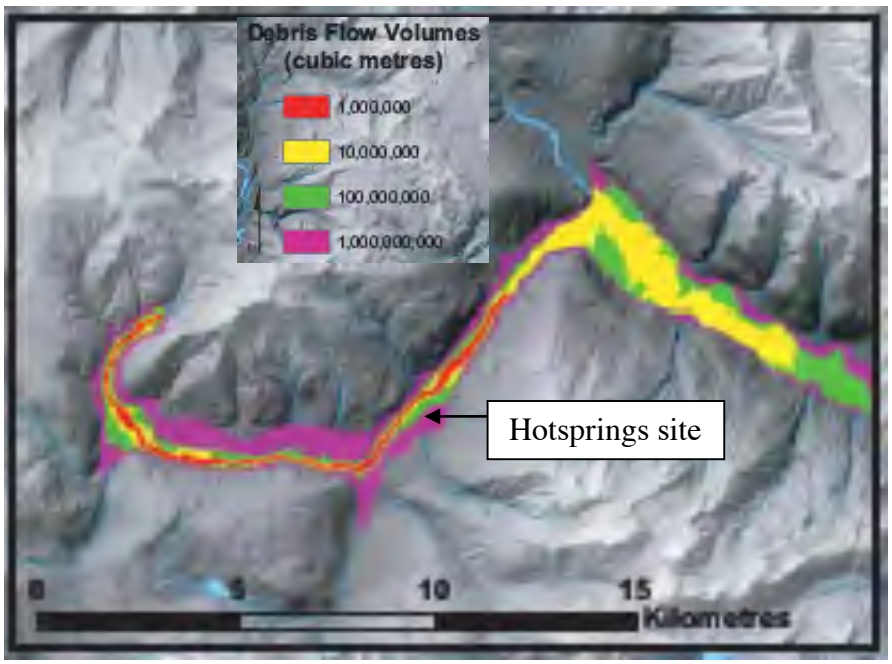


Figure 3. Model results for debris flows initiated in Devastation Creek. Magnitudes range from 10^6 m^3 to 10^9 m^3. Source: Simpson et al. (2006).

4.3.5 Rock avalanches and debris flows from Hotsprings or Canyon Creek

The slope east of Hotsprings basin is called Pika Ridge. This slope is cut by slope parallel bedrock faults indicating slope sagging (Bovis and Evans 1996). The south end of this area is truncated by a bowl shaped amphitheatre, 1 km wide by 700 m deep, forming the north side of Hotsprings Creek basin. This bowl is evidently a landslide headscarp, and is the major debris source for Hotsprings Creek fan. It is not known whether this bowl originally formed as a single large collapse, or progressively by several or hundreds of individual collapses and debris flows, but its angular rim suggests it is a post glacial feature. That it is cross cut by the linears suggests that it was structurally controlled, and that it would not be impossible for a similar collapse to develop on Pika Ridge. Thus evidence exists for large (>10^6 m^3) rock avalanches from Hotsprings Creek and possibly Canyon Creek, although this is less certain. However, there are no documetned or dated deposits from these sites on the valley bottom, and the frequency of prehistoric rock avalanches directly impacting the Hotsprings site appears to be Low (Table 1).

On Hotsprings Creek, the tree ring record (Jakob 1996) indicates an average return period for small (10^4 m^3) debris flows reaching the apex of the alluvial fan is High (Table 1), with one every 7 years. Most of the debris flows spread out at the fan apex above 750 m elevation. Although, some debris flows remain channelized and traveled further down the fan (e.g. October 8, 1984), the last debris flow to reach the toe of the fan occurred sometime between 1950-56. Jordan (1987) stated that this event (erroneously ascribed to 1978) dammed Meager Creek resulting in an outburst flood that formed the main boulder terrace underlying the Hotsprings site, situated about 3-m above river level. Recent Insar data (Figure 4) has identified an area in Hotsprings basin where slope movement is occurring on the order of 8-9 mm/yr (see blue circle around cluster of red dots, Figure 4). This unstability has a area of 3000-10,000 m^2, and a failure on the order

of 10s of meters thick could produce a debris flow on the order of 30,000-100,000 m^3, or larger. There is an area upslope on the basin rim that appears to be displaying movement on the order of 3-5 mm/yr. These observations indicate that Hotsprings Creek is certainly vulnerable to large (10^5 m^3, Class 5; Table 2) debris flow activity.

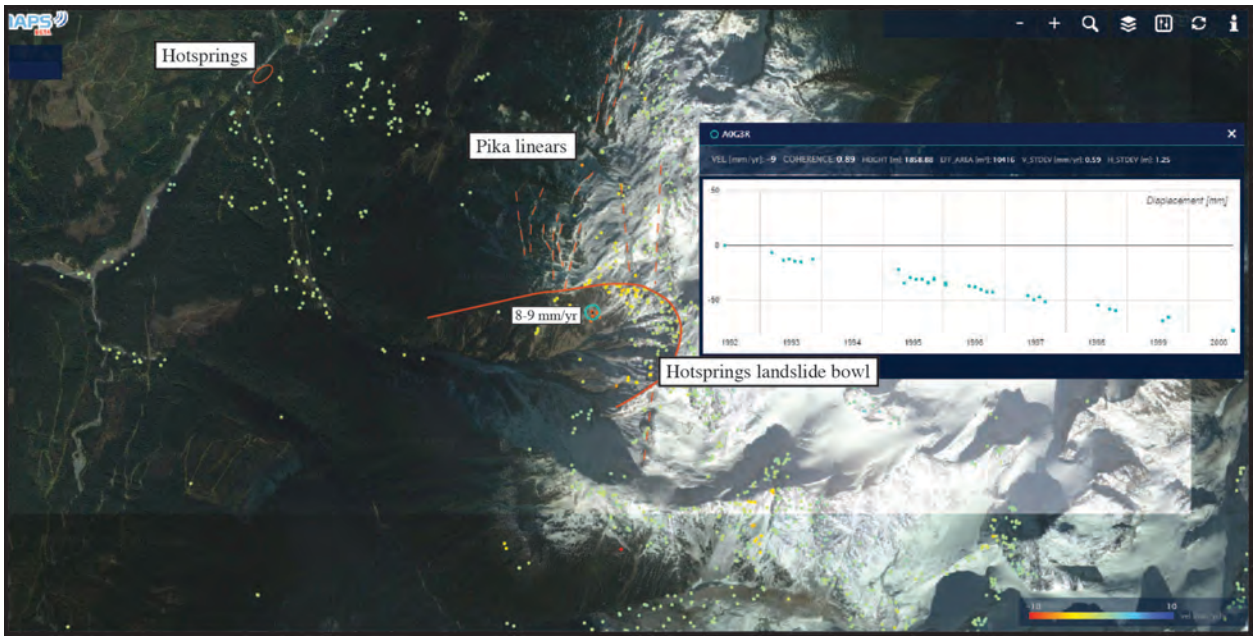


Figure 4. Insar data, Hotsprings Creek subbasin, unpublished, courtesy of G. Roberti, 2016.

On Canyon Creek, the return interval for small (10^4 m^3) debris flows reaching the fan is 6-years (Jakob 1996). The fan experienced debris flows in August 1987 and October 1990. The 1990 event inundated the old CRB shop site in debris up to 5-m deep (Jordan 1994). These events had peak discharges of 290 m^3/s and 580 m^3/s, respectively. More recently, about 2008, small debris flows reached the toe of Canyon Creek fan (Malc Shulz, pers obs), and the source for this event is evident on Google Earth Imagery dated Oct 2010. Clearly, both Hotsprings and Canyon creeks present a high (Table 1) potential for debris flow affecting the Hotsprings Recreation site, by direct impact or by blockage of Meager Creek and backwater inundation.

4.4 Hazards affecting the Pebble Creek Hotsprings Recreation site

The Pebble Creek recreation site (Figure 5) is located in a 146-200 m deep canyon incised in the 2400 year old Pebble Creek Formation syneruptive volcanic materials. The canyon was formed by rapid erosion during a catastrophic outburst flood that followed the volcanic damming of the upper Lillooet River. The entire landscape of this part of Lillooet River valley, extending from the surface of the debris at a maximum elevation of about 860 m on the north side of the valley to the summit of Plinth Peak on the south side, is a product of the eruption, syndeposition and subsequent erosional processes (Figure 5). The hotsprings are located on the floor of the canyon at river level.

Presently, the hotsprings are accessed from the downstream end of the canyon, from a new trailhead located at 42 km on the upper Lillooet FSR (Figure 5). The parking

area is on a terrace about 40 m above river level. From the parking area, the trail heads 100 m south to an escarpment crest then drops down to follow the footslope of the escarpment for 450 m, then shifts out onto the river floodplain for 375 m, then back on the escarpment slope for 275 m, and finally crosses Truckwash Creek to reach the original overflow campsites. The total length is about 1300 m. It is another 450 m, or so, along the floodplain to get to the main pools. A second original camp location is found on a 100 m wide by 200 m long terrace located 25-30 m vertically upslope of the pools. The original trail descended from a parking lot west of Truckwash Creek at about 660 m elevation straight down to the hotsprings site.

4.4.1 Hydrologic Clear Water Floods

The trail into Pebble Creek Hotsprings is in part located on the active floodplain of upper Lillooet River, as are both the shallow pools and the main pools. These areas are affected by hydrologic flooding, with the lowermost of the main pools being flooded out probably yearly (Photo 3). The sections of trail on the active floodplain and the pools are judged to be affected by very high to high flood hazard (Table 1).

4.4.2 Coarse Woody Debris and Sediment Loading

As with Meager Creek, the reach of upper Lillooet River directly upstream of the hotsprings is confined in a bedrock canyon with steep unstable banks up to 260 m tall (Photo 4), with direct connectivity to the river. A large failure encompassing the entire escarpment height was identified on 1962 air photos (Knight Piesold 2010) on the north escarpment wall (Figure 5). Slides from the escarpment slope are judged to have high (Table 1) potential for channel impact and associated effects on channel stability.

4.4.3 Outburst Floods

Upstream of Keyhole Falls, the upper Lillooet River valley is very wide with gentle fan slopes on the south side. Landslides reaching Lillooet River will have a low potential for creating tall narrow barriers susceptible to rapid breach. However, there is evidence (Friele et al., 2008), discussed below, that large landslides pond at the upstream end of the Keyhole Falls canyon, near the location of the HEF Intake, and the breach of these barriers could result in flood surge or outburst flooding. Based on the frequency of large debris flow from upstream sources, the outburst flood frequency affecting Pebble Creek Hotsprings is judged to be low to moderate (Table 1).

4.4.4 Volcanic Debris Flows along upper Lillooet River

Friele and Clague (2008) described the stratigraphy of a 20-m high bank along Lillooet River at the northeast margin of the Job Creek fan. The section exposes sediments deposited since the 2400 year eruption. At the base, at river level, is a 2200 year old volcanic landslide deposit, and it is overlain by at least 11 upward-coarsening, silt to sandy gravel units, eight of which were deposited over a 600-year period. These units were interpreted to be backwater deposits associated with successive landslides that blocked the canyon at the upstream end of Keyhole Falls. Thus, in the post-eruptive period, the upper Lillooet River has been affected by large volcanic debris flows, up to 10^6-10^7 m^3 in volume, on average every 200-years or so. The last large event was dated to

670 years ago (Friele et al., 2008). This suggests that the frequency of Class 6-7 (Table 2) debris flows from upstream on Lillooet River and affecting the Pebble Creek Hotspings is Moderate (Table 1).

A large edifice collapse landslide deposit, with an estimated volume of 10^8-10^9 m^3 has been documented along upper Lillooet River (Friele et al., 2008), and has been assigned a tentative age of 6200 years old, by correlation with dated debris flow diamicton discoved in drill core from Pemberton Meadows (Friele et al., 2005). Future landslides of this size are possible (Hetherington 2014). Roberti et al., (2015) has documented extensive instability, with settlement rates of cm/yr on the NW flank of Plinth Peak. This area and the Affliction Creek linears (Bovis 1990) could fail catastrophically, yielding debris flows exceeding 10^7 m^3 in volume. These extremely large edifice collapse type failures are judged to have a low (Table 1) frequency of occurrence.

Debris flow modelling (Simpson et. al., 2006) indicates that a Class 6 event (Table 2) would be largely constrained to the active channel and floodplain of the upper Lillooet River; while Class 7 events and larger would be thicker, and would spread wider where confinement diminished. Debris flow thickness (±10 m) at Boulder Creek confluence was estimated to be 10 m for a 10^7 m^3 event, 20 m for the 10^8 m^3 event and 50 m for the 10^9 m^3 event (Knight Piesold 2016), and would likely be somewhat thicker in the Pebble Creek Hotsprings reach.

4.4.5 Meager North Slope Landslides with Direct Channel Impact below Keyhole Falls

Evans (1987) documented a rock avalanche that occurred in spring 1986 from the north flank of Mount Meager and reached upper Lillooet River forming temporary blockage. The estimated volume was $5x10^5$ m^3; Evans noted tension cracks in the initiation zone and suggested a landslide with a volume of 1 x 10^7 m^3 was possible from this site. Jordan (1987) documented a field of bedrock linears (Photo 5), 1.5 km in length and 500 m in width, on the south ridge of Mount Meager between 1500-1700 m elevation. Knight Piesold (2015) considered that a rock avalanche with a maximum credible volume of $1x10^7$ m^3 was possible at this site. Finally, Hetherington (2014) indicated the north flank of Plinth Peak was potentially unstable, and failure there could produce a landslide with a volume of 10^7-10^8 m^3.

There has been no past attempt to estimate potential frequency of occurrence for these sites. Taking the reach from Pebble Creek to Keyhole Falls as a whole, the largest failures (10^7 m^3, or greater) are judged to have low to very low (Table 1) frequency; while events of 10^7 m^3 or smaller would have moderate to low (Table 1) frequency.

4.4.6 Debris Flow and Rockfall at Truckwash Creek

Truckwash Creek has a basin area of about 5.6 km^2, a relief of 1600 m, basin ruggedness of 90% and is 9% glaciated. Based on basin slope and percent glaciation, the basin is considered to be debris flow prone. With the ongoing retreat of glaciers, debris flow hazard may be increasing. Cordilleran (2013a) conducted a hazard assessment for the proposed Truckwash Creek bridge on the portal bypass road. The site was completely buried by the Pebble Creek formation deposits (Photo 6), and the modern landforms incised since 2400 years ago. In the left (campside) 15 m tall cutbank at the bridge

crossing, 3-4 granitic debris flow layers were noted near the crest of slope, and 2-3 mid way up the bank. This evidence, the cross sectional area of the ravine, and assumed landslide velocities, were used to estimate that 7-10 debris flows ranging from 80,000-270,000 m^3 may have affected the crossing site in the last 2000 years, with an average return interval of 250 years.

Snow avalanche affects Truckwash Creek, but it is judged that they do not travel downstream past the new Truckwash Bridge (Cordilleran 2013a). However, based on vegetation patterns, there may be small Class 1 snow avalanches off the Truckwash Creek ravine left bank sidewall that could affect the Truckwash footbridge crossing on the new trail.

Truckwash Creek has incised a deep notch in the canyon sidewall formed in the Pebble Creek Formation. On the downstream side there are large (multi-metric) blocks that have fallen from the canyon wall (Photo 7). Trail descriptions available on the internet indicate an active rockfall hazard at this site: "we experienced rockfall when we arrived here; the rocks were fist-sized and were flying across the trail, making the area hazardous" (www.ashikaparsad.com). Further, debris flow on Truckwash Creek could destroy the footbridge (Photo 8).

4.4.7 Snow Avalanche

Knight Piesold (2010) maps numerous snow avalanche paths along upper Lillooet River (Figure 1) The limit of one of these paths affects the parking area for the new trail. Another path, confined in a tributary creek channel, is shown crossing the trail downstream of Truckwash Creek.

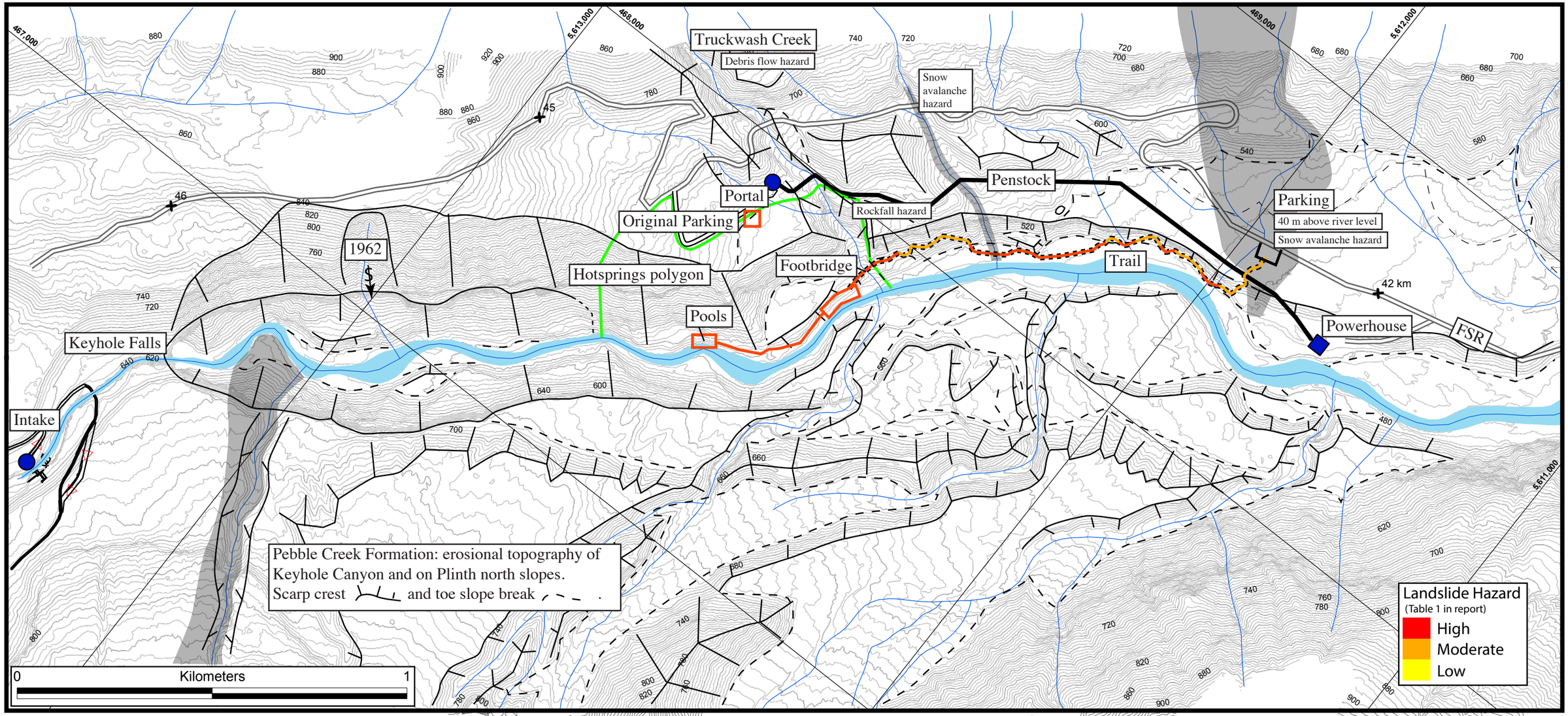


Figure 5. Detail showing New Pebble Creek Hotsprings Parking and Access trail, with colour code to indicate landslide hazard rating relative to height above river level. Also indicated is location of hydro electric facility components (Base map after Knight Piesold 2016).

5.0 Potential Campground Locations & FSR Hazards

Selection of a campground/staging area for overnight use by campers using the hotsprings sites during the day is complicated by several factors. Since the road access to each site is now on either side of the upper Lillooet River (Figure 6), there will need to be a campsite/staging area for each hotspring, instead of a single site like the old 36 km campsite. For each hotspring, the chosen sites will have to be close enough to be convenient, but not so close to be in harm's way. Finally, the farther up the FSRs one travels, the more risk there is of becoming trapped by events that sever road access downstream, or in a worst case, becoming directly affected by flooding, landslide or snow avalanches reaching the roads.

Cordilleran (2012) presented an access management plan for the upper Lillooet River valley, with downstream access control points at 9 km on the north side FSR and 0 km on the south side FSR. In the report a hazard map for the Lillooet River floodplain downstream of the Meager-upper Lillooet rivers confluence was presented, whereby the valley bottom was divided sequentially into zones of high, moderate and low hazard (Figure 6). The low hazard area extends from downstream to the South & North creek pinch point; the moderate hazard area extends up to a point 500 m downstream from Perkin's Creek; while the high hazard area extends to the Lillooet Meager confluence.

The valley bottom volcanic landslide hazard is valley filling, and would diminish in thickness downstream from perhaps 20 m thick in the high hazard zone (the 2010 Mount Meager landslide was 10-15 m thick in this area; Guthrie et al., 2012), to say 10 m thick at the downstream end (drill core data discovered a volcanic debris flow unit 8 m thick at Hillaby farm (Figure 6), near the 0 km mark on Lillooet South FSR; Friele et al., 2005). Thus, any proposed recreation site used as a refuge would have to be located higher off the floodplain than these elevations.

In addition, to volcanic hazards, there are slope hazards affecting the Lillooet North and South FSRs, notably around creek crossings on alluvial fans, and snow avalanche paths.

5.1 Meager Creek Hotsprings Camping and Access

5.1.1 Meager Creek Hotsprings Camping

No campsite/staging location has yet been proposed for Meager Creek hotsprings. It will be located somewhere along the Lillooet South FSR, but outside the Meager Creek valley (Figure 6).

The South Lillooet FSR from 0-16.7 km is located on the floodplain surface and is highly vulnerable to flooding, channel braiding and avulsion. In addition, it has a moderate to low volcanic landslide hazard affecting. This makes this portion of the FSR unsuited to campground location, unless a site can be found sufficiently high off the floodplain and safe from hillslope hazards.

Bushside of the 16.7 km mark, the Lillooet South FSR climbs off the floodplain and follows the lower slope, generally sufficiently high off the valley bottom to be safe from volcanic landslides (Figure 6). Thus, ensuring a proposed site avoids hillslope hazards, as on occur for example on alluvial fans, the reach between 16.7 km and the proposed gate location would be the most likely site to search for a prospective camp location.

5.1.2 South Lillooet FSR

The South Lillooet FSR from 0-16.7 km (Figure 6) is highly vulnerable to washout. This situation is expected to get worse with time as the sediment from the 2010 Mount Meager landslide progresses as a wave downstream with each significant bedload transporting flood. This results in a high risk of campers becoming stranded upstream of any washout should a significant flood and erosion event occur while a campsite upstream is occupied.

Debris flows and washouts from tributary valleys have been common on the South Lillooet FSR, with recent washouts at Spidery Creek, South Creek, and other locations. These side valleys have substantial relief, up to 2200 m or more, may have glaciated headwaters, with retreat exposing morainal materials for reworking by floods and debris flows, and they are rugged, so gemorphic events initiated upstream will affect the valley bottom.

A notable tributary landslide occurred at 1 km, whereby an entire forest stand, at least 7 ha in size, was destroyed by a massive bouldery debris flow 3-5 m thick (Cordilleran, 2013c). Based on the area and thickness of the preserved deposit, the landslide had a volume of 2.0-3.5 x 10^5 m^3. Stand age and tree ring dating of scarred trees on the slide periphery yielded an age of 1927 for this event.

In the summer or early fall of 2009, a debris flow at Spidery Creek destroyed the Spidery Creek bridge on Lillooet South (Cordilleran Geoscience 2009). Low level helicopter overview of the watershed indicated that the debris flow was not triggered by a sidewall slide, rather it was triggered by progressive bulking of runoff from sediment stored along the channel with initiation of channel scour evident in the glacier forefield.

South Creek has had a long history of channel instability on the fan. Chronic channel instability required that in the late 1990s, the FSR was rerouted from its original alignment on the mid part of the fan, up to the fan apex. On September 19/20, 2015, the South Creek bridge was overwhelmed by about 5 m of sediment aggradation during a 20 year return rainstorm that followed immediately on a long hot summer drought (Cordilleran 2015). Access was severed for about 1 month until the bridge was repaired. This event was a debris flood, that appeared to affect the entire channel length from the fan to the glacier forefield, and was likely related to glacier retreat, possible subglacial drainage, and excess morainal sediment availability. It was not a one time occurrence: eroded banks revealed buried tree stems (Photo 9), suggesting that a similar event had occurred sometime within the previous century.

5.2 Pebble Creek Hotsprings Camping and Access

5.2.1 Pebble Creek Hotsprings Camping

A potential campsite location for upper Lillooet River has not yet been established. However, one site has been suggested for consideration, located at 650 m elevation, near 39.5 km on the upper Lillooet FSR (Figure 1). This site is 200 m above river level and underlain by basement rock and glacial sediment, unaffected by volcanigenic processes in the Holocene. Directly below this site there is a broad terrace at 490 m elevation, some 45 m above river level. Stasiuk et al (1996) mapped this terrace as part of the Pebble Creek formation, formed syneruptively, associated with the outburst of Lake Salal. Both sites are directly opposite the north flank of Mount Meager.

Knight Piesold (2015) considered several sites along upper Lillooet River for the location of an HEF operator's residence. Based on the landslide hazards from upstream of Keyhole Falls, and the fact that the site was considered a permanent residence with year round occupancy, the risk to the proposed building from edifice collapse-type debris flow from upstream of Keyhole Falls was first mitigated by only considering sites that were more than 50 m above upper Lillooet River water level. The required 50 m elevation buffer was determined from the results of the maximum credible debris flow inundation depth, as discussed in Section 4.4.4.

The suitability of the remaining sites was assessed based on vulnerability to edifice collapse (5 x 10^7 m^3, max credible) of the north flank of Mount Meager, with a landslide following the same path of the 1986 landslide documented by Evans (1987). Based on analogy with the 2010 Mount Meager landslide, which exhibited 270 m runup on the opposing wall, any sites within this zone of direct runup were ruled out (Knight Piesold 2015).

With respect to the proposed campsites considered herein, the lower site would be unacceptable, as it is too low, and could be affected by either upstream edifice collapse type events (e.g., from Job Creek), or by direct impact arising from opposing wall runup of a large event from Mount Meager. The upper site, 200 m above river level, is within a maximum observed 270 m runup that occurred on the opposing wall of Capricorn Creek during 2010 Mount Meager landslide, suggesting it might not be high enough. On the other hand, there is considerable variablity in runup for a landslide of any given size: the two prehistoric Class 8 (Table 2) landslides from Pylon Peak (Friele and Clague 2004) had much less runup; the 8700 year old event ran up about 100 m; while the 4400 year old event appeared not to runup at all. Runup is a function of velocity; and velocity is a function of many factors including fall height, grain size distribution and moisture content; and all these differ between events. Thus, the 270 m runup might be viewed as an extreme case. The 200 m height above river level is sufficiently high, such that the site could still be considered. However, other sites should be selected and a final decision based on a weighing of options.

5.2.2 North Lillooet FSR

The North Lillooet FSR is also vulnerable to floods, snow avalanche and landslides. While the road traverses floodplain for most of its length, and would be vulnerable to extreme floods (100-200 year return), there are sections, for example near 14 km, that have a very high (Table 1) flood hazard. As with the south side, sediment migration downstream from the 2010 landslide will likely worsen the flood hazard in select areas. Seasonal snow avalanches affect the road at 27.5 km (Cordilleran 2012), with the most recent event, reported February 18, 2017, temporarily trapping 50 Innergex workers on the bush side of the deposit (Dave Southam, pers comm). In 2014-2015 there were a few small debris slides that affected the mainline around 26 km.

On the morning of January 29, 2015 a rockslide was noted blocking Lillooet FSR at 6 km (Photo 10). At least one vehicle and several snowmobiles were trapped on the bushside of the deposit. The rockfall occurred from a steep, southerly rock face of Mount Pauline (Figure 6) rising 840 m above the Lillooet River floodplain. The rock is highly jointed and there is a high natural rockfall hazard at this site.

A large rock avalanche has been recently documented on the Lillooet Valley floor at about 29 km. Exposures at river level have been dated (Friele and Clague, unpublished) indicating that this event occurred 7650 years ago, or earlier.

6.0 Operational Shutdown & Landslide Risk Management

In response to the landslide risk, District of Squamish (MoFLRO) contracted Baumann/EBA (1999) to provide a management strategy for the Meager Creek drainage. As a result of this work, Meager Creek hazards and risk management measures were described by signage at several key locations along Pemberton Meadows Road and Lillooet River FSR. For the Meager Creek hotsprings recreation site, only day use (8:00 am-8:00 pm) during the summer season (May-Sept) was permitted. For the fall/winter, access was prevented by a gate on Br 3 on the river right abutment of Lillooet River bridge at the mouth of the Meager Creek drainage.

Part of the summer use management strategy was a protocol for weather-based operational shutdown. Where long and detailed weather and stream flow records are absent, like at Meager Creek, linking landslide activity to climate and runoff triggers is problematic. The method used at Meager Creek is largely based on sparse data comparison of landslide occurrence and simple metrics for temperature and precipitation.

These methods are not without their detractors (Marquis 2001), largely because they are not considered accurate predictors of landslide activity. The phenomenon that extreme climate events sometimes fail to trigger landslides, while at other times apparently milder climate events do was noted by Church and Miles (1987), and this remains a problem in landslide forecasting. This is not to say that shutdown protocols should not be taken seriously. Clearly, with the potential for loss of life, especially in the valleys flanking the Meager massif, the best available method should be applied.

After Baumann Engineering/EBA (1999), summer season operational shutdown guidelines for Meager Creek drainage were established. When a trigger was indicated, then the valley was to be evacuated. The shutdown triggers were as follows:

- Instantaneous high flows to the various tributaries within the Meager Creek drainage during spring runoff;
- When average temperature for 6 days exceeds 25°C;
- Sudden drop in water flow or significant colour change of Meager Creek or its tributaries shall warrant immediate shutdown of Meager Creek hotsprings and restriction of vehicle access into drainage;
- An actual rainstorm or the forecast of a high intensity rainstorm (20mm/24 hour) in conjunction with 2 to 5 days of temperatures averaging more than 25°C warrants immediate shutdown of the drainage;
- Rainfall intensity exceeds 70mm/24 hour.

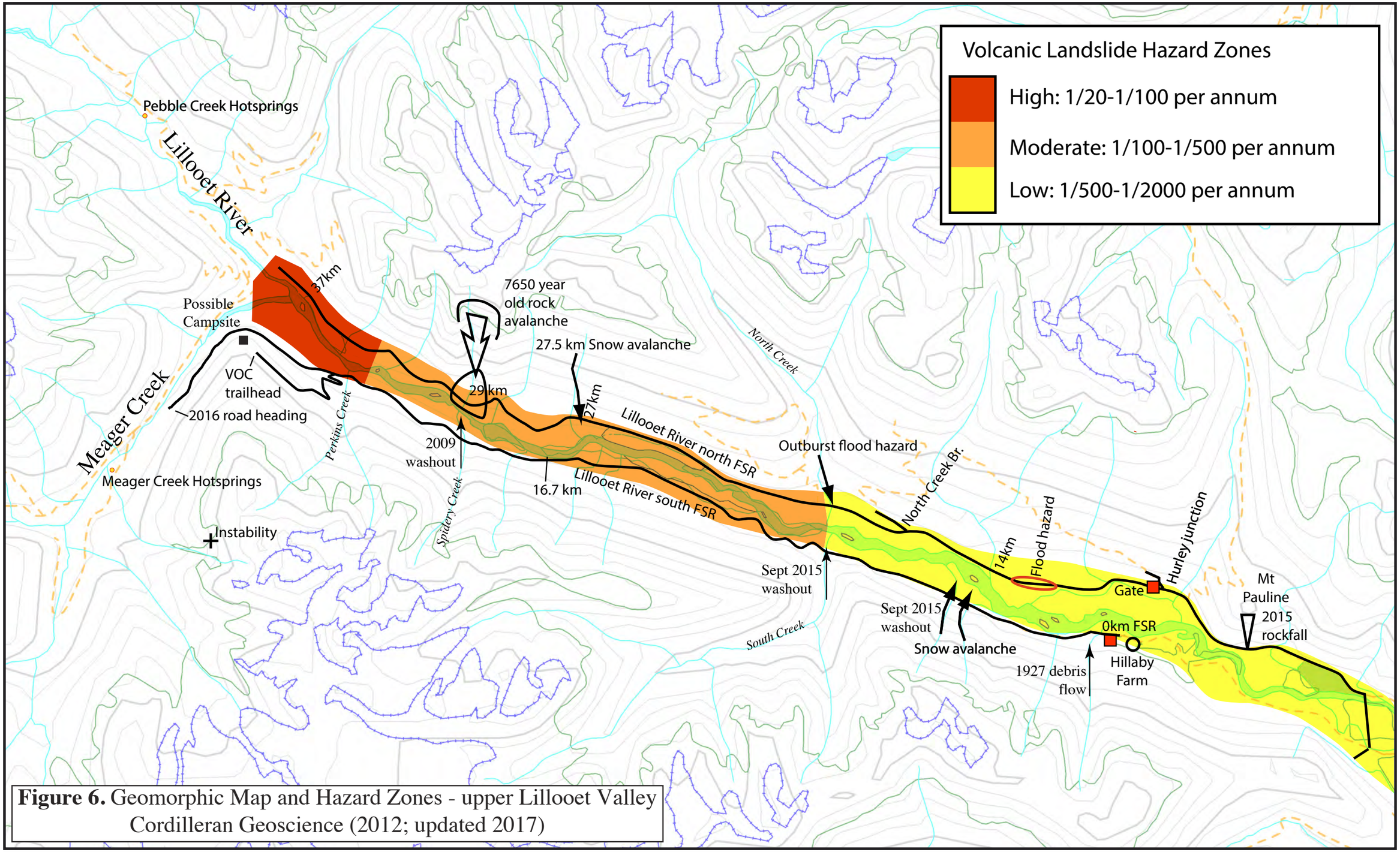


Figure 6. Geomorphic Map and Hazard Zones - upper Lillooet Valley
Cordilleran Geoscience (2012; updated 2017)

Subsequent to the 2009 Capricorn landslide, Cordilleran (2009) reviewed the management system and found several problems related to manual weather recording (selected time of data collection wrt to time of max. daily T; legibility of records; consistency wrt zero data; and data gaps due to absence), which then led to imperfect execution of the shutdown policy, and as a result it was decided that weather observations should be automated. In spring 2010 an automated weather station was installed near the mouth of Meager Creek, and remains functional.

A modified version of the Baumann/EBA (1999) shutdown criteria was being applied by Squamish Mills, whose crews were rebuilding the Capricorn Creek crossing following the September 2009, Capricorn Landslide. In late July/Early August 2010 they were shutdown by the occurrence of an extended heat wave. Snow & ice melt produced by the heatwave triggered the August 6, 2010 landslide (Roberti et al., in press). Because of the shutdown, no crew was onsite, although all heavy machinery was lost.

Subsequent to the 2010 Mount Meager landslide, Cordilleran (2012) updated the weather-based operational shutdown criteria for use by MoFLNRO for the upper Lillooet River valley (Table 3). It was based on seven landslides with known dates of occurrence that could be associated with climate data from Pemberton weather stations, and on existing rainfall shutdown criteria (BCTS 2010). This present framework (Table 3) was adopted by CRT/Innergex for the construction and operation phase of the Upper Lillooet Hydro facility (Knight Piesold 2014, 2016).

Table 3. Hazard levels for landslide risk management. These thresholds should be revised and updated as new data allow.

	Max. daily temp. (ºC)		Rainfall (mm)	
Hazard Level	Daily max.	6 day av.	24 hr	48hr
Low	<25	..	..	..
Low	<20	<20	<20	<50
Moderate	≥25	..	..	..
Moderate	≥20	≥25	..	..
Moderate	..	..	≥20	≥50
Moderate	≥20	≥20	≥10	..
High	≥30	..	..	..
High	≥25	≥30	..	..
High	..	..	≥50	≥75
High	≥25	≥25	≥20	..
Extreme	≥35	..	..	..
Extreme	..	..	≥70	≥100

7.0 Discussion & Recommendations

1. The headwater valleys on either side of MMVC are prone to both high (Table 1) non-volcanic and volcanic landslide hazards. Flooding, debris flooding and outburst floods, as well as Class 4-8 volcanic landslides with volumes of 10^4-10^8 m^3 (Table 2) could affect the hotsprings sites. The aggregate hazard level affecting the hotsprings sites is judged to be high, and as such requires landslide risk management for public safety (Table 4).

2. The policy adopted in 1999 for management of Meager Creek and modified in 2012 to include the entire upper Lillooet River from the Forestry Bridge upstream should be applied for the future use of both Meager Creek and Pebble Creek Hotsprings. This includes day use only at the hotsprings sites, with overnight camping at refuge sites outside proximal valleys and/or otherwise high enough off the valley floors to be safe from large volcanic landslides and also in locations safe from valleyside hillslope hazards.
3. Daily shutdowns should be governed by automated weather-thresholds using both the Meager Creek weather station and the Pemberton Fire Base, whichever yields a trigger first, following the caveats of Cordilleran (2009) and the criteria of Cordilleran (2012)(Table 3). For forecasting, refer to Pemberton weather forecasts provided by Environment Canada.
4. Overnight campsite locations have not yet been selected by MoFLNRO. Overnight camping outside Meager Creek valley should not be located on the upper Lillooet Floodplain (Figure 6) or within 20 m relief of the floodplain surface. For Meager Creek hotsprings, assuming the overnight campsite will be located somewhat close to Meager Creek valley mouth, the location should be bushside of 16.7 km, the point where the South Lillooet FSR leaves the floodplain surface and follows the toe of slope. A spot with a view to be considered could be on the ridge where the road turns into Meager Valley (Figure 6). At this location there is a wide pullout and a spur road going to a small block. Being on a shedding site on the ridge, and high off the floodplain, this area would provide safe camping.

   For Pebble Creek Hotsprings, if a site is selected within the proximal valley it should be located at least 50 m off the valley floor, and higher if directly opposite an identified potential edifice collapse feature. One such location has been identified; it is located 200 m above the valley floor, directly opposite the north flank of Mount Meager (Figure 5), opposing an identifed potential rock avalanche source area. While this site might be considered suitable, other areas should be sought for comparison. Another suitable location might be near the old parking spot, at the top of the original trail down the escarpment. This site is >140 m above river level. This site would have the advantage of the trail avoiding high hazard floodplain areas and the high hazard Truckwash Creek crossing area. The latter may prove to be a maintenance issue if the footbridge is destroyed by debris flow.

   Alluvial fans from valley side tributary subbasins should not be considered for proposed campground areas. It is assumed that a proposed campsite will be on bench areas on faces between tributary creek gully/fan landforms. With this criteria, a nearby water source may be problematic and will be a factor in consideration.

   The final short list of proposed campsite locations should be subjected to detailed terrain stability assessment (TSA) to review site specific terrain conditions. If there is any concern regarding safety, then the TSA could be supported by Quantitative Risk Assessment (QRA) to evaluation landslide risk more closely.
5. Under extreme weather conditions, the access to Lillooet River valley should be barred. Gates should be located downstream of the first occurring high hazard zone. Along Lillooet North FSR (Figure 6), the most a logical location to consider placing a gate is at the existing location at 9.2 km, just past the Hurley FSR junction. Along the Lillooet South FSR the gate should be placed at 0 km.

Access to proximal and distal valleys should also be restricted appropriately when conditions are noted that suggest landslides have occurred upstream, such as sudden changes in creek discharge or colour. Note that SLRD has established a water level gauge at the forestry bridge. This gauge is monitored for sudden changes in water level, and SLRD has developed an emergency management response. MoFLNRO should be included as part of this system. Return access into Lillooet River valley would be a reduction of climate conditions to below thresholds with no evidence of landslide occurrence.

6. Educational and/or warning signage should be placed at distal and proximal valley gate locations, and at specific locations crossed by the access roads or trails that are affected by high hazard. Signage at Gate or other key sites should display the hazard zoning maps, hazard levels, consequences of landslide impact, risk management measures, and must also indicate to users that they may become trapped upvalley should events occur downstream that prevent egress. Where the roads or trails cross high hazard areas, signage should indicate "no stopping – high hazard area."High hazard areas are alluvial fans (e.g., 1 km South Lillooet FSR), snow avalanche paths (e.g., 27.5 km North Lillooet FSR) and rockfall sites (Mt Pauline, North Lillooet FSR; Truckwash campside)(examples provided are not exhaustive).
7. With respect to snow avalanche activity, the Lillooet River drainage shall be gated sometime in early winter coincident with valley bottom snow accumulation restricting wheeled vehicle travel over Hurley Pass, or if the hazard in the start zones is such that avalanches could affect the roads. The preceding management plan used December 5 as the closure date. This is reasonable, but could be varied year to year as conditions dictate. The road would be opened in the spring once it has been determined by a qualified professional that the snow avalanche risk is low to moderate and will not have an impact on the road.
8. Industrial users are required to operate under a "natural hazards operational safety plan" prepared and signed off by a qualified professional, consistent with the guidelines set out by APEGBC/ABCFP (2008) and WorksafeBC regulations.

Table 4. Recommended landslide hazard/risk management matrix and measures.

		Landslide Hazard Zones			
		No Apparent Hazard	Low	Moderate	High
		Aggregate hazard <1/2500 per annum	Aggregate hazard 1/500-1/2500 per annum	Aggregate hazard 1/100-1/500 per annum	Aggregate hazard >1/100 per annum
		High use campsite locations. Site selection suppported by TSA/QRA.	High use campsites discouraged. Moderate to low use campsites considered. Site selection suppported by TSA/QRA.	No campsites allowed. Low use campsites considered	No campsites allowed. Day use only.
Landslide Hazard Level	Low	No action required	No action required	No action required	No action required.
	Moderate	No action required	Tolerable risk for public.	Traffic should keep moving. Overnight camping not recommended.	Traffic should keep moving. Meager and Pebble Creek Hotsprings closed.
	High	May be local terrain hazards. Use judgment.	Traffic should keep moving. Overnight camping not recommended.	Traffic should keep moving. Close low use campgrounds.	Actively avoid these areas if possible, otherwise traffic should keep moving. Access to proximal valleys closed.
	Extreme	Public access to Lillooet River Valley is restricted at FSR Gates.			

Note: When landslide hazard level is above LOW, industrial operations must be governed by detailed TSA.

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9.0 Caveat

This report was prepared for use by MoFLNRO, including distribution as required for purposes for which the report was commissioned. The work has been carried out in accordance with generally accepted geoscience practice. Judgment has been applied in developing the conclusions stated herein. No other warranty is made, either expressed or implied to our clients, third parties, and any regulatory agencies affected by the conclusions.

This report does not address possible consequences of bridge destruction with regard to loss of life or economic losses. It is therefore not a risk assessment and cannot be interpreted as such. Neither Cordilleran Geoscience nor BGC Engineering Inc. have made any statements as to the acceptability of the existing hazard or risk for either options discussed in this report. Risk acceptance remains entirely with B&B Forestry and CRB Logging Co. Ltd.

Should you have any questions please call.

Sincerely,

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Senior Geoscientist

Appendix 1. Annotated Photos

Photo 1. Meager Creek Hotsprings pool on the lower terrace is vulnerable to a full suite of hazardous events including floods, outburst floods, debris floods, debris flows and backwater inundation. The site has been destroyed by debris flow in the historic period, and the aggregate hazard is judged to be high to very high.

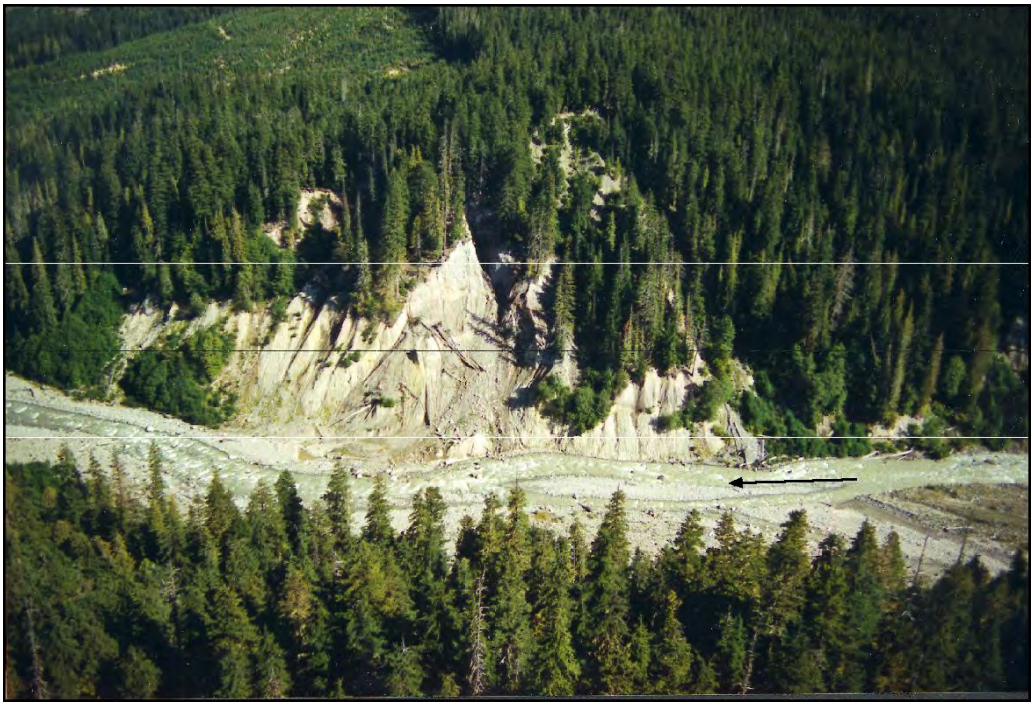

Photo 2. Bank failure in edifice collapse debris, 140 m tall and 200 m wide on the south bank of Meager Creek just upstream of Hotsprings Creek fan. Debris at the foot of slope has deflected the channel left, and sediment additions likely affect bed stability downstream.

Photo 3. Pebble Creek hotsprings pools awash by seasonal high water.

Photo 4. View down the upper Lillooet River canyon showing steep slopes directly connected to the river. Note the colluvial cone affected by snow avalanche on the right foreground, undercut toe slopes. A large slide first noted in 1962 affected the river left foreground.

Photo 5. View south of the sackung slope SE of the peak of Mount Meager. The stability of these features has not been assessed.

Photo 6. 35 m tall exposure of Pebble Creek Formation on the bush side abutment of the Truckwash Creek FSR bridge. Rock avalanche debris (grey) overlying tephra (white).

Photo 7. Truckwash Creek. View upstream at footbridge crossing area. Truckwash Creek is vulnerable to debris floods, periodic debris flow, and rockfall detached from the canyon walls. Also, Class 1 snow avalanche from ravine sidewalls may affect the crossing.

Photo 8. The Truckwash Creek footbridge. The bridge may be destroyed by debris flow activity. Further small, Class 1 snow avalanche from the left ravine sidewall may affect the crossing site and damage the bridge.

Photo 9. Right bank of South Creek near the fan apex. Buried tree stems exhumed by the Sept 19/20 debris flood. These stems indicate that a similar event of rapid aggradation has occurred on South Creek fan in the last century. Ongoing glacier recession will lead to chronic geomorphic activity on South Creek fan.

Photo 10. The February 2015, Mt Pauline rockfall. Rockfall at this site severs access on North Lillooet FSR.