Landslide Risk Management for the Construction and Operation of the Upper Lillooet River Hydroelectric Facility near Pemberton, BC

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ABSTRACT

The Upper Lillooet River Hydroelectric Facility is situated approximately 60 km northwest of Pemberton in southwest British Columbia, Canada. The site is located on the north side of the Mount Meager Volcanic Complex (MMVC), which comprises weak, locally hydrothermally altered rocks and is especially prone to large (>1 Mm^3) landslides. Landslide risk management plans were developed for both the construction and operational phases of the project. Under the framework of the landslide risk management plans, the work areas at the site were assigned one of three hazard ratings (Low, Moderate or High). The ratings reflect the return-frequency and magnitude of landside that would be anticipated to affect the work area. A risk analysis was completed taking account of the predicted workforce requirements for each work area and the vulnerability of individuals to the hazards. The landslide hazard from the MMVC is seasonal and conditioned by weather. Four hazard alert levels were defined based on rainfall and temperature criteria. Risk mitigation requirements for each work area were determined with respect to the different hazard alert levels. In moderate and high risk areas, the key mitigation measures implemented at elevated alert levels were the use of a 'spotter', restricting access and temporarily implementing 'Shutdown' of work. Rainfall and temperature were continually monitored during construction using an on-site climate station, and the mitigation measures were varied accordingly. The landslide risk was exacerbated when, in the summer of 2015, the area was affected by a wildfire. Rock fall and boulder fall hazards were mitigated by undertaking scaling work and constructing a protection berm, and enhanced 'Shutdown' procedures were implemented. The management plan for the operational phase of the project incorporates a full Quantitative Risk Assessment for each work area and work activity with respect to Personal Individual Risk. The risk was evaluated against a threshold risk tolerance criteria of 1:10,000 per annum to verify the mitigation requirements.

RÉSUMÉ

À une soixantaine de kilomètres au nord-ouest de Pemberton, dans le Sud-Ouest de la Colombie-Britannique, au Canada, la centrale hydroélectrique Upper Lillooet est aménagée du côté nord du complexe volcanique du mont Meager. La géologie régionale se distingue par la présence de roches affaiblies par altération hydrothermale, et d'importants glissements de terrain (>1 Mm^3) peuvent se produire. Des plans de la gestion des risques ont été élaborés pour les phases de construction et d'exploitation de la centrale. Chaque site affecté a reçu une cote correspondant à son niveau de risques (faible, moyen et élevé), en fonction de la périodicité et de l'ampleur des glissements de terrains qui pourraient s'y produire. Une analyse du risque qui prend en compte les besoins prévus de main-d'œuvre pour chaque site et l'exposition aux risques des personnes a aussi été faite. Les risques d'éboulement varient selon la saison et les conditions météorologiques. Quatre niveaux d'alerte ont été définis, selon les pluies et la température. Pour chaque secteur de travail, des mesures de prévention ont été prévues pour répondre aux exigences des différents niveaux d'alerte. Dans les secteurs de travail à risque moyen et élevé, les mesures suivantes sont appliquées lorsque le niveau d'alerte est élevé: poster un observateur, limiter l'accès ou suspendre les travaux. Une station météorologique sur le site permettait de suivre au jour le jour les précipitations et les températures pendant la construction. À l'été 2015, les risques d'éboulement ont été amplifiés lorsque des feux de forêt ont sévi dans la région. Pour réduire les risques d'éboulement, les parois rocheuses ont été décapées, des talus de protection ont été construit ou les travaux ont été suspendus temporairement. Pour le plan de gestion des risques de la phase d'exploitation de la centrale, une analyse quantitative complète des risques pour chaque secteur de travail et chaque activité liée à l'exploitation de la centrale a été faite et prend en compte les risques pour les personnes. Les mesures de prévention ont été évaluées en fonction de risques dont la période de récurrence est de 10 000 ans.

1 INTRODUCTION

The Upper Lillooet Hydro Project, owned by Creek Power Inc. (an affiliate of Innergex Renewable Energy Inc.) is situated approximately 60 km northwest of Pemberton in southwest British Columbia, Canada. The project comprises two run-of-river facilities (the Upper Lillooet River and Boulder Creek Hydroelectric Facilities). This paper describes the management of landslide risk for the Upper Lillooet River Hydroelectric Facility (HEF).

The intake structure of the Upper Lillooet River HEF is located at the head of a bedrock canyon approximately 250 m downstream from the confluence of the Upper Lillooet River with Salal Creek and approximately 550 m upstream from Keyhole Falls. Water is diverted to the powerhouse along an approximately 2.5 km long tunnel and 1.6 km long section of buried penstock located on the north side of the Upper Lillooet River. The powerhouse site is located approximately 6 km upstream from the confluence of the Upper Lillooet River with Meager Creek. Access to the site is along the Lillooet River Forest Service Road (FSR) on the north side of the Lillooet River. Figure 1 shows the site setting.

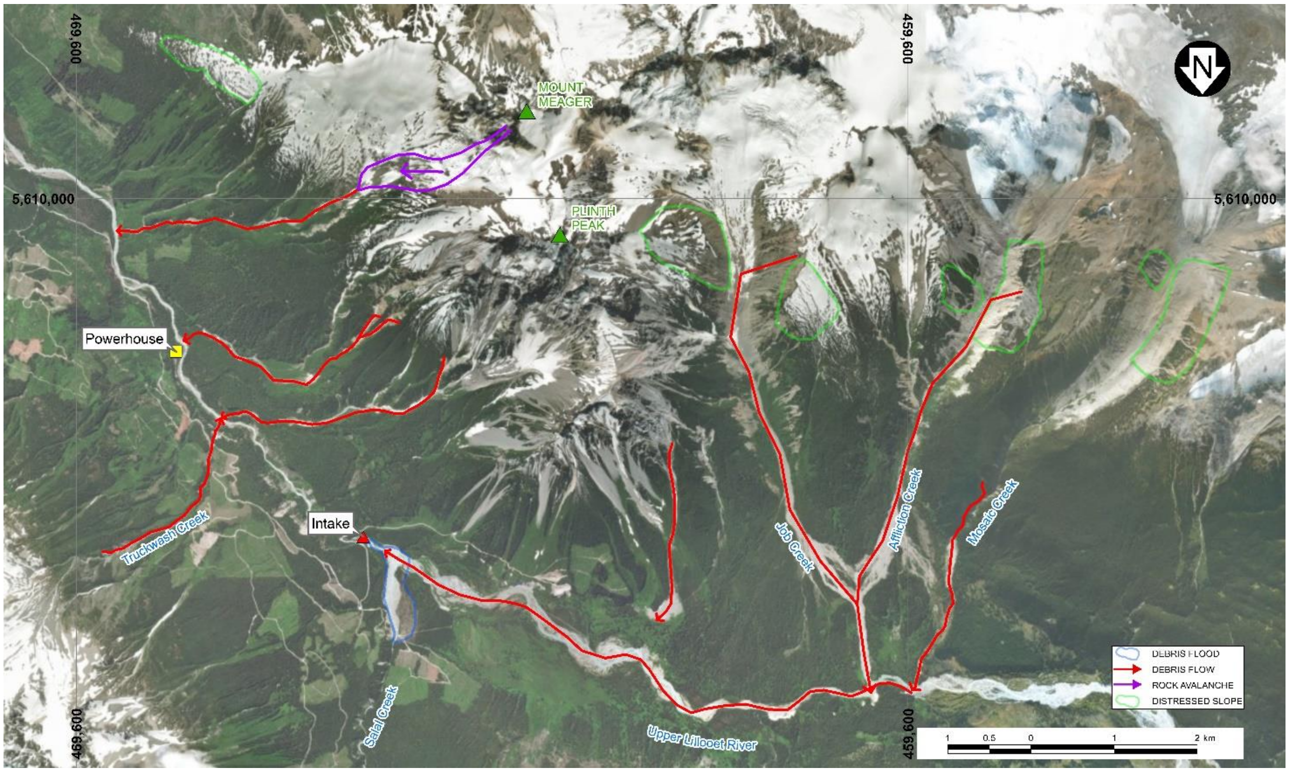

Figure 1. Site setting and key landslide hazards

The project site is located on the north side of the Mount Meager Volcanic Complex (MMVC). The MMVC is a group of coalescent stratavolcanoes comprising approximately 20 km^3 of eruptive volcanic rocks. The local relief is about 2000 m extending from river level at 700 m above sea level (asl) to the highest summit at 2700 m asl. The MMVC is the largest volcanic center in the Garibaldi Volcanic Belt, which includes Mount Garibaldi and Mount Cayley near Squamish, BC (Hickson 1994). Volcanism at MMVC spans a period of approximately two million years (Read 1990) with the most recent eruption dated at approximately 2,360 years before present (Clague et al. 1995).

The MMVC comprises weak volcanic rocks with zones of hydrothermal alteration associated with vents. The natural slopes are especially prone to slope instability (Hetherington 2014). The landslides range from frequent small (10^3 to 10^5 m^3) events (Jordan 1994; Jakob 1996) to rare but very large (10^8 to 10^9 m^3) landslides (Friele and Clague 2004; Friele et al. 2005). Signs of slope distress, manifest as extensive areas of sackung (Bovis and Evans 1996) especially in the vicinity of convex slope breaks associated with glacial trim lines (Holm et al. 2004, Roberti et al. 2018). Several predisposing factors, including the presence of weak, clay-rich, hydrothermally altered bedrock and abundant water sources (surface and phreatic water, and water from melting glacier ice), render the landslides prone to especially high mobility (Friele et al. 2005, Simpson et al. 2006).

On August 6, 2010 a major landslide occurred in the Capricorn Creek catchment of the MMVC (Guthrie et al. 2012a, Allstadt 2013, Roberti et al. 2017a, b and c). The volume of the 2010 Mount Meager Landslide has been estimated as $53 \pm 3.8 \times 10^6$ m^3 (Roberti et al. 2017c). A large rock avalanche from the face of Mount Meager transformed into a debris flow that travelled along Capricorn Creek, Meager Creek and into the Upper Lillooet River Valley. The run-out distance of the landslide was approximately 12.5 km. Landslide debris blocked the Lillooet River for a few hours and Meager Creek for approximately 19 hours. The breaching of the Meager Creek debris dam resulted in an outburst flood, which was recorded at Pemberton approximately 65 km downstream (Guthrie et al. 2012).

A Landslide Risk Management Plan was initially developed for CRT-EBC S.E.N.C. (the main civil works contractor) and was followed throughout the 3.5 year construction period. An addendum to the document was developed after the site was affected by a wildfire in the summer of 2015. A Landslide Risk Management Plan was subsequently developed for the Owner's operations team, the Upper Lillooet River Power Limited Partnership

(ULRPLP), and the facility became operational in March 2017. This paper describes the landslide risk management plans for the construction and operation of the Upper Lillooet River HEF.

2 BACKGROUND STUDIES

Between 2004 and 2006 a series of research papers (Friele and Clague 2004, Friele et al. 2005, Simpson et al. 2006) documented that very large debris flows (Class 7 to 8 debris flows according the classification scheme presented in Jakob 2005) have affected Meager Creek and the Upper Lillooet River and at least four had exceptionally long run-out affecting Pemberton Meadows and extending up to 65 km downstream from the Meager Creek confluence. This work led to a Landslide Quantitative Risk Assessment being undertaken (Friele et al. 2008), which concluded the risk to residents in the Pemberton Meadows area from volcanic landslides initiated within MMVC is unacceptable by International Standards.

The August 6, 2010 Mount Meager Landslide heightened awareness of the landslide risks associated with the MMVC. The Ministry of Forests, Lands and Natural Resource Operations (MoFLNRO) commissioned a revised Lillooet River Valley Access Management Plan (Cordilleran Geoscience 2012). The 2012 report established climate thresholds for landslide initiation in the MMVC with four hazard alert levels (‘Low’, ‘Moderate’, ‘High’ and ‘Extreme’) being established for landslide risk management.

The report recommended restrictions to public access to the valley reaches proximal to the volcano depending on the hazard alert level. The exception to the access restrictions applied to industrial users operating under a ‘Natural Hazards Operational Safety Plan’ prepared and signed-off by a Qualified Professional, consistent with the practice guidelines set out in APEGBC/ABCFP (2008) and Worksafe BC Regulations.

3 LANDSLIDE RISK MANAGEMENT DURING CONSTRUCTION

3.1 Overview of Hazards

The natural terrain landslide hazards affecting the site were characterized in a terrain hazards assessment report (KP 2011) undertaken at the preliminary design phase of the project. The study included a desk top review of historic studies and mapping of hazards from BC Provincial historic airphotos.

The predominant landslide types in the MMVC are debris and rock slides, debris flows and rock avalanches. Debris flows and rock avalanches have the longest run-out distances and pose the greatest potential threats to worker safety at the site. The majority of the dated ‘recent landslides’ (ones occurring within the period of the historic air photo record) are debris flows. In addition, volcanic rock avalanches have a tendency to transition to debris flows upon intersecting drainage lines. It is, therefore, inferred that the landslide risk associated with the MMVC is dominated by debris flow hazards.

Figure 1 shows the key landslide hazards at the site. The terrain hazards assessment for the Upper Lillooet River HEF highlighted the project to be at risk from debris flows initiating in the Job Creek, Affliction Creek and Mosaic Creek Catchments.

Several areas of sackung features have been identified in the recently glacially de-buttressed upper slopes in the north part of the MMVC (Bovis 1990, Roberti et al. 2018). Sackung features comprise distressed and sagging bedrock slopes characterized by tension cracking and uphill facing scarps. They are potential source zones of future large-scale instability.

An area of sackung features was identified on the high, north-facing slopes of Plinth Peak in the Upper Lillooet River HEF Terrain Hazards Assessment report (KP 2011). The largest instability potentially affecting the project site is on the west flank of Plinth Peak, which forms the east sidewall of Job Creek. Roberti et al. (2018) mapped tension cracks in this area, and using remote sensing methods measured slope displacements of up to 17 mm/yr from 1992 to 2000 and deformation of 40 mm over a 24-day period in July and August 2016. Roberti et al. (2018) show there has been considerable depletion of the glacier at the slope toe between 1987 and 2016, and infer that collapse of this slope could generate a 10^8 to 10^9 m^3 landslide. Additional sackung features were mapped in the Job Creek catchment in the Upper Lillooet River HEF Terrain Hazards Assessment report (KP 2011). An extensive area of sackung features with extensive tension cracks is documented on the west side of Affliction Creek (Read 1978, Bovis 1990, Jordan 1994). Over a period of seven years, Bovis (1990) recorded 1 to 5 m of horizontal movement and up to 4 m of vertical displacement across individual tension cracks (i.e. movement of several 10’s cm to almost 1 m/yr). Photo 1 shows this area.

Photo 1. Sackung features with extensive tension cracks in the Affliction Creek Catchment.

Recently, Roberti et al. (2018) identified slope displacements on the east side of Affliction Creek of up to approximately 3 mm over a 24-day period in July and August 2016, and they infer these instabilities in the

Affliction Creek catchment could generate landslides up to 10^7-10^9 m^3 in volume.

The mapped features in the Job Creek and Affliction Creek catchments could produce a rock avalanche or debris flow large enough to reach and extend well beyond the project area.

The project Terrain Hazards Assessment (KP 2011) identified a debris flow in the 1990 air photos on a drainage line that intersects the Upper Lillooet River approximately 250 m downstream from the Powerhouse site. The debris flow initiated on a steep gully side slope in the upper part of the catchment and terminated approximately 200 m from the Upper Lillooet River.

Evans (1987) documented a 500,000 m^3 rock avalanche from the north side of Mount Meager, which occurred in the spring of 1986. During or somewhat after the primary event, a debris flow followed a drainage line and reached the Upper Lillooet River in an area approximately 1.5 km downstream from the Powerhouse site.

Jordan (1994) mapped an area of sackung features on the north aspect of the east shoulder of Mount Meager in the eastern-most portion of the MMVC. This area of distressed terrain is approximately 1.5 km-wide and is upslope from the final portion of the access route to the site. The area of sackung features is a potential source zone for a rock avalanche, which could affect the access road.

Some areas of the site are affected by landslide hazards that originate outside the MMVC, for example non-volcanic debris flow and debris flood hazards along tributary creeks and open slope landslide hazards. On the north side of the Upper Lillooet River, a 'recent' debris flow was identified along 'Truckwash Creek' in the 1990 air photos. The penstock alignment crosses this drainage line. There is a debris flood hazard along Salal Creek, which intersects the Upper Lillooet River just upstream of the intake site.

3.2 Risk Analysis

Risk was analyzed in terms of Personal Individual Risk (PIR). PIR is calculated using the following Equation 1:

$$PIR = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V \quad [1]$$

Where:

- PIR is the risk (annual probability of loss of life of an individual)
- $P_{(H)}$ is the annual probability of the hazardous event
- $P_{(S:H)}$ is an estimate of the probability that a hazardous event will reach or otherwise affect the site of the element at risk (spatial probability)
- $P_{(T:S)}$ is an estimate of the probability that the element at risk will be at the site when a hazardous event occurs (temporal probability), and
- V is an estimate of the vulnerability of the element at risk (probability of loss of life of the individual given the impact).

The frequency-magnitude distribution of debris flows initiating in the MMVC ranges from debris flows with a volume of <10^5 m^3 with return intervals of approximately 5 to 10 years (Jakob 1996) to a maximum credible debris flow of approximately 1.0×10^9 m^3 with an annual probability in the order of 1:5,000 (Friele et al. 2008).

The landslide hazards affecting the work areas were characterized quantitatively in terms of an expected annual probability/return frequency.

Table 1. Qualitative and quantitative probability estimates for landslide hazards affecting work areas.

Hazard Rating	Expected Annual Probability / Return Frequency
Very High	>1/20
High	1/100 to 1/20
Moderate	1/500 to 1/100
Low	1/2500 to 1/500
Very Low	<1/2500

One of the five hazard ratings in Table 1 was assigned to each hazard type affecting each of the work areas at the site. Many of the work areas are affected by several hazard types, and in these cases, the individual hazard ratings for the different hazard types were aggregated. The end result was that the work areas at the site were each assigned one of the three hazard ratings: 'Low', 'Moderate' or 'High' Hazard.

The ratings were assigned on the basis that if a landslide were to occur there would be an approximately 100% probability of it reaching or otherwise affecting the work area (i.e. $P_{(S:H)}$ is equal to 1). Thus, the ratings are an evaluation of the partial risk (Wise et al. 2004). A High Hazard rating was applied if a landslide was identified to have affected the subject work area in the historic period from the earliest airphoto coverage in the 1940's.

The hazard ratings for volcanic debris flows were estimated using magnitude-frequency plots and the results of landslide run-out assessments undertaken using *DanW*. A frequency-magnitude plot was established for the Job Creek and Affliction Creek catchments and was used for analyzing the debris flow risk for the main work areas. A combined frequency-magnitude plot including the main catchments on the north and south sides of the MMVC (Friele et al. 2008), was used when considering the frequency of occurrence of volcanic debris flows affecting the portion of the access road downstream from the Meager Creek/Upper Lillooet River Confluence.

Separate debris flow run-out assessments were undertaken for 'proximal' and 'distal' areas. For 'proximal' areas, including the Intake site, the run-out assessment was based upon the findings of a dynamic debris flow run-out assessment, undertaken with the program *DanW*. The assumed landslide source zone comprised the closest area of distressed ground to the intake site identified in the project Terrain Hazards Assessment (KP 2011). The input parameters used were consistent with those obtained in the published back-analysis of the 2010 Mount Meager Landslide (Guthrie et al. 2012b).

All the other parts of the work site were considered to be 'distal' areas. The hazard ratings for these areas were estimated using the published results of a semi-empirical run-out assessment for 10^6, 10^7, 10^8 and 10^9 m^3 landslides initiating in the MMVC, undertaken with the *Laharz* Model (Simpson et al. 2006).

The maximum potential extents of debris run-out downstream from the Meager Creek/Upper Lillooet River Confluence were estimated for 10^6, 10^7, and 10^8 m^3 debris flow events in relation to the road chainage system along the Lillooet River FSR. For each of the run-out limits, the potential cumulative frequency of landslides that could reach the location was calculated by adding the estimated frequencies of all the landslide classes that are expected to reach or travel beyond the location. The results of the *Laharz* modelling were assumed to be somewhat conservative as the underlying semi-empirical methodology does not account for energy dissipation at path obstructions (e.g. opposing valley walls and the base of Key Hole Falls).

The predicted lateral extents of a 10^7 m^3, 10^8 m^3 and 10^9 m^3 volcanic debris flow were interpreted from the inundation maps presented in Simpson et. al. (2006) supplemented by estimates of the thickness of the deposits that were predicted by the 2006 model. The latter estimates were provided by NRCan.

In consideration of the open slope debris slide hazard, the hazard rating was judged to be Moderate in those areas of moderately steep to steep terrain immediately upslope from work areas where no debris slides were identified in the historic air photos but if one were to occur the run-out would be expected to affect the area based on an empirical run-out assessment using the predicted travel angle for an estimated landslide volume (Corominas 1996).

The potential consequences of the hazards were considered qualitatively. CRT-EBC provided estimates of the minimum and maximum numbers of workers expected to be in each work area per day. Consideration was given to the temporal probability and vulnerability of the workers.

The Vulnerability depends upon the predicted landslide velocity and depth as well as the level of protection provided by any structure or vehicle. The vulnerability of workers to volcanic debris flows was additionally considered by comparing the height of the work area above the adjacent watercourse with the predicted debris flow thickness. Consideration was also given to the likelihood of escaping a landslide, which is partly controlled by the distance from the source zone and the anticipated velocity of the specific hazard type, and partly by the mode of transport being used.

Workers in the upstream portion of the tunnel, and at the intake and powerhouse sites were considered to be most vulnerable to volcanic debris flows. In general, heading downstream down the Upper Lillooet River Valley, progressively lower debris flow velocities are expected, and therefore the vulnerability is expected to reduce progressively.

3.3 Hazard Alert Levels

Cordilleran Geoscience (2012) compiled the climate data from Pemberton for historic landslides with known dates of occurrence. The dated historic landslides generally occurred between mid-July and early-November. There are several reasons for an enhanced landslide occurrence during this period of the year. First, the hottest time of the year straddling July/August coincides with enhanced snow/ice melt from alpine glaciers, which has been implicated in triggering several large landslides including the 2010 Mount Meager Landslide (Roberti et al. 2017c); secondly, prolonged summer heat waves often lead to dry ravelling of steep volcanic slopes; thirdly, the first fall rains often trigger gully channel flushing debris flows; and finally, prolonged and intense fall rain and/or rain-on-snow events may trigger shallow and deep-seated landslides. Thus, landslide probability varies markedly throughout the year with seasonal changes in heat and rainfall, and in order to be effective, the management plan needed to account for these changes.

Cordilleran Geoscience (2012) developed a weather alert system for managing the landslide risk along the Lillooet River FSR. The hazard level was ascribed to one of four classes (‘Low’, ‘Moderate’, ‘High’ and ‘Extreme’), which relate to the likelihood of the climate conditions triggering a landslide.

This classification system, which is presented in Table 2, was adopted in the Risk Management Plan for the Upper Lillooet River HEF.

Table 2. Climate Thresholds for Landslide Hazard Alert Levels.

Hazard Level	Max. Daily Temp. (˚C)		Rainfall (mm)	
	Daily Max.	6 Day Avg.	24 hr	48 hr
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

There was no onsite weather gauge at the MMVC prior to 2010. The Pemberton climate station was therefore used as a common point of reference for the regional back-analysis as well as for monitoring the hazard level under the management plan. Some microclimate differences are anticipated between Pemberton and the project site area, and large differences are anticipated between the valley bottoms and the high elevation areas where many of the landslides initiate.

In developing the management plan for the Upper Lillooet River HEF, it was considered appropriate to incorporate local meteorological data collected using a climate station installed at the project site in order to provide an opportunity to capture localized weather patterns, specifically precipitation, which might lead to an increased hazard level rating.

Under the management plan, rainfall and temperature readings were recorded hourly with the climate station. The data was processed to provide rolling values (every hour) of the 24-hr rainfall, 48-hr rainfall, daily maximum temperature and 6-day average maximum daily temperature. The hazard level was assessed daily using a combination of Environment Canada's recorded and forecast data for Pemberton and the recorded data from the climate station at the site.

During the summer months, while temperatures in Pemberton are somewhat higher, they are correlated with those at the site, and since the Pemberton temperature records were used to establish the hazard levels, the Pemberton temperature data was generally used to establish the hazard level.

In contrast, site-specific rainfall data was important for capturing locally intense rainfall that might not have occurred at Pemberton.

3.4 Mitigation Strategy

The findings of the risk analysis were used to develop a detailed mitigation strategy for the work site. A varying mitigation response was applied to each work area dependent upon the hazard alert level. The mitigation measures required for each of the work areas under different hazard alert levels were summarized in a Hazards Matrix.

In moderate and high risk areas, the key mitigation measures implemented at elevated alert levels were the use of a 'spotter', restricting access to select work areas and temporarily implementing full 'Shutdown' within select work areas. During periods of 'Shutdown, workers were stationed at the construction camp, which was located in a 'Very Low' Hazard area. Work at the Intake site 'Shutdown' when the hazard alert level reached High and work at the Powerhouse site 'Shutdown' when the hazard alert level reached 'Extreme'. Additional mitigation measures implemented included the installation of hazard signage, establishment of emergency evacuation procedures, implementation of 'log in-log out' safety checks, and safety meetings to heighten the awareness of workers to the hazards. In addition, limitations were placed on the use of the access road dependent upon the hazard alert level.

Annual inspections of known potential landslide source zones were undertaken by helicopter. Visual inspections were undertaken to check for any new small-scale slope instability that might be a pre-cursor to a large landslide. A toe slope failure was recorded on the east side of the Affliction Creek Valley in December 2016. A debris flow was generated. The landslide reached the Upper Lillooet River but a landslide debris dam did not form. No changes to the management plan were deemed necessary based on the condition of the slope surrounding the source zone.

3.5 Post-wildfire Landslide Risk Management

During construction, in the summer of 2015, the site experienced an extensive wildfire. A post-wildfire Landslide Risk Management Plan was developed incorporating a post-wildfire landslide risk assessment. In relation to the classification system for vegetation burn severity for coniferous forest presented in Land Management Handbook 69 (Hope et al. 2015); the wildfire predominantly produced areas of 'High Vegetation Burn Severity' in which the understory was burnt, the needles were consumed and the canopy trees blackened. Photo 2 shows the vegetation burn in the Truckwash Creek catchment:

Photo 2. Predominantly High vegetation Burn Severity in the Truckwash Creek Catchment from the 2015 Wildfire

The specific landslide risk, $R_{(S)}$ was analyzed for every scenario where an increased hazard was identified for the post-wildfire condition compared to the pre-wildfire condition. Consequence factors were assessed and related to consequence terms using a classification system by Arksey and VanDine (2008). A Risk Matrix was then used to analyze the Specific Risk ($R_{(S)}$).

The wildfire exacerbated the rock fall risk within the final portion of the access road alignment, where the road follows the toe of a steep rock slope. A 'High' post-wildfire risk associated with a boulder fall hazard was identified along the Upper Lillooet River Powerhouse Access Road. The study identified the development of water-repellent soils in the Truckwash Creek Catchment. It was interpreted from the development of these soils that the wildfire had rendered the catchment more prone to debris flows and debris floods under intense rainfall and this situation would prevail until the vegetation could recover. A 'High' post-wildfire risk was assigned to the debris flow and debris flood hazards at the Truckwash Creek crossing along the Upper Lillooet River Penstock alignment.

A mitigation strategy was developed for those areas where the risk was shown to have increased, the aim being to reduce the landslide risk as close as practicable to the pre-wildfire level. Scaling of the steep rock slope along the final portion of the access road alignment was undertaken.

The Upper Lillooet River Powerhouse Access Road was re-aligned and a 2 m-high boulder fall protection berm was constructed. The berm was designed with a 95% boulder retention requirement using charts presented in Pierson et al. (2001).

In order to mitigate the enhanced debris flood and debris flow risks at the Truckwash Creek crossing of the Upper Lillooet River Penstock alignment, an additional rainfall 'Shutdown' threshold for high intensity rainfall of 5 mm/hr was applied. In addition, a requirement was added to station a 'spotter' at a vantage point during the penstock installation at the Truckwash Creek crossing when the rolling 24-hr rainfall exceeded 20 mm in 24 hrs.

4 LANDSLIDE RISK MANAGEMENT DURING OPERATIONS

4.1 Methodology

For the operational phase of the project, the risk analysis process evolved to a full Quantitative Risk Assessment with ranges of temporal probability and vulnerability factors being included in the risk calculations for the work areas, and the PIR values being evaluated with respect to established risk tolerance criteria. The work activities were sub-divided into operational activities associated with the running of the facility and permit compliance monitoring activities. PIR values were calculated for both types of activities in each of the work areas by multiplying the temporal probability and vulnerability factors by the partial risk value determined previously. Upper and lower-bound estimates were made to reflect the uncertainties with the input parameters.

4.2 Quantitative Risk Analysis

Estimated manpower requirements for all of the anticipated work activities were provided by ULRPLP. This information was used to estimate temporal probability values for each work area. Vulnerability values were judged based upon considerations discussed in Section 3.2. The PIR Values calculated for the main work areas are summarized in Table 3.

Table 3. Personal Individual Risk Values for Main Work Areas

	Personal Individual Risk (per annum)		
Work Area	Operational Activities	Permit Compliance Monitoring (Year 1 to Year 5)	Permit Compliance Monitoring (after Year 5)
Intake	1:6,350 to 1:3,750	1:6,450	1:25,850
Penstock	1:869,550 to 1:35,200	1:9,100	Negligible
Powerhouse	1:20,300 to 1:16,250	1:26,300	1:144,100
Access Road	Approx. 1:22,950	Approx. 1:17,200	Approx. 1:100,400

4.3 Risk Tolerance

A target tolerable PIR threshold was established in consultation with Creek Power Inc. by reviewing criteria established in other jurisdictions and considering typical risks that an individual would be expected to be exposed to outside the workplace.

Risk guidelines, which establish the maximum allowable risk as the tolerable risk or required 'level of landslide safety', are used to evaluate risk. Risk guidelines for residential development relating to the individual risk from landslides have been developed in Hong Kong, Australia and by the District of North Vancouver, BC. Such guidelines set limits on individual risk for the most vulnerable people affected by the landslide hazard, as follows:

Table 4. Example Landslide Risk Guidelines for Individual Risk

Type of Development	Maximum Allowable Individual Risk
New	$1x10^{-5}$ (1:100,000)
Existing	$1x10^{-4}$ (1:10,000)

[1] Risk refers to the likelihood of a fatality per annum.

At present, there is no provincial or federal legislation that addresses risk tolerance for industrial facilities in relation to landslide hazards, which could have been used as a framework in the risk evaluation. The level of landslide safety and extent of mitigation measures employed were therefore heavily dependent upon professional judgement.

The construction and operation of the facility has necessitated a significantly higher tolerance to risk than the criteria applied to residency described above. As discussed in Porter and Morgenstern (2012) though, an elevated risk tolerance associated with the work environment is not untoward because there is an enhanced motivation and responsibility for continuous monitoring and risk management, and it is easier to control access of workers to affected areas than it is to control public access. In addition, the risk to workers from landslides might be considered somewhat voluntary if education is provided to the worker and they are not penalized for refusing unsafe work.

Bunce and Martin (2011) suggested a risk of fatality of 1:10,000 per annum represents a reasonable target for train crews operating in landslide prone terrain. The risk of death while driving in BC is approximately 1:10,000 per annum (Transport Canada 2011).

In consideration of the above, a target PIR value close to 1:10,000 per annum was selected.

4.4 Risk Evaluation

A rudimentary risk evaluation was undertaken in relation to the PIR, the intent being to guide the determination of the appropriate extent of mitigation measures.

Comparing the results of the risk analysis (Table 4) to the individual risk threshold of 1:10,000 per annum confirms the need for operating a comprehensive landslide risk management plan, especially at the intake site.

5 DISCUSSION

Landslide Risk Management was undertaken during the construction of the Upper Lillooet River HEF and continues into the operational phase of the project. A key component of the mitigation strategy throughout has been to limit the exposure of workers to the hazards at times when, based on ongoing climate monitoring, the hazard alert level reaches specified thresholds. A discussion on the reliability of this mitigation method is presented below.

A pre-cursor to the hazard alert level system discussed herein was used for the Capricorn Creek Bridge reconstruction project in 2010, and resulted in the temporary 'Shutdown' of work at the time of the August 6, 2010 Mount Meager Landslide (Roberti et al (2017c). Clarke et al. (2016) describe how the implementation of Wet Weather Safety Shutdown Guidelines mitigated possible exposure of workers to landslides that occurred during the construction of a hydroelectric project near Squamish, BC.

In considering the reliability of the same classification system, Cordilleran Geoscience (2012) showed that the seven dated landslides with climate data generally occurred under a 'High' or 'Extreme' hazard level. The key exception is the September 19, 2009 debris flow in the Capricorn Creek drainage. This landslide is ascribed to a combined rainfall and temperature trigger. The temperature and rainfall conditions at the time of the landslide were such that the landslide hazard level would have been described as 'Moderate', and would therefore not have resulted in a 'Shutdown'.

The mitigation method assumes landslides are conditioned by a climate-related trigger. However, the data upon which the hazard alert thresholds are based is very limited: there are few (<10) historic landslides with known dates of occurrence allowing evaluation of antecedent/triggering weather conditions and derivation of thresholds. Even in data-rich settings, there is not a particularly strong link between threshold exceedance and event occurrence. This disparity is attributed to complexities of the hydrologic response to rainstorms and landslide generation mechanisms, and is compounded by the fact that there are expected to be significant microclimate variations between Pemberton, (the source location of the meteorological data for establishing the climate thresholds) and the landslide initiation areas.

The rainfall threshold criteria in the hazard classification system do not specifically account for high intensity rainstorms. Cordilleran Geoscience (2009) determined that a high intensity rainstorm, with a maximum 1-hour rainfall intensity of 6.4 mm, occurred over an 8-hour time period in the early hours of September 19, 2009, preceding the debris flow in the Capricorn Creek drainage. Short duration periods of intense rainfall such as this have been found to be sufficient to trigger landslides (Jakob and Weatherly 2003).

In addition, the rainfall threshold criteria do not explicitly account for factors (including the elevation distribution of snow cover, the ambient temperature and the wind speed) that influence snowmelt generation during rain-on-snow events. These factors have been accounted for in other hazard classification systems e.g. BCTS, 2010. However, there are additional uncertainties associated with these factors and it is challenging to incorporate them reliably into a simple and practical system.

Landslides at the MMVC can occur without a climate trigger. Other possible triggers include earthquake and volcanic activity in the MMVC. In addition, slope instability may be manifested as a gradual progressive failure with the detachment of a landslide from the source zone being controlled by the time when the rock mass strength deteriorates to a critical threshold.

Climate change is expected to result in a progressive increase in the number of days per year with High and Extreme hazard levels at the site. It should be considered that climate change was occurring, to some extent, throughout the historic period of landslide occurrence (the preceding 90 years), which was used to gauge the relationship between climate thresholds and landslide occurrence. For example, in consideration of temperature change, a mean annual temperature increase of approximately 1.6ºC is expected over the 40 year design-life of the project. However, there has been an additional period of approximately 90 years between the date of the first historic landslide used in the analysis and the inception of the project during which time there is the possibility that additional temperature change occurred.

The reliance on climate-related 'Shutdown' as a key component of the mitigation strategy ultimately means engineering judgment plays an important role in confirming whether the mitigation strategy has reduced the risk to a tolerable level.

In evaluating risk, it is recognized there is a case for considering the societal (group) risk as well as the individual risk. This applies particularly to the construction phase of the project when there was a relatively large workforce. The estimation of the required mitigation measures during construction included consideration of the anticipated number of workers in each work area. There are several reasons why the methodology was not extended to the development of an F-N plot. First, there are large variations in the risk across the site, so ideally the workforce would need to have been divided into sub-groups and, even then, the situation would have been complicated by temporal variations in risk related to work being concentrated in different areas at different times. In addition, it was recognized that the management plan needed to be maintained as a relatively simple procedural document for it to be followed routinely and consistently.

A target tolerable risk threshold of 1:10,000 per annum was used in the Operational Risk Management Plan with respect to the individuals most at risk. In assigning this value, consideration was given to risk tolerance criteria that have been established in other jurisdictions and to typical risks that an individual would be expected to be exposed to outside the workplace such as the risk of being killed in a traffic accident. It is noted that the example risk tolerance criteria from other jurisdictions generally relate to residential development. There are relatively few case examples relating to risk tolerance within the work environment.

Monitoring is an important component of the risk management plans. During construction, annual visual inspections of potential landslide source zones were undertaken by helicopter. On December 13, 2016 the sudden onset of creek turbidity triggered a helicopter inspection that detected a small landslide in the west fork of Affliction Creek. Work at the intake was restricted until the hazard was evaluated. Moving into the operational phase of the project, it is recognized there is an opportunity to develop a cost-effective ground displacement monitoring program incorporating remote sensing techniques such as InSAR or LiDAR, as initiated by Roberti et al. (2018).

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