CATHEDRAL MOUNTAIN 2014 ICE FALL AND DEBRIS FLOW

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Des défis du Nord au Sud

ABSTRACT
Cathedral Mountain is located in the southern Rocky Mountains of British Columbia, 7 km east of the community of Field. Its northern slopes are situated in Kicking Horse Pass, the most traveled route across the Continental Divide of the Canadian Rocky Mountains. The higher elevations of the mountain are occupied by the Cathedral Glacier, which includes a supra-glacial lake that drains north towards the Kicking Horse River through a valley known as Cathedral Gulch. Since 1925, 16 debris flows have been recorded in Cathedral Gulch including several that buried or eroded one or more levels of the Canadian Pacific railway mainline and the TransCanada Highway. The debris flow activity at Cathedral Gulch caused by large volume releases from reservoirs within and adjacent to the glacier, glacial down-wasting, loss of stagnant ice and the subsequent entrainment of colluvial sediment has been larger and more frequent than other similar, small steep watersheds in the Rockies. At 06:30 on July 10, 2014, approximately 100,000 m^3 of ice collapsed from Cathedral Glacier allowing the supra-glacial lake to partially drain. The ice and water descended Cathedral Gulch and transformed into a debris flow through entrainment of channel sediments that buried the uppermost CP tracks. Analysis of the event included: an initial rapid assessment and safety plan for workers who had the track functional by 14:20 on the day of the incident, a qualitative assessment using detailed 3D surface models from oblique aerial photos taken during the days following the incident, the analysis of the stability of the remaining glacier and supra-glacial lake, and a magnitude frequency analysis of Glacial Lake Outburst Floods (GLOF) and debris flows that have occurred down Cathedral Gulch. This case study highlights the key results of the analyses and reports on some of the innovative techniques available for rapid Geohazard assessments in similar terrain.
RÉSUMÉ
La montagne Cathedral est située dans les montagnes Rocheuses du sud de la Colombie-Britannique, à 7 km à l'est de la communauté de Field. Ses pentes septentrionales sont situées dans le col Kicking Horse, la route la plus voyagée à travers la division continentale des Rocheuses canadiennes. Les altitudes les plus élevées de la montagne sont occupées par le glacier Cathedral qui comprend un lac supra-glaciaire se déversant au nord vers la rivière Kicking Horse à travers une vallée connue sous le nom de Cathedral Gulch. Depuis 1925, 16 coulées de débris ont été enregistrées dans la vallée Cathedral Gulch dont plusieurs ont enterré ou érodé un ou plusieurs niveaux de la ligne principale du chemin de fer Canadien Pacifique (CP) et de l'autoroute Transcanadienne. Les coulées de débris dans Cathedral Gulch, causées par de grands volumes de relâche provenant de réservoirs intérieurs et à proximité du glacier, de la détérioration en aval, de la perte de glace stagnante et de l'entrainement subséquent de sédiments colluviaux, ont été plus importantes et plus fréquentes que dans d'autres petits bassins versants escarpés similaires dans les Rocheuses. Le 10 juillet 2014 à 06h30, environ 100 000 m3 de glace se sont effondrés du glacier Cathedral permettant au lac supra-glaciaire de se vider partiellement. La glace et l'eau sont descendues de Cathedral Gulch et se sont transformées en coulées de débris, en entrainant des sédiments du canal pour finalement enterrer les voies supérieures du CP. L'analyse de l'évènement comportait : une évaluation initiale rapide et un plan de sécurité pour les travailleurs qui ont ramené la voie ferrée fonctionnelle à 14h20 le jour de l'incident, une évaluation qualitative en utilisant des modèles de surface 3D détaillés à partir de photos aériennes obliques prises au cours des jours suivants l'incident, l'analyse de la stabilité du reste du glacier et du lac supra-glaciaire, ainsi qu'une analyse de fréquence et d'ampleur des inondations catastrophiques des lacs glaciaires et des coulées de débris qui ont eu lieu dans la vallée Cathedral Gulch. Cette étude de cas met en lumière les principaux résultats des analyses et des rapports sur certaines des techniques innovatrices disponibles pour l'évaluation rapide des géorisques en terrains similaires.

1 INTRODUCTION

Cathedral Mountain is located in the southern Rocky Mountains of British Columbia, 7 km east of the community of Field (**Figure 1**). Its northern slopes are situated in Kicking Horse Pass, rising over 1,000 vertical meters above the Canadian Pacific railway and the TransCanada Highway. The higher elevations of the mountain are occupied by Cathedral Glacier, which partially drains to the north towards the Kicking Horse River though a large gully unofficially known as Cathedral Gulch. A prominent east-west trending snow ridge forms at the head of the Cathedral Gulch, likely formed by wind accumulated snow. South of the snow ridge, a small supraglacial lake forms in a depression formed by the snow ridge to the north, Cathedral Glacier to the east and south, and bedrock to the west.

Historically, Cathedral Gulch has been the location of several large debris flows that have buried or eroded one or more levels of the CP mainline at this location during the summers of 1925, 1946, 1962, 1978, 1982, and twice in 1984. Of these 7 events, 5 crossed at least two levels of CPR track, and 2 crossed all three (Jackson et al., 1989). Compared to similar small steep watersheds in the Rockies, the debris flows at Cathedral Gulch tend to be larger and more frequent. This increased activity is caused by the storage of water within the closed depression, the unstable condition of the Cathedral Glacier and loose glacial and colluvial sediments. The supra and sub-glacial hydrology is key to the understanding and prediction of ice mass failures and debris flow occurrences, as many of these events have likely been caused by the periodic storage of water in the glacial lake and meltwater tunnels. This was then followed by their rapid drainage as a Glacial Lake Outburst Flood (GLOF) (Jackson et al., 1989).

In this paper we discuss the details of a major failure and subsequent debris flow which occurred on July 10, 2014, and the technical analyses and hazard mitigation that followed.

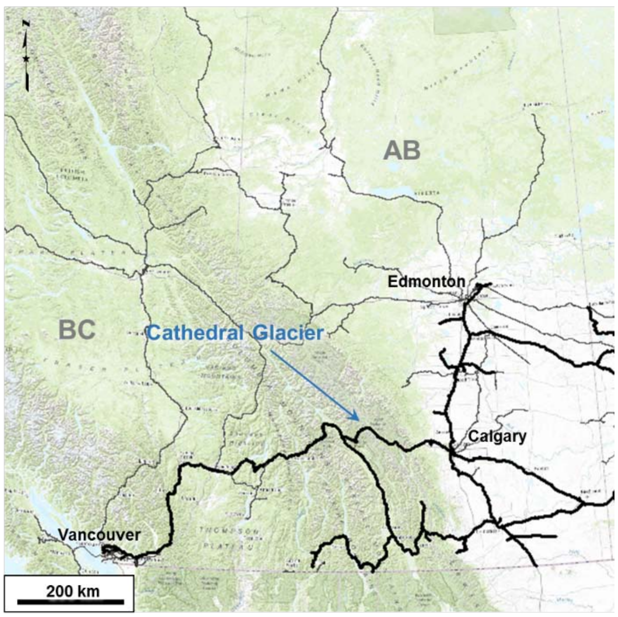

Figure 1. Location of Cathedral Glacier in the Canadian Rockies near Field, BC. CP tracks are identified in thick black lines. Other railway lines are in grey.

In order to reduce the hazard from the supraglacial lake creating a catastrophic GLOF, lake pumping and lake drainage was initiated in the 1980's and 1990's, respectively. Pumping began in 1985 and but was stopped in the early 2000's.

1.1 Geology

The bedrock surrounding Cathedral Mountain is formed of Cambrian aged sedimentary rock that has been thrust and folded into its current orientation. The higher elevations of the mountain including the Cathedral Summit are composed of dolomites and limestones of the middle Cambrian Cathedral Formation. The slopes which make up most of the Cathedral Gulch are composed of competent, cliff forming, lower Cambrian Quartzite sandstones of the Gog Group. Smaller outcrops of shale and limestone of the middle Cambrian Stephen Formation are also found in the study area (Geological Survey of Canada, 1973). Glacial erosion has oversteepened the valley sides and led to commonly occurring talus and scree slopes, landslides, and rock glaciers (Jackson, 1979).

1.2 Weather

The Yoho Park weather station, at an elevation of 1602 m and located 5 km east of Cathedral Mountain, is anticipated to be representative of the conditions at the ice fall-debris flow. Precipitation in July was relatively low, with only 1 mm falling in the week leading up to the July 10, 2014 event. The trend in mean daily temperatures was increasing over 14 days preceding the ice fall-debris flow, and varied between 13.5°C and 17.2°C between July 3 and July 10, 2014 (Environment Canada, 2014). Cathedral Glacier occupies elevations above 2800 m, 1200 m above the weather station in the valley. Using the dry adiabatic lapse rate of air temperature with altitude of -0.98°C per 100 m (Rolland, 2003), air temperatures are expected to be 11°C to 12°C lower than the observed values at the Yoho Park. Based on this extrapolation, the mean daily temperature at Cathedral Glacier had likely been above 0 C for 10 days leading up to the ice fall.

2 JULY 10, 2014 ICE FALL-DEBRIS FLOW DESCRIPTION

At 06:30 on July 10, 2014, the CP rail traffic controller reported that a signal fence above the railway at Laggan 128.2 had been tripped (D. Symborski, personal communication, July 14, 2014). The cause was an ice fall from the Cathedral Glacier which had been channeled down Cathedral Gulch and transformed into a debris flow that ultimately crossed the uppermost level of the CP mainline (**Figure 2**).

The ice fall originated from a section of the glacier's snow ridge marked by visibly degraded ice and tension cracks (**Figure 3**). The failure was preceded by little to no precipitation, and therefore rainfall triggering can be excluded. The cause appears to be a progressive failure produced by the build-up of strain and increase in water pressure in and below the glacier which eventually overcame the strength of the ice. Due to the warm temperatures leading up to the failure, strain was likely exacerbated by glacial melt. Historical debris flows in Cathedral Gulch suggest that the rapid drainage of meltwater from Cathedral Glacier is a common cause of GLOF, and has been supplied at least in part by the supraglacial lake (Jackson, Hungr, Gardner, & MacKay, 1989). Photographs taken within 8 hours of the event indicate a drop in the supraglacial lake level evidenced by a lowering of the shoreline and beached ice on the lake shore (**Figure 3**). The remaining water observed in the supraglacial lake was 1.5 m deep on July 11, 4.5 m lower than the high watermark corresponding to a release of approximately 10,000 m^3.

Figure 2. Overview of Cathedral Gulch showing the debris flow and two of the three CP tracks and the TransCanada Highway. The glacier is just visible above the Gulch.

A wedge-shaped piece of ice broke off the glacier and fell into Cathedral Gulch (**Figures 3 and 4**). The volume of the wedge was estimated as 100,000 m^3 based on visual assessment. The mass of ice broke apart over bedrock below and mixed with sediment on the landing slope. The ice fall allowed the supra-glacial lake to drain and initiate a debris flow downslope. Entrainment was limited, however, as most of the material was derived from the main V-shaped gully. On the upper colluvial slope, the debris flow was largely confined to a channel less than 100 m wide, with only a thin layer of sediment deposited on the surrounding slopes. The majority of ice and debris deposition occurred at a slope break above the tree line between the elevations of 2,000 and 2,400 m (**Figure 2**). Water and debris continued to flow downslope through the historical debris flow channel and the trees.

Sediment overwhelmed the first debris basin upslope of the track, then overran the first level of the CP mainline and deposited into a second debris basin downslope (**Figure 5**) built to protect the two lower tracks and the TransCanada Highway. While much of the debris flow deposition remained on the slope above, an estimated 3,200 m^3 to 4,600 m^3 of debris reached the track and debris basins.

Canadian Pacific railway workers were able to clear the mainline of debris, and trains were running by 14;20 the same day.

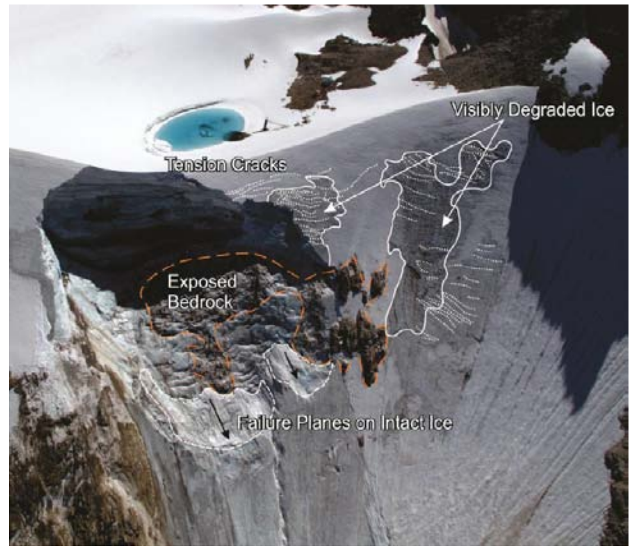

Figure 3. The ice fall showing the drop in lake level and the wedge shape failure in the glacier.


Figure 4. The ice fall into Cathedral Gulch.

Figure 5. Sediment basins above and below the CP tracks. The first basin and the tracks were overrun.

3 CREATION OF A 3D SURFACE MODEL

CP conducted helicopter surveys of the site on 11 and 31 July, and again in September and October of 2014. Photos collected during these surveys were suitable for oblique aerial photogrammetry (OAP) processing. The photos were used to create detailed 3D surface models of the glacier, the failure area, and the runout, using the 'structure from motion' approach to photogrammetry, available in the commercial software package 'Photoscan' by AgiSoft. The first detailed 3D model was generated less than 48 hours after the failure, and involved only a few hours of computer processing of approximately 100 photos. After registering the model approximately, using ground control data from a site plan, we could directly measure the failure volume (approximately 90,000 m^3), and compare relative elevations of key hydrological features, such as the water surface elevation in the post-failure supraglacial lake, and the outlets observed along the failure surface.

Subsequently, aerial LiDAR (ALS) data were collected by the University of Northern British Columbia between the 11 and 31 July surveys. The ALS could then be used for 3D registration and georeferencing of the OAP models. An iterative closest point best-fit alogorithm available in the freeware 'Cloud Compare' was used to do this. Using this same approach, we co-registered the September and October OAP data, and compared them quantitatively, and in 3D, to observe any changes that may have occurred around the failure surface in the intervening months. Figure 6 shows the 3D model from October 2014, with an inset showing the detected model differences between then and July 31. In this case the subjective limit of detection is approximately +/- 0.5 m. Small areas of positive change were observed which seem to correspond to snow accumulation; areas of negative change within the failure area may include both further failure of discrete ice chunks, erosion of the outlet channels, and presumably some melt. No large bulk displacements (greater than 0.5 m) were detected, although smaller movements could have occurred.

The 3D model assisted in the quantification of the ice fall volume, the volume lost from the lake, and the geometry for the stability analysis. The use of OAP change

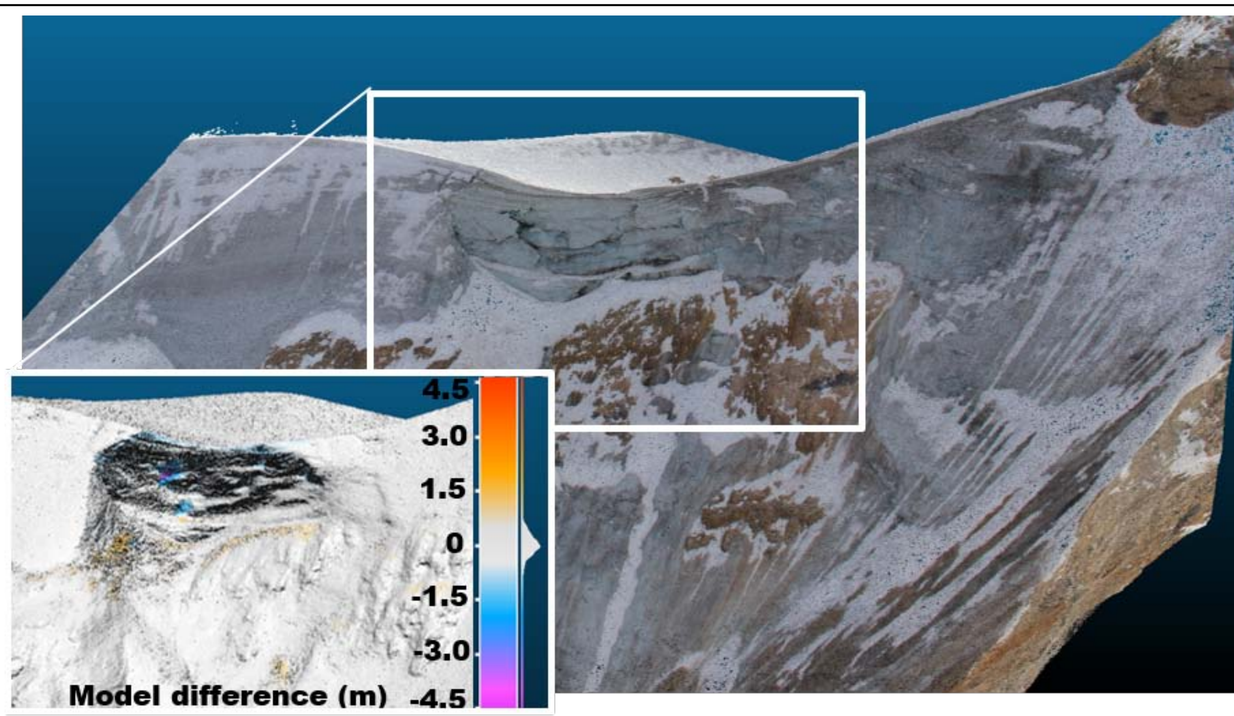

Figure 6. Oblique view of the 3D OAP model from October, 2014, showing measured differences compared to 31 July. Detection limit is approximately +/- 0.5 m. Note areas of loss of ice within the failure area.

detection provided quantitative assurance that the glacier remained stable following the initial event despite the identification of numerous cracks in the north face and failure scar. Only since employing OAP and 3D processing has CP had the ability to quantify these parameters this quickly at such a low cost.

4 GLACIER STABILITY ASSESSMENT

Following the event, two sets of stability assessments were carried out. An initial assessment was performed to evaluate the immediate hazard from Cathedral Glacier. This was followed by a more detailed stability assessment to evaluate future hazards and provide guidance for mitigation measures.

Based on the observations made and discussed above, the following chain of events was likely responsible for the failure of the ice and the debris flow, which is illustrated in a before and after sketch of the failure zone in **Figure 7**:

1. A supraglacial lake is present behind the ice ridge and in the depression. The main source of the water is likely melt water of snow and firn (old snow from the previous year(s) from Cathedral Glacier.

2. Water is connected through a system of intraglacial and subglacial meltwater channels to a vertical crack that opened at the top of the bedrock ridge covered by the glacial ice.

3. As the water level in the lake rises, the hydrostatic pressure on the ice wedge and/or the bedrock-ice interface increases. The ice wedge then failed due to a combination of various contributors: increase in water pressure at the back of the ice wedge and/or its base (i.e., the driving force) and the decrease in the resisting force of the ice wedge caused by :

i) warming of the ice-bedrock interface;

ii) build-up of hydrostatic pressure at the base of the failure surface.

iii) general reduction in the length of the ice-bedrock interface due to thinning and melting of the ice wedge, reducing the frictional resistance, and

iv) reduction in tensile resistance at the top of the vertical crack due to its expansion.

4. Failure of the ice wedge allowed water from Cathedral Glacier to drain as an outburst flood, triggering the debris flow.

5. The ice bridge, that separated the supraglacial lake from the subglacial lake, collapsed and a new, larger glacier lake formed on the subglacial bedrock, now mostly surrounded by ice. The water from this lake could likely drain freely through a network of subglacial channels that had previously formed under the ice ridge.

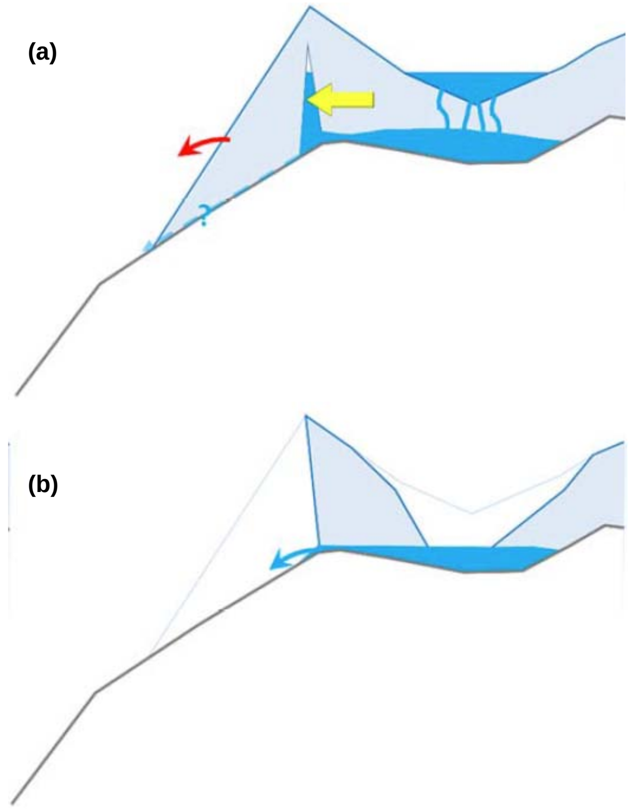

Figure 7. Schematic sketch of the cross section through the centre of the ice failure before (a) and after (b) the failure event. The yellow arrow indicates the direction of hydrostatic pressure that built up behind the ice face. The red arrow shows the direction of ice fall movement.

For the short-term it was then suggested that in the absence of a lengthy cold weather period, the subglacial channel system would remain open through the remainder of the summer, allowing free drainage of melt water and precipitation into Cathedral Gulch. These initial suggestions were confirmed and no rapid drainage event occurred during summer 2014.

A more detailed slope stability analysis was carried out to evaluate the long-term stability. Similar to Figure 7, an ice wedge model was used for a planar wedge slope stability assessment. With information collected immediately after the failure, pre-failure conditions in terms of the ice ridge geometry and lake level could be established and used to calibrate strength parameters at failure.

The cohesion between the ice and bedrock was determined via back-analysis. It was further determined that the uplift caused by water pressure under the wedge likely exceeded the weight of the ice block. Therefore normal force and frictional resistance was zero. Hence, the stability of the ice block depended on the cohesion between the ice and the bedrock alone. Under these assumptions, the cohesion was 90 kPa, which seemed reasonable compared to Davies et al. (2000; 2001; 2003), who reported cohesions between 54 kPa and 115 kPa in combination with frictional coefficients of 0.20 to 0.27.

It is important to recognize that the actual ice fall failure surface was part ice and part rock. Hence, the sub-glacial water may not have affected the entire failure surface, but was likely localised in sub-glacial channels. As such, the calculated 90 kPa cohesion is representative of an average cohesion over the entire failure surface. Where water was flowing along the bedrock-to-ice interface it would be zero but higher where ice was frozen to the bedrock.

Using the back-calculated cohesion, the stability of the remaining ice wedge as a function of the supraglacial lake level was determined. The remaining, approximately 53 m wide ice wedge showed a factor of safety against sliding at the ice-to-bedrock interface above 3 for conditions following the GLOF. Those conditions are expected to continue as long as the water level remains at an elevation of about 2902 m. As the water level increases and a hydrostatic pressure starts to build behind the ice wedge, the factor of safety against sliding will decrease. Even though the water level is the dominating factor that controls the sliding hazard, the ice wedge width also must be considered as it provides resistance against the hydrostatic pressure.

5 FREQUENCY-MAGNITUDE ANALYSIS OF THE GLOFS

A frequency-magnitude analysis assesses how often debris flows occur and how large they can become. Frequency can be expressed either as a return period or an annual probability of occurrence. Frequency and magnitude (volume and peak discharge) of flows and debris flows are inversely related.

To analyse debris flow frequency we applied the magnitude-cumulative frequency (MCF) technique (Gutenberg and Richter, 1954). An inventory of debris flow volumes of known dates in a given time interval T_i is ranked from largest to smallest. The incremental debris-flow frequency of rank i is determined as $1/T_i$ and the MCF then states the cumulative incremental frequencies. The MCF curve is then produced by plotting the annual debris-flow frequency of an event of greater than a certain volume against that volume.

The use of MCF assumes that all events are known, and volumes can be combined in reasonable volume classes, or that the dataset is stratified into classes where confidence exists that all such events have been included. The MCF technique is sensitive to the number of events as adding events will invariably decrease the individual return periods for events smaller than those newly added. It is suited for situation where there is confidence that all events have been recorded during a specific time window.

In recognition of different data populations, the MCF method was applied to the events thought to be rain-fall generated and those that were assumed to be GLOF-generated debris flows. The decision as to the triggering mechanism was based largely on the literature (Jackson, 1979, 1980 and Jackson et al. 1989 as well as CP's records that referred to the most likely triggering mechanism). A logarithmic function was fitted to the data. Errors of up to 30% for such volumetric estimates can be expected but are not shown.

Figure 7 indicates that for a given volume, GLOF-triggered debris flows are more common than non-GLOF debris flows. Based on information from CPR, the design capacity of the debris basin upstream of the mainline is 30,000 m^3. Table 1 indicates that nearly six GLOF-triggered debris flows of this size would occur for every one non-GLOF-triggered debris flow and that the projected design capacity will capture GLOFs for return periods well below that of non-GLOFs.

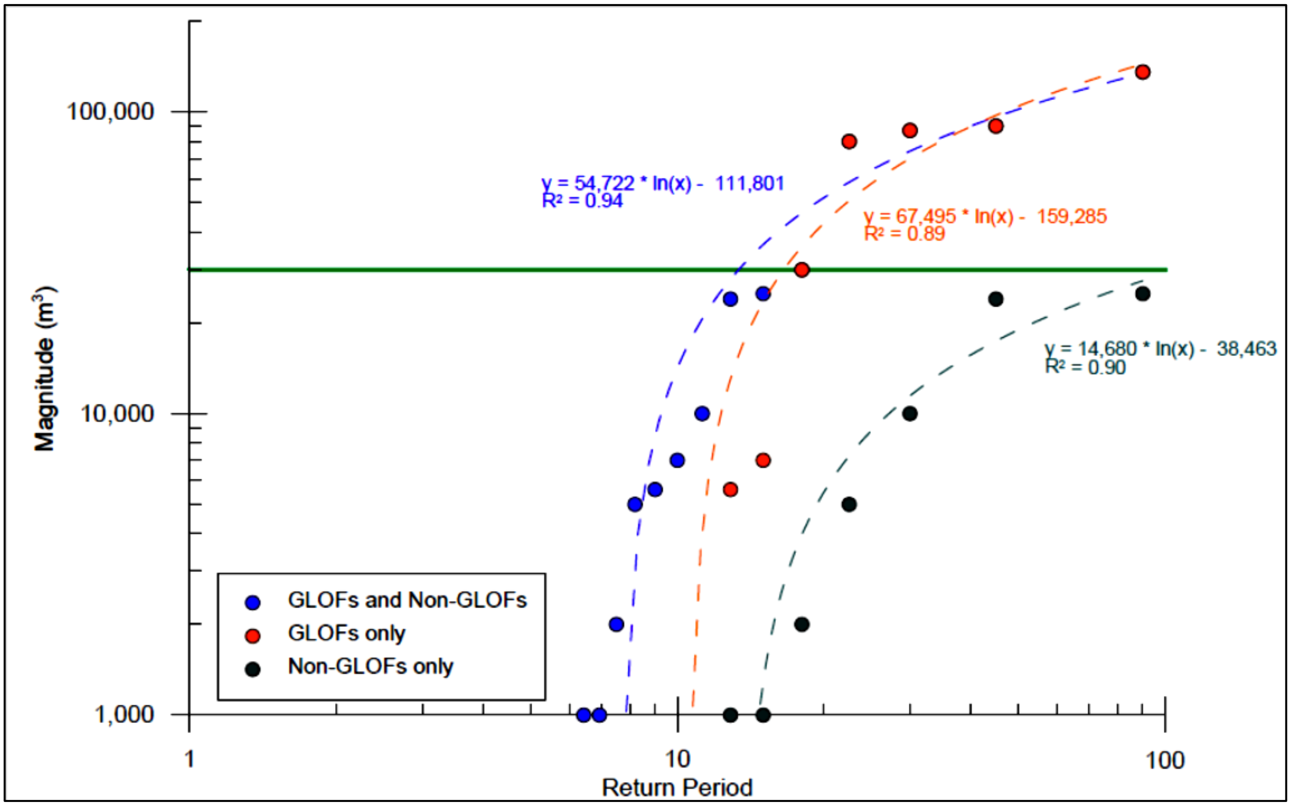

Figure 8. Magnitude-cumulative frequency (MCF) curves for Cathedral Gulch debris flows. The green line at a magnitude of 30,000 m^3 identifies the designed capacity of the upper debris basin.

Table 1 Return periods for different debris-flow triggering mechanism for a design storage volume of 30,000 m^3.

Triggering Process	Return Period (years)
GLOFs and Non-GLOFs	13
GLOFs	17
NON-GLOFs	100

6 CONCLUSIONS

The work summarized in this paper is important for four reasons. First, it highlights some new techniques that can be employed rapidly to assess hazards to an infrastructure that cannot be shut down for extended periods of time to await detailed study. Such methods rely on remote sensing paired with simplifying assumptions on the geotechnique of the geomorphic system under consideration. Second, the glacial stability analysis was used to assess the relationship between water level in the supraglacial lake and the stability of the remaining ice. This was used to monitor the potential of further GLOF through the 2014 construction season. Third, the MCF analysis was used by CP to establish the design capacity of the expanded debris flow basin capacity above the upper track such that it would capture debris flows between 10 and 20 year return period for GLOF-triggered debris flows and approximately 100 year return period for non-GLOF-triggered debris flows.

Fourth, this event while isolated, could be symptomatic for other such events which appear to be occurring more frequently. An ice fall and outbreak flood from Ghost Glacier at Mount Edith Cavell (Quinn et al. 2014) in August of 2014 may also have been triggered by climatic amelioration in a zone that is at least partially underlain by permafrost. Increasing melt rates due to an upward trend in air temperatures and the thickening of the seasonally unfrozen active layer through progressive permafrost degradation could lead to a further increase in ice falls as well as rock falls and rock slides in the Canadian Rocky Mountains. A deepening of the active layer could also provide additional debris that can be entrained during debris flows. Careful documentation of such events is recommended as it may affect railways, highways and other infrastructure in the future.

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