Ghost-busting: Risk Response following the Ghost Glacier failure, Mt. Edith Cavell, Jasper National Park

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ABSTRACT

An ice avalanche fell from Ghost Glacier on Mount Edith Cavell in Jasper National Park during the night between 9 and 10 August, 2012. It displaced water from a glacier tarn and caused significant damage to park facilities. The timing of the event, outside normal park use hours, ensured no casualties occurred, however, had the event occurred during the day, many park visitors would have been exposed to the outburst flood that washed out a high use hiking trail and buried the picnic area. Parks Canada commissioned a hazard and risk assessment following the event. This paper describes the assessment and discusses the evaluation, selection and implementation of risk mitigation measures. A companion paper in this conference discusses the event and the initial emergency response.

Résumé

Une avalanche de glace est tombé de Ghost glacier sur le mont Edith Cavell dans le parc national Jasper pendant la nuit entre 9 et 10 Août 2012, causant des dommages importants aux installations du parc. Le moment de l'événement, en dehors de la durée normale d'utilisation du parc, assuré sans faire de victimes ont eu lieu, cependant, a eu l'événement s'est produit au cours de la journée, de nombreux visiteurs du parc auraient été exposés à la débâcle qui a lavé une forte utilisation sentier de randonnée et enterré le pique-nique zone. Parcs Canada a commandé une évaluation des dangers et des risques après l'événement. Ce document décrit l'évaluation et examine l'évaluation, la sélection et la mise en œuvre de mesures d'atténuation des risques. Un document d'accompagnement à cette conférence traite de l'événement et la réponse d'urgence initiale.

1 INTRODUCTION

This paper discusses a geohazard risk assessment completed in response to an ice avalanche and outburst flood in August 2012 at Mt. Edith Cavell in Jasper National Park. The paper also discusses the selection of risk mitigation measures. A description of the event and the initial response is provided in a companion paper by Wedgwood (2014).

BGC Engineering Inc. (BGC) was commissioned by Parks Canada (PC) to develop a "risk zones map," to aid in the future management of visitor safety in the area. The scope of the investigation included a broad range of plausible geohazards, including ice avalanche, snow avalanche and landslides (e.g. rock slides, rock avalanche), as well as associated secondary hazards, including air blast or outburst flood. Figure 1 shows the conceptual distribution of these geohazards in the study area, and shows the risk assessment corridor in the valley bottom, where park visitors may be present in areas affected by geohazards.

A number of interesting questions presented themselves during the work, and the following are examined in this paper:

- What geohazards dominate the risk, and where, when and how do they occur?
- What level of risk, in this setting, can be considered "tolerable" or "acceptable?"
- What combination of risk mitigation measures strikes a practicable balance between risk, cost, and use of the area?

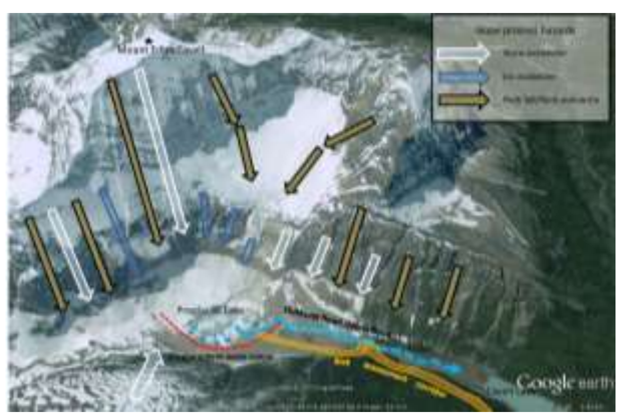

Figure 1 Conceptual illustration of primary geohazards affecting Mt Edith Cavell day use area.

2 HAZARD ASSESSMENT

2.1 Geohazard Risk Assessment Framework

The geohazard risk assessment completed for this study used a semi-quantitative approach. The hazard frequency and expected consequence were quantified, and risk was expressed as a combination of hazard and consequence using qualitative descriptors ranging from Very Low to Very High.

The hazard areas are shown in Figure 2, and Figure 3 shows the risk evaluation matrix used in the work and consequence assessment to determine a risk rating. The probability of the undesirable outcome and the severity of the consequence define an intersection point in the matrix that ranks the risk scenario from Very Low to Very High.

The top five rows of the risk evaluation matrix in Figure 3 present suggestions for risk evaluation and response. These are intended to guide the possible responses by the owner to each risk level. These recommended actions presume the adoption of risk tolerance criteria consistent with the actions, and were based on experience with other types of projects, clients, and elements at risk. Ultimately, the determination or “acceptable” or “tolerable” risk is a societal one, not a technical one, and requires input from the Owner (PC in this case) and affected stakeholders.

The question of risk tolerance criteria is of critical importance, as it drives decisions on risk response. Risk tolerance is a social decision, not a technical one. Geohazard experts can estimate risk based on their expertise and available evidence, but those exposed to the risk must then decide what risk can be tolerated, and this may vary in different circumstances.

In examining the risk evaluation matrix, one can see that an annual probability of 10^{-4} for a single fatality is considered “Low” risk, which implies the risk is “tolerable,” but not “broadly acceptable.” Geohazard scenarios in this risk category are suggested for monitoring and, if practicable, further measures to reduce risk. This corresponds roughly to individual risk and group risk tolerance criteria used in some jurisdictions (e.g. Hong Kong, Australia, District of North Vancouver). However, there are no known risk tolerance criteria for recreational users of wilderness areas, including national parks. These criteria were used by PC as a starting point to guide decision making, rather than a compulsory standard.

2.2 Geohazard Assessment

The project site is affected by several geohazard processes, some of which can trigger additional hazardous processes. The spatial and temporal distributions of these geohazards vary across the study area, which was subdivided into three assessment areas as shown in Figure 2: Lake Area (around Cavell tarn); Loop Trail (Path of the Glacier hiking trail); and Parking and picnic area.

The geohazard assessment was completed on the basis of available desktop information, investigation data provided by PC, and a very brief site visit in November 2012 with 0.3 to 0.5 m snow cover obscuring ground features. Additionally, a low ceiling limited visibility of the upper slopes and prevented a helicopter overflight above Angel Glacier. Hazard frequencies discussed in the following paragraphs have been estimated from available information using consensus judgment of the technical team.

Table 1 provides a general framework for describing the various primary and compound hazards at Mount Edith Cavell, and also indicates the areas of the site affected by the respective hazards. The following paragraphs provide a brief discussion of the various geohazards examined in this assessment, which included, generally:

- Rock fall, rock slide and rock avalanche;
- Snow avalanche;
- Ice fall and ice avalanche;
- Moraine dam failure;
- Compound hazards, including:
    - Air blast,
    - Impact wave,
    - Outburst flood and debris flow / flood.

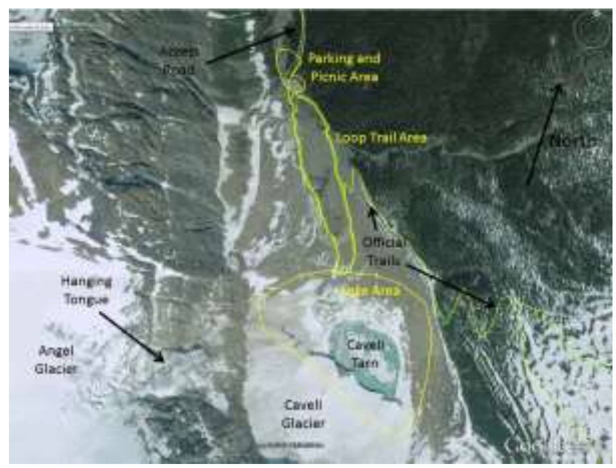

Figure 2 Geohazard assessment areas (three areas outlined in yellow).

Sturzenegger and Stead (2009) presented summary data with orientations of bedding and major joint sets for the east face of Mount Edith Cavell, as observed through limited field mapping and ground-based remote-sensing techniques (i.e., LiDAR and photogrammetry). Their data were interpreted for analysis of kinematically feasible failure mechanisms. This analysis suggests the potential for wedge failure for near vertical blocks, with failure potential depending on the orientation (aspect) and slope angle of the rock face. Examples of old failures of this type are evident along the rock face above Cavell tarn, as illustrated in Figure 4.

Extensive scree / talus slopes mantling the base of the valley wall suggest that rock fall is common along the steep rock face of the west valley wall. The extent of rockfall impact is generally limited to the footprint of these talus deposits, although individual blocks could roll some distance further. An existing lateral moraine that extends from the day use parking lot to the valley wall to the southwest (Figure 5) catches rock fall debris from west of the moraine. Additional rock fall may initiate from the east slopes of that moraine as individual blocks detach from the fine grained moraine matrix. Additional rock fall may also initiate along the steep, west-facing moraine immediately east of the Cavell tarn. Areas potentially affected by episodic rock fall are illustrated in Figure 6.

Likelihood Descriptions and Indices (Likelihood of Negative Outcome)

Risk Evaluation and Response		
VH	Very High	Risk is imminent; short-term risk reduction required; long-term risk reduction plan must be developed and implemented
H	High	Risk is unacceptable; long-term risk reduction plan must be developed and implemented in a reasonable time frame. Planning should begin immediately
M	Moderate	Risk may be tolerable; more detailed review required; reduce risk to As Low As Reasonably Practicable
L	Low	Risk is tolerable; continue to monitor and reduce risk to As Low As Reasonably Practicable
VL	Very Low	Risk is broadly acceptable; no further review or risk reduction required

Likelihood Descriptions	Indices		Annual Probability Range	1	2	3	4	5	6
Event can reasonably be expected to occur at least once per year	A	Very Likely	>0.9	M	H	H	VH	VH	VH
Event typically occurs every few years	B	Likely	0.1 to 0.9	L	M	H	H	VH	VH
Moderate chance of event occurring within ~ 30-50 years	C	Moderate	0.01 to 0.1	L	L	M	H	H	VH
Event unlikely to occur within ~ 30-50 years	D	Unlikely	0.001 to 0.01	VL	L	L	M	H	H
Event very unlikely to occur within ~ 30-50 years	E	Very Unlikely	0.0001 to 0.001	VL	VL	L	L	M	H
Event is possible but is extremely unlikely to occur within ~ 30-50 years	F	Extremely Unlikely	<0.0001	VL	VL	VL	L	L	M

Consequence Descriptions and Indices						
Indices	1	2	3	4	5	6
	0.0001	0.001	0.01	0.1	1	10
	Incidental	Minor	Moderate	Major	Severe	Catastrophic
Safety	Minor first aid incident (e.g. minor cut)	Minor first aid incident requiring clinic visit (e.g. deep cut, sprain)	Moderate injury requiring hospital visit (e.g. broken bone)	Serious injuries (1 - 2) requiring hospitalization	Multiple serious injuries (> 2); public fatality	multiple fatalities

Figure 3 Risk evaluation matrix.

Table 1. Geohazards framework.

Primary Hazard	***Affected Location(s)***	***Potential Compound Hazards[1]***		
Rock Fall	Lake area Loop Trail Parking and picnic area	N/A		
Rock Slide, Rock Avalanche		Air blast Impact wave	Outbreak flood	Debris flow /debris flood
Snow Avalanche		Air blast Impact wave	Outbreak flood	Debris flow / debris flood
Ice Avalanche		Air blast Impact wave	Outbreak flood	Debris flow / debris flood
Moraine Dam Failure	Loop Trail Parking and picnic area		Outbreak flood	Debris flow / debris flood

Notes: 1. Compound hazards apply only to large rock slide, rock avalanche, ice avalanches or large snow avalanche and are, to some degree, dependent on the Cavell tarn water level at the time of the geohazard occurrence.

Figure 6 shows that rock fall hazards do not reach either the Loop Trail, or Parking and Picnic Area. A review of available air photos dating to the late 1940s shows no evidence of rock slides with volumes greater than approximately 500 to 1,000 m^3. The existence of wedge shaped scarps in the rock face suggests that larger rock slides may have occurred in the past, and thus are considered plausible hazards. Rock fall, rock slide, and rock avalanche events have been grouped into three broad categories as shown in Table 2, along with estimated approximate annual probabilities. There is considerable uncertainty associated with these probabilities, given the relative lack of direct data available for the analysis. Further, climate warming is expected to change freeze–thaw related rock weathering at higher elevations, and together with permafrost degradation and active layer thickening an increase in rock fall hazard may occur with time (Gruber and Haeberli, 2007). For these reasons, order of magnitude estimates were developed based on consensus judgement.

Figure 4 Typical scarps of presumed past wedge failure (shown with red dashed outline).

Figure 5 Lateral moraine along west valley wall, looking west (top of moraine partially outlined in red).

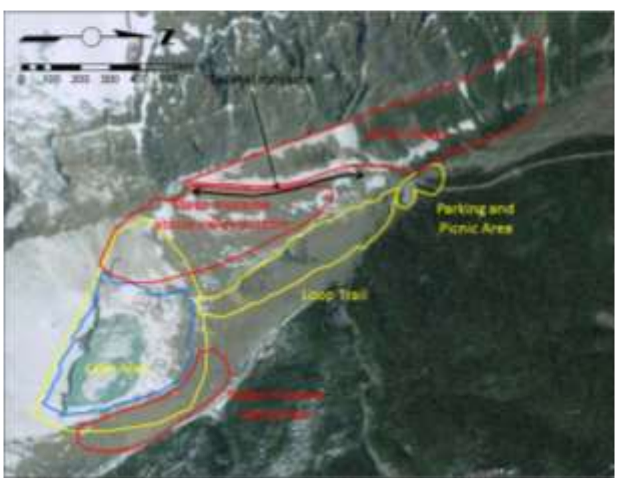

Figure 6 Rock fall hazard zones (in red outline).

Three sizes of snow avalanche are considered in the assessment:

- Small – Size 2, according to the Canadian Avalanche Size Classification (McClung and Schaerer, 2006), with typical mass of 100 t, path length of 100 m and impact pressure of 10 kPa.
- Medium – Size 3, with typical mass 1,000 t, path length 1,000 m and impact pressure 100 kPa.
- Large – Size 4, with typical mass 10,000 t, path length 2,000 m and impact pressure 500 kPa.

Smaller (Size 1) snow avalanches are not expected to pose a risk. Larger (Size 5) snow avalanches could potentially develop in the project area if the entire north face of Mount Edith Cavell released; however, for the purpose of present analysis there is no difference between Size 4 and Size 5 in terms of expected consequence to park visitors, so they are grouped as a single "large" category.

Avalanche paths have been mapped to show runout limits for 1-year, 10-year and 100-year return period events within the area, and these are illustrated in Figure 7. Each of the three assessment areas can be affected by snow avalanches, with estimated annual probabilities for different size events summarized in Table 3.

Table 2. Rock fall / slide / avalanche hazard scenarios.

Rock Fall / Rock Slide / Rock Avalanche Scenario	Estimated Annual Hazard Likelihood, P_H
Rock Fall (< 100 m^3) along west valley wall	0.01 to 1
Rock Slide (< 100,000 m^3) in tarn area	0.001 to 0.01
Rock Avalanche (> 100,000 m^3) in tarn area	< 0.001

Table 3. Snow avalanche hazard probability ranges.

Assessment Area	Snow Avalanche Size	Estimated Annual Hazard Likelihood, P_H
Lake Area	Small (Size 2)	1
	Medium (Size 3)	0.1 to 1
	Large (Size 4)	0.01 to 0.1
Loop Trail	Small (Size 2)	N/A
	Medium (Size 3)	0.01 to 0.1
	Large (Size 4)	0.01 to 0.1
Parking and Picnic Area	Small (Size 2)	N/A
	Medium (Size 3)	0.01 to 0.1
	Large (Size 4)	N/A

Various climate, weather and glaciological factors likely interacted to lead to the potential detachment of an ice mass from Ghost or Angel Glaciers. These factors are summarized in Figure 8 and include:

- Existence of a bergschrund. Figure 9 and shows the bergschrund above the failing mass on Ghost Glacier prior to the August 2012 event. Various bergschrund have been observed along Angel Glacier.

- System of crevasses and moulins. Angel Glacier is highly fractured with crevasses and potential moulins so that infiltration of water to the base is considered very likely. However, the fact that the ice body is segmented by these series of crevasses decreases the size of the blocks that potentially may collapse and fall onto the proglacial area.
- Air temperature regime and precipitation - Warmer air temperatures and the presence of rain will enhance the collection of water which may increase the water pressure.
- Topography and hydrology - Angel Glacier overlies a series of bedrock steps associated with the sub-horizontal bedding of the rock where the ice is located within its hanging terminus. Where the slope changes within the steps, water accumulates and it has been observed that subglacial conduits develop. These conduits can align with a fracture system that has surficial signature on the ice body.
- Orientation of the slope and existence of snow accumulation - Ghost Glacier is located in the northeast facing slopes of Mount Edith Cavell. Above it, along the east ridge cornices develop. If these cornices collapse, they will transport considerable amounts of snow downhill and create impact forces that could trigger the failure of the ice apron.
- Existence of seracs in Angel Glacier - Angel Glacier has a number of seracs (near vertical ice columns) that are continuously changing their appearance since ice flow velocities are often the highest in those areas and seracs are prone to toppling. A large serac at the upper edge of the hanging tongue of Angel Glacier is shown in Figure 10.

Several ice fall scenarios are considered plausible. Figure 11 delineates approximate boundaries of potential failure surfaces in the lower tongue of Angel Glacier, with approximate ice volumes of 75,000 m^3 (lowest block), 250,000 to 300,000 m^3 (lowest two blocks combined) and 700,000 m^3 (entire tongue). These blocks have been selected from a review of available air photos and low oblique photos, and demark transitions in slope of the underlying rock, where water and stresses will concentrate and failure may be more likely to occur. Figure 12 shows plausible failure surfaces in Ghost Glacier, corresponding to volumes ranging between approximately 30,000 and 80,000 m^3. As there is very little glacier ice left on Ghost Glacier, those ice avalanches volumes are related to the failure of firn and ice (aprons) currently frozen to the flanks of Mount Edith Cavell.

Additional sources of ice fall exist along the southern end of Angel Glacier within its cirque where the glacier lies below the steep north face of Mount Edith Cavell, and rock fall or large snow avalanches impacting the glacier could trigger a release of ice. For the purpose of the hazard and risk assessment, ice fall hazards have been divided into three broad categories: small, medium and large. The size boundaries and estimated likelihoods are summarized below in Table 4

The estimated probabilities are highly uncertain, and are based on consensus judgment of the project team. The August 2012 event would fall within the “Medium” ice avalanche category. Only one such event is known in the history of the Mount Edith Cavell day use area. Smaller falls are suspected over the last 100 years, based on photographic evidence. The estimated probability for the large event is speculative, but considered reasonable on the basis of a lack of reported incidents of that size in the Rockies over time.

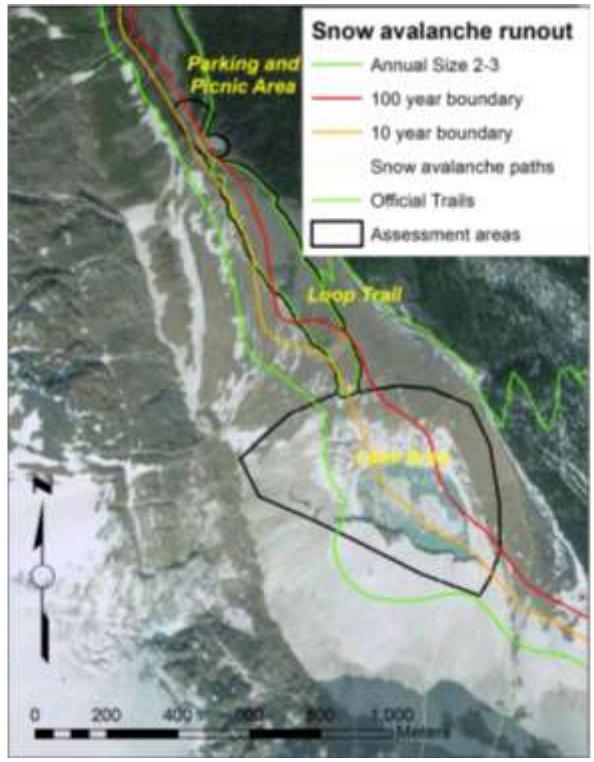

Figure 7 Overview of interpreted snow avalanche hazard areas.

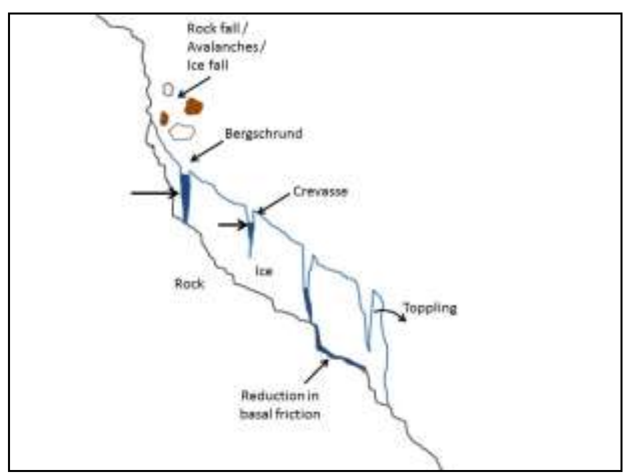

Figure 8 Schematic representation of factors promoting ice avalanches and ice falls.

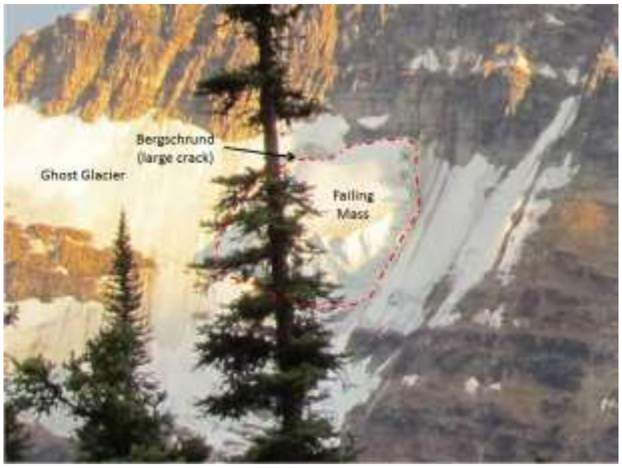

Figure 9 Bergschrund on Ghost Glacier, partly obscured by tree. Photo taken prior to August 2012 ice avalanche event.

Figure 10 Large serac at edge of Angel Glacier.

Figure 11 Ice Fall Scenarios – Tongue of Angel Glacier, looking west.

Cavell tarn is flanked by Cavell Glacier to the southwest, and is dammed to the north by a recessional moraine, a glacial landform spanning across the valley and forming a post-glacial lake. This moraine dam is illustrated in Figure 13, which also shows the one of two deeply incised outlet channels that drains the lake.

The existing moraine dam retaining the tarn could fail over time, either as a result of erosion during overtopping, or due to piping failure resulting from concentrated seepage over time. McKillop and Clague (2007) present a review of moraine dam outburst flood hazard in southwestern British Columbia. They determined from regression analysis of 175 moraine dams that the likelihood of outburst depends primarily on moraine dam geometry.

Moraine dam failure is more probable for higher, steeper moraine dams with large lakes and the absence of an ice core. The moraine sill downstream of Cavell tarn is believed to be unfrozen, however this is not known with certainty. It is expected to be stable due to relatively gradual downstream slope angle (typically 10 % or less) and relatively low height of impounded water. We interpret a very low probability of outburst due to natural failure of the moraine dam, and assign an estimated annual probability of 0.005 to 0.001 for this specific hazard scenario. Failure of the moraine dam would lead to the compound hazard of an outbreak flood.

Figure 12 Ice Fall Scenarios – Ghost Glacier.

Table 4. Ice fall / avalanche hazard probability ranges.

Ice Fall / Ice Avalanche Scenario	**Estimated Annual Hazard Likelihood, P_H**
Small (< 100,000 m^3)	0.01 to 0.05
Medium (> 100,000 m^3 and < 300,000 m^3)	0.001 to 0.005
Large (> 300,000 m^3)	< 0.001

Several primary hazards may result in second and third order effects, and may thus be classified as compound hazards. Ice or rock fall from significant height above the tarn will achieve high terminal velocities. This can result in an air blast occurring coincident with impact (see, e.g., Wieczorek et al. 2000). Effects of an air blast in the August 2012 ice avalanche event were observed by PC staff, and a typical example of a wind-blown tree is shown in Figure 14.

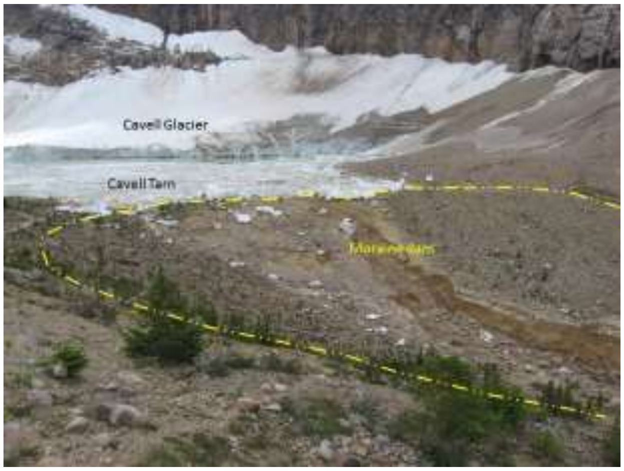

Figure 13 Moraine dam at north edge of Cavell Tarn.

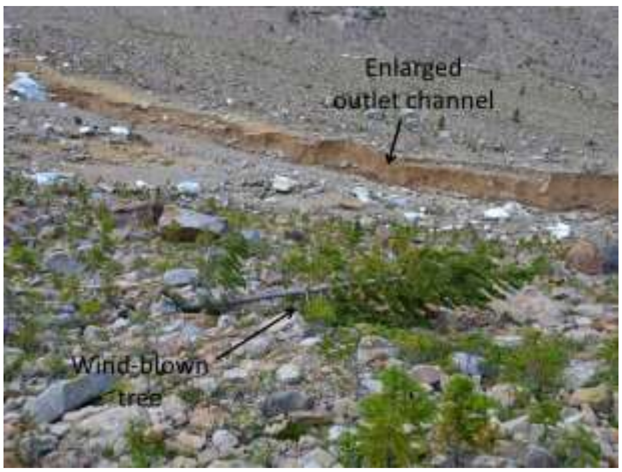

Figure 14 Air blast effects near Cavell tarn – uprooted tree.

The potential damaging effects of air blast due to ice avalanches and large landslides have been documented by Petrakov et al. (2007) and Wieczorek et al. (2000). While the extent and specific effects of such an air blast are difficult to predict, it is expected that an air blast will occur in conjunction with any size ice avalanche, a large (i.e. size 4) snow avalanche, or a rock avalanche, and will potentially affect the entire Lake Area, with spatial extent to be proportionally larger for larger events. The occurrence of an air blast is therefore assumed to be included in the occurrence of these events in the risk analysis.

It may be noted that the damage associated with air blast is expected to be minor, relative to that from impact by falling rock, ice or snow, or from direct impact by an impact wave or outbreak flood. In the cases examined by Wieczorek et al. (2000), the damaging effects to human health have generally been limited to injury, with no fatalities reported, even in the case of major disasters (e.g. Goldau slide in Austria of 1806, which caused over 450 fatalities, none of which was attributed to the air blast. The potentially damaging effects of an air blast are therefore expected to be less serious than those of other second or third order geohazards.

Impact of a large falling mass, such as that due to ice avalanche, rock slide, rock avalanche or large snow avalanche, can generate a wave that would travel across the Cavell tarn and run up on the opposite bank. The lack of ice blocks above the high water mark or rill erosion from water rushing back into the lake suggests the absence of any significant impact wave due to the August 2012 ice avalanche. It is postulated that the absence of a significant wave is due to the fragmented nature of the ice mass when it reached the valley bottom so that impact would have occurred over some finite duration, rather than instantaneously. This implies that the water level in the tarn was raised by the addition of a large volume of ice and then overflowed the sill which is evidenced by stranded ice blocks at that location (Figure 15).

Figure 15 Limits of disturbance or ice displacement around and at outlets of Cavell tarn.

The August 2012 ice avalanche was back-analysed to determine appropriate rheological factors for use in forward analyses, and these have been used to estimate the height and runup of potential future waves generated by ice avalanches from the tongue of Angel Glacier. The analyses were conducted using the commercial runout analysis software DAN-W (Hungr, 1995), and empirical wave generation equations presented by Heller et al. (2009).

Preliminary material parameters were selected for parametric analysis based on previous experience analyzing ice-on-rock and rock-on-ice events. A range of turbulence and friction coefficients were trialled and compared to back-analysed ice avalanches, using a range of assumed ice volumes. The best fit parameters were used to analyse three potential ice avalanche scenarios from Angel Glacier: small (75,000 m^3), medium (250,000 m^3) and large (700,000 m^3). The calibrated parameter values are consistent with values used by McDougall et al. (2006) to back-analyze the 2002 Zymoetz River rock slide-debris flow, which entrained snow in the proximal path, by Evans et al. (2008) to back-analyze the 2002 Kolka Glacier ice avalanche, and by

Tamburini et al. (2011) to back-analyze the 2007 Monte Rosa rock avalanche, which ran out onto glacier ice.

The results indicate the impact waves associated with this range of events could run up approximately 5 m, 20 m and 30 m for the small, medium and large events, respectively. The approximate extents of wave run up are shown in Figure 16. These limits may be taken as upper limits for the indicated events, as they assume the ice mass to fall in one block and remain largely intact until impact, neither of which is likely to be the case.

The probability of occurrence of an impact wave of significant height is lower than that of the initiating event, since its occurrence depends on lake levels to be high, and the ice to impact the lake intact. The occurrence of the impact wave is included in the hazard and risk analysis as part of the occurrence of the initiating event, being a snow, rock or ice avalanche.

The August 2012 ice avalanche caused an overtopping event that led to channel erosion in its two outlet channels and subsequent debris deposition in the vicinity of the parking lot and picnic area. Figure 15 shows the moraine dam the day following the ice avalanche, with water draining the lake via the two outlet channels. The maximum extent of the peak flood that overtopped the moraine dam can be inferred from the presence of ice blocks and subtle differences in texture and colour. The east channel on the bottom of the photo widens substantially at the edge of the photo.

The lake level was slightly higher than the inverts of its two draining streams on 10 August, and lake levels dropped rapidly in the following weeks. Water levels had dropped 8 to 10 m by end September, and up to 11 to 12 m by the time the lake had frozen over in mid-October.

High velocities in the outbreak flood, combined with moderately steep (approximately 10 %) channel gradients and channelized flow, resulted in significant erosion and entrainment of debris in the uppermost reaches of the two outlet channels, up to and beyond the point of their convergence at the toe of the moraine dam, where the valley bottom widens, resulting in a wider cross section and lower flow velocities. Flow in the middle reach of the valley, between the toe of the moraine dam and head of the alluvial fan beginning at the parking lot, is believed to have witnessed no net gain or loss of sediment. Post-peak flows are shown in Figure 18, which also shows the maximum extent of the peak flood in mud marks on the parking lot pavement. Debris deposition initiated at the head of the fan in the picnic area, and extended to Cavell Lake.

A significant proportion of the lower part of the Loop Trail was inundated by the flood and destroyed. The flood depths along the trail associated with that event, assumed to have been a “medium” size event (i.e. greater than 100,000 m^3), ranged up to about 4 m near the tarn, and 1 to 2 m further down valley. It may be noted that significant lengths of the lower Loop Trail rise along the valley side slopes, and were thus not affected by the flood.

The extent of a potential future outbreak flood has been inferred from available information, including photographs taken after the event, available stereo air photos and topographic data. The middle reach of the valley, between the toe of the moraine dam and the parking lot, is U-shaped and, is bounded on either side by a distinct break in slope and steeper valley walls, and is comprised of coarse glacial sediments (i.e. lateral moraine), as shown in Figure 19. This natural break in slope confines a potential flood through this reach of valley; however, this geometric constraint does not exist beyond the parking lot, where the valley bottom abruptly widens.

Figure 16 Inferred maximum extent of wave runup across Cavell tarn due to small, medium and large ice avalanches from the tongue of Angel Glacier.

The extent of a potential future outbreak flood has been inferred from available information, including photographs taken after the event, available stereo air photos and topographic data. The middle reach of the valley, between the toe of the moraine dam and the parking lot, is U-shaped and, is bounded on either side by a distinct break in slope and steeper valley walls, and is comprised of coarse glacial sediments (i.e. lateral moraine), as shown in Figure 19. This natural break in slope confines a potential flood through this reach of valley; however, this geometric constraint does not exist beyond the parking lot, where the valley bottom abruptly widens.

The approximate extent of the outbreak flood associated with the maximum possible initiating event (i.e. 700,000 m^3 ice avalanche coinciding with full lake) has been inferred from air photo interpretation and is estimated as being approximately 5 m wider than the August 2012 peak flood, which would correspond to a peak flood height of about 2 m higher, and thus significantly greater peak flow. Beyond the start of the parking area, the potential peak flood has been inferred as extending across the full width of the head of the alluvial fan, thus overlapping part of the parking lot, picnic area and access road. The inferred boundaries are imprecise, due primarily to a lack of high quality topographic data.

The probability of occurrence of an outbreak flood is proportional to the hazard probability for the initiating primary hazard, being potentially ice avalanche, large snow avalanche or rock avalanche. The lake level fluctuates, and therefore the probability of an outbreak flood varies seasonally. Figure 17 shows the approximate shape of the Cavell tarn, as inferred from basic bathymetric survey data from PC. These data have been used to infer lake storage versus water level, as shown in the right side of the same Figure. It can be seen that displacement due to an event of 100,000 to 200,000 m^3 would result in lake levels rising about 1 to 2 m. It is therefore inferred that the lake must have been full, or nearly full, in early August 2012, and this is consistent with records of recent heavy rainfall, and recollections of PC staff from observations shortly before the event. It may also be inferred from this figure that an outbreak flood due to displacement of water by ice would not have been possible if the lake had been more than 2 m lower than the rim of the moraine dam unless it had impacted in few intact large ice fragments which could have led to a significant wave overtopping the moraine sill.

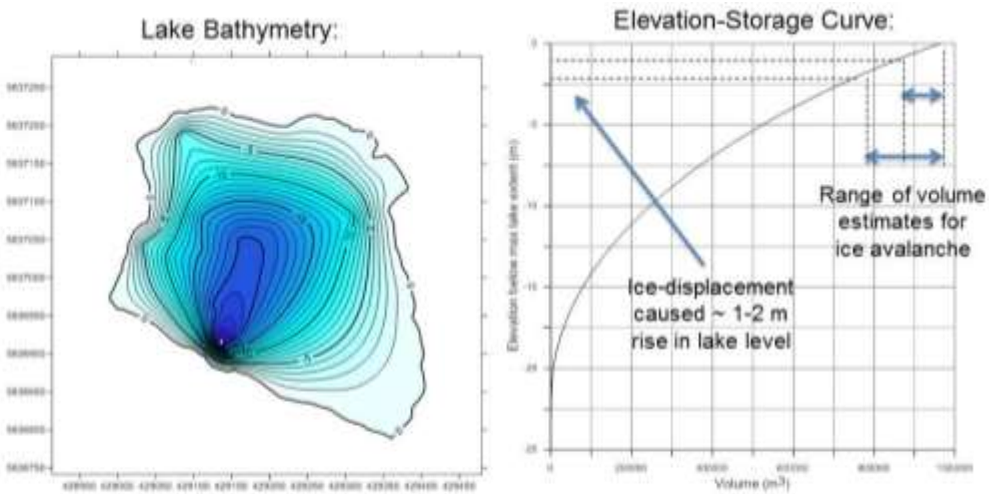

Figure 17 Inferred potential lake level rise associated with August 2012 ice avalanche event. Lake bathymetry inferred from basic water level survey at left. Elevation-storage curve and interpreted displacement effects at right.

Figure 18 Flood levels on 10 August, the day following the outbreak flood, looking north toward Cavell Lake.

Figure 17 shows the potential lake level rise associated with the maximum credible initiating event, a 700,000 m^3 ice avalanche, corresponding to the sudden release of the entire tongue of Angel Glacier. This event would raise lake levels by roughly 9 m. In contrast, when lake levels are more than 9 m below peak, as appears to be the case in a typical fall and winter, the probability of a significant outbreak flood is lower, even in the case of the maximum credible ice avalanche. The conditional probability of a potential initiating event that occurs during the summer visitor season also occurring during sufficiently high lake levels is estimated to be approximately 0.5 to 0.9, depending on the magnitude of the initiating event. Therefore, the temporal probability of visitor presence during various outbreak flood scenarios is modified by a factor ranging between 0.5 and 0.9.

Figure 19 Geometric confinement of potential flood extent in middle reach of valley showing the approximate extent, in red, of a maximum credible flood.

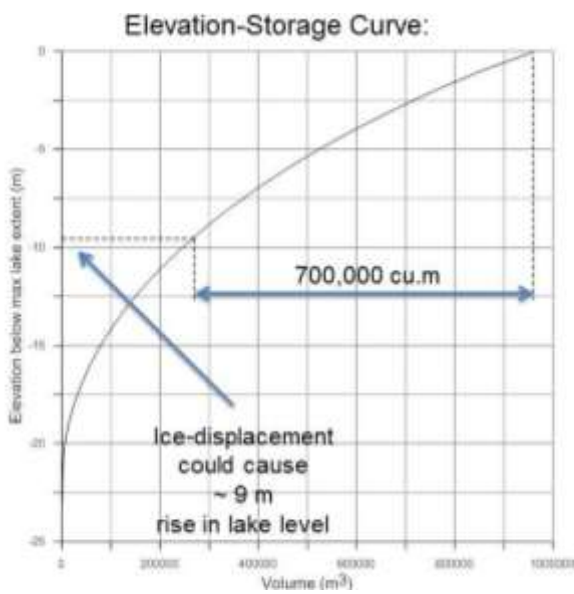

Figure 20 Potential lake level displacement associated with maximum possible ice avalanche (700,000 m^3).

3 RISK ASSESSMENT

3.1 Geohazard Scenarios

A broad range of credible geohazard scenarios were considered and are summarized below in Table 5. The hazard scenarios are based on particular assessment area locations. The consequences only consider safety losses, specifically the potential for park user fatalities.

The risk estimates consider the baseline "unmitigated" case, assuming current conditions. This is a necessary assumption to estimate geohazard risk for the purpose of prioritizing mitigation measures. Park visitors are assumed to be walking or sitting outdoors. The risk estimates consider hikers and other "typical" park visitors. It does not consider visitors who engage in inherently riskier activities like rock climbing, mountaineering and back country skiing, activities that are associated with voluntary risk and to which higher risk tolerance thresholds might be considered to apply.

Table 5. Geohazard scenarios considered in the analysis.

Hazard Index	Hazard Scenario
Lake Area	
LA-01	ice avalanche small (< 100,000 m^3), including air blast and flood wave
LA-02	ice avalanche medium, including air blast and flood wave
LA-03	ice avalanche large (> 300,000 m^3), including air blast and flood wave
LA-04	direct impact - snow avalanche small (size 2)
LA-05	direct impact - snow avalanche medium (size 3)
LA-06	direct impact - snow avalanche large (size 4)
LA-07	fragmental rock fall
LA-08	rock slides (< 100,000 m^3) including air blast and flood wave
LA-09	rock avalanche including air blast and flood wave
Loop Trail Area	
LT-01	outburst flood from ice avalanche small
LT-02	outburst flood from ice avalanche moderate
LT-03	outburst flood from ice avalanche large
LT-04	outburst flood from snow avalanche large (size 4)
LT-05	direct impact - snow avalanche medium (size 3)
LT-06	direct impact - snow avalanche large (size 4)
LT-07	outburst flood from medium rock slide
LT-08	outburst flood from rock avalanche
LT-09	moraine dam outbreak flood
Parking and Picnic Area	
PP-01	outburst flood from ice avalanche small
PP-02	outburst flood from ice avalanche moderate
PP-03	outburst flood from ice avalanche large
PP-04	outburst flood from snow avalanche large (size 4)
PP-05	direct impact - snow avalanche medium (size 3)
PP-06	outburst flood from med rock slide
PP-07	outburst flood from rock avalanche
PP-08	moraine dam outbreak flood

The likelihood of an undesirable outcome is taken as the annual probability of occurrence of the hazard, P_H. The vertical axis in Figure 3 defines categories used for likelihoods of an undesirable outcome, based on the product of the probabilities listed above. For example, “Moderately Likely” corresponds to an annual probability ranging between 0.1 and 0.01. Raw hazard probabilities, P_H, and the rationales for their selection, have been discussed in previous sections.

Each geohazard scenario considered in this analysis has a potential consequence for human safety. Safety involves the potential for loss of life. Fatalities are considered as Severe (single public fatality) or Catastrophic (multiple public fatalities) consequences. Economic consequence estimates have been examined but are not shown for simplicity, since the safety consequences dominate the risk in all considered hazard scenarios.

The consequence category is determined by estimating the expected loss given the occurrence of the hazard. In the present analysis, the most significant loss is potential loss of life for a park visitor or PC worker. This category is selected from the range of consequence descriptors shown in Figure 3 on the basis of expected number of visitor fatalities given the occurrence of the geohazard.

The expected number of visitor fatalities given the occurrence of a specific geohazard is calculated by considering: the expected number of park visitors within the area potentially affected by the hazard; the likely spatial extent of the hazard in relation to the spatial distribution of park visitors; the likely temporal coincidence of hazard occurrence and visitor presence; and, finally, the vulnerability of visitors to the given hazard.

Visitor use has been examined on the basis of visitor use surveys conducted by PC. While the number of park visitors fluctuates significantly, it is assumed that during the summer months, when the area sees active visitor use there will be an average of 70 visitors at a time at some point along the Loop Trail, 6 visitors somewhere in the Lake Area, and 15 visitors in the Parking and Picnic Area. These values are used as representative values in the analysis for the respective assessment areas. It may be noted that these visitors are assumed to be distributed randomly across these assessment areas, and are not considered to be at fixed locations.

Spatial probability is defined as the chance that the hazard, should it occur, reaches the element at risk. They are based on judgment, considering factors such as the geohazard type and extent relative to the location of potentially affected visitors. Spatial probability estimates are obtained by determining the expected size of a given geohazard scenario within the total area of the assessment area. For example, consider an outbreak flood within the Loop Trail area. The maximum credible outbreak flood will affect approximately 7,000 to 8,000 m^2 of a total of 17,000 m^2 of the Loop Trail assessment area (see Figure 21). The spatial probability of such an event affecting those visitors presently using the Loop Trail is 0.41 to 0.47, or a “most probable” or expected probability of 0.44.

Average visitor use has been estimated for the peak summer season. Since visitor use is largely constrained between mid-June and September, a total of 105 days (i.e. 3.5 months) of active use is assumed. Additionally, visitor use is concentrated between the hours of 7 am and 7 pm, approximately. Combining these two considerations yields a temporal probability of visitor presence, given the occurrence of a hazard, of 0.144 (i.e. 105/365 x 12/24). This value has been assigned for all hazard scenarios, since numerous visitors are present for 14.4 % of the whole year, and are rare otherwise (i.e. outside the peak summer season and at night).

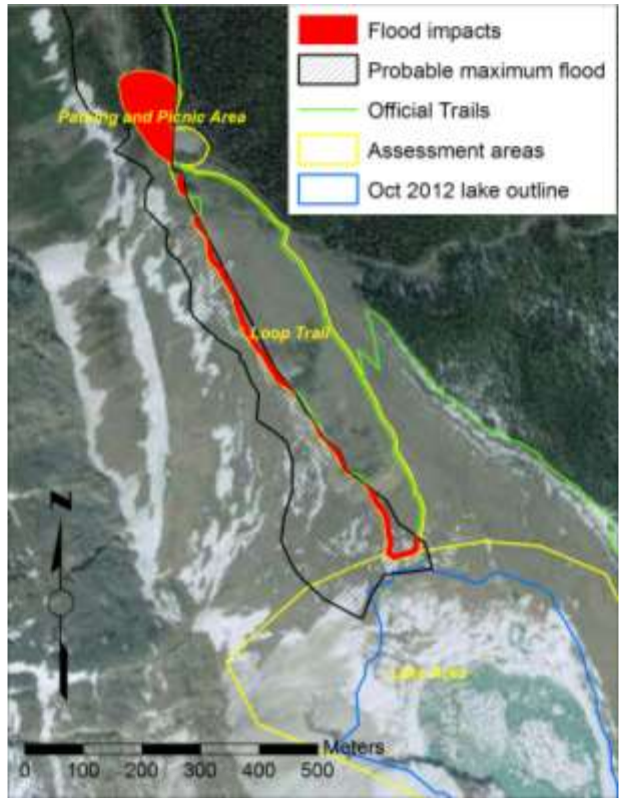

Figure 21 Potential areas affected by outbreak flood due to maximum possible ice avalanche (700,000 m^3).

Selected hazard scenarios are less likely to occur at certain times of year, and so the temporal probabilities are modified accordingly. Snow avalanche hazard is modified by a factor of 0.25, to account for the fact that damaging snow avalanches are most likely outside the peak summer season, being relatively likely only in one month (i.e. June) of active visitor use. Using a similar rationale, the probability of an outburst flood, given the impact of ice, snow or rock avalanche into the tarn, is less likely when lake levels are low, which is expected to be the case for more than half the summer visitor season. A factor of 0.5 to 0.9 has been applied to impact-related outbreak floods, being 0.5 for the smaller initiating events (i.e. small ice avalanche, rock slide and large snow avalanche) and 0.9 for large ice avalanche.

Vulnerability is defined as the likelihood the element at risk will sustain damage or loss of function (the undesirable outcome) if impacted by a geohazard. In the case of safety hazards, the vulnerability, V, is the conditional probability of a fatality given presence of a person within the area affected by the hazard. Visitors are assumed to be present in areas of the park formally identified by PC as being intended for use (e.g. parking lot, picnic area, prepared trails), or exploring the general area of the tarn. Ranges of vulnerability ratings selected by consensus judgement for use in the analysis are shown in Table 6.

Table 6. Selected vulnerability values.

Hazard Scenario	Vulnerability
Ice Avalanche (direct impact or effects of air blast and flood wave)	
Small (< 100,000 m^3)	0.5 to 1
Medium	0.8 to 1
Large (> 300,000 m^3)	0.9 to 1
Snow Avalanche (direct impact or related effects)	
Small (Size 2)	0.1 to 0.5
Medium (Size 3)	0.5 to 0.9
Large (Size 4)	0.9 to 1
Rock Fall / Slide / Avalanche (direct impact or related effects)	
Fragmental rock fall	0.1 to 0.5
Slide	0.5 to 0.8
Avalanche	0.9 to 1
Outbreak Flood (due to the indicated initiating event)	
Small ice avalanche	0.1 to 0.3
Medium ice avalanche	0.3 to 0.5
Large ice avalanche	0.5 to 0.9
Large snow avalanche	0.1 to 0.3
Rock slide	0.1 to 0.3
Rock avalanche	0.3 to 0.5
Moraine dam failure	0.1 to 0.3

The qualitative risk category for a given combination of geohazard frequency and consequence is determined from the matrix in Figure 3. Summary results from the risk analysis are presented in Table 7.

The areas affected by elevated risk are shown in the risk zones map in Figure 22, which shows the extent of high risk areas within the three assessment areas. These high risk areas also contain the low and moderate risk geohazard extents. The specific scenarios resulting in low, moderate or high risk within these affected areas are listed in Table 8. Elevated risk is concentrated in the Lake Area (around Cavell tarn), along the lower part of the Loop Trail, and in sections of the Parking and Picnic area closest to the valley bottom.

Table 7. Summary Risk Statistics for the Unmitigated Base Case.

Risk	*Lake Area*	*Loop Trail*	*Parking / Picnic Area*	*Totals*
Very High	0	0	0	**0**
High	4	9	5	**18**
Mod	3	0	3	**6**
Low	2	0	0	**2**
Very Low	0	0	0	**0**
TOTAL	9	9	8	**26**

Table 8. Summary Risk Scenarios (see Table 5 for risk scenario descriptions).

Area	*Risk Scenarios*		
	High	*Moderate*	*Low*
Lake Area	LA-01, LA-02, LA-05, LA-06	LA-04, LA-05, and LA-09	LA-07 and LA-08
Loop Trail Area	LT-01, LT-02, LT-03, LT-04, LT-05, LT-06, LT-07, LT-08, and LT-09	N/A	N/A
Parking and Picnic Area	PP-01, PP-02, PP-03, PP-05, and PP-08	PP-04, PP-06, and PP-07	N/A

3.2 Uncertainty in the Risk Analysis

The geohazard risk findings are based on a review of existing available information, supported by a brief field reconnaissance conducted with > 0.3 m of snow cover. Thus the inferences presented in this paper rely on information provided by others, with variable or unknown accuracy or completeness. As such, all assumptions are subject to uncertainty, which is in many cases significant.

Key uncertainties include:

- Size of the August 2012 ice block, the style of movement of ice into the lake, and peak discharge flow depths and velocities.
- Actual probability or frequency of ice avalanche, snow avalanche and rock fall / slide / avalanche events.
- Seasonal variation of lake levels.
- Presence or absence of an ice core in the moraine damming the Cavell tarn.
- Topography, and inferred extent of future effects of impact wave, air blast, outbreak flood and debris flow / flood.

Figure 22 Spatial extent of 'unmitigated' risk zones.

4 RISK MITIGATION

4.1 Identification and Selection of Risk Mitigation measures

Selection of preferred risk mitigation measures followed the general steps listed below:

- Generation of a cost-benefit evaluation framework for comparing and contrasting various mitigation measures;
- Development of an initial long list of technically feasible risk mitigation measures;
- Scoring and ranking of individual mitigation measures to develop a prioritized (ranked) list of alternatives;
- Grouping of individual mitigations into broader strategic alternatives addressing the range of hazards in time and space;
- Scoring and ranking of the strategic alternatives;
- Development of a recommended path forward to manage geohazard risk.

The cost-benefit options analysis scoring framework used in the work is presented in Table 9. The logic in this system is to compare the expected value of risk reduction against cost or effort associated with a given alternative.

Table 9. Options Analysis Framework.

The value of expected risk reduction is assigned a numeric score ranging from 0 to 8, with the highest score implying full elimination of all risks, and the lowest score implying no risk reduction. Each mitigation alternative starts with some value associated with expected risk reduction, and then this score is subsequently reduced for expected cost, or challenge, due to a wide variety of factors, including for example initial capital cost, long term cost, public acceptance and environmental approval effort. These factors were initially developed by the BGC team, and then modified slightly following discussion with PC.

Each of the cost factors is assigned a value ranging between 0 (no cost/effort) and -4 (high cost/effort). Possible scores range from a maximum of + 8 to a minimum of – 32, with higher scores suggesting more attractive alternatives. The total scores do not have an absolute meaning, being drawn from subjective interpretations of a range of factors. However, they do allow direct comparison between options, and the results are reproducible. A sensitivity analysis was conducted to examine the relative importance of specific scoring factors. While minor changes in scoring were obtained with changes in weighting of specific factors, such changes did not have a material impact on the relative value of various alternatives.

A long list of technically feasible risk mitigation measures was initially prepared by the BGC team, and subsequently modified following discussion with PC. Possible mitigation measures have been subdivided into four broad categories, as follows:

A – Risk Acceptance - maintain the status quo, take no further action;

B – Risk Avoidance – measures intended to remove visitors from harm's way, for example trail closures, warning signs, or day use area closures;

C – Risk Reduction through Physical Protective Measures – construction of physical infrastructure to reduce hazard occurrence or protect visitors from hazards, should they occur;

D – Risk Mitigation through Emergency Preparedness – measures to reduce the expected loss given a hazard affecting visitors (e.g. emergency phones or safety equipment)

A total of 31 individual technically feasible mitigation measures were proposed and considered in the analysis. Each individual mitigation alternative was assessed according to the cost-benefit scoring framework by a team of three BGC assessors, based on consensus judgment. The scores were presented to PC, and subsequent minor modifications were made to account for considerations not previously known to the BGC team.

The risk reduction measures with higher cost-benefit scores represent a menu of alternatives that may be combined in various ways to reduce risk. An optimum mitigation strategy will address all hazards in all three assessment areas, yielding best overall value in risk reduction for least overall cost or effort.

Beneficial Factors	Benefit Score			
	+ 0-2 points	**+ 3-4 points**	**+ 5-6 points**	**+ 7-8 points**
Residual risk	High, limited risk reduction	moderate	low	None, complete risk elimination
Cost/Risk Factors	**Cost Score**			
	0 to - 1 points	**- 2 points**	**- 3 points**	**- 4 points**
Initial capital cost	< $10K	< $100K	< $1M	> $1M
Long term cost	< $10K	< $100K	< $1M	> $1M
Planning/design effort	None/very little required	1 week	2-10 weeks	> 10 weeks
Construction or implementation effort	None/very little required	1 week	2-10 weeks	> 10 weeks
Public acceptance: Single-use visitors	No/limited concern	Moderate concern	Significant resistance	Likely letters to MPs
Public acceptance: Frequent visitors	No/limited concern	Moderate concern	Significant resistance	Likely protests or similar public concerns
Other stakeholder acceptance (regulators, businesses)	No/limited concern	Moderate concern	Significant resistance	Likely intense lobbying and negative media campaign
Environmental approvals	None/very little required	Simple screening, no field work	Significant field work to support detailed assessment	Public hearings

Seven strategic alternatives were considered, each consisting of a set of technically feasible risk mitigation measures. These strategic alternatives were each then assessed according to the framework presented in Table 9.

The preferred alternative is “Permanent partial day use area closure, no monitoring.” This alternative may be more fully described as follows:

- Continue normal seasonal day use area operations, with day use area closures from the onset of snow until the following snow free period;
- Develop and post educational and/or warning signs to inform day use area visitors of the dangers of existing natural hazards;
- Adjust existing formal trails and other facilities to:
    - Discourage access to the Cavell tarn area,
    - Remove visitor traffic from the Path of the Glacier Loop Trail where it passes through hazard exposure areas, either by closing or relocating appropriate trail sections,
- Close or relocate the picnic area, and
- Close or relocate part of the parking lot exposed to hazards, including outhouses within hazard exposure areas.

These risk mitigation measures result in the expectation of low residual risk due to natural geohazards, as this combination of measures would effectively remove visitors from harm’s way, or at least reduce the number of visitors who would expose themselves to the site’s natural hazards.

4.2 One Year Later

The first author visited the park on vacation a year after the ice avalanche, on 11 August, 2013. PC had implemented all of the proposed administrative mitigation measures, including closure of the lower loop trail, erection of warning signs and initiation of adjustments to the parking and picnic areas. Additionally, an interpreter was on site advising visitors about natural hazards as one aspect of the visitor experience. Additional access road and parking area modifications were in development for later in the year or 2014.

5 DISCUSSION

This paper has described a qualitative geohazard risk assessment and identification and selection of risk mitigation measures to reduce risk to park visitors in a day use area in Jasper National Park. The work was complicated by the diverse range of relevant geohazards, with different rates of occurrence and different temporal and spatial distribution. Uncertainty in the hazard assessment was limited as much as practical through the use of consensus judgement. Determination of an appropriate risk response was complicated by the lack of an accepted risk tolerance criterion for recreational users in a wilderness area within a national park.

ACKNOWLEDGEMENTS

Parks Canada had proactively investigated the ice avalanche very deliberately immediately after it occurred. Pam Clark, the project manager, provided direct access to all available Parks Canada resources. Rupert Wedgwood, a Parks Canada visitor safety specialist, led the initial investigation and provided thorough and detailed information to support the hazard assessment, which would not have been possible without insights gained from the initial investigation work completed by him and his colleagues. Dr. Michael Demuth of the Geological Survey of Canada and Professor Brian Luckmann of the University of Western Ontario provided constructive input based on their prior experiences studying the site.

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