Geohazards 7
Canmore
2018

# Steep Creek Geohazard Risk and Risk Control Assessment in the Town of Canmore, Alberta

Kris Holm, Matthias Jakob, Sarah Kimball, Alex Strouth
*BGC Engineering, Vancouver, BC, Canada*
Andy Esarte, and Felix Camire
*Town of Canmore, Alberta, Canada*

ABSTRACT
In June 2013, heavy rainfall caused flooding on most rivers in southwest Alberta, Canada, producing one of Canada's most expensive natural disasters. In addition to large scale flooding, debris flows and debris floods also caused extensive highway closures and damages to development on fans at the outlet of steep creeks. In this paper we summarize geohazard risk and risk reduction studies of fans containing over $2.6 billion in developed land within the Town of Canmore. We also discuss challenges and opportunities to integrate the study results into local government policy, including Canmore's Municipal Development Plan.

RÉSUMÉ
En juin 2013, de fortes pluies ont causé des inondations sur la plupart des cours d'eau du sud-ouest de l'Alberta, au Canada, provoquant l'une des catastrophes naturelles les plus dispendieuses au Canada. En plus des inondations à grande échelle, les coulées de débris et les inondations de débris ont également causé la fermeture d'autoroutes et des dommages considérables aux aménagements sur les cônes alluviaux à la sortie des ruisseaux de montagnes. Dans le présent document, nous résumons les évaluations des dangers et des risques ainsi que la réduction des risques liés aux développements des cônes alluviaux qui contiennent plus d'un milliard de dollars en infrastructure dans la ville de Canmore et le district municipal de Bighorn. Nous discutons également des défis et des possibilités d'intégrer les résultats de l'étude dans la politique des administrations locales, y compris le plan de développement municipal de Canmore.

## 1 INTRODUCTION

In June 2013, two days of high-intensity rainfall in southwestern Alberta triggered one of the most expensive natural disasters in Canadian history. A low-pressure system, blocked by a high-pressure system to the north, caused 48-hour precipitation to exceed 100 mm. Flooding occurred along all major river systems and hundreds of debris flows and debris floods were triggered on steeper tributaries.

The Town of Canmore, Alberta, sustained over $40 M in damages with closure of both the Trans-Canada Highway (Highway 1) and the Canadian Pacific Railway line for a period of several days.

Canmore contains the most developed debris flood and debris flow fans in Canada, with 13 fans containing almost $2.6 billion in developed land, over 7000 temporary or permanent occupants, and businesses generating over one quarter of Canmore's annual revenue. Following immediate response and recovery efforts, Canmore commissioned 'steep creek risk assessments' (SCRAs) to improve the understanding and management of debris floods and debris flows within the town. A total of 10 creeks have been assessed including Cougar, Three Sisters, Pigeon, Stone, Stoneworks, X,Y, and Z, Echo Canyon, and Stewart creeks, and additional studies are ongoing or anticipated (BGC Engineering (BGC) 2013a-g, 2014a-d, 2015a-e, 2016a,b, Tetra Tech 2016).

The results of SCRAs support decision making by Canmore in areas such as:

- Land use and development planning
- Bylaw development and enforcement
- Mitigation planning and design
- Emergency response
- Justification for funding applications for further geohazard risk assessment, mitigation design and construction.

Canmore has integrated the results of SCRAs into a risk-based approach to manage development within steep creek hazard areas. Specifically, the results of these assessments allow Canmore to:

- Determine the approximate level of economic and safety risk due to steep creek geohazards
- Evaluate whether these risks should be considered tolerable
- Identify requirements for further assessments and mitigation planning.

The Town may consider expanding this risk-based approach for the management of other known hazards or where new hazards are identified. In this paper we describe the SCRAs completed and their integration into local government policy, including Canmore's Municipal Development Plan.

## 1.1 Study Area

The upper Bow River valley as discussed in this paper is located west of the town of Exshaw and east of Harvie Heights Creek (Figure 1). The valley is characterized by a broad floodplain drained by a meandering and largely aggrading Bow River. Numerous tributaries discharge onto the floodplain and have created expansive alluvial fans that interfinger with the floodplain deposits. The tributaries range in basin area from less than 1 $km^2$ to several 10s of $km^2$. The tributary creeks are subject to debris flows, while the larger watersheds are subject to debris floods.

## 1.2 Steep Creek Geohazard and Risk Assessments

Initial investigations of 10 affected creeks were completed immediately after the June 2013 events (BGC 2013a-g, 2014a, Jakob et al. 2017). The initial investigations included visual inspection of the creek's watersheds by helicopter and foot and the identification, documentation, and categorization of sites that suffered some form of damage during the June storm. Preliminary frequency analysis was conducted through air photo interpretation and conceptual risk reductions options were considered for each creek.

Following the initial assessments, detailed hazard and risk assessment were completed for 4 creeks (Cougar, Three Sisters, Stone, and Stoneworks), and risk assessment for an additional creek (Pigeon; EBA-Tetratech, 2016). Hazard and risk assessments for 3 creeks (Stones Canyon, Three Sisters, Stoneworks) were completed on behalf of developers in accordance with Canmore's steep creek hazard and risk policy (Town of Canmore 2016a). At a regional level of detail, 18 steep creeks within Canmore were also characterized as part of a larger inventory and risk-based prioritization of steep creeks in the Alberta Rockies (Holm et al., 2016).

## 2 STEEP CREEK RISK ASSESSMENT

Geohazard risk assessments estimate the probability and severity of an adverse effect to health, property or the environment (AGS 2007), and evaluate the results against risk tolerance criteria. As a type of geohazard risk assessment, SCRAs provide a systematic way to consider both geohazards and associated consequences in risk management decision making.

We completed SCRAs that estimated the likelihood that steep creek geohazard scenarios occur, impact elements at risk, and cause types and severities of consequences. Each of these components were estimated separately and then combined. The objective at each creek was to provide a systematic, repeatable assessment with an appropriate level of detail for the information available.

The major steps in the assessment of each creek were to:

1. Complete hazard analyses leading to the development of numerically modelled debris flow and debris flood geohazard scenarios
2. Assess potential direct consequences of these scenarios for buildings and infrastructure
3. Assess risk to life (safety risk) due to geohazard impact to persons located within buildings
4. Compare the results of safety risk estimation to risk tolerance thresholds.

The following sections summarize each step of the assessment.

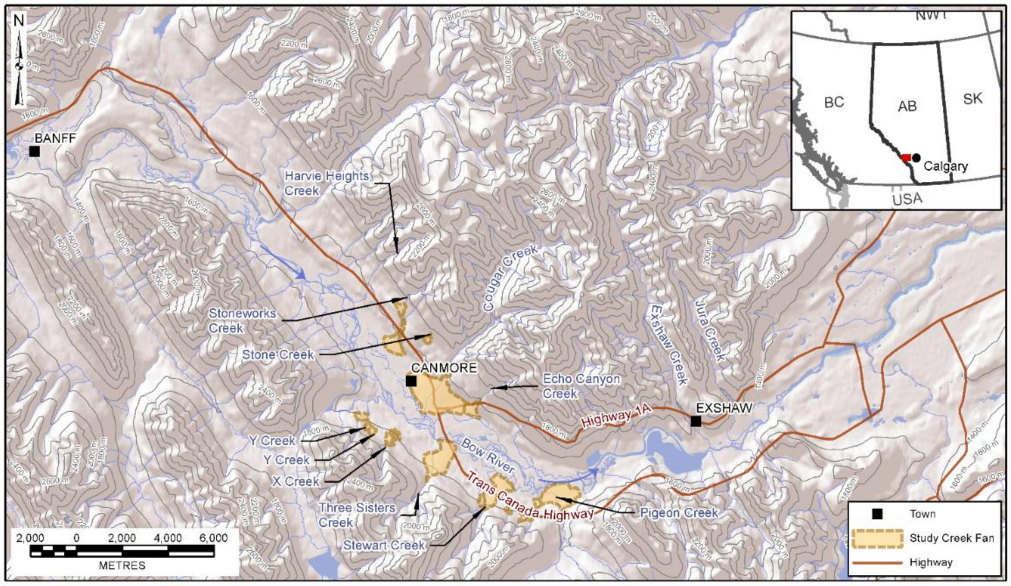

Figure 1. Study area

## 2.1 Geohazard Analysis

Geohazard analysis involved developing an understanding of the underlying geophysical conditions (geological, hydrological, atmospheric, etc.); identifying and characterizing geohazards in terms of factors such as mechanism, causal factors, trigger conditions, intensity (destructive potential), extent, and change; developing hazard frequency-magnitude relationships, and identifying and characterizing the geohazard scenarios to be considered in risk analysis.

Geohazard mapping formed a key component of this work, including geohazard intensity mapping for individual steep creek hazard scenarios. Composite maps that amalgamate all scenarios considered into one final map were also generated for public communication and use in policy development. Hazard maps developed as an outcome of geohazard analysis supported both risk estimation and communication of results (Town of Canmore 2016a).

### *Step 1 – Hazard Characterization: Desktop Analysis*

Initial desktop analysis included the review of existing reports, geology, terrain, landslide, and hydrologic information; historic airphoto analysis, compilation of compile remotely-sensed (LiDAR, Airphoto) and basemap data in GIS format, and LiDAR change detection analysis based on available topography prior to and following the June 2013 steep creek events.

### *Step 2 – Hazard Characterization: Field Work*

Fieldwork included physical and visual assessment of channels and fans based on channel and fan traverses, test pitting, dendrochronology, inspection of elements at risk, inspection of surface water drainage, inspection of existing protective works, and assessments of upper watershed areas including rock slope assessments, characterization of sediment supply mechanisms, and evaluation of snow avalanche-debris interactions.

During the channel traverses, we identified high water marks, cross-sections, grain size distributions, sediment supply sources and stratigraphy of natural exposures. We also traversed upper watersheds to identify alternative sediment mechanisms and the potential for large rock slope movements that could possibly discharge material into the watersheds. We used dendrochronological methods to estimate the timing and magnitude of debris flows in approximately the past 150 years.

### *Step 3 – Hazard Analysis: Frequency-Magnitude Relationships*

Frequency-magnitude relations are defined as volumes or peak discharges related to specific return periods (or annual frequencies). This relation forms the root of any hazard assessment because it combines the findings from frequency and magnitude analyses. Any frequency-magnitude calculation that spans time scales of millennia necessarily includes some judgment and assumptions, both of which are subject to uncertainty. However, our analysis was based on the best data available and was considered appropriate for the scale and level of detail of the assessments. Uncertainty in frequency-magnitude estimation could further be addressed by including redundancies in risk reduction measures.

Once developed, we defined representative event classes of varying return period and magnitude (sediment volume) for subsequent use in numerical modelling and risk analyses.

### *Step 4 – Numerical Modelling*

To estimate flow intensity (flow depth and velocity) and hazard extent, we modelled 5 to 20 geohazard scenarios per creek using the commercially available two-dimensional hydraulic model, FLO-2D (2004). At a minimum these scenarios were chosen to represent the following return period ranges: 10 to 30, 30 to 100, 100 to 300, and 300 to 1000 years. Where applicable and where justified with the methods applied, we also modelled scenarios representing a 1000 to 3000-year return period event. In addition to the return period classes, we developed and modelled avulsion scenarios at channel locations identified during field investigation. In most instances, avulsion scenarios applied to the higher return periods, as the probability of avulsions increases with return period. Area reduction factors were included in model inputs to account for buildings that deflect flows and different Manning's n roughness coefficients were applied to roads, undeveloped and developed fan portions.

Outcomes of numerical hazard modelling were expressed using a debris flood intensity index as a proxy for destructive power, calculated according to Jakob et al (2011) as follows:

$$I_{DF} = v^2 d \quad [1]$$

where:

$v$ is flow velocity in m/s

d is flow depth in m.

Along with their estimated probability of occurrence, numerically modelled geohazard scenarios formed the primary hazard input to risk estimation.

## 2.2 Risk Estimation

Risk assessment involved estimating the likelihood that a debris flood or debris flow will occur, impact elements at risk, and cause types and severities of consequences.

Elements impacted by these scenarios and considered in the risk assessment included buildings, roads, utilities, critical facilities, and persons within buildings. Of these, the risk analysis focused on estimation of direct building damage and safety risk. These were selected as the key elements that can be systematically assessed and compared to risk tolerance standards, and then used to optimize mitigation strategies. These mitigation strategies, once implemented, would reduce relative risk levels for a broader spectrum of elements than those explicitly considered in the assessment. We completed the risk analysis at a cadastral parcel (property boundary) level of detail based on the maximum intensity of flows impacting buildings within a given parcel.

We applied a qualitative or semi-quantitative approach to assess potential impacts to other types of elements at risk. For example, as a proxy for relative level of business impact, we calculated the total annual revenue for businesses in areas impacted by a debris-flow scenario. We also identified critical facilities, roads and utilities within the debris-flow impact zones that may suffer loss of function following impact.

Risk ($P_E$) was quantified using the following equation:

$$P_E = \sum_{i=1}^{n} P(H)_i P(S:H)_i P(T:S)_i \, N \qquad [2]$$

where:

$P(H)_i$ is the annual hazard probability of debris-flow or debris-flood scenario $i$ of $n$, where *n* is the total number of scenarios. It addresses the question, "how likely is the event"?

$P(S:H)_i$ is the spatial probability that the event would reach the element at risk. It addresses the question, "what is the chance that the event will reach an element at risk"?

$P(T:S)_i$ is the temporal probability that the element at risk would be in the impact zone at the time of impact. It answers the question, "what is the chance of someone or something being in the area affected by the hazard when it occurs"?

$N = V_i E_i$ describes the consequences [3]

where:

$V_i$ is the vulnerability, which is the probability elements at risk will suffer consequences given hazard impact with a certain severity. For persons, vulnerability was defined as the likelihood of fatality given flood impact. For buildings, it was defined as the level of damage, measured as a proportion of the assessed building value or as an absolute cost.

$E_i$ is a measure of the element at risk, quantifying the value of the elements that could potentially suffer damage or loss (e.g., number of persons, building value).

In the case of safety risk (risk to life), risk was estimated separately for individuals and groups (societal) risk. Estimated risk for combined debris-flood scenarios was calculated by summing the risk quantified for each individual debris-flood scenario.

Individual risk considered the annual probability that hazard scenarios resulted in loss of life for a certain individual, referred to as Probability of Death of an Individual (PDI). Individual risk levels are independent of the number of persons exposed to risk.

In contrast, group risk considered the cumulative probability of at least a certain number of fatalities. Unlike individual risk, a greater number of persons exposed to the same hazard correspond to increased risk. For this reason, it is possible to have a situation where individual risk is considered tolerable, but group risk is not tolerable due to the large number of people affected.

Group risk was represented graphically on an F-N curve, as shown in Figure 2. The Y-axis shows the annual cumulative frequency, $F$, of each hazard scenario, and the X-axis shows the estimated number of fatalities, $N_i$, where:

$$F = \sum_{i=1}^{n} P(H)_i P(S:H)_i P(T:S)_i \qquad [4]$$

and $N_i$ is represented by equation [3] above. We calculated lower, best-estimate, and upper bounds for estimated group risk based on a range in estimated vulnerability of people within buildings to geohazard impact. Criteria relating debris flow intensity to human vulnerability were based on judgement with reference to Jakob et al. (2011).

For areas of lower intensity flow ($I_{DF} < 1$) we used flood stage-damage functions of FEMA (2013) to estimate flood damages as a proportion of building assessment value. While Alberta-specific flood stage-damage functions were also developed following the 2013 flood events (IBI Group 2015), their release post-dated BGC's earlier assessments and for consistency the depth-damage criteria of FEMA was used for all creeks assessed.

## 2.3 Risk Evaluation

At each creek, we compared estimated individual safety risk to individual and group risk tolerance criteria adopted by Canmore (Town of Canmore, 2016a). These criteria are similar to those adopted by the District of North Vancouver, British Columbia in 2009, which followed guidelines originally developed in Hong Kong (Hong Kong Geotechnical Engineering Office (GEO) 1998). The criteria for individual geohazard risk tolerance are as follows:

- Maximum 1:10,000 (1x$10^{-4}$) annual PDI for existing developments
- Maximum 1:100,000 (1x$10^{-5}$ annual PDI for new developments.

For risk to groups, we compared estimated risks to Canmore's group risk tolerance thresholds, which are also consistent with criteria adopted in Hong Kong (GEO 1998) as shown in Figure 2. Three zones can be defined as follows:

- Unacceptable – where risks are generally considered unacceptable by society and require mitigation
- As Low as Reasonably Practicable (ALARP) – where risks are generally considered tolerable by society only if risk reduction is not feasible or if costs are grossly disproportionate to the improvement gained (this is referred to as the ALARP principle)
- Acceptable – where risks are broadly considered acceptable by society and do not require mitigation.

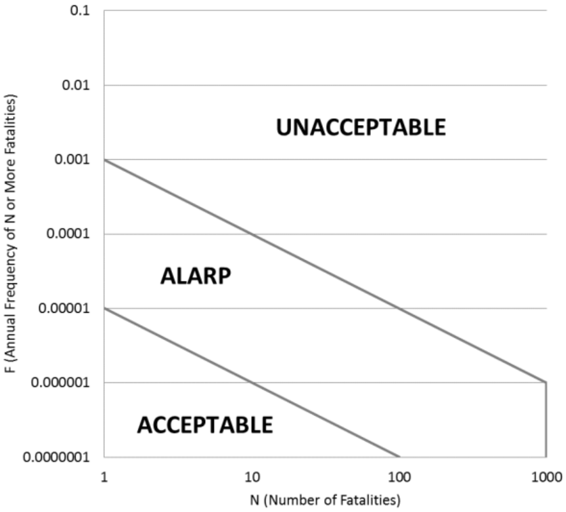

Figure 2. Group risk tolerance criteria as defined by GEO (1998).

## 2.4 Outcomes

The hazard analysis resulted in debris flood intensity maps, which formed the basis of the risk assessment. Hazard intensity maps displayed modelled flow extents with hazard intensity grid cell values $I_{DF} > 1$, and flow depths where $I_{DF} < 1$. The choice to display both flow intensity and depth on the same map related to the mechanism of damage, expected to be more strongly related to impact forces in higher intensity flow areas, and flood inundation depth in lower intensity flow areas.

The various hazard scenarios were overlaid to create a composite hazard map showing maximum flow extents and intensities at all return periods assessed. This composite hazard map was typically similar to the largest geohazard scenario. Where forced avulsions created different flow paths, such scenarios were included in the composite hazard map.

While care was taken to run models long enough to identify areas likely be affected by fine-grained afterflows, these maps did not consider auxiliary hazards such as potential downstream damming events. While the individual return period debris-flow and debris-flood intensity maps and the composite hazards maps are thought to be reasonably accurate representations of the physical processes, they are a snapshot in time. New developments, added mitigation works, or new debris floods or debris flows will alter the topography and require updates to hazard analysis and mapping.

Quantitative outcomes of the risk analysis included identification of parcels where estimated individual risk exceeded Canmore's risk tolerance thresholds, group risk estimates for each fan, and estimated direct damage costs expressed for each scenario and as annualized figures.

To check that vulnerability criteria and results of the safety risk estimate at Cougar Creek were reasonable (BGC 2014c), we compared results to documented events in other regions where loss of life and the population that was exposed to hazard were both known, and other cases where loss of life did not occur but that were still considered relevant for comparison. Cases chosen included the October 1921 Debris Flood at Britannia Beach, BC; December 1981 Debris Flow at Charles Creek, BC; July 11, 1997 debris flow at Hummingbird Creek on Mara Lake; the June 13, 2010 debris flow at Testalinden Creek near Oliver, BC.; February 2010 Debris Floods in Funchal, Madeira; and the August 2005 flooding in New Orleans, USA. Compared to estimated mortality rates for these case studies, BGC's Cougar Creek group risk best-estimate fell in the middle of the range, close to the lower range for lower magnitude scenarios and towards the middle range for larger scenarios.

For Cougar Creek, we also re-analysed group risk using mortality functions in the Standard Dutch Damage and Casualty Model (Jonkman et al, 2008, De Bruijn and Klijn 2009). Estimated group risk based on these mortality functions compared to BGC's upper bound estimate of group risk at Cougar Creek fan. Criteria relating debris flood intensity to vulnerability of loss of life calibrated at Cougar Creek were applied across all debris flood creeks, to allow consistent comparison of relative risk.

# 3 RISK CONTROL STRATEGIES

A variety of risk control measures have been implemented by the Town of Canmore in areas where assessed steep creek risk is intolerable. The primary risk control strategies for existing development have been structural debris-flow and debris-flood protection measures and emergency response plans. Risk to new development is further managed by a municipal development plan that specifically addresses debris-flow and debris-flood hazards and includes zoning based on potential hazard intensity.

## 3.1 Municipal Development Plan

Canmore's Municipal Development Plan (MDP) and Steep Creek Hazard and Risk Policy (Town of Canmore 2016a,b) integrate the community's vision with municipal planning and decision making. The MDP addresses environmental, economic, social, cultural and governance aspects of the community from a land use and development perspective, and sets the Town's overall policy direction for community land use decisions. The MDP also provides direction to Town Council to help prioritize initiatives for capital projects, strategic planning and budgeting.

Part of the MDP concerns development constraints in 'Hazard Lands', which include steep slopes, areas requiring wellhead protection from contaminants, areas of high groundwater, clear-water flood hazard areas, and steep creeks.

Canmore has integrated a risk-based approach into managing development within steep creek hazard areas and may consider expanding this risk-based approach for the management of other known hazards as required, or where new hazards are identified. Steep Creek Hazard Zones are defined in Canmore's Steep Creek Hazard and Risk Policy (Town of Canmore 2016a), which will be periodically updated as new assessments are completed. The MDP defines Canmore safety risk tolerance thresholds and outlines requirements for geohazard risk assessments for development proposals.

Steep Creek Hazard Zones are areas defined by Canmore based on generalized outcomes of the hazard analysis. They show the maximum estimated intensities of a potential steep creek hazard in categories defined as follows:

- Extreme/High ($I_{DF} > 10$): areas characterized by very fast flowing and deep water and debris that could cause severe building structural damage, severe sediment and water damage, and that could be dangerous to people in buildings, on foot or in vehicles.
- Moderate ($I_{DF} = 1 \text{ to } 10$): areas characterized by fast flowing but mostly shallow water and debris, which could cause moderate building structural damage and a high likelihood of major sediment and/or water damage, and that could be potentially dangerous to people on the first floor or the basement of buildings, on foot or in vehicles.
- Low ($I_{DF} < 1$): areas characterized by slow flowing, shallow or deep water with little or no debris, in which there is a high likelihood of water damage to buildings, and where areas with higher water depths could be potentially dangerous to people in buildings, on foot or in vehicles.

Note that Canmore's hazard zone maps are intended to encompass maximum credible flow intensities and extents in a composite format for all studied return periods and scenarios, and do not show hazard probability or risk level. They are development permit areas that identify where site-specific SCRAs are required for development permit applications. In a Steep Creek Hazard Zone, development may be allowed in accordance with the following:

- Extreme/High hazard area: no new development is allowed. Expansion or intensification of existing development is limited to development that does not materially increase the hazard or risk, such as accessory buildings and minor increases in building footprint.
- Moderate hazard area: expansion or intensification of existing development that does not materially increase the hazard or risk will be allowed, such as accessory buildings or uninhabited buildings. Additional development and new development may be allowed where a risk assessment is completed and the results show that PDI is less than 1:100,000.
- Low hazard area: development is allowed. Where a significant development proposal may increase the level of group risk above ALARP, Canmore may require a risk assessment to be prepared.

The MDP also defines Development Hold Zones where existing steep creek group risk has been deemed intolerable. No new development is allowed in these areas, but redevelopment of existing development with the same use or intensity of use may be allowed, as well as expansion or an increase in the intensity of use if it does not materially increase the risk, such as accessory buildings and minor increases in building footprint. Development Hold Zones are subject to removal where mitigation has been constructed and an updated hazard and risk assessment determines that the risk is within the Acceptable or ALARP range for group risk (Figure 2).

## 3.2 Structural Measures

Structural debris-flow and debris-flood protection measures constructed in Canmore have included sediment and debris barriers, channel widening and erosion protection, and flow diversion berms. Wooden flow diversion walls (up to approximately 1 m high) have also been designed to divert shallow flows away from some developed areas.

Recent structural measures have been designed using a risk-based approach, meaning the design-event is selected such that the residual risk (risk after structures are constructed) is tolerable. Therefore, the design event selected for different structures across Canmore can vary based on the site-specific elements at risk and hazard intensity. In general, this means that a larger design event (e.g. 300- to 1,000-year return period) is used where risk is high and appropriate risk reduction cannot be achieved by other means or lower return period designs. Where lower return period designs are adequate, they may be checked and modified for greater resiliency in higher return period events.

Temporary protection structures were constructed at Cougar Creek within the first year following the 2013 event. These measures included an approximately 6 m high and 40 m wide flexible debris net at the fan apex, increasing the capacity of the channel, and lining the banks with articulated concrete mats to increase erosion protection. The emphasis during design of these structures was on constructing the measures as quickly as possible, before peak runoff in 2014.

More robust, permanent structural measures are being designed for Cougar Creek. The principal design element is a 30 m tall debris flood retention structure. The structure is designed to capture sediment mobilized during a debris-flood and attenuate flood discharge, such that downstream discharge can safely pass through existing culvert and bridge openings.

## 3.3 Monitoring and Warning

Not all creeks studied that have unacceptable risk will be mitigated by solely structural measures. Even in those cases where a structural mitigation budget has been allocated, many years may pass until a structure has been erected because of permitting and the design process. Therefore, and until those creeks with unacceptable risk have been mitigated, other risk management strategies are being contemplated. These include the possibility of monitoring and warning systems.

For example, the Town of Canmore has installed a telemetered full weather station at high elevation in the Cougar Creek watershed to improve their understanding of snow pack and high elevation precipitation and its effects on runoff. In addition, a high-resolution rainfall forecast system operated by the Geophysical Disaster Computational Fluid Dynamics Centre has been in place since 2013 for the upper Bow Valley. This system does not formally provide real-time warning for specific creeks and does not attempt to predict the triggering and magnitude of debris flows and debris floods. However, it does allow emergency preparedness if a heavy rainfall event is forecasted, and it could be expanded to support a real-time warning system in conjunction with further public education and emergency response planning.

## 4 CHALLENGES AND OPPORTUNITIES

For the upper Bow Valley, as for many other mountainous regions in Canada, development has historically occurred without full appreciation of rare catastrophic events. Unlike some European and Asian nations with federal geohazard risk management programs, Canada lacks a unified approach. Hazard or risk management policies differ widely between jurisdictions, and many areas lack sufficient geohazards information to make informed policy decisions.

While the efforts to complete quantitative SCRAs for Canmore were substantial, every step of the assessments required judgment and contained uncertainties. For example, confidence in frequency-magnitude estimation is much lower for longer return periods, and numerical flow modelling is a simplification of reality that does not fully capture rheological complexities or scour and debris deposition. Elements at risk characterized at a fan level of detail contain uncertainties that limit the accuracy and precision of vulnerability estimation, and the types of risks assessed consider only some of the consequences of geohazard events. Recognizing these uncertainties, Canmore is applying the fan-scale SCRAs to inform policies and bylaw development, while still requiring site-specific SCRAs to improve assessment confidence at individual proposed development sites. Over time, the site-specific SCRAs will inform periodic updates to the larger scale studies, to improve Canmore's overall understanding of steep creek geohazard risk.

Effective communication of risk and risk based decision making is an ongoing challenge. Engagement with local government, the public, land owners and developers is an essential requirement in implementation of new policies and bylaws. Well informed stakeholders better understand the risks and the intent of the change in policies. Without stakeholder buy-in of risk criteria, SCRA process and new policies, efforts to study and mitigate geohazards can stall or reverse.

## 5 CONCLUSIONS

The Town of Canmore has developed one of Canada's most comprehensive steep creek geohazard risk management strategies. This effort continues to evolve, and lessons learned during its development are applicable to mountainous communities in BC, Alberta and elsewhere. Challenges to apply similar approaches in other regions include gaps in the completeness and quality of geohazard information, fragmented or inconsistent hazard and risk management policies, inequality in the capacity of local governments to manage land use in the face of increasing development pressure and effects of climate change. Further work is needed to enable coherent, transparent, and fair geohazard risk management policy and define the roles and responsibilities of different levels of government in this effort.

While challenges remain, the Town of Canmore has demonstrated that integrating quantitative geohazard risk assessment into policy can be done successfully. We hope that this contribution acts as a catalyst to other municipalities and governments to follow their lead.

## 6 ACKNOWLEDGEMENTS

This work would not have been possible had it not been for the tireless support of the Town of Canmore's engineering and planning departments, Mayor John Borrowman, and a progressive council. Many more individuals contributed to the technical work herein than are listed as authors on this paper, and we are grateful for their contributions.

## 7 REFERENCES

Australian Geomechanics Society (AGS) 2007. A national landslide risk management framework for Australia. Vol. 42 No. 1.

BGC Engineering Inc. (BGC) 2013a. Pigeon Creek, Forensic Analysis and Short-Term Debris Flood Mitigation. *Project Memorandum prepared for* the Town of Canmore dated December 2, 2013.

BGC Engineering Inc. (BGC) 2013b. Stone Creek, Forensic Analysis and Short-Term Debris Flow Mitigation. *Project Memorandum prepared for* the Town of Canmore dated December 2, 2013.

BGC Engineering Inc. (BGC) 2013c. Stoneworks Creek, Forensic Analysis and Short-Term Debris Flood Mitigation. *Project Memorandum prepared for* the Town of Canmore dated December 2, 2013.

BGC Engineering Inc. (BGC) 2013d. X, Y, and Z Creeks, Forensic Analysis. *Project Memorandum prepared for* the Town of Canmore dated December 2, 2013.

BGC Engineering Inc. (BGC) 2013e. Cougar Creek, 2013 Forensic Analysis and Short-Term Debris Flood Mitigation. *Report prepared for* the Town of Canmore dated December 11, 2013.

BGC Engineering Inc. (BGC) 2013f. Three Sisters Creek, Forensic Analysis and Short-Term Debris Flood Mitigation. *Project Memorandum prepared for* the Town of Canmore dated December 11, 2013.

BGC Engineering Inc. (BGC) 2013g. Echo Canyon Creek, Forensic Analysis and Long-Term Debris Flow Mitigation Concepts. *Project Memorandum prepared for* the Town of Canmore dated December 18, 2013.

BGC Engineering Inc. (BGC) 2014a. Stewart Creek, Forensic Analysis and Conceptual Debris Flood Mitigation. *Report prepared for* the Town of Canmore dated January 3, 2014.

BGC Engineering Inc. (BGC) 2014b. Cougar Creek, Debris Flood Hazard Assessment. *Report prepared for* the Town of Canmore dated March 7, 2014.

BGC Engineering Inc. (BGC) 2014c. Cougar Creek Debris-Flood Risk Assessment. *(Revised) Report prepared for* the Town of Canmore dated June 11, 2014.

BGC Engineering Inc. (BGC) 2014d. Three Sisters Creek Debris-Flood Hazard Assessment. *Report prepared for* the Town of Canmore dated October 31, 2014.

BGC Engineering Inc. (BGC) 2015a. Three Sisters Creek Debris-Flood Risk Assessment. *Report prepared for* the town of Canmore dated January 20, 2015.

BGC Engineering Inc. (BGC) 2015b. Cougar Creek Baseline Debris-Flood Risk Assessment Update. *Letter Report* prepared for the Town of Canmore dated May 21, 2015.

BGC Engineering Inc. (BGC) 2015c. Stone Creek Debris-Flow Risk Assessment. *Report prepared for* the Town of Canmore dated October 23, 2015.

BGC Engineering Inc. (BGC) 2015d. Stoneworks Creek, Debris Flood Hazard Assessment. *Report prepared for* the Town of Canmore dated November 16, 2015.

BGC Engineering Inc. (BGC) 2015e. Stone Creek, Debris Flow Hazard Assessment. *Report prepared for* the Town of Canmore dated April 21, 2015.

BGC Engineering Inc. (BGC) 2016a. Pigeon Creek Debris-Flood Risk Assessment. *Report prepared for* the Town of Canmore dated September 27, 2016.

BGC Engineering Inc. (BGC) 2016b. Stoneworks Creek Debris-Flood Risk Assessment. *Report prepared for* the Town of Canmore dated September 30, 2016.

Cruden DM and Hu X-Q 1988. Basic friction angles of carbonate rocks from Kananaskis country, Canada. *Bulletin of the International Association of Engineering Geology* 38(1): 55-59. DOI: 10.1007/BF02590448.

De Bruijn KM, Klijn F. 2009. Risky places in the Netherlands: a first approximation for floods. *Journal of Flood Risk Management*, 2: 58–67.

FEMA (Federal Emergency Management Agency) 2013. Hazus-MH Technical Manual: Flood Model. Online source: http://www.fema.gov/media-library/assets/documents/24609

Gadd, B. 1995. *Handbook of the Canadian Rockies*, 2nd ed.; Jasper, A.B., Ed.; Corax Press: Jasper, AB, Canada.

Geotechnical Engineering Office (GEO) 1998. Landslides and boulder falls from natural terrain: interim risk guidelines. *Hong Kong Government, GEO Report,* 75.

Henderson, C.M., Richards, B., Johnson, D. 2009. Rocky Mountain Field Trip. In Newsletter of the Subcommission on Permian Stratigraphy, Number 53, Supplement 2. *In Proceedings of the 2nd International Conodont Symposium (ICOS 2009)*, Calgary, AB, Canada.

Holm, K., Jakob, M. and Scordo, S. 2016. An inventory and risk-based prioritization of steep creek fans in Alberta. *3rd European Conference on Flood Risk Management (FLOODrisk 2016)*, Lyon France.

Hong Kong Geotechnical Engineering Office (GEO) 1998. Landslides and Boulder Falls from Natural Terrain: Interim Risk Guidelines. *Geo Report 175*, Geotechnical Engineering Office, Civil Engineering Department, Hong Kong Special Administrative Region: 184 pp.

Jakob, M., Stein, D., and Ulmi, M. 2011. Vulnerability of buildings to debris flow impact. Natural Hazards, 60(2): 241-261.

Jakob., M., Weatherly, H., Bale, S., Perkins, A., and MacDonald, B. 2017. A multi-faceted debris-flood hazard assessment for Cougar Creek, Alberta, Canada. *Hydrology* 4 (7): 1-33.

Jonkman, S., Vrijling, J., and Vrouwenvelder, A. 2008. Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method. *Natural Hazards*, 46: 353-389.

Tetra Tech EBA (EBA) 2016. Pigeon Creek Hazard Assessment. *Report prepared for* the Town of Canmore dated November 2016.

Town of Canmore 2016a. Steep Creek Hazard and Risk Policy, Council Resolution 239-2016.

Town of Canmore 2016b. Municipal Development Plan Bylaw 2016-03.