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# Quantitative risk management process for debris flows and debris floods: lessons learned in Western Canada

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**Abstract**

Debris flows and debris floods are common in mountainous regions of Western Canada, but there is no provincial or national standard for debris-flow/flood hazard or risk management. Instead, each local government manages hazards in its own way. Quantitative Risk Management (QRM) is being increasingly adopted, largely due to the effort of practitioners promoting its use. QRM uses numerical estimates of risk parameters to help risk managers within local government answer the following questions: Are present and future residents of my community safe enough? Is debris-flow/flood protection needed? How much should my community invest in debris-flow/flood protection? After roughly a decade of application, the benefits and challenges of QRM are emerging. This paper presents examples of the QRM process applied to debris-flow/flood risk management for communities, with a focus on debris-flow/flood mitigation decision making and remaining challenges.

*Keywords: Risk assessment; hazard management; risk management; debris-flow mitigation; debris flood*

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## 1. Introduction

Debris flows and debris floods are widespread in mountainous regions of Western Canada, and numerous events have impacted residential areas in the past decade, resulting in fatalities and economic damage (Moase, 2017). Development on debris-flow and debris-flood prone fans has historically occurred without adequate recognition of the hazard, and few developments are effectively protected from these hazards. A variety of communities have been impacted, ranging from densely-developed, wealthy, urban settings to the sparsely-developed, rural settings that are prevalent in British Columbia and Alberta.

Typically, assessments are triggered following debris-flow or debris-flood events, often in areas that were not fully aware of the threat to their community. A provincial code, standard, or specification for debris-flow/flood hazard management does not exist, and there is no nationally or provincially-adopted level of debris-flow/flood safety. Hazard and risk management is delegated to the municipal level of government, and each municipal government manages hazards in its own way. Some guidance exists for assessing landslide hazards (including debris flow/flood) for proposed developments (e.g. EGBC, 2010; Cave 1993), but there is little guidance for existing developments.

A few municipal governments, such as District of North Vancouver (DNV) and Town of Canmore (TOC), have responded to landslide and debris-flow/flood events by developing local regulations for assessing hazards and managing risk using a Quantitative Risk Management (QRM) process. QRM is modelled after the process initially developed in Hong Kong for landslide hazards (GEO 1998, Malone 2004, VanDine 2018). Smaller municipal governments are now increasingly referencing the local regulations adopted by DNV and TOC.

With this evolving adoption of the QRM process there is a need to understand the benefits, challenges, and lessons learned from previous applications of QRM for debris flows/floods. This paper presents examples of the QRM process

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applied to debris flows/floods that affect existing residential development, with a focus on the decision-making process for mitigation and remaining challenges of the QRM process.

The QRM process presented in this paper is designed for management of rapid-onset, highly-destructive hazards, where risk associated with direct impact is the controlling factor for decision making. Debris flows/floods are an ideal hazard type for this methodology. The process is distinct from those that manage slowly unfolding hazards (e.g. environmental contamination, flooding) where concepts of resilience and response as an event unfolds are relevant. The QRM process presented here is one of many tools for managing geologic hazards, each with its own strengths and weaknesses. This paper is not an argument for or against the QRM process, but rather an open discussion of its strengths and weaknesses.

## 2. Quantitative Risk Management

The QRM process described in Table 1 is well documented in literature (e.g. VanDine 2018, Holm et al. 2018, Hungr 2016, VanDine 2012, Fell et al. 2005, IUGS 1997, GEO 1995, Jakob 2019, this volume). It involves three overlapping phases: hazard assessment, risk assessment, and risk management. When applied to debris flows/floods, the hazard assessment phase involves estimating the frequency and magnitude of flows, typically in terms of total volume and peak discharge at the fan apex. Numerical modeling allows estimation of potential runout extent and impact intensity across the fan surface in terms of flow velocity and depth. Considerable experience and judgement is needed to calibrate the numerical models, interpret the raw model output, and create a comprehensive debris-flow/flood hazard map that considers a range of possible volumes, rheologies, and avulsion scenarios. Output of the hazard assessment is an estimated occurrence probability, spatial impact probability, and impact intensity, which varies across the hazard area, for each debris-flow/flood scenario.

Table 1. Quantitative risk management framework (adapted from Fell et al. 2005, VanDine 2012).

| | | | | | |
|---|---|---|---|---|---|
| Hazard Assessment | Risk Assessment | Risk Management | **Risk Communication and Consultation**<br>Informing stakeholders about the risk management process | **1. Scope Definition**<br>a. Recognize the potential hazard<br>b. Define the study area and level of effort<br>c. Define roles of the client, regulator, stakeholders, and Qualified Registered Professional (QRP)<br>d. Identify 'key' consequences to be considered for risk estimation | **Monitoring and Review**<br>Ongoing review of risk scenarios and risk management process |
| | | | | **2. Geohazard Analysis**<br>a. Identify the geohazard process, characterize the geohazard in terms of factors such as mechanism, causal factors, and trigger factors; estimate frequency and magnitude; develop geohazard scenarios; and estimate extent and intensity of geohazard scenarios. | |
| | | | | **3. Elements at Risk Analysis**<br>a. Identify elements at risk<br>b. Characterize elements at risk with parameters that can be used to estimate vulnerability to geohazard impact. | |
| | | | | **4. Geohazard Risk Estimation**<br>a. Develop geohazard risk scenarios<br>b. Determine geohazard risk parameters<br>c. Estimate geohazard risk | |
| | | | | **5. Geohazard Risk Evaluation**<br>a. Compare estimated risk against risk tolerance criteria adopted by the governing jurisdiction<br>b. Prioritize risks for risk control and monitoring | |
| | | | | **6. Geohazard Risk Control Assessment**<br>a. Identify options to reduce risks to tolerable levels<br>b. Select option(s) with the greatest risk reduction at least cost<br>c. Estimate residual risk for preferred option(s) | |
| | | | | **7. Action**<br>a. Implement chosen risk control options<br>b. Define and document ongoing monitoring and maintenance requirements | |

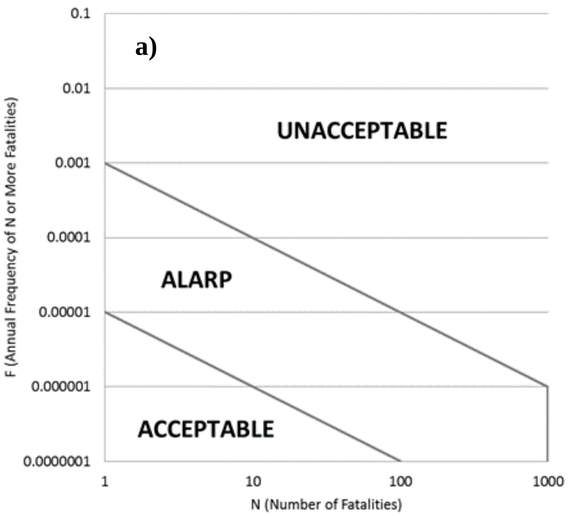
The risk assessment phase involves identifying elements (e.g. buildings, roads, bridges, pipelines) that could be impacted by a debris flow/flood, estimating risk, and comparing the estimated risk to risk tolerance criteria. The comparison of risk estimates with risk tolerance criteria addresses questions like: “Is my community safe enough?”, and “Is debris-flow/flood protection needed?”

Elements at risk are identified by overlaying the hazard map with a map of buildings and infrastructure. Risk of loss of life (safety risk) can be estimated for individuals or groups. Individual risk is an estimate of the annual likelihood that a specific person is killed by a debris flow/flood. Typically, individual risk is estimated at each building for the person most at risk, who is typically the person who spends the longest time per year within the hazard zone. Group risk (societal risk) is an estimate of the number of people who would be killed by each debris-flow/flood scenario. Risk is estimated using Equation 1. Individual risk is the sum of risks estimated for each debris-flow/flood scenario. Group risk considers the number of fatalities (N) that would be lost during each debris-flow/flood scenario. Group risk is typically represented graphically on an F-N plot, which displays the cumulative annual probability (F) of N or more lives being lost (Fell et al. 2005).

$$R = P(H) * P(S:H) * P(T:S) * V * E \tag{1}$$

In this equation, *R* (safety risk) is the probability that a person is killed by the specific debris-flow/flood scenario; *P(H)* is the probability per year that the debris-flow/flood scenario occurs; *P(S:H)* is the probability that the debris-flow/flood scenario reaches the element at risk; *P(T:S)* is the probability that the person is present, given the building or infrastructure is impacted; *V* is the probability that the person is killed, given they are impacted; and *E* is the number of people exposed to the hazard, taken as 1 for individual risk.

Risk tolerance is treated as a social, rather than a technical, question that is to be defined by decision makers who represent society’s interests. In practice, risk tolerance thresholds referenced in Western Canada (Fig. 1) have been introduced by landslide risk management professionals and adopted by municipal managers with varying degrees of public input. The thresholds are based on those developed in Hong Kong for landslide risk, and those developed in the UK, Australia, The Netherlands, and the United States for risk related to large industrial accidents and water retaining dams (Porter and Morgenstern 2013, Baecher 2015, Hungr et al. 2016). Risk tolerance thresholds adhere to principles described by IUGS (1997), including: landslide risk should not be significant compared to other risks to which a person is exposed in everyday life; society is intolerant to incidents that cause many simultaneous casualties; higher risks are tolerated for existing rather than planned projects; and risk should be reduced wherever reasonably practicable (ALARP principle).



**b)** **Individual risk tolerance thresholds**
Annual probability of death to the individual most at risk

**New development**
1:100,000 ($1x10^{-5}$)

**Existing development**
1: 10,000 ($1x10^{-4}$)
Similar to an individual’s risk of death in an automobile accident in the United States or Canada

Fig. 1. (a) Group (societal) risk tolerance criteria for landslides commonly referenced in Western Canada (GEO 1998); (b) Individual risk tolerance thresholds commonly referenced in Western Canada (Porter and Morgenstern 2013).

If the risk assessment identifies that debris-flow/flood risks are unacceptable, risk management may be pursued. The risk management phase refers to design and implementation of mitigation measures or non-structural options like monitoring and evacuation protocols, education, and land-use planning. The risk management assessment addresses questions like, “How much should my community invest in debris-flow/flood mitigation?” and “What impacts will debris-flow/flood mitigation have on my community?” The assessment involves identifying options to reduce risk and selecting a preferred option that optimizes cost and benefit. The preferred option often includes a combination of structural and non-structural measures.

The quantitative risk framework is used to select the location and size of the mitigation measures. Using an iterative process, the designer selects a combination of measures that reduces risk to tolerable levels, considering the full range of possible risk scenarios including different magnitude classes and avulsion scenarios. Structures are sized to manage a “design event” defined for the structure (i.e. the debris-flow/flood magnitude that controls sizing of the mitigation structure). Often the structure’s design event is the largest magnitude debris flow/flood that results in intolerable risk. Where it is not feasible to construct mitigation for large magnitude events, structures are sized for the maximum event that can feasibly be controlled, and larger, lower-probability scenarios are managed with non-structural measures like monitoring and evacuation.

The QRM process provides answers to basic risk management questions, identifies priorities, allows direct comparison of different hazard types, and can be used to demonstrate and communicate the decision-making process. However, for projects requiring some form of structural mitigation, a primary outcome of the QRM process is selection of the structure’s design event. When the QRM process is used, the structure’s design event is site-specific and corresponds to the number and distribution of people in the hazard zone. In general, smaller structures (e.g. designed for the 100-year return period event) are derived for areas that are infrequently occupied, while larger structures (e.g. designed for the 1,000 or even 10,000-year return period event) are derived where debris flows/floods have potential to impact an urban area (Fig. 2).

From a worldwide hazard management perspective, the QRM process is rare (Lateltin et al. 2005, ASI 2009, MOC 2000). Most geologic hazard types, including landslide and flood hazards in most countries, are managed using a prescriptive standards-based process. For example, in Canada flood control elements (e.g. dikes, conveyance structures) are commonly designed for 100-year to 200-year return period flood stages plus freeboard regardless of the number and distribution of elements at risk, and buildings are designed to resist the 2,475-year return period earthquake loads (NRC 2015). In Switzerland, the 100-year return period debris flow/flood is commonly taken as the design event for structural mitigation measures (Lateltin et al. 2005). This prescriptive standards-based process is much simpler to systematically apply, but it ignores the number of people at risk and is not flexible enough to consider site-specific conditions that would justify use of a larger or smaller mitigation design event. The standards-based approach also cannot be used to prioritize mitigation, which is a substantial limitation in Western Canada, where there currently are many developed fans without risk management measures, and limited funding available to allocate to such measures.

Fig 2. An undeveloped fan (left) and a highly-developed fan (right) in Alberta, Canada, both prone to debris floods. A prescriptive standards-based process would call for the same design event (100 or 150 years in the case of Switzerland, Japan or Austria) for mitigation for each fan. The QRM process would prescribe a relatively small structure for fan A, and a major structure or series of structures for fan B.

## 3. Application of the Quantitative Risk Management Process

The QRM process has been applied at more than 50 sites across British Columbia and Alberta for debris-flow/flood hazards during approximately the last ten years. Typically, where risk is found to be intolerable, the process is used to both inform and justify applications to government for mitigation funding, and to select the size of structural mitigation measures. However, the final, most-important step of risk management, which is construction or implementation of the mitigation design (item 7, Table 1), is often not completed. Local governments responsible for managing the hazards typically have a strong political mandate to protect their citizens, but they rarely have the financial resources to fund structural mitigation measures. Local governments compete for funding from a variety of provincial and federal grants, which can take years and for which there is no guarantee of success. Winning a grant is a function of many factors that may be unrelated to urgency of need for a particular community (e.g. number of applicants, knowledge of applicant, size of existing development and associated infrastructures, timing of submittal). While they wait for provincial and federal funding, local governments manage the situation as best they can with limited resources, often with strategies like educating residents about hazard and risk zones, empowering individuals to protect themselves, developing emergency response plans, and sometimes devising a warning system whose enforcement is largely voluntary and not associated with evacuation orders. Where the QRM process exposes levels of risk that are intolerable, but that cannot be managed under current policies and financial resources, it can lead to unintended hardships such as loss of property value. At the same time, avoiding assessment of identified geohazards can expose local governments to liability, leading to a 'catch-22' situation. QRM offers some solution to this conundrum in that it provides a defensible process for decision-making, even when solutions have yet to be realized.

In an ideal world, all hazard types affecting a province or nation would be characterized, prioritized, and managed using a single comprehensive framework that allocates resources based on need, so that resources and mitigation are provided to the communities exposed to highest risks. Unfortunately, although western Canada is beginning large scale efforts to prioritize areas based on risk to inform risk management decisions, the risk management process is not yet mature. Fig. 3 provides an indication of risk and estimated mitigation cost for ten debris-flow/flood hazard sites where the QRM process has been used by the authors. It demonstrates that funding is currently not preferentially allocated (or available) to the highest risk communities, and that there must be other factors that influence which communities acquire funding for debris-flow/flood mitigation.

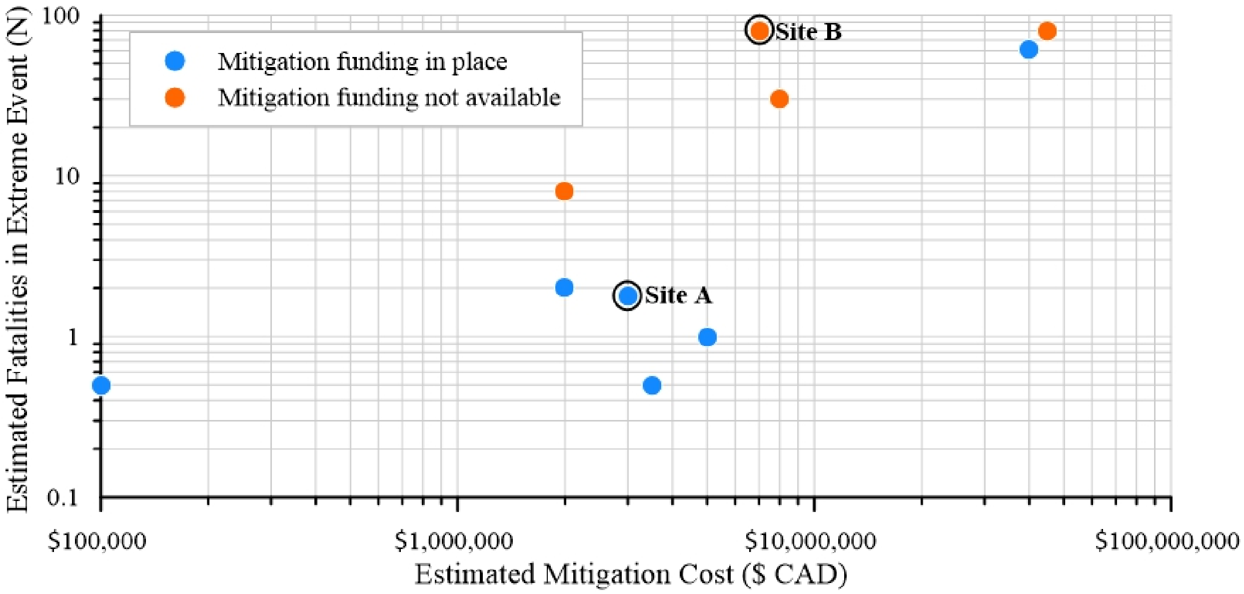


Fig 3. Each point is a debris-flow or debris-flood hazard site in Western Canada where the QRM process has been applied. Y-axis is the estimated number of fatalities that could occur during the most extreme event considered in the risk assessment (typically a 3,000-year or 10,000-year return period event) and is a proxy for risk. X-axis is the estimated mitigation cost in Canadian dollars, estimated based on a conceptual mitigation design that would reduce risk to a tolerable level.

The following two sites are each at extreme ends of the risk management spectrum, and while they may not illustrate 'typical' examples, they do highlight some of the issues:

**Site A** is a popular tourist destination in the Vancouver, British Columbia metropolitan area. The parking lot is in the distal region of a debris-flow fan. Small debris flows and floods that have eroded the fan surface have occurred during the past few decades, but a significant debris flow has not reached the parking lot in historical times. A debris-flow hazard and risk assessment identified that debris flows would rarely impact the parking lot (~3,000 year return period) and that parking lot impact could cause one to two fatalities (N 1 to 2). Individual risk at this site is acceptable (Fig. 1). Group risk plots in the As Low As Reasonably Practicable (ALARP) zone on the group risk tolerance diagram (Fig. 1), implying that risks should be reduced if the cost of mitigation is not disproportionate to the risk reduction achieved. The QRM process identified that debris-flow mitigation was not required, but indicated that the ALARP principle should be applied. The site is owned by a large and well-funded municipal government, who have applied the ALARP principle by designing flexible net debris-flow barriers to protect the parking lot. The proposed barriers are 4 m tall, more than 200 m long, and will cost several million dollars. Funding, provided by the municipality, is in place for the proposed mitigation, and construction is planned to begin in 2019.

**Site B** is a residential community in a rural area of Squamish-Lillooet Regional District, British Columbia. The community includes 114 occupied lots that are located on an active debris-flow fan (see Jakob 2019, this volume, for a summary of the risk profile). Debris flows have occurred frequently since the community was developed, including three debris flows between 2004 and 2013 that destroyed vehicles and buildings, but luckily did not result in loss of life. The QRM process identified that 76 residences exceeded the individual risk tolerance threshold of 1:10,000 (Fig. 1), and 18 residences exceeded 1:1,000 annual risk of fatality. Group risk plotted entirely within the unacceptable zone, including a scenario indicating that a 3,000-year to 10,000-year return period debris flow could result in up to 80 fatalities. The risk management phase of the QRM process identified that the 10,000-year return period debris flow would need to be addressed by structural and non-structural mitigation to move group risk into the ALARP zone on the group risk plot (Fig. 1). It was recognized that funding to protect against a 10,000-year event was unlikely to be available, so structural mitigation designs were developed for both a 1,000-year and 10,000-year design event. The preferred mitigation option was a debris-flow conveyance channel (which was possible due to the steep fan gradient), with estimated cost ranging from \$4 Million to \$9 Million, depending on the selected design event. The local government does not have resources to provide this mitigation, but has spent the past several years seeking funding from provincial and federal grants. Unfortunately, they have not yet been successful in acquiring mitigation funding.

## 4. Quantitative Risk Management Benefits and Challenges

At each site for which it has been applied, the risk management phase of the QRM process has consistently identified an appropriate design event and preferred mitigation option, but has not frequently led to implementation of structural or non-structural mitigation measures. Therefore, it can be questioned whether the recent adoption of the QRM process at individual sites has improved management of debris-flow/flood hazards and risks on a society-wide scale. The short-comings could be a result of Canada's fragmentary system of managing and funding natural hazard mitigation. Alternatively, and as long as grants are being issued from provincial and federal sources, it may simply be a matter of time until funding reaches high-risk communities. At times, it appears that a systematic risk-based provincial debris-flow prioritization should have preceded application and refinement of the QRM process at specific sites. Irrespective, the past decade of experience has highlighted several important benefits and challenges associated with the QRM process, as described in the following paragraphs.

When compared to a prescriptive standards-based process for debris-flow/flood hazard management, the QRM process has the following benefits:

- **Prioritization** – The QRM process provides a way for local government to compare and prioritize different hazard types and sites, and to justify mitigation funding applications to higher orders of government. This is particularly helpful in large, sparsely populated areas where there are more hazard areas than can be feasibly managed by a standards-based process. Costs and benefits of hazard management can be optimized, which can reduce long-term hazard management costs.
- **Site-specific** – The QRM process is specific to the hazard, elements at risk, stakeholders, and objectives of the community at the particular site. This leads to debris-flow/flood risk management that is targeted for the local risk profile. Hazards and risks are typically well understood at the conclusion of the QRM process.
- **Consideration of non-structural measures** – Non-structural mitigation measures, such as public education, land use planning, warning and evacuation protocols, and emergency response planning can substantially reduce debris-

flow/flood risk in some cases. The QRM process is well suited to demonstrate the level of risk reduction achieved by these measures, allowing them to be considered alongside structural mitigation.

- **Communication** – The QRM process provides a clear language to define the factors that contribute to debris-flow/flood risk. This promotes informed discussion of risk and risk management options by community members and decision makers and promotes community resilience. QRM as a communication tool could be thought of as a by-product to the products described in this paper, but improved communication may be the most effective risk management step.

The following points describe challenges of the QRM process at achieving risk reduction:

- **Complication** – Due to its flexibility, the QRM process can be difficult and expensive to implement and it requires input from the full range of stakeholders and specialists to execute. Most processes that are intended to be applied by a wide range of people and environments (e.g. building codes) are intentionally designed to be simple and rigid to facilitate adoption and compliance. Experts are required to carry out the QRM process, and experts are rare and expensive.
- **Limited adoption** – Currently only a handful of geotechnical consulting firms are familiar with the QRM methods as they pertain to debris flows and debris floods. A more widespread adoption is desirable to promote homogenous application. Similarly, decision makers need to be educated about the advantages and disadvantages of the QRM process to allow adaptation at the local government level.
- **Lack of context** – In theory, the QRM process would allow multiple geohazard types to be directly compared to a consistent risk tolerance threshold. However, in practice, debris-flow/flood hazards are mostly assessed independently from other geohazard types. The risk tolerance thresholds that have been referenced lead to selection of mitigation structure design events (e.g. 300-year, 1,000-year, or even 10,000-year return periods) that are much more stringent than is applied for other geohazards (e.g. floods, snow avalanches). This could lead to inappropriate allocation of society's resources to debris-flow/flood hazard sites and away from other higher-risk sites or hazard types where risk tolerance thresholds have not yet been applied.
- **Communication challenges** – The QRM process is promoted as a tool for decision making, but it requires decision makers who are well-informed about the QRM process and the origin and implications of risk tolerance thresholds. The QRM process is more complex than prescriptive standards-based methods, and it frequently refers to complex mathematics (e.g. $1 \times 10^{-4}$) that is unfamiliar to many people. Improved tools are needed to provide context and explain the "real" meaning of the quantities referred to by the QRM process.
- **Promotes stagnation** – In its current application, the QRM process may lead to designs that are too expensive to be funded, which leads to stagnation and a lack of risk management implementation. This is primarily due to strict risk tolerance thresholds that have been adopted (Fig. 1) and because extreme events (e.g. 1,000-year and 10,000 year) tend to control group risk (Jakob et al. 2018).

## 5. Towards a More Effective Debris-Flow/Flood Risk Management Process

From a worldwide hazard management perspective, the QRM process is rare. However, it is increasingly being adopted by western Canadian municipalities for management of debris-flow/flood hazards and risks due to its important benefits, including flexibility to meet needs of a particular community, utility as a prioritization tool, consideration of event consequences, and ability to directly compare non-structural to structural risk management measures. Theoretically, the QRM process is an effective tool for managing debris-flow/flood risk on a societal level, but applications to date have highlighted practical challenges, such as lack of funding, expertise, and momentum to construct mitigation, that need to be overcome. The following could improve QRM practice in Western Canada, and facilitate adoption of the QRM process in other regions and for other hazard types:

- Shift responsibility for geohazard (including debris-flow/flood) risk management from the municipal to provincial level. This was the case prior to 2003 in British Columbia, and may soon be the case in Alberta as far as steep creek hazards are concerned. Higher levels of government have more resources and are better suited to view hazards at a particular site in context with other hazard sites and hazard types.
- Adoption of consistent risk assessment and risk tolerance guidelines by provincial or national government that are applicable to all geohazard types. This will help promote distribution of resources to the most critical locations and hazard types.
- Educate geoscientists and engineers about the QRM process and its application, to address the current shortage of qualified practitioners.

- Develop tools to improve communication of QRM concepts, allowing the public to understand debris-flow/flood risks in the context of other hazard types and risks faced in everyday life.
- Develop strategies to promote action and implementation of risk reduction measures (where mitigation investments are appropriate). For example, at existing developments, this may include a shift away from defining a risk tolerance threshold that must be met, towards quantifying the risk reduction that could be achieved by various economically-feasible mitigation options. This may also include adopting a risk-informed decision making approach, which considers risk evaluation as one of many decision inputs, rather than an approach focused on precisely meeting the strictly-defined risk tolerance threshold line.
- Develop funding mechanisms that encourage short-term action with available resources, and long-term action through a disaster prevention fund allocated according to risk-based regional geohazard prioritization. Note that large-scale, regional geohazard risk prioritization has begun in British Columbia, setting the stage for policy review within the next few years.

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