Review of Landslide Management in British Columbia

Ministry of Forests, Lands and Natural Resource Operations

Province of British Columbia

April 16, 2013

Acknowledgments

This report is an internal review of the current practices associated with the management of landslides in BC. The review was initiated at the request of the Minister of Forests, Lands and Natural Resource Operations in response to the damaging landslides and debris flow events of the summer of 2012, including the fatal landslide at Johnsons Landing on Kootenay Lake.

Staff of the Ministry of Forests, Lands and Natural Resource Operations, Ministry of Justice (Emergency Management BC), Ministry of Transportation and Infrastructure, and other ministries contributed to this review. In particular we would like to acknowledge the contributions of Peter Jordan, Dwain Boyer and Neil Peters of FLNRO; Ralph Morhmann and David Curtis of EMBC; and Don Gillespie and David Fisher of MOTI. In addition, hydrologist Arelia Werner of the Pacific Climate Impacts Consortium has provided a summary of current climate change projections and the potential impact on the frequency and severity of landslides in British Columbia. We wish to thank these individuals for their contributions on the subject of landslide hazard management in BC.

The authors of the report offer our condolences to those affected by the events of 2012. It is our hope that this document will guide discussions which will lead to improved landslide hazard management in BC.

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Top – Johnsons Landing/Gar Creek
Bottom – Fairmont Creek

EXECUTIVE SUMMARY

In June and July 2012 numerous landslide events occurred across southern British Columbia. Most events occurred in the backcountry, without significant negative impacts to infrastructure or people. However, some populated and developed areas in the fore country or valley bottoms experienced significant damage to private property and public infrastructure. A landslide at Johnsons Landing in the Kootenays resulted in four fatalities.

On July 17, 2012 the Minister of Forests, Lands and Natural Resource Operations requested a review of how landslide hazards are managed in BC and the circumstances of the most damaging events of 2012 to identify lessons to be learned. The review examined the management of landslide hazards under the four pillar approach of preparedness, mitigation, response and recovery. The review found that generally the greatest effort by government staff and other stakeholders is directed at preparedness as success in preparedness sets up and reduces pressure on the remaining three pillars.

Natural hazards, of which landslides are only one type, occur in most areas of BC. The province is typically steep and with limited land readily amenable to development. Long-established communities are exposed to some risk of hazards from flooding and landslides. Both small and large landslide events have impacted numerous communities across the province for over 100 years, and many lessons have already been learned in managing new developments. Previous reviews on a fatal landslide in North Vancouver in 2005 and the Testalinden Dam Failure near Oliver in 2010 have provided recommendations and spurred some new initiatives in the province. Recommendations herein are made to build on these previous reviews.

The most damaging events in 2012 occurred near Sicamous, Johnsons Landing and Fairmont Creek. Each of these events had different circumstances, however high precipitation and previous winter high snowpacks were common contributing trigger mechanisms. The Sicamous and Fairmont Hot Springs sites were known debris flow or flood hazard areas with existing management tools in place designed to mitigate the risks. In Johnsons Landing, a landslide was initiated on relatively pristine steep terrain above the small remote community.

Recent climate change models project that British Columbia will experience more frequent and severe rainstorm events and years with higher snowpacks at high elevations. The models also project earlier onset of freshets and more prevalent summer droughts and wildfires. These projections are in line with observed trends over the past several decades and have the potential to increase the likelihood of landslides occurring. Given ever-increasing pressure for more development in areas potentially exposed to landslide hazards, these projections will need to be taken into consideration in the preparation and planning of measures to reduce the landslide risks to existing and future developments.

The best practice to reduce landslide hazard risks to people and infrastructure is to be aware of and avoid the hazard altogether or reduce exposure and risk. Landslide and flood hazard maps have been created in the past to help inform development decisions however, the management of the information is relatively uncoordinated making it difficult to access. Furthermore, resources for mapping programs have been reduced over time. Key to preparedness for landslide (and flood) hazards is a modern and comprehensive all-hazard mapping program.

As noted above, mapping programs help to identify developments and resource use proposals which should be studied through more detailed hazard mapping and assessments. Some guidelines for landslide and terrain stability assessments have recently been published in collaboration between government and professional associations in BC. However, outstanding issues of reaching agreement on a common definition of what constitutes safe and acceptable risk and further clarifying the scope of the assessments require further work and direction.

Local and provincial government staff and the public would benefit from greater awareness and training into landslide hazards near their communities. Currently local governments are required by law to write and maintain emergency response plans for events such as landslides and other natural hazards as part of their emergency preparedness roles. The proper application of mapping and hazard information to support timely and effective early response depends on users' competence and field recognition skills. Preparedness for various types of emergencies is generally well set up in British Columbia however the landslide preparedness appears to be somewhat slight and recommendations have been made to improve in this regard.

Where new or existing developments and infrastructure are identified as being at risk of landslide hazards, various physical methods can be employed to mitigate the risks. Such measures include the use of deflection berms and catch basins, as well as prediction and early warning systems. These approaches have been implemented in British Columbia and worldwide, however high costs and difficult implementation and maintenance has generally meant that these methods are only used as a last resort in densely populated areas where there is a high known probability of damaging landslides or other natural hazards. In rural areas with low population densities, local governments may be challenged to acquire the funding to construct and assume responsibility for the long term ownership of operation and maintenance of the works. The presence of old and unmaintained structures as well as requirement for some new structures presents liabilities to public safety and to governments. Recommendations have been made to address the funding models to work around these challenges.

The *Emergency Program Act* details the roles and responsibilities of local governments and authorities, and provincial agencies in response to emergency events. Typically the various groups work together with shared responsibility to provide optimum response and service to communities and individuals. For example, in the Kootenay Boundary Region, long standing relationships between staff in provincial ministries and local governments have resulted in landslide and flood event response rosters which are updated annually with specialist staff and a phone contact list, to provide rapid response time of the most local and appropriate individuals in a coordinated fashion. This system has proved to be effective in responding to many landslide and flood emergencies. Recommendations are made to continue efforts to increase public awareness of who to contact during emergencies, maintain the necessary emergency responder training, and ensure that all regions of the province maintain coordinated landslide and flood response rosters.

Disaster Financial Assistance is made available in certain cases under established guidelines and thresholds to support response and recovery efforts. As well, the federal government may provide additional funding for these efforts under its own programs.

A full list of recommendations made in this review is summarized below. The recommendations are grouped into different categories and presented in the sequence they appear in the body of the report.

Background:

Recommendation 1: The Province should update the terms of reference for the inter-ministry Landslide Policy and Mitigation Working Group to include responsibility for overseeing the implementation of the approved recommendations from this review, including undertaking detailed cost/benefit analyses of individual recommendations where appropriate. The membership of the working group should be renewed to ensure it has capacity for providing ongoing provincial leadership on landslide management issues in BC.

Climate Change:

Recommendation 2: Provincial and local governments should consider projected impacts of climate change on the level of landslide risk expected over the life of any proposed developments, resource use activities and the construction and maintenance of infrastructure projects when authorizing these activities.

Preparedness (Risk Identification):

Recommendation 3: The Province, in cooperation with local governments and qualified professionals, should investigate the feasibility of reinstating a mapping program to update and maintain maps of landslides, debris flows, alluvial fans and related natural hazards on both public and private lands. The program should place emphasis on mapping areas of greatest potential risk to public safety.

Recommendation 4: Pursuant to the recommendation in the 2008 Coroner's Report, the Province, local governments and professional associations should engage in discussions to explore the feasibility of building a publicly accessible central databank of natural hazard information.

Recommendation 5: The Province should work with the Association of Professional Engineers and Geoscientists of British Columbia, the Union of BC Municipalities, academia, industry and other stakeholders to identify a provincial standard for minimum acceptable risk thresholds for landslide hazards which would be applicable to Crown land dispositions, new developments, subdivision approvals and the design of mitigative works to protect existing development.

Recommendation 6: Agencies with responsibility for authorizing or regulating resource development activities, including the design, construction and maintenance of roads in steep, potentially unstable terrain, should be explicitly required to consider the landslide risks to public safety, both upslope and downslope of the activity being authorized or regulated. Policy direction should be provided to staff in these agencies with respect to the use of qualified professionals to evaluate landslide risks.

Preparedness (Subdivisions and Land Development Approval):

Recommendation 7: The Province should work with the Union of BC Municipalities and the Association of Professional Engineers and Geoscientists of BC to prepare a comprehensive training package for provincial and local government staff summarizing landslide hazard identification and what to do when hazards are identified.

Recommendation 8: Land Officers involved in the disposition of Crown land and provincial approving officers should receive training and policy direction in recognizing and managing landslides and related natural hazards. Local government development and land use staff should also receive their own training and policy direction on managing landslides.

Recommendation 9: The Province should encourage local governments to enact bylaws and policies to guide development away from areas at risk of landslides and to require the use of qualified professionals to assess the risk in hazard zones.

Recommendation 10: With regard to public education, the Province should undertake a review of available best practices, reference materials and websites information used in other jurisdictions in the management of landslide risks.

Recommendation 11: The Province should update its websites on public education and information related to landslide risks, awareness, mitigation, response and recovery, and undertake ongoing outreach activities to raise awareness and promote the use of these websites.

Mitigation of Risk:

Recommendation 12: FLNRO should complete its recent Terrain Stability Guidance Project to develop policies and other guidance material for staff working in Crown lands to ensure that terrain stability risks are managed on an appropriate basis.

Recommendation 13: The Province should identify standards for landslide mitigation works design and maintenance, as well as consider legislative changes to enable regulation of ownership and operation of landslide protection works using the model used for regulating flood protection works under the *Dike Maintenance Act.*

Recommendation 14: The Province and the Union of BC Municipalities should explore new funding models to better facilitate the ownership of orphan landslide and flood mitigation structures, and the construction of new flood and landslide protective measures.

Emergency Response and Recovery:

Recommendation 15: The provincial and local governments should update their websites and other information media to ensure they provide clear guidance to the public on emergency phone numbers and purposes of each call centers.

Recommendation 16: The Province, in collaboration with provincial ministries and local governments, should establish annually updated landslide and flood response rosters of trained persons in each region.

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INTRODUCTION

The winter of 2011-2012 produced a high snowpack in the southern interior of British Columbia and was followed by record spring rainfalls in the Okanagan and Kootenay regions. The preceding year also experienced a high snowpack and above normal precipitation. These two wet years triggered several landslide events in June and July 2012 across southern British Columbia. Many dozens of landslides occurred in unpopulated backcountry area where impacts were largely limited to damage to resource roads. A few events occurred in more populated areas where they caused significant damage in communities such as Sicamous, Johnsons Landing and Fairmont Hot Springs.

In the community of Johnsons Landing on the east side of Kootenay Lake some residents observed uncharacteristic pulsating mud and water flows with debris in the Gar Creek gully upslope of the community in the day or two preceding the event. Their concerns prompted them to send an email message of alarm and appeal for advice to fellow community members. The next day this email was relayed to a provincial government hydrologist. Unfortunately, the hydrologist was doing fieldwork that morning and did not read the email message until later that day. By the time the message was read a landslide and debris flow had travelled down Gar Creek and jumped onto a bench at a sharp bend in the creek destroying houses and killing four people. Emergency responders and governmental professionals immediately acted to assess and evacuate the hazard area and worked to recover the missing persons.

The events at Johnsons Landing and elsewhere attracted considerable public, media and political interest into landslides management practices in BC. This attention raised questions regarding the circumstances surrounding the individual landslides and what could be done to reduce the risks and consequences of future landslides in the province.

PURPOSE OF THE REPORT

On July 17, 2012 the Minister of Forests, Lands and Natural Resource Operations requested an internal review of the recent landslide events to identify lessons to be learned and to prepare recommendations for the Province to consider which will improve landslide risk management in BC. The review considers the circumstances of select historic landslide events and examines the potential for climate change to impact the frequency and severity of future events. Finally the review summarizes and assesses current practices in landslide risk management in BC including risk identification, assessment and mitigation, and considers general roles and procedures in landslide response and recovery.

BACKGROUND

NATURAL HAZARDS IN BRITISH COLUMBIA

The geological history, topography and climate in British Columbia expose communities, individuals and property to a variety of natural hazard risks. Similar circumstances also exist in places like the European Alps, Japan, the Andes, and other parts of North America. Landslides are just one type of natural hazard within this suite of hazards which also include:

- floods,
- wildfires,
- extreme weather events (lightning, hailstorms, tornadoes, hurricanes, windstorms, etc.),
- snow avalanches,
- earthquakes,
- tsunamis, and
- volcanic eruptions.

These natural hazards have different probabilities of occurrence and different consequences. For example, damaging earthquakes are infrequent but if a large earthquake occurs near an inhabited area very large consequences are possible. In addition earthquakes may trigger landslides and tsunamis.

Floods and wildfires are arguably the most commonly occurring hazards in BC and cause the greatest amount of damage to property and infrastructure. However, they seldom result in death, partly because of well-organized programs to manage the risks and because they are relatively slow to initiate and are quite predictable. By contrast snow avalanches occur suddenly and cause the greatest number of deaths in most years, mainly to backcountry recreationists, but cause relatively little property damage. Most risks to the general public from snow avalanches are to travelers along highways, and these risks are managed effectively by the Ministry of Transportation and Infrastructure.

This document focuses primarily on landslides but does provide some comments on related hazards such extreme weather events, floods and earthquake-induced landslides.

In British Columbia natural hazards, which pose different types of risk to public safety, property and infrastructure are managed in different ways by government agencies, corporations, and individuals. However, most use the four pillars approach to natural hazard management: Preparedness, Mitigation, Response and Recovery. The four pillars are led by and involve different local, provincial, First Nation and federal government agencies, as well as volunteer search and rescue groups. There are numerous areas of overlap and the roles are typically fulfilled through collaborative relationships and processes as described in later sections.

LANDSLIDES

On average, landslides result in the death of about one person per year in British Columbia. On this basis they could be considered a less significant risk relative to some of the other natural hazards. However, fatal landslide incidents are treated as high profile disasters because they sometimes kill people in their own homes, with little or no warning and are dramatic to observe. They also cause considerable long lasting damage to property and infrastructure. Management of landslide risks is a major consideration in land use planning, zoning, subdivision, building permitting, and construction of highways and industrial infrastructure.

Landslide Types

"*Landslide* is a generic term used to describe the downward movement of soil, rock, or other earth material under the influence of gravity" (Geertsema et al., 2010). There are many kinds of landslides – they are named on the basis of the type of material (e.g. rock, debris, earth) and the type of movement (e.g. slide, fall, flow, avalanche). This report will not attempt to give a thorough description of landslide classification as such reviews are available elsewhere (e.g. Cruden and Varnes, 1996). Some common types of landslides which can present risks to public safety in British Columbia are briefly described below.

Debris flows are probably the most common type of landslide which can present risks to dwellings, other buildings, and infrastructure in valley bottoms. A debris flow is a saturated slurry of earth, rock, and vegetation, which most often flows in a confined channel. It can originate as a debris slide which then enters a gully or steep channel, or it can result from an unusual discharge of water entering a steep channel and entraining sediment from the channel bed and banks. Most debris flows terminate on alluvial fans; most steep (over about 5°) fans were formed in whole or in part by repeated debris flows. Alluvial fans are subject to a continuum of hazards, from debris flows (which have more sediment than water by volume), to debris floods (which have more water than sediment), to floods (Wilford et al., 2009). Many communities in British Columbia were constructed long ago on alluvial fans as these are more gently sloped areas amid steep mountain slopes, and typically contain a surface water source.

Debris slides and *debris avalanches* are landslides consisting mainly of unconsolidated earth materials ("soil") which occur on open slopes, usually in an unsaturated state. These landslides can move at rates from very slow to very rapid, and the movement is usually more or less planar. Debris avalanches refer to events which travel very rapidly, and may have long runout distances.

Rock slides and *rock avalanches* are similar, consisting of bedrock sources. They can be extremely large. Notable examples are the Hope slide of 1965, and Alberta's Frank slide of 1903.

Slumps are a type of complex landslide in which the failure plane is more or less circular. Slumps can occur in cohesive (clay-rich) soil, or in weak bedrock. The rate of movement is usually slow. Many slumps persist for centuries or millennia, moving very slowly or not at all, until they are reactivated by some disturbance or by unusually high groundwater levels. Slumps are common in the Prince George area and especially in the Peace region.

Rockfall is a common process on steep or vertical rock slopes, both natural and constructed. Rockfall is the most common hazard affecting highways in steep terrain. It can range from individual boulders, to large masses of rocks which completely cover the highway.

A mudslide is a particular type of landslide which is very rare in mountainous regions of BC. The word “mudslide” should not be used as a general term for landslide.

Landslide Triggers

In general, most landslides are caused by an increase in the supply of water, either high groundwater levels or soil moisture contents in the case of deep-seated landslides, or surface flows and near surface flows leading to a gully in the case of debris flows. Therefore, most landslides occur in the wet season, which in the interior is the snowmelt period of April to June; at the coast this occurs in the fall and winter. Landslide hazard risk can be increased by any development activity which leads to an increased supply of water to a potentially unstable location. Concentration or diversion of water by roads is a very common cause of shallow debris slides and debris flows in the interior. At the coast, loss of root strength following logging is a common cause of landslides. Research in forest geomorphology has shown that forest development typically increases the incidence of landslides by 5 to 10 times (Jordan et al., 2010). Landslides can also be caused directly by mechanical excavation which removes material from the base, or adds material to the top of a slope.

Landslides may also be triggered by seismic activity such as earthquakes and volcanoes.

EXAMPLES OF LOCAL HISTORIC LANDSLIDE EVENTS

Many large landslides occurred soon after deglaciation about 12,000 years ago. Landslide scars, hummocky deposits in valley bottoms, and raised or inactive debris flow fans from this period are common throughout BC. These features are, in most cases, of little or no concern, and do not indicate a continuing landslide hazard under present climatic and geologic conditions. Most were formed in early post-glacial times as over steepened valley sides adjusted. However, prehistoric landslides which have been dated as younger than the early postglacial period may be of concern, because they indicate that there could be a landslide hazard under present conditions.

Ridge-top cracks and other signs of previous slow movement exist above many large landslides (e.g. Frank, Hope and Mount Meager landslides). However, such ridge-top cracking is common throughout mountain ranges in BC and elsewhere, and the vast majority of such sites have never produced rapid landslides in historic time.

Some landslide incidents that have occurred in or near British Columbia, focusing on events which have caused fatalities or serious damage to property and infrastructure, include:

- The Frank slide was a rock avalanche which buried part of the town of Frank, Alberta in the Crowsnest Pass in 1903, killing at least 70 people. Signs of instability, including cracks in the mountaintop and movement in the coal mines, had been observed before the landslide. Underground coal mining at the base of the mountain may have contributed to the failure. There is ongoing movement in the mountaintop, which is being monitored with geotechnical instruments.

- The Jane Camp rock avalanche of 1915 caused 56 deaths in a mining camp near Britannia Beach (Evans and Savigny, 1994).

- The Hope slide of 1965 is one of the largest landslides to have occurred in Canada in historic time, with an estimated volume of 47 million cubic meters. It caused four fatalities on Highway 3. Like most very large landslide events, it was a rock avalanche and it originated on a mountain slope which had indications of ongoing instability, including ridge-top cracks and previous smaller landslides.

- Camp Creek near Three Valley Gap (west of Revelstoke) experienced a debris flow in 1968 which apparently originated in a large first-time debris slide in deep glacial soil deposits. The resulting debris flow is reported to have killed five people on the Trans-Canada Highway (VanDine, 1985).

- On the Peace River east of Hudson's Hope, the Attachie landslide of 1973 occurred in glacial lake sediments and temporarily dammed the Peace River.

- The Devastation Glacier landslide of 1975 was a large debris avalanche which originated in weak volcanic deposits and killed four people working on a BC Hydro geothermal exploration crew. Numerous other landslide incidents have occurred in the Meager Creek valley, including a large debris flow in 1984 which damaged a recreation site and several vehicles, and another in 1990 which destroyed a logging maintenance facility.

- Howe Sound debris flows were active in the 1980's and earlier along Highway 99 between West Vancouver and Squamish. Between 1958 and 1983, fourteen debris flows resulted in twelve deaths (Evans and Savigny, 1994). Since 1983, defensive structures have been built on several channels.

- The Belgo Creek landslide in 1990, east of Kelowna, was a large debris avalanche which occurred during a heavy rain-on-snow event. It destroyed a house and caused three fatalities. Old logging roads and more recent logging above the initiation point were identified as causes of the landslide.

- In 1997, a large debris flow descended a relatively low gradient channel on Hummingbird Creek and caused considerable damage to property and infrastructure on a densely developed alluvial fan on Mara Lake near Sicamous. It started as a debris avalanche below a culvert which received water diverted by a spur road and cut block logged three years previously.

- In 1999 at Telkwa Pass (Howson) and in 2002 at the Zymoetz River two large, complex landslides originated as rock slides. Both of them ruptured a natural gas pipeline between Telkwa and Terrace.

- Following a 2003 wildfire at Kuskanook north of Creston, an intense rainstorm in 2004 occurred on severely burned, water repellent soils and triggered a debris flow which destroyed two houses and blocked Highway 3A for several days. This event and several others which followed the 2003 wildfires led to a new realization of the significant landslide and flood hazards that can follow some wildfires which alter the soil structure and composition. As a result, the Ministry of Forests at the time developed a policy and procedure for identifying and analysing post-wildfire natural hazards.

- At Legate Creek near Terrace in 2007, a large landslide caused two fatalities on Highway 16 and closed the highway for several days.

- At Van Tuyl Creek in 2008, following a large wildfire in 2007 (the Springer Creek fire near Slocan), a debris flow resulted in one fatality. The debris flow was triggered by an increased snowmelt rate in the burned area as well as by an accidental drainage diversion on a deactivated old logging road and landing. Several other debris flows in subsequent years occurred on this and nearby creeks in the Springer fire. The potential of post-wildfire landslide risks had been identified by a ministry report written in 2007 (Nicol et al., 2007).

- The Mount Meager landslide of 2010 near Pemberton was of similar size to the Hope Slide. It started as a rockfall or rock avalanche from near the summit of Mount Meager and entrained weak volcanic rock and earth lower on the mountain, progressing to a debris avalanche and then a debris flow. It occurred on the flanks of a large dissected volcano which has had a history of many large landslides as well as one major volcanic eruption since deglaciation. It did not cause any fatalities, but it temporarily dammed Meager Creek and Lillooet River, leading to a possible flood hazard (which did not materialize) to populated areas downstream.

District of North Vancouver Landslide (January 2005) and Coroner's Report (2008)

On January 19, 2005 a landslide occurred on a steep slope in a residential neighbourhood in the District of North Vancouver. The landslide destroyed one residence and injured two occupants, one fatally. Following the event the BC Coroners Service investigated the circumstance which contributed to the occurrence of the landslide and the death of Eliza Kuttner. A report summarizing the Coroner's findings was released in 2008. The report contained twelve recommendations to improve the management of landslide risks in BC. Of these recommendations nine were directed at the province. A summary of all the recommendations is provided in Appendix A. Two of the key recommendations were:

- "That the Province of British Columbia develop a comprehensive Landslide hazard Management Strategy focused prevention and mitigation of risk."
- "That the Province of British Columbia create an inter-ministry technical working group tasked with overseeing the implementations of recommendations arising out of the report."

After receiving and considering the report the Province's Interagency Emergency Preparedness Council (IEPC) established the Landslide Policy and Mitigation Working Group. Membership on the working group included representatives from the Ministries of Public Safety and Solicitor General; Community and Rural Development; Forests and Range; Transportation and Infrastructure; Environment; and possibly Energy, Mines and Petroleum Resources. The IEPC provided the working group with a number of objectives related to landslide policy and mitigation, and implementation of some of the recommendations from the Coroner's report. Since its establishment the working group has developed or contributed to a number of products such as the landslide guidelines released by the Association of Professional Engineers and Geoscientists of British Columbia in 2010.

The Testalinden Dam Failure in June 2010

In June 2010, the failure of a small earthen dam on Testalinden Creek south of Oliver triggered a very large debris flow which destroyed or damaged several homes and covered about 24 hectares of agricultural land downstream on the alluvial fan. Although the debris flow hazard on this fan was apparently not appreciated by residents or local government, investigations after the event found evidence of many smaller debris flows in the channel upstream and found much of the fan to be composed of deposits of prehistoric debris flows. A review of the Testalinden Dam failure was published by the Ministry of Public Safety and Solicitor General in July 2010. The review listed twelve recommendations regarding dam safety management and incident response. A summary of all the Testalinden recommendations is provided in Appendix B.

Sicamous Area (Sicamous and Hummingbird Creeks) in June 2012

On June 23 to 25, 2012, flooding and channel avulsions caused severe damage to houses, businesses and Highway 97A on the alluvial fans of Sicamous Creek and Hummingbird/Mara Creeks. The flooding and avulsions on both creeks were due to high streamflows which followed several weeks of exceptionally heavy rainfall. One small debris flow occurred as a result of a road washout in a tributary of Sicamous Creek; however it appears to have contributed only a small amount of debris to the channel. No significant landslides were reported in the affected watersheds. The Hummingbird Creek fan is the same fan that was affected by the Hummingbird Creek debris flow of 1997. The two events impacted many of the same properties.

Johnsons Landing in July 2012

The Johnsons Landing landslide occurred in the late morning of July 12, 2012. Its approximate volume was 300,000 cubic meters and its debris covers an area of about 10 hectares. It originated entirely in deep unconsolidated material (soil) consisting of glacial till and colluvium. The initial event, which comprised most of the volume, was a rapid debris avalanche which descended the channel of Gar Creek, a steep narrow valley which had occasionally carried small debris flows and snow avalanches in the past. The avalanche rode up over a low ridge at a sharp bend in the creek channel, and spread out over a terrace which was occupied by forest, cultivated land and houses. Three houses in this ridge area were destroyed, two of which were occupied at the time, and two other houses were damaged. There were four fatalities. A small part of the debris was saturated with water, and it continued flowing down the narrow creek channel as a debris flow, destroying the public road crossing and damaging a house on the fan. About 24 hours later, a second debris flow occurred. This event was formed from loose landslide debris in the channel which had been soaking up the creek flow for the past day and eventually became sufficiently saturated and began to flow. This debris flow was larger than the previous debris flow and covered most of the fan and destroyed one of the previously compromised houses.

The landslide occurred during dry sunny weather, about a week after the end of an unusually rainy period of early summer during which the West Kootenays experienced record rainfall during the month of June. The high June precipitation combined with heavier than normal winter snowpack and a comparatively wet year in 2011 probably produced early July groundwater levels which were at or near record highs.

For at least a few days prior to the event there were indications of increasing instability in the creek in the form of increasingly muddy water. In the day or two immediately preceding, local residents observed small debris flows descending the creek. At 4:56 am on the day of the event an email was sent from a resident to their neighbors expressing concern about possible hazards in the creek. An email was sent to the Ministry of Forests, Lands and Natural Resource (FLNRO) Regional Forest Hydrologist in Nelson at 8:47 am suggesting a helicopter reconnaissance of the upper watershed. At the time the Hydrologist was in the field attending to other business and did not read the email until shortly after the event had already occurred.

The site where the debris avalanche originated is on a densely forested slope on the steep mountainside above the community. There are no roads or trails at the site; although there is a narrow old road nearby, it is not a site which is likely to be visited frequently. The area is covered by terrain stability mapping. The slide initiation site was rated as terrain stability class 3 and 4 (i.e., a low to moderate likelihood of landslides following forest development or road construction). The terrain mapping showed no previous landslide deposits in the valley below. Recent field work following the event confirms that there were no significant landslide deposits younger than the early postglacial period in the area affected by this event.

Although the small alluvial fan of Gar Creek did not have a recorded history of debris flows it was identified as a potential debris flow fan on provincial flood hazard maps created in 2001. The hazard polygon was subsequently incorporated into the Regional District of Central Kootenay Floodplain Bylaw. Therefore, while the debris flow hazard on the Gar Creek fan was previously recognized the potential for the large debris avalanche that inundated the properties on the upper bench was not.

The mountainside above the landslide source consists of weak metasedimentary rocks of a geological formation (the Lardeau Group) which has a high incidence of bedrock landslides, both slow slump-type failures and more rapid debris slides. There is evidence of several old, slow-moving, bedrock failures near the landslide source, with some evidence of slight recent movement. However, this type of slow bedrock failure is common in similar geological formations. There are many locations in the Kootenay Lake area where old landslide scars and ridge-top cracks are visible on air photos or have been observed on the ground.

In summary, preliminary investigations have concluded that a debris flow hazard had been identified for the Gar Creek fan area however, before 2012 there were no obvious indications that there was a significant debris avalanche hazard above the Johnsons Landing bench of sufficient size or mobility to present a risk to the community. In consideration of the thousands of steep mountain slopes in the Kootenay Boundary Region and the absence of any recorded landslide activity at Johnsons Landing, professional geological staff consider it extremely unlikely that the Johnsons Landing landslide could have been predicted ahead of time, especially an event with the magnitude and runout of debris that actually occurred.

A team of landslide specialists, including a consultant retained by the local government and staff from FLRNO and MOTI has been assembled to produce a comprehensive report on the landslide. The anticipated completion date for the report is May 2013.

Fairmont Hot Springs in July 2012

On Sunday afternoon July 15, 2012, a debris flow ran out onto the Fairmont Creek fan at Fairmont Hot Springs. The landslide caused extensive damage to Fairmont Hot Springs Resort infrastructure, condos, single family homes, flood/debris flow control works and roads. Resort infrastructure damaged included water pipes from the hot springs, a road to an RV and camping area and within a golf course. The debris flow resulted from the mobilization of in-channel debris high in the mountains above the community. The trigger for the event was localized heavy rain on July 14 and 15. Hill slopes were already saturated from record rainfall amounts in June and early July 2012.

The debris flow hazard at the site had been identified in previous studies required by FLNRO and MoTI as a condition of subdivision approvals starting in the late 1980's and early 1990's. As a condition of subdivision approval, FLNRO required the construction of debris flow protection works. In 1996 the Regional District of East Kootenay (RDEK) passed a Local Services Bylaw and debris flow control structures (armoured dike and debris catch basin) were built to protect existing and proposed development on the fan area. The RDEK is the site's Diking Authority under the *Dike Maintenance Act*. Although the 2012 event overwhelmed the debris flow control works, residents have indicated that had the structures not been in place there would have been much more damage and possible personal injury or death.

In 2002, as part of a flood hazard mapping project, FLNRO prepared a flood hazard map of the hazard area to assist the RDEK and MOTI with future land use decision making. The observed debris runout onto the fan was consistent with the flood hazard map polygon prediction.

With funding assistance from Emergency Management BC and technical assistance from FLRNO, the RDEK has hired a consultant to document the 2012 event and assess the residual hazard to the community.

Findings:

The events of 2012 have renewed collaboration of experts in government on landslide issues. While some progress has been made since the Kuttner report and Testalinden Dam failure review were released, some recommendations have yet to be addressed.

Recommendation 1: The Province should update the terms of reference for the inter-ministry Landslide Policy and Mitigation Working Group to include responsibility for overseeing the implementation of the approved recommendations from this review, including undertaking detailed cost/benefit analyses of individual recommendations where appropriate. The membership of the working group should be renewed to ensure it has capacity for providing ongoing provincial leadership on landslide management issues in BC.

POTENTIAL IMPACTS OF CLIMATE CHANGE ON FUTURE LANDSLIDES

There are a number of factors which affect slope stability and the likelihood of a landslide occurring. These factors include the steepness of a slope, the integrity of the soil and rock material forming a slope, the amount of precipitation and how wet the ground conditions are, seismic activity, and various human activities which might destabilize a slope. A change in climate that alters precipitation patterns would make a substantial impact on the amount of water introduced to an unstable slope.

Landslides events can be triggered by extreme precipitation, snowmelt, rain-on-snow events and high surface streamflows. When the frequency and severity of these types of events increases, the probability of terrain instability events also increases. Several studies have noted statistical increases in the magnitude and severity of heavy precipitation in BC over the past 50 years. These trends are consistent with the results from global and regional climate models which predict increasing intensity and frequency of extreme precipitation events. In BC the models are projecting higher winter minimum and summer maximum temperatures and increased winter precipitation. A more in depth description of climate change projections in BC and their potential impacts on landslide risks is provided in Appendix C.

The climate change projections for warmer winter temperature and higher winter precipitation are also expected to increase the likelihood of heavier winter precipitation falling as rain at lower elevations as well as more frequent rain on snow events at higher elevations. The warmer and drier summers which are projected to occur may result in more wildfires which in turn can create localized water repellant soils which lead to more rapid rates of runoff and flooding at wildfire sites. Spring freshet could occur earlier in the year, and summer low flows and droughts could be more prevalent.

Findings:

These anticipated climate change impacts (storms, rain-on-snow, wildfires and hydrophilic soils) and others such as increases in freeze-thaw cycles and increased glacial runoff are likely to contribute to an increase in the risk of landslides and debris flows in the mountainous areas of BC.

Recommendation 2: Provincial and local governments should consider projected impacts of climate change on the level of landslide risk expected over the life of any proposed developments, resource use activities and the construction and maintenance of infrastructure projects when authorizing these activities.

PREPAREDNESS ASPECTS OF LANDSLIDE MANAGEMENT IN BRITISH COLUMBIA

The preparedness for landslides in British Columbia comprises the widest range of work and activities, and the widest range of participating agencies and stakeholders. A combination of legislation and policy, mapping and professional practice guidelines serve to avoid or reduce risks. Government agencies make land use decisions and authorizations, and undertake resource development planning and permitting. Risk identification and mapping are key decision support tools used by governments and involve professional sciences experts in industry businesses, consultants, and government. Public and government staff education on hazard recognition and management are required to optimize the effectiveness of available tools.

Wherever possible, risk avoidance is generally the most cost effective approach to reducing the long term costs to a development associated with natural hazards. The first step in avoiding a risk is to recognize or otherwise be aware of a potential hazard which could affect or be affected by any development activity on site at the earliest stage of the development process. Where a potential hazard has been identified, it is desirable to undertake a risk assessment of the hazard, including mapping of the hazard and the area at risk.

Finally, emergency preparedness for identified risks is a key part of a successful response and recovery should a landslides occur.

RISK IDENTIFICATION: HAZARD MAPPING AND SITE ASSESSMENTS

Mapping as a Screening Tool

Local and provincial governments' subdivision Approving Officers, local government Building Inspectors and Land Officers in the Ministry of Forests, Lands and Natural Resource Operations (FLNRO) often require hazard assessments when adjudicating subdivisions, land tenures or sales, or building permit applications to assess and reduce risk to people and property. Regional hazard maps are useful to these agencies to help them identify and screen where hazard areas may exist and to assist them in determining when to require a land developer to hire a qualified professional to assess natural hazards, including landslides, in a more site specific and detailed manner.

Similarly, in the back country, terrain stability maps and other maps provide general guidance to forest companies and other natural resource developers to know where to require a qualified professional to help reduce risk to the environment, forest values, existing developments and third parties when constructing roads and planning resource development or extraction in these areas.

The following mapping subsections describe mapping types and programs, ending with a summary of findings and recommendations.

Flood Hazard Management

The Flood Hazard Management program is responsible for administration of the *Dike Maintenance Act* including the oversight of regulated dikes and other mitigative works. The program also provides specialized technical and strategic expertise to other agencies involved in flood hazard management. The program has previously developed a number of tools to assist Approving Officers, building inspectors, qualified professionals and to others involved in adjudication of applications for subdivisions, land tenures and building approvals to identify potential at-risk areas, including alluvial fans and other potential debris flow zones. The tools which were developed include flood hazard maps, floodplain maps and provincial guidelines for managing development in at risk areas.

Flood Hazard Mapping

The *Flood Hazard Statutes Amendment Act* (2003) removed the authority of the Ministry of Environment, Lands and Parks with respect to flood hazard land use regulation. To assist with the transferring of this authority to others, the Flood Hazard Management Program (now part of FLNRO), with assistance from the Fraser Basin Council, created a set of Flood Hazard Maps for the province. The maps depict flood and debris flow hazard areas that program staff had mapped and accumulated information on during the provincial Floodplain Development Control Program (1975 to 2003). The maps were then provided to local governments and provincial approval authorities to aid them in identifying known alluvial and debris flow fans. Their ongoing use by local governments is unknown but likely varies across the province.

Local and provincial subdivision and building permit approval officers can use the maps to screen applications and, where appropriate, require a proponent to engage a qualified professional to develop site specific, detailed flood and debris flow hazard reports and maps for development on fans. Through this process there has been increased awareness of hazard areas and a reduction in the risk of exposure of new development to landslide hazards.

For example, the 2012 Johnsons Landing landslide inundated properties, destroyed or damaged a number of homes, and killed four people on the Johnsons Landing bench. The initial landslide directly contributed to two debris flows within the following 24 hours that ran onto the Gar Creek fan at the confluence with Kootenay Lake. The debris flows demolished an additional house and covered additional properties. The Gar Creek fan area was previously delineated as a potential debris flow fan area through the FLNRO Flood Hazard Mapping project and as a hazard polygon in the Regional District of Central Kootenay floodplain bylaw. Although the existing private lots on the fan were created and developed long before the creation of the flood hazard map and floodplain bylaw, if the map and bylaw had been available they would have been instrumental in identifying the risk to people and property on this fan if a new land development application had been received after creation of these tools.

Landslide Hazard and Terrain Stability Mapping

Landslide hazard and terrain stability mapping is used to broadly categorize landslides into four general categories on the basis of the land status of their source and destination areas in the landscape:

a. Landslides that occur entirely within developed areas: The 2005 District of North Vancouver landslide is an example. Typically, these incidents occur within a single municipality or regional district, and may originate on one property and affect another property below. This category also includes landslides that originate from below, such as slumps that retrogress from a river bank and affect a property above.

b. Landslides that originate on undeveloped Crown land, and enter populated areas or highway corridors. Most debris flow incidents are of this type, as are most of the very large landslide incidents described above, such as the Frank, Hope and Johnsons Landing landslides.

c. Landslides that originate on Crown land that are caused, or contributed to, by resource development, and enter populated areas or highway corridors. Examples include the 2010 Testalinden dam failure, and debris slides and debris flows caused by resource roads and/or logging activity.

d. Landslides that occur entirely within unoccupied Crown land. This includes the most landslides by number. These events are of interest if they cause indirect risks, for example, downstream hazards of flooding and sedimentation (e.g. the 2010 Mt. Meager landslide), or if they affect recreational users (e.g. the 1984 Meager Creek Hot Spring debris flow) or industrial workers (e.g. the 1975 Devastation Glacier landslide, also in Meager Creek).

Categories b) and c) represent a large proportion, probably most instances of landslide risk that affect populated areas. Local governments typically do not have Jurisdiction over vacant Crown land which lies above private land. As a result local governments and individual residents may be unaware of development plans or of terrain hazards on upslope Crown land.

Landslide hazard and risk mapping can follow two basic approaches; from the top down, and from the bottom up. As noted above, many landslides originate in upland areas, which are usually (but not always) provincial forest land or other Crown land. Many landslides, including those of primary concern for public safety, terminate in valley bottom areas which may be occupied by private property, habitation, or infrastructure. “Top end” mapping involves mapping the upland areas where landslides may originate, while “bottom end” mapping involves mapping valley bottom features such as alluvial fans and floodplains which might be at the receiving end of landslides, floods, or other natural hazards.

Most systematic mapping of landslide hazard (and other terrain features) in British Columbia has been “top end”, and consists of various types of mapping covering large areas of Crown land. These include:

- **Soil mapping** – Early soil maps covered areas with agricultural potential (including both private and Crown land). In general, soil mapping is not useful for identifying landslide hazards.

- **Soil and landform mapping** – In the 1970s and early 1980s, this variation of soil mapping was applied in some project areas, and typically consisted of 1:50,000 scale maps comprising a large map-area block. Mapping projects often concentrated on remote areas for which little or no previous mapping existed, and which were being considered for forestry or other resource development. Soil and landform mapping was based on air photo interpretation combined with field work in accessible areas. Most such mapping was done in-house by provincial government professional staff. This mapping did not have the identification of landslide prone terrain or other natural hazards as an objective, but large landslide features were sometimes identified, or described in accompanying reports.

- **Terrain mapping and terrain stability mapping** – This is the type of mapping is now most commonly used in British Columbia for the purpose of identifying landslide prone terrain. Our present system of terrain mapping originated in the forest industry on the BC coast in the 1970s and was adapted by provincial geoscience professionals who further refined the methodology and produced technical manuals and standards (Howes and Kenk, 1997). Mapping is based on air photo interpretation with field checking. In the 1970s and 1980s, several BC government terrain mapping projects covered large blocks of 1:50,000 map sheets, mainly in northern BC and in several other areas of interest because of impending resource development, such as the East Kootenay coal block. Landslide features are identified on these maps by on-site symbols as well as in the terrain labels for large features. Several interpretive ratings were sometimes applied to the mapped polygons, including terrain stability, using a Class I to V scale (now usually replaced by 1 to 5). Because of the relatively small scale of these maps, they are useful from a natural hazards perspective mainly for identifying large landslide features.

- **Terrain stability mapping for forestry purposes** – In the 1990s, with the introduction of the Forest Practices Code, terrain stability mapping was widely adopted throughout British Columbia in areas of existing or proposed forest development. Standards and methodology were prescribed in a Forest Practices Code guidebook (B.C. Ministry of Forests, 1999). Two types of mapping were defined including reconnaissance and detailed, with several “survey intensity levels” or degrees of field checking. Mapping was usually done at a scale of 1:20,000, on a topographic map base. The mapping was funded in most cases by Forest Renewal BC (FRBC) and was coordinated by Forest Regions or Forest Districts, but was done almost entirely by professional consultants working for the forest industry. Identification of landslide prone terrain is the primary purpose of this mapping, and therefore the maps are highly useful for identifying landslide features, potentially unstable areas, and sometimes other natural hazards such as snow avalanches.

  Maps and associated digital files typically reside with forest companies, but copies were provided to Forest District or Region offices and to the FRBC data repository. The mapping is therefore in the public domain, and is available to government agencies and the public, although not at this time readily accessible. Many Forest Districts produced compilations of terrain stability mapping done in their districts; this usually was limited to a Geographic Information System (GIS) layer identifying unstable and potentially unstable (or class 4 and 5) terrain polygons.

The Ministry of Environment has started a long-term program to compile all the existing biophysical mapping, including terrain stability mapping, and make it available on-line as scanned maps or GIS files.

Other landslide hazard mapping projects

A number of landslide hazard mapping projects have been completed in various parts of the province, which do not fit into the above categories of systematic mapping. These are typically valuable for some specific purpose in a limited area, but more importantly, they may use methods which can be adopted for future mapping. Some examples are:

- Systematic mapping of debris flow hazards was done by consultants working for the Ministry of Transportation and Infrastructure for the Highway 99 Sea to Sky corridor and some other highway corridors subject to high risks from debris flows.

- Several local or regional landslide inventories were done for research purposes by Forest Service and Ministry of Environment staff. In one case (on Vancouver Island) the mapping included computer modeling of potential debris flow runout over a large area in GIS form. The results of these projects were typically published as research papers, but the mapping itself is not readily available.

- In the southeast a project was conducted by one of the present authors (P. Jordan) in the early 1990s to do reconnaissance landslide hazard mapping of population and highway corridors in the entire region. The mapping was done mainly for the purposes of identifying where detailed terrain stability mapping should be done, and prioritizing forest road deactivation projects. The mapping is still available for most of the region and although it has been largely superseded by more detailed terrain stability mapping. The mapping includes an element of risk mapping, and it may be useful to revisit it for identifying areas where landslide risks potentially affect public safety. Some of the mapping may be archived off-site or potentially even lost following office closures.

- A terrain stability and natural hazard mapping project was begun for a large study area on private land in the Slocan Valley by consultants working for the previous Ministry of Forests and the Regional District of Central Kootenay. The project was initiated by public concerns over proposed forest development on Perry Ridge, and was innovative in that it included a number of attributes describing various types of landslides originating in or affecting each polygon. Half of the project mapping was completed. No similar projects have been conducted on private land, despite the obvious value of this approach in mapping landslide risks at the “bottom end”.

- The Regional District of East Kootenay (RDEK), with assistance from FLNRO staff, has recently retained a consultant to complete phase one of a regional flood hazard assessment and mitigation plan that will identify and prioritize flood and debris flow hazard areas within the RDEK boundaries. The first phase of the project will result in an inventory of all available hazard maps and reports. Phases 2 and 3 will include conducting site visits to identified tip prioritized areas and recommended mitigation strategies.

Aerial Photography Imagery for Landslide Hazard Mapping

Air photos are essential for all types of landslide hazard mapping. Typically the mapping process involves inspection of air photo prints under a stereoscope to identify landslide related features and then the delineation of terrain polygons on the photos. For landslide hazard studies, it is often very useful to obtain historical photos to examine changes that may have occurred over time to a landslide, stream channel or suspected unstable area. Many parts of the province have had repeated air photo flights at least every 10 to 20 years, sometimes going back as early as the 1930s. Most air photos have been taken by or for the provincial government, and the original negatives are housed in a collection in Victoria.

In 2010, the provincial government closed its air photo library and photographic lab, which prior to 2010 made and sold air photo prints. This service was replaced by making digital scans of recent air photos, and selling the scans as digital files. For some purposes, this product is useful; however, many geoscientists and engineers have found that the quality of the scans is inferior to photographic prints. Also, most of the older air photos have not been scanned. In 2012, an agreement was reached to transfer the air photo collection to the University of British Columbia, who will make air photo prints available for loan. In addition, several provincial offices in various ministries possess prints of regional air photos.

In the last few years, Google Earth has emerged as a widely used online program for viewing the landscape, and is quite useful for preliminary reconnaissance of landslide features. The imagery used by Google Earth for British Columbia is orthophotos provided by the provincial government, which have been prepared from air photo scans. The orthophotos, which are available in digital form, are of lower resolution than the original photos. The Google Earth imagery is compressed and therefore of still lower resolution. Although orthophotos are useful for an overview of large areas and for making planimetric maps, they do not allow stereoscopic (3D) viewing, and therefore much less useful for terrain mapping and landslide studies than air photo prints.

Other forms of remote sensing are useful for some types of landslide studies, including high-resolution satellite imagery such as Quickbird and Geo-Eye. A very useful remote sensing product is LiDAR, which is a form of airborne imagery which can provide a detailed, digital 3-dimensional image and elevation model of the ground underneath the forest canopy. LiDAR is very expensive, which generally restricts its use to localized, detailed landslide investigations, and mapping for major engineering projects. It may potentially become a valuable tool for landslide hazard mapping, as the cost becomes more affordable.

Findings on the Mapping Sections:

Flood Hazard Maps can play an important role during flood and landslide emergency planning and response. As demonstrated in the emergency responses for Johnsons Landing and Fairmont Creek this year, the Flood Hazard Map polygons provide a shelf ready map to assist with declaring areas for a state of emergency.

The hazard maps are also used in development planning and review processes. While the maps have helped steer more recent development away from high hazard areas and have saved lives, they do have limitations and could be improved.

Similarly terrain stability mapping is valuable for identifying landslide-prone terrain and other natural hazards, there are several limitations:

- Mapping usually covers only those areas which were of interest to a forest licensee for development. Many other areas remain unmapped.
- Very little mapping has been done since the end of Forest Renewal BC.
- Some early mapping was done only as hard-copy, or in digital formats which are incompatible with modern GIS systems.
- Forest Districts typically retained as GIS files only the unstable and potentially unstable (or class 4 and 5) attributes of each polygon. The terrain labels and on-site symbols, which contain most of the useful natural hazards information, were not usually captured, and often the original maps were lost or discarded. The full mapping information is currently rarely used and the FRBC archive's permanent storage is no longer readily available.
- Mapping was usually truncated at the Crown-private land boundary. Therefore, in most areas of interest for public safety (i.e., the "bottom end") were never mapped.
- The mapping is technically complex and it cannot be readily interpreted by people other than geoscience specialists (or by some specialists in related subjects such as soils, ecology, and engineering). It is not easily used by most of the general public, or by non-specialists in local government or other agencies. The number of provincial government science specialist positions in district and regional offices has reduced considerably, and so terrain stability mapping is not used to the extent it once was for land management planning or for consultation with the public or local governments. Ongoing staff attrition is further reducing the usefulness and application of this information.
- The Ministry of Environment has a program to compile all the existing biophysical mapping, including terrain stability mapping, and make it available on-line as scanned maps or GIS files. However because of limited staff and resources, this project is proceeding very slowly, and little of the 1:20,000 terrain stability mapping has been compiled.

Recommendation 3: The Province, in cooperation with local governments and qualified professionals, should investigate the feasibility of reinstating a mapping program to update and maintain maps of landslides, debris flows, alluvial fans and related natural hazards on both public and private lands. The program should place emphasis on mapping areas of greatest potential risk to public safety.

Recommendation 4: Pursuant to the recommendation in the 2008 Coroner's Report, the Province, local governments and professional associations should engage in discussions to explore the feasibility of building a publicly accessible central databank of natural hazard information.

Site Specific Hazard Assessments

More detailed and site specific mapping and hazard risk assessments are routinely performed as part of the application processes for proposed land development, forestry and other resource use projects. FLNRO's Forest Research Program provides science specialist expertise and support to regional and district operations. This support has included terrain stability mapping of study areas, developing and maintaining local or regional landslide inventories, post-event investigations of selected landslides and undertaking or overseeing individual geotechnical, hydrological and terrain stability research projects.

Government authorizing agencies work under legislation that, where appropriate, requires professional hazard assessments be undertaken to determine if a proposed use is safe. A proponent will then use the completed assessment to inform his or her development plans or activities to either avoid a risk by relocating the development or activity to a safer area or incorporating strategies to reduce or remove the risk. An assessment might also undertaken to evaluate the potential for a proposed development to increase the level of landslide risk for existing nearby developments or the public, and to identify measures which can be taken to avoid increasing the level of risk.

For many years there were inconsistencies and gaps in how hazard assessments were undertaken. As well, there has been extensive debate about how to define the term "safe." Recognizing the need for standard guidelines, government agencies and professional associations have been working in partnership to develop guidelines for landslides and terrain stability assessments. The 2008 Coroner's Report and the failure of Testalinden Dam were two events that accelerated the completion of some of these guidelines.

Guidelines for Legislated Landslide Assessment for Proposed Residential Development in British Columbia (APEGBC 2010)

Qualified Professionals play a significant role in landslide hazard identification and mapping in the Province of British Columbia, including the preparation of hazard assessment reports and maps for both the land development and resource development sectors. In 2006, with amendments in 2010, the Province contracted the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) to help write *Guidelines for Legislated Landslide Assessment for Proposed Residential Development in British Columbia* to assist Qualified Professionals involved in the preparation of landslide hazard assessments. These guidelines provide a risk-based approach for professionals to assess and mitigate building sites and to design structures at the sites. Authorities may also find the guide helpful in defining criteria for and evaluating results from professional geotechnical reports. The document is available online at
http://www.apeg.bc.ca/ppractice/documents/ppguidelines/guidelineslegislatedlandslide1.pdf

The guidelines also outline roles and responsibilities for those involved in land use regulation and provide guidance for professional practice and quality assurance criteria to help qualified professionals provide quality reports on landslide hazards.

Guidelines for Legislated Flood Assessments in a Changing Climate in British Columbia (APEGBC 2010)

In 2010 the Province contracted APEGBC to begin drafting a guideline document, similar to the residential landslide guideline, to assist professionals in writing flood hazard reports and creating flood hazard maps. The guideline document entitled *Guidelines for Legislated Flood Assessments in a Changing Climate in BC* was released in October 2012. Although the title of the document references flood hazards, the document provides a significant amount of guidance on debris flow hazard assessment. Debris flows and debris flood landslide hazards are gully/stream channel processes that cannot be dealt with as a separate hazard from normal flooding, especially in BC with the predominance of steep mountain terrain and proliferation of alluvial and debris flow fans.

Guidelines for Professional Services in the Forest Sector - Terrain Stability Assessments (APEGBC & ABCFP, 2010)

In 2010 APEGBC and the Association of British Columbia Forest Professionals (ABCFP) issued the *Guidelines for Professional Services in the Forest Sector – Terrain Stability Assessments* which superseded APEGBC's 2003 *Guidelines for Terrain Stability Assessments in the Forest Sector*. A Terrain Stability Assessment (TSA) is carried out by a qualified terrain specialist to assess the potential for forest operations to affect or to be affected by landslide hazards. A TSA may also be done to evaluate the risk and/or provide options to manage hazards and risks associated with operations. The ultimate goal of a TSA is to protect the safety, health and welfare of the public, to protect the environment and to provide for health and safety with the workplace. TSAs are conducted to:

- assess the potential for landslides to occur as a result of forest development activities,
- identify potential hazards upslope of roads or operational activities,
- assess terrain conditions and landslide hazards along proposed road corridors, and
- prepare strategies and recommendations for managing risks associated with roads and other forest activities.

The 2010 Guidelines establish a standard of care for carrying out TSA related to forest planning and operations in BC.

Guidelines for Management of Terrain Stability in the Forest Sector (APEGBC & ABCFP, 2008)

In 2008 APEGBC and ABCFP produced the *Guidelines for Management of Terrain Stability in the Forest Sector*. The guidelines were developed for the forest sector to assist in the management of terrain stability by providing guidance for establishing, implementing and updating a Terrain Stability

Management Model. The model provides guidance on when and where a TSA should be conducted and to manage terrain stability, whether a TSA has been conducted or not. A model also provides guidance for establishing risk criteria and selecting strategies for development which are consistent with the risks.

Mining Industry Project Hazard Assessments

The Ministry of Energy, Mines and Natural Gas (MEMNG) is responsible for administering the *Mines Act*, its regulations and the Health, Safety and Reclamation Code for Mines in British Columbia (the Code). The ministry utilizes provincial delegated Inspectors of Mines, and requires mining operators to make use of professionals such as engineers and geoscientists to explore for and develop mines and quarries in the province. *Mines Act* applications for new mines and expansions are typically very detailed. They are reviewed by provincial science and engineering experts and subject to public consultation. In its Purpose statement, the first two purposes of the Code are to:

"(1) Protect employees and all other persons from undue risks to their health and safety arising out of or in connection with activities at mines.
(2) Safeguard the public from risks arising out of or in connection with activities at mines. "

Findings on Hazard Assessments and Professional Guidelines:

The *Forest Act* currently does not identify public safety and potential consequences to downslope people and property as a key value that they must plan for. However, qualified professionals work under the 2010 Guidelines for Professional Service in the Forest Sector – Terrain Stability Assessments and the 2008 Guidelines for Management of Terrain Stability in the Forest Sector, and under Codes of Ethics as part of membership of relevant professional associations. The duty to the public is commonly a top priority in such Codes of Ethics.

Often, professional geoscience consultants and their clients do not distribute reports. Consequently hazard assessment reports (including hazard maps) required for subdivision, building permit and Crown land tenures in many instances do not become public documents, making important information in the reports related to safety of people and property difficult to access.

Similarly, most hazard assessment reports and maps conducted for forestry and resource use development by industry proponents are not made readily available. They may be stored with agencies but not intended to be uploaded to a central databank for broader access.

"The Guidelines for Legislated Landslide Assessment for Proposed Residential Development in British Columbia" point out the need for governments worldwide to define what acceptable risk means in terms of safety for residential development. Currently landslide hazard maps and perceived or defined acceptable risk levels vary significantly across the province. APEGBC maintains that it is not the role of the qualified professional to define what is safe. In the absence of a provincial policy on the definition of acceptable risk for landslides some jurisdictions in British Columbia such as the District of North

Vancouver and the Fraser Valley Regional District have implemented their own landslide hazard risk levels. The establishment of a provincial policy would reduce the risk of inconsistent reporting and mapping of landslide hazards for residential development.

The Guidelines for Legislated Flood Assessments in a Changing Climate in British Columbia discusses the need for provincial policy to establish a consistent description and procedure for establishing acceptable risk for the mapping and regulation of development in debris flow hazard areas.

Recommendation 5: The Province should work with the Association of Professional Engineers and Geoscientists of British Columbia, the Union of BC Municipalities, academia, industry and other stakeholders to identify a provincial standard for minimum acceptable risk thresholds for landslide hazards which would be applicable to Crown land dispositions, new developments, subdivision approvals and the design of mitigative works to protect existing development.

Recommendation 6: Agencies with responsibility for authorizing or regulating resource development activities, including the design, construction and maintenance of roads in steep, potentially unstable terrain, should be explicitly required to consider the landslide risks to public safety, both upslope and downslope of the activity being authorized or regulated. Policy direction should be provided to staff in these agencies with respect to the use of qualified professionals to evaluate landslide risks.

NEW SUBDIVISIONS AND DEVELOPMENT

New developments and activities on private rural and municipal properties, and Crown land are managed by various local governments and provincial agencies who are guided by an assortment of legislation, regulations, bylaws, plans and professional practice guidelines. For example, municipalities and regional districts administer subdivision and development approvals, and transportation and land use planning under legislation. Official Community Plans, bylaws and development permits are example tools used by local governments to regulate to development within their boundaries Provincial ministries administer numerous Acts and accompanying regulations and policies addressing Crown land tenures, rural subdivisions, flooding, water use, working in and near streams, dikes, dams, forestry operations and transportation. Irrespective of the applicable approving authority, where a site has been identified as susceptible to known landslide hazards it should not be subject to further development.

Residential and Commercial Development on Crown Land

Crown Land makes up 94 % of the area of British Columbia. The province operates within a framework of policies that govern the disposition, administration and management of Crown land. These policies have been developed to assist staff, stakeholders and the public by establishing principles on land use, allocation, tenure terms, pricing and all other aspects associated with the tenuring of Crown land.

When making decisions on the disposition of Crown land officials must consider potential natural hazards. For instance, Land Officers must consider the "Flood Hazard Area Land Use Management Guidelines" when selling, tenuring or leasing Crown land. Where there are natural hazards such as landslides, Land Officers may establish conditions which are attached to a new lease, tenure or other disposition with the intent of protecting public safety and future uses of the land from the hazard. For example, where a parcel is located in a floodplain, or where provincial staff express concern about flooding, a restrictive covenant prohibiting development in the floodplain, and a corresponding indemnity covenant are registered on the title.

Rural Land Subdivision

Provincial Approving Officers in the Ministry of Transportation and Infrastructure (MoTI) are responsible for the approval of subdivision applications in rural areas outside of municipalities. In this capacity the Approving Officers are authorized to consider the natural hazards risk, including landslides, when making a decision on a rural land subdivision application. However, once a decision is made MoTI Approving Officers have no mandate to monitor that risk, nor to forecast or respond to a landslide event.

Approving Officers have the authority to ask for professional assessment of situations where they have reason to suspect a risk of landslide, looking for indication that the land in question is safe for the use intended. However, they do not have criteria in statute as to what conditions define safe. In the absence of provincially accepted criteria various techniques are used by qualified professionals to address this issue. The Approving Officers provide some guidance to qualified professional as to an acceptable level of risk (what is safe) by referring to:

- past practice by MoTI of considering a probability of 1:475 of a property damage only event as a maximum acceptable risk, and
- Referring to case law that cited as unacceptable the risk of a catastrophic event that had a suggested probability of 1:10,000.

For assessment methodology, the qualified professionals refer to the guidelines jointly developed by the Province and APEGBC and which are described elsewhere in this report.

If a risk is present on part of the land, it may require the registration of a restrictive covenant against the title which acknowledges the hazard and that prevents building in unsafe parts of the land to avoid the identified hazard risk. However, after a decision is made to approve a subdivision plan, neither the Approving Officer nor MOTI monitor long term compliance with such covenants.

Where a dike or other works are proposed to mitigate or reduce a landslide or flooding risk, the Approving Officer will require a local government to agree to assuming responsibility for monitoring and maintenance of the works in accordance with provincial policy and legislation. This includes requiring a long-term operation and maintenance plan for the mitigation structures be developed and implemented as a condition of subdivision approval. Usually FLNRO Water Stewardship staff will work informally with local governments and proponents on the specifics of the long-term management of the structures and to establish the local government as the diking authority as regulated by the *Dike Maintenance Act*.

Local Government Regulation and Planning

There are a number of tools available to local governments which they can use to promote that future land uses that are planned and buildings which are constructed in a manner which take into consideration different natural hazards including landslides.

1. Official Community Plans (OCP) contain general land use policy statements and maps respecting restriction on the use of land that is subject to hazardous conditions such as landslides. OCPs may also be used to designate development permit areas where measures are required to reduce the risk to public safety and protect future developments from specific natural hazards.
2. Bylaws and Development Permits specify and enable enforcement of measures and requirements for new development in designated areas to protect against hazards. Bylaws can be used to regulate parcel configurations, the density of the land use, siting and standards of buildings and structures. Development permits may be used to specify areas of land which may be subject to landslides or other natural hazards, and which should not be developed except in accordance with the conditions contained in the development permit.
3. Subdivision approvals within municipal boundaries are coordinated by municipal governments similar to the MoTI Approving Officers' role in approving rural subdivisions. In this capacity an Approving Officer may require an engineering report from the proponent certifying that the land may be safely used for the intended purpose.
4. Restrictive covenants are used by local governments when a subdivider, developer or other proponent is required to register a restrictive covenant against the title of the property to establish conditions under which the property can be safely developed and/or to provide a waiver of liability in favour of a local government and/or the province for damages due to the natural hazard.

BC Building Code Amendments for Slope Instability and Seismic Hazard Consideration

Partially driven by the recommendations of the 2008 Coroner's Service "Kuttner" report, effective February 1, 2010, the BC Building Code was amended with the new additions of Sentence 4.1.8.16 (8) and Sentence 9.4.4.4 (2). With the new changes:

1) the consideration of potential for slope instability and its consequences at a building site becomes an explicit requirement in designs of structures and their foundations, and
2) the seismic hazard probability level to be used in the consideration, particularly in assessment of seismic slope stability, will be as referenced in Subsection 1.1.3 of Division B of the BC Building Code, namely a 2%-in-50 year probability of exceedence.

As a result, the Geotechnical Slope Stability (Seismic) Regulation, B.C. Reg. 358/2006 was repealed. The companion Commentary on Geotechnical Slope Stability (Seismic) Regulation issued by the Building and Safety Policy Branch in January 2007 was also withdrawn. As originally intended, the repealed B.C. Reg. 358/2006 served as an interim provision for specifying a seismic hazard probability level to be used for slope assessments for building sites. That level was a 10%-in-50 year probability of exceedence. Copies of the Minister's Orders amending the BC Building Code and repealing the Geotechnical Slope Stability (Seismic) Regulation are available online at http://www.housing.gov.bc.ca/building/regs/codes/index.html (see Revision 7).

Technical guidance on seismic slope assessment to the 2%-in-50 year seismic hazard probability level can be found in the document *Guidelines for Legislated Landslide Assessments for Proposed Residential Development in British Columbia,* published by the Association of Professional Engineers and Geoscientists of BC (see earlier section).

Highway and Resource Road Design, Construction and Maintenance

MoTI is responsible for the design, construction and maintenance of provincial highway infrastructure. Specifically with respect to landslides MoTI is responsible for ensuring provincial highway infrastructure and public safety are protected from landslides by:

- taking the steps to ensure slide risks are identified, assessed, mitigated or avoided during project design and construction,
- monitoring and maintaining mitigation measures, monitoring risk factors and responding to events, and
- if a previously unidentified, extensive natural hazard risk is discovered, advising relevant agencies such as a local government which can respond with appropriate land use controls.

In FLNRO, Forest Service Roads and non-status resource roads are managed similar to the provincial highway network. The Engineering program is responsible for the management, prioritization and maintenance of roads and associated works, including stream crossings and road drainage.

Findings on New Subdivisions and Development:

There are available mapping tools and knowledge about landslide hazards, and different provincial ministries have some policies in place which guide landslide hazard risk management for areas under their jurisdiction. However, the application of zoning, OCPs and bylaws by regional districts and many municipalities to address landslides is variable.

Staff in provincial ministries, municipalities and regional districts possess varying levels of knowledge of landslide hazards. As well, many new hires must learn a substantial amount of information and policy in their course of their "on the job" training. Gaps likely exist in the ability of land officers, approving officers, building inspectors, and local government authorizing and land use staff to fully consider the potential hazards.

British Columbia shares the difficulty of managing development and resource use in landslide prone terrain with other jurisdictions in Europe, Japan, Australia, etc. Those countries also continuously assess and improve their landslide management tools.

Recommendation 7: The Province should work with the Union of BC Municipalities and the Association of Professional Engineers and Geoscientists of BC to prepare a comprehensive training package for provincial and local government staff summarizing landslide hazard identification and what to do when hazards are identified.

Recommendation 8: Land Officers involved in the disposition of Crown land and provincial approving officers should receive training and policy direction in recognizing and managing landslides and related natural hazards. Local government development and land use staff should also receive their own training and policy direction on managing landslides.

Recommendation 9: The Province should encourage local governments to enact bylaws and policies to guide development away from areas at risk of landslides and to require the use of qualified professionals to assess the risk in hazard zones.

PUBLIC EDUCATION ABOUT RISKS OF LANDSLIDES AND RELATED HAZARDS

In the aftermath of the Johnsons Landing landslide, a review of an email exchange between local residents indicated some familiarity but also much uncertainty about the warning signs of a potential landslide, imminent risk indicators and steps for notifying authorities and others of their concerns. Media coverage addressed and questioned what citizens should be looking out for with respect to landslides risks and who they should contact for guidance in regarding terrain stability concerns and in the event of an emergency.

Public knowledge of natural hazards and early warning signs of increasing risk varies with different types of hazards. Hazards involving little or no warning, and which occur infrequently in developed areas, such as landslides, appear to be most wanting.

Highland and Bobrowsky (2008) state that "people living in areas prone to fast-moving, deadly debris flows need information on the likelihood of the hazard; for example, when it is most dangerous to be in the path of potential debris flows (such as during heavy rainstorms) and at what point to evacuate and (or) cease walking or driving in a hazardous area."

Emergency Management BC websites on Emergency Preparedness Information are a source of educational information and important links for numerous types of emergencies including:

- flooding
- weather events
- wildland fires
- tsunamis
- earthquakes
- backcountry accidents
- wildlife interface
- disease outbreaks
- landslides
- avalanches
- HAZMAT and spills
- volcanoes, and
- drought.

Several of these sites, including the flooding site, contain detailed and comprehensive reference information. By contrast the current website for landslides is at present less thorough.

However, there are a number of other sources of information on landslides which are published elsewhere. Available information includes both introductory and advanced technical handbooks, guidelines and other reference materials. These sources provide excellent reference information on landslides which is beyond the scope of this report.

Recommendation 10: With regard to public education, the Province should undertake a review of available best practices, reference materials and websites information used in other jurisdictions in the management of landslide risks.

Recommendation 11: The Province should update its websites on public education and information related to landslide risks, awareness, mitigation, response and recovery, and undertake ongoing outreach activities to raise awareness and promote the use of these websites.

EMERGENCY INCIDENT PREPAREDNESS

Much of landslide preparedness work in British Columbia involves risk assessment and informed land use decision making. This work is done to reduce the risk of landslides affecting public safety and new development and infrastructure, and to reduce the potential for proposed resource development and construction to affect pre-existing developments.

An additional aspect of preparedness is response planning and preparing for when landslides actually occur. Preparing for the possibility of an emergency is a shared responsibility of individuals and all levels of government.

All individuals should be aware of the landslide risks in their area and the early warning indicators of an escalating risk of an event occurring. To the extent practical they should also take measures to mitigate the exposure of their property to risks from landslides and ensure they are familiar with the appropriate actions to take should a landslide occur.

At the local government level municipalities and regional governments are required by law to prepare emergency plans and maintain an emergency management organization for all types of emergencies including landslides. This regulation is intended to ensure the safety of citizens when a situation escalates beyond the first responder level.

At the provincial level multi-agency hazard plans for British Columbia are prepared and updated regularly by Emergency Management BC to ensure an effective response strategy is in place to address the many possible types of emergencies and disasters. These plans foster cooperation amongst the multiple organizations which are responsible for public safety, the protection of infrastructure and property, and managing the aftermath of emergency events.

As noted previously, landslides are most often triggered by surface and groundwater conditions changing, which are tied to precipitation patterns. The River Forecast Centre of FLNRO monitors streamflows, snowpacks and weather conditions across the province, models conditions to support flood forecasting and provides flood forecasts and bulletins to provincial and other emergency response agencies as and when required. While this information is targeted to flood hazards, the same climatic conditions which may result in flooding typically coincide with increased risk levels to landslide hazards.

An example of specific landslide response planning is in the Kootenays where a landslide response roster maintained and annually updated to ensure that landslides are responded to as efficiently as designed in preparedness plans set up for other hazards. That roster is discussed later in this report.

MITIGATING RISKS OF LANDSLIDE HAZARDS TO EXISTING DEVELOPMENTS

There are many communities where the risks of landslides to existing communities are not realized until long after development has occurred. Where the newly assessed risk is determined to be unacceptable it may be most appropriate to relocate the development to a safer location. Unfortunately, in most cases relocation may be neither a practical nor economically viable option. In these situations consideration may be given to other mitigation options such as notification of those at risk, taking action to stabilize the potential initiation zone, constructing structural measures to protect at risk communities or infrastructure, or developing and maintaining a prediction and early warning system. However, experience has found that the costs/benefits ratio for the structural and early warning options can be prohibitive, making them economically viable only in densely developed areas.

Notification of Potential Landslide Risk

There are situations where a terrain hazard assessment being undertaken for other purposes may indicate a previously unidentified risk of landslides to existing development. Two recent examples of where previously unidentified risks were discovered are:

- an assessment undertaken as part of a BC Timber Sale in the Cascade Bay area of Harrison Lake which identified a risk of slope instability to a number of existing Crown leases for recreational lots, and
- an assessment of a slope near the Village of Lions Bay which found a previously unidentified gully on Crown land which could direct a debris flow towards several private residences.

In both situations, regardless of fault or liability for any resulting landslide, as soon as the Province became aware of the risk there was a requirement under section 25 of the *Freedom of Information and Protection of Privacy Act* to inform the at risk leaseholders and landowners of the possible risk. Failure to warn them of the risk could result in the Province becoming liable for resulting damages in a landslide was to occur.

Partially in response to the circumstances at Cascade Bay the FLNRO Lands Tenure Branch, in partnership with the Ministry of Justice (JAG), has initiated a Terrain Stability Guidance Project to develop a new risk management policy around new, replacement and existing *Land Act* tenures in areas where a terrain stability analysis has determined there is a high risk of landslide.

Stabilizing the Initiation Zone

For both new and established at risk developments, a review of upslope conditions and the nature of the landslide hazard may reveal that the most viable mitigative options may include stabilization at initiation zones. For example, prescriptions can be developed to unload weight from certain areas and/or undertake other slope stabilization measures such as groundwater drainage as part of an overall solution. It is recognized that not all landslides are natural events; many can be triggered by resource development or other ground disturbances. Therefore, mitigative measures which reduce the impact of these disturbances in the potential initiation zones such as upgrading road drainage can also be used to reduce landslide hazard.

Structural Measures - Debris Flow Mitigation Structures

Over the past four decades a number of debris flow mitigation structures have been constructed in BC. Most existing structures have been built to protect forestry resources and highways with relatively few structures built to protect residential development. The complexity of design has generally been related to the associated elements at risk. For example, the standard of design for works to protect a remote forestry road is considerably less than the standard required for a major highway. The protection of residential developments has typically warranted the most complex design as well as the establishment of arrangements for ongoing operation and maintenance. This review focuses on works designed to protect residential development.

There are two general types of structures used to protect against debris flows:

- Deflection berms/channel improvements deflect the flow, provide lateral constraint to the deposition area, and/or channelize the material further downstream where there may be less impact.   A critical parameter is the design flow rate.
- Debris basins and barriers contain all or part of the debris flow material.   A critical parameter is the design volume.

The Provincial Inspector of Dikes has designated several debris flow mitigation structures protecting residential areas as "dikes" and these are regulated under the provincial *Dike Maintenance Act* (DMA). In these cases, local governments own the works, have legal access to the land where the works are located, complete annual inspections and fund ongoing operation and maintenance.

Current practices and issues associated with implementing debris flow mitigation structures are best illustrated by a few examples:

Port Alice

Port Alice is a small village of about 800 people on the northwest coast of Vancouver Island.   After the town site experienced two damaging and life threatening debris flow events in 1973 and 1975, a system of deflection berms, totalling 2.3 km in length was constructed by the BC Ministry of Environment for a cost of $0.25M (1976 dollars).   The Village owns and maintains the dikes as the Diking Authority under the DMA.

Over the last three decades, the berms have protected the town from a number of smaller events. However, in 2011 FLNRO staff noted potential problems with the geometry of the works and have recommended that the Village complete a comprehensive debris flow assessment and dike safety review.

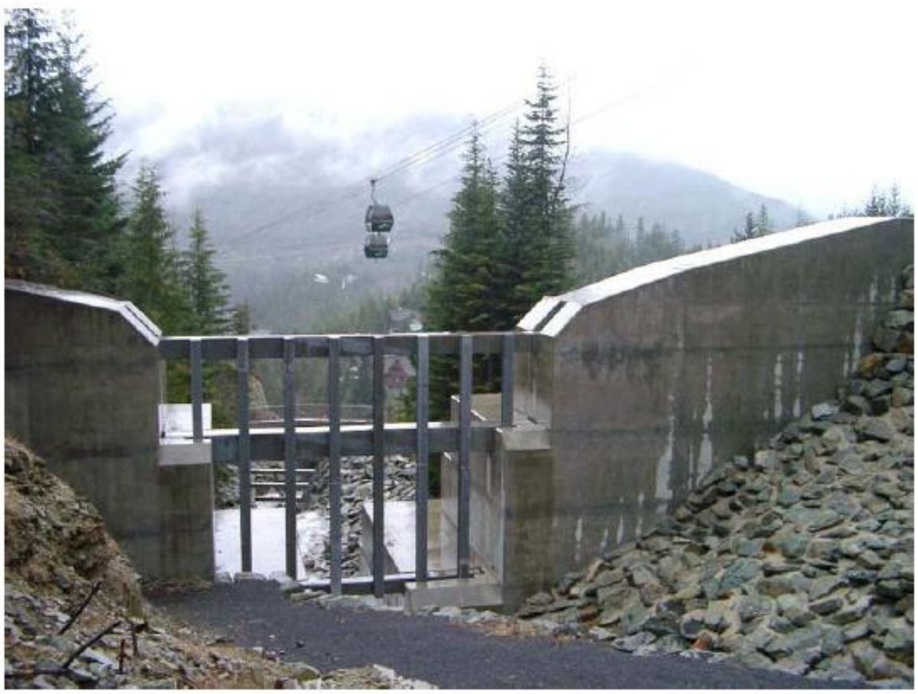
Lions Bay

Major debris basins were constructed by the then BC Ministry of Transportation and Highways on three debris flow prone creeks (Charles, Harvey and Magnesia) in the vicinity of Lions Bay in the mid 1980's after debris flows occurred along this section of Highway 99. The cost of the debris basins (in 1986 dollars) was $11 million. While the works were constructed primarily to protect Highway 99, the works also protect residential development. Maintenance costs are currently covered by the Ministry of Transportation and Infrastructure.   Because these works are owned and maintained by the Province, they have not been designated as dikes under the *Dike Maintenance Act.*

Whistler (Whistler Creek)

A debris barrier was constructed in the late 1990's as part of redevelopment of the "Gondola Base" area at Whistler Mountain (now called "Whistler Creekside"). The structure is designed to retain a 1:2,500 debris flow event with a design volume of more than 25,000 m^3, including 12 tonne boulders moving at 5 metres/second. The mass concrete structure is 16 m high and 34 m long and has a 12 m wide central passage furnished with a steel grillage (see photo below).

The barrier was required as a condition of subdivision approval at the time by the Ministry of Environment under the former Section 82 of the *Land Title Act*. The structure and related stream works have been designated as a dike under the DMA with the Resort Municipality of Whistler being the Diking Authority responsible for operation and maintenance. A similar $3.8 million barrier was constructed on Fitzsimmons Creek in 2009 to reduce the impact of a potential debris flood event.



A debris barrier on Whistler Creek, Whistler, B.C., designed to retain 30000 m^3 of debris.

Chilliwack River Valley, Baker Trails Trailer Park - Tank Creek and Guy Creek Works
In January, 2002 a debris flow on Tank Creek narrowly missed destroying mobile homes in an existing 157-home residential development. A subsequent hazard assessment determined that a number of the homes were at high risk from debris flows originating on both Tank and Guy Creeks. For a cost of approximately $0.25 million the province constructed a deflection berm on Tank Creek and a debris barrier on Guy Creek. The Tank Creek berm has subsequently performed well, protecting the homes from a debris flow event.

The design of these structures were reviewed and approved by FLNRO staff under the *Dike Maintenance Act*. As the Diking Authority, the Fraser Valley Regional District owns and maintains the works. The berms' design volumes and flows were estimated for a 1:500 year event.

District of Squamish- Cheekye Fan

The community of Brackendale and a section of Highway 99 are located on a large gently sloping debris flow fan of the Cheekye River, a tributary of the Squamish River. The debris flow hazard was first recognized in the early 1980's, and has resulted in a restriction of development in this area. There is geological evidence that volcanic debris flows of up to several million cubic metres, sourced in the Cheekye headwaters, have reached the fan periodically during the past few thousand years. The largest of these flows covered the surface of the fan with deposits up to 5 m thick approximately 1100 years ago.

Studies aiming at quantifying the debris flow hazard at this site in order to allow major residential development are continuing. Large debris barriers and containment berms have been proposed to mitigate the risk. Outstanding issues include tolerable risk limits, uncertainties in design parameters for the structural works and the high costs of maintenance and rehabilitation of the works after events occur.

District of North Vancouver

After a damaging debris flow event on Mackay Creek in 1995, the District of North Vancouver issued an overview study of debris flow hazards and risks in residential areas of the District, which was followed by a detailed study of the highest priority creeks and a quantitative risk assessment of those creeks. A debris flow barrier was constructed in 1996 at Mackay Creek to reduce risk to acceptable levels for adjacent residential properties.

The District is also constructing a debris barrier (metal cable net anchored into rock) on Mosquito Creek. The $240,000 structure is estimated to cost $10,000 per year to maintain. Without the barrier, several homes would be subject to a higher than acceptable risk (defined in the District as a 1:10,000 chance of death of an individual).

Metro Vancouver is currently studying additional measures to reduce the potential impacts on development at the base of Grouse Mountain. New protective works are expected to cost several million dollars.

Prediction and early warning systems

In densely populated areas where more well known landslide hazards exist, mostly in European and Asian countries, highly technical instrumentation networks and real-time monitoring are utilized to help evacuate risk-prone areas prior to landslide events actually occurring. There is a large range of instrumentation that can be utilized on a slope, using one or a combination of groundwater and actual slope movement instruments. Movements can be detected using antennas and radar type technology, lasers and optical instruments, inclinometers, GPS, extensometers (stretched string, etc), or even manual measurements with tape rules. Many of these technologies are very expensive and have highly specific uses and applicability depending on each site and circumstance. More recent and future technological developments may well provide for more affordable and more widely useful application of this type of method of landslide hazard mitigation. These systems require initial studies and construction costs along with ongoing maintenance and staffing resources. At-ready emergency response protocols and staff would be required for actual triggering of early warning detection systems.

The United Nations Environment Programme recently published a comprehensive document on the topic for numerous hazards, "Early Warning Systems, A State of the Art Analysis and Future Directions" (UNEP, 2012). As well, the International Consortium on Landslides and numerous geo-hazard conferences and organizations have written on the subject.

Findings:

Once an unacceptably high risk of debris flow hazard has been identified there are a number of potential issues which may be associated with the design, construction, maintenance and regulation of debris flow mitigation structures. These include:

- High capital cost.
- Lack of an adequate tax base in the protected area to meet high maintenance costs and costs of rehabilitation in the case of major events.
- Various design standards have been applied to historical mitigation works. There is a need to develop and adopt provincial standards, particularly where the works are intended to protect new development.
- The approval of residential development in debris flow hazard areas (*Local Government Act* and *Land Title Act*) may require an engineer's report certifying the land is "safe". However, this approval is not necessarily linked to any requirements for structural mitigation works (Section 82 of the *Land Title Act* was repealed in 2003). Under the current model, the need for structural works may only become apparent after the development has been approved and after an event occurs that brings forward new information or changes the landscape for the future.
- Regulation of ownership, operation and maintenance can be covered by the existing *Dike Maintenance Act.* However, the *Act* could be amended to include special provisions related to debris flow dikes.

- Orphan Works exist in several places in BC. As part of past emergency response and/or recovery work to historical debris flow events the province and other parties have funded or constructed non-standard works on numerous debris flow fans without setting up any ownership or maintenance arrangements. These orphan works currently represent a liability to the province and local governments.

As well, there are instances where new dikes and berms are desired for flood and landslide protection however the cost and long term ownership issues make for difficulty in constructing new works. The separation of roles between the province and local governments are clear in that the Province provides advice and legislative approvals while regional districts have the accountability to make assessments, fund and undertake necessary remedial works and monitor developing situations.

Emergency Management BC 's Strategic Business Services administers the Flood Protection Program which provides funding to assist with the design and construction costs for prescribed flood protection works. Projects qualifying for financial assistance are identified through a review of applications submitted by local authorities. As the focus of the program is to support flood mitigative works on waterways, landslides and debris flows mitigation works do not fall within the mandate of the program and are not eligible for funding.

Recommendation 12: FLNRO should complete its Terrain Stability Guidance Project to develop policies and other guidance material for staff working in Crown lands to ensure that terrain stability risks are managed on an appropriate basis.

Recommendation 13: The Province should identify standards for landslide mitigation works design and maintenance, as well as consider legislative changes to enable regulation of ownership and operation of landslide protection works using the model used for regulating flood protection works under the *Dike Maintenance Act.*

Recommendation 14: The Province and the Union of BC Municipalities should explore new funding models to better facilitate the ownership of orphan landslide and flood mitigation structures, and the construction of new flood and landslide protective measures.

EMERGENCY RESPONSE AND RECOVERY

RESPONSE

Communities in British Columbia can experience natural disasters such as landslides and debris flows throughout the year. Local governments often have critical local knowledge and expertise required to provide effective site level response and support for different emergencies. Therefore, legislation, regulations and program have been structured to support municipalities and regional districts in leading the initial response to emergencies and disasters in their communities. In the event of a significant landslide or similar event the local government, as required by the *Emergency Program Act,* will typically initiate a response through the activation of its emergency plan and directly controlling the resources under their jurisdiction for the purpose of emergency response and recovery.

Where required, the BC Emergency Response Management System (BCERMS) will be activated to coordinate provincial support to local governments upon request. BCERMS provides a consistent standard for Incident Command used by the Province. Many local government and other authorities also use BCERMS to guide their local emergency response efforts. Landslide emergency events response activities generally require cross-government provincial coordination and collaboration. Ensuring enhanced readiness and effective response activities require the assistance and participation of all stakeholders including senior levels of government, local government and individuals.

Emergency Management BC (EMBC) supports response activities by local authorities as per the *Emergency Program Act*. EMBC response actions include operation of the 24/7 Provincial Emergency Coordination Centre (PECC) and activation of regional Provincial Regional Emergency Operations Centres (PREOCs) and the PECC. If several ministries are involved in an emergency response, EMBC will coordinate an integrated provincial emergency management through the PREOCs and PECC.

Provincial legislation provides the legal authority for ministries to engage in response activities. The *Emergency Program Act* details roles and responsibilities of the province, provides parameters for declaring local or provincial emergencies and the emergency powers a declaration provides. The Emergency Program Management Regulation details the responsibilities and authorities of provincial Ministers, ministries, programs, and government corporations and agencies. Other relevant legislation may also be applicable depending on the specific event.

British Columbia's Comprehensive Emergency Management Plan (CEMP) aligns with the BC Emergency Response Management System (BCERMS). The CEMP (http://www.pep.bc.ca/hazard_plans/All-Hazard_Plan.pdf) or All-Hazard Plan provides a detailed outline of the operational structure and responsibilities for a Provincial coordinated all-hazard response. A coordinated provincial response may include:

- Subject matter (professional) experts;
- Access to geographical information systems and mapping;
- Aviation resources for reconnaissance, surveying and planning; and,
- Provincial trained staff for deployment to assist local authorities.

The Emergency Program Management Regulation and All Hazards Plan identify the Ministry of Justice (EMBC) as the technical lead for landslides other than those affecting highways. MOTI takes the lead for coordinating the response to landslides that affect a highway. FLNRO is the provincial ministry primarily responsible for responding to debris avalanche and debris flow events involving Crown land.

Coordinated Response Model Example – Kootenay Boundary Landslide Response Model

The smaller municipalities and regional district governments in the Kootenay Boundary Region do not have sufficient in-house experts to assist with landslide hazard identification and response during an emergency. Consequently, FLNRO regional staff members are usually involved directly and immediately with local governments in the response to all landslide events in the region wherever they occur.

Due to the high frequency of landslides in the Kootenays, sometime in the 1990's the Ministry of Environment regional Public Safety Section Head started organizing and maintaining a roster of landslide specialists with business and personal phone numbers to respond to landslide emergencies. As a consequence of organizational changes this function is now delivered by FLNRO. Landslide specialists are recruited from FLNRO, MOTI and occasionally a private consultant. At one time a Ministry of Energy, Mines and Natural Gas (MEMNG) geotechnical engineer was on the roster when the position was staffed in the Kootenays. Each spring, landslide specialists along with flood assessors and flood observers are provided with training and refresher sessions/opportunities to become familiar and comfortable with the emergency response system including the incident command system. The EMBC Emergency Manager and PECC response centers have access to this list of specialists via the Public Safety Section Head. The result is a 24/7 response capability.

Landslides, especially debris flows, often start in higher elevation Crown land managed by FLNRO and by forest licensees where logging is occurring. In the Kootenay Boundary Region, FLNRO has regional and district Landslide Standard Operating Procedures (SOP). The SOP provides direction to FLNRO and forest companies on how to report landslide events to reduce risk to people and property. The SOP identifies procedures to follow when a landslide reaches private property or highways. It requires prompt notification to the EMBC emergency response system.

Landslides often impact highway infrastructure. During these events efforts are made to establish a joint response with MOTI and FLNRO specialists in the same helicopter or vehicle for the initial reconnaissance trip. Sometimes the number of events and limited numbers of specialists preclude this but when it happens it provides for a well organized and coordinated response.

On occasion landsides originate from mining properties or mine access roads. While there currently is no MEMNG specialist on the landslide roster team, this year experience was gained towards establishing a coordinated response with MEMNG through Inspectors of Mines and MEMNG geotechnical engineers who are stationed elsewhere in the province.

The recent Johnsons Landing landslide provides an example on how the system works. The landslide occurred at approximately 10:37 am PDT on July 12, 2012. FLNRO staff received a call to investigate the site from the PREOC at 11:15 am. FLNRO staff were in a helicopter and on their way to the site from Nelson at 11:45 am, reaching Johnsons Landing at 12:20 pm. Upon arrival an initial assessment of the area was made from the air. Staff landed at the site and provided a report to the promptly deployed

Regional District Incident Commander at 12:50 pm. The helicopter then became an immediate valuable asset to ferry RCMP and other emergency responders across and onto the slide.

Similarly with the Fairmont Creek debris flow on Sunday, July 15, 2012, geotechnical and flooding specialists from FLNRO and operational staff from MoTI responded to the scene by helicopter within two hours of the event. Once at the site staff viewed the site on the ground and collaborated on the response with Regional District of East Kootenay emergency response staff who had set up a temporary Emergency Operation Center at the Windermere Fire Hall.

Findings:

Initial media and public reaction to the Johnsons Landing landslide was that unlike with a medical emergency, citizens may not be sure about whom to call in the case of a natural hazard emergency.

Some local governments may not have a 24-hour reporting number for public to utilize in the event of a landslide.

In the future, EMBC's 24 hour Emergency Coordination Centre (1-800-663-3456) may receive calls from the general public reporting concerns (i.e. muddy waters, restricted flows, etc.) however, there is not a clearly defined or supported provincial escalation process to assess the public calls and to respond or follow up by local government or provincial government staff.

The examination of the 2012 landslide events revealed that response and escalation issues are similar and related to Recommendations 4 and 5 of theTestalinden Dam Failure Review.

As part of a high functioning reporting and escalation process, a quick reference list or roster of key persons and contact numbers, with annual preparation meetings, has proven effective where utilized.

Recommendation 15: The provincial and local governments should update their websites and other information media to ensure they provide clear guidance to the public on emergency phone numbers and purposes of each call centers.

Recommendation 16: The Province, in collaboration with provincial ministries and local governments, should establish annually updated landslide and flood response rosters of trained persons in each region.

RECOVERY

Following initial emergency response and the provision of search and rescue, and medical services to affected people at a site, provincial and local government emergency response staff collaborate to restore essential services, utilities and access. Typically, evacuation orders and declared states of emergency are maintained and adjusted as appropriate. In some situations sustained provincial incident management operations and support activities may be required over the long term to support community recovery and mitigation. The damages and response fees from a landslide can be very expensive for citizens and governments.

EMBC administers the Disaster Financial Assistance (DFA) Program which provides financial support to help Local Government Bodies and the private sector recover from disasters. The DFA program operates under the *Emergency Program Act* (the “Act”) and the ensuing Compensation and Disaster Financial Assistance Regulation (the "Regulation"). The DFA program is obliged to provide compensation in compliance with this legislation. DFA eligibility criteria, as defined in the Act and the Regulation, have been applied consistently and fairly throughout the province since 1995. The Regulation can be found at http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/10_124_95

The Compensation and Disaster Financial Assistance Regulation details the financial assistance available to local government bodies and the private sector to help them respond to and recover from disasters.

For large costly provincial disasters, the Province (through EMBC) may request federal cost-sharing under Public Safety Canada’s Disaster Financial Assistance Arrangements (DFAA). If DFA is approved, the Province can recover a portion of its disaster response and recovery costs including costs incurred by other ministries. The federal government provides emergency assistance to provinces when requested and justified.

CONCLUSION

The fatal and damaging landslides in the interior of British Columbia in 2012 prompted this review of the most significant events to assess what factors contributed to the occurrence of the events, how they were responded to in early stages, how landslide hazard risks in BC are managed in general, and to identify any lessons that were learned. This review is structured around the four-pillar approach to hazard management which consists of preparedness, mitigation, response and recovery. As with other natural hazards, it is recognized that efforts made on landslide preparedness will significantly reduce the pressure on the other three pillars of landslide hazard management. The review also recognized the close ties between the management of and response to landslide and flood risks and events.

The review found that the landslide at Johnsons Landing, especially in terms of its magnitude and runout extents, was largely unpredictable, and that it was the first such incident to occur at this location in recorded history. In contrast, Fairmont Creek, Sicamous Creek and Hummingbird Creek had each experienced flooding and debris flow events in the past and were known hazard areas.

Overall the responses to the events in 2012 were well handled due to established and practiced emergency response plans and organized networks of prepared persons in local and provincial governments. However, the ability for the province to maintain even its current level of preparedness with in-house landslide specialists may be at risk.

Climate change models indicate that BC's climate appears to be changing in a manner which has the potential to increase the future frequency of landslide and flood events. At the same time there is ongoing pressure for additional development to be approved in areas vulnerable to landslide hazards.

This review recommends ways to improve and expand hazard mapping and other information, along with enhancing its accessibility and application by land use planners, developers and government decision makers.

Given the rapid onset of landslides and their general lack of advance warning, increasing public understanding and awareness of landslide hazards is an important step in avoiding activities which may increase the hazard and in reducing the number of activities which take place in hazard areas during risky times. The report contains recommendations to increase public education and awareness of landslides.

Some established communities are located in hazard areas where there are old mitigation dikes and berms which were constructed to protect the community. Often these works were built to an unknown standard and have been poorly or inconsistently maintained over time. In other communities it may be desirable to construct new and expensive landslide and flood mitigation structures but they are often too difficult for the local governments to fund, operate and maintain. Recommendations are made to standardize the design and construction of mitigative works, supplement existing flood protection regulations to enable them to be used to regulate landslide mitigation works, and to explore funding models that would better enable the construction and operation of protective works.

Landslide and flood emergency response can protect people and infrastructure best when communities are fully prepared and coordinated regionally. Recommendations are made to ensure all areas of the province are optimally ready to respond when a landslide emergency occurs.

Finally it is recommended that incorporating the findings of this review into the mandate of the existing cross ministry Landslide Policy and Mitigation Working Group would help to assess, prioritize and implement these recommendations appropriately and efficiently.

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APPENDIX A - SUMMARY OF RECOMMENDATIONS FROM THE CORONER'S REPORT INTO THE DEATH OF ELIZA WING MUN KUTTNER (2008)

The BC Coroners Service completed its report in 2008 into the death of Eliza Wing Mun Kuttner who was killed in a landslide on January 19, 2005 in North Vancouver. The report contained twelve recommendations, nine of which were directed at the Province. The following is a verbatim summary of the Coroner's recommendations.

Coroner's Recommendations

1. That the Province of British Columbia develop a comprehensive Landslide Hazard Management Strategy focused on prevention and mitigation of risk.

2. That the Province of British Columbia, with input from local governments, coordinate the development of provincial Landslide Safety Levels for proposed and existing residential developments.

3. That the Province of British Columbia consider establishing a legislated provincial standard for how landslide assessments for existing and proposed residential development should be conducted, by referencing Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) *Guidelines for Legislated Landslide Assessments for Proposed Residential Development*, in pertinent regulations.

4. That the Province of British Columbia coordinate the development of a provincial guideline to assist local governments in recognizing when an assessment of landslide risk should be carried out.

5. That the Province of British Columbia coordinate the development and administration of provincially standardized training and education for approving officers, building inspectors, local government planners and councils, in identification of landslide hazard and risk, and interpretation of risk assessments prepared by qualified professionals.

6. That the Province of British Columbia work jointly with local governments to develop an Internet based databank which would allow for depositing, storage, universal access, retrieval and effective use of landslide hazard and risk information, in order to facilitate informed decision-making and effective risk management by all stakeholders, including regulatory bodies, qualified professionals, property owners and the public.

7. That the Province of British Columbia provide leadership and work jointly with local governments towards the development of a strategy for prioritizing, collection, storage and use of landslide hazard information.

8. That the Province of British Columbia create an inter-ministry technical working group tasked with overseeing the implementation of recommendations arising out of this report.

9. That the Union of British Columbia Municipalities, and its members, consider developing a framework through which external qualified professionals are retained to examine local governments' internal procedures for reviewing landslide assessment reports, evaluating landslide risk and implementing mitigation measures in a timely manner.

10. That the Union of British Columbia Municipalities create a forum where local governments can share their knowledge and lessons learned with respect to natural hazard risk prevention and mitigation.

11. That the Province of British Columbia, jointly with the Association of Professional Engineers and Geoscientists of British Columbia, consider the development of a provincial standard, referenced in legislation, which sets specific qualification requirements for professionals conducting landslide analyses and assessments. A consideration should also be given to the development of a professional designation for qualified professionals conducting landslide analyses and assessments.

12. While it is acknowledged that members of the Association of Professional Engineers and Geoscientists of British Columbia are obligated, in relation to work they carry out on behalf of their clients, to keep confidential all information unless disclosure is authorized by the clients, the APEGBC may wish to encourage its members, and their clients, to support initiatives related to the development and maintenance of a publicly accessible landslide information databank.

APPENDIX B - SUMMARY OF RECOMMENDATIONS FROM THE REVIEW OF THE TESTALINDEN DAM FAILURE (2010)

Following the failure of Testalinden Dam south of Oliver in June 2012, David Morhart, Deputy Solicitor General, conducted an independent review of the circumstances surrounding the failure of and the BC's Dam Safety Program. In his report released in July 2012 Mr. Morhart made 12 recommendations directed to various provincial ministries. The following is a full list of his recommendations.

Recommendation 1: The Ministry of Environment should review its record keeping practices to ensure that proper and complete files are kept and archived on all dam structures, including details of water licenses, transfers of appurtenancy, and correspondence with owners.

Recommendation 2: The Ministry of Environment should review the historical warnings about the conditions of the dam and any actions taken to hold the owner(s) responsible for inspection and maintenance as per the Dam Safety Regulation.

Recommendation 3: The Ministry of Environment should consider implementing signage at all dam locations to make it clear to passersby that the structure is a dam and to provide direction and emergency contact information, including contact information for the owner, to report any issues observed.

Recommendation 4: Emergency Management BC should work with local officials, local and provincial policing and first response agencies, and ministry provincial and regional offices to provide a quick reference list of key contact numbers, focused on "who to call when," and develop an alert matrix to quickly escalate priority issues.

Recommendation 5: The Ministries of Forests and Range and Environment should review their call-out procedures to ensure that compliance and enforcement personnel are familiar with the issues escalation process noted in Recommendation 4, as they are often among the first individuals aware of local incidents.

Recommendation 6: Building on Recommendation 4, Emergency Management BC should continue to coordinate awareness and encourage training and orientation for local emergency response agencies, local government officials, and provincial government agency personnel to prepare for emergency situations. Local governments are required to have emergency plans in place, per the *Emergency Program Act*, and Emergency Management BC can assist with the development and testing of these plans.

Recommendation 7: The Ministry of Environment should review and update the Dam Safety Regulation to incorporate best practices on dam safety found in other jurisdictions. This would include but is not limited to an update to the downstream consequence classification tool, inclusion of a requirement for the owner to develop an emergency preparedness plan for the structure, and consideration of further regulatory oversight to enhance enforcement and compliance.

Recommendation 8: The Ministry of Environment should complete its Rapid Dam Assessment Project and update its consequence rating system accordingly to determine priority areas in need of attention. The Ministry should develop an action plan to address those areas needing immediate attention and schedule appropriate follow up based on overall findings.

Recommendation 9: The Ministry of Environment should continue its work in building a robust Dam Registry, with linkages through to geo-reference tools which can be utilized by other partners.

Recommendation 10: The Ministries of Environment and Transportation and Infrastructure need to continue to ensure effective communication and information sharing of community development and transportation initiatives as they relate to downstream consequences for dam safety. This information should be periodically reviewed on a priority basis to account for any historical changes. In addition, other ministries such as Forests and Range and Energy Mines and Petroleum Resources should be linked in to any consequence review initiatives to ensure that all appropriate information is considered on a periodic basis.

Recommendation 11: The Ministry of Environment should ensure the consistent oversight and regulation of all water related structures, including licensing, standards and risk assessments, by working with the ministries that have the legislative authority. The Ministry should build a business case to rationalize the types of resources and supports that would be needed to accomplish this recommendation.

Recommendation 12: The Ministry of Environment should continue and expand its education and awareness initiatives with dam owners and should work with Emergency Management BC to ensure that dam owners are working directly with local government officials in tying together their emergency preparedness and response plans. In addition, the Ministry of Environment should publish an annual Dam Safety Program report on its public website for the information of the public.

APPENDIX C - PACIFIC CLIMATE IMPACTS CONSORTIUM – CLIMATE CHANGE TECHNICAL SUMMARY

Arelia T. Werner, Hydrologist. September 7th 2012

Frequency and Severity of Triggering Weather Events

Hydro-climate induced terrain stability events can be triggered by extreme precipitation, snowmelt, rain-on-snow and peak streamflow. The frequency and severity of these hydro-climatic events may be increasing with climate change and with them the risk of terrain instability. Several studies have noted increases in the magnitude and frequency of heavy precipitation in BC and the Pacific Northwest over the second half of the past century. Both global and higher resolution regional climate models project future increases in the intensity and frequency of extreme precipitation events. When rain falls on a pre-existing snowpack, large flood events, known as rain-on-snow (ROS) events can result. These events have been increasing at high elevations and decreasing at low elevations in the Western United States. Peak streamflow has been occurring earlier and has decreased in magnitude for many, primarily snowmelt-driven, rivers in BC over the last few decades. This trend is projected to continue with future warming.

Background

Extreme Precipitation

Trends in extreme precipitation are subject to inter-annual and inter-decadal variability (*Trenberth et al*., 2007). Nevertheless, there is evidence for a global trend of increasing extreme precipitation (*Min et al.*, 2011; *Trenberth et al*., 2007). In areas where total accumulation remains constant or even decreases, changes in frequency of heavy events can still occur (*Trenberth et al*., 2007). For example, the frequency of heavy precipitation events in south-western Canada showed increasing trend from 1950 to 1995, even though total accumulation had a slight negative trend (*Stone et al*., 2000). Significant increases in heavy rainfall events occurred during May, June and July over this period (*Stone et al*., 2000). In BC south of 55 °N, from 1910 to 2001, there is evidence of a trend in increasing heavy precipitation (*Groisman et al*., 2005). Stations in southern BC show significant increases in two extreme indices: (1) the highest annual 5-day precipitation accumulation, and (2) the number of very wet days annually (the number of days with precipitation greater than the 95th percentile) over 1950-2003 and 1900-2003 (*Vincent and Mekis,* 2006). There is a projected increase in the magnitude and frequency of the 20-year return value annual maximum precipitation, P_{20}, in BC for 2046-2065 and 2081-2100 versus 1981-2000 with the possible exception of south-eastern BC (*Kharin et al*., 2007; *IPCC*, 2012). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) report (*IPCC*, 2012) states that based on Global Climate Model (GCM) projections there is *high confidence* that there will be a likely increase in *heavy precipitation days* (when precipitation is greater than the 95th percentile) and *heavy precipitation* *contribution* (when the fraction from precipitation is greater than the 95th percentile). Work with Regional Climate Models (RCMs) in the Columbia River Basin (*Murdock and Sobie,* 2012) and Georgia Basin (*Murdock et al.,* 2012) supports these findings.

Rain-on-Snow

The severity of rain-on-snow (ROS) events depends on the magnitude of precipitation, the ratio of rainfall versus snowfall, the elevation of the freezing level, and the volume and areal extent of the snowpack (*McCabe et al*., 2007). There has been a trend towards more precipitation falling as rain instead of snow over 1949 to 2004 in response to warming across the western United States (*Knowles et al*., 2006). Our understanding of historical trends in ROS events in the region are based primarily on studies in US Pacific Northwest. They show a trend of increasing numbers of ROS events at high elevation and decreasing numbers of ROS events at low elevations; however, there is some regional variability (*McCabe et al.,* 2007). Changes in ROS events are correlated with changes in temperature. Generally, the number of ROS events has decreased with increasing temperature due to reduction in snow and thereby the reduced opportunity for ROS. However, the correlation decreases with increasing elevation because higher elevations are still cold enough to maintain snow in spite of temperature increases (*McCabe et al.,* 2007). April 1st snowpack volume decreased for the majority of snow monitoring sites in BC over the longer term (1951-2007) and responses were mixed for the more recent 1978-2007 period, suggesting that there is strong decadal-to-decade variability (*Rodenhuis et al.,* 2009).

Peak Streamflow

Streamflow in BC can be rainfall, snowmelt, rainfall/snowmelt or snowmelt/glacial-driven. Peak-flow events occur during different times of the year in each regime; e.g., in winter in rainfall-driven regimes and in spring/summer in snowmelt-driven regimes. These peak-flow events often contribute to flood risk. Under climate warming, where less precipitation accumulates over winter as snow, spring peak-flow volumes generally decrease and occur earlier. For the most part, negative trends in annual maximum daily flow, or peak-flow, have been observed for BC over the last 30-50 years of the 20th century, especially in the south (*Zhang et al.* 2001; *Cunderlick and Ouarda,* 2009). The date of annual maximum daily mean streamflow has trended to earlier in the season on average over this time (*Zhang et al.* 2001). In a 2009 update to Zhang et al.'s (2001) analysis, Rodenhuis et al. (2009) found that average daily maximum streamflow decreased for the majority of rainfall-dominated streams on the South Coast and was mixed (-8% to 23%) for rainfall/snowmelt-dominated regimes in the same region over 1976-2005. In snowmelt-dominated regimes in the Okanagan and Columbia River basin, daily maximum streamflow decreased and increased, respectively. In snowmelt/glacial-driven regimes maximum annual daily streamflow decreased in regions with less glacier cover and increased in those with more glacial cover (*Rodenhuis et al*., 2009). Changes in snowpack accumulation are resulting in earlier spring peak-flow in the Okanagan region (*Pike et al*. 2010). In the Fraser and Columbia the snowmelt/glacial systems show increased peak-flows and lower recessional flows, perhaps because they are transitioning from glacier-dominated regime towards snow-dominated regimes with an earlier freshet and faster recessional period (*Pike et al*. 2010). Flood risk has also been affected by climate variability associated with the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO) over the 20th century and is particularly high when ENSO and PDO are in phase (*Hamlet and Lettenmaier,* 2007). Also, Jefferson et al. (2011) found that a key control on flooding in maritime mountainous regions in the Pacific Northwest is the amount of watershed susceptible to rain-on-snow events. Where warming increases the percent of watershed impacted by rain-on-snow events, flood magnitude has increased, but where warming has decreased the percent of watershed impacted by rain-on-snow, flood magnitude has decreased.

Average peak-flows in the Fraser River at Hope are projected to decrease, while average annual flows are projected to increase modestly for the 2070-2099 period (*Morrison et al.* 2002). Hydrologic projections throughout the Fraser River basin suggest that mean annual peak discharge will decrease by mid-century (*Shrestha et al*. 2012). Loukas et al. (2002) found that the magnitude of annual maximum flood peaks will be significantly reduced in the Illecillewaet River in the Columbia basin due to precipitation falling more as rain than snow, snowpack decreasing and snowmelt occurring earlier in the season. In the snowmelt/glacial-driven Columbia above Donald, peak-flows are projected to occur in June instead of July and are projected to not increase (*Bürger et al.* 2011). In a study by Sobie et al. (in prep.), peak-flows in the majority of sub-basins in the Columbia, including the Columbia above Donald, are projected to increase in the 2020s, 2050s and 2080s. Observational data, GCMs, downscaling technique, hydrologic model and representation of glaciers differ between these two studies. Thus, diverging projections in peak-flow are related to the different methodologies applied. Increased magnitude and more numerous storm events are projected to result in increasingly frequent and larger storm-driven streamflow (including peaks) in the winter, in rain-dominated regimes in BC (*Pike et al.* 2010).

Uncertainties

The statistical evaluation of changes in extremes, such as trend, is difficult. This is due to challenges in securing datasets long enough for the analysis of these rare events, especially in the case of extreme precipitation. Projecting future changes to extreme precipitation becomes difficult when translating the change in precipitation modelled at the coarse-scale, such as several 100 km a side per grid cell in a GCM or ~50km a side per grid cell in an RCM, to the local-scale where land-slides and debris flows may be triggered. However, while projections of increased frequency and severity of extreme precipitation differ quantitatively between different climate models, qualitatively results are in agreement. Capturing and classifying rain-on-snow events can be highly uncertain in complex topography with a sparse station network. Physically-based models run at high-resolution are therefore required to investigate future projections of changes in ROS events. Such work is limited by the computational expense of running these models and the paucity of observational snow data. Lastly, changes in peak-flows depend upon the nature of the river basin, leading to a diverse response over large regions like BC. However, the majority of basins in BC are snowmelt-driven and have shown decreasing trends in peak-flow. Projected changes to peak-flow, especially in glaciated basins, are sensitive to calibration approach, observational data, the selected GCMs, downscaling technique, hydrologic model and the representation of glaciers.

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