1st Specialty Conference on Disaster Mitigation
1ère conférence spécialisée sur l'allégement des désastres

Calgary, Alberta, Canada
May 23-26, 2006 / *23-26 mai 2006*

Developing a Risk Analysis Procedure for Post-Wildfire Mass Movement and Flooding in British Columbia

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Abstract: Many communities in British Columbia are situated on alluvial fans fed by steep mountain creeks, which are subject to debris flow or flooding hazards. Development on most of these fans has taken place without planning for debris flow hazard. Several severe wildfires in 2003 were followed by incidents of debris flows and flooding, that affected inhabited private property and infrastructure. In the past, the increased hazard of flooding, erosion, and mass movement caused by wildfire has not been fully appreciated in British Columbia. A process is now underway to develop a systematic procedure for risk analysis following wildfires in British Columbia, and recently there have been some government initiatives to address the risk associated with natural hazards. Some semi-quantitative examples illustrating risk assessment on fans are presented. Some related aspects of planning for risks on alluvial fans, and the challenges of conducting risk analyses over large areas with low population density, are discussed.

1. Introduction: Hazards on Steep Channels in British Columbia

Much of British Columbia consists of mountainous topography, in which populated areas and infrastructure such as highways are situated in narrow valleys. Many communities are situated on alluvial fans fed by steep mountain creeks, and highways, railways, and pipelines frequently cross these steep fans and creeks, many of which are subject to debris flow or flooding hazards.

Engineers are often called upon to design stream crossings for highways and other facilities, based upon estimates of probable peak streamflow. Very few small streams in mountainous environments have a record of stream gauging. Engineers and geoscientists also must identify debris flow or other hazards which may affect these crossings, assess stream channel stability, and assess the suitability of land on alluvial fans for residential construction or other uses.

On steep mountain creeks, peak discharge events are sometimes caused by phenomena other than "normal" rainfall or snowmelt floods, such as channel blockage by landslides or snow avalanches. Many steep creeks are subject to debris flows, with peak discharges one or two orders of magnitude greater than streamflow floods (Jakob and Jordan, 2001; Wilford et al., 2004). Debris floods can cause aggradation or avulsions of stream channels on fans and in valley bottoms; these channel changes are often more responsible than peak stream discharge for damage during flood events. The peak discharge for events of a given return period, as well as the likelihood of unusual events such as debris flows or debris floods, can be increased by land use or other changes in the upland areas of a watershed. One of these changes, which can have profound hydrologic and geomorphic impacts on a watershed, is wildfire.

A preliminary identification of fans subject to debris flow and debris flood hazards can be made on the basis of morphometric characteristics (Jackson et al., 1987; Wilford et al., 2004) such as the Melton ratio (watershed relief divided by the square root of watershed area) and the relief ratio (watershed relief divided by watershed length). These indices are essentially surrogates for average channel slope. In a study in northwestern British Columbia, Wilford et al. (2004) found that watersheds subject to debris floods and debris flows could be distinguished, with about 90% accuracy, by Melton ratios of 0.3–0.6 and >0.6 respectively. In the authors' experience in southeastern British Columbia, these criteria are reasonable for watersheds underlain by coarse-textured rock such as granite, but some watersheds with fine-textured geology and lower Melton ratios may be subject to debris flows. In this paper, the definitions of Hungr et al. (2001) are used: debris flow is defined as "a very rapid to extremely rapid flow of non-plastic debris in a steep channel", and a debris flood is "a very rapid, surging flow of water, heavily charged with debris, in a steep channel".

Not all watersheds meeting the above criteria are subject to debris flows and debris floods, but simple morphometric indices are a useful screening tool. The level of debris flow hazard can be better evaluated by examining the watershed and fan geomorphology, including such indicators as confined channels, prevalence of slope instability in the watershed, evidence of previous channel scouring by debris flows, and levées and lobes of debris on alluvial fans (Costa, 1984; Hungr et al., 1984; VanDine, 1985; Hungr et al., 2001; Jakob and Jordan, 2001). However, it is important to realize that some watersheds, which showed little or no evidence of debris flow activity in the recent geologic past, have experienced debris flows following land use changes such as logging or wildfire.

2. Effects of Wildfires on Hydrologic and Geomorphic Processes

Following a wildfire, loss of vegetative cover and forest floor material, and alteration of the soil physical properties, can result in increased runoff of overland flow as well as an increased likelihood of erosion and mass movement. Several processes can cause these hydrologic changes (Scott and Pike, 2003; Cannon and Gartner, 2005; Curran et al., 2006):

- Combustion of the organic litter layer (duff) comprising the forest floor can produce hydrophobic compounds which accumulate below the surface, resulting in water repellent soil conditions.
- Loss of the litter layer by burning removes the water storage capacity which normally exists on the forest floor.
- The interception capacity of the forest canopy and understory shrub layer is removed.
- The vegetation and forest floor layers which protect the soil from raindrop energy are removed, exposing the underlying sediment to erosion.
- Loss of the forest vegetation results in less evapotranspiration, increased snow accumulation, and potentially higher groundwater levels.

Due to the normally high infiltration capacity and storage capacity of forest soils, most forested watersheds produce very little overland flow during rainstorms. The hydrologic changes caused by fire can, if an intense rainstorm occurs soon after a fire, result in increased runoff 2 to 3 orders of magnitude greater than under pre-fire conditions (Cannon and Gartner, 2005). This increased runoff and accompanying erosion can greatly increase the likelihood of debris flows. These severe impacts typically persist for about 2 to 3 years. The effects depend on the severity of the burn (degree to which canopy, forest floor and soil have been altered), which in turn can depend largely on the pre-fire moisture conditions in the forest. The hydrologic changes also depend on the proportion of a watershed which has been burned. The unusually dry conditions which preceded the 2003 fires in southern British Columbia may have resulted in severe burns and therefore relatively great hydrologic impacts.

Only a very small proportion of wildfires in British Columbia present a risk to communities and infrastructure, and in the past, the flooding and debris flow risks caused by wildfires were not appreciated. It is possible that climate change, increased fuel supply due to the mountain pine beetle infestation, and increased fuel loads resulting from a legacy of fire suppression, may increase these risks in the future.

3. Example of Recent Post-Wildfire Events in Southern British Columbia

The summer of 2003 was an exceptionally severe wildfire season in the southern interior of British Columbia. Several large wildfires affected population interface areas, including the well-known disaster in Kelowna, in which many houses were burned. In the two years since these wildfires, there have been at least 8 incidents of debris flows or debris floods in drainages burned by the fires, and several of these incidents affected populated areas. Three notable examples are mentioned here.

3.1. Kuskonook and Jansen Creek debris flows

In August 2003 a wildfire burned most of the upper watershed area of Kuskonook Creek and Jansen Creek above the small community of Kuskonook on the east shore of Kootenay Lake. The fire caused severe burning over approximately 10% of the 4.2 km^2 watershed area, and created water repellent (hydrophobic) soils in the severely burned area (Figure 1). During a rainstorm on August 6, 2004 debris flows were initiated in the creek channel downslope from the burn area resulting in the destruction of two homes and damage to Hwy 3A and other buildings on the Kuskonook Creek fan (Figure 2). Luckily nobody was home in the one house that was totally demolished and the occupants of the other dwelling were not injured. The estimated volume of deposition was 20,000 to 30,000 m^3. A second smaller debris flow (approximately 200 m^3) occurred during a rain event on September 12, 2004. This event spilled onto the highway but did not cause any additional property damage. The August 6, 2004 rainfall event also caused a debris flow on the adjacent Jansen Creek fan. One car drove into the debris on the highway but nobody was injured. These events are described in more detail by Jordan et al. (2004) and by VanDine et al. (2005). The provincial highways ministry is contemplating the construction of a debris flow catch basin on Kuskonook Creek to reduce the hazard for traffic on Hwy 3A.

Figure 1. Erosion of water repellent soils, in the watershed of Kuskonook Creek. (Photo from Curran et al, 2006)

Figure 2. Kuskonook Creek fan following the debris flow of August 6, 2004.

The Kuskonook Creek event is a good example of a populated alluvial fan which is at risk from debris flows and other events with long return periods, and where the likelihood of a severe event was greatly increased by wildfire. This incident is used to illustrate some the difficult issues related to the preservation of public safety on alluvial/debris flow fans subject to wildfire hazard in British Columbia.

3.2. Cedar Hills Debris Flood Event

The Cedar Hills fire burned about 35 km^2 near Falkland, BC, in August 2003. On June 25, 2004, an intense rainstorm occurred, causing several debris floods on gullied slopes (Grainger, 2005). In the valley below the burned area, Highway 97 was blocked by debris for a hour, three residences were impacted by flooding, and debris was deposited on private property. Although there are no weather stations nearby, radar imagery and local anecdotal information suggest a rainfall of perhaps 25 mm in about 30 minutes. Water repellent soils in areas of severe burn were identified as a cause of the flood event.

3.3. Okanagan Mountain Park fire

This wildfire burned a large area (260 km^2) adjacent to and south of the city of Kelowna in August-September 2003. About a third of the population of the city was evacuated, and 250 houses were destroyed. On October 22, 2003, an intense rainstorm occurred in the Kelowna area. About 12-20 mm of rain fell over a 20-45 minute period, and the storm was estimated to have a return period of about 100 years. The rainstorm caused severe flooding and sediment deposition in several small drainages on the outskirts of Kelowna, notably Rembler Creek (Rogers, 2004). Several homes as well as infrastructure such as streets and creek crossings were damaged by this event.

4. Issues Related to Planning and Public Safety on Alluvial Fans and Other Areas at Risk from Natural Hazards

Fans and narrow valley bottoms naturally attracted settlement in mountainous regions, and often the early development took place without recognizing the risks from flooding or debris flows. As a result, there is a legacy of settlements in the southern interior of British Columbia that are potentially at risk from natural hazards. The Kuskonook Creek fan is one of these areas. The community was built at the south end of Kootenay Lake at a terminus of the Canadian Pacific Railway.

Land use regulatory tools used by local governments include Official Community Plans, bylaws, and development approval area designations. Municipal governments (cities, towns and villages) also regulate development through a subdivision review process. In unincorporated areas under regional district jurisdiction subdivisions are approved by the provincial Ministry of Transportation subdivision approval officer. A development permit may be refused under the Land Title Act if it is felt to be subject to “flooding, erosion, land slip, or avalanches”. Prior to granting of a building permit, a Building Inspector can also request an assessment of natural hazards if the area is felt to be subject to “land slips, debris flows, debris torrents, mud flows, and rock falls”.

Building inspectors have been placed in a position of having to make judgments on natural hazards when they were not qualified. Furthermore, the Province had not developed criteria that indicated what was considered an acceptable level of hazard or risk. This situation led to potentially awkward relationships between land owners, the local governments, and the professionals retained to carry out the natural hazard assessments.

There is currently no legislation in place in British Columbia that administers or directs issues with existing development when they are discovered to potentially be at risk from a natural hazard. The Province can activate a response through the Provincial Emergency Program (PEP) should an emergency occur as a result of natural hazards. The program is activated when a community or any significant infrastructure is threatened by an emergency or disaster which may overwhelm a local authority’s ability to respond. It is important to note that the program’s resources cannot be used unless a natural hazard has occurred or is imminent.

Maps that identify hazards on alluvial fans are a basic resource that are necessary to direct development away from high hazard areas. Many properties at risk of increased hazards due to wildfire are located in rural unincorporated areas where hazard maps are generally not available. Except for a series of flood hazard maps prepared for local governments by the BC Ministry of Environment in 2003, there is no comprehensive hazard mapping program. Local governments, especially regional districts and small towns and villages, typically do not have the expertise or financial resources required to prepare hazard maps. In some areas, local government does not have any restrictions on land development and homes continue to be built in known high hazard alluvial fan areas. In these areas the only control on where and how homes are built is exercised by the provincial subdivision approval officer.

The control and suppression of wildfire on Crown Land is the responsibility of the Ministry of Forests, Protection Branch. When an area burns or is threatened by a wildfire, and public funds are used to suppress or control it, the Ministry is responsible only for rehabilitating damage from fire suppression and control activities on Crown and private land. This rehabilitation does not include the damage to the watershed caused by the wildfire. Typically, the Protection Branch prepares a rehabilitation plan that specifies treatments for fireguards, fire access trails, stream crossings, and other suppression works.

There is presently no lead agency in government responsible for carrying out post-wildfire hazard and risk assessments, and there is no requirement that any government or agency conduct assessments or rehabilitation treatments following fires to help reduce the threat to populated areas, infrastructure, or water sources.

The importance of having a lead agency responsible for post-wildfire risk screening became apparent during the 2003 fire season. There were obvious burn areas in the southern interior where threats to communities and infrastructure were identified, and there was no protocol or consistent approach for government ministries, regional districts, municipalities or other agencies to address this threat. The relatively large cities of Kelowna and Kamloops undertook reviews of the potential affects of the burned areas within their boundaries, and implemented programs to mitigate the risk of hazardous landslide and flooding events. However, no such action was taken in the smaller cities, towns, and rural areas that comprise most of the region.

Following the fire in the Kuskonook Creek watershed, provincial Ministry of Forests (MoF) staff recognized that there was an increased risk of debris flow hazard on the Kuskonook fan. The local regional district government was advised to warn residents of this increased hazard. The regional district responded by asking the MoF to provide detailed maps indicating which residents should be warned. Before the MoF could respond the debris flow occurred. The MoF subsequently responded by indicating that it was not the MoF mandate to map areas on valley bottom private lands below areas affected by natural events, such as wildfire. The regional district maintained that they did not have the expertise to create a map, nor did they have the ability to acquire funds to hire a consultant to create a map without first going through the onerous and often unsuccessful process of establishing a Local Services Area to enable local taxation. The regional district also pointed out that the debris flow originated on crown land where the regional district did not exercise any control over land use, and that even if they did they did not have qualified professionals on staff to assess the hazards associated with forest fires.

5. The Natural Hazards Mitigation Fund and the Post-Wildfire Risk Analysis Procedure

In 2005 the provincial government established the Natural Hazards Mitigation Fund (NHMF) to assist local governments and diking authorities to prevent and mitigate natural geological and hydrological hazards, and to construct flood and debris flow protect works. Hazard mapping and risk assessment reports are eligible for funding assistance under this program. However, due to the lack of technical resources and/or limitations of the funding, very few local governments have taken advantage of this program to undertake hazard mapping projects.

Projects for engineering studies and mitigation treatments of wildfires may be eligible to receive funding under the NHMF if there is an unacceptable risk to human settlements, private property, or infrastructure. However, the NHMF does not address all post-wildfire risk management needs. Applications for funds must be made early in the fiscal year (which in British Columbia begins April 1); however, wildfires typically occur during the summer, after the funds for that year have been granted. To be effective, a post-wildfire assessment should be done within weeks of the fire being contained.

In 2005, the Southern Interior Forest Region (SIFR) of the Ministry of Forests received a grant from the NHMF to develop a risk analysis procedure for post-wildfire natural hazards. Also, the SIFR is preparing a Standard Operating Procedure to address post-wildfire flooding, erosion, and landslide risks. The former is a technical document (Dobson Engineering Ltd., 2006) which provides guidance to professional engineering and earth science practitioners carrying out risk analyses for fires and watersheds where a potential post-wildfire risk has been identified. It is based to some extent on the “burned area emergency response” (BAER) procedure used by the US Forest Service and other US federal agencies.

The Standard Operating Procedure is an internal document, which defines the roles and responsibilities within the Ministry of Forests to assess risks following wildfires. It contains three main elements:

- Post-wildfire risk screening – initial fire reports are screened by specialists in the Ministry of Forests. Where screening identifies a fire for which life, property, or other values at risk then a more detailed risk analysis may be completed.
- Risk analysis – this is completed by the Ministry of Forests’ regional specialists and considers burn severity, soil condition, hydrology, slope stability, and the potential consequences should a hazardous event occur. Where the risk analysis determines the risk to human life, property, infrastructure or other specified values is moderate or high, then the results are communicated to appropriate land managers or stakeholders.
- Risk evaluation and control – The lead agency or stakeholder will consider the risk analysis and determine if the assessed risk is acceptable or tolerable. If the risk is unacceptable then risk control (mitigation) measures should be considered. Additional or more refined risk analyses may be required for some circumstances, as determined by those stakeholders.

6. Principles of Risk Assessment and their Application to Post-Wildfire Risks on Fans

Risk assessment is the process of analyzing risk (risk analysis) and determining if the analyzed risk is acceptable or tolerable and whether risk reduction works are required (to reduce the risk to acceptable or tolerable levels). A risk analysis is “the systematic use of information to identify hazards and to estimate the chance for, and severity of, injury or loss to individuals or populations, property, the environment, or other things of value” (CSA 1997). The Risk (R) to something of value (an element) can be expressed with a mathematical relationship as follows:

[1] $R = P(H) \times P(S{:}H) \times P(T{:}S) \times V(L{:}T) \times E$

where:

- P(H) is the probability of occurrence of a specific hazardous landslide;
- P(S:H) is the probability that, given the specific hazardous landslide occurs, it will physically reach the area that the element occupies or passes through (spatial effect);
- P(T:S) is the probability that, given there is a spatial effect, the element will be present within the area of impact when the landslide occurs (temporal effect);
- V(L:T) is the probability that, upon landslide impact, there is total loss or damage of the element, or it is the estimated proportion of loss or damage to a specific element;
- E is the worth of the element.

If the element at risk is human life then E is dropped and R is expressed as PDI (probability of death of an individual) or PDG (probability of death to a group). Elements at risk that are located on fans can include human life, private land, private assets (homes, vehicles, water systems, etc), transportation infrastructure (highways and railways), and utilities (power, natural gas, water delivery).

This approach to landslide risk assessment in a forestry context is discussed further in Wise et al. (2004).

After a wildfire the probability of occurrence of a specific hazardous landslide, P(H), will generally increase for several years above its pre-fire level. Several factors determine the degree that P(H) will increase and they include the burn location within the watershed, the hydrogeomorphic watershed processes, the size of the burn, and the burn severity. A high burn severity refers to an area where trees, understory vegetation, most large ground fuels, and the forest floor have been consumed (Curran et al., 2006). For some watersheds in BC the 2003 post fire sum of all the P(H)’s likely exceeded 0.1 for given storm intensities. In fact, in other jurisdictions such as California, empirical based post fire risk analysis have estimated P(H) as high as 0.98 for given storm intensities (Cannon et al., 2004).

While there are several causes that contribute to P(H), the triggering event will almost always be a rainfall of sufficient intensity and duration to cause substantial overland flows, surficial erosion and excessive stream flows. The required rainfall intensity and duration to trigger an event likely decreases as the burn area and burn severity increase. P(H) can be roughly redefined to equal the probability that such a triggering rainfall event occurs after a wild fire but before natural recovery occurs (usually 2 to 5 years). Thus for a large severely burned area located on steep slopes, the triggering rainfall event may be a 1 in 3 year return period summer convective rainstorm. If natural recovery occurs after 3 years P(H) would at least equal $(1-(1-.33)^3)$or 0.7 over the 3 year period. Conversely an area that was burned with low to moderate severity may require at least a 30 year return storm trigger and P(H) would then equal 0.1 over the 3 year period.

However, with limited local data, it is very difficult to accurately estimate the required storm that will trigger a post wildfire event. Therefore it is more prudent to develop tolerable limits on likelihood of a hazardous landslide impacting an element of value (or the product of P(H) x P(S:H) x P(T:S)) assuming that a significant rainfall will occur. In BC for subdivision approval in rural areas, guidelines state that when assessing hazards the applicant should consider "a 10% chance of occurrence of a particular hazard over a 50 year period" which translates to 1 in 475 per year annual probability (presumably impacting an element of interest). This does not imply however that the yearly P(H) x P(S:H) x P(T:S)) should be less than 0.002 for every year. For many years the yearly P(H) x P(S:H) x P(T:S) could be well below 0.001; however, immediately following a wildfire P(H) x P(S:H) x P(T:S) could soar to above 0.01, but still meet the long term average guideline of less than 0.002. This poses obvious problems in determining post wildfire acceptable risk levels. How high can P(H) x P(S:H) x P(T:S) be for the few years post wildfire until the long term hazard significantly exceeds the predetermined long term acceptable limits? Is it reasonable (and tolerable) to expose individuals to a high risk immediately following wildfires as long as the long term average risk remains below an acceptable limit?

One approach is to summarize the available empirical data, determine failure rates (regardless of storm magnitude), and compare the failure rates with the existing subdivision guidelines. After the 2003 fires a preliminary risk analysis was conducted for every interface fire (fires where there were nearby elements of value such as people, property and infrastructure). The risk analyses considered the likelihood of landslide occurrence due to the effects of the fire and the likelihood that a landslide would impact or effect an element of value (P(H) x P(S:H) x P(T:S)). The analyses were conducted primarily with the use of fire boundary maps, contour maps, stereo air photos, and helicopter overviews of the burned watersheds and values at risk. In some cases the areas were field reviewed on the ground. The risk analyses were qualitative with rankings of moderate or high requiring communication of the risk with local governments and stakeholders. During 2003, 26 risk analysis were completed on interface fires in the BC Southern Interior with 11 of these identified as having a moderate or high risk requiring local government or stakeholder notification. Of these 11, 7 experienced either flooding, debris flows, or debris slides, and 6 of these impacted residences or infrastructure (in some cases houses were impacted or destroyed and highways damaged). Approximately 64% of the fires identified as posing moderate to high risk experienced debris flows or floods while 55% impacted residences or infrastructure. Of the 15 fires identified as having no or low risk to people or infrastructure, one of these had an event (debris flood) that had a minor impact on infrastructure. The debris flows and floods often occurred during storm events that would typically be considered less than 1 in 20 year return storms.

The simple methodology used in identifying the fire hazard appears to have been successful in separating the hazardous fires from the non-hazardous fires. At the same time the high failure rates (27% of 2003 interface fires experienced debris flows, debris floods or flooding with 23% impacting residences or infrastructure) suggests that for the fire conditions experienced in 2003, P(H) x P(S:H) x P(T:S) exceeded, by an order of magnitude, the tolerable limit of 0.002/year (for five years) used for subdivision approval in rural areas. Where the risk is determined to be unacceptable, several risk control strategies can be implemented ranging from public notification, to erosion protection (in the burn area) to debris flow catch basin/diversion structures.

7. Changes in Flood and Debris Flow Hazards Following Wildfire

As described above, a specific hazard, P(H), may increase after a fire. P(H) may refer to any of several hazards, including landslide, debris flow, or flood. In attempting to quantify hazards, two important principles must be kept in mind: first, that many hazards can be expressed in the form of a frequency distribution, similar to a flood frequency curve; and second, that the probability of an event of given magnitude is not constant over time, but may change in response to changing conditions in a watershed, in particular wildfire.

Figure 3 shows a hypothetical flood frequency curve (after Jakob and Jordan, 2001), based on data from a small watershed in the West Kootenay region which has similar characteristics to Kuskonook Creek. It illustrates the principle that, for many such small, steep streams, the design event for longer return periods is not a streamflow flood, but a debris flow. Following a wildfire, the maximum annual discharge for a given return period will increase, for several reasons as outlined above. Also, the likelihood of a debris flow will increase; this is shown as a shift left and upwards of the debris flow frequency curve.

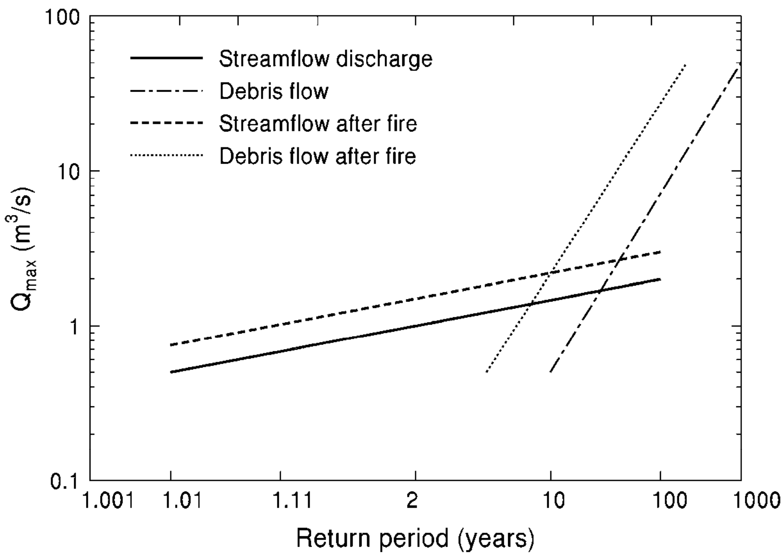

Figure 3. Flood frequency curves for a small creek subject to debris flows.
Q_{max} = annual maximum instantaneous discharge.

For the analysis of debris flow hazard, an event of interest is considered, which is a debris flow large enough to reach the element at risk. For example, referring to Figure 3, the 200 year return period event or larger events may be likely to reach the houses on the fan; smaller events are unlikely to travel beyond the fan apex, and so are not considered. Figure 4 shows the changes in the probability of the debris flow of interest which might occur following a severe wildfire. Unlike streamflow, there is almost never sufficient observational history of debris flows to accurately determine probabilities. Instead, typical return periods of debris flows on a particular fan are usually estimated by examining debris flow deposits and other evidence on a fan. This evidence can include dendrochronoligical or radiometric dating as well as geologic observation. In this example (which might represent Kuskonook Creek), the average return period for a debris flow of interest is estimated as 200 years. In the absence of wildfire or other disturbance in the watershed, the actual probability may be less than this. However, immediately following a fire, the probability may increase by 10 to 100 times. If a debris flow occurs (as happened on Kuskonook Creek one year after the fire) then the probability of further debris flows drops to much lower than the pre-fire probability, because most of the available debris, which may have accumulated over a period of centuries, has been removed from the channel (although for one or several years, there may still be some hazard of smaller debris flows). The probability of a debris flow then gradually recovers over time, as weathering, tree fall, and other processes gradually cause debris to accumulate in the channel. If no debris flow occurs for several years following the fire (which is likely, if no unusually intense rainstorms occur) then, over a period of time which might be several decades, the probability of a debris flow returns to pre-fire levels as vegetation and soil properties recover after the fire.

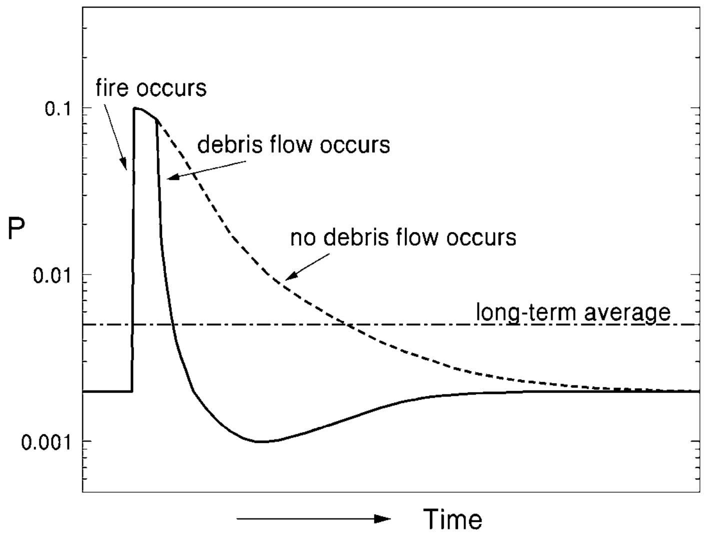

Figure 4. Changing probability of a debris flow following a severe wildfire.
P = probability of occurrence in a year.

8. Conclusions and Recommendations

This paper has discussed some aspects of the risks presented by post-wildfire changes on hydrologic and geomorphic processes in British Columbia, and the methods being applied for risk analysis of post-wildfire flooding and debris flows. However, much work remains to be done to better quantify the post wildfire risk and to better define acceptable or tolerable risk to affected communities. We offer several recommendations, aimed at engineering practitioners, and at provincial and local government agencies in British Columbia.

- Communities located in high hazard areas should develop and practice emergency response plans. Plans should include a map showing the probable extent of the hazardous lands (for debris flow and/or flooding hazards often this will be the extent of the alluvial/debris flow fan area), describe what conditions are likely to trigger an event (climatic and/or changes in upslope areas such as wildfires) and an evacuation plan.
- With changing climatic conditions and the resulting increase in flooding and debris flow hazards, engineering professionals should work towards a national and/or provincial natural hazards assessment and response strategy, which would assist local governments in land use and emergency response planning.
- Engineers and geoscientists responsible for designing or maintaining stream crossings and making recommendations for subdivisions and construction should be aware of the changes in flood and debris flow hazard which can occur following wildfires.
- Governments at all levels should attempt to define post wildfire (and other natural hazard) risk levels so that available resources can best be directed where required.

9. Acknowledgements

Glenn Moore contributed to the work described in this paper, both through helping to obtain funding for the project under the NHMF, and through his work on risk assessment methodology. Don Dobson and Tim Smith were involved in field work and analysis of the events described here, especially the Okanagan

Mountain Park fire, and did a great deal of work to raise awareness of post-wildfire hazards in British Columbia. Doug VanDine contributed to the application of risk analysis methods to the Kuskonook Creek event, and also to the science of natural hazards risk assessment in general. Bill Grainger, Mike Curran, Pete Robichaud, and David Scott participated in field work on the fires discussed in this paper, and contributed to our understanding of post-wildfire processes.

Note on names of government agencies: The names of some ministries in the British Columbia government have changed several times in the last 5 years. For simplicity, the names “Ministry of Forests” and “Ministry of Environment” are used throughout this paper.

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