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Post-wildfire landslides in southern British Columbia

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ABSTRACT: A number of post-wildfire landslide and flood events have occurred since 2003 in the southern interior of British Columbia. Such events had not been previously reported in Canada, although they are common in more southerly latitudes. A total of 22 events were documented after the extreme 2003 wildfire season. In one event, several houses were destroyed. Severe wildfire seasons also were experienced in 2007 and 2009. In the three years following these fires, 14 significant events occurred, including one which caused a fatality. Post-wildfire landslides have occurred in spring, summer, and fall. Three types of weather event have triggered the landslides: spring snowmelt, high-intensity summer rainstorms, and low-intensity fall rainstorms. Most events were debris flows, and the most common initiating mechanism was high peak flow in channels. A variety of hydrologic changes contribute to the prevalence of post-wildfire landslides and floods, including water-repellent soils, loss of forest floor, and more rapid snowmelt.

1 INTRODUCTION

Following wildfire, significant changes can occur to the hydrological and physical properties of soil, and the loss of forest canopy and forest floor can result in further hydrological effects. Increased overland flow and surface erosion often follow these changes. One effect of wildfire is an increase in the incidence of landslides.

Many occurrences of post-wildfire landslides and severe erosion events have been documented in the western United States (Cannon & Gartner 2005) and elsewhere in the world (Shakesby & Doerr 2006). Some of these, especially in southern California, have resulted in fatalities and significant property damage (Scott 1971; Wells 1987).

Several effects of wildfire have been implicated in the increased incidence of post-wildfire landslides and other hydrologic/geomorphic events. Loss of the forest floor litter and duff reduces water storage capacity and increases the susceptibility of the soil to erosion from raindrop impact and rilling (Robichaud et al. 2000). Water repellency can occur as a result of the accumulation during fire of hydrophobic compounds below the soil surface (DeBano 1981; Doerr et al. 2006). Sealing of surface soil pores by ash and fine particles can reduce infiltration capacity (Larsen et al. 2009). The extent and significance of soil water repellency and other affected hydrologic properties is dependent on soil burn severity (Doerr et al. 2006). Loss of the forest canopy reduces the interception capacity and can cause increased snow accumulation and melt rates (Jordan 2011).

Despite these changes, most wildfires in British Columbia have been observed to have only minor effects on hydrology and geomorphology, and before 2003 there were very few reported examples of landslides or severe erosion following wildfire in the province. However, in several cases since 2003, significant landslide events have followed wildfire. The objectives of this paper are to document these landslide events, and examine the factors that contributed to their occurrence.

The fire season of 2003 was the most extreme in British Columbia history. In the following two years, significant landslide or flood events occurred in five of the fires, and for the first time alerted the geotechnical community in British Columbia of the potential post-wildfire risks that exist in the province. In 2007 and 2009, severe fire seasons were again experienced in parts of the southern interior, and subsequent landslide events occurred in three fires. These events are described below, and the locations of the fires that experienced events are shown on Figure 1.

2 METHODS

The landslide and flood events following the 2003 fires were investigated by British Columbia (BC) Forest Service engineering and geoscience special-

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ists, including the author, or by consultants to the province or local governments. These investigations were reconnaissance in nature, and included estimation of event volumes, inspection of debris flow initiation areas, visual description of burn severity, and tests for water repellency, but without any detailed mapping or data collection.

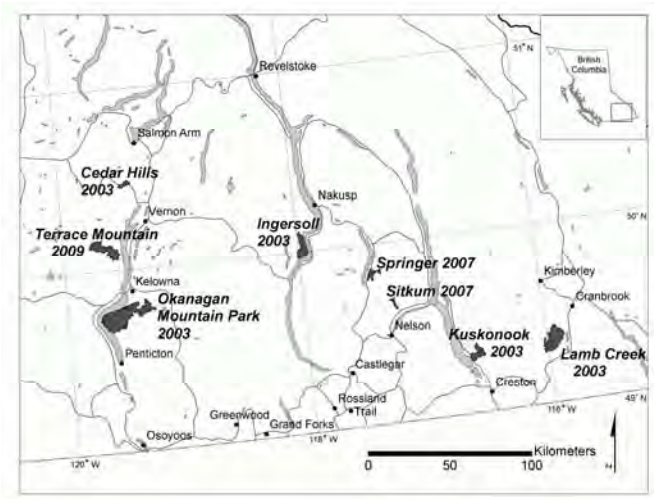

Figure 1. Location of fires in southeastern BC in which post-wildfire landslides and flood events have occurred.

In 2007, the Southern Interior Forest Region of the BC Forest Service began a research project on post-wildfire hydrologic and geomorphic processes, and implemented a program to conduct systematic risk analyses of post-wildfire natural hazards for wildfires that threatened populated areas or infrastructure. As a result, several of the larger and more severe wildfires in 2007 and 2009 had detailed mapping of burn severity, hazardous terrain, and elements at risk soon after the fires were out.

Burned area reflectance classification (BARC) maps were prepared from Landsat satellite images taken before and after the fires, using methods developed by the US Forest Service. Data from field plots were used to calibrate the BARC images, by assigning high, moderate, and low classes that correlate as well as possible with field observations of vegetation burn severity, and that are consistent between fires (Parsons et al. 2010). Watershed boundaries were delineated from 1:20,000 topographic maps, and burned areas in each watershed were tabulated by burn severity class.

Following landslide events, field observations were made where access and terrain conditions permitted. Most events were debris flows. Debris flow deposits were identified and distinguished from flood deposits on the basis of characteristics such as matrix support, boulder fronts and levees, and inverse grading. Approximate debris flow deposit volumes were calculated by field traverses with a GPS (for large events), or by mapping on low-level aerial photographs, combined with estimates of depth at various locations. Where possible the full length of channels was walked, but in some cases the channels were inspected only from the air due to inaccessible or dangerous terrain.

Field observations were made in the burned areas above initiation zones where access was possible. Qualitative observations were made of soil burn severity, based on methods given in Robichaud et al. (2000) and Parsons et al. (2010). To test for soil water repellency, we used the water drop penetration test (DeBano 1981; Robichaud et al. 2008).

Weather data during each of the events were collected from various stations, including the official Environment Canada climate station network, fire weather stations operated by the BC Forest Service, and snow pillow stations operated by the BC Ministry of Environment. Following the 2007 and 2009 fires, we installed a total of 16 additional rain gauges in areas selected for research field work. Several of these provided data near landslide locations.

3 LANDSLIDE AND FLOOD EVENTS FOLLOWING THE 2003 FIRES

The wildfire season of 2003 was exceptionally severe in southern British Columbia (Filmon et al. 2004). Record drought conditions were experienced, and as a result some fires exhibited extreme behaviour, which resulted in high burn severity in many locations. Two of the largest fires, and those which received the most attention due to the destruction they caused to communities, were the Okanagan Mountain Park Fire near Kelowna and the McClure Fire near Barriere. However, several other fires burned near communities or infrastructure, and, as subsequent events proved, some of these presented significant risks of post-wildfire flooding or mass movement.

A total of 16 significant events, including 8 debris flows, 6 debris floods, and 2 debris slides were documented after the 2003 fires. Detailed descriptions and maps are given in Jordan and Covert (2009); a brief summary of the events is given here. Most of these events occurred as a result of high-intensity mid-summer rainstorms, although some events occurred during a long-duration, low-intensity fall rainstorm. In addition, a number of minor events were observed, such as localized flooding and gully erosion.

In October 2003, debris floods occurred on two creeks draining the Okanagan Mountain Park fire, and caused some damage to residential areas on the southern periphery of the city of Kelowna. The flood events were attributed to overland flow in areas of moderate to high burn severity, in which water repellency was observed (Rogers 2004). Most of the sediment carried by the floods was apparently de-

rived from the channel bed and banks in the lower reaches of the creeks, rather than from erosion in upland areas.

In the Cedar Hills fire near Falkland, an intense rainstorm occurred in June 2004; it caused erosion in approximately 50 small gullies along a 2.5 km slope (Grainger 2005). In a convergent gully complex that had a contributing area of 30 hectares, eroded sediment bulked into a debris flow, and then turned into a debris flood before reaching the fan below. The event crossed the highway, and flowed into two residential yards. On the upper part of the slope, high soil burn severity and strong water repellency were extensive.

The most destructive events occurred in the Kuskonook fire, about 25 km north of Creston. On the night of 6-7 August 2004, a heavy rainstorm occurred in the area, triggering large debris flows in the channels of Kuskonook and Jansen Creeks (Jordan et al 2006; VanDine et al. 2005). Two houses were destroyed, and a large part of the Kuskonook Creek fan was covered with debris. Field investigations after the events found extensive high soil burn severity, water repellent soils, and evidence of overland flow in a plateau area draining into the steep channels. Although shallow surface erosion was widespread, relatively little debris was produced in the source area. The Kuskonook Creek debris flow initiated from failure of the bed and banks, at a point where the channel steepened to about 29 degrees and entered a confined gully in glacial deposits (Figure 2). Almost all of the estimated 20,000 to 30,000 m^3 of debris originated from the channel.

Figure 2. Overview of Kuskonook fire debris flows of August 2004. Debris flow initiation points are shown by arrows.

In the Lamb Creek fire near Cranbrook, a heavy rainstorm on 19 August 2004 affected the severely burned upper drainage basin of Gold Hill Creek, and caused a large debris flood. Overland flow from the burned slopes in the headwaters accumulated in a wetland and spilled over an escarpment of deep glacial till, causing several meters of incision along the creek channel. Most of the 4.5 km channel has too gentle a slope (about 5 to 10 degrees) to support debris flow, and although there is some evidence of debris flow processes, fluvial transport is predominant in the channel. The volume of eroded debris is estimated at 30,000 to 50,000 m^3, which was deposited on a small fan at the creek mouth, and farther down the larger Lamb Creek channel.

The Ingersoll fire burned a very steep, bedrock-dominated slope, and a plateau above, bordering Lower Arrow Lake. In October 2005, two years after the fire, a 2-day rainstorm triggered 15 debris flows and debris slides (Figure 3). Most of the events were debris flows, which initiated in the upper parts of steep gullies incised in bedrock and apparently were triggered by overland flow spilling from the plateau into the gullies. This incident differed from the others in that the rainfall was of low intensity and long duration. It is likely that snowmelt contributed to the supply of water, and it is possible that lingering water repellency or other effects of high soil burn severity reduced the infiltration capacity.

Figure 3. Several of the October 2005 debris flows in the Ingersoll fire. Debris flow initiation points are shown by arrows.

At most of these events (Ingersoll being the exception), extensive strong water repellency was observed in the headwaters of the affected drainage basins, and this was probably a major cause of overland flow generated during intense rainfall. Most of the debris flows (except for the Cedar Hills event) originated in the channels, due to exceptionally high peak discharge from overland flow, and the vast majority of debris was derived from the channels, not from surface erosion of burned slopes.

Smaller mass movement and erosion events were reported in several of the 2003 fires, including the Strawberry Hills fire near Kamloops and the McLure fire near Barriere.

4 LANDSLIDE EVENTS FOLLOWING THE 2007 AND 2009 FIRES

Another severe fire season occurred in 2007 in south-eastern BC, with drought conditions almost as extreme as in 2003. Several large wildfires burned near populated areas. In the following two years, several significant landslides occurred in the Springer fire near Slocan, which burned from 29 July to mid August 2007.

In the channel of Middle Van Tuyl Creek, a debris flow with an estimated total volume of 5000 m^3 was triggered by snowmelt on 17-18 May 2008 (Figure 4). It crossed Highway 6 and caused one fatality (Nicol et al. 2009). About two-thirds of its drainage area had high and moderate burn severity. The event, which comprised two debris flows on successive days followed by a much smaller one two days later, occurred during the peak snowmelt event of the season. Increased snow accumulation and melt rate in the burned area apparently caused a much higher than normal peak discharge in the channel. An accidental drainage diversion from an old logging landing, which nearly doubled the effective drainage area, was also implicated as a cause. A second, smaller, debris flow occurred in the channel in May 2010, initiating at a higher point (Figure 5). In the adjacent channel of South Van Tuyl Creek, a similar debris flow occurred in May 2011.

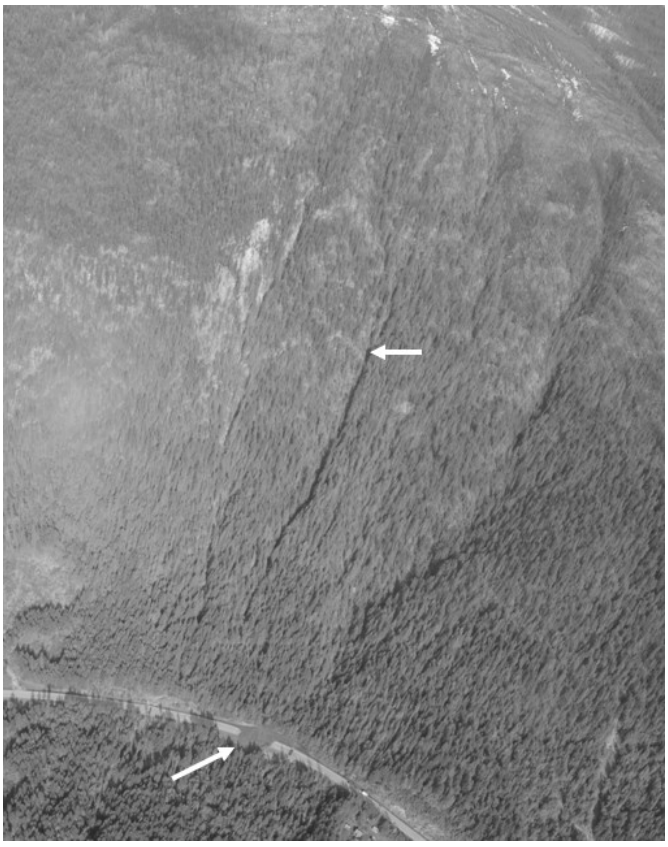

Figure 4. The Middle Van Tuyl Creek debris flow of May 2008 in the Springer fire. Arrows show the initiation point, and deposit on the highway.

Figure 5. Initiation point of the May 2011 debris flow in the Middle Van Tuyl Creek channel.

Four large (about 1000 to 3000 m^3) debris flows and several smaller ones occurred in the nearby Enterprise Creek drainage, in very steep, bedrock-dominated, gully systems, during moderate rainfalls in August 2007, August 2008, and September 2009. Three of these occurred in the same channel, the upper part of which is shown in Figure 6. These channels were subject to occasional debris flows before the fire, with estimated return periods of several decades. However, the likelihood of debris flows was substantially increased after the fire, probably by the loss of large woody debris in the channels and on adjacent steep slopes, and possibly by water repellency on slopes above the gullies. Due to extremely steep and inaccessible terrain, we did not walk the channels. From aerial observations, it appears that at least two of them started in multiple diffuse sources, in rockfall-fed gullies. The rate of rockfall typically increases greatly after a fire, and fallen wood in the gullies which normally stabilizes the rockfall debris was consumed by the fire; these two factors may have led to much more debris being available for mobilization in the gullies.

In June 2011, in the Memphis Creek drainage, a shallow debris slide of about 300 m^3 in volume occurred on a relatively gentle (40-50%) slope, in a patch of high severity burn. It continued down the channel of Memphis Creek as a debris flow which reached the highway, with an estimated total volume of 3000 to 4000 m^3. This event happened during a period of heavy rain (37 mm in 24 hours, with a peak hourly rainfall of 16 mm) at the end of the snowmelt period. High groundwater level in the burned area was the probable cause.

Figure 6. Headwaters of a tributary of Enterprise Creek burned in the Springer fire, in which debris flows occurred in 2007, 2008, and 2009. Photo taken 6 September 2007.

In the Sitkum fire near Nelson, a debris slide occurred on a mine road during snowmelt in May 2008 (Figure 7). High groundwater level caused by increased snow accumulation and snowmelt rate on the burned slopes above was the most likely cause. This slide affected water quality in a community watershed.

Figure 7. Debris slide of May 2008 below the Sitkum fire. The road is at the top of photo. Several holes from piping of groundwater are visible in the middle part of the slide scarp.

A severe fire season in 2009 affected the south-central and southwest interior, and several large fires burned near populated areas. In one of these, the Terrace Mountain fire near Kelowna, a small debris flow occurred in March 2010 in a steep gully. The site had been identified as high risk, and a protective berm was built in October 2009 above a house, as well as road deactivation and straw mulching treatments on the plateau above (Jordan 2011). The berm successfully prevented the debris flow from impacting the house. The cause of the event was identified as a higher-than-normal water table on the severely burned plateau above, which created areas of standing water and caused unusually high peak flow in the small stream feeding the gully.

Several debris flows and debris floods occurred in August 2010 in the area burned by the 2009 Kelly Creek fire near Clinton in the Cariboo region (T. Giles, BC Forest Service, Kamloops, pers. comm.).

5 DISCUSSION AND CONCLUSIONS

Significant landslide and flood events have been documented in eight wildfires in southeastern British Columbia, out of hundreds of wildfires that occurred in the 2003, 2007, and 2009 fire seasons. The sample of documented landslides is small, but we have sufficient information to make some observations on why these particular fires were especially hazardous.

All of these events occurred in large fires with extensive high soil and vegetation burn severity. In four of the five 2003 fires in which debris flows occurred, water repellency was observed in the burned areas, and this, combined with intense, short-duration rainstorms, was concluded to be a factor in the events (Jordan and Covert 2009). Water repellency was observed in the 2007 burns, although it was not as extensive as in the 2003 fires, and is not believed to be a significant cause of the 2007 and later events. It appears probable that fires that burn under extreme drought conditions, as in 2003, are likely to have relatively high soil burn severity, one manifestation of which is water repellency. Consequently such fires are likely to have a significantly increased hazard of post-wildfire landslides and flooding. In the 2007 fires, most events occurred during spring snowmelt, when water repellency was unlikely to be a factor. In these cases, increased snowmelt runoff from burned areas was probably the main cause. In several of these events, logging roads and trails above the initiation point were, or may have been, a factor.

Table 1 summarizes the characteristics and probable initiating mechanisms of post-wildfire debris flows and other landslides in this study.

Table 1. Summary of 36 post-wildfire events in southeastern British Columbia.

Type of event:		
debris flow	22	
debris slide	9	
debris flood	5	
Summary of initiating mechanisms:		
peak flow in channel (runoff-triggered)		24
sediment bulking – from soil erosion		1
sediment bulking – in steep gully headwalls		2
debris slide/avalanche (infiltration-triggered)		9
Season of occurrence:		
spring (snowmelt)	8	
summer (short-duration rainstorms)	13	
fall (long-duration rainstorms)	15	

Research and incident investigations since 2003 have enabled us to make some conclusions or inferences about the special characteristics of post-wildfire debris flows, slides, and floods, and to identify several factors that aid in the identification of these hazards:

- Post-wildfire landslides can occur in three seasons – spring, summer, and fall – in response to snowmelt, localized high-intensity rainstorms, and long-duration frontal rainstorms.
- Post-wildfire debris flows typically start in the channel, due to high peak flow. This differs from non-fire-related debris flows in forested environments, which most often start as small debris slides that enter a channel.
- Post-wildfire landslide hazard increases in approximate proportion to burn severity.
- The distribution of high-severity burn in the catchment is important – severely burned areas at upper elevations cause the greatest hazard.
- "Gentle-over-steep" topography, where a severely burned plateau area drains into a steep channel or gully, appears to present a greater hazard than steeper, concave-up, topography.
- The deforested area (or "equivalent clearcut area") in a watershed due to severe wildfire can approach 100%, which can lead to an increased hazard of spring snowmelt-triggered events.
- Post-wildfire debris flows usually occur in gullies and channels that were subject to hazard under pre-fire conditions, but the likelihood of occurrence can be much greater (or, the return period much shorter) after wildfire.
- The greatest hazard from high-intensity rainfall is in the first 2 to 3 years after fire, and is reduced each year as vegetation is re-established. However, the hazard of events caused by elevated groundwater levels during spring snowmelt can persist for decades.

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