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Key Terms: *Debris Flows, Landslides, Wildfire, British Columbia*

ABSTRACT

A number of post-wildfire debris flow and debris flood events occurred in the two years following the extreme fire season of 2003 in the southern interior of British Columbia. Such events had not been previously documented in Canada. Rainstorms following five fires caused significant events in the Okanagan and Kootenay regions of the province, including the Okanagan Mountain Park, Cedar Hills, Kuskonook, Lamb Creek, and Ingersoll fires. Damage to residential property and infrastructure downstream of the fires occurred in three cases. Most of the damaging events were debris flows, although several large debris floods occurred on lower gradient streams. At four of the fires, the events were triggered by short-duration, high-intensity rainstorms. At the fifth fire, a long-duration, low-intensity rainfall triggered the events. In all cases, severe burns with water repellent soils were identified or suspected as contributing to the events. The debris flow and debris flood events described here illustrate three initiation mechanisms: runoff-triggered debris flows caused by erosion of channel bed and banks by critically high discharge; debris flows and floods caused by progressive sediment bulking of runoff with material eroded from headwater slopes; and landslide-triggered debris flows caused by a landslide that enters a steep channel. In the burned areas studied, the first mechanism is the most common, whereas in unburned forested landscapes in the region, the third mechanism is the most common.

INTRODUCTION

The fire season of 2003 was the most catastrophic in recorded British Columbia history (Filmon et al.,

2004). A record-breaking drought in the southern interior of the province was accompanied by 1800 fires, which burned 228,000 hectares in the Southern Interior Forest Region, compared to a long-term average of 9,500 hectares per year. Many were interface fires—adjacent to urban development or rural populated areas. At least 334 homes and several businesses were destroyed. A number of debris flows, landslides, and floods followed the 2003 fires. Rainstorms on five burns produced major events, defined as events that caused, or could have caused had they been in a populated area, significant consequences to public safety or infrastructure. These events were investigated by the British Columbia (BC) Forest Service, local governments, or their consultants, and are discussed in detail here. On several other burns, relatively minor or low-consequence events occurred.

Although debris flows, floods, and severe erosion events due to wildfire are common in the western United States, they have been rarely documented in British Columbia or elsewhere in Canada until 2003. The authors speculate that there may be several reasons for this: rainfall intensities are lower than at more southerly latitudes; typical soil burn severity may be lower than farther south because of thicker, moister forest floors and wetter climate; and most Canadian wildfires are in remote areas, and events may have occurred that have not been observed or documented.

The objectives of this paper are: (1) to document the post-wildfire flood and mass movement events that followed the 2003 fire season in British Columbia; and (2) to investigate the initiating mechanisms of debris flows following wildfire in this region. In particular, we examine the processes of landslide triggering, runoff triggering, and progressive sediment bulking, and their relative importance in the initiation of debris flows in burned and unburned areas in this region. We also examine the role of soil burn severity and water repellency in contributing to debris flow and debris flood initiation, and the rainfall conditions that led to the observed debris flow and debris-flood events.

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It is well established that in many parts of the world, wildfires are often followed by an increased incidence of flooding, erosion, and landslides (Cannon and Gartner, 2005; Shakesby and Doerr, 2006). Severe burns have significant effects on both vegetation and soil. The loss of forest floor due to fire reduces infiltration rates and water storage capacity, and increases the susceptibility of the soil to raindrop erosion (Robichaud et al., 2000). Infiltration rates can also be reduced by clogging of soil pores by ash and fine soil particles (Shakesby and Doerr, 2006). Water repellency can occur below the surface of the soil in response to high severity burns (Doerr et al., 2006; Robichaud et al., 2007), although the effects of fire severity on water repellency can vary depending on the pre-fire conditions, such as background water repellency and the availability of hydrophobic materials (Shakesby and Doerr, 2006). Post-fire runoff events are sometimes attributed to water repellency (Osborne et al., 1964; Wells, 1987; Letey, 2001; and Scott and Pike, 2003); however, such events have also occurred on burned areas where water repellency was not observed (Meyer and Wells, 1997; Cannon et al., 2001b; and Doerr et al., 2006).

Large erosional events are often attributed to intense rainstorms (e.g., Wells, 1987), and total rainfall during a storm may also be a factor (e.g., Scott, 1971; Meyer et al., 2001). However, post-fire debris flows have been reported in response to rainstorms with return periods of only about 2 years (Cannon et al., 2003) and with intensities and durations much lower than rainstorms that typically cause events in unburned areas (Cannon and Gartner, 2005). The high intensity of convective rainstorms can exceed the infiltration capacity of the soil in burns, causing surface flow (Shakesby and Doerr, 2006) and erosion of exposed mineral soil. As the surface runoff becomes concentrated in rills and headwater channels, further sediment entrainment can lead to progressive sediment bulking (Meyer and Wells, 1997) and to debris flow-initiation in sufficiently steep and confined channels (Cannon et al., 2003).

Mass movement events following fire have received considerable attention in the last decade, due mainly to some destructive debris flow incidents in the western United States. Cannon (2001) examined the roles of geology, watershed morphometry, and soil water repellency on post-fire debris flow generation in California, Colorado, and New Mexico. Gartner et al. (2005) compiled a database of post-fire landslides, sediment floods, debris flows, and other erosion events that have been documented in the United States. In southern California, the fire season usually peaks in late fall, and erosion events then occur during the winter rainy season (Cannon et al., 2008).

Several major post-fire debris flow events in California have resulted in fatalities and significant property damage (Scott, 1971; Wells, 1987). In the Rocky Mountain region, convective rainstorms that trigger significant erosive events usually occur in summer to early fall. Debris flow events have been documented in all the Rocky Mountain states, (Cannon, 2001; McDonald and Giraud, 2002; and Parrett et al., 2004), although the impacts have generally been less severe than in California.

METHODS

The observations and data reported here were collected primarily as part of investigations of debris flow and debris-flood incidents by the British Columbia (BC) Forest Service, or, in one case (Okanagan Mountain Park Fire), by the City of Kelowna. The initial observations 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; no detailed mapping or data collection was performed. For three of the fires (Kuskonook, Lamb Creek, and Ingersoll), further field visits were made by the authors and their colleagues, and more systematic data were collected, especially for the Kuskonook Fire, where repeated visits were made over a 4-year period.

Field assessments of the debris flow or debris flood events involved traverses and measurements in the initiation zones and the deposit areas. 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 (Costa, 1984; Hungr et al., 2001). Approximate debris flow deposit volumes were calculated by field traverses using a global positioning system receiver (GPS) or by mapping on low-level aerial photographs, combined with estimates of depth at various locations. Normally, debris depth cannot be measured directly, except where an excavation or road cut has been made. Therefore, volume estimates have considerable uncertainty, typically ± 50 percent. The initiation of debris flow and debris-flood events was classified in the field as landslide-triggered, runoff-triggered with progressive sediment bulking, or runoff-triggered at a point in the channel. This was based on observations of features in the initiation zones such as landslide scars on adjacent slopes, extensive rill and tributary channel erosion, and failures of the channel bed and banks, respectively (Meyer and Wells, 1997; Cannon et al., 2003; and Hungr et al., 2005). Where possible, channels were walked from their headwaters to the point of

initiation, but, in some cases, the channels were inspected only from the air due to inaccessible or dangerous terrain.

Burned area reflectance classification (BARC) maps for the five fires investigated in detail were prepared from Landsat satellite images taken before and after the fires, using methods developed by the U.S. Department of Agriculture (USDA) Forest Service (Hudak et al., 2004). Field data from burn-severity plots on three of the fires 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. Although BARC mapping does not give a direct measurement of burn severity (Keeley, 2009), we found that in our study areas, the BARC classes correlated very well with vegetation burn severity, based on field traverses with the BARC maps in hand, not on statistical analysis.

Field observations were made in the burned areas above initiation zones where access was possible. For three of the fires, plots were located in the field with a GPS, and systematic data were recorded on vegetation and soil burn severity. Vegetation burn severity was categorized qualitatively as high, moderate, or low based on consumption of the forest canopy. For soil burn severity, a checklist was used that included qualitative observations of the consumption of wood fuels, litter and duff, mineral soil exposure, and depth to live roots. The criteria are described in Curran et al. (2006) and are based on those given in Robichaud et al. (2000) and Parsons (2003). To test for soil water repellency at each plot, we used the water drop penetration test (WDPT) (DeBano, 1981; Parsons, 2003; and Robichaud et al., 2008). A shallow trench about 0.5 to 1 m long was dug with a trowel, exposing the layer where water repellency was suspected; in our study areas, this was typically 1 to 2 cm below the mineral soil surface. Water drops were applied, and the proportions of weak, moderate, and strong repellency were recorded. These are defined as having absorption times of <10 seconds, 10–40 seconds, and >40 seconds, respectively. Exploratory tests of water repellency were also made at many random locations without recording plot data. In all areas, we found an apparent positive correlation between water repellency and soil burn severity, although this relation was not statistically tested.

Weather data for each of the events were collected from various stations, including the official Environment Canada Climate Station Network, automatic-recording fire weather stations operated by the BC Forest Service, and automatic-recording snow pillow stations operated by the BC Ministry of Environ-

ment. These data were supplemented with radar images collected by Environment Canada at its Silver Star Mountain station, which covers most of the southern interior of British Columbia. These images are taken every 10 minutes, and they provide an approximate color-coded scale of rainfall intensity. The scale can be used to estimate, although with considerable inaccuracy, total storm rainfall for a location by summing the intensity classes for a series of sequential images.

For each watershed that experienced a debris flow or debris-flood event, drainage area boundaries and elevation data were obtained from topographic maps and used to compile morphometric data and burn-severity distributions. The data are summarized in Table 2. To describe drainage basin relief, the Melton ratio was used, which is the total watershed relief divided by the square root of watershed area (Melton, 1965). Wilford et al. (2004) used this index in a study in northwestern British Columbia and concluded that watersheds subject to debris flows and debris floods in unburned terrain typically have Melton ratios of >0.6 and 0.3–0.6, respectively.

STUDY AREA AND THE 2003 FIRE SEASON

The southern interior of British Columbia is a diverse region of plateaus, valleys, and mountain ranges (Holland, 1964), covering an area of about 250,000 km². The vegetation ranges from grassland and ponderosa pine–Douglas fir forest in the main valley bottoms in the western and southern parts of the region, to Engelmann spruce and lodgepole pine forests on the western plateaus, to western red cedar–western hemlock rain forest in parts of the Columbia Mountains. The region is characterized by cool snowy winters and relatively dry warm summers. The hydrology is dominated by the spring snowmelt, with minor peaks in runoff caused by occasional summer and fall rainstorms. Forest fires are common throughout the region in mid- to late summer, although their incidence has been reduced over the last century by fire suppression. Fire suppression has resulted in changes to forest structure and a build-up of fuel in some forest types (Taylor et al., 1998), which is commonly believed to lead to an increased hazard of large fires in dry years (Filmon et al., 2004). Forestry is an important industry throughout the region, and, in many areas, the vegetation is a mosaic of mature forests, immature fire successional stands, recent clear-cuts, and second-growth plantations. Most land at lower elevations in larger valleys is privately owned and is a mix of agricultural land, urban areas, and forest. Above the valley bottoms, almost all land is publicly owned; it is known as Crown land, and most

Table 1. Summary information on 2003 fires with significant post-wildfire events.

	Fire Name				
	Okanagan Mountain Park	Cedar Hills	Kuskonook	Lamb Creek	Ingersoll
Fire Number	K50628	K40300	N70820	N10470	N50617
Nearby location	Kelowna	Falkland	Creston	Cranbrook	Burton
Latitude (N)	49°43'	50°27'	49°19'	49°18'	49°59'
Longitude (W)	119°41'	118°33'	116°40'	116°02'	118°03'
Start date	16 Aug. 2003	01 Aug. 2003	27 Aug. 2003	07 Aug. 2003	10 Aug. 2003
Size	25,912 ha	1,620 ha	4,839 ha	11,882 ha	7,310 ha
Mean annual precipitation range (mm) ^a	533–650	450–550	785–1,255	530–1,035	765–1,065
Physiographic region ^b	Thompson Plateau	Shuswap Highland	Purcell Mountains	Purcell Mountains	Monashee Mountains
Elevation range (m)	400–1,400	540–1,250	750–2,200	1050–2,100	550–2,050
Aspect (in area of interest)	N, W	S, SE	W, SW	SE, E, NE	S, E
Geology ^c	Gneiss, granite	Mudstone, siltstone, shale	Granite	Argillite, graywacke, conglomerate	Granite
BEC zones ^d	MSdm1, IDFdm1, IDFxh1, PPxh1	IDFmw1, xh1, xh2, ICHmk	ESSFdm, dmw, ICHdm, xw, dw1	ESSFdk1, MSdk, ICHdm	ESSFwc4, ICHmw2
Burn severity ^e					
High	36%	24%	12%	28%	23%
Moderate	37%	43%	29%	37%	45%
Interface fire or structures at risk	Yes	Yes	Yes	No	No
Event date	22 Oct. 2003	25 June 2004	7 Aug. 2004	19 Aug. 2004	17 Oct. 2005

^aAnnual precipitation is estimated from British Columbia Forest Service 400-m grid climate maps (Wang et al., 2006).

^bPhysiographic regions are from Holland (1964).

^cGeology information is based on a compilation of Geological Survey of Canada maps.

^dBEC (biogeoclimatic ecosystem classification) zones are: MS = montane spruce; IDF = interior Douglas fir; PP = ponderosa pine; ICH = interior cedar-hemlock; ESSF = Englemann spruce-subalpine fir. The following lowercase letters and numbers indicate subzones and variants, which are described in Meidinger and Pojar (1991).

^eVegetation burn-severity categories are based on BARC mapping; approximate percentages are given for the drainages of interest.

of it is provincial forest, administered by the British Columbia government.

In the summer of 2003, the southern interior of British Columbia experienced record drought conditions. As a result, the fire hazard was exceptionally high, and a number of large wildfires occurred, some of which exhibited extreme fire behavior (British Columbia Ministry of Forests, 2004), and which resulted in high burn severity in many locations. Two of the largest fires, 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, there were many other fires that burned near communities, highways, or other infrastructure, and as subsequent events proved, some of these presented significant risks of post-wildfire flooding or mass movement.

The five fires that produced significant post-wildfire events are described next, in chronological order of the events. Geographic data for each of the five major fires are summarized in Table 1, and their locations are shown on Figure 1.

Okanagan Mountain Park Fire Debris Floods of October 2003

The Okanagan Mountain Park fire began on 16 August 2003 in rugged terrain about 20 km southwest of the Kelowna city center, and about 10 km from the nearest homes on the rural fringe of Kelowna. By 21 August, it had reached the outskirts of the city, and on 22–23 August, 30,000 people were evacuated and over 250 homes burned (British Columbia Ministry of Forests, 2004).

Several streams, the contributing watersheds of which were totally or partly burned by the fire, drain into the south part of the city (Dobson, 2006). The City of Kelowna began a process to assess post-fire risks, and on 22 October 2003, while this was under way, a severe rainstorm affected the watersheds (Rogers, 2004). An estimated 20 mm of rain fell in 20 minutes at the center of the storm, as determined from radar imagery. Severe flooding and debris transport occurred on two creeks, Rembler and Lebanon Creeks; several houses were impacted by

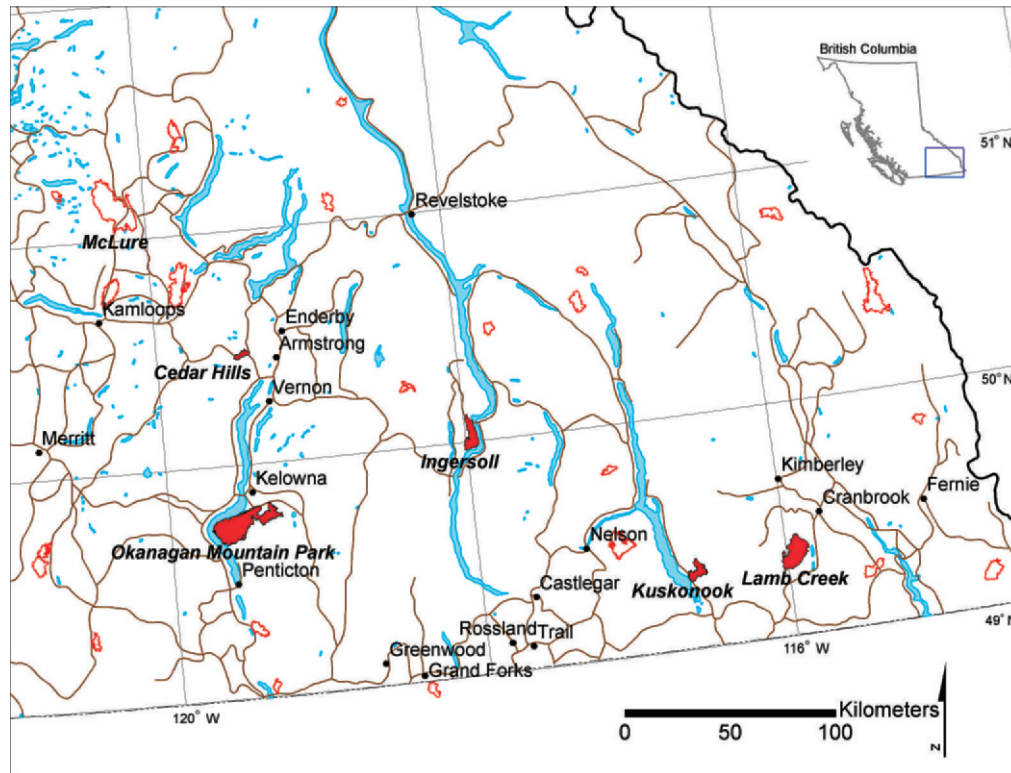


Figure 1. Location map, showing the southeastern interior of British Columbia, and perimeters of the 2003 fires. The five fires described in detail are shaded with dark fill; other fires are outlined.

mud and debris; and many roads and culverts were damaged (Rogers, 2004). The peak discharges on the two creeks were estimated at five to 15 times the pre-fire 200-year discharges (Dobson, 2006).

The drainages affected by the floods (Figure 2a) range in elevation from 500 to 1,500 m and consist mainly of rolling or benchy terrain, with glacial till and minor glaciofluvial deposits alternating with bedrock ridges. Soils are typically of fine sandy loam texture, derived from sandy glacial till, with areas of stony soils near bedrock outcrops. The bedrock in the area is competent gneiss and granite. The channels of Rembler and Lebanon Creeks have average slopes of about 5 to 10 degrees, with locally steeper reaches in bedrock canyons. Before the fire, higher elevations were mostly covered by Douglas fir forest that had been partially logged, and grassland and rural residences occupy lower elevations.

Rembler Creek has only seasonal flow, and it has a large flat area in the lower part of its watershed, with no defined channel. During the flood, a 1.2-km-long lake formed on this flat (Dobson, 2007, personal communication), and water poured from the flat into a steeper (5 degrees), confined channel leading to a residential area of the city 500 m downstream. Lebanon Creek is a larger stream, and it is characterized by perennial flow and a defined, incised

channel along most of its length. The flood on Lebanon Creek was not as extreme as on Rembler Creek, but it overflowed its banks and caused some damage on its floodplain near its mouth. The authors, inspecting the area 4 years after the event, observed that significant local downcutting of the channel had occurred due to the flood at a location 3 km above the mouth. Following the event, extensive water repellency and high burn severity were reported in the drainages of the affected streams (Rogers, 2004; Dobson, 2006), although no quantitative measurements or mapping were done.

The flood events were attributed to overland flow caused by high-intensity rainfall on areas of moderate to high burn severity (Rogers, 2004; Dobson, 2007, personal communication). Localized areas of deep gully erosion were observed in upland areas, in places where overland flow had occurred on glacial deposits. However, based on the authors' field observations in 2007, most of the sediment carried by the floods was derived from the channel bed and banks in the lower reaches of the creeks.

Cedar Hills Fire Debris Floods of June 2004

The Cedar Hills fire, located 12 km east of Falkland, BC, burned 1,620 hectares on the north slope of

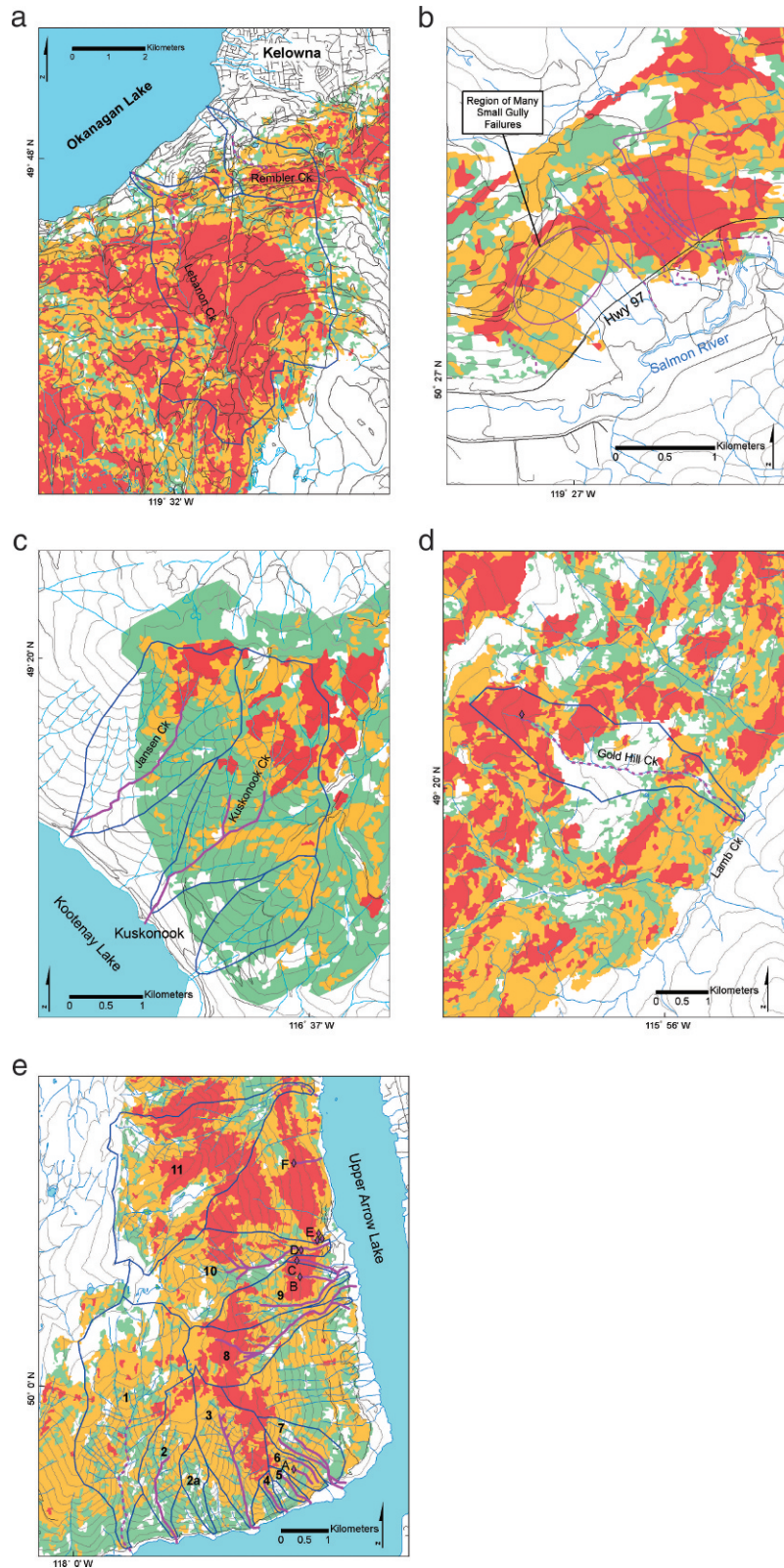


Figure 2. Maps showing BARC burn severity, watersheds, and post-wildfire events for portions of the five fires. Solid-color thick lines indicate debris-flow paths, dashed lines indicate debris-flood paths, and diamond symbols indicate landslides. Shading indicate burn severity: red = high; orange = moderate; green = low; white = unburned. Watershed boundaries are outlined; contour interval is 100 m. (a) Okanagan Mountain Park fire; (b) Cedar Hills fire; (c) Kuskonook fire; (d) Lamb Creek fire; (e) Ingersoll fire.

the Salmon River Valley in August 2003. The fire burned though forest and logged areas on Crown land and some forested private land. Several rural residences and farms are located along Highway 97 at the base of the slope below the fire. On 25 June 2004, following a week of dry antecedent conditions, a high-intensity rainstorm triggered debris floods and flows on the steep valley side, causing minor damage to three residences and impacting the highway and one vehicle. This section summarizes the findings of Grainger (2005), who conducted an investigation of the event.

Part of the burned area consists of a steep, south-facing slope extending from an upper plateau to the Salmon River Valley bottom (Figure 2b). This slope had most of the high-severity burn areas, was the main area affected by the rainstorm, and experienced all of the debris flow/flood events on the burn. The elevation ranges from 500 to 1,200 m. The bedrock is mostly friable sedimentary rocks, and the soils are typically silty gravelly sand derived from colluvium and, to a lesser extent, shallow glacial till (Grainger, 2005).

Before the 2003 fire, the slope was forested with Douglas fir, ponderosa pine, lodgepole pine, and western larch, part of which had previously been burned and salvage harvested in 1970. BARC mapping (Figure 2b) shows that 67 percent of the slope is in the high and moderate categories. Soil burn severity and water repellency were assessed on ground traverses (Grainger, 2005); although both were quite variable over the burn, in the area most affected by erosion and failures in gullies, burn severity was continuously high and water repellency was extensive. The presence of water repellency was confirmed by Scott et al. (2008), who measured strong repellency at depths of 2 to 5 cm at most plots in an area where they set up treatment effectiveness tests in 2004.

Erosion events occurred in approximately 50 small gullies along a 2.5 km section of the burned south slope (Figure 2b). Overland flow was initiated in areas of high water repellency and high soil burn severity, which were observed on gentler slopes immediately above the steep gullied slope. The events originated in fine-textured colluvial soils and began as a series of rills that formed where the slope steepened below the plateau. The most significant erosion events initiated in an area of convergent gullies on the east part of the slope (Figure 2b) that had a combined contributing area of 30 hectares. This area generated a minor debris flow that turned into a debris flood before reaching the fan below. The event crossed the highway and flowed into two residential yards. Farther west along the slope, many single gullies generated smaller debris floods that initiated from upslope sheet and gully erosion. These small gullies

had contributing areas from 5 to 18 hectares. Most of these debris floods were attenuated by unburned trees and debris at the toe of the slope, and they either did not reach the highway or were contained by the highway ditch and culverts. One small debris flood caused minor damage to a residence at the toe of the west part of the slope.

There is no weather station in the immediate vicinity of the Cedar Hills fire. Stations 20 km away or farther recorded only showers, with daily totals of 13 mm or less. Radar imagery obtained for 25 June clearly shows an intense rainstorm moving over the south slope area of the burn from 7:40 to 8:10 p.m. From the sequence of images, it is estimated that at least 25 mm of rain fell in 30 minutes on the south slope area of the burn.

Grainger (2005) observed that much of the sediment originated as rill and sheet wash erosion on the upper slopes; scour of the gullies was not a significant sediment source. Typically, rills were initially 2 to 5 cm deep and were caused by overland flow above the water repellent layer that was observed in many locations. As the flow progressed downslope, the rills deepened and coalesced, causing erosion to a depth of 15–20 cm. In most gullies, the events were classified as debris floods because they did not develop sufficient sediment concentration to become true debris flows, as indicated by deposit morphology (Grainger, 2005). In a few areas, small debris flows formed, as interpreted from levees deposited along the channel margins; these were deposited at the first break in slope and did not progress onto the lower gradient fans below. The debris floods deposited most of their coarse sediment on the upper to mid-portions of the fans, and only silt and sand were carried to the distal part of the fans.

Kuskonook Creek Debris Flows of August 2004

The Kuskonook fire burned 4,832 hectares on the east side of Kootenay Lake about 25 km north of Creston in August and September 2003. The terrain in the area of the fire consists of steep slopes above the lake, between about 550 and 1,900 m elevation, with a rolling plateau above. Highway 3A follows the lakeshore at the base of the slope, and the small community of Kuskonook occupies the alluvial fan of Kuskonook Creek.

The area is underlain by granitic rocks, which are massive and resistant in some places and weathered to sandy grus in other places. On slopes less than about 30 degrees, there are shallow deposits of sandy glacial till with abundant large boulders. Soils, whether derived from glacial till or weathered bedrock, are sandy and are commonly highly erodible, in the



Figure 3. Kuskonook Creek debris flows of August 2004. (a) Kuskonook Creek fan from the air. (b) Aerial view of the watersheds; A is the start of the debris flow in Kuskonook Creek channel; B is a smaller debris flow that started below a small severely burned patch; C is the start of the debris flow in Jansen Creek channel. (c) Shallow soil erosion caused by overland flow near headwaters of Kuskonook Creek. (d) Kuskonook Creek channel from the air, just below the point of transition to a debris flow. Photos by: Peter Jordan (a, d), Doug Nicol (b), Mike Curran (c), BC Forest Service.

experience of the authors from doing forestry work in the area.

On the night of 6–7 August 2004, a heavy rainstorm occurred in the area, triggering a large debris flow in the channel of Kuskonook Creek. The event has been described by Jordan et al. (2004), VanDine et al. (2005), and Jordan et al. (2006). The debris flow destroyed two houses on the fan, damaged several other buildings, and closed the highway for several days (Figure 3a). The affected houses were not occupied at the time, and there were no fatalities or injuries. A smaller debris flow occurred on Jansen Creek, an adjacent drainage to the north (Figure 3b); this event also blocked the highway but did not damage any residences.

Field investigations immediately after the August events found that the burned area in the upper part of the Kuskonook Creek watershed had extensive water repellent soils, and there was abundant evidence of overland flow (Figure 3c). Further field visits were

made in October 2004 and July 2005, and plots were established to record burn-severity data. In areas of high and moderate soil burn severity, strong water repellency was measured in seven of eight plots; it was typically a discontinuous thin layer at a depth of 1–2 cm in the mineral soil, covering 60 to 100 percent of the trench length. Apart from the plots, repellency was observed in quick tests in all areas that showed evidence of overland flow. There was a visually apparent correlation between soil burn severity and overland flow: evidence of rills, small terraces and fans, and flattened grass was observed in and below most areas of high soil burn severity. Areas of moderate or low soil burn severity had little evidence of water repellency or overland flow initiation. Much of the headwaters area of the watershed has relatively gentle slopes, and severely burned areas produced overland flow that accumulated in hollows and ephemeral channels while causing only shallow erosion (Figure 3c). As the headwaters channels steepened

Debris Flows in British Columbia

Table 2. Watershed morphometry, burn severity, discharge, and debris volume data for streams draining the 2003 fires with major post-wildfire events. Only those events for which a watershed could be distinguished on 1:20,000 topographic maps are included.

Fire	Watershed	Drainage Area (km ²)	Elevation Range (m)	Melton Ratio ^a	Typical Fan Slope (°)	High Burn Severity ^b (%)	Moderate Burn Severity ^b (%)	Date of Event	Type of Event ^c	Deposit Volume ^d (m ³) or Peak Discharge (m ³ /s)
Okanagan Mtn. Park	Rembler Creek	3.97	350–880	0.27	— ^e	27	42	22-10-2003	Debris flood A	13 m ³ /s
Okanagan Mtn. Park	Lebanon Creek	26.1	350–1,564	0.24	3	56	30	22-10-2003	Debris flood A	—
Cedar Hills	“converging gully”	0.53	560–1,100	0.74	6–10	56	28	25-06-2004	Debris flood B	—
Kuskonook	Kuskonook Creek	4.59	560–2,130	0.73	9	17	31	06-08-2004	Debris flow A	25,000 m ³
Kuskonook	Jansen Creek	3.66	560–2,120	0.82	10	10	18	06-08-2004	Debris flow A	—
Lamb Creek	Gold Hill Creek	5.48	1,140–2,098	0.41	—	36	18	19-08-2004	Debris flood A	40,000 m ³
Ingersoll	1	7.37	470–2,120	0.61	8	4	53	17-10-2005	Debris flood A	—
Ingersoll	2	2.13	460–1,920	1.00	7	8	54	17-10-2005	Debris flow A	>8,000 m ³
Ingersoll	3	2.84	480–1,920	0.85	13	26	61	17-10-2005	Debris flow A	8,000 m ³
Ingersoll	7	1.21	480–1,620	1.04	7	3	47	17-10-2005	Debris flow C	3,000 m ³
Ingersoll	8	2.57	480–2,020	0.96	6	38	46	17-10-2005	Debris flow A	30,000 m ³
Ingersoll	9	2.13	480–1,900	0.97	5	41	39	17-10-2005	Debris flow A	15,000 m ³
Ingersoll	9a	0.16	480 ^b –1,000	1.30	—	62	26	17-10-2005	Debris slide-flow C	5,000 m ³
Ingersoll	10	4.42	480–2,218	0.83	7	14	51	17-10-2005	Debris flow A	2,000 m ³
Ingersoll	Slide F	—	—	—	—	—	—	17-10-2005	Debris slide-avalanche C	3,000 m ³
Ingersoll	11	8.03	460–2,218	0.62	—	31	37	17-10-2005	Debris flood A	—

^aThe Melton ratio is the ratio of watershed relief to the square root of drainage area (Melton, 1965).

^bVegetation burn-severity categories based on BARC mapping.

^cDominant process and initiation mechanism: A = runoff-triggered, in channel; B = runoff-triggered, sediment bulking in headwaters; C = landslide-triggered.

^dWhere the original source gives a range of estimated deposit volumes, the mean value is given here.

^eA dash (—) indicates not measured or not applicable.

downslope to 25 degrees or more, the running water began to erode the bed and entrain coarse gravel as well as finer sediment. High-water marks along the channels indicate that the width and depth of flow were several times greater than the bankfull width and depth. Farther downstream, the channel steepens to about 29 degrees and enters a confined gully in glacial deposits (Figure 3d). At this point, the bed and banks failed, and the flood flow became a fully developed debris flow.

From the point of debris flow initiation to the fan, the channel is confined and has a slope of 16 to 35 degrees. The fan has a slope of 8 to 11 degrees and is composed mainly of bouldery debris flow deposits, although no large debris flows had reached the fan for at least the previous 100 years (VanDine et al., 2005). The volume of the debris flow was estimated to be 20,000 to 30,000 m³, and debris was deposited over part of the fan surface to a depth of 1 to 2 m. Measurements of channel cross-sections 0.5 km above the fan, and application of the super-

elevation equation (Costa, 1984) provide estimated velocities of 4 to 8 m/s and peak discharges of 200 to 500 m³/s.

A heavy rain shower was reported on the evening of 6 August by a resident who was driving on the highway near Kuskonook. Shower activity was apparently localized, as nearby weather stations did not report any unusual rainfall. Radar images from the Environment Canada station at Silver Star Mountain showed rain showers in the area, but Kuskonook Creek is too far from the radar station (220 km) to use the data for quantitative purposes (Lakeman, 2004, personal communication). The nearest weather stations, at Akokli Creek, 15 km northwest, and Creston, 25 km south, recorded only 4.0 mm and 6.6 mm of rain, respectively, on 6 August. Several other significant rainfalls in the previous year did not cause any observed debris flow or erosion events. Local residents reported that following rain showers earlier in 2004, black sludge contaminated their water intakes in the creek. These

reports suggest that overland flow and erosion of the burned surface soil layer were occurring, and might have provided a warning of the impending debris flow hazard had their significance been understood.

BARC mapping shows that 17 percent of the Kuskonook Creek watershed is in the high category, and 31 percent is in the moderate category (Table 2); field traverses showed a good correlation between the BARC categories and both vegetation and soil burn severity. The burn was concentrated in the headwaters (Figure 2c); in the higher part of the watershed, above 1,200 m, the proportions of high and moderate BARC categories are 36 percent and 39 percent, respectively. The Jansen Creek debris flow was not studied in detail, but the extent of high and moderate burn severity in its headwaters is similar to Kuskonook Creek, and evidence of overland flow was observed from the air.

Lamb Creek Debris Flood of August 2004

The Lamb Creek fire, 20 km southwest of Cranbrook, burned 11,882 hectares in August 2003. The area is predominantly hilly, ranging from 1,200 to 2,000 m in elevation, with outcrops of resistant bedrock alternating with thick deposits of glacial till. The bedrock is mostly fractured sandstone and argillite. Soils developed from glacial till are silty to sandy, and they are very stony where bedrock is close to the surface. Slopes over 30 degrees are relatively scarce, as are landslide-prone terrain and channels subject to debris flows.

A heavy rainstorm on 19 August 2004 affected the burned area, including the upper drainage basin of Gold Hill Creek, a tributary of Lamb Creek. Runoff generated in the severely burned upper part of the watershed caused a debris flood in Gold Hill Creek (Jordan et al., 2004). In this area, at about 1,850 m elevation near the headwaters of the creek, several small debris slides occurred in deep glacial till deposits, although they did not contribute directly to the event (Figure 2d). Overland flow from the burned slopes apparently accumulated in an unburned wetland and spilled over an escarpment of deep glacial till, causing several meters of incision along the creek channel. From here to the mouth of the creek 4.5 km downstream, the creek has alternating reaches of relatively steep, confined channels and less steep, unconfined channels with slopes mostly between 5 to 10 degrees. In steeper reaches, the flood incised deeply into the underlying glacial till and transformed into a debris flow (Figure 4a). In gentler reaches, debris was deposited, and the debris flow apparently transformed into a flood (Figure 4b). Evidence for these transitions is based on observation of the deposits during a traverse on foot of most of the length of the channel. Levees characteristic of

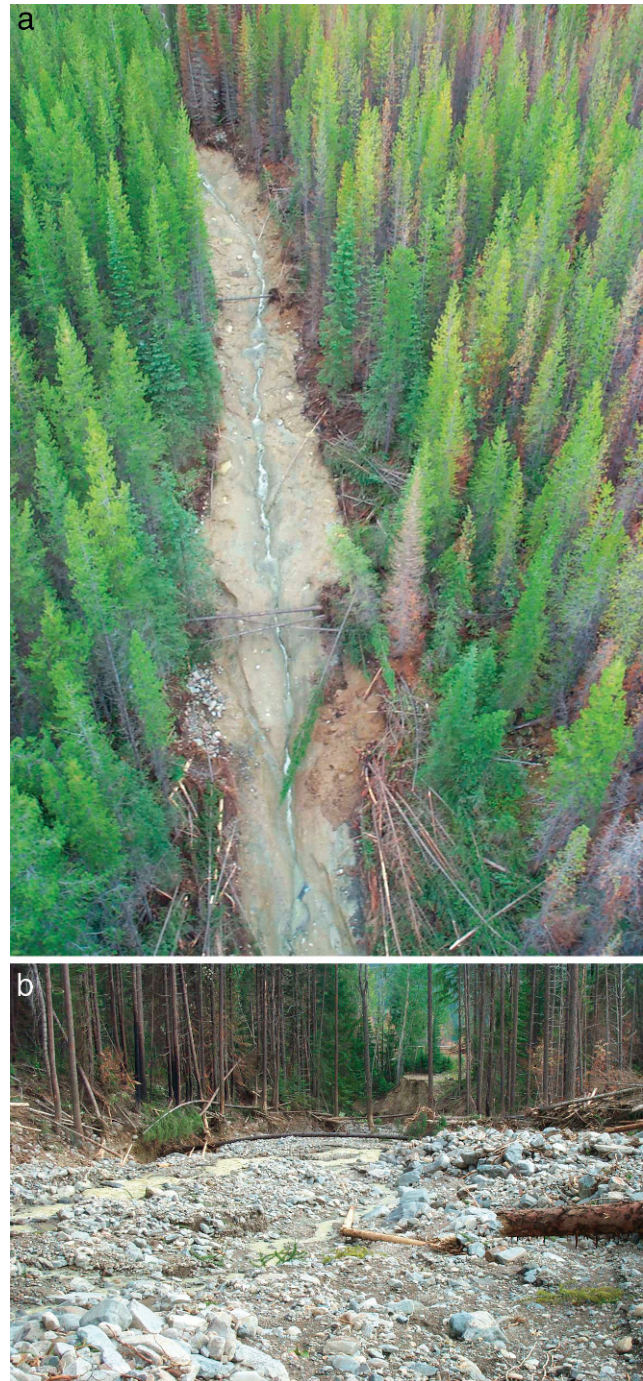


Figure 4. Lamb Creek debris flood of September 2004. (a) An erosional reach of Gold Hill Creek channel, showing glacial till exposed after flood has stripped away overlying sediment. (b) Debris-flood deposits lower down Gold Hill Creek channel. Photos by: Doug Nicol, BC Forest Service.

debris flows were observed along the steeper, mostly erosional reaches, but in long, low-gradient reaches, most deposits were stratified and clast-supported, typical of fluvial rather than debris flow deposition. At its confluence with the larger, low-gradient Lamb

Creek, about 10,000 m³ of fluvial sediment was deposited, forming a temporary dam on the larger creek. On breaching, this blockage caused flooding and debris deposition for a further 7 km along Lamb Creek to its mouth in Moyie Lake, a large lake with many houses along its shoreline, which was noticeably turbid for several weeks after the event. The total volume of debris transported by the event is estimated at 30,000 to 50,000 m³; the debris was deposited at several locations along the channel of Gold Hill Creek and in the Lamb Creek channel. The event is classified as a debris flood. Although there is evidence of debris flow processes in some locations, such as levees and unsorted deposits, for much of its length, the channel was apparently not steep enough to sustain a debris flow, as fluvial deposits are predominant.

The nearest weather station, 13 km north of Gold Hill Creek, at an elevation of 1,572 m, recorded 22.1 mm of rain on the day of the event, with 16.3 mm in 1 hour. Two other streams that drain the burn area experienced flood events with much less severe damage than Gold Hill Creek, as reported by forestry workers who also noted localized erosion and gully incision in other parts of the burn.

Mount Ingersoll Debris Flows of October 2005

The Ingersoll fire burned 7,310 ha on the west side of Lower Arrow Lake across from the small community of Burton in August and September 2003. Mount Ingersoll is a plateau-topped mountain, about 10 km long in a north-south direction, with steep slopes on three sides. The fire burned almost the entire east and south sides, from near lake level at 450 m to tree line at 2,050 m elevation (Figure 2e). The mountain is underlain by competent granitic rocks, and bedrock ridges and bluffs are common on steeper slopes. Gentler slopes are covered with sandy morainal deposits of a range of depths, and the lakeshore area below 550 m consists mainly of deep, sandy glaciofluvial and glaciolacustrine terraces and small alluvial fans. The mountain is drained by small, steep creeks, many of which are subject to debris flows. Most of the area of the fire is within forested Crown land, of which a small part had been developed for logging.

On 17 October 2005, during a 2-day rainstorm, about 15 debris flows, debris slides, and debris avalanches occurred in the southern part of the burn (Figure 5), destroying or damaging at least 10 stream crossings on the main forest road accessing the area. The events were inspected the next day from the air by a geotechnical consultant (Miller, 2005, personal communication). Because of bad weather and the arrival of winter snow soon after, further field



Figure 5. Mt. Ingersoll mass movement events of October 2005. (a) Overview of part of the burn, showing debris flows 8, 9, and 10, and landslides B and C. (b) Debris-flow 2; note initiation point (arrow) where gullies converge. (c) Initiation area of debris-flow 3 (arrow), where gullies converge below plateau rim. Photos by: Peter Jordan, BC Forest Service.

Table 3. *Rainfall data at stations near the Ingersoll fire for the October 2005 event.*

Station	Operator and Type of Station ^a	Distance from Ingersoll Fire	Elevation (m)	One-day Rainfall, 17 Oct. (mm) ^b	Two-day Rainfall, 16–17 Oct. (mm)	Maximum Hourly Rainfall (mm)
Nakusp	Env. Canada	30 km N	512	30.6	38.4	—
Fauquier	Env. Canada	15 km SW	490	14.6	23.8	—
Falls Creek	BCFS fire	40 km N	790	38.8	56.2	4.0 ^c
St. Leon Creek	BCMOE	40 km NE	1,800	60	97 ^d	4 ^e
Barnes Creek	BCMOE	25 km W	1,620	—	<66 ^f	—

^aEnv. Canada = Environment Canada climate station; BCFS fire = British Columbia Forest Service fire weather station with tipping-bucket gauge; BCMOE = British Columbia Ministry of Environment snow pillow station with cumulative precipitation gauge.

^bFor climate stations, based on reporting day of 0800–0800; for hourly recording automatic stations (BCFS and BCMOE), based on 2400–2400 day.

^cMaximum 1-hour rainfall from hourly recording rain gauge.

^dStorage precipitation gauge; may include mixed rain and snow.

^eEstimated from cumulative record of storage precipitation gauge.

^fStation not operating 13–18 October; cumulative total precipitation for this period.

investigations were not made until the summer of 2006.

The October 2005 events were unlike others investigated here and most post-wildfire events from the U.S. interior regions reported in the literature because they were caused by a long-duration, low-intensity rainstorm. Rainfall data from several nearby stations are summarized in Table 3; there are no weather stations in the immediate vicinity of the Ingersoll fire. At Nakusp, the station with the longest period of record, the one-day rainfall of 30.6 mm on 17 October has an estimated 5-year return period. The St. Leon Creek snow pillow station may be the most representative of conditions at the Ingersoll fire, since its elevation of 2,000 m is close to that of the plateau where much of the runoff that triggered the debris flow events occurred. At this station, a storage precipitation gauge recorded 60 mm on 16–17 October (Table 3); on 16 October, precipitation was probably mixed rain and snow. The snow pillow recorded 22 mm of snow-water equivalent accumulation on 16 October, and 8 mm of snowmelt on 17 October as the temperature rose from 0 to 4 degrees Celsius. Snowmelt therefore may have added significantly to runoff on the second day of the storm at this elevation.

Radar images from the Silver Star station, 95 km to the northwest, were acquired from Environment Canada for the period of the storm and analyzed in an attempt to estimate storm rainfall for the location of interest. The estimated 2-day rainfall total from the radar images was 38 mm for Mt. Ingersoll, and the maximum 10-minute rainfall intensity shown by the radar was in the 2 to 4 mm/hr category. However, the radar imagery appears to underestimate the total storm rainfall in comparison with recorded rainfall at nearby stations.

The events at Mt. Ingersoll are shown in Figures 2e and 5, and data for the larger debris flows are summarized in Table 2. Twelve debris flows, two debris floods, two debris avalanches, and four small debris slides are mapped; one of these, a small debris flow in watershed 6 (Figure 2e), is reported to have occurred in fall 2004. The other events are all believed to have occurred on 17 October 2005, although it is possible that some of the smaller events that did not damage the road occurred on other dates.

No debris flow or landslide events occurred in the northern half of the burn, although this area also has a number of steep drainages subject to debris flows. The fact that about 15 events occurred in adjacent drainages in the southern part of the burn suggests that higher rainfall intensities or totals may have occurred there, although there is no evidence of this on the radar images. Another possible explanation is that watershed shape and elevation distribution may be factors. In the south part of the fire, a large, gently sloping, plateau area is at the top of the watersheds, which collected overland flow from rain and snowmelt and fed it into the steep channels. At the north end of the fire, there is no such contributing plateau area; the watersheds are steep at their headwaters and originate at a narrow ridge.

Three of the largest debris flows, in watersheds 3, 8, and 9, were inspected in their deposition areas (Figure 5a), and volume estimates were made. The three deposits and the other events that were examined in less detail consisted of bouldery debris and a sandy matrix derived from granitic rocks. These deposits are typical of coarse-textured debris flows in this region, although the slopes of deposition of the two largest events are somewhat lower than typical (5 to 6 degrees). A large debris flow also occurred in watershed 2 (Figure 5b); its volume could not be

measured because most of the debris entered the lake, but based on its channel dimensions, it was larger than the watershed 3 event.

Inspection of the debris flow initiation zones from the air indicated that all the larger events, and some of the smaller ones, started in the channels near the stream headwaters. These channels are steep gullies incised in bedrock; they have slopes of 30 to 40 degrees and are filled with coarse colluvium and bouldery stream channel sediment. Three of the smaller debris flows, in watersheds 4, 5, and 7, appear to have been initiated from rockfalls above the channel headwaters. However, no landslides were observed entering the channels in watersheds 2, 3, 8, 9, and 10; the debris flows appear to have been initiated within the channels (Figure 5c). None of the channels was traversed on the ground due to the extremely steep and inaccessible terrain. The plateau in the headwaters area of watersheds 3 and 8 was visited in September 2006, using a helicopter for access. Most of this area is in the high-severity category on the BARC map (Figure 2e). Soil conditions were examined at seven plots. Moderate to high vegetation and soil burn severity were observed at six plots; water repellency, measured by the WDPT, was strong at three plots and moderate at two plots. The observations were made 3 years after the fire, when there was considerable regeneration of plants in the burned area. At four plots, there was visible evidence of overland flow and surface erosion. Several small ephemeral channels at the edge of the plateau had evidence of recent high streamflow and bed-load transport in the form of sand deposits and high-water marks, although it was not possible to determine whether this occurred during the October 2005 event or at some other time. These observations support the hypothesis that unusually large amounts of runoff, generated by overland flow on severely burned areas of the plateau, caused debris flows to initiate within the steep channels below.

Two debris slides occurred on the same date, above the logging road (Figure 5a, slides B and C). They started on a moderately steep (30–35 degrees), slightly gullied slope blanketed with sandy glacial till and progressed into debris flows as they entered gullies below. These slides started below a re-contoured logging trail, which was constructed for salvage logging soon after the fire. The area was inspected on the ground in September 2006, and moderate to weak water repellency, high to moderate soil burn severity, and some evidence of overland flow and soil erosion were observed in the area above the slides. However, no obvious surface-flow pathways leading to the slides were observed. A possible mechanism for the initiation of these slides is surface runoff from the

severely burned slope above, which may have infiltrated into the soil along the deactivated trail, and the resulting subsurface flow may have triggered the failures where the slope steepened. Another large event (slide F), a debris avalanche, occurred below the logging road. Evidence in the form of ditch erosion and plugged culverts indicates that it was caused by runoff diverted down the road, from areas of high and moderate burn severity above.

DISCUSSION

Debris Flow and Debris-Flood Initiation Mechanisms

Debris flows can be initiated by several different mechanisms, although no widely accepted classification system exists. Coe et al. (2008) proposed three categories: (1) small debris flows that start as shallow landslides and flow downslope without entraining additional material; (2) debris flows that begin as landslides and grow as they flow downstream by entraining channel and hillslope material; and (3) debris flows initiated by surface-water runoff that progressively erodes and entrains sediment from hillslopes and channels. The second category is responsible for most documented debris flows in British Columbia, especially those related to forestry development (Fannin and Rollerson, 1993; Millard, 1999; Jordan, 2001, 2002; and Rollerson et al., 2005). These events have sometimes been referred to as “infiltration-triggered” debris flows (Cannon and Gartner, 2005). The third category has been identified as responsible for many or most post-wildfire debris flows by a process that has been referred to as “progressive sediment bulking” (Meyer and Wells, 1997; Cannon et al., 2003). Although in some cases (e.g. Cannon et al., 2001a), sediment eroded from hillslopes constituted most of the debris flow volume, Santi et al. (2008) found that in most post-wildfire debris flows, the majority of sediment was derived from erosion and incision of the channel.

Takahashi (1981) proposed a mechanism by which debris flows can initiate within a steep stream channel by failure of the streambed, if the streamflow depth and shear stress exceeds a critical value. This process differs from the progressive sediment bulking model in that failure takes place at a discrete location in the channel, and the flow above this point may not necessarily have a high concentration of sediment.

A debris flood is a type of streamflow flood in which large amounts of coarse sediment are transported by the tractive force of water flowing above the sediment (Hungr et al., 2001). It differs from a debris flow, which is the non-Newtonian flow of a single-phase slurry of saturated debris (Pierson and

Costa, 1987). Debris floods can transport amounts of sediment comparable to debris flows, but they typically have lower peak discharge and are less destructive (Hungr et al., 2001). Hyperconcentrated flow (Pierson and Costa, 1987) is a related phenomenon, intermediate between normal streamflow and debris flow, and it is distinguished by very high suspended sediment concentrations. Pierson (2005) noted that debris floods differ from hyperconcentrated flow in rheology, type of sediment transported, and deposit characteristics. Similar initiation mechanisms can produce debris flows, debris floods, and hyperconcentrated flow. Debris flows can evolve into debris floods or hyperconcentrated flow through downstream dilution (Hungr et al., 2001; Pierson, 2005). From the perspective of hazard analysis, it is important to distinguish between these processes because of the greater destructive potential of debris flows.

For the post-wildfire debris flow and debris-flood events described here, the most common initiation mechanism appears to be high peak flow in the channel, which results in erosion of the channel bed or undercutting of the banks. In the case of the Kuskonook Creek debris flow, which had good ground observations in the upper channel 4 days after the event, evidence of high peak flow was seen in the headwaters channels in the form of flattened grass and bits of vegetation and burned wood fragments forming high-water lines. However, there was little mud or sand deposited, which would have indicated high suspended sediment concentrations. As the channels steepened downslope, there was evidence that the streams eroded gravel and cobbles from the bed, although embedded boulders made the channels resistant to erosion. At a point downstream where the slope steepened to about 30 degrees and several channels converged, downcutting and widening of the channel indicated that a transition to debris flow had occurred. The probable mechanism was sudden deep erosion into the bed, possibly because of lack of armoring at some point or because the shear stress on the bed exceeded a critical value, and undercutting of the banks (Figure 3d). The debris flow then increased rapidly in volume as it entrained the large volume of colluvial and fluvial material that was stored in the channel.

At the Ingersoll fire, aerial observations showed that five debris flows, including the four largest ones, originated by a similar mechanism. Here, the channels were steeper and the terrain was rockier than at Kuskonook Creek, and the upper channels appear to contain abundant coarse rockfall colluvium. There were no significant landslides entering the channels; the debris flows began in the channels at or a short

distance below the point where they steepened to at least 30 degrees, and in some cases where several gullies converged (Figure 5).

On Gold Hill Creek at the Lamb Creek fire, ground observations (Jordan et al., 2004) showed that the event began where the creek steepens to about 17 degrees as it flows over deep morainal deposits; at this point, the flow of water cut deeply into the deposits and entrained large quantities of sediment. The process can be described more as gully erosion than debris flow initiation in a channel. Downstream, the lack of depositional features characteristic of debris flows indicates that for most of its length, the event was a debris flood, not a debris flow. The amount of downcutting into glacial deposits suggests that this was the first event of such magnitude for a very long time, possibly since deglaciation. The Rembler Creek debris flood at the Okanagan Mountain Park fire originated by a similar process, where floodwater from a temporary lake spilled into a steep channel, entraining sediment as it cut into the underlying glacial deposits.

In these examples, field observations above the initiation points of the debris flows and debris floods indicated that the events were triggered by high discharges of water. Although evidence of soil erosion was observed in the headwaters areas (e.g., Figure 3c), this was not extensive, and there was no indication that sediment concentration sufficient to be classified as debris flow or hyperconcentrated flow existed. If high sediment concentration had occurred, it would have left traces in the form of mud films or deposits on stones or vegetation, or in flat areas. It appears that erosion was inhibited by stony soils, by the remains of large roots or woody debris, or by gentle slopes in the areas where overland flow occurred. In all cases where debris flows occurred, they initiated at a point where the channel was confined, and where it steepened to about 30 degrees or greater. This observation supports the hypothesis that the debris flows initiated either by the mechanism of failure of the streambed or by entrainment of sediment due to sudden downcutting or undercutting of the banks.

At the Cedar Hills fire, there is photographic evidence (Grainger, 2005) that extensive rill and sheet erosion took place on the slopes leading to the many gullies that carried events. The soils in this area are relatively fine textured, being derived from weak sedimentary rocks. Grainger (2005) observed that most of the sediment was derived from erosion of the slopes, and that relatively little material was produced by downcutting in the gullies. In all but two of the gullies, the events were described as debris floods rather than debris flows, suggesting that insufficient sediment

was entrained to produce debris flow. The initiating process for these events was progressive sediment bulking from slope erosion, as described for some post-wildfire events in the western United States (Meyer and Wells, 1997; Cannon et al., 2003). From the photos in Grainger (2005) showing fine-textured deposits (sand, silt, and small gravel), it appears likely that some of these events were hyperconcentrated flow.

At the Ingersoll fire, two large debris flows were initiated by debris slides on an open slope that entered shallow gullies (Figure 5a). Several other small debris flows appear to have been initiated by rockfall. These events are typical of the landslide-initiated debris flows that are commonly observed in unburned forested landscapes in this region.

In summary, three debris flow initiating processes were observed: runoff-triggered events caused by failure of bed or banks due to high discharge in a steep channel; runoff-triggered events caused by progressive sediment bulking with eroded sediment from soil erosion on burned slopes and channel headwaters; and landslide-triggered debris flows. The most common process following the 2003 fires (Table 2) was the first of these: runoff caused by post-wildfire overland flow triggered debris flows in steep channels.

Burn Severity and Overland Flow

The burn severity data in Table 2 are estimates based on BARC mapping, assuming there is a good correlation between field observations of burn severity and the BARC categories, as was the case where sufficient field data were collected. The combined high and moderate burn severity in the 15 watersheds that produced debris flows and debris floods ranges from 28 percent to 87 percent. The areal distribution of burn severity is perhaps more important; for most of the affected watersheds, the maps (Figure 2) show that high burn severity is concentrated in the headwaters.

In four of the five burns that produced major events, the area was inspected in the field within a few days of the events, and water repellency was observed at severely burned sites but not at nearby unburned sites. In all the burns, there was evidence of overland flow produced from the severely burned areas, such as rill or sheet erosion, sand deposits behind obstructions, and high-water marks in small headwater channels. Although other effects of severe burn probably contributed to these events, such as loss of forest floor and understory canopy, in all cases, overland flow due to water repellent soils was suspected as a contributing factor by the investigators, based on WDPT measurements in the source areas. It is possible that the extreme drought

conditions that preceded the 2003 fires led to higher soil burn severity, and possibly to more widespread water repellency, than is typical in this region.

Rainfall Intensity

Four of the five major events following the 2003 fires were caused by short-duration, high-intensity rainfall events, although rain gauge data close to the sites are lacking. For the Okanagan Mountain Park fire and Cedar Hills fire, radar data provide estimates of the rainfall intensities during the events of 20 mm in 20 minutes, and 25 mm in 30 minutes, respectively. These rainfall intensities are comparable to, or slightly higher than, rainstorms that have been known to cause post-wildfire debris flows and floods in Colorado (Cannon et al., 2008).

The 2005 Mt. Ingersoll post-wildfire events are unusual for this region because they were caused by a long-duration, low-intensity, fall rainstorm; however, such rainstorms have caused post-wildfire events in coastal regions such as southern California. The estimated rainfall of 50 mm in 2 days, with a peak intensity of 4 mm/hr, is much less than the magnitude and intensity of most long-duration winter rainfalls that caused debris flows in southern California (Cannon et al., 2008). The rainfall at Mt. Ingersoll was apparently not unusually heavy, and the meteorological cause of these events remains uncertain.

CONCLUSIONS

The post-wildfire events described here illustrate the increases in landslide, flood, and erosion hazards that can be expected following severe wildfire. Three mechanisms were identified for debris flow initiation following the 2003 fires in British Columbia:

- runoff-triggered debris flows caused by erosion or failure of the channel bed and banks due to critically high discharge;
- progressive sediment bulking of runoff as soil erosion in burned headwater areas causes sediment-laden flow to accumulate in channels; and
- landslide-triggered (or infiltration-triggered) debris flows caused by a landslide that enters a steep channel.

Post-wildfire debris flows differ from debris flows originating in unburned forests in this region in several ways. They occur most frequently during summer rainstorms, whereas in unburned areas, most events occur during the spring snowmelt runoff season. The most common initiation mechanism for post-wildfire debris flows is high peak flow in the

channel, whereas non-fire-related debris flows most commonly are initiated by landslides. Finally, as has been observed elsewhere, the events that followed the 2003 fires show that the probability of occurrence of debris flows in susceptible channels can increase greatly following a high-severity wildfire.

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