PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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Short Contributions— Colorado Front Range Project

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HYDROLOGIC AND GEOMORPHIC IMPACTS OF THE 2010 FOURMILE CANYON FIRE, BOULDER CREEK WATERSHED, CO

BEN PURINTON, Wesleyan University
Research Advisor: Peter Patton

INTRODUCTION

Wildfire dramatically alters the hydrologic regime and movement of sediment in watersheds. This disturbance has the small-scale effect of decreasing infiltration and increasing runoff on hillslopes and the large-scale effect of increasing sediment yield and peak flows in channel networks (Shakesby and Doerr, 2006). Over long time scales, repeated severe fires are capable of significant geomorphic change (Swanson, 1981). Steep, fire-prone terrains, such as those found in the Colorado Front Range, are especially susceptible to this impact. Wildfire impacts water quality by increasing suspended sediment and through nutrient loading of soluble alkaline oxides from combusted organic matter (Smith et al., 2011).

The physical effects of wildfire can be divided into (1) the development of soil water repellency in severely burned topsoil, (2) the deposition of a wettable ash layer on the soil surface, and (3) cover loss through the combustion of vegetation and ground litter (Wondzell and King, 2003; Shakesby and Doerr, 2006). This results in decreased interception and infiltration of rainfall causing increased runoff and sediment yields (Ice et al., 2004). In steep, severely burned basins, this is evident in short-duration, high intensity, low volume rainfall events of frequent recurrence intervals generating floods with long recurrence intervals (Shakesby and Doerr, 2006). Studies describe some postfire sediment yields of 200 times background levels (Moody and Martin, 2001; Wilkinson et al., 2009).

Spatial and temporal differences in burning and rainfall lead to a complex response in basin-wide sediment delivery (Moody and Martin, 2001). Prefire periods represent supply-limited erosional systems with less available sediment. But following wildfire these systems become transport-limited, requiring intense rainfall events to transport exposed soil prior to revegetation (Shakesby and Doerr, 2006; Ryan et al., 2011).

The impact of wildfire is ephemeral with significantly elevated runoff and erosion typically lasting for two years (Kunze and Stednick, 2006; Wilkinson et al., 2009). This initial disturbance is followed by elevated hydrological and erosional effects persisting for about 3–10 years, mostly dependent on the time required for revegetation (Moody and Martin, 2001; Benavides-Solorio and MacDonald, 2005; Shakesby and Doerr, 2006).

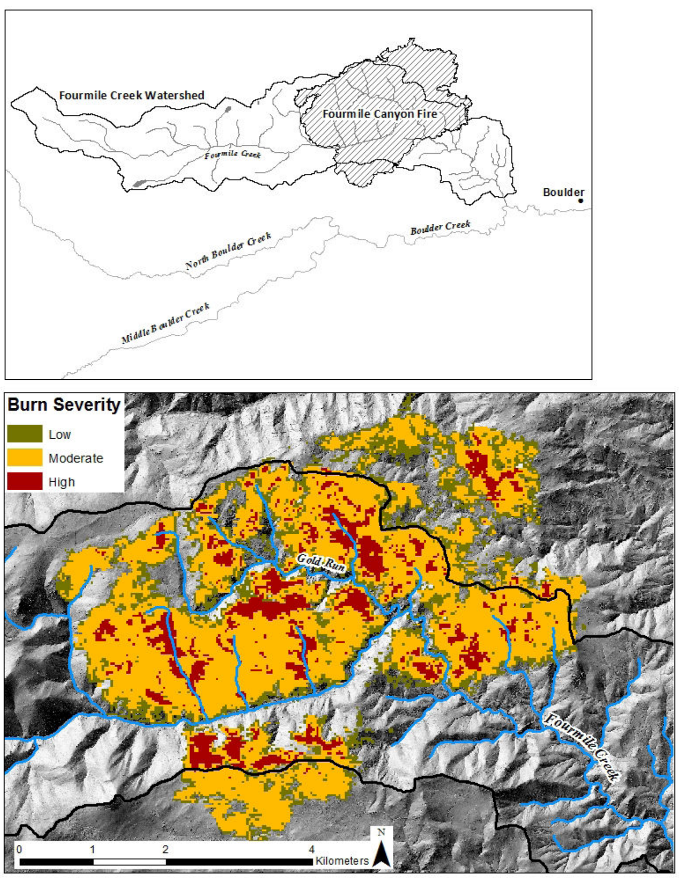
Long-term (kyr-Myr) erosion rates cannot consistently be determined by short-term erosional studies in undisturbed areas. When compared to long-term rates, short-term erosion rates have been found to be 17 times lower in the Rocky Mountains (Kirchner et al., 2001). It is theorized that the higher rate of long-term erosion in these cases is caused by episodic sediment delivery from catastrophic events such as fire, flooding, or the combination of both (Pierce et al., 2004).

Study Site and Fire

Fourmile Creek is a high elevation tributary to the upper Boulder Creek basin in the Front Range just west of Boulder, CO. The drainage area of Fourmile Creek at the point of a U.S. Geological Survey stream gauge–0.4 km upstream of its confluence with Boulder Creek–is 63 km^2 (StreamStats, 2012; USGS Surface-

Water, 2012). The Fourmile Canyon watershed is generally steep with an average slope of 20° and numerous side slopes approaching or above 45° (Graham et al., 2012; StreamStats, 2012). Vegetation is aspect controlled with south-facing ponderosa pine and north-facing Douglas fir forests. The Canyon contains numerous intrusive dikes and the upper basin is composed primarily of gneisses and schists. Boulder Creek Granodiorite is the dominant near surface bedrock, and well-drained gravelly sandy loam soils derive predominantly from this (Ebel et al., 2012).

Fourmile Canyon originally was a mining settlement in the early 1850s (Twitty, 2007). The legacy of this is apparent in many abandoned mines and tailings piles. The presence and abundance of mine waste is a concern for sediment chemistry and water quality in the drainage (Beganskas, 2012).



[Boulder: ESRI ArcGIS Online; Hydrography: USGS; Watershed: USGS StreamStats; Burn Severity and Fire Perimeter: Boulder County GIS; Hillshade: Colorado University, Boulder CZO]

Figure 1. (Top) Fourmile Creek drainage overlain with area encompassed by 2010 Fourmile Fire. (Bottom) Burn severity map for the fire. The town of Boulder is 3 km downstream of the confluence of Fourmile Creek and Boulder Creek. Note the extent of burn around Fourmile Creek's primary tributary, Gold Run.

Igniting on September 6, 2010, the Fourmile Fire burned for 10 days covering a total area of approximately 25 km^2 (Fig. 1) (Graham et al., 2012). The fire was preceded by above normal temperatures and below normal rainfall in August, creating a short-term drought in early September (Ebel et al., 2012; Graham et al., 2012). Only 14.5 km^2 of the Fourmile Creek drainage was burned in a mosaic pattern of low (2.6 km2), moderate (9.4 km^2), and high (2.5 km^2) severity (Fig. 1). This resulted in 169 homes destroyed and $217 million in damages (Writer and Murphy, 2012).

Building on Keck student Sarah Beganskas' (2012) study and other USGS studies (Ebel et al., 2012; Moody and Ebel, 2012; Murphy et al., 2012; Writer and Murphy, 2012), this work seeks to quantify the hydrologic and geomorphic impacts of the 2010 Fourmile Fire along with the combined impact of wildfire and mining on sediment chemistry.

METHODS

Field observations provided insight into both wildfire and anthropogenic impacts in Fourmile Canyon. The large flood magnitude in July 2011 created distinct flood deposits along Fourmile Creek allowing for sampling and comparison between 2011 and 2012 sediment delivery. Sediment samples included channel bank deposits from upstream and overbank deposits from downstream of the fire, ash, coarse material from some gullies, and bedload material from Fourmile Creek. Observations and width and thickness measurements of overbank flood and gully deposits were used to create valley floor maps and calculate 2-year fire-associated sediment storage. This is combined with limited data on ash thickness and hillslope plot yield to generate a sediment budget.

Hydrologic analyses were accomplished using two stream gauges located along Fourmile Creek and from rainfall data sources. The stream gauge located at the mouth of Fourmile Creek (Station 06727500; USGS Surface-Water, 2012) had historic mean daily flow records for 1947–1953, 1983–1995, and 2011–2012. Additional prefire instantaneous discharge was available at this gauge from 1983–1994 and 2011–2012. This allowed for some comparison of pre- and postfire streamflow. The only spatially accurate source of rainfall data, seven tipping bucket gauges operated by the Urban Drainage and Flood Control District (2012), did not overlap with the prefire discharge record, limiting rainfall-runoff analysis to the postfire period.

Amalgamated samples were created for the 2011 and 2012 overbank deposits downstream of the western fire perimeter. These were compared to an amalgamated channel bank sample from upstream of the disturbed area. Laser grain-size analysis was carried out on the <2 mm fraction, and these samples were also observed under a standard binocular microscope. Further analysis consisted of commercial ICP-MS and ICP-ES analysis of the <150 μm fraction and XRF analysis of the <2 mm fraction at Wesleyan. This provided both major oxide and trace metal concentrations for selected samples. Radionuclide activity of ^{137}Cs and ^{210}Pb were also analyzed in selected samples as a potential tracer of ash from hillslopes to channel banks.

RESULTS

Observations

Two years of flooding has produced unique features throughout the disturbed area. Extensive overbank fine sediment deposits were documented within and downstream of the fire perimeter. These ranged in thickness from a few centimeters to tens of centimeters. In contrast, upstream of the fire zone both overbank deposits and signs of recent flooding were absent. Small storm events were capable of remobilizing fines within the fire area causing stream turbidity to persist for several days after rainfall had ceased.

Common within the fire area were thick fan deposits at gully mouths. In places the fans draped over a historic railroad grade on the south bank of Fourmile Creek, but did not reach the valley floor. As Fourmile Drive runs along the channel's north bank, gully deposits along this road were quickly excavated prior to this study. Gully fans were absent outside of the fire area.

A tour of the severely burned north-facing hillslope monitored by the USGS (Ebel et al., 2012; Moody and Ebel, 2012) gave insight into the current state of erosion and recovery. The return of waste-high grasses and shrubs and the stripping of ash deposits among groves of torched Douglas fir and Limber pine on moderate to steep slopes was the most notable feature. In other areas eroding ash deposits were still apparent. A recently uncovered tarp plot on a ~15° slope allowed for sampling of in-situ ash associated with the fire that had not been stripped and transported downslope.

Hydrologic Analysis

Intense rainfall with a recurrence interval of about two years, centered over severely burned portions of Fourmile Canyon, created a 70-year flood event–based on a Log Pearson III analysis of the historic peak flow record–on July 13, 2011, peaking at 23.2 m^3/s. More intense rainfall with about a 5-year recurrence interval on July 30, 2012 only caused a 5-year flood event, peaking at 3.7 m^3/s (Fig. 2). The 2011 flood was well above the previous 7.3 m^3/s record for Fourmile Creek recorded on June 1, 1991. July events in both 2011 and 2012 caused an increase in July daily mean discharge by 0.14 m^3/s compared with prefire flow.

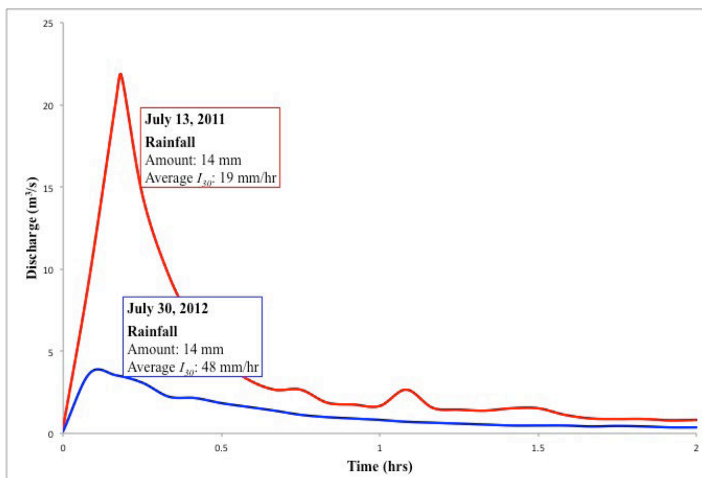


Figure 2. Comparison of rainfall-runoff response between 70-year flood event 10 months after the fire on July 13, 2011 and 5-year flood event just under two years after the fire on July 30, 2012. More intense rainfall, as measured by maximum 30 minute intensity (I_{30}), directly over severely burned portions of the drainage, Gold Hill, on July 30, 2011 led to a much smaller discharge event. This indicates the watershed's rapid hydrologic recovery since the 2010 fire.

Average prefire peak discharge from selected hydrographs from the instantaneous record was only 0.9 m^3/s, while this rose to 4.7 m^3/s postfire. Results also indicate a shortened time base of postfire discharge events by two hours. Furthermore, the time to rise was shortened from 15% to 9% of the total time base in the postfire period.

Sediment Budget

Channel floor maps were drafted and rendered in ArcGIS for a few key areas along Fourmile Creek using field observations and measurements (Fig. 3). Extrapolation of overbank deposit measurements from these mapped reaches provides a conservative estimate for fire-associated channel bank storage of 19,000 t. The contribution of recent gully deposits to overall storage is omitted, as these were only found within the burned area, and most of them were not mapped. Limited data on 2012 sediment delivery from one severely burned hillslope plot (B. Ebel, personal communication) and average ash thickness and density (Ebel et al., 2012; Moody and Ebel, 2012) was used to extrapolate total 2-year sediment delivery. Using reasonable estimates for 2011 yield from this plot and assumed yields from moderate and low severity areas, a total of 39,400 t potential yield is calculated for the burned area within the Fourmile Canyon watershed.

Grain-size and Characteristics

Microscopic evaluation revealed the prevalence of pyrogenic material (charcoal) in nearly all samples. Non-ash samples were composed of grüs formed from the local granodiorite and included primarily mica, quartz, and feldspar, with some additional amphibole. Most grains were angular to sub-angular, indicating recent weathering from parent material.

Comparison of grain-size results between the 2011 and 2012 amalgamated samples with respect to the upstream sample and *in situ* hillslope ash is summarized in Figure 4. Mean diameter of the ash was 75±55 μm. This, along with its frequency distribution, matched closely with the amalgamated 2011 overbank fine deposit, with its mean of 72±48 μm. On the other hand, the 2012 overbank sample and the upstream channel bank sample had mean diameters of 112±62 μm and 286±285 μm respectively.

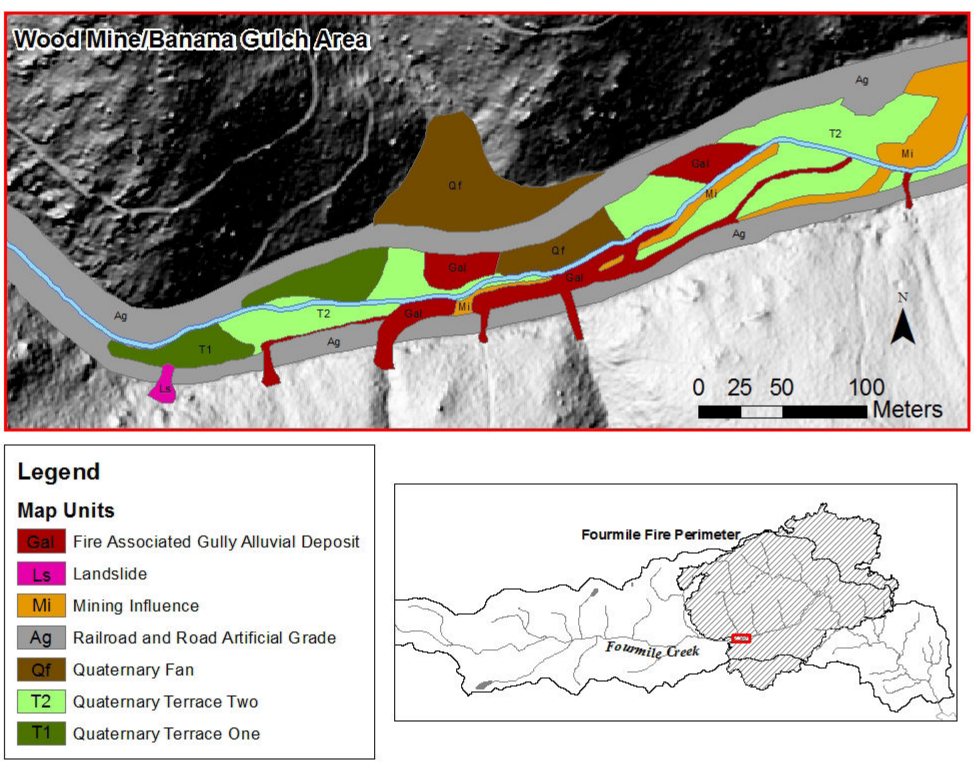


Figure 3. Channel floor map created for one reach of Fourmile Creek within the fire perimeter. Two other areas were mapped within and downstream of the fire perimeter. Not displayed are widths of 2011 and 2012 overbank flood deposits along Fourmile Creek. Fire-associated gully alluvial deposits (Gal, dark red) were only present within the burned area below severely burned drainages. As these were not all mapped they are excluded from the storage estimate, but likely contribute a large amount of sediment.

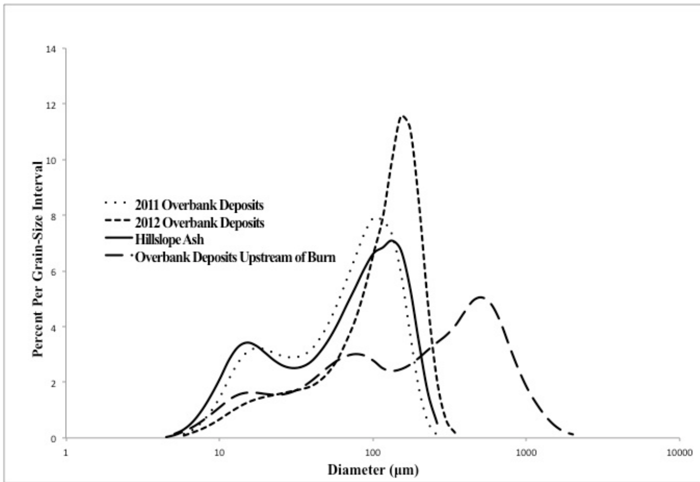


Figure 4. Grain-size frequency distribution for amalgamated 2011 and 2012 overbank deposits from the disturbed area, an upstream amalgamated channel bank sample, and the in situ hillslope ash sample. The distribution of the 2011 overbank sample matches closely with the ash and an increase in grain-size is seen in both the 2012 and upstream samples.

Geochemistry

Major oxide results displayed reduced SiO_2 and increased oxides of trace nutrients in disturbed area overbank deposits compared with upstream, undisturbed values. The in situ hillslope ash composition confirmed that these nutrient oxides were the result of organic matter combustion, mineralization, and deposition in the easily erodible ash layer. Downstream plots of MgO, CaO, and P_2O_5 illustrate this (Fig. 5A).

Trace metal delivery from mine refuse was evident in overbank deposits, spiking after the entrance of Gold Run to Fourmile Creek. A downstream plot of gold concentration illustrates this (Fig. 5B). This trend was also observed for arsenic, lead, mercury, tungsten, and zinc.

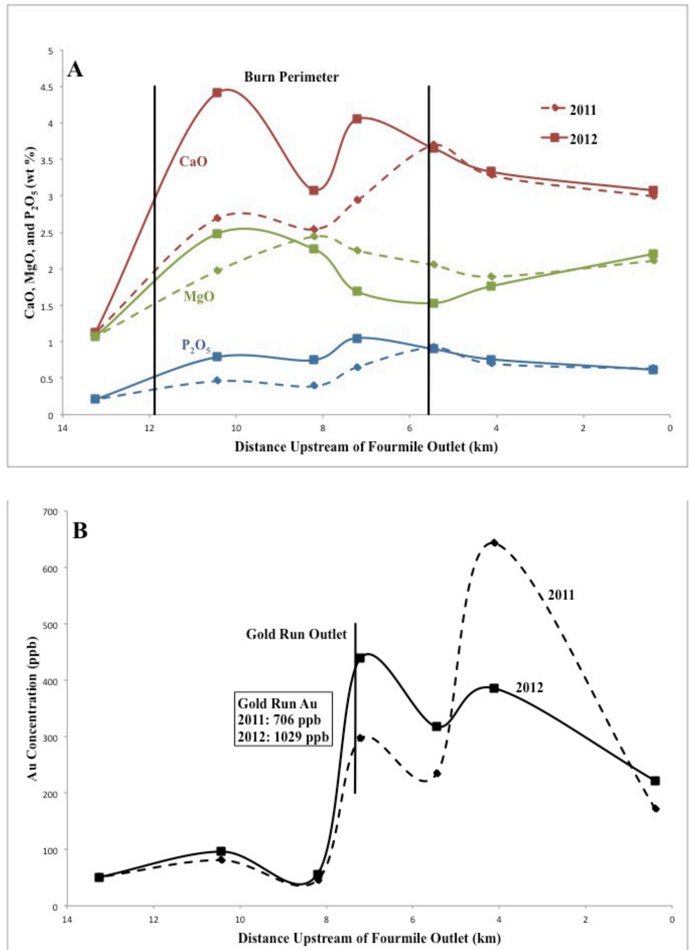


Figure 5. (A) Downstream plot of CaO, MgO, and P_2O_5 in overbank deposits caused by contribution of hillslope ash to these deposits. Ash concentrations of CaO, MgO, and P_2O_5 are 4.34, 2.66, and 0.52 weight % respectively. (B) Downstream plot of gold in Fourmile Creek overbank deposits caused by historical mining. Note the spike in concentration after Gold Run's outlet to Fourmile Creek. Inset box displays gold concentration of overbank deposits from Gold Run near its outlet. 2012 concentrations of gold are greater than 2011 in both the Gold Run overbank deposits and the Fourmile Creek overbank deposits immediately downstream of Gold Run

DISCUSSION

The 70-year flood on July 13, 2011 is expressive of the ephemeral postfire hydrologic shift. Rapid recovery is evident in July 2012 events, which experienced order of magnitude reductions in unit-area peak discharge compared with the 2011 flood (Fig. 2). Elevated mean discharge during July displays the importance of high intensity convective storms, common to this season in the Front Range, in generating the bulk of flooding and subsequent sediment transport following wildfire. It must be noted that July 2011 and 2012 total precipitation was significantly elevated versus the long-term average (High Plains Regional Climate Center, 2012; National Atmospheric Deposition Program, 2012). Shortened time bases and shortened time to rise in the postfire hydrographs indicate the disturbed area's flashy response to rainfall caused by decreased foliage and groundcover and reduced infiltration of hydrophobic soils (Moody and Ebel, 2012).

The prevalence of charcoal in overbank samples confirms the contribution of burned slopes to these deposits. Angularity of grüs indicates rapid stream transport of bedload and overbank sediments in this steep catchment. Fine mica fragments constitute a significant portion of suspended sediment and overbank deposits, as its platy nature allows for transport during low energy flows.

Grain-size results reveal that ash delivery dominated sediment input during the July 13, 2011 event (Fig. 4). Furthermore, the 2012 amalgamated overbank and undisturbed samples have an increasing grain-size distribution. The lack of an ash grain-size signature in the 2012 deposits indicates the rapid stripping of ash during the first year after the fire.

Geochemical results further confirm the delivery of ash to overbank deposits by increased concentrations of nutrient oxides (Fig. 5A). Nutrient influxes associated with the fire are responsible for increased stream biofilm but are not currently a concern for water quality (Writer and Murphy, 2012; Writer et al., 2012).

Trace metal concentrations display the effects of historical mining in Fourmile Canyon. As Gold Hill was the locus of this mining activity (Twitty, 2007), the spike in concentration downstream of this is expected (Fig. 5B). Based on the number and size of tailings piles throughout this drainage and the potential long residence time of sediment deposits far from the channel, elevated concentrations of trace metals will persist in Fourmile for many decades, indicating a need for continual monitoring. Geochemistry results are in agreement with trends found in the water and sediment chemistry by S. Beganskas (2012) associated with wildfire and mining.

The discrepancy between the 39,400 t potential yield and 19,000 t estimated storage is caused by the omission of gully fan deposits, sediment delivered by south-facing slopes and excavated from Fourmile Drive, sediment storage along Gold Run's 5.4 km reach, and throughput of fire-associated sediment flushed into Boulder Creek. Back calculation of potential sediment delivery yields an average depth of erosion of 1.6 mm over the entire 14.5 km^2 burned area. However, assuming that the vast majority of sediment was delivered from severely burned slopes (Benavides-Solorio and MacDonald, 2005), an average depth of erosion of 9 mm is calculated for this 2.5 km^2 area. The fact that sediment tended to be localized below severely burned slopes supports the idea that near-channel fire-related sediment deposits represent only a portion of the burned area.

Revegetation and the sparse presence of remaining hillslope fine deposits–ash–suggest that sediment yields will decline. Moderate rainfall events are capable of remobilizing near channel deposits, flushing them out to Boulder Creek. However, many deposits lie some distance from the channel. It is likely that these will become persistent landscape features dependent on additional stochastic geomorphic events.

Using reasonable assumptions for the combined probability of severe fire return periods, moderate rainfall return periods, and the likelihood of moderate rainfall events shortly after a severe fire, a recurrence interval for this fire-flood event may be calculated (Elliot and Parker, 2001). The recurrence of severe fire is assumed to have three probable values: 40 years with anthropogenically influenced increasing fire frequency (Westerling et al., 2006), 60 years from previous Front Range studies (e.g. Kaufmann et al., 2000), and a high estimate of 100 years.

Average depths of erosion from this event combined with recurrence intervals are extrapolated to kyr and Myr scales to assess potential fire-associated long-term denudation in Table 1. The significance of these events to landscape geomorphology in the arid, mountainous Western US is apparent in this calculation. For comparison, denudation rates gathered from cosmogenic radionuclides for basins within Fourmile Canyon average 55 m/Myr, averaging the last 15–20 ka (W. Ouimet, personal communication). Assuming that severely burned slopes are the primary contributor of sediment, the calculated denudation rates represent 70–170% of this long-term value (Table 1, bottom). This indicates that increasing fire frequency associated with anthropogenic climate change has the potential to increase long-term erosion rates in these landscapes, assuming that sediment generation can keep pace with these rates.

Table 1. Extrapolated long-term denudation caused by fire-flood events based on calculated denudation from the 2010 Fourmile Fire. Top represents the denudation taken over the entire burned area, whereas the bottom confines the denudation to the severely burned area. Recurrence intervals of fire-flood events are calculated using 40, 60, and 100-year severe fire return periods, 2-year rainfall return periods, and an 80% chance of said rainfall occurring soon after the fire.

Total Burned Area (1.6 mm over 14.5 km²)

Recurrence Interval for Fire-Flood Event (RI_{FF}) (yrs)	Potential Denudation Rate (m/kyr)	Potential Denudation Rate (m/Myr)
100	0.016	16
147	0.011	11
250	0.006	6

Severely Burned Area Only (9 mm over 2.5 km²)

Recurrence Interval for Fire-Flood Event (RI_{FF}) (yrs)	Potential Denudation Rate (m/kyr)	Potential Denudation Rate (m/Myr)
100	0.093	93
147	0.063	63
250	0.037	37

CONCLUSIONS

The rapid response of this basin following the fire is followed by a rapid decline in peak flows and erosion. The legacy of fire-associated deposits is expected to persist for decades. Movement of sediment, and the continued flushing of contaminated mining refuse, is dependent on recurrence of large floods, which in turn appear to depend on recurrence of severe wildfire. High, fire-related erosion rates further confirm the significance of infrequent wildfire and flooding to geomorphic change in the West and the potential for its increasing influence with climatic forcing (Swanson, 1981; Kirchner et al., 2001).

All results and discussions are not included in this short contribution. See the full work for additional hydrologic, grain-size, and geochemistry results (including radionuclides) and a further discussion of sediment budget.

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