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# ANALYZING GEOMORPHIC EFFECTS OF THE SEPTEMBER 2013 FLOOD IN FOURMILE CANYON, COLORADO, USING LIDAR AND FIELD STUDIES

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## INTRODUCTION

In the past decade repeat LiDAR studies have increasingly been used to quantify sediment flux and geomorphic change from debris flows, landslides, and fluvial transport (Wheaton et al., 2010; Shürch et al., 2011; DeLong et al., 2012; Croke et al., 2013; Anderson and Pitlick, 2013). Flooding in the Front Range of Colorado from September 9 to 15, 2013, resulted in extensive damage to the city of Boulder, Colorado and adjacent areas. Rainfall totals of up to 43.6 cm caused extensive flooding and local debris flows in the foothills west of Boulder. This research uses the results of field measurements and remote sensing to reconstruct flood discharge, sediment transport, channel change, and sediment budgets for the catastrophic September 2013 flood in Fourmile Canyon, an undammed catchment in the Front Range foothills west of Boulder, Colorado.

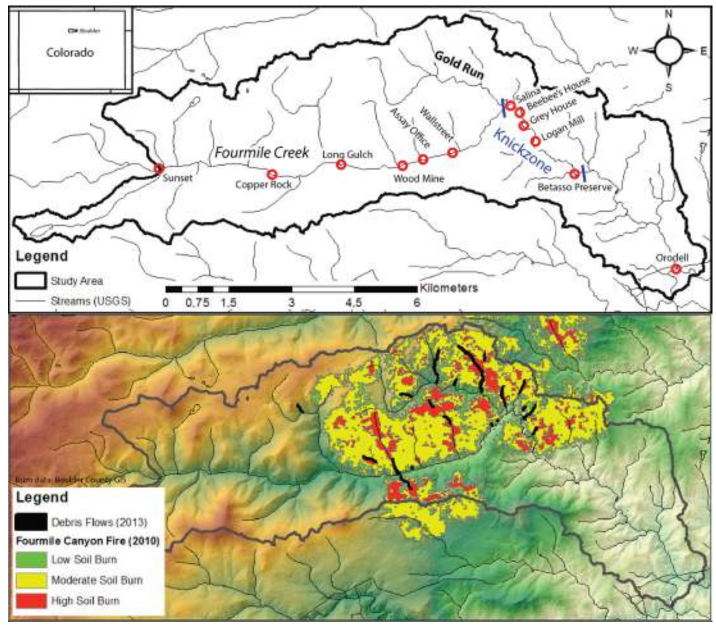


*Figure 1. Overview map showing location of Fourmile Canyon, 2010 burn area, debris flows, knickzone, and study sites.*

## SETTING

Fourmile Canyon is a 64 km² catchment located in the piedmont of the Colorado Front Range, which stretches from the High Plains near Boulder west to the Continental Divide (Fig. 1). Although Fourmile Canyon's source lies in the alpine zone, the 50.3 km² study area considered here lies between 2500 and 1600 m, spanning the subalpine and piedmont zones. The steep-sided, V-shaped valleys of this zone reflect its lack of glaciation during Pinedale time, with slopes ranging from 25 to 45º (Leonard, 1989). Vegetation patterns correspond to the elevation-determined climate zones (Ebel et al., 2012). In the arid foothills, vegetation is strongly controlled by aspect, with north-facing slopes holding far more trees than the south facing slopes.

The foothills of the Front Range have experienced many floods throughout recorded history, with major floods affecting Fourmile Canyon in 1844, 1864, 1894, 1921, 1964 and 2011 (Follansbee & Sawyer, 1948; Antsey & Thomas, 2013). In addition to frequent flooding, wildfires occur regularly throughout the Front Range (Graham, 2012). Tree-ring records indicate fire recurrence intervals of 5-30 years in the lower elevation ponderosa pine forests prior to the mid 19th century, (Veblen & Donnegan, 2005), while wildfire frequency and scale has increased in recent decades across the western U.S. (Westerling et al., 2006). Fourmile Canyon experienced a major wildfire in 2010, burning 16.5 km² (23%) of the watershed and destroying 160 homes, affecting infiltration and slope stability in the area (Moody and Martin, 2001; Graham, 2012). The Gold Run sub-catchment, which drains into Fourmile Creek at Salina Junction, was hit especially hard by the 2010 fire, with 90% of the drainage area burned (Fig. 1). Partially as a result of the fire, almost all of the 2013 debris flows in Fourmile Canyon occurred in the Gold Run catchment (Fig. 1), contributing large amounts of sediment and discharge to the main channel.

Flashy rainfall-driven events during the summer months often account for the annual peak discharge events in the Front Range, and can be amplified by wildfire (Moody and Martin, 2001). These events generally are characterized by a short period of very intense rainfall (>200mm/hr) with 'flashy' hydrographs that cause short-duration floods such as the Big Thompson flood of 1976 (McCain et al., 1979). However, the September 2013 flood had relatively lower rainfall intensity (<25mm/hr) sustained over 5 days, from the $9^{th}$ to $15^{th}$ (Pitlick, 2013; Coe et al., 2014) (Fig. 2). This meant that while the peak discharge was high, the 5 day bankfull duration was the most unusual aspect of the flood (U.S. Geological Survey, 2014) (Fig. 2).

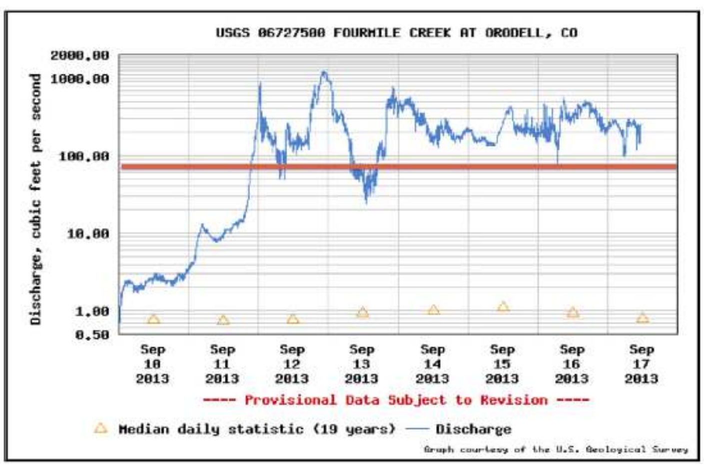


*Figure 2. Provisional hydrograph for Fourmile Creek at Orodell, Colorado, red line indicates bankfull discharge (US Geological Survey, 2014).*

## METHODS

This study uses a combination of field methods and LiDAR analysis to characterize the geomorphic effects of the September 2013 flood. The study stretch of Fourmile Canyon was chosen due to its accessibility and dramatic flood response (Fig. 3). I mapped a 15 km reach of the floodplain in reconnaissance and selected 12 more detailed survey sites, mapping flood deposits, measuring high water marks and floodplain width, making point counts of the gravel-cobble sized surface deposits, and collecting samples of deposit matrices (Fig. 3). These data were then used to estimate discharge with the slope-area and critical-depth methods, which have been developed or applied in high-gradient systems (Jarrett, 1984; Jarrett and Tomlinson, 2000). Geographic information system (GIS) analysis of repeat LiDAR elevation surveys from 2010 and 2013 was used to: (1) corroborate the field data; (2) quantify sediment flux; and (3) make morphometric measurements. With the assistance of Matthias Leopold (University of Western Australia), electric resistivity tomography (ERT) and shallow seismic reflection (SSR) geophysical surveys at two sites helped determine the depth of alluvium and flood deposits.

*Figure 3. Flood deposition in Logan Mill; coarse deposits are 1.5 m deep; grubber for scale.*

## RESULTS

Results from both field observations and repeat LiDAR analysis showed dramatic geomorphic change along Fourmile Creek and adjacent tributaries from the September 2013 flood. Field observations indicated 10 zones of major deposition (>0.5m thick) over 100s of meters of channel, with areas of bypass or mixed erosion and minor deposition in between. Flood deposits were characterized by cobble gravel in a matrix of coarse sand. Although major deposition zones were found both above and below Salina Junction, the occurrence and scale of the deposits increased downstream. The most extensive deposits were found at the Logan Mill site (Fig. 1), stretching for over 250 m and covering the entire floodplain width of 25-35 m with thicknesses of 0.6 to 1.5 m. At both this site and others, multiple phases of flood deposition are visible in the coarse deposits, each with distinct grain sizes and bedding patterns. Some deposits are unsorted, matrix supported, and nonimbricated, some are distinctly imbricated, clast supported, and sorted, while still others are a mix of the two. Although sediment deposits are the most apparent, channel incision and migration occurred throughout the study reach, eroding both vertically and laterally, and locally into the road that parallels Fourmile Creek (Fig. 4).

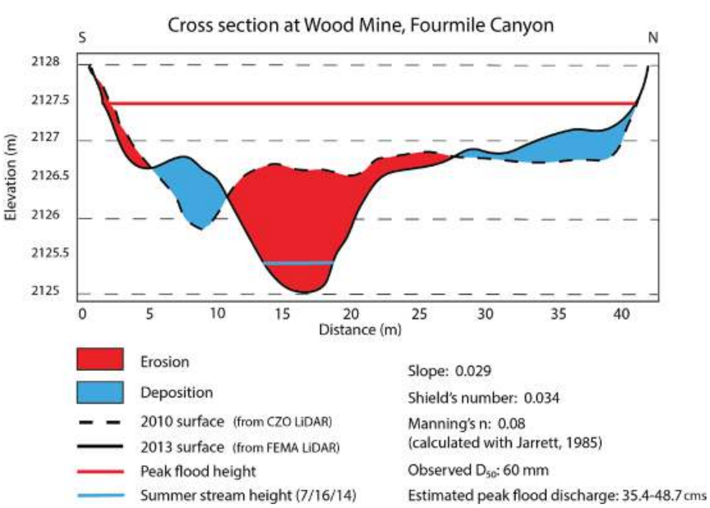


*Figure 4. Cross section of Fourmile Creek at Wood Mine showing areas of erosion, deposition, and evidence of channel migration and incision.*

In addition to these general depositional trends, areas with larger clasts and local, slackwater areas where suspended sediment accumulated could also be found. Large boulders (>1x1x0.5 m) were found at 3 sites, with slightly smaller boulders (~0.5x0.5x0.5 m) found at 5 other sites. Deposition zones filled with fine silt to coarse sand-sized sediment were found at Logan Mill and Betasso Preserve (Fig. 1), where three man-made depressions captured ~400 $m^3$ of suspended sediment through a spillway that allowed only peak flood water and no bedload transport to pass through.

Raster subtraction of the pre- and post-flood LiDAR data checked with field measurements show that the 15 km study stretch of Fourmile Canyon experienced 35,000 - 56,500 $m^3$ of local deposition despite 53,500-105,000 $m^3$ of net erosion within the floodplain. LiDAR analysis also indicates that 42,000-60,000 $m^3$ of sediment was mobilized by debris flows in side tributaries and 55,500-120,000 $m^3$ of sediment may have been eroded due to sheetwash (Table 1). Estimates of total suspended sediment loss from the system are ~4,000 $m^3$ (Murphy et al., in review); bedload flux has not yet been estimated.

Geophysical surveys at Wood Mine and Copper Rock show an alluvial wedge of sediment ~10 meters deep. ERT surveys with a penetration depth of 11m barely show bedrock at the base of the survey, with SSR measurements corroborating the data. In addition, these surveys show a 1-2m thick layer of highly resistive sediment on the surface, corresponding closely to the depth of deposits observed in the field and calculated with LiDAR.

Peak discharges at 8 sites in the study reach were derived using field observations and the slope-area or critical-depth methods. Peak discharge values range from 9.7 - 19.4 $m^3/s$ at Sunset (furthest upstream) to 58.5 - 96.9 $m^3/s$ at Betasso Preserve (furthest downstream). These values roughly correspond to previous estimates, which found values of 12.9 $m^3/s$ and 65.1 $m^3/s$, respectively (CH2M HILL, 2014). For comparison, bankfull discharge at the USGS gaging site at Orodell is 2.5 $m^3/s$ (US Geological Survey, 2015).

| SEDIMENT FLUX | Lower estimate, in $m^3$ | Upper estimate, in $m^3$ | Erosion depth, in cm | Source |
|---|---|---|---|---|
| **FLOODPLAIN**[1] | | | | |
| **Deposition** | | | | |
| **In-channel** | 34000 | 55000 | | Calculated from field surveys, checked with LiDAR |
| **Slackwater** | 1000 | 1500 | | Calculated from field surveys, checked with LiDAR |
| **TOTAL** | 35000 | 56500 | | |
| **Erosion** | | | | |
| **In-channel** | 108000 | 137000 | | LiDAR-based estimate |
| **Road material** | 2000 | 3000 | | Calculated from LiDAR |
| **TOTAL** | 110000 | 140000 | | |
| **NET FLOODPLAIN FLUX** | 53500 | 105000 | | |
| **Floodplain flux/area** | | | 7.6-15 | |
| | | | | |
| **SLOPES**[2] | | | | |
| **Slope erosion** | | | | |
| **Debris flows** | 42000 | 60000 | | Calculated from LiDAR |
| **Sheetwash** | 13500 | 60000 | | Estimated using values of Reneau et al. (2007) |
| **TOTAL** | 55500 | 120000 | | |
| **Slope flux/area** | | | 0.11-0.24 | |
| | | | | |
| **Sediment loss from basin** | | | | |
| **Suspended load** | 4000 | >4000 | | Estimate from Murphy et al. (submittted) |
| **Bedload** | ? | ? | | Estimate in progress |
| **TOTAL** | >4000 | >4000 | | |
| | | | | |
| **TOTAL FLOOD EROSION** | 113000 | 229000 | 0.22-0.46 | |
| | 1. Floodplain area is 700,000 $m^2$. 2. Slope area is 49621800 $m^2$ | | | |

*Table 1. Estimated sediment transport budget of the September 2013 flood in the Fourmile Canyon catchment.*

## DISCUSSION

The September 2013 flood was exceptional in many ways, lasting for over 5 days with multiple peak flows (Fig. 2). The flood was also an extremely complex event, with a plethora of sediment sources, contributing factors, and local exceptions. The geomorphic effects of the flood (deposits, erosion, etc.) were affected by the knickzone found midway up Fourmile Canyon and by debris flows that entered Fourmile Creek near Salina and above Wood Mine (Fig. 1). Upstream and downstream from the knickzone, the floodplain widens to 30-80 m across, resulting in more areas of channel migration and major deposition during the flood (Fig. 5). Within the knickzone the floodplain is 15-25 m wide and locally bedrock-floored. Slopes range from 0.02-0.035 above the knickzone, 0.025-0.053 within the knickzone, and 0.02-0.038 below the knickzone. Although width had some affect on deposit occurrence, channel migration, local scour and fill, and large woody debris from the long flood event and debris flows were also contributing factors. Since large deposits are found throughout the channel reach, local slope is clearly not the dominant factor in deposition. The pattern of deposition and erosion we see today is the last overlay of the flood events, locally recording the reworking of deposits from earlier stages. Debris flows periodically injected energy and sediment into the system throughout the flood, most significantly from the mostly burned Gold Run sub-catchment, which added ~30,000 $m^3$ of sediment into Fourmile Creek at Salina Junction (Fig. 1). The distribution of deposits, therefore, was a function of many factors including width, location within the canyon, and temporal change. The low proportion of fine-grained slackwater deposits suggests that most of the fine-grained sediment exited the system, stopping only in local sinks such as the Betasso Preserve site and Poorman Reservoir.

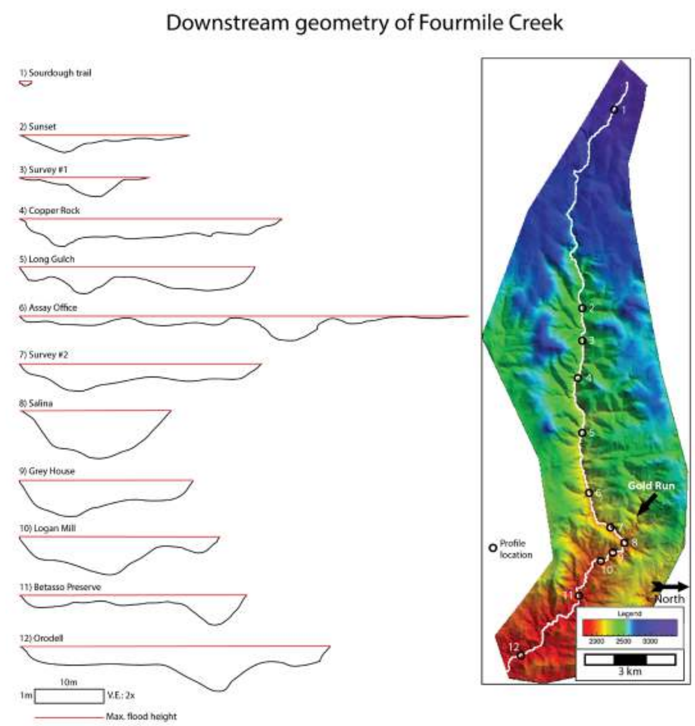


*Figure 5. Channel profiles of Fourmile Creek at peak flow from the Sourdough Trail to Orodell.*

Evidence from the field and remote sensing indicates that the September 2013 flood eroded an average of 0.11 to 0.24 cm from the slopes of Fourmile Canyon and 7.6-15 cm from the floodplain of Fourmile Creek. From both the historic record and estimates compiled by hydrologists, floods of a similar scale as the 2013 event recur on an interval between 50-75 years (Gingery, 1981; Jacobs, 2014). The 1894 flood was closest in scale to the September 2013 event, with smaller events taking place at 20-50 year intervals. Although records specific to Fourmile Creek are not available, the discharge was estimated at 255-283 cms at the outlet of Boulder Creek in the 1894 event (Follansbee & Sawyer, 1948), with the 2013 flood estimated at 136 cms at the same location (CH2M HILL, 2014). When seen in the context of the long-term erosion rate of Front Range slopes, estimated at 4-5 cm/ky (Dethier et al., 2014), 50-75 year floods can account for 74.6-182% of the basin erosion in a millennium at steady state. This conclusion shows that infrequent floods play a significant role in landscape evolution, especially when combined with the consequences of wildfire. However, as not all floods are amplified by wildfire like the 2013 event, this estimate represents the maximum value.

Total sediment volume in the Fourmile catchment above bedrock is estimated at 29,546,400 $m^3$, assuming 50 cm of overburden throughout the basin and using geophysical measurements and field observations to estimate the depth of the alluvial wedge within the floodplain. Using the same overall erosion rate of 4-5 cm/ky, sediment in Fourmile Canyon has a residence time between 11.7-14.7 ky. Weakly developed soils characterize the area, supporting this estimate (Birkeland et al., 2003).

Episodic fire and flooding occurred before the arrival of humans, and although climate change is influencing wildfire recurrence in the Colorado Front Range (MacDonald and Stednick, 2003), anthropogenic climate change is not thought to have amplified the weather patterns which caused the 2013 flood (Hoering et al., 2014). The effects of the 2013 event can therefore be plausibly extrapolated over longer time scales. Although destructive, the September 2013 flood helps inform our understanding of sediment budgets and channel evolution in the Front Range.

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