

Hillslope sediment fence catch efficiencies and particle sorting for post-fire rain storms

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ABSTRACT: Sediment fences are often used to monitor hillslope erosion, but these can underestimate sediment yields due to overtopping of runoff and associated sediment. We modified four sediment fences to collect and measure the runoff and sediment that overtopped the fence in addition to the sediment deposited behind the fence. Specific objectives were to: (1) determine the catch efficiency of sediment fences measuring post-fire hillslope erosion; (2) assess particle sorting of sand, silt/clay, and organic matter from each hillslope through the sediment fence and subsequent runoff collection barrels; (3) evaluate how catch efficiency and particle size sorting relate to site and rainfall-runoff event characteristics; and (4) use runoff simulations to estimate sediment fence volumes for future post-fire monitoring.

Catch efficiency ranged from 28 to 100% for events and 38 to 94% per site for the entire sampling season, indicating a relatively large underestimation of sediment yields by sediment fences. Most of the eroded sediment had similar proportions of sand and silt/clay as the hillslope soils, but the sediment behind the fence was significantly enriched in sand while the sediment that overtopped the fence was more strongly enriched in silt/clay. The sediment fences had capacities of 3 m³ for hillslopes of 0.19–0.43 ha, but simulations of runoff for 2- to 100-year storms indicate that the sediment fences would need a capacity of up to 240 m³ to store all of the runoff and associated sediment. More accurate measurements of sediment yields with sediment fences require either increasing the storage capacity of the sediment fence(s) to accommodate the expected volume of runoff and sediment, reducing the size of the contributing area, or directly measuring the runoff and sediment that overtop the fence. © 2020 John Wiley & Sons, Ltd.

KEYWORDS: hillslope scale; post-fire; sediment fence; runoff and erosion; sediment sorting; sediment catch efficiency

Introduction

Land surface disturbances such as wildfire, agriculture, and construction expose bare soil to raindrop impacts, which can lead to increased runoff, erosion, and sediment delivery to streams. Sediment fences are commonly used to mitigate and monitor sediment yields on plots, road segments, and hillslopes due to their low cost and ease of installation, which has led to their widespread use (e.g. Benavides-Solorio and MacDonald, 2005; Ramos-Scharrón and MacDonald, 2007; Wagenbrenner and Robichaud, 2014; Wagenbrenner *et al.*, 2015; Sosa-Pérez and MacDonald, 2017; James and Krumland, 2018; Schmeer *et al.*, 2018). Sediment loss is generally estimated from the dry mass of sediment deposited behind the fence; dividing this by the contributing area provides sediment yields (Mg ha⁻¹). When the volume of runoff and sediment is greater than the storage capacity of the sediment fence, the overtopping runoff and sediment lead to underestimated total sediment yields (Benavides-Solorio and

MacDonald, 2005; Ramos-Scharrón and MacDonald, 2007; Vinten *et al.*, 2014).

This problem has been addressed by installing larger or sequential sediment fences (e.g. Wagenbrenner *et al.*, 2006; Vinten *et al.*, 2014; James and Krumland, 2018; Robichaud *et al.*, 2019), but the quantity and characteristics of the runoff and sediment overtopping the fence are almost always unknown. Where contributing areas are small (<0.01 ha), soil textures are relatively coarse, and sediment fences are large enough to store much of the runoff and sediment yields, a fence may catch ≥90% of sediment (Robichaud *et al.*, 2001; Bugg *et al.*, 2017). However, sediment fences have been used on hillslopes and in small ephemeral catchments with drainage areas up to 1.5 ha (Benavides-Solorio and MacDonald, 2005; Wagenbrenner and Robichaud, 2014; Wagenbrenner *et al.*, 2015; James and Krumland, 2018; Schmeer *et al.*, 2018; Robichaud *et al.*, 2019), and the reported data generally have no way to account for the amount of sediment that may have been lost due to overtopping of the sediment fence.

In this study, we examine sediment fence catch efficiency, which we define as the ratio of sediment deposited upslope of the fence to the total sediment yield (i.e. deposited sediment plus the sediment that overtopped the fence). This work is part of a larger post-fire monitoring effort that began after the 2012 High Park Fire in the Colorado Front Range (Wohl, 2013; Kampf *et al.*, 2016; Brogan *et al.*, 2017, 2019; Schmeer *et al.*, 2018; Wilson *et al.*, 2018). In this region, post-fire runoff and erosion are almost exclusively driven by high-intensity convective rainfall events that occur between June and September (Benavides-Solorio and MacDonald, 2005). The combustion of organic material during wildfire can create an ash layer that may initially increase infiltration capacity (Cerdà and Doerr, 2008; Woods and Balfour, 2008; Shakesby, 2011) in the absence of ash clogging of soil pores (Stoof *et al.*, 2016). Once the ash is removed, subsequent raindrop impacts on bare soil can lead to soil sealing (Larsen *et al.*, 2009) and reduced infiltration capacities via changes in soil organic matter, soil structure, and soil water repellency (Shakesby, 2011; Moody and Ebel, 2012). The effects of these changes decrease with time since burn, but initially result in increased runoff and erosion (Wagenbrenner and Robichaud, 2014) and headwater extension of the channel network (Wohl and Scott, 2017). As a result, the potential for sediment delivery from hillslopes to streams increases, particularly in areas of high burn severity (Ortiz-Rodríguez *et al.*, 2019) due to increased sediment transport capacities (Prosser and Williams, 1998; Wainwright *et al.*, 2000; Moody and Martin, 2001; Parsons *et al.*, 2006; Moreno-de las Heras *et al.*, 2010).

The quantity and type of erosion and sediment transport varies with rainfall and site characteristics. Typically, increased rainfall intensity leads to higher erosivity and the potential for overland flow and detachment and transport of sediment (Farmer, 1973; Bagnold, 1977; Wan and El-Swaify, 1998; Shi *et al.*, 2012; Cawson *et al.*, 2013). While rainsplash can detach a wide range of soil particle sizes, smaller particles are more readily entrained and transported from hillslopes by diffuse overland flow (Sutherland, 1991; Wan and El-Swaify, 1998). In cases where the surface runoff is concentrated into rills, the deeper and faster flow can both detach and transport coarser particles (Wan and El-Swaify, 1998; Shi *et al.*, 2012). Along a hillslope, coarser particles tend to be deposited in areas with lower slopes, while organic matter and finer particles are more readily transported downslope (Parsons *et al.*, 2006), where they are more likely to enter streams, affect water quality, and pose problems for water treatment and supplies and aquatic organisms (Emelko *et al.*, 2011; Smith *et al.*, 2011; Jones *et al.*, 2012; Bixby *et al.*, 2015; Martin, 2016; Hallema *et al.*, 2019). The rate of runoff and erosion from burned hillslopes decreases with vegetative regrowth, litter accumulation, and commonly with mulch treatments, as these tend to increase cover, intercept rainfall, increase infiltration, reduce rainsplash, and slow overland flow (Inbar *et al.*, 1998; Wainwright *et al.*, 2000; Wagenbrenner *et al.*, 2006; Yanosek *et al.*, 2006; Larsen *et al.*, 2009; Moreno-de las Heras *et al.*, 2010; Robichaud *et al.*, 2013a,b).

Measurement of these dynamic runoff and erosion processes after a wildfire requires rapid deployment of instrumentation because conditions change rapidly over the first few years after burning (Robichaud, 2005). The goal of this study was to modify the standard sediment fence design to measure the total overland flow and sediment yields after a wildfire in the Colorado Front Range. This allowed us to quantify sediment fence catch efficiency, defined as the ratio of sediment deposited behind the fence to the total sediment yield, and the sorting of sediment particle sizes through our sediment and runoff

collection system. Specific objectives were to: (1) determine the catch efficiency of sediment fences measuring post-fire hillslope erosion; (2) assess particle sorting of sand, silt/clay, and organic matter from each hillslope through the sediment fence and subsequent runoff collection barrels; (3) evaluate how catch efficiency and particle size sorting relate to site and rainfall-runoff event characteristics; and (4) use runoff simulations to estimate sediment fence volume for future post-fire monitoring.

Methods

Study sites

In June 2012 the High Park Fire burned 330 km² of primarily coniferous forest in the northern Colorado Front Range west of Fort Collins (Figure 1). This fire was a major concern because the burned area drains into either the Cache la Poudre or Big Thompson Rivers, which supply drinking water for Fort Collins, Greeley, Loveland, and other municipalities. To reduce runoff and erosion, mulch treatments were applied to some of the steeper areas burned at moderate to high severity (BAER, 2012; Figure 1). In this study, rainfall, surface cover, runoff, and sediment yields were monitored for four severely burned convergent hillslopes within two watersheds from July through early October 2014 (Figure 1).

The geology within the two study watersheds is Precambrian meta-sedimentary and meta-igneous schists, gneisses, and plutonic igneous rocks (Abbott, 1970); the soils are predominantly Redfeather sandy loam (BAER, 2012). The climate of this region is semi-arid with peak streamflow generated primarily by rainfall when mean watershed elevation is below 2000 m, and snowmelt when the mean watershed elevation is above 3100 m (Kampf and Lefsky, 2015). The elevation of our study sites ranges from 2280 to 2490 m (Table 1), so streamflow is driven by a mix of rainfall and snowmelt. Post-fire runoff and erosion at the hillslope scale are predominantly generated by summer thunderstorms (Benavides-Solorio and MacDonald, 2005) because these have the highest rainfall intensities. For our study sites, estimated summer (June–September) precipitation from 1981 to 2010 averaged 200 mm (PRISM Climate Group, Oregon State University, 2017). Rainfall intensities for 30- and 60-min storms with a 2-year recurrence interval from a nearby NOAA Atlas Station (Site 05-6925) are 31 and 18 mm h⁻¹, respectively (Perica *et al.*, 2013).

Four convergent hillslopes were selected during summer 2014 for monitoring runoff and sediment yields, with two sites in Skin Gulch (SG) and two in Hill Gulch (HG) (Table 1; Figure 1b). The perimeter of each hillslope was delineated in the field using a Trimble GeoXH handheld GPS unit (resolution 30 cm). Contributing areas ranged from 0.19 to 0.43 ha, and analysis of a 2 m digital elevation model (DEM) indicated that average slopes ranged from 17 to 19° with predominantly north, east, or northeast aspects (ESRI, 2013). Width-to-length ratios, calculated as the hillslope width divided by the main axis length, were similar for the two SG sites and HG3 at 0.13 to 0.15, but this ratio was higher for HG4 at 0.35 (Table 1; Figure 1b).

The timing of monitoring equipment installation varied by site. The sediment fences in Hill Gulch were installed in summer 2012, and runoff collection equipment was installed on 7 July 2014. The sediment fences at SG1 and SG2 were installed by 1 and 10 July 2014, respectively, and runoff collection equipment was installed on 23 July 2014. This paper reports on the runoff and erosion data from early July through the beginning of October 2014.

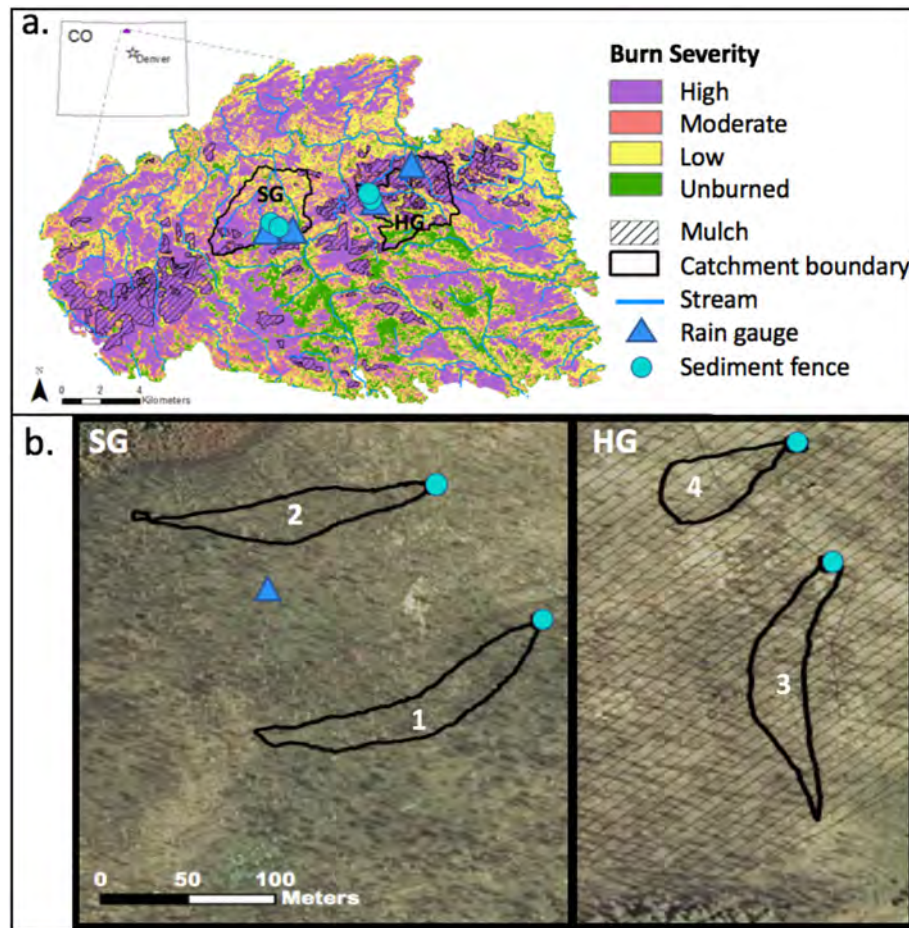


FIGURE 1. (a) High Park Fire burn severity (Stone, 2015), areas targeted to receive mulch treatments, study watersheds (Skin and Hill Gulch; SG and HG, respectively), streams, rain gauges, and sediment fences. (b) Monitoring sites with aerial imagery (USDA FSA, 2013), sediment fences, and co-located rain gauges in SG and HG. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1. Characteristics of the four study hillslopes in Skin Gulch (SG) and Hill Gulch (HG)

	SG1	SG2	HG3	HG4
Area (ha)	0.43	0.32	0.32	0.19
Elevation (m)	2420–2480	2430–2490	2300–2370	2280–2300
Average slope (°)	17	19	19	19
Dominant aspect	NE	E	N	NE
Width-to-length ratio	0.15	0.15	0.13	0.35
Mulch cover (%)	0	0	10	27
Bare soil (%)	56	50	47	29

Surface cover in the drainage area of each hillslope was measured in mid-August 2014 using systematic point counts conducted along transects placed 15 m apart perpendicular to the fence axis. Surface cover was classified at 2 m intervals as bare soil, bedrock, live vegetation, litter, rock (>1 cm diameter), wood (>1 cm diameter), tree, straw mulch, or wood mulch, yielding 100 points per hillslope. Although the Hill Gulch sites were scheduled to receive 2–3 Mg ha⁻¹ of wood strands in October–November 2012 and 14 Mg ha⁻¹ of straw in June 2013 (Figure 1a), the application rates varied and much of the straw was removed by wind and overland flow. By summer 2014 the residual mulch cover was only 10% in HG3 and 27% in HG4 (Table 1; Figure S1), and bare soil was relatively similar for the two SG sites and HG3 at 47–56%, while HG4 had the lowest percentage of bare soil at 29% (Table 1; Figure S1).

Precipitation

Rainfall was measured using tipping bucket rain gauges (Rainwise Inc., Trenton, Maine, USA) with a resolution of 0.25 mm. The distance to the closest operating rain gauge for each site varied throughout the season. From 1 June to 9 August, the closest gauge in Skin Gulch was 1 km east of the sites; on 9 August, an additional gauge was installed 0.1 km from the sites (Figure 1). In Hill Gulch, the closest rain gauge was 0.4 km east of the sites from 1 June to 11 September, but this gauge malfunctioned and the nearest gauge after 11 September was 2.4 km northeast of the sites (Figure 1).

Rainfall data were processed using the USDA Rainfall Intensity Summarization Tool (ARS, 2013). Discrete storms were separated by at least 6 h with <1 mm of rain (Renard *et al.*, 1997). The rainfall metrics calculated for each storm were: rainfall depth (mm); duration (h); maximum intensity (mm h⁻¹) over 5-, 15-, 30-, and 60-min intervals (MI₅, MI₁₅, MI₃₀, and MI₆₀); depths of rainfall exceeding MI₅ thresholds of 10, 15, and 20 mm h⁻¹ ($P > 10$, $P > 15$, and $P > 20$) (Kampf *et al.*, 2016); and erosivity (EI₃₀) calculated as the product of storm rainfall kinetic energy and maximum 30-min intensity (Brown and Foster, 1987).

Runoff and sediment yields

Runoff and sediment yields at each hillslope were measured with a sediment fence (cf. Robichaud and Brown, 2002) and a series of runoff collection barrels. The sediment fences were

constructed by attaching landscape fabric (Lumite®) to 7–10 pieces of metal rebar that were pounded into the ground to form a U-shape in the main channel axis of each hillslope; sediment fences were approximately 0.6 m high. Landscaping fabric was also placed over the ground surface inside each fence to provide a clear floor for removing the deposited sediment. At the downstream apex of each sediment fence we installed a sharp-crested 90° V-notch weir with the bottom of the notch approximately 0.3 m above the ground surface (Figures 2a and b). The estimated storage capacity behind each fence and below the notch of the weir was about 3 m³. When runoff exceeded this volume, excess runoff and associated sediment were directed over the weir and into a pipe that drained into the first of a series of three 250-l barrels (Figure 2c) (cf. Bonilla *et al.*, 2006).

The first and second runoff collection barrels were fitted with 15-way flow splitters (Bonilla *et al.*, 2006), with 1/15th of the flow from each of the first two barrels directed into a pipe that led into the next barrel downstream (Figure 2b). Therefore, the sampling proportions were 1/1 in barrel 1, 1/15 in barrel 2, and 1/225 in barrel 3. These proportions were used to calculate the total overtopped runoff volume (Q_v) as

$$Q_v = B1_v + (15 \times B2_v) + (225 \times B3_v) \quad (1)$$

where $B1_v$, $B2_v$, and $B3_v$ were the volumes of runoff collected in barrels 1–3, respectively. The volume in each barrel was determined using a stage–volume relationship, and the total runoff volume from Equation 1 was normalized by contributing area and reported as depth in millimeters (Q). This approach under-reports runoff by an estimated 5% because it does not account for any runoff that entered the fence but did not overtop into the barrel collection system. In contrast, sediment deposited in the barrels would cause this method to over-estimate runoff because we assumed the full barrel volume was water. The runoff ratio (RR) was calculated as Q

(mm) divided by the depth of rainfall (P , mm) for the rain storm associated with the runoff response.

If multiple rain storms occurred between site visits or if multiple rain gauges were associated with a site, the rain storm with the highest El_{30} was assigned to the runoff- and sediment-producing event (Figure 3). Although runoff and sediment yields were positively related to El_{30} (Wilson *et al.*, 2018), it is possible that one or more less-intense storms also produced runoff and sediment between site visits. However, this is unlikely as the rainfall events without a runoff or sediment response did not exceed the MI_{60} thresholds previously identified to generate runoff and sediment in summer 2014 in the High Park Fire (Wilson *et al.*, 2018).

The sediment measured in this study consisted of the sediment that was deposited behind the fence and the sediment that overtopped the fence and was captured in the collection barrels (Figure 2). To determine the overtopped sediment yield (OS), the suspended sediment concentration (SSC, mg l⁻¹) of the runoff in each barrel was measured by stirring the water in the barrel and collecting approximately 500 ml of the water by either a grab sample or a DH-48 depth-integrating sampler mounted on a 0.9 m wading rod (Federal Interagency Sedimentation Project; <https://water.usgs.gov/fisp/products/4101002.html>). The mass of sediment within each sample was determined by wet sieving and filtration (ASTM D3977-97 Test Method C; ASTM Standard D3977-97, 2013), and the overtopped sediment load (mg) was calculated as

$$\text{Overtopped sediment load} = \sum_{B=1}^3 SSC_B \times Q_B \quad (2)$$

where SSC_B and Q_B are the SSC (mg l⁻¹) and Q_v (l) in each barrel (B) [Equation 1]. The overtopped sediment yields (OS) for each storm and site were divided by the contributing area and reported in megagrams per hectare.

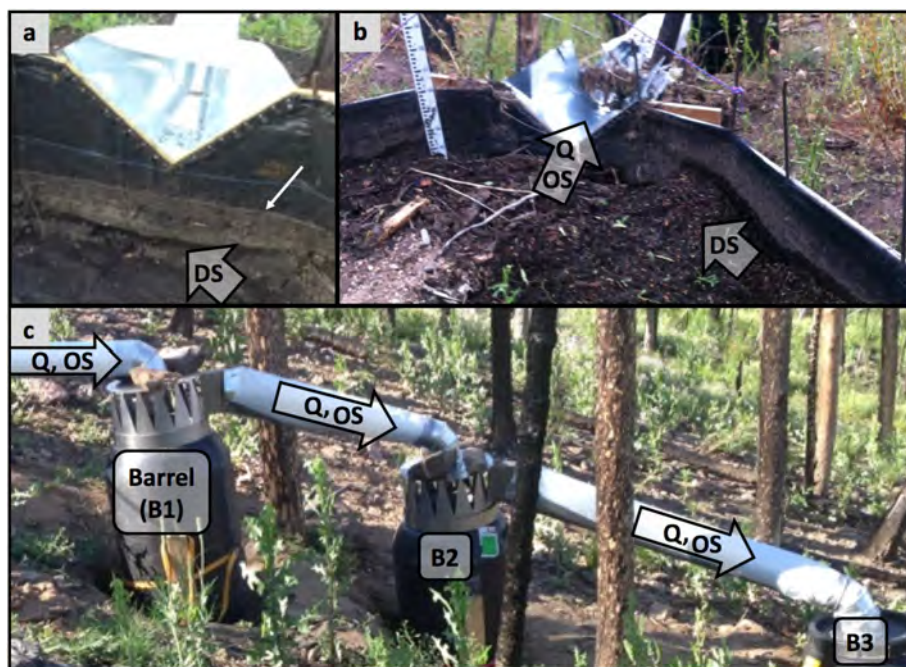


FIGURE 2. Photos of a hillslope runoff and sediment collection site showing: (a) downslope view of a sediment fence containing deposited sediment (DS) produced by a storm at HG4 on 7 July that did not result in any overtopped runoff or sediment in any of the downstream barrels; the white arrow points to the high-water mark below the V-notch weir; (b) downslope view of a sediment fence in the foreground with deposited sediment (DS); the 90° V-notch weir routed runoff (Q) and overtopped sediment (OS) into a series of three collection barrels; (c) side view of the barrel collection system – the first two barrels (B1 and B2) were equipped with flow splitters that each sent 1/15th of the runoff into the next barrel downslope. [Colour figure can be viewed at wileyonlinelibrary.com]

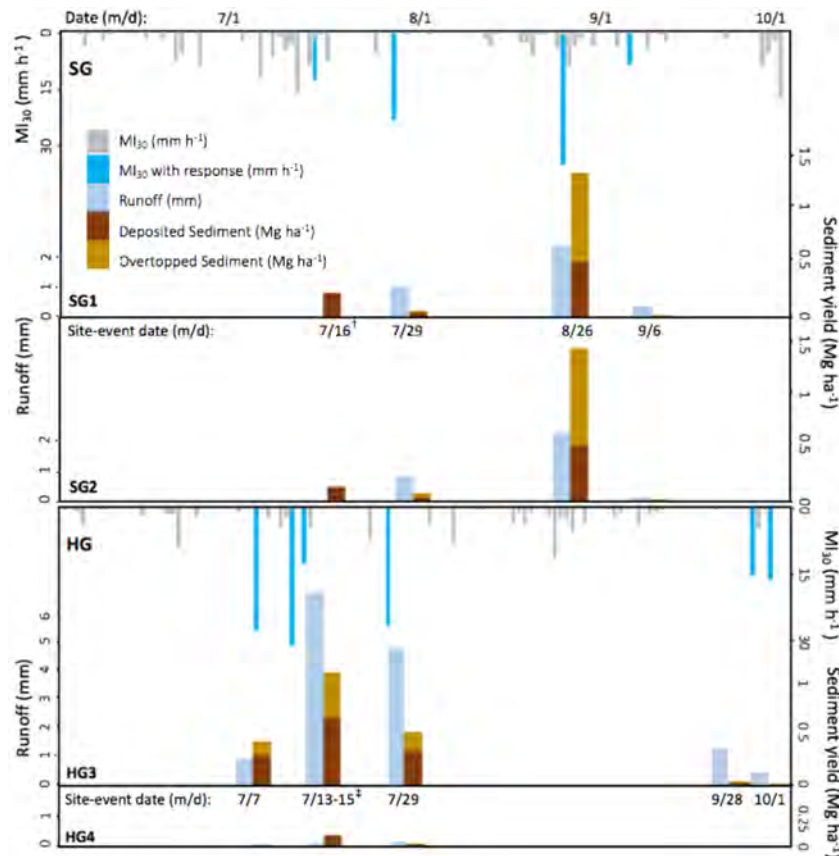


FIGURE 3. June–October 2014 rainfall intensities (MI_{30} , mm h^{-1}), event runoff, and event sediment yields for the hillslopes in Skin Gulch (SG1 and SG2) and Hill Gulch (HG3 and HG4). Only one rainfall value is shown for each pair of hillslopes as they shared a rain gauge; note the differences in rainfall and event timing in the two watersheds. [†] indicates that the 7/16 event occurred before the runoff collection equipment was installed at SG; [‡] indicates that the runoff and sediment resulted from a combination of two rainstorms. [Colour figure can be viewed at wileyonlinelibrary.com]

The mass of deposited sediment was measured by shovelling the sediment deposited behind the fence into 20 l buckets and weighing these in the field to the closest 0.5 kg using a hanging scale. Each time a sediment fence was emptied, a representative grab sample of approximately 0.5 kg of the deposited sediment was collected and stored in a sealed 0.65 l plastic bag until gravimetric water content could be determined (ASTM D2974-13 Test Method A; ASTM Standard D2974-13, 2013). Water content was used to adjust the mass of wet sediment measured in the field to a dry mass. For each event the dry mass was divided by the contributing area to produce the deposited sediment yield (DS) in megagrams per hectare. The total sediment yield (TS, Mg ha^{-1}) was calculated as the sum of OS and DS, and the total sediment concentration (TSC, g l^{-1}) was calculated as TS divided by Q_v .

The separation of eroded sediment into DS and OS allowed us to compute the catch efficiency of each sediment fence as the ratio of DS to TS. If runoff from one or more rain storms did not overtop the sediment fence, DS was equal to TS and the catch efficiency was 1. Catch efficiency was calculated by site for each sediment collection event and across the entire sampling season.

Soil texture and particle sorting

The soil texture for each hillslope was determined from three aggregated soil samples of about 60–100 g collected at a depth of 0–5 cm in the summer when each fence was installed. Percentage sand, silt/clay, and organic matter were determined using either sieving and the hydrometer method (Gee and Orr, 2002; Schmeer, 2014), or wet sieving and filtration (ASTM

D3977-97 Test Method C; ASTM Standard D3977-97, 2013). Hillslope soils were loamy sand at all sites except for HG4, where the soils were classified as a sandy loam.

The DS and sediment in each barrel were analysed to determine the coarse ($>53 \mu\text{m}$ in diameter) and fine ($<53 \mu\text{m}$ in diameter) mineral and organic matter fractions. Samples were separated into coarse and fine fractions using wet sieving and filtration (ASTM D3977-97 Test Method C; ASTM Standard D3977-97, 2013). The percentage organic matter was determined by combusting each sample at 400°C for at least 1 h (ASTM D2974-13 Test Method C; ASTM Standard D2974-13, 2013). The sum of all particles and just the mineral fraction allowed us to respectively calculate total catch efficiency (i.e. minerals and organic matter) and mineral catch efficiency.

Enrichment ratios (ER) were calculated to indicate how the collected mineral sediment compared to the hillslope soil textures. The ER is defined as the fraction of coarse (i.e. sand) or fine (i.e. silt/clay) particles within DS, OS, or TS divided by the corresponding sand or silt/clay fraction of the surface soil in the contributing area for each site (Wan and El-Swaify, 1998). ER values greater than 1 indicate enrichment of the particle size in the sediment collection system relative to the hillslope soils, while ER values less than 1 indicate depletion (Wan and El-Swaify, 1998).

Controls on catch efficiency and particle sorting

The effects of different variables on catch efficiency (CE) and enrichment ratios (ER) were assessed by computing Pearson correlations between the dependent variables of CE and ER and the rainfall metrics, sample location (DS and OS in barrels

1–3), day of the year, and production variables (i.e. Q , DS, OS, TS, RR, and TSC). We also explored correlations between the rainfall metrics and each production variable to further understand how different rainfall-runoff events affected CE and ER. Analysis of variance (ANOVA) was used to assess differences in production variables and CE by rainfall-runoff event and site, and ER by sample type (DS or OS averaged across barrels). All analyses were conducted in JMP Version 13 (JMP, 2016), with variables being transformed to natural logarithms to normalize distributions when needed. The significance level for all analyses was set at $p \leq 0.05$.

Runoff modelling and sediment fence volume

During the period of study there were two to five moderate storms that overtopped the sediment fences at the different sites, but no storm caused all three collection barrels to overtop. To determine how large the collection system would need to be for more extreme storms, we calibrated HYDRUS-1D Version 4.17 (Šimunek *et al.*, 2019) to produce runoff depths that matched the measured values. We assumed uniform soils with loamy sand water retention parameters and an initial volumetric water content of 0.2. The upper boundary of the model domain was an atmospheric boundary condition, which allows for the input of time-varying precipitation and the generation of infiltration-excess overland flow. The lower boundary condition was free drainage at a depth of 1 m. We calibrated the simulations by modifying the saturated hydraulic conductivity (K_s) for each 2014 rainfall-runoff event. These simulations were forced with 5-min rainfall from each observed event, and K_s was modified to produce simulated runoff depths that matched those observed. We then used the calibrated K_s values to develop a series of hypothetical runoff simulations for 2- to 100-year storms with durations in the range of those observed (i.e. 0.5–2 h) using rainfall from a nearby NOAA Atlas Station (Site 05-6925).

Results

Rainfall, runoff, and erosion

The number of rain storms, total rainfall, and rainfall intensities between June and October 2014 were similar for Skin Gulch and Hill Gulch. There were 44 storms in Skin Gulch totalling 310 mm of rain, and 46 storms in Hill Gulch totalling 267 mm of rain (Figure 3). Maximum storm rainfall was 76 mm in Skin Gulch ($\bar{x} = 7$; $s = 12$) and 81 mm in Hill Gulch ($\bar{x} = 6$; $s = 12$). MI_{30} was slightly higher in Skin Gulch with a maximum of 36 mm h^{-1} on 29 July ($\bar{x} = 6$; $s = 7$), while the maximum MI_{30} in Hill Gulch was 32 mm h^{-1} on 13 July ($\bar{x} = 5$; $s = 7$) (Figure 3). The highest MI_{30} values exceeded the estimated 2-year storm value of 29 mm h^{-1} .

Four storms in Skin Gulch and six storms in Hill Gulch delivered runoff and sediment into one or both of the sediment fences (Figure 3). The four storms in Skin Gulch generated relatively similar responses from both hillslopes, but there are no data on overtopping for the first storm because the runoff collection barrels had not yet been installed (Table 2; Figure 3). In contrast to Skin Gulch, the two sites in Hill Gulch had quite different responses: in HG3 six rain storms generated large amounts of runoff and erosion, while in HG4 just four rain storms generated much smaller amounts of runoff and erosion (Table 2; Figures 2 and 3).

Runoff was highest at HG3 with a maximum of 6.7 mm and an average of 2.9 mm ($s = 2.9$), followed by the Skin Gulch sites

with a maximum runoff depth of 2.4 mm and an average of 1.1 mm ($s = 1.0$) (Table 2; Figure 3). Runoff was lowest at HG4 where the maximum value was just 0.3 mm, and the average was only 0.2 mm ($s = 0.1$). Runoff ratios were highest at HG3 (0.03–0.24; $\bar{x} = 0.1$; $s = 0.09$), comparatively similar for the two sites and different storms in Skin Gulch (0.01–0.07; $\bar{x} = 0.04$; $s = 0.03$), and significantly lower at HG4 (0.004–0.005; $\bar{x} = 0.005$; $s = 0.0007$) (ANOVA; $p = 0.02$, 12 d.f., F-ratio = 5.4) (Table 2; Figure 3). In addition to having the most runoff, HG3 also had the highest DS with a maximum and average of 0.64 and 0.26 Mg ha^{-1} , respectively (Table 2; Figure 3). The two Skin Gulch sites generated slightly less DS than HG3 with a mean value of 0.21 Mg ha^{-1} . HG4 had the lowest DS with a mean of only 0.05 Mg ha^{-1} . OS was highest for the Skin Gulch sites with maxima of 0.95–0.96 Mg ha^{-1} generated during the storm with the highest MI_{30} (36 mm h^{-1} ; Table 2).

Catch efficiency and particle sorting

For the two sites in SG the total catch efficiency (i.e. both minerals and organic matter) ranged from 36 to 75% ($\bar{x} = 56$; $s = 17$), and in HG3 the range was relatively similar at 28 to 67% ($\bar{x} = 53$; $s = 16$) (Table 2). In contrast, the total catch efficiency was 86 to 100% in HG4 ($\bar{x} = 95$; $s = 8$), and these values were significantly higher than any of the other three sites (ANOVA; $p = 0.001$, 13 d.f., F-ratio = 17.9). The much higher catch efficiency in HG4 corresponded to much smaller amounts of runoff allowing for longer settling times. Mineral catch efficiencies were slightly higher than total catch efficiencies (Table 2).

The total sediment load had similar percentages of sand and silt/clay relative to the hillslope soils, but there was a marked sorting by particle size through the collection system. The sediment behind the fence was significantly enriched in sand, whereas the sediment that overtopped the fence was significantly enriched in silt/clay (Tables 2 and 3). The enrichment ratios for sand in the deposited sediment were significantly higher than in the overtopped sediment (ANOVA; $p = 0.0004$, 25 d.f., F-ratio = 16.7), while the enrichment ratios for silt/clay were significantly higher for the overtopped sediment than the deposited sediment (ANOVA; $p = 0.01$, 25 d.f., F-ratio = 8). There were no clear temporal trends in enrichment ratios over the monitoring period ($r = 0.02$ –0.20).

Significant particle sorting was also evident with sample location along the collection system (i.e. sediment deposited behind the fence through collection barrels 1–3) (Figure S2). The percentage of sand was highest in the sediment deposited behind the fence, ranging from 45 to 83%. The proportions of sand and total minerals decreased significantly from the fence through the collection barrels ($r = -0.51$ and -0.33 , respectively; Figure S2), while the amounts of silt/clay, total OM, and fine OM increased significantly at each subsequent sampling location through the collection system ($r = 0.33$ –0.49; Figure S2).

Controls on catch efficiency and particle sorting

Catch efficiency was not significantly related to any rainfall metrics, but it did decrease with greater runoff ratios ($r = -0.62$; Table 3). Catch efficiency decreased with increasing drainage area between 0.19 and 0.43 ha, particularly for events with higher runoff ratios, although our sample size and range of drainage areas were relatively small. Catch efficiency also decreased with increasing percentage bare soil and was highest for the site with the smallest area and highest width-to-length ratio (HG4; Figure 1).

Table 2. Runoff and sediment production (includes mineral and organic matter) by site and date with maximum 30-min rainfall intensity (MI_{30}), runoff (Q), deposited sediment yield (DS), overtopped sediment yield (OS), total sediment yield (TS), runoff ratio (RR), total sediment concentration (TSC), total catch efficiency (CE) with mineral CE in parentheses, and enrichment ratios (ER) for sand with silt/clay in parentheses for the DS, OS and TS. – indicates no data; * indicates that the runoff and sediment resulted from a combination of two rain storms. Note that the CE values are calculated from more precise data than can be presented here.

Site	Date (m/d)	MI_{30} (mm h ⁻¹)	Q (mm)	DS (Mg ha ⁻¹)	OS (Mg ha ⁻¹)	TS (Mg ha ⁻¹)	RR (Q/P)	TSC (g l ⁻¹)	CE (%)	ER-DS	ER-OS	ER-TS
SG1	7/16	13	–	0.24	–	0.24	–	–	–	–	–	–
	7/29	24	0.92	0.05	0.02	0.07	0.01	7	74 (76)	0.8 (1.8)	0.4 (3.5)	0.7 (1.8)
	8/26	36	2.44	0.59	0.96	1.55	0.07	64	38 (42)	1.1 (0.5)	0.9 (1.3)	1.0 (0.9)
	9/6	10	0.31	0.02	0.01	0.03	0.06	11	57 (59)	1.0 (1.1)	0.4 (3.4)	1.0 (1.2)
	7/16	13	–	0.15	–	0.15	–	–	–	–	–	–
SG2	7/29	24	0.71	0.05	0.04	0.09	0.01	12	58 (56)	0.9 (1.4)	0.2 (4.0)	0.8 (1.7)
	8/26	36	2.05	0.54	0.95	1.49	0.06	73	36 (39)	1.1 (0.5)	0.9 (1.4)	1.1 (0.8)
	9/6	10	0.08	0.01	0.003	0.013	0.02	17	75 (77)	0.9 (1.2)	0.2 (4.0)	0.9 (1.2)
	7/7	28	0.95	0.28	0.14	0.42	0.05	44	67 (68)	1.0 (0.9)	0.9 (1.2)	1.0 (1.0)
	7/13*	32	6.71	0.64	0.42	1.06	0.24	16	60 (63)	1.1 (0.5)	1 (1.1)	1.1 (0.6)
HG3	7/29	27	5.14	0.32	0.18	0.50	0.06	10	64 (66)	1.2 (0.5)	0.9 (1.5)	1.1 (0.6)
	9/28	16	1.16	0.02	0.03	0.05	0.12	4	44 (48)	1.0 (1.0)	0.6 (2.2)	1.0 (1.1)
	10/1	17	0.38	0.004	0.01	0.01	0.03	4	28 (26)	1.1 (0.7)	1.2 (0.3)	1.1 (0.6)
	7/7	28	–	0.02	–	0.02	–	–	100 (100)	–	–	–
	7/13*	32	0.13	0.10	0.001	0.10	0.005	79	99 (99)	1.1 (0.7)	0.9 (1.2)	1.1 (0.7)
HG4	7/29	27	0.32	0.03	0.01	0.04	0.004	11	86 (87)	1.1 (0.7)	0.5 (2.0)	1.1 (0.8)

Overall, sediment yields increased with rainfall intensity for rain storms with the highest MI_{30} ($r = 0.57$ – 0.60 , respectively; Table 3; Figure 4), particularly for the large storms on 26 August in Skin Gulch and the double storm on 13–15 July at HG3 (Table 2; Figure 4). The deposited sediment yield was more strongly correlated with maximum 5-min intensities ($r = 0.73$) than the maximum 15- and 30-min intensities (Table 3; Figure 4).

The nature of particle sorting from hillslopes to sediment fences varied by sample location (i.e. DS vs. OS) and rain storm characteristics. Enrichment ratios for both DS and OS were correlated with rainfall intensity, with higher-intensity rainfall events producing sediment more enriched in sand ($r = 0.48$ – 0.51 ; Table 4). For DS, enrichment ratios for sand also increased with the depth of rainfall exceeding an MI_5 threshold of 10 mm h^{-1} (i.e. $P > 10$; $r = 0.48$) and greater runoff depths (Table 4; $r = 0.38$). For OS, higher ER for sand was correlated with higher maximum 30-min intensities ($r = 0.51$) and total sediment loads (Table 4; $r = 0.48$).

Runoff modelling and sediment fence volumes

We found that simulating observed Q (mm) in HYDRUS-1D required K_s values from 2.5 to 29 mm h^{-1} ($\bar{x} = 14$). Rainfall depths for 2- to 100-year storms with durations in the range of those observed (0.5–2 h) were 14–61 mm with corresponding intensities of 11–84 mm h^{-1} ($\bar{x} = 40$; $s = 22$). Simulations with these combinations of K_s and rainfall resulted in predicted Q depths of 0.3–56 mm (Figure 5). In some instances, when the rainfall intensities were lower than K_s , the model could not converge, and no Q values could be calculated. Assuming similarly sized hillslopes as those monitored here (i.e. 0.19–0.43 ha), simulated runoff for these hypothetical storms would require sediment fence volumes from 1 up to 110 and 240 m^3 , respectively. This is the theoretical range of volumes needed to capture only the runoff, excluding the eroded sediment. For our study hillslopes, inclusion of the runoff collection barrels and flow splitters allowed us to collect a representative sample for 63 m^3 : 3 m^3 stored behind the fence and an additional 60 m^3 from the barrels (including the split overflow volume). This collection system volume was adequate for the 3–24 m^3 ($\bar{x} = 9$; $s = 6.7$) of runoff we measured from rain storms with return intervals up to 2 years. The model results indicate that the collection system would have been under-sized for lower-frequency rainfall events, hillslopes with lower infiltration capacities, or hillslopes with larger contributing areas.

Discussion

Catch efficiency and sediment fence sizing

Our findings indicate that the sediment fences at our monitoring sites would have underestimated sediment production by roughly a factor of two if they had not been modified to capture the runoff and sediment overtopping the fence. Sediment fences very similar to those used in our study have been used to monitor post-fire erosion at sites averaging 0.2–0.3 ha following the Bobcat, Hayman, and High Park fires (Benavides-Solorio and MacDonald, 2005; Wagenbrenner *et al.*, 2006; Schmeer *et al.*, 2018). For sites smaller than 0.01 ha, catch efficiencies of up to 90% have been reported (Robichaud *et al.*, 2001). At the other extreme, sediment fences have been used to monitor post-fire erosion from sites of up to 1.5 ha, but these larger contributing areas typically have used a different design to provide for much larger storage capacities (e.g.

Table 3. Pearson correlation coefficients between rain storm metrics and runoff (Q), deposited sediment yields (DS, Mg ha^{-1}), overtopped sediment yields (OS, Mg ha^{-1}), total sediment yield (TS, Mg ha^{-1}), runoff ratios (RR, Q/P), total sediment concentration (TSC, g l^{-1}), and total catch efficiency (CE). Lower portion of table shows the cross-correlations among the response variables. Sample size is 16 for deposited sediment yields and 13 for all other variables. The natural logarithm (log) was used to transform all response data except CE to achieve normality. Values in bold are significant at $p \leq 0.05$.

	Log [Q]	Log [DS]	Log [OS]	Log [TS]	Log [RR]	Log [TSC]	CE
P (mm)	0.30	0.17	0.09	0.16	−0.40	−0.12	0.28
Rainfall duration (h)	0.15	0.00	−0.07	−0.08	−0.46	−0.33	0.29
MI ₅ (mm h^{-1})	0.51	0.72	0.61	0.83	0.28	0.72	−0.13
MI ₁₅ (mm h^{-1})	0.47	0.66	0.53	0.82	0.19	0.75	−0.03
MI ₃₀ (mm h^{-1})	0.56	0.60	0.57	0.85	0.09	0.67	0.00
MI ₆₀ (mm h^{-1})	0.53	0.33	0.41	0.59	−0.14	0.29	0.14
El ₃₀ (MJ $\text{mm ha}^{-1} \text{h}^{-1}$)	0.48	0.42	0.43	0.54	−0.19	0.27	0.06
$P > 10$ (mm)	0.56	0.54	0.58	0.71	0.02	0.46	−0.08
$P > 15$ (mm)	0.54	0.61	0.65	0.82	0.09	0.65	−0.13
$P > 20$ (mm)	0.53	0.62	0.65	0.85	0.11	0.73	−0.12
Log [DS]	0.73						
Log [OS]	0.87	0.77					
Log [TS]	0.79	0.97	0.86				
Log [RR]	0.71	0.44	0.74	0.54			
Log [TSC]	0.03	0.67	0.30	0.63	−0.02		
CE	−0.44	0.00	−0.62	−0.24	−0.62	0.17	

Robichaud *et al.*, 2013b; James and Krumland, 2018) or multiple sediment fences in a series (Benavides-Solorio and MacDonald, 2005; Wagenbrenner *et al.*, 2006; Robichaud *et al.*, 2019). In this study, we observed a decline in catch efficiency as the drainage area increased from 0.19 to 0.43 ha; the site with the smallest drainage area, HG4, was the only site with catch efficiency $>90\%$.

Predominantly single-sediment fences were used in the High Park Fire because many of the contributing areas were relatively small, but a number of these fences were still overtopped in the first two summers after burning when there was an exceptionally large storm or multiple storms in quick succession (Schmeer *et al.*, 2018). In contrast, the sediment yields we measured in summer 2014 were much smaller, and the volume of DS never came close to the bottom of the 90° V-notch weirs. Assuming a dry bulk density of 1.1 Mg m^{-3} , the maximum volume of deposited sediment was 0.2 m^3 , or less than 10% of the estimated total available storage capacity behind the sediment fence. Even though sediment did not fill the fence, catch efficiencies were still low because of the suspended sediment carried over a fence by water.

For a given fence, the sediment catch efficiency will vary with the rate and total volume of incoming flow and sediment, whether there is any sediment or water already present in the fence, and the particle size distribution of the incoming sediment. A key factor for the CE of sediment fences is the duration the incoming water is stored behind the fence in order to allow the incoming particles to settle out. If inflow rates are low and there is no overtopping of the sediment fence by runoff, the catch efficiency will approach 100% (Robichaud and Brown, 2002). In contrast, if inflow rates are rapid and/or the available storage capacity is small, many more particles will overtop the fence. If the water behind the fence is not flowing, Stoke's law indicates that coarse sand would settle out below the weir in less than 1 s, fine sand in less than 2 min, and coarse silt in 2.2 min. However, for finer particles the settling time becomes substantially larger, approaching 24 h for fine silt. We did not have data recording the timing of runoff response for the storms presented in this study, but in 2015 we captured data for a 26 mm rain storm (Wilson, 2019). During this storm the fence filled for 7 min before beginning to overtop, and overtopping flow lasted for 22 min. These time intervals would have been long

enough for settling of coarse silt and sand, but fine silt and smaller particles would most likely have overtopped. Extending this logic to other collection systems, the catch efficiency is likely to be higher for sites with greater fractions of coarse sediments, lower runoff generation, and higher sediment fence capacities.

The modelling approach we used to estimate the required sediment fence capacities is a simplified first-order estimate of required capacities for large storms. The modelling approach represents infiltration-excess overland flow generation for a one-dimensional soil column rather than a spatially variable hillslope, and we used hypothetical storm depths and durations rather than actual time series of rainfall. Even though this spatial and temporal variability has a large influence on runoff generation (Ebel *et al.*, 2016), the simplified approach allowed us to estimate reasonable ranges of post-fire soil hydraulic conductivity, which is a key variable influencing runoff generation. Although K_s and infiltration rates can be substantially reduced by wildfire (e.g. Martin and Moody, 2001), the K_s values we obtained from calibration ($2.5\text{--}29 \text{ mm h}^{-1}$) are within the range estimated from the soil survey for these sites ($1.5\text{--}51 \text{ mm h}^{-1}$) (Soil Survey Staff, 2019), suggesting the K_s may have mostly recovered to pre-burn values. Recovery times for K_s after wildfire can vary from less than a year to over 30 years, but most sites recover in 2–7 years (Ebel and Martin, 2017). Assuming K_s was even lower during the first 2 years after fire at our study sites, the required capacity of the runoff and sediment collection systems would have needed to be greater than our model estimates.

Multiple strategies can be used to increase sediment fence catch efficiency. Collection capacity can be expanded, contributing area reduced, and field visit times can be scheduled as frequently as possible to keep collection capacity high. However, the need to quickly empty out sediment fences becomes increasingly problematic when there are a relatively large number of sediment fences and when storms come in quick succession. Continuous telemetered monitoring of runoff and sediment levels (e.g. Robichaud *et al.*, 2013b) is costlier but allows for more efficient prioritization of which sediment fences need emptying. Real-time rainfall data can also help determine when a given sediment fence is likely to need emptying using estimated thresholds for erosion-producing storms (Wilson *et al.*, 2018).

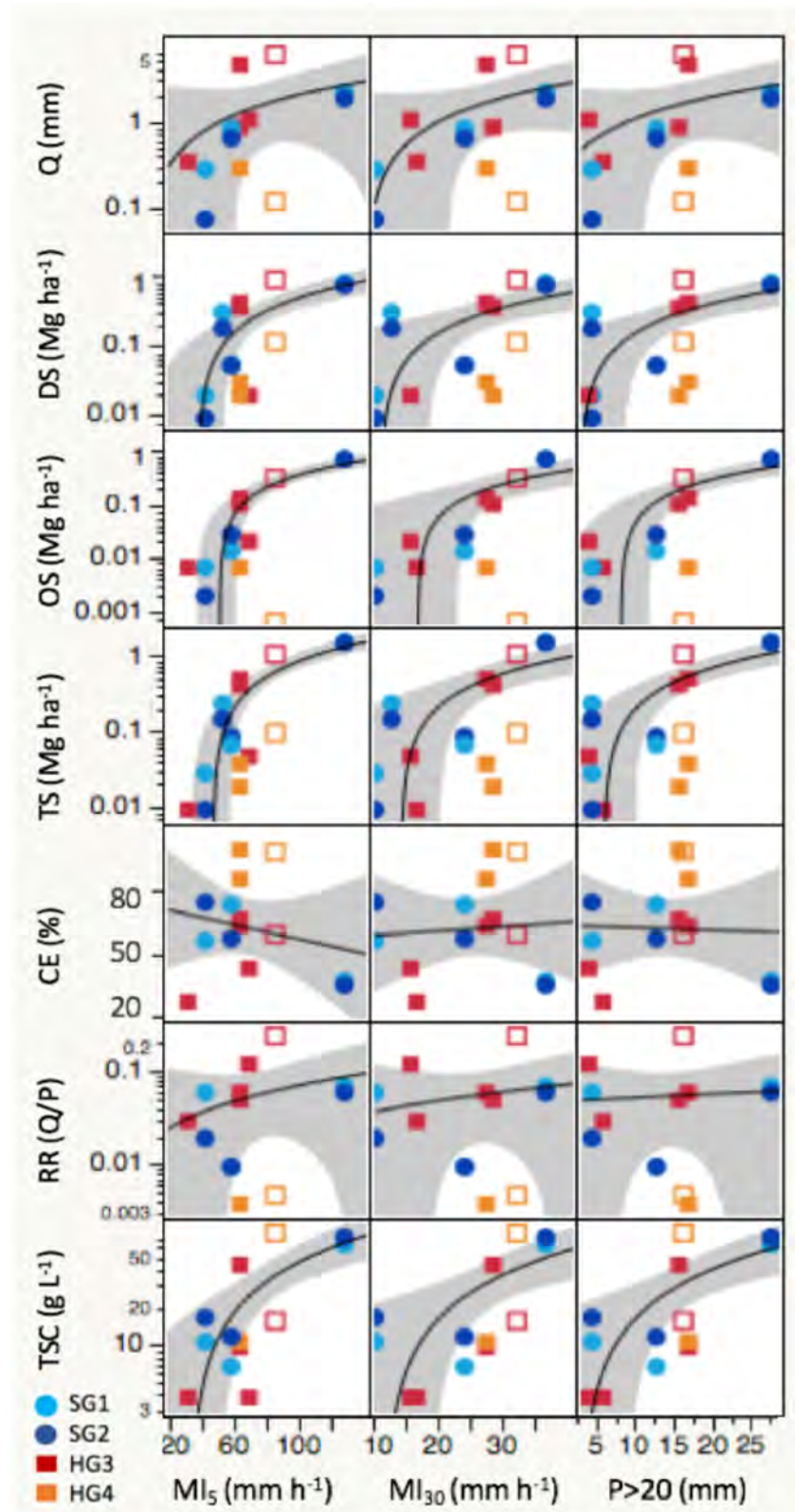


FIGURE 4. Runoff (Q), deposited sediment yield (DS), overtopped sediment yield (OS), total sediment yield (TS), total catch efficiency (CE), runoff ratio (RR), and total sediment concentration (TSC) vs. maximum 5- and 30-min rainfall intensities (MI_5 , MI_{30}) and $P > 20$ for all sites and storms that generated measurable runoff and sediment. Open symbols for HG3 and HG4 are data points that represent two rainfall events over 13–15 July. The shaded areas represent the 95% confidence interval for each regression line. [Colour figure can be viewed at wileyonlinelibrary.com]

Particle sorting

Soil detachment and transport on hillslopes is highly dependent on particle size, with larger particles being more resistant to detachment and more likely to settle out during transport, whereas smaller particles are preferentially detached and

transported downslope (Parsons *et al.*, 2006). Rainfall intensity is one of the most critical controls on the size and number of soil particles being eroded and transported, as higher-intensity rainfall events tend to have larger raindrops with higher velocities and hence much more kinetic energy to detach larger soil particles (Morgan, 2009). Shallow overland flow can provide

Table 4. Pearson correlation coefficients relating enrichment ratios (ER) for sand and silt/clay within deposited sediment (DS) and overtopped sediment (OS) to rainfall metrics, and Q (mm) deposited sediment yields (DS, Mg ha^{-1}), overtopped sediment yields (OS, Mg ha^{-1}), total sediment yields (TS, Mg ha^{-1}), runoff ratio (RR, Q/P), total sediment concentration (TSC, g l^{-1}), total catch efficiency (CE), and day of year. Most production variables were transformed to natural logarithms (log) to achieve normality. Bold text indicates significance at $p \leq 0.05$.

	ER-DS		ER-OS		ER-TS	
	Sand	Silt/clay	Sand	Silt/clay	Sand	Silt/clay
P (mm)	-0.02	0.17	-0.21	0.17	-0.19	0.24
Rainfall duration (h)	-0.18	0.35	-0.39	0.36	-0.33	0.37
MI_5 (mm h^{-1})	0.38	-0.52	0.37	-0.38	0.23	-0.22
MI_{15} (mm h^{-1})	0.30	-0.43	0.46	-0.45	0.20	-0.20
MI_{30} (mm h^{-1})	0.45	-0.52	0.51	-0.54	0.31	-0.29
MI_{60} (mm h^{-1})	0.31	-0.27	0.32	-0.38	0.15	-0.12
El_{30} ($\text{MJ mm ha}^{-1} \text{ h}^{-1}$)	0.24	-0.18	0.05	-0.09	0.00	0.04
$P > 10$ (mm)	0.48	-0.48	0.30	-0.36	0.25	-0.23
$P > 15$ (mm)	0.46	-0.52	0.36	-0.39	0.24	-0.23
$P > 20$ (mm)	0.43	-0.52	0.40	-0.42	0.24	-0.23
Log $[Q]$	0.38	-0.39	0.45	-0.39	0.14	-0.23
Log $[DS]$	0.39	-0.48	0.40	-0.36	0.19	-0.22
Log $[OS]$	0.30	-0.41	0.39	-0.32	0.05	-0.15
Log $[TS]$	0.43	-0.53	0.48	-0.44	0.21	-0.26
Log $[RR]$	0.30	-0.40	0.43	-0.32	0.19	-0.31
Log $[TSC]$	0.23	-0.38	0.22	-0.22	0.16	-0.14
CE	-0.19	0.26	-0.37	0.28	-0.03	0.14
Day of year	-0.03	0.01	-0.03	0.05	0.00	-0.04

some protection from rainsplash erosion and may not have enough shear stress to detach more than ash and fine particles, but this overland flow is able to transport fine particles down-slope (Wan and El-Swaify, 1998; Shi *et al.*, 2012). As rainfall intensities and infiltration-excess overland flow increase, the deeper and faster runoff will have greater detachment and transport capacity (Bagnold, 1977; Wan and El-Swaify, 1998; Shi *et al.*, 2012). In cases where the surface runoff is

concentrated into rills or other channels, the increasing flow depth and velocity can detach and transport progressively larger particles (Wan and El-Swaify, 1998).

Our results are consistent with this sequence of processes as we found that enrichment ratios for sand increased with higher rainfall intensities (Tables 2 and 4). Enrichment ratios were not significantly correlated with the day of year, which indicates no change or limitation in hillslope sediment supply. Across all sites and sample types, enrichment ratios averaged 1.5 for silt/clay and only 0.9 for sand, which indicates that rainsplash and sheetwash were the predominant erosion processes rather than rill erosion (Sutherland, 1991; Wan and El-Swaify, 1998). In the High Park Fire, post-fire regrowth led to a rapid decrease in post-fire drainage densities (Wohl and Scott, 2017), suggesting that rilling ceased to be an important erosion process several years after burning (Robichaud *et al.*, 2020).

The particle sorting observed along our collection system highlights how the particle size distributions of sediment change during transport (Figure S2). The sediment that overtopped the fence was more enriched in finer mineral particles and organic matter than the hillslope soils. Our sediment collection system modified the natural sediment transport regime by causing water to pond where it would otherwise have flowed downhill, and the 'deposited' and 'overtopped' sediment yield values given here are specific to the collection system. Although our collection system did not measure transport beyond the study hillslopes, natural flow paths will likely also sort sediments, with finer particles much more likely to be delivered further downstream than sand or larger particles.

Conclusions

We modified hillslope sediment fences to measure runoff volumes and capture the amount and types of sediment that overtopped sediment fences on four severely burned hillslopes, 2 years after the High Park Fire in north central Colorado. Total- and mineral-sediment fence catch efficiency averaged 63–65%, respectively, which means that in some cases nearly as much sediment overtopped the sediment fence as was deposited behind the fences. This indicates that the sediment fences

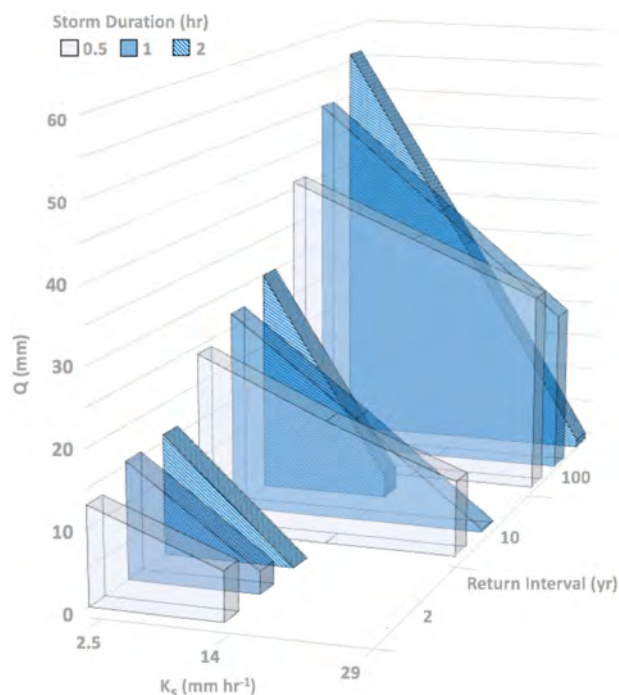


FIGURE 5. Runoff depths (Q) from HYDRUS-1D for storms with return intervals of 2, 10, and 100 years from nearby NOAA Atlas Station (Site 05-6925) across the range of saturated hydraulic conductivity (K_s) needed to simulate observed runoff. Storm durations of 0.5–2 h match those observed in 2014. Missing results for some of the high- K_s scenarios indicate that the model did not converge due to rainfall less than K_s . [Colour figure can be viewed at wileyonlinelibrary.com]

substantially underestimated sediment yields without the addition of the runoff and suspended sediment collection system. Higher rainfall intensities increased not only runoff and sediment yields, but also resulted in more erosion and transport of coarser particles. These intense rainfall events with high runoff production are most likely to cause overtopping of sediment fences, with fine sediments more readily carried over the top. In these cases, the size fractions of sediment collected behind a fence may not be indicative of the full range of sediment sizes eroded.

Our results indicate that sediment production will be most accurately measured from plots or smaller hillslopes where overtopping can be eliminated, or at least reduced. In more heterogeneous situations, such as post-fire salvage logging, there is a clear need to accurately measure erosion from larger hillslopes. For more accurate measurements of sediment yields researchers should consider installing larger or multiple sediment fences in a series, adjusting the location of sediment fences in accordance with the predicted runoff volumes, and increasing the storage capacity behind the sediment fence, particularly for sites with high fractions of fine sediments in the soil. Researchers should also consider modifying sediment fences to allow for the measurement of the runoff and sediment that overtops the sediment fence. In the absence of such measurements, reported sediment yields using sediment fences may be substantially underestimated.

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Conflict of Interest

No conflict of interest has been declared by the authors.

Data Availability Statement

The data supporting the findings of this study are available within the paper and its supplementary materials.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Surface cover in August 2014 for each hillslope in Skin Gulch (SG1 and SG2) and Hill Gulch (HG3 and HG4).

Figure S2. Percentage sand, silt/clay and organic matter (OM) for the sediment deposited behind the fence (DS) and the overtopped sediment collected in barrels 1 (B1), 2 (B2), and 3 (B3) for each sediment-producing event at each site during the study period of 2014. Sand is defined as the mineral fraction $>53\ \mu\text{m}$ and silt/clay is the mineral fraction $\leq 53\ \mu\text{m}$.