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Rainfall thresholds for post-fire runoff and sediment delivery from plot to watershed scales

Codie Wilson[a,*], Stephanie K. Kampf[b], Joseph W. Wagenbrenner[c], Lee H. MacDonald[d]

[a] Department of Geosciences, 1482 Campus Delivery, Colorado State University, Fort Collins, CO 80523-1482, United States
[b] Department of Ecosystem Science and Sustainability, 1476 Campus Delivery, Colorado State University, Fort Collins, CO 80523-1476, United States
[c] USDA Forest Service, Pacific Southwest Research Station, Arcata, CA 95521, United States
[d] Natural Resource Ecology Laboratory, 1499 Campus Delivery, Colorado State University, Fort Collins, CO 80523-1499, United States

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ABSTRACT

Wildfire increases the likelihood of runoff, erosion, and downstream sedimentation in many of the watersheds that supply water for Colorado's Front Range communities. The objectives of this study were to: (1) identify rainfall intensity thresholds for a post-fire runoff or sediment delivery response at plots ($\leq$0.06 ha), hillslopes (0.07–5.2 ha) and watersheds (100–1500 ha) after three Colorado Front Range wildfires for up to four years post-fire; (2) determine how the rainfall thresholds varied by fire location, year post-fire, spatial scale, and mulch treatments; and (3) use long-term rainfall data to map the likely frequency of rainfall events above these intensity thresholds as an indicator of risk for post-fire runoff or sediment delivery from future high severity fires in Colorado. Maximum 60-min rainfall intensity (MI_{60}) thresholds were identified as the values that best separated rain storms that generated responses from those that did not. We found that thresholds did not significantly differ among fires for any year post-fire. Thresholds did significantly vary among spatial scales; for the first two years post-fire, high-confidence thresholds ranged from 4 to 8 mm h^{-1} across unmulched plots, hillslopes and watersheds. Compared to post-fire year 0, thresholds in year 3 were significantly higher, with high-confidence thresholds up to 22 mm h^{-1}. NOAA Atlas rainfall data were used to compute and map frequencies of threshold exceedance across Colorado. Within the Front Range study area, rain storms with MI_{60} of 4 mm h^{-1} have frequencies ranging from 5 to 11 times per summer, while MI_{60} values of 8 mm h^{-1} have frequencies of 2–5 times per summer. Maps of threshold exceedance frequency can help identify areas most vulnerable to post-fire runoff and sediment delivery and prioritize post-fire emergency planning.

1. Introduction

In the western United States, higher temperatures and earlier spring snowmelt have increased the frequency and duration of large wildfires (Westerling et al., 2006; Litschert et al., 2012). After a wildfire, runoff and erosion can be up to several orders of magnitude higher than pre-fire conditions (e.g., Larsen et al., 2009; Noske et al., 2016; Wagenbrenner and Robichaud, 2014); this can lead to difficulties for both emergency management and water treatment, such as flooding and delivery of sediment, ash and other constituents to streams (Hohner et al., 2016; Martin, 2016).

In the Colorado Front Range, post-fire runoff and erosion are almost exclusively driven by summer thunderstorms and subsequent infiltration-excess (Hortonian) overland flow (Benavides-Solorio and MacDonald, 2005; Moody et al., 2013; Wagenbrenner and Robichaud, 2014). The generation of infiltration-excess overland flow exhibits threshold behavior, as high rainfall intensities are needed to exceed the infiltration capacities of soils and generate runoff on plots or hillslopes.

Rainfall thresholds for post-fire response (defined here as runoff or sediment delivery) vary with fire severity, time since burning and soil type (Benavides-Solorio and MacDonald, 2005; Miller et al., 2011). The lowest thresholds are immediately after a high severity fire due to the loss of surface cover, decrease in soil organic matter, and exposure of the soils to raindrop impact and soil sealing (Moody and Martin, 2001a; Larsen et al., 2009). Previous research on plots and hillslopes ($\leq$5.2 ha) has shown that post-fire mulch treatments and vegetation regrowth increase surface cover, surface roughness, and rainfall interception, thereby protecting soil from raindrop impact, slowing overland flow, and reducing runoff and erosion (Wagenbrenner et al., 2006; Robichaud et al., 2013a,b; Wainwright et al., 2000; Moreno-de las Heras et al., 2010; Inbar et al., 1998).

While the factors affecting post-fire runoff and erosion on plots and

* Corresponding author.
E-mail address: Codie.Wilson@colostate.edu (C. Wilson).

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hillslopes are relatively well-documented, predicting post-fire runoff and sediment delivery for watersheds remains difficult due to high variability in rainfall, burn severity, soil properties and topography (Moody et al., 2008; Kutiel et al., 1995). This increasing variability with larger drainage area generally causes thresholds to increase (Cammeraat, 2002; Cammeraat, 2004) due to longer flow paths (Wagenbrenner and Robichaud, 2014) that allow more opportunities for water infiltration and storage.

After a fire, the production of infiltration-excess overland flow reduces over time and typically only the most extreme storms generate overland flow by three to four years after burning (Ebel and Martin, 2017; Moody and Martin, 2001a; Wagenbrenner et al., 2015). As recovery conditions and rates may vary among fire locations and responses of interest (e.g., runoff or sediment delivery), modeling specific complex hydrological processes remains difficult, particularly across spatial scales. However, approaches that simplify interactions between fire, rainfall and landscape properties may be more important than the exact hydrologic transfer processes that occur in a recovering landscape (Nyman et al., 2013).

Rainfall thresholds can be used to integrate complex processes into a single comparable metric for predicting the frequency of post-fire runoff and sediment delivery without having to rely on more complex process-based models. Comparing thresholds between spatial scales, fires, and post-fire treatments is useful for interpreting the hydrologic processes and scale-effects that emerge with post-fire mulch treatments and recovery. Therefore, the goal of this study is to provide information on post-fire thresholds for runoff and sediment delivery across multiple fires, years post-fire, spatial scales, and mulch treatments in the Colorado Front Range. Specific objectives are to:

1. Identify rainfall intensity thresholds for a post-fire runoff or sediment delivery response at plots (≤0.06 ha), hillslopes (0.07–5.2 ha) and watersheds (100–1500 ha) after three Colorado Front Range wildfires for up to four years post-fire;
2. Determine how rainfall thresholds varied by fire location, year post-fire, spatial scale, and mulch treatments;
3. Use long-term rainfall data to map the likely frequency of rainfall events above these intensity thresholds as an indicator of risk for post-fire runoff or sediment delivery from future high severity fires in Colorado.

2. Materials and methods

2.1. Site descriptions and sample sizes

Post-fire rainfall, runoff and sediment delivery data were compiled for three Colorado Front Range wildfires: the 2000 Bobcat fire (Wagenbrenner et al., 2006; Wagenbrenner and Robichaud, 2014; Kunze and Stednick, 2006), the 2002 Hayman fire (Robichaud et al., 2013a,b, 2008; Wagenbrenner and Robichaud, 2014), and the 2012 High Park fire (This study; Schmeer, 2014; S. Ryan, USFS, unpublished data; Fig. 1). These fires were selected because they each had relatively detailed rainfall data linked with either runoff or sediment delivery data for at least three years post-fire and two or more spatial scales.

Elevations of the study sites within these fires ranged from 1700 to 2700 m. Climate within the study area is semiarid and monsoonal with 60–75% of the annual 400–600 mm of precipitation occurring as rain during the spring and summer months (April - September; PRISM Climate Group 2018). The primary pre-fire vegetation was ponderosa pine (*Pinus ponderosa*) at lower elevations and denser mixed conifer forests at higher elevations, with grasses and shrubs on drier south-facing slopes (BAER, 2012; Robichaud et al., 2013b; Kunze and Stednick, 2006; Schmeer et al., 2018). Soils are derived from granitic (Robichaud et al., 2013b; Schmeer et al., 2018) and metasedimentary parent materials (Braddock et al., 1970). The dominant soil type in the Bobcat and High Park fires is sandy loam, whereas soil in the Hayman fire is gravelly coarse sand (Robichaud et al., 2013a; Wagenbrenner and Robichaud, 2014; BAER, 2012).

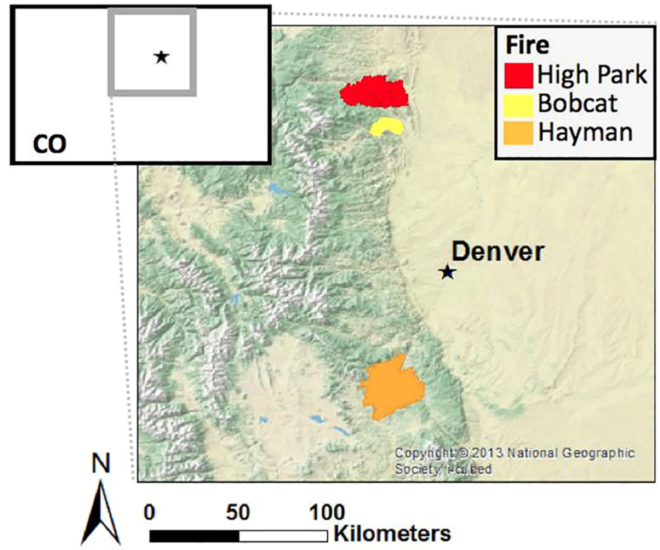

Fig. 1. Location of the three Colorado Front Range fires used in this analysis; from north to south, they are the 2012 High Park fire, the 2000 Bobcat fire, and the 2002 Hayman fire. Imagery from ESRI (2013). Maps produced using GCS WGS 1984.

We classified each monitoring site as a plot, hillslope or watershed. Plots were typically on planar slopes with an area of ≤0.06 ha in which sediment fences were used to measure sediment delivery (cf. Robichaud and Brown, 2002). Data were available for eleven plots within the Bobcat fire and 32 plots within the Hayman fire (Table 1). The Bobcat, Hayman and High Park fires each had 23–32 hillslopes, defined here as ephemeral, convergent swales or headwater channels with contributing areas of 0.07–5.2 ha. Sediment fences or larger sediment traps were used to measure hillslope sediment delivery. In both plots and hillslopes, sediment fences were cleaned out after major storms to measure deposited sediment mass. At the watershed scale of 100–1500 ha, runoff responses were measured at two watersheds within the Bobcat fire and six watersheds within the High Park fire (Table 1).

Site characteristics and treatments to mitigate post-fire responses varied by spatial scale. Plots and hillslopes were generally placed in locations burned at high severity, whereas watersheds covered larger areas and therefore had combinations of moderate and high severity. Average slopes by spatial scale were 17° for planar plots, 15° for the convergent hillslopes, and 17° for watersheds. Treatments included straw mulch, contour felling, straw wattles, and aerial seeding in the Bobcat fire; straw mulch, hydromulch, wood mulch, contour felling, and aerial seeding in the Hayman fire; and straw and wood-shred mulch in the High Park fire. Aerial seeding in parts of the Bobcat and Hayman fires did not significantly affect vegetation regrowth or post-fire sediment delivery rates (Wagenbrenner et al., 2006; Rough, 2007). Contour felled logs at two plots in the Bobcat fire and one hillslope in the Hayman fire also did not significantly reduce sediment yields (Wagenbrenner et al., 2006; Robichaud et al., 2008). Because mulch was the most common treatment used across all fires, we chose to consider only the effects of mulch treatments on thresholds. We stratified sites by the presence or absence of mulch rather than the extent of mulch cover because the extent and type of mulch varied widely, and not all locations had data on the amount of mulch cover over time. One Bobcat plot and 16 Hayman plots were mulched. For hillslopes, 6 Bobcat, 11 Hayman, and 9 High Park fire sites were mulched (Table 1). Mulch was applied to 0–16% (average = 8%) of the watershed areas in the Bobcat fire (Kunze and Stednick, 2006) and 1–77% (average = 22%) of the watershed areas in the High Park fire. We chose