103 Objective Definition of Rainfall Intensity-Duration Thresholds for Post-fire Flash Floods and Debris Flows in the Area Burned by the Waldo Canyon Fire, Colorado, USA

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Abstract

We present an objectively defined rainfall intensity-duration (I-D) threshold for the initiation of flash floods and debris flows for basins recently burned in the 2012 Waldo Canyon fire near Colorado Springs, Colorado, USA. Our results are based on 453 rainfall records which include 8 instances of hazardous flooding and debris flow from 10 July 2012 to 14 August 2013. We objectively defined the thresholds by maximizing the number of correct predictions of debris flow or flood occurrence while minimizing the rate of both Type I (false positive) and Type II (false negative) errors. The equation $I = 11.6D^{-0.7}$ represents the I-D threshold (I, in mm/h) for durations (D, in hours) ranging from 0.083 h (5 min) to 1 h for basins burned by the 2012 Waldo Canyon fire. As periods of high-intensity rainfall over short durations (less than 1 h) produced all of the debris flow and flood events, real-time monitoring of rainfall conditions will result in very short lead times for early-warning. Our results highlight the need for improved forecasting of the rainfall rates during short-duration, high-intensity convective rainfall events.

Keywords

Wildfire • Debris flow • Flash flood • Threshold

103.1 Introduction

Wildfire dramatically alters the hydrologic response of a watershed such that even modest rainstorms can produce dangerous flash floods and debris flows. Recently, four intense convective thunderstorms have produced hazardous flooding and debris flows in the Waldo Canyon burn area near Colorado Springs, Colorado, USA. Floods and debris flows initiated during these rainstorms closed major highways and damaged residences and businesses in Manitou Springs, Colorado. Tragically, the 09 August 2013 event resulted in a fatality. These events provide sobering examples of the threat that post-fire debris flows pose to lives, property, infrastructure and important resources within and downstream of recently burned steeplands. Given these hazards, it is imperative to provide guidance to government agencies, emergency managers and concerned citizens regarding the rainfall conditions that initiate post-fire flash floods and debris flows in or below recently burned areas.

Intensity-duration (I-D) thresholds are commonly used to determine the rainfall conditions that initiate flash floods and debris flows in recently burned areas (e.g., Cannon et al. 2008, 2011; Staley et al. 2013). Rainfall I-D threshold values represent the point at which slight increases in rainfall intensity produce abrupt increases in the likelihood of flood or debris-flow initiation (Schumm 1973; Caine 1980; Cannon et al. 2008). For recently burned areas, the actual values of the thresholds vary with fine-scale physiographic properties such as topography, lithology, soil properties and land cover. Several studies have identified that antecedent moisture (within storm and seasonal) is not a factor in the timing of post-fire debris flows and floods (Cannon et al. 2008; Schmidt et al. 2011), and the occurrence of these destructive

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events are temporally best correlated with measurements of rainfall intensities over short durations (e.g., <60 min) (Kean et al. 2011, 2012; Staley et al. 2013). The goals of this paper are to document the conditions of storm rainfall that triggered debris flows and flash floods in the Waldo Canyon burn area and use this information to define rainfall I-D thresholds that can be used to identify the meteorological conditions that produce events that pose a significant hazard to the downstream communities of Manitou Springs and Colorado Springs, Colorado, USA.

103.2 Study Area

The Waldo Canyon fire burned 73.8 km^2 near Colorado Springs, Colorado, USA during June and July of 2012 (Fig. 103.1). Lithology in the burn area consists of Pikes Peak Granite in the western portion with a gradational transition to early Proterozoic gneisses in the south-central portion of the burn area (Trimble and Machette 1979). The eastern extent of the Waldo Canyon burn area consists of sedimentary units, predominantly Williams Canyon Limestone and the Fountain Formation (sandstones and conglomerates) (Trimble and Machette 1979). Much of this area has been determined to have a relatively high likelihood (>40 %) of post-fire debris flow in response to relatively modest amounts of rainfall (i.e. a 10-year recurrence interval rainstorm lasting 1 h) (Verdin et al. 2012). Evidence of pre-fire debris flow activity of unknown age was present in several canyons within the burn area (Verdin et al. 2012). There are no regionally specific rainfall intensity-duration thresholds for post-fire debris flows and flash floods available for the burn area, only general thresholds for the intermountain western United States (Cannon et al. 2008).

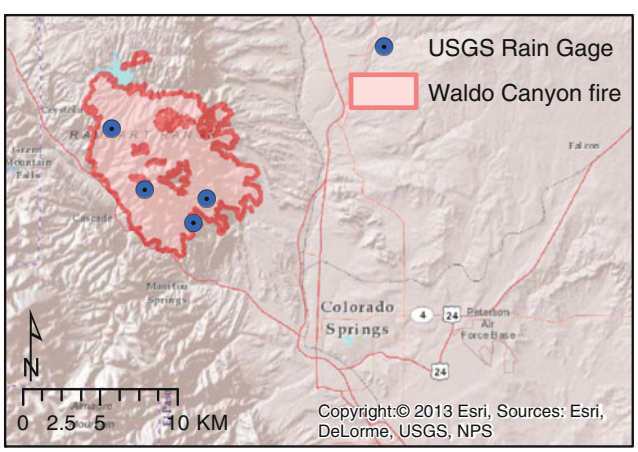

Fig. 103.1 Overview map of the area burned by the 2012 Waldo Canyon fire near Colorado Springs, Colorado, USA

103.3 Methods

We use established empirical methods (Cannon et al. 2008, 2011; Staley et al. 2013) to define the rainfall I-D thresholds for flash flooding and debris flow for the Waldo Canyon burn area. No attempt was made to differentiate between the rainfall conditions that contributed to flash flood or debris flows as evidence of both processes was found often within individual basins in response to single storms. Herein, we refer to flash-flood and debris-flow events collectively as debris floods.

Rainfall information from four U.S. Geological Survey gage installed in the burn area provided information regarding storm characteristics (Fig. 103.1). Tipping bucket rain gauges (resolution = 0.254 mm) reported rainfall accumulations in 5-min intervals. Rainfall intensities were calculated from 5-min accumulation totals using backwards differencing (Kean et al. 2011; Staley et al. 2013). Peak storm rainfall intensities for specified durations (5, 10, 15, 30, and 60 min) were calculated from the measured time series. Data were only available for three significant storms that generated flows within the burn area (01 July 2013, 10 July 2013 and 09 August 2013) as rain gauges had not yet been installed prior to the first post-fire debris-flood in July of 2012. In total, our database includes the rainfall conditions leading up to 8 debris floods (a storm may produce several flows in basins associated with different rain gauges) and 445 rainfall events that did not generate any debris floods. Individual rainfall events were defined by a minimum period of 30 min without rainfall and a minimum accumulation of 1.0 mm (~4 bucket tips). We selected this value for our minimum inter-storm period since all of the floods or debris flows occurred during high-intensity but short-lived bursts of rainfall during afternoon convective thunderstorms. We considered only records from rain gages located within 2 km of a debris-flood-producing watershed to minimize the effects of the spatial variability of rainfall amounts and intensity. We also only included basins in the analysis that produced at least one debris flood to ensure that the basins included in the analysis were at least minimally susceptible to flood or debris flow. In total, 12 drainage basins were inspected for evidence of debris floods after each significant rainstorm where 10-min rainfall intensities exceeded 50 mm/h. This field reconnaissance provided the rainfall-response data used to define the threshold values. Data related to the precise timing of debris-flood initiation were unavailable. Instead, we used peak rainstorm intensity values to define our thresholds.

Following the methods of Staley et al. (2013) we calculated an objectively defined rainfall I-D threshold using the threat score (TS) metric. This method objectively defined the thresholds by maximizing the number of correct predictions of debris-flood occurrence while minimizing the rate of both

Type I (false positive) and Type II (false negative) errors. Event occurrence is considered to be either True or False (it either occurred or did not occur), whereas model predictions are considered to be Positive or Negative (successful prediction or prediction failure). The relationship between model prediction and event occurrence is then assigned to one of four classes. A true positive (TP) represents an event where rainfall rates exceeded the threshold, and a debris flood was recorded. A true negative (TN) represents an event where rainfall rates were below critical threshold and no debris floods were recorded. False positive (FP) events occur when rainfall rates exceed the threshold but no debris floods were triggered. This can also be considered a "false alarm" or type I error. A false negative (FN) occurs when rainfall rates were below threshold, yet a debris flood was reported. This represents a "failed alarm" situation or Type II error. TS combines these metrics into a single measure of the overall performance of the classifier model where a perfect model score would equal one, and each incorrect prediction (FP or FN) reduces the value of TS (Schaefer 1990).

We chose to use the TS as the metric used in the optimization analysis, because it equally weights the reduction in score for both FN and FP events, and is an easily calculated measure that can be updated during a storm season for areas where existing thresholds are unavailable. We used TS to define the I-D thresholds by iteratively calculating TS for all analyzed durations for intensities ranging from 1 to 150 mm/h at 0.1-mm/h intervals. The threshold was defined at the maximum value of TS. The highest rainfall intensity was defined as the critical I-D threshold when maximum TS was calculated for multiple rainfall intensities.

103.4 Results

Rainfall accumulations for debris-flood producing rainstorms ranged from 7.2 to 34.9 mm with total storm durations between 10 and 125 min. Precise timing of flow events was unavailable and timing accounts from eyewitnesses suggest that floods and debris flows may have occurred with as little as 4 mm of rainfall and within 5 min of the beginning of the storm.

Rainfall intensities measured over durations less than 60 min have proven to be well correlated with the initiation of post-fire debris floods, independent of the amount of antecedent rainfall (Kean et al. 2011; Staley et al. 2013). For this reason we defined our rainfall intensity-duration thresholds at individual durations from 5 to 60 min. These thresholds were well defined for all analyzed durations as the data exhibit little overlap between positive and negative events (Fig. 103.2).

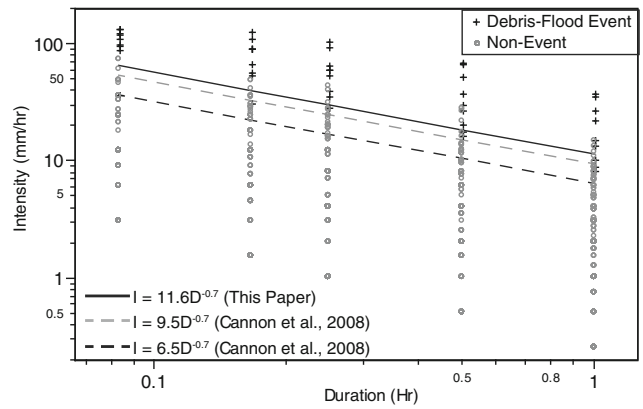

Fig. 103.2 Rainfall intensity duration data for debris-flood-producing events (*black crosses*) and non-events (*grey circles*) for areas burned in the Waldo Canyon fire. The equation for the thresholds defined in this study is represented as a *solid black line*, whereas the Cannon et al. (2008) thresholds for other burned areas in Colorado are represented as *dashed grey* and *dashed black lines*

From these data, we calculated the best-fit power-law threshold equation for the occurrence of post-fire debris floods as (Fig. 103.2):

$$I = 11.6D^{-0.7}$$

($r^2 = 0.99$), where I is rainfall intensity (mm/hr) and D is the duration over which rainfall intensity was measured (in hours). Rainfall I-D thresholds were much higher for the areas burned by the Waldo Canyon fire compared to those calculated for other recently burned areas in Colorado (Cannon et al. 2008) (Fig. 103.2). However, the thresholds defined by Cannon et al. (2008) were derived at durations greater than or equal to 1 h, as the strong correlation between high-intensity rainfall over short durations and the occurrence of debris flows and flash floods had not yet been documented (Kean et al. 2011; Staley et al. 2013).

103.5 Conclusions

In this paper we have objectively defined rainfall I-D thresholds for post-fire flash floods and debris flows in the area burned by the 2012 Waldo Canyon fire near Colorado Springs, Colorado, USA. Debris flows and flash floods included in this study occurred in response to bursts of high-intensity rainfall during short duration convective thunderstorms. The thresholds defined in this study were substantially higher than those defined for other burn areas in Colorado (Cannon et al. 2008). Differences in the threshold values between this study and Cannon et al. (2008) likely reflect differences in basin morphology, lithology, soil properties and burn intensity, and the longer durations used to calculate rainfall intensities in the earlier study.

Although I-D thresholds may be used as guidance for early-warning of post-fire debris flows and flash floods, the importance of rainfall intensities measured over short durations highlights the importance of accurate forecasting of rainfall conditions during short-duration convective rainstorms. Real-time monitoring of rainfall intensities within the burned watersheds provides little or no lead time for warning or evacuation. Improvement of rainfall intensity forecasting and monitoring of rainfall conditions upwind of the area of concern are of utmost importance for early warning of debris flows in recently burned watersheds. Recent improvements in radar technology, such as dual-polarization (Jorgensen et al. 2011), may improve forecasters' ability to resolve areas of high intensity rainfall within a storm and provide better guidance to emergency management teams and public dissemination of short lead-time warning.

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