The spatial distribution of debris flows in relation to observed rainfall anomalies: insights from the Dolan Fire, California

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Abstract. A range of hydrologic responses can be observed in steep, recently burned terrain, which makes predicting the spatial distribution of large debris flows challenging. Studies from rainfall-induced landslides in unburned areas show evidence of hydroclimatic tuning of landslide triggering, such that the spatial distribution of events is best predicted by the observed rainfall anomaly relative to climatic norms rather than by absolute rainfall. In this paper, we test whether the spatial distribution of debris flows in response to rainfall can be similarly predicted by rainfall anomaly. The 520 km\textsuperscript{2} Dolan Fire burn scar in Monterey County, California, USA, spans a sharp hydroclimatic gradient and experienced a widespread storm in January 2021 that triggered floods and debris flows, providing a natural experiment in which to test this hypothesis. In this study, we use remote and field methods to map debris-flow response and examine its spatial heterogeneity. Together with rainfall data, our mapping reveals that the observed anomalies in peak 15-min rainfall intensity (I\textsubscript{15}) relative to the intensity of the 1-yr return interval storm predict debris-flow occurrence better than the absolute peak I\textsubscript{15}. Our findings indicate that debris-flow processes and threshold rainfall required for debris-flow initiation may be tuned to local hydroclimate.

1 Introduction

1.1 Post-wildfire debris flows

Anthropogenic climate change and human activity have increased the size and scope of severe wildfires in the Western United States, increasing the amount of steep burned area in proximity to population centers and critical infrastructure [1]. These burned areas face a range of post-fire hydrologic hazards, from clear water floods to catastrophic debris flows.

Although this range of flow types is often observed in burned landscapes, predicting the type of flow that will debouch from any particular basin still proves challenging. This difficulty becomes more pronounced as one moves into areas with limited observations of past post-fire debris flows on which existing empirically based predictive models can be trained [2, 3].

1.2 Hydroclimatic tuning of surface processes

Studies of rainfall-induced shallow landslides have shown evidence that landslide initiation is more sensitive to rainfall anomaly (the observed rainfall normalized by metrics of rainfall climatology) than it is to the absolute quantity of rainfall delivered, possibly due to a coevolution of surface processes with long-term local climate [4, 5, 6, 7].

In this study, we test whether the spatial distribution of runoff-generated debris flows across a hydroclimatic gradient can be similarly explained through the use of rainfall anomaly maps.

1.3 Study area and rainfall event

In August 2020, the Dolan Fire burned ~520 km\textsuperscript{2} of steep, remote, heavily vegetated terrain in Monterey County, California. The resulting burn scar stretched up to ~30 km inland from the Pacific coast, ~40 km north to south, and spanned a sharp east-west hydroclimate gradient with mean annual rainfall ranging from ~50-130 cm/yr [8] and the climatological 15-minute rainfall intensity at 1-year return interval (1yr I\textsubscript{15}) ranging from ~26-52 mm/hr [9].

On 27 January 2021, the area received widespread heavy rainfall from an atmospheric river event, triggering numerous debris flows across the burn scar, as well as widespread rainfall runoff that exited basins simply as flood flows. This triggering rain event, together with the diverse hydroclimatology at the site, makes the Dolan Fire a suitable natural experiment for testing whether the observed heterogeneity in hydrologic response can be explained in part by observed rainfall anomalies.
2 Methods

2.1 Debris-flow mapping

We qualitatively mapped flow type at each segment of the stream network using pre- and post-event WorldView satellite imagery [10], according to the following scale: 0: no erosion visible; 1- minor erosion visible interpreted to be from standard flood flows; 2- severe erosion visible with potential to be a debris flow; 3- clear evidence of debris flows. We performed field investigations in June 2021 and January 2022 to refine our remote mapping using direct observations of deposit and channel morphology. The locations of fluvial erosion and debris flows are summarized in Figure 1.

2.2 Rainfall data acquisition

Due to the sensitivity of runoff-generated debris flows to short-period (~15 min) rainfall, we focus on short-period rainfall and associated climatological metrics. Rainfall data for the triggering event were recorded by 12 nearby tipping-bucket gauges (time resolution 1-15 min) and several satellite-based products (time resolution 60 min). In this study, we omit radar products due to a poor Radar Quality Index [11] in the remote, mountainous study area, choosing to focus on instantaneous gauge-based products and 1-hour satellite products from PERSIANN and IMERG for validation purposes [12, 13].

Using QGIS 3.16.8, we created a spatially continuous raster of gauge-based peak 15-minute rainfall intensity (peak I₁₅) through inverse distance-weighted spatial interpolation of the gauge peak values. We calculated and inspected the spatial pattern of peak 60-minute rainfall intensity from the satellite estimates to ensure that there were no major discrepancies between the continuous satellite product and the gauge-interpolation scheme. We acquired gridded data on long-term rainfall-intensity climatology from the National Oceanic and Atmospheric Administration (NOAA) Atlas14 dataset [9].

2.3 Data analysis

To compute the rainfall anomalies across the study area, we normalized the measured peak I₁₅ map by the I₁₅ map for a 1-year return interval storm [Equation 1].

\[
\text{Anomaly} = \frac{\text{Observed peak intensity}}{1yr \ return \ interval \ intensity}
\]  

(1)

We then associated each stream segment with a corresponding measured peak I₁₅, 1-year climatological I₁₅, and corresponding rainfall anomaly. To test whether rainfall anomalies can explain the observed locations of debris flows better than peak I₁₅, we constructed histograms of total network length for each response type above and below 1.0 rainfall anomaly and above and below an I₁₅ of 30 mm/h (the fire-averaged threshold predicted by the existing operational model) [14].

3 Results

Fig. 1. Map of observed peak I₁₅ (A) and I₁₅ anomaly (B) across the study area, with debris flows and fluvially eroded stream segments shown.

3.1 Remote and field-based mapping

Our field verification efforts indicate that close assessment of pre- and post-event satellite imagery generally produces an accurate characterization of fluvially eroded and debris-flow-dominated stream segments in this landscape, but field investigation may be necessary in densely forested areas where the channel is not visible on satellite imagery. The lack of intense rain in the months following the triggering event allowed us to conduct field investigation six months to a year after the event, but more rapid assessment may be necessary in landscapes with frequent intense rain.

Hotspots of debris-flow activity were mainly found in the northwestern, southern, and eastern portions of the burn scar. Evidence of fluvial erosion was more widespread, except for a large region in the north-central area. This region of little to no erosion spans across much of the variation in peak I₁₅ [Figure 1A], but lies almost entirely below the 1.0 rainfall anomaly contour [Figure 1B].
4 Discussion

![Image](https://doi.org/10.1051/e3sconf/202341504003)

**Fig. 2.** Percent of network length (e.g., probability of response given a particular rainfall) in the Dolan Fire and in each response class, above and below 1.0 I_{15} anomaly (top) and 30 mm/h I_{15} (bottom). Compared with the overall stream network (black horizontal dashed line), debris flows are ~37% more likely to occur at sites with rainfall anomaly greater than 1. Meanwhile, debris flows were only 1.6% more likely to occur at sites with absolute rainfall above a 30 mm/h threshold.

**4.1 Absolute rainfall vs. rainfall anomaly**

Compared to the overall stream network within the Dolan burn scar, debris flows were 1.6% more likely to occur above a fixed I_{15} threshold of 30 mm/h, but ~37% more likely to occur above an I_{15} anomaly threshold of 1.0 [Figure 2]. This pattern indicates a higher sensitivity of debris-flow processes to climatologically extreme rainfall than to rainfall above a constant, climatologically insensitive threshold.

We also plotted the full stream network and debris-flow locations on a two-dimensional phase space, with the x-axis representing the climatological 1-year I_{15} and the y-axis representing the observed peak I_{15} at a given point [Figure 3]. This visualization scheme allows us to reduce the geographic contours from Figure 1 to simple lines which highlight the predictive power of rainfall anomaly versus peak rainfall. Any point on the space that lies above the 1:1 line represents a point that received a rainfall anomaly greater than 1, while any point on the space that lies above a horizontal line represents a point that received a peak I_{15} above a particular constant value.

The full stream network occupies a large portion of this space, but the debris-flow locations are almost exclusively limited to the area above the 1:1 line. This indicates that a threshold equal to the local 1-year recurrence interval storm explains the prevalence of debris flows more effectively than any climatologically insensitive threshold that would plot as a horizontal line in the space.

**4.2 Possible coevolution of geomorphic processes to local climate**

A correlation between geomorphic process thresholds and local hydroclimate has been observed in prior studies of landslide and debris-flow events in unburned areas [15, 4, 5, 6, 7], and in a regional-scale analysis of post-fire debris-flow initiation [16]. Such a correlation may indicate a coevolution of processes to long-term local climate, part of a long-studied link between climate and geomorphology.

Our study did not seek to identify the precise mechanisms driving the association between debris-flow initiation and local climate, and future studies could further investigate this link. Following findings from related aspects of geomorphic and landscape evolution research, mechanisms may include the adjustment of soil hydraulic properties [17, 18], mechanical properties [19], and/or drainage network geometry [20], among others.

**4.3 Implications for debris-flow hazard prediction**

The sensitivity of post-fire debris flows to local rainfall anomaly has implications for debris-flow hazard prediction in hydroclimatically diverse regions. Further focus and understanding of this pattern may be critical for predicting post-fire debris-flow processes in areas that are facing unprecedented levels of severe wildfire, have sparse observational history, and/or are far from areas in which existing predictive models were trained.
Additionally, many areas are facing hydroclimatic shifts associated with climate change, such as increased rainfall intensity [21]. The adjustment of geomorphic process to long-term local climatology may have substantial implications for debris-flow frequency and severity in areas that are facing hydroclimatic conditions far more intense than those to which the landscape has historically adjusted.

5 Conclusions

The sharp hydroclimate gradient and widespread rainfall event at the Dolan Fire in California provide a natural experiment to demonstrate whether debris-flow processes and rainfall-intensity thresholds for debris-flow initiation are sensitive to local climatology.

By mapping flow type across the burn scar through remote and field methods and comparing with observed peak rainfall as well as rainfall anomaly, we are able to investigate the underlying climatological factors driving the spatial pattern of debris-flow generation. We show that rainfall anomaly explains debris-flow occurrence more effectively than any single fixed rainfall intensity threshold.

Similar to past studies of landslide and debris-flow activity in unburned areas, this indicates that the factors governing debris-flow generation may have co-evolved with the local climatology of intense rainfall. This finding has implications for post-fire debris-flow hazard prediction that will prove important as the size and scope of severe wildfire expands globally, as well as for general debris-flow hazard prediction as global hydroclimatic conditions shift with climate change.

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