

Seasonal **Influence** on Post-Fire Debris Flow **Likelihood** after the 2020 Lake Fire

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Abstract

The increasing severity of wildfires in Western North America is widely hypothesized to lead to an increase in the likelihood of post-fire debris flows (PFDF), specifically those triggered by high-intensity rain. PFDF likelihoods are highest in the first year and tend to decrease over time. However, it is not well understood how seasonal variation affects the PFDFs initiation in the years following a fire. Here, we investigated how different physical parameters influence seasonal PFDF likelihood, informed by four years of field and satellite observations from the 2020 Lake Fire in Southern California. We found that unsaturated hydraulic conductivity was an order of magnitude greater during the dry season than during the wet season, significantly reducing the PFDF likelihood. Our simulations show that vegetation cover has less of an impact on PFDF likelihood than hydraulic conductivity or grain size. This study helps clarify the relative importance of hydraulic conductivity, grain size, and vegetation on PFDF as these parameters vary seasonally and evolve over four years after the fire. Our results suggest that seasonal variation plays a major role in determining PFDF likelihood and therefore, climatic and seasonal patterns need to be considered in future field and modeling studies.

1. Introduction

Wildfires have increased in size and severity in recent years, especially in the western United States (Abatzoglou and Williams, 2016; Singleton et al., 2019). Wildfires significantly alter the landscape by increasing overland flow, which ultimately produces runoff-generated post-fire debris flows (PFDF) in steep basins when the infiltration rate capacity is overwhelmed by rainfall intensity (Kean et al., 2011; Kean et al., 2016). PFDF likelihood is generally exacerbated in areas with high-intensity fires where vegetation canopy interception is significantly reduced, topsoil hydrophobicity is increased (Granged et al., 2011; Nyman et al., 2014; Robichaud et al., 2016), and hydraulic roughness is reduced (e.g., Stoff et al., 2015; Hoch et al., 2021).

Runoff-generated debris flows are considered water-dominated flows that can include a wide range of sediment sizes (Kean et al., 2019), with initiation points varying significantly between watersheds (DeGraff et al., 2015; McGuire et al., 2017). The rainfall intensity-duration (ID) threshold defines the rainfall needed over a set duration that leads to triggering of PFDF (Staley et al., 2013; Staley et al., 2017). Rainfall ID threshold is lowest in the first year for runoff-generated debris flows, regardless of the rainfall regional regimes (DeGraff et al., 2015; Hoch et al., 2021; McGuire et al., 2021a). While the rainfall ID threshold increases over time, runoff-generated debris flows can still be triggered up to 10 years after the fire, especially in extreme precipitation events (DeGraff et al., 2015; Graber et al., 2023).

Estimating an accurate rainfall ID threshold for a large area can be challenging using generalized parameters, but we can attribute several parameter such as soil infiltration capacity, median grain size, and canopy interception that contribute to the yearly changes of PFDF likelihood in the southwestern United States (Ebel and Martin, 2017; Tillery and Rengers, 2020; McGuire et al., 2021a; Hoch et al., 2021; Gorr et al., 2023). Additionally, recent studies have shown that seasonal variations in the first two years post-fire can alter the rainfall ID threshold (Gorr et al., 2023; Martinez et al., 2025) and that post-fire debris can still occur 3 years after the fire (Ridgway et al., 2026). However, it is still unclear how seasonal variations after the first two years can influence the PFDF likelihood.

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95 In this study, we investigate how seasonal variation influences post-fire debris flows (PFDF) likelihood four years after the 2020 Lake Fire, drawing on information from five high burn severity basins. Specifically, we use data collected from three field surveys, during the first year, during a dry and wet month in the fourth year, along with high-resolution, high-repeat satellite imagery and field measurements to estimate how seasonal changes could affect PFDF likelihood immediately after the fire and four years after the fire. Our study aims to (1) evaluate long-term changes in post-fire debris flow (PFDF) likelihood in high-burn-severity areas over the four years following a fire, (2) assess the relative importance of vegetation cover, hydraulic conductivity, and grain size in controlling the rainfall intensity-duration (ID) threshold over the long term, and (3) assess the significance of seasonal variation relative to long-term post-fire recovery. Overall, we show that the rainfall ID threshold remains highly sensitive to seasonal changes in soil hydraulic conductivity even several years after the fire. This study improves our understanding of how seasonality, climatic patterns, and post-fire recovery interact to drive PFDF dynamics.

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2. Study area

110 The 2020 Lake Fire was the second-largest fire of the year for Los Angeles County, with an estimated burned area of ~125.4 sq. km (USGS Landslide Hazard Program, 2020). US Burned Area Emergency Response (BAER) reports that the area of unburned and very low burn severity was ~7% (117.5 sq km), low burn intensity was ~21% (26.7 sq km), moderate burn severity was ~53% (67.5 sq km), and high burn severity was ~18% (23.1 sq km) (USDA Forest Service, 2020) (Figure 1). We selected five northwest-facing (Basin A to E), moderate-to-high burn severity basins with a high likelihood of debris flow (80-100%) at a peak 15-minute rainfall intensity of 24 mm/hr (USGS Landslide Hazard Program, 2020) (Figure 1). The basins are in the southern region of the burned perimeter, along Lake Hughes Road, with a mean slope of 34 degrees, and with a similar Late Cretaceous lithology of quartz diorite (Valencia et al., 2022). 120 The fire burned within a largely unpopulated portion of the Angeles National Forest, with the overall land cover in the five basins exhibiting a mix of shrubs, deciduous forest, evergreen forest, and mixed forest, including bigcone Douglas fir (*Pseudotsuga macrocarpa*), oak, and gray pine (Figure 3) (Yang et al., 2018).

3. Methods

3.1 Field sampling and observation

125 We selected five basins with the highest probability (high burn severity) for debris flow in all rain intensities as predicted by the USGS Landslide Hazard Program. Post-fire field samples and measurements were collected at 3 months (Year 0), 45 months (wet season of Year 4), and 50 months (dry season of Year 4). We classify the wet season (winter months) between November and March, and the dry season (summer months) between April and October. Due to the difficulty of accessing the basin interiors, we collected field samples at basin outlets for grain size analysis, assuming most eroded sediment passes through the main channel (Santi et al., 2008) (Figure 2). We measured unsaturated soil hydraulic conductivity for the second and third field surveys using a Mini Disk Infiltrometer (METER Group) adjacent to our soil samples within the basin outlet without disturbing the surface material (i.e., flattening) (METER, 2021; Watson et al., 1986). We only report the initial hydraulic conductivity values for each basin, as there is a limited undisturbed area with a suitable flat area. During the first field survey, due to the lack of

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instruments and access, we assumed a hydraulic conductivity of 10 mm/hr as a conservative estimate based on data from the 2016 Fish Fire in the adjacent San Gabriel Mountains with no vegetation cover (McGuire et al., 2021a). We also performed a Water Droplet Penetration Test (WDPT) at the basin outlets during this survey. The 2016 Fish Fire occurred in an area with similar granitic bedrock, average slope (46°-51°), northwest-facing aspect, and vegetation types (Table S7) as compared to the 2020 Lake Fire (McGuire et al., 2021a; Paysen et al., 1980; Staley et al., 2018). We also collected soil core samples (down to 20 cm) during the second and third surveys and visually inspected for stratification and performed. The canopy throughfall coefficient was defined as the open space calculated by subtracting the satellite-derived vegetation cover (Section 3.3) from 1 (100%).

3.2 Precipitation record

Rainfall intensity was calculated from the precipitation record obtained from the Los Angeles Department of Public Works (LADPW) Elizabeth Lake monitoring site, located 1 mile southeast of the area of interest (34.6083, -118.5594). To evaluate whether each precipitation event can trigger debris-dominated flows or water-dominated flows, we report the peak 15-minute rainfall intensity (I_{15}) for each year. The threshold used to distinguish between these flow types is based on the lower limit of the dimensionless discharge threshold in Tang et al. (2019a). We also apply the same threshold when reporting our modeling results as a conservative estimate to trigger debris flows.

Rainfall intensity is highest in the first year at $I_{15} \sim 13$ mm/hr. There were a total of 12 precipitation events exceeding $I_{15} = 15$ mm/hr throughout the study period. 4 events exceeded $I_{15} = 20$ mm/hr, but none exceeded $I_{15} = 25$ mm/hr (Table S6; Figure S2). Specifically, these 12 events are occurred as follows: 2 events in November 2021- March 2022 (mean $I_{15} = 19.01$ mm/hr and max $I_{15} = 22.35$ mm/hr), 7 events during the November 2022- March 2023 wet season (mean $I_{15} = 19$ mm/hr, max $I_{15} = 24.38$ mm/hr), 1 event in the dry season of August 2023 ($I_{15} = 18.28$), and 2 events in February 2024 (mean $I_{15} = 17.65$ mm/hr, max $I_{15} = 19.03$ mm/hr).

The cumulative rainfall recorded for the first, second, third, and fourth years was 127.5 mm, 404.1 mm, 1329 mm, and 693.7 mm, respectively. There was a cumulative rainfall of 25.4 mm before the first survey in December 2020, with a maximum 15-minute duration (I_{15}) of ~ 1 mm/hr during this period.

3.3 Differenced Normalized Difference Vegetation Index (dNDVI)

We estimated the vegetation changes using high-resolution satellite imagery from pre-fire to the fourth year. We acquired PlanetScope (3 m) images and calculated the Normalized Difference Vegetation Index (NDVI) (Equation 1) within the basins and estimated the differences between two dates of interest, a reference, and a subsequent image, to estimate the vegetation changes and possible soil mobilization (i.e., debris flows) (Equation 2). Here we classify "pre" and "post" imagery as the before and after the Lake Fire. "Reference" imagery represents the earlier-date image (which may be before or after the fire) and "subsequent" represents the later-date image.

We applied several selection criteria for PlanetScope imagery, including cloud-free within the area of interest, high solar elevation angle (45°-90°) to reduce shadow artifacts, and interoperable with image products from Sentinel-2 (PSB.SD). PlanetScope images consist of 8 bands: Red-

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sixth band, Green-fourth band, Blue-third band, and Near-infrared-eighth band. We calculated NDVI for each image in QGIS's *raster calculator* using the following equation (Carlson and Ripley, 1997):

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

Where Near-Infrared (NIR) is the eighth band and Red is the sixth band. The NDVI values range between -1 to 1.

Positive NDVI values indicate greener or healthier vegetation, whereas lower or negative NDVI values show less healthy vegetation, bare soil, snow, or water (e.g., Dye and Tucker, 2003).

Pixels with vegetation loss or exposed bare ground exhibit lower dNDVI values, whereas vegetation growth or cover is represented by higher dNDVI values. Although it is difficult to distinguish debris flows and flood events solely from satellite imagery, affected areas from sediment accumulation or high erosion could still show lower dNDVI values (<0) due to the lack of vegetation or exposed soil. The use of dNDVI is similar to the dNBR (differenced normalized burn ratio), where Landsat's mid-infrared band is used (Miller and Thode, 2007).

$$dNDVI = postNDVI - preNDVI \quad (2)$$

Where dNDVI represents the difference in the Normalized Difference Vegetation Index.

We acquired a total of 61 monthly images from August 2020 (including 3 months before the fire) to September 2024, conforming to the aforementioned criteria (**Table S1**). For simplicity, we compare the yearly changes of dNDVI to estimate vegetation cover for our model input while qualitatively tracking the vegetation recovery and loss (**Table 1**). Our yearly dNDVI images start and end in either August or September to align with the fire's conclusion in September 2020. We also processed dNDVI between our two surveys in 2024 (**Figure 4**) and defined the observation period leading up to our field surveys: Year 4-Wet spans September 2023 to April 2024, and Year 4-Dry spans April 2024 to September 2024.

We estimated vegetation cover within a given basin using dNDVI from satellite imagery by calculating the fraction of pixels with dNDVI values greater than 0, which are considered to be vegetated (**Table 2**). The dNDVI values are later used as an input for the PFDF likelihood modeling. We also performed a 20-meter point-intercept survey (Herrick et al., 2009) during the second field survey along the riverbank outside the burn scar to compare with our dNDVI values for vegetation cover. We noted the surface cover (canopy/vegetation, litter, or soil) every 20 cm, where litter includes exposed loose plant material, and calculated the vegetation cover as the fraction of points intercepting canopy/vegetation.

3.4 Numerical modeling inputs

We used a modeling approach to allow us to investigate the effects of the measured parameters on PFDF initiation, regardless of whether debris flows actually occurred within the study area. We used the KWAVE numerical model (Rengers et al., 2016b; Rengers et al., 2019), which uses the kinematic wave approximation for overland flow routing, the Green-Ampt equation for infiltration, and the Rutter et al. (1975) for canopy interception, to simulate runoff discharge. We

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285 then used a slope-dependent dimensionless-discharge numerical model to estimate the rainfall
intensity-duration (ID) needed to trigger runoff-generated debris flows based on simulated
infiltration, interception, and runoff across a catchment's topography (Tang et al., 2019b). In this
study, we varied the input parameters, including the unsaturated hydraulic conductivity,
vegetation cover, grain size, and rainfall intensity, while maintaining other parameters similar
290 across basins and years (Supplement Section 4). A complete list of input parameters used in our
models can be found in Table 2 and in the supplement (Section 4 and Table S2).

We estimate the rainfall ID thresholds that are needed to trigger runoff-generated debris for all
sampled basins for Year 0 (immediately after fire), Year 1 (1 year since the fire), Year 4 (Wet),
and Year 4 (Dry). The threshold for post-fire debris flow generation (red line in Figure 5) is
295 based on the calibrated lower limit threshold from the Fish Fire (Tang et al., 2019a). We used a
1-m bare-Earth DEM acquired by the USGS 3DEP lidar program before the fire (last accessed
December 2020 from OpenTopography).

Our simulations use an idealized Gaussian rainfall intensity distribution at 15-minute intensities
300 (I_{15}) of 15 mm/hr, 20 mm/hr, and 30 mm/hr. These intensities were selected based on rain
intensities recorded at the Elizabeth Lake rain gauge, which had a max 5-year recurrence interval
for I_{15} of 30 mm/hr (NOAA, last accessed July 2025). Our highest simulated rain intensity is
sufficient given that most PPDFs in the southwest US are triggered during rain events with
recurrence intervals less than 2 years (Staley et al., 2020). In our simulations, we input the
305 parameters (i.e., grain size distribution, hydraulic conductivity, and vegetation cover) from our
field and satellite observations to estimate the rainfall threshold needed to trigger runoff-
generated debris flows for the four basins.

In Year 1, we assumed that only vegetation cover changed during that period, while maintaining
310 other parameters the same as in Year 0. Grain size distributions (d_{50} and d_{84}) were measured from
all three field surveys. Field-measured hydraulic conductivity is only used in the models for the
final two surveys (wet and dry months in 2024).

315 Additionally, we performed a sensitivity test to better understand how each parameter influences
the PPDF likelihood of each basin using the dimensionless discharge model (Tang et al., 2019a)
(discussed in Section 5.2). More specifically, we vary the individual parameters in our model
input (i.e., hydraulic conductivity, vegetation cover, and grain size) either one at a time or
changing more than one parameter simultaneously at different rain intensities (i.e., $I_{15} = 10, 20,$
30, and 40 mm/hr). All simulations started with the baseline parameters based on the field
320 surveys and assumptions immediately after the fire: a hydraulic conductivity of 10 mm/hr, no
vegetation cover (0%), and median grain sizes for each basin from the first-year sample.

4. Results

4.1 Postfire recovery surveys

325 Our dNDVI results show the burn perimeter outlined clearly by the negative dNDVI values
(corresponding to the loss of vegetation) immediately following the fire (Figure 3a). The highest
negative dNDVI values correspond to the lower elevations of Basin C, in the larger basin north
of Basin C, and along the portions of the river. These negative dNDVI values could indicate
significant vegetation loss, increased soil exposure, or sediment deposition (e.g., a culvert

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conductivity of 10 mm/hr from nearby fires in the San
Gabriel Mountains (Rengers et al., 2019; Hoch et al., 2021).
We set a suction head of 0.01 m, an initial volumetric soil
moisture content of 0.1, and a lower end member of a
volumetric soil moisture at saturation of 0.3 as observed from
nearby fires (Tang et al., 2019b; Hoch et al., 2021; Carsel and
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375 transporting sediments across Basin C). The areas with the lowest dNDVI values are similar to
 380 locations identified by the US Burned Area Emergency Response (BAER), which uses either
 Landsat or Sentinel-1 for their estimates. Immediately after the fire, our simulations show that
 Basins A, B, D, and E require at least $I_{15} = 30$ mm/hr to trigger runoff-generated debris flows
 (Figure 5), although there were no significant high-intensity rainfall events recorded during that
 time (Figure S3). We did not report Basin C as we did not have sufficient data collected in the
 subsequent years. We found an overall decrease in median grain size from the first survey was
 larger than in the subsequent surveys. We also did not observe significant changes in the median
 grain size between the second and third survey (Table 2).

4.1.1 Year 1

385 In Year 1, the precipitation record shows a cumulative precipitation lower than in the subsequent
 years and a peak rainfall intensity (I_{15}) of 13 mm/hr (Figure S2). The majority of positive
 dNDVI values are located along the river and within some of the basins (i.e., Basin A, Basin C,
 Basin E). We also observe a positive dNDVI region along the slopes downstream of Basin A,
 390 which we suspect is rapidly growing vegetation (i.e., grasses). Given the maximum observed
 rainfall intensity throughout the year (max $I_{15} = 13$ mm/hr), we found that it was unlikely that
 runoff-generated debris flow occurred during this period because the rainfall intensity threshold
 ($I_{15} = 30$ mm/hr) was not exceeded (Figure 5). During the first field survey, we did not observe
 any changes after 10 minutes during the Water Droplet Penetration Test, indicating a strong
 repellency. We also identified dry ravel, including on slopes outside our basin boundaries.

4.1.2 Year 2

395 In Year 2, there is an increase in areas of negative dNDVI values along the river, possibly
 indicating sediment deposition or exposure of soil. The negative dNDVI along the river is
 unlikely to be vegetation die-off due to the surrounding positive dNDVI during the same period
 400 (Figure 3c). We also identified negative dNDVI values southeast of our basins on the slope face,
 outside of the burn perimeter, but we could not discern if they indicate erosional or depositional
 features. We propose that the negative dNDVI along the river is likely associated with sediment
 deposition, given that we recorded days with higher rain intensities (March 2022 exceeded 20
 mm/hr) that could trigger debris flows either within our basins or upstream (outside our study
 405 area).

4.1.3 Year 3

410 In Year 3, we observed a greater positive dNDVI along the river than in the basins, which likely
 indicates increased vegetation growth along the river due to increased precipitation, as seen in
 the precipitation record (Figure 3d). There were seven events exceeding 15 mm/hr within this
 period, with three exceeding 20 mm/hr (Figure S2). Due to road closures that prevented access
 to the site, we are unable to verify if the negative dNDVI within some areas of the hillslope and
 along the river was due to sediment erosion or debris flows (Figures 3c & 3d).

4.1.4 Year 4

415 Increased positive dNDVI in the basins and negative dNDVI along the river were observed from
 September 2023 to April 2024, which was supported by field observation and (Figures 3e & 4).
 We posit that the positive dNDVI is indicative of the growth of dense shrubs and grasses due to
 increased precipitation in the months prior, while negative dNDVI values indicate sediment

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deposition or removal from rain events, vegetation change, or water ponding. Between April 2024 and September 2024 (**Figure 4**), we observed significant vegetation change with basin slopes exhibiting negative dNDVI values and areas along the river exhibiting positive dNDVI, possibly showing different vegetation responding to the seasonal changes with the shift from wet season to dry season (**Figure 2e & 2f**). Measured hydraulic conductivity increased by nearly an order of magnitude except for Basin A (**Table 2**). Grain sizes were comparable between April 2024 and September 2024 across all basins but were generally reduced compared to the first survey in 2020 (**Table 2**).

Our simulations show that all basins during the wet month of Year 4 could trigger debris flows at $I_{15} = 30$ mm/hr, except Basin D, where they could be triggered at 20 mm/hr (**Table 3, Figure S2**), for which we identified two rain events with very closely matching rain intensity (4th and 7th February 2024). We do observe an increase in areas of negative dNDVI along the river while the basins have mostly positive dNDVI (**Figure S4d**). During the dry months of Year 4, all basins except for Basin A were unlikely to trigger debris flows, and possibly had no surface runoff even at $I_{15} = 30$ mm/hr. In contrast, Basin A could potentially trigger debris flows at $I_{15} = 20$ mm/hr. Simulation results further indicate that at least $I_{15} = 80$ mm/hr is needed to trigger PFDFs in the dry season for basins B, D, and E, which correspond to the I_{15} associated with a 100- to 200-year precipitation event (NOAA, last accessed July 2025).

We suspect that the bell-shaped curves in our modeled dimensionless discharge (**Figure 5**) result from a lack of loose sediments at steeper slopes (e.g., >45 degrees), where the angle of repose is exceeded (e.g., Statham, 1976). The limited slope data available within the basin may also contribute to the high variability at steeper slopes (e.g., >50 degrees in Basin A). The results of the sensitivity tests for each basin at different rain intensities to isolate the effects of hydraulic conductivity, grain size, and vegetation cover on post-fire debris flow triggers are discussed in Section 3.2 (**Figure 6; Table 4**).

5. Discussion

5.1. Evolution of the landscape and post-fire debris flow likelihood

Our simulations informed by the three field surveys suggest that most basins require at least $I_{15} = 30$ mm/hr to trigger debris flows. Observations from nearby fires in Southern California have indicated a wide range of triggering rain intensity in the first year, ranging from less than 10 mm/hr (Cannon et al., 2008; Hoch et al., 2021) to 30 mm/hr (McGuire et al., 2020). In subsequent years, the threshold increased by at least a factor of two (McGuire et al., 2020; McGuire et al., 2021a; Hoch et al., 2021).

Contrary to other fires with records less than 4 years (e.g., DeGraff et al., 2015), our simulations of the Year 4 wet season show higher PFDF likelihood in Year 1 despite having more vegetation cover in Year 4 (e.g., DeGraff et al., 2015) (**Figure 5**). We suspect the main causes of this increase in PFDF likelihood are due to the relatively lower hydraulic conductivity (wetter soil) measured in the wet months and finer grain sizes as compared to the first survey (**Figure 5; Table 2 & 3**). Similarly, lower measured hydraulic conductivity in Basin A during the dry months also contributes to a higher PFDF likelihood shown in our simulations. Our field observations revealed that moist and wetter soil around Basin A during dry months could have lowered the hydraulic conductivity.

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For the other basins with measured high hydraulic conductivity in the dry months, the drier conditions can promote the opening of macropore fractures in the soil, allowing for a significant increase in hydraulic conductivity by several factors (Ritsema and Dekker, 1994; Nyman et al., 2014; Perkins et al., 2022; Martinez et al., 2025). Despite relying on a single measurement, we observed an increase in hydraulic conductivity from the wet to dry season, consistent with Martinez et al. (2025), who also estimated an increase (~5-fold) in mean field hydraulic conductivity at the Contreras Fire in Arizona. By comparison, our highest measured hydraulic conductivity shows several orders of magnitude variation in seasonal variability and is approximately 2 to 4 times greater than values reported by Martinez et al. (2025).

Hydraulic conductivity measurements taken immediately after a fire can be generalized across multiple basins under certain conditions, such as similar burn severity (Rengers et al., 2019). However, regional climate and the timing of field surveys must also be considered as monsoons, droughts, and seasonal variability can influence soil properties (Cannon et al., 2001; DeGraff et al., 2015; Ebel et al., 2022; Thomas et al., 2023; Gorr et al., 2023; Gorr et al., 2024; McGuire et al., 2024; Martinez et al., 2025). The large variability in hydraulic conductivity between seasons within the first two years (Martinez et al., 2025) or even longer, as shown here. This underscores the importance of considering seasonal influence in estimating longer-term PFDF likelihoods.

Although vegetation cover can play a role in debris flow initiation (Rengers et al., 2016a; Tillery and Rengers, 2020; McGuire and Youberg, 2020; McGuire et al., 2021a; McGuire et al., 2024), our simulations suggest a minimal influence on PFDF likelihood as compared to grain size and hydraulic conductivity. For example, when we maintain all parameters from immediately after the fire but include higher vegetation cover a year after the fire (Year 1), the rainfall ID threshold shows little difference in all the basins (Figure 5). This implies that vegetation cover does not significantly reduce the likelihood of debris flow at these basins. This differs from the 2016 Fish Fire in the San Gabriel Mountains, where vegetation recovery plays a bigger role in raising the threshold for triggering debris flows (McGuire et al., 2021a; Hoch et al., 2021). We further examine the influence of increasing vegetation cover through a sensitivity test in Section 5.2.

Despite a significant increase in vegetation cover in our dNDVI after Year 2 due to precipitation (Keeley et al., 2005; Horn and St. Clair, 2017) (Figure 3; Figure S2), a full vegetation recovery does not necessarily inhibit triggering of PFDF if other conditions enable it (Garber et al., 2023). We note, however, that vegetation cover and hydraulic conductivity are not necessarily independent of each other (Atchley and Maxwell, 2011) – increased vegetation cover increases evapotranspiration demand, resulting in faster drying of soils (Zhang et al., 2001), and potentially a more rapid return to higher hydraulic conductivity states. A grass-dominated region combined with evaporation can continue to remove water from the surface soil down to a depth of 50 cm, which leads to further increases in hydraulic conductivity during the dry season (Chavez Rodriguez et al., 2024). Our temporal sampling is insufficient to resolve this phenomenon but would be an important avenue for future study.

Grain size distributions from other fires showed little change or increased over the course of the recovery period (e.g., Hoch et al., 2021). We observed a reduction in measured grain size in the 2024 surveys relative to the first survey in 2020. It is possible that our point source grain size

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measurements ~~do not~~ represent the change in the entire basin, despite prior work suggesting that basin outlets capture representative grain sizes (Santi et al., 2008). Another explanation is that repeated rainfall has removed coarser material and revealed a finer baseline grain size that could represent the hillslope materials (Kean et al., 2019), as shown by consistent grain sizes across the wet and dry seasons. Since we collected samples at the basin outlets, any existing debris flow would leave behind a higher concentration of finer materials in the body (center) as it exited the basin outlet (Iverson et al., 2010). Alternatively, we could be observing deposited finer sediments that are easier to mobilize (Lamb et al., 2008), burying the coarser sediments. ~~We note that the lack of upslope data does limit our ability to verify the samples collected at the outlets of the basins.~~ In any case, the observed variation in grain sizes was not the most significant factor affecting PFDF in our results (Figure 5). ~~Debris flow deposits could rework the sediments in subsequent years (e.g., Hoch et al., 2021; Wall et al., 2022). However, we did not identify strong indications of rework in the basin outlets from our field sampling. We did not observe any significant stratification from our soil cores during the second and third surveys. We recognize that these samples may not fully represent the full range of grain sizes needed to characterize basin-scale grain size.~~ Future work ~~should examine~~ variability ~~within the basin interior and at the outlets~~ over the recovery period ~~to better understand how grain size changes within basins.~~

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5.2 Sensitivity tests between hydraulic conductivity, grain size, and vegetation cover

Higher rain intensities lead to an increase in PFDF likelihood. Studies have also shown that greater rainfall intensities are required to trigger debris flows in the subsequent years after a fire (Caine, 1980; Cannon et al., 2008; Kean et al., 2011; Staley et al., 2013; Tang et al., 2019a; Hoch et al., 2021; Thomas et al., 2021; Thomas et al., 2023). ~~In this section, we show our sensitivity tests on the effects of different parameters (i.e., hydraulic conductivity, vegetation cover, and grain size) at different rain intensities in this section (Figure 6; Table 4).~~

A major difference between the wet and dry seasons from our field surveys is the hydraulic conductivity and vegetation cover (Figures 6 & 7). The significant increase in our measured hydraulic conductivity plays a strong role in changing the PFDF likelihood despite having an increase in vegetation cover (Figure 6), similar to our simulation results. The sensitivity tests indicate that different parameters have a varying degree of influence on the post-fire debris flow. For instance, Basins B and D show that $I_{15} = 30$ mm/hr will trigger a significant PFDF for a number of slopes when the grain sizes are reduced by 50%, whereas Basin E is less affected (Figure 6). These results are also sensitive to changes in the magnitude of hydraulic conductivity. For example, if the hydraulic conductivity increases by an order of magnitude or more, as seen in our field observation from the wet to dry season, we expect the hydraulic conductivity will play a stronger role than the grain size. We suspect that the hydraulic conductivity has a greater impact than grain sizes when comparing seasonal impacts, as it is less likely for grain sizes to have such large variability in a short amount of time (Hoch et al., 2021).

While hydraulic conductivity recovery has been shown to increase monotonically to pre-fire levels (Ebel and Martin, 2017), our observations suggest a potentially non-monotonic relationship of hydraulic conductivity despite tracking seasonal variation for only a year. Such non-monotonic changes have been observed in fires in the southwest United States and could have a significant impact in inhibiting or promoting post-fire debris flows (Hoch et al., 2021; Garber et al., 2023; McGuire et al., 2024; Martinez et al., 2025). Despite needing a higher

temporal resolution to capture the seasonal signal of hydraulic conductivity, we suggest that it is important to account for seasonal variation when estimating the PFDF likelihood. We suspect the temporal variability in rainfall patterns could also influence the triggering of debris flows (Thomas et al., 2021).

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Our sensitivity test on vegetation cover also shows little to no change in the PFDF likelihood between a basin with full vegetation cover and with no vegetation cover, assuming other soil properties remain constant (Figure 6). One potential explanation for why vegetation cover could have a lower impact is that in high-intensity rain events, canopy storage capacity can be saturated, reducing the influence of canopy interception (Hoch et al., 2021). We also note that satellite-derived vegetation cover used in our model input can include shrubs or grasses in areas without tree cover. Areas with high tree cover presence can obscure the understory. Therefore, the vegetation cover here does not necessarily represent understory density and surface roughness, and canopy interception can vary depending on the vegetation type (Zhao et al., 2019). The estimate from our 20-meter point-intercept survey vegetation cover (~81%) is in reasonable agreement with the mean NDVI (0.5191) along the same transect (max NDVI within image is 0.74), which yields ~70% vegetation cover. The dNDVI between the field measurement (April 2024) and 7 months earlier (Sept 2023) was low, with a mean of 0.034.

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Overall, our study suggests that for our study area basins, the combination of lower hydraulic conductivity and finer grain sizes has the greatest impact on triggering runoff-generated debris flows relative to vegetation cover. We propose that the increase in debris flow likelihood in the wet season in the 4th year could reflect short-term variability such as intense rainfall shortly before our field collection, which resulted in significantly low hydraulic conductivity values rather than a long-term yearly increase of debris flow likelihood. Further studies are needed to understand how long-term seasonal PFDF likelihood varies across regions with different climates (e.g., He et al., 2025; Zhou et al., 2026; Ridgway et al., 2026).

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5.3 Applicability of high-resolution imagery to estimate vegetation cover

We demonstrated that PlanetScope's high-resolution and high repeat times can successfully track vegetation change and complement field observation, despite challenges in standardizing the images due to low consistency in orbit and imagery acquisition time. Ground cover surveys and Leaf Area Index (LAI) can estimate vegetation cover and vegetation recovery over time but are limited to basins that are accessible or large enough to not be affected by the coarse spatial resolution from satellites such as Sentinel-2 (10 to 30 meters) and MODIS (500 meters) (Rutter et al., 1975; Hoch et al., 2021; Garber et al., 2023). PlanetScope-derived dNDVI can further distinguish between burned and unburned areas even two years post-fire, showing comparable capabilities to LAI measurements in other fire studies (Garber et al., 2023) (Figures 2 & 3). We note that the point-intercept survey focuses on the understory, but satellite imagery captures the vegetation cover or canopy from tree cover, exposed understory, and bare ground, which could explain the variations in vegetation cover between these two methods.

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We suggest that the strong seasonal vegetation signal observed between the drier and wetter months four years after the fire is due to the transition from perennial shrubs to annual grasses (Figures 4 & 7). This vegetation transition has been observed in other fires in the southwest United States and has the potential to increase fire hazard due to rapid drying (e.g., Keeley et al.,

2005; Horn and St. Clair, 2017; Underwood et al., 2021; Thomas et al., 2021) (Figure 2). Further research is needed to determine the persistence of large seasonal pattern variations and whether they will return to pre-fire levels, with some studies suggesting recovery may take more than a decade (Bright et al., 2019) (Figure 7).

We observed that some trees survived despite the high burn severity as reported in US BAER and our dNDVI. This could indicate that the satellite-derived products are showing changes from either burned or drying out of leaves during the fire. The effects of low cumulative precipitation correspond to low positive dNDVI values, which indicate low levels of vegetation recovery across the burn scar (Figure 3b) (Table 2). Our dNDVI might not be able to fully represent Manning's roughness on channels or hillslopes, and more work is needed to validate the best practices of using dNDVI for constraining Manning's roughness. For example, we identified grasses and shrubs in the field that show comparable dNDVI values as trees with green leaves but no dense undergrowth.

Additional method validation through field and/or other techniques is needed to ensure dNDVI can accurately detect, delimit, and quantify debris flow features. Future studies should integrate lidar, a tool that is successful in detecting and estimating surficial erosion rates and volumes from channel incisions, interrill and rill erosion (Santi et al., 2008; Wagenbrenner and Robichaud, 2013; Sankey et al., 2017). Future studies also need to track vegetation properties such as types, height, and density, along with the sediment changes, to help refine the interpretation of dNDVI variations (e.g., Omasa et al., 2006; Scheip and Wegmann, 2022). This proposed integration of high-repeat, high-resolution remote sensing methods will provide more reliable data for models in post-fire debris flow emergency assessment.

Conclusion

Estimating changes in post-fire debris flow likelihood in multi-year studies can be challenging with limited resources. Here, we showed that we can track landscape changes during the post-fire recovery period, across multiple years, using limited field sampling in combination with temporally and spatially high-resolution satellite imagery. This approach allowed for a post-fire debris flow likelihood assessment following the 2020 Lake Fire in the Los Angeles National Forest. We were able to use field and satellite observations to identify that fast-growing grasses continue to dominate the landscape four years after the fire, and their distribution is largely dependent on precipitation availability. However, our simulations suggest that an increase in vegetation cover does not contribute as significantly to PFDF as the seasonal variability of hydraulic conductivity. Our measured hydraulic conductivity measurements show an order of magnitude difference between wet and dry conditions even in the fourth year after the fire. Despite our inability to verify debris flow occurrence due to limited site access following the fire, our study reveals the complex interaction between hydraulic conductivity, grain sizes, and vegetation canopy in contributing to post-fire debris flow likelihood several years after the fire.

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Figures

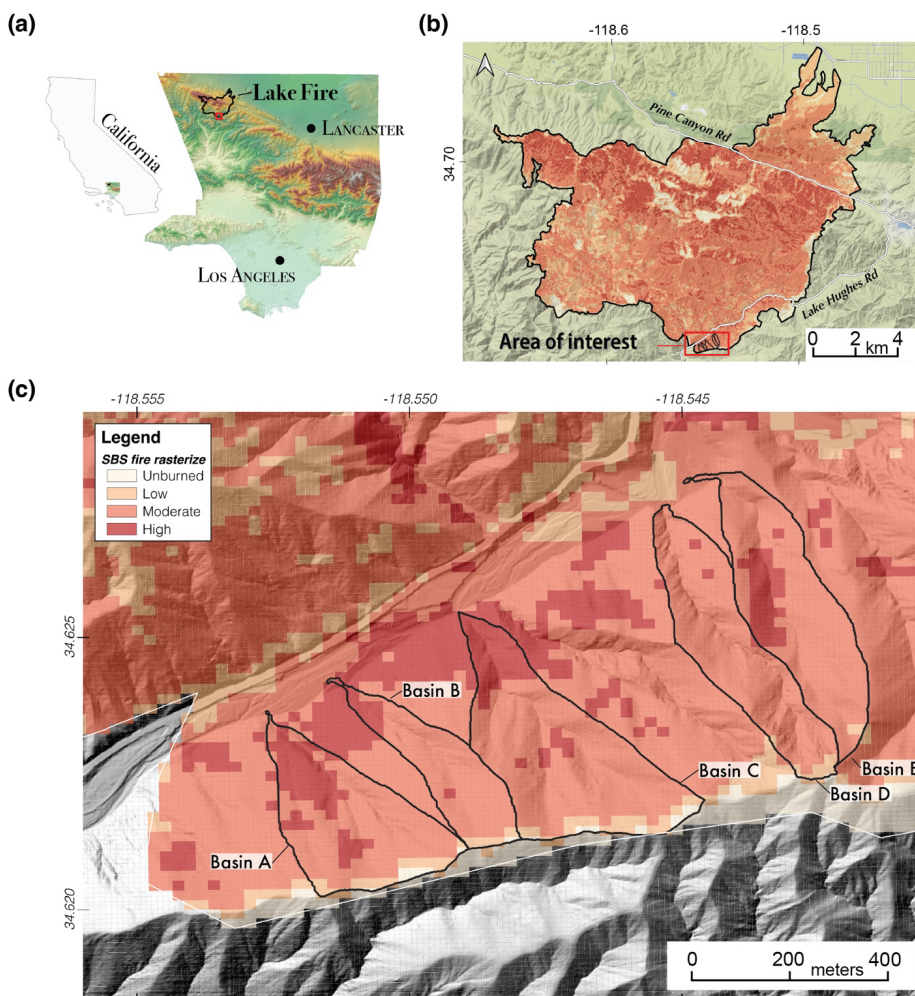
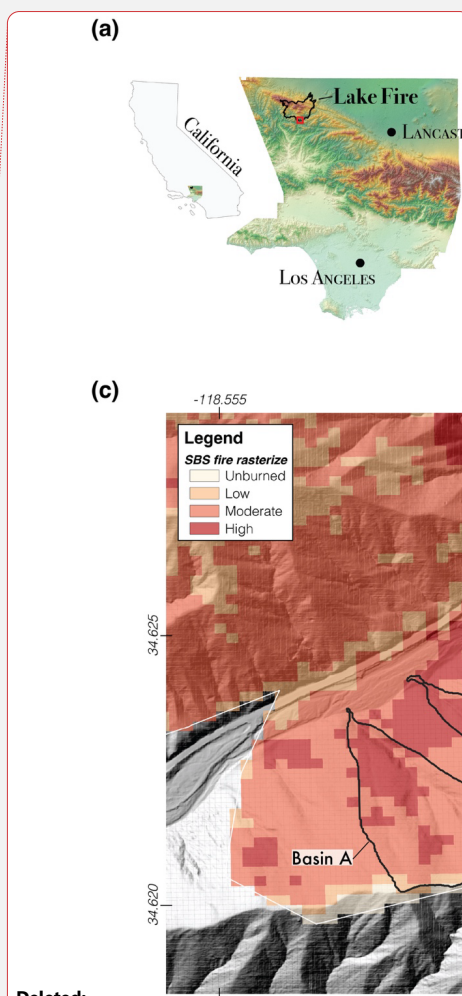
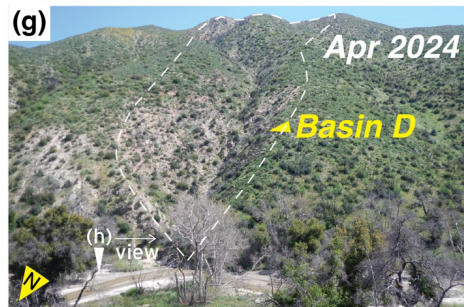
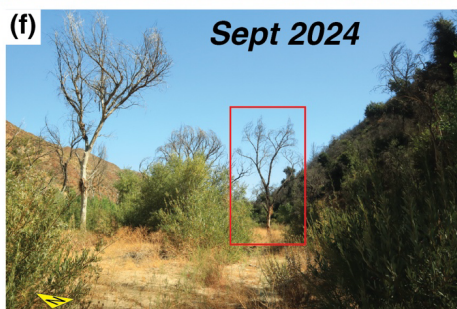
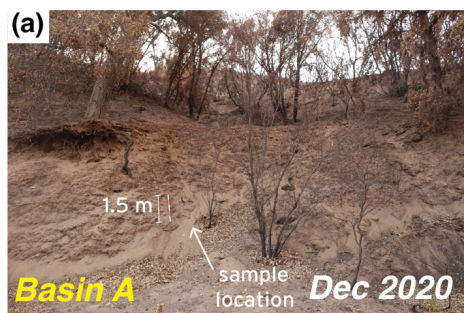


Figure 1: (a) General study area location map, (b) The Lake Fire perimeter. Colors represent the different soil burn severity (SBS) from the US Forest Service (US BAER) in (c). The five sub-basins used in this study (Black outlined areas). Basin outlets are located at the northern tip of each basin.





780 **Figure 2:** Field comparison of the three field surveys (December 2020, April 2024, and
September 2024). (a) Direct view of the Basin A outlet and the location of soil collection in
December 2020. (b) Same as (a) in September 2024. (c) Looking NW towards the vegetation
differences between burned and unburned in September 2024. arrow indicates basin location
only. (d) Basin A in December 2020. (e) Looking NE from Basin A to Basin B in April 2024. (f)
785 Same as (e), but in September 2024, the box identifies the same tree as a reference. (g) Looking
south at Basin D in April 2024 from the highway. (h) Looking SW at Basin D with the river of
lower height in September 2024.

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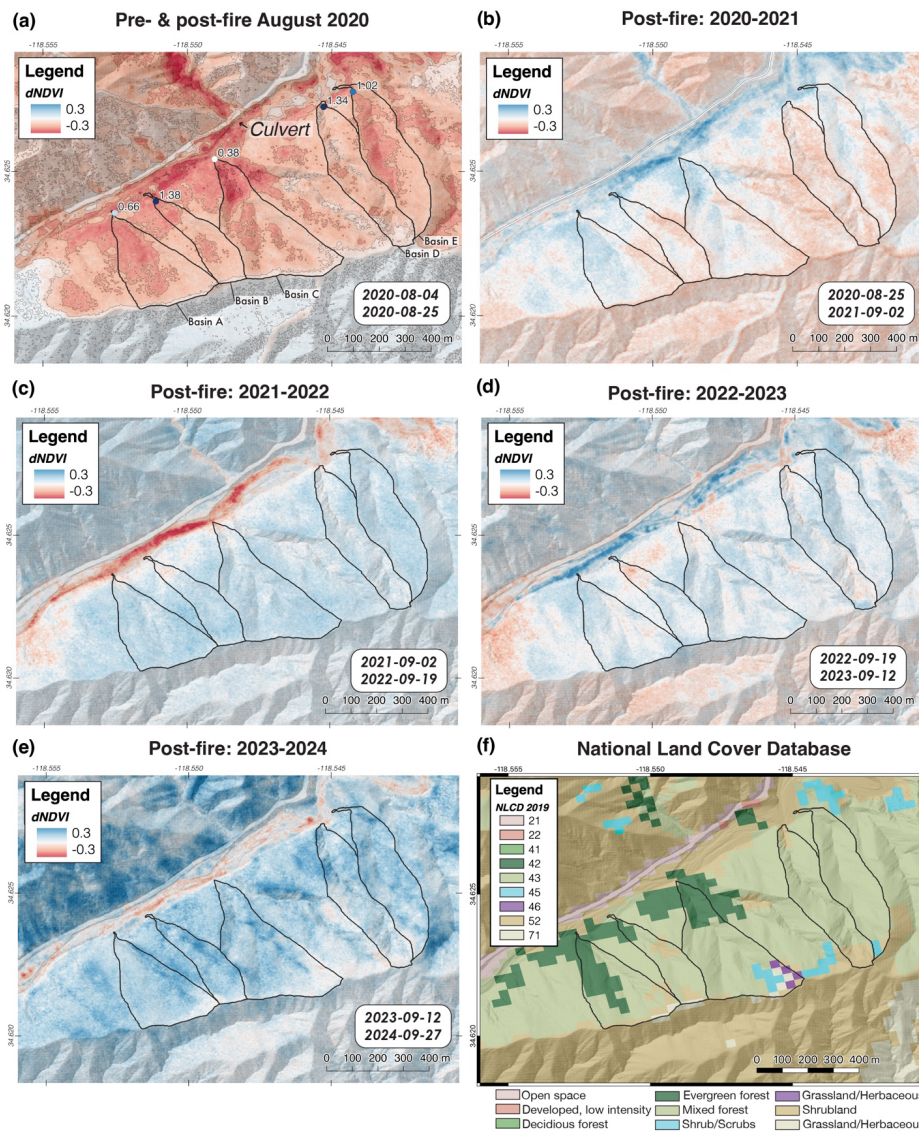
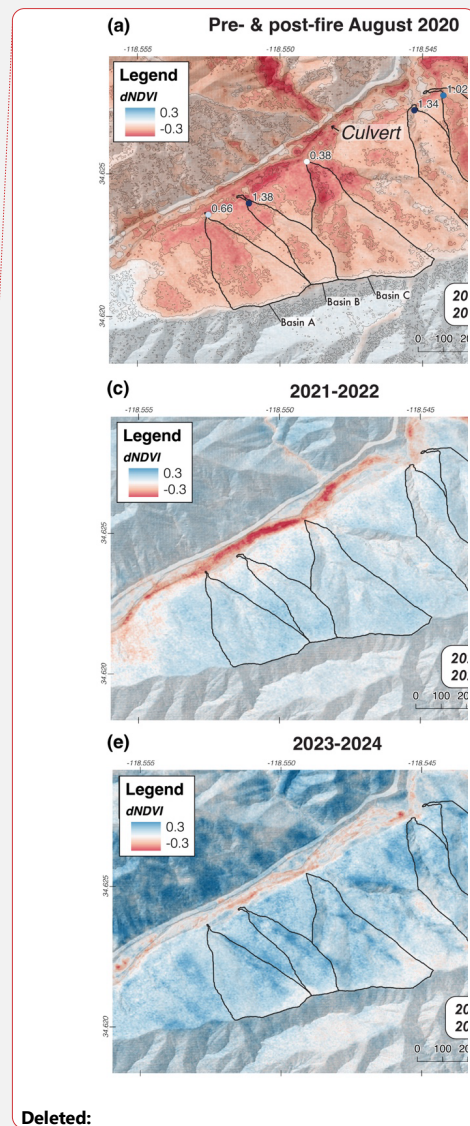


Figure 3: dNDVI of the study sites (a) changes immediately after the fire, (b-e) the subsequent 4 years, and (f) vegetation classification from NLCD2019 (Yang et al., 2018). Cooler colors indicate an increase in the green index (i.e., vegetation), and warmer colors indicate a loss of the



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green index (i.e., soil exposure, drying vegetation). The grain sizes of each of the first field surveys are indicated by the circles labeled with the median grain size in mm (d_{50}).

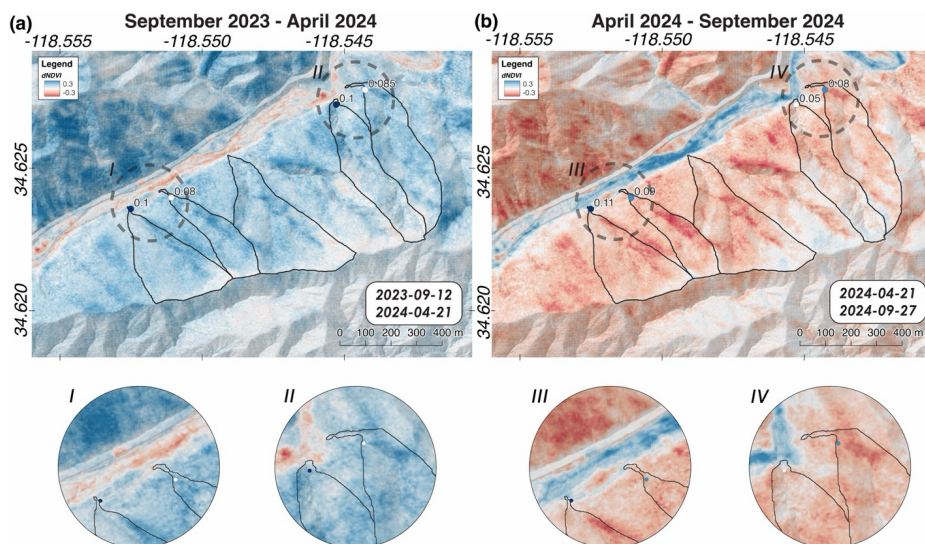


Figure 4: dNDVI of the two field surveys (April 2024 and September 2024) post-September 2023. The bottom panel shows a close-up view of the basin outlets. Values within (a) and (b) represent the median grain sizes (mm), shown here are listed in Table 2.

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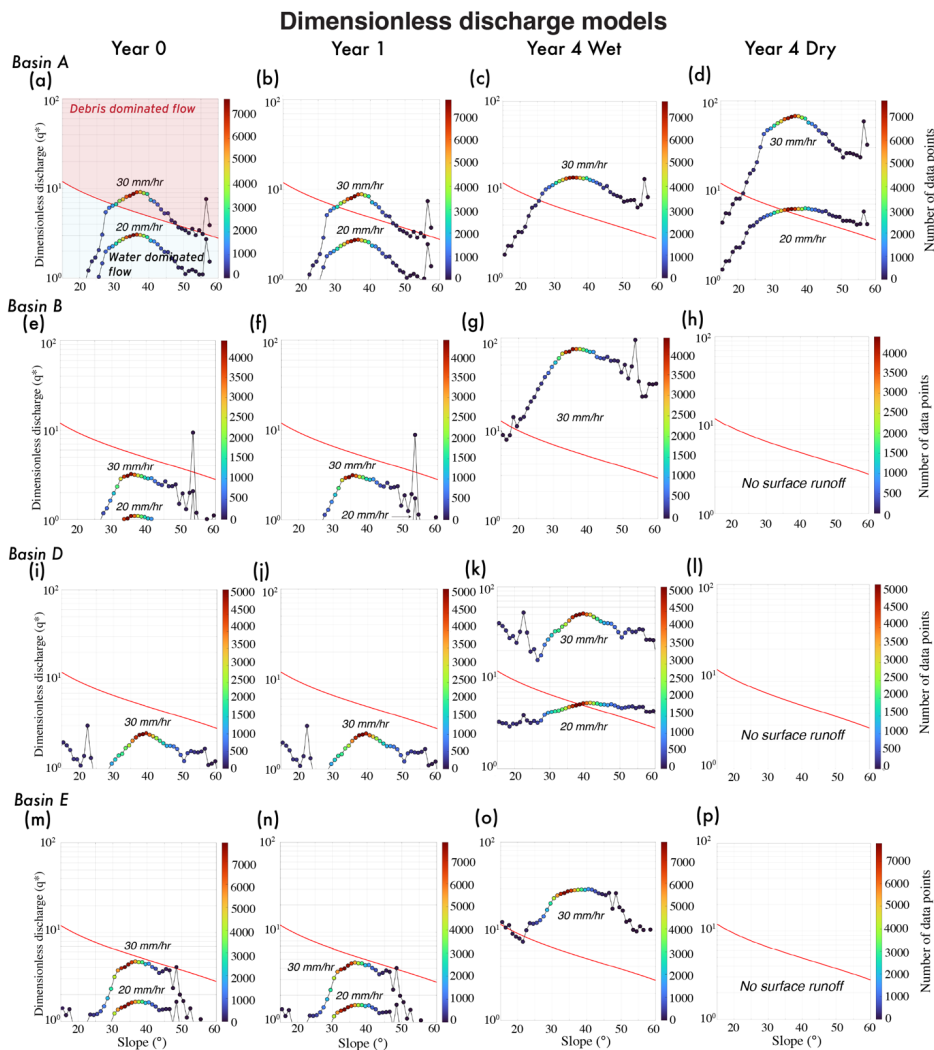
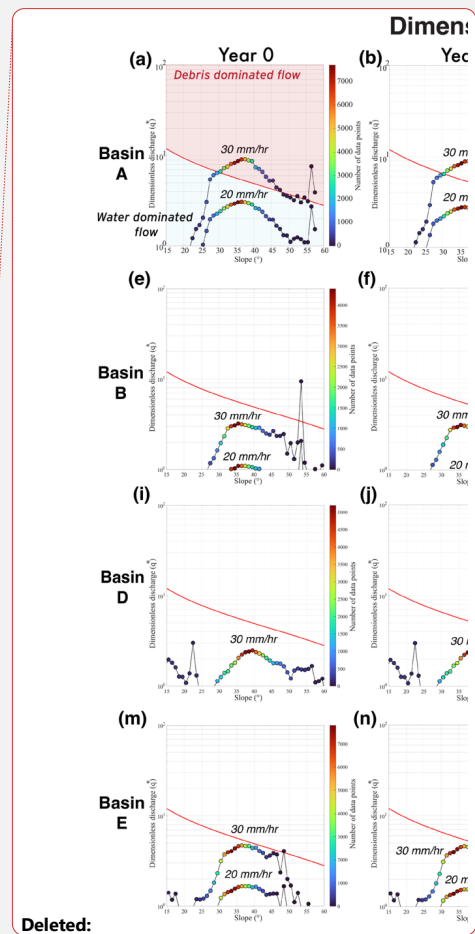


Figure 5: Dimensionless discharge models for the 4 basins (A, B, D, E) showing the number of slopes (x-axis) within each basin exceeding the dimensionless discharge threshold (red line) that is capable of producing debris-dominated flows at different 15-minute rain intensities (i.e., $I_{15} = 20 \text{ mm/hr}$ or 30 mm/hr). Year 0 represents immediately after fire, Water-dominated flows are indicated below the threshold (red line), and greater rain intensity values (I_{15}) indicate a higher rain intensity. Year 1 represents the first year since the fire, where we assumed the same soil



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properties as in Year 0 but with 100% vegetation cover. Year 4 consists of the two field surveys during a wet and a dry season.

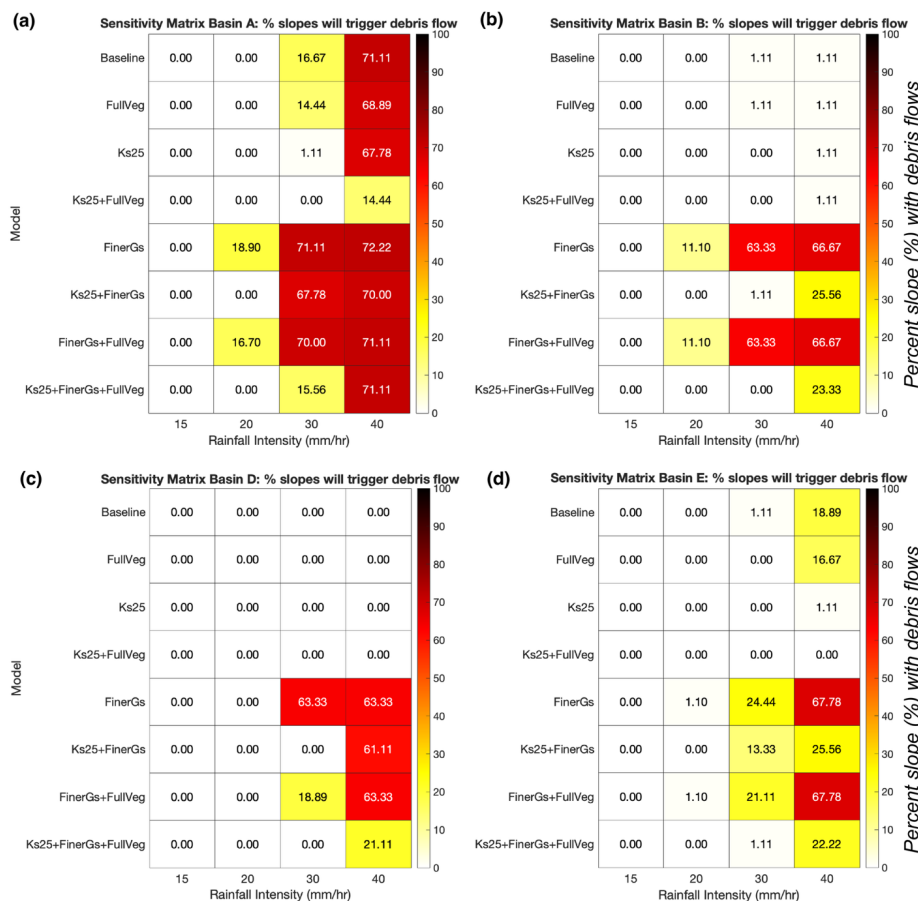


Figure 6: Sensitivity analysis showing how vegetation cover, grain size, and hydraulic permeability affect debris flow initiation across different slopes and 15-minute rainfall intensities (I_{15}). Warmer colors indicate a higher percentage of slopes (% out of 90 degrees) that exceed the debris flow initiation threshold. Percentages do not reach 100% because the maximum slope in each basin is less than 90°. The baseline model uses parameters from the first survey, 3 months after the fire. The rows indicate the different parameters changed from the baseline. For example, Ks25 indicates a hydraulic conductivity of 25 mm/hr (baseline: 10 mm/hr), FullVeg indicates 100% vegetation cover (baseline: 0%), and Finer Grain Size (FinerGs) indicates a reduction of

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grain size by 50% relative to the baseline. See **Table 4** for the description of parameters for each model.

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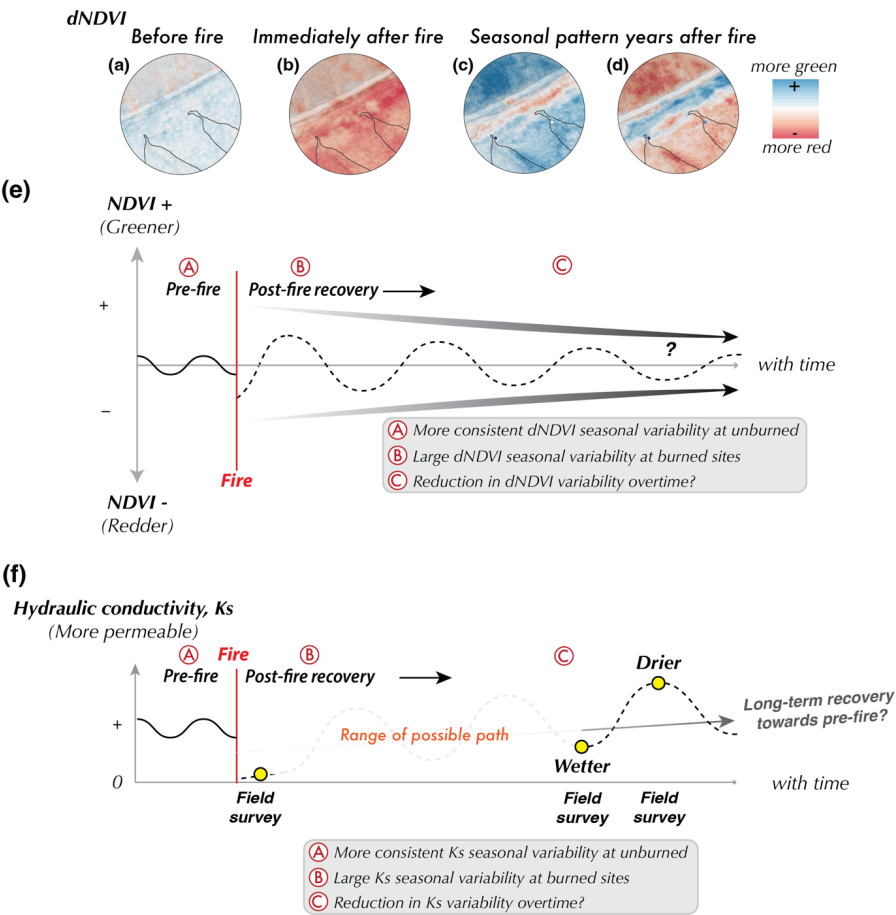


Figure 7: Summary time-series of dNDVI changes (a-d) and conceptual time-series model of (e) NDVI changes over time, along with the dNDVI panel above, and (f) proposed non-monotonic hydraulic conductivity changes over time.

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Tables

Years since fire	Reference date	Subsequent date
Pre-Fire	2020-08-06	2020-08-25
1	2020-08-25	2021-09-02
2	2021-09-02	2022-09-19
3	2022-09-19	2023-09-12
4	2023-09-12	2024-09-27
4-Wet	2023-09-12	2024-04-21
4-Dry	2024-04-21	2024-09-27

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Table 1: The pairs of dNDVI images used to track the yearly vegetation cover and vegetation recovery estimates. Year 4-Wet and Year 4-Dry are defined as the observation period leading up to the field surveys, which also correspond to the seasonal conditions.

Basins	Months since fire (MM/YY)	Hydraulic Conductivity (mm/hr)	Vegetation Cover (fraction)	Pi (Throughfall coefficient)	Average d ₅₀ (mm)	Average d ₈₄ (mm)
A	3 (Dec 2020)	10 ^a	0	1*	0.66	1.77
	12 (Sep 2021)	10 ^a	0.57	0.43	0.66	1.77
	45 (Apr 2024) Wet	34	0.99	0.01	0.1	0.24
	50 (Sep 2024) Dry	22	0.0047	0.99	0.11	0.34
B	3 (Dec 2020)	10 ^a	0	1*	1.38	2.45
	12 (Sep 2021)	10 ^a	0.29	0.71	1.38	2.45
	45 (Apr 2024) Wet	24	0.99	0.01	0.08	0.26
	50 (Sep 2024) Dry	405	0.018	0.99	0.09	0.39
C	3 (Dec 2020)	10 ^a	0	1*	0.38	0.9
	12 (Sep 2021)	10 ^a	0.47	0.53	0.38	0.9
	45 (Apr 2024) Wet	-	0.98	0.02	-	-
	50 (Sep 2024) Dry	-	0.97	0.03	-	-
	3 (Dec 2020)	-	0.054	0.99	-	-
D	3 (Dec 2020)	10 ^a	0	1*	1.34	2.45

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	12 (Sep 2021)	10 ^a	0.03	0.97	1.34	2.45
	45 (Apr 2024) Wet	22	0.97	0.03	0.1	0.27
	50 (Sep 2024) Dry	576	0.13	0.87	0.05	0.2
E	3 (Dec 2020)	10 ^a	0	1*	1.02	1.77
	12 (Sep 2021)	10 ^a	0.26	0.74	1.02	1.77
	45 (Apr 2024) Wet	31	0.99	0.01	0.085	0.25
	50 (Sep 2024) Dry	157	0.049	0.99	0.086	0.32

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Table 2: Input parameters for our dimensionless discharge model over time. dNDVI used for vegetation cover, see the methods section. 45 months since the fire (Year 4) is considered the wet season, and 50 months since the fire (Year 4) or 5 months after the wet season months later is considered the dry season.

^a denotes values used from McGuire et al., (2021). We there are no vegetation cover immediately after the fire (Year 0). Basin C does not have subsequent measurements due to accessibility issues.

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Basins	Months since fire (MM/YY)	Debris flow occurrence (slope) in 15 mm/hr	Debris flow occurrence (slope) in 20 mm/hr	Debris flow occurrence (slope) 30 mm/hr
A	3 (Dec 2020)	None	None	>30
	12 (Sep 2021)	None	None	>30
	45 (Apr 2024) Wet	None	None	>26
	50 (Sep 2024) Dry	None	>34	>22
B	3 (Dec 2020)	None	None	None
	12 (Sep 2021)	None	None	None
	45 (Apr 2024) Wet	None	>48	>18
	50 (Sep 2024) Dry	None	None	None
C	3 (Dec 2020)	>55	>30	>27
	12	>57	>33	>29

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	(Sep 2021)			
	45 (Apr 2024) Wet	-	-	-
	50 (Sep 2024) Dry	-	-	-
D	3 (Dec 2020)	None	None	None
	12 (Sep 2021)	None	None	None
	45 (Apr 2024) Wet	None	>38	All
	50 (Sep 2024) Dry	None	None	None
E	3 (Dec 2020)	None	>50	>45
	12 (Sep 2021)	None	None	48 only
	45 (Apr 2024) Wet	None	None	>24
	50 (Sep 2024) Dry	None	None	None

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Table 3: Slope thresholds for debris flow initiation at $I_{15} = 15, 20$, and 35 mm/hr. Years 0 and 1 have grain size measurements from the first sampling. No vegetation cover immediately after fire (Year 0), and the vegetation cover in Year 1 is from our dNDVI results.

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Properties	Vegetation Cover (0 to 1)	Grain Size (d_{50}) Values from first survey	Hydraulic Permeability (mm/hr)
Baseline	0	Field measured	10
FullVeg	1	Field measured	10
Ks25	0	Field measured	25
Ks25 + FullVeg	1	Field measured	25
FinerGs	0	50% of the field measured value	10
Ks25 + FinerGs	0	50% of the field measured value	25
FinerGS + FullVeg	1	50% of the field measured value	10
Ks25 + FinerGs + FullVeg	1	50% of the field measured value	25

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Table 4: Description of the parameters changed for the sensitivity test. The baseline grain sizes are from the first survey in 2020. Simulation results from the three field surveys are shown in Figure 6, S5, and S6. Baseline: reference parameters from the first field survey; FullVeg: only

940 increased the vegetation cover by 100% (1); Ks25: increasing the hydraulic conductivity to 25 mm/hr; FinerGs: Grain size reduced by half (50%).

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Code and data availability

945 The numerical model (KWAVE) used to simulate model runoff can be found through the
Community Surface Dynamics Modeling System (CSDMS) model repository at
<https://csdms.colorado.edu/wiki/Model:KWAVE>. The MATLAB codes, results, and descriptions
for the models will be available ~~upon acceptance of the manuscript in Dryad~~ (Chong et al., 2026,
950). The rainfall precipitation record can be obtained from LADPW
(<https://dpw.lacounty.gov/wrd/rainfall/>). PlanetScope images can be obtained via
<https://www.planet.com/explorer/> through the education and research program.

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Author contribution

Conceptualization: JHC, ~~AG, BP, GJ, DS~~, SH, EL, LS; Data curation: JHC; Formal analysis:
955 JHC; Funding acquisition: JHC; Investigation: JHC, AG, BP, GJ, DB, ML, DU, DS, SH;
Methodology: JHC, AG, BP, GJ, DB, ML, DU, DS, SH, LS, EL; Resources: JHC, SH; Software:
JHC; Supervision: SH, LS, EL; Visualization: JHC, AG, BP, GJ, DB, ML, DU, DS, SH, EL, LS;
Writing (original draft preparation): JHC, AG, BP, GJ, DB, ML, DU, DS, SH, EL, LS; Writing
(review and editing): ~~JHC, AG, BP, GJ, DB, ML, DU, DS, SH, EL, LS~~.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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