COLLECTION | RESEARCH PAPER
https://doi.org/10.1071/WF25136

CSIRO PUBLISHING

International Journal of WILDLAND FIRE

International Association of Wildland Fire

Insights from a 25-year database of post-fire debris flows in California

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Received: 6 June 2025
Accepted: 3 November 2025
Published: 3 December 2025

Cite this: Oakley NS *et al.* (2025) Insights from a 25-year database of post-fire debris flows in California. *International Journal of Wildland Fire* **34**, WF25136. doi:10.1071/WF25136

ABSTRACT

Background. Post-wildfire debris flows (PFDFs) frequently threaten life, property and infrastructure in California. To date, there is no comprehensive assessment of their spatial distribution, seasonality, atmospheric drivers and interannual variability across the state. **Aims.** We develop a database of PFDF events in California for the period 2000–2024 and analyze the database to describe spatial and temporal variability and impacts of PFDFs. **Methods.** We use peer-reviewed literature, media and agency reports to compile the PFDF event database and various meteorological sources to classify events by storm type. **Key results and conclusions.** We identify 97 PFDF events producing 595 individual PFDFs; events occur predominantly in the Transverse Ranges and the Sierra Nevada. There is high interannual variability in PFDF events. Event frequency tends to be greatest following years with well above-average area burned. PFDF events occur predominantly in the cool season (October–May) and 55% are associated with atmospheric rivers. Approximately 31% of PFDF events occur in the warm season (June–September) associated with the North American Monsoon, tropical cyclones and other thunderstorms. **Implications.** Improved understanding of where, when and why PFDFs occur supports hazard planning and mitigation efforts and allows us to track changes in a warming climate.

Keywords: atmospheric rivers, California, database, extreme precipitation, flood, landslide, natural hazards, post-fire debris flow, wildfire.

Introduction

Post-fire debris flows (PFDFs) are the most severe hydrologic response following wildfire, capable of sweeping away vehicles, washing away bridges and roads, and destroying homes. PFDFs are fast-moving slurries of soil, ash, rocks, burned vegetation and water. They are typically initiated by short-duration (<1 h), high-intensity rainfall within the first few years following a wildfire (Parise and Cannon 2012; Staley *et al.* 2013; McGuire *et al.* 2024). This rainfall need not be extreme; rainfall thresholds observed and prescribed for debris-flow initiation in California are typically associated with the 1–2-year recurrence interval at the 15-min duration (Kean *et al.* 2011; Staley *et al.* 2020; California Geological Survey (CGS) 2024). However, more severe responses are often associated with rainfall multiple times over threshold (Kean and Staley 2021).

Concern for PFDF impacts has increased in California following several years of above-average wildfire activity across the state during the past decade (CAL FIRE 2024*a*) as well as a catastrophic PFDF event on the Thomas Fire burn area in Santa Barbara and Ventura Counties on 9 January 2018 that resulted in 23 deaths, damage to 558 structures, and over US$1 billion in damages (Lancaster *et al.* 2021). A detailed database of events is needed to improve understanding of where, when and why PFDFs occur, their impacts and to track how these characteristics change with time. Previous efforts have compiled PFDF events regionally within California (e.g. Oakley *et al.* 2017; DeGraff *et al.* 2022), or compiled characteristics from well-monitored basins for the purpose of model

Collection: Establishing Directions in Postfire Debris-Flow Science development and verification (e.g. Staley *et al.* 2016; Graber *et al.* 2023) or provided detailed analysis of specific events (e.g. Schwartz *et al.* 2021; Swanson *et al.* 2024). However, a comprehensive database of PFDF events has not been established in California.

Herein, we compile previously disparate sources of California PFDF events into a 25-year database spanning 2000–2024. We then analyze PFDF characteristics in the database such as spatial variability, seasonality, interannual variability and impacts. The database will be maintained as a California Geological Survey product. New PFDF events will be added, and users can submit information to refine event information in the database, add historic events, or provide additional information on new events. This database will be used to improve understanding of PFDF hazards and our ability to mitigate their impacts across the state, inform engineering design and infrastructure planning, and support model verification and post-fire hazard evaluation.

Methods

Criteria for PFDF event inclusion in database

Post-fire flow types occur on a continuum ranging from flood flows to hyperconcentrated, or sediment- and debris-floods, to debris flows. The distinction between flows along this continuum is made based on the volumetric sediment concentration and grain size distribution. Characteristics differentiating flood flows, debris floods and debris flows, summarized from Hungr *et al.* (2001) and Pierson (2005*a*, 2005*b*) are:

- *Flood flows* – closely resemble normal streamflow with sediment concentrations less than 20% by volume, bedload transport composed of sands to cobbles and have predictable Newtonian fluid behavior.
- *Debris floods* – rapid, surging flow that is heavily charged with debris and sediment. Suspended sediment composed of sand-sized particles is common with bedload transport composed of cobbles to boulders. Approximately Newtonian flow behavior with 20–60% sediment concentration by volume. Transient debris dams of boulders and woody material are common. Highly erosive.
- *Debris flows* – rapid, surging flow composed of a slurry of sediment and water with suspended gravels and boulders. Less predictable non-Newtonian flow behavior with sediment concentrations of $>50\%$ by volume. Has the ability to cause catastrophic damage, destroying automobiles, buildings and infrastructure, and can infill and divert streams (Fig. 1).

The goal of the database is to capture PFDFs specifically, distinguishing them from other post-fire runoff-generated flow types as well as from landslide-induced flows. As PFDFs are typically the most impactful post-fire runoff response (e.g. Kean *et al.* 2019), it is valuable to make this distinction and study their characteristics independently from other responses. Defining characteristics used to distinguish debris flows from debris floods in the field following an event include the following (Pierson 2005*a*, 2005*b*):

- Lateral levees are common and are preserved along channel margins as accumulations of coarse clasts (Fig. 1*a*).
- Deposits are typically poorly sorted, matrix-supported and lack imbrication (organization of coarse-grained clasts like fallen dominoes tilted in the downstream direction).
- Deposits can exhibit a convex shape with marginal lobes, which often have an abrupt debris 'snout'. Dunes or ripples are not typically present in debris flow deposits.
- Damage to objects in the flow path is extensive (Fig. 1*b*). Damage to trees results in broken and splintered trunks with rock fragments embedded in wood.

In many cases, these defining characteristics can be overprinted by water-dominated recessional flows or by subsequent flows, making it difficult to distinguish between flood flows and debris flows. For this reason, scientists should consider multiple lines of evidence and observations along the flow path when characterizing a flow as a debris flow.

We define a PFDF 'event' as a 24-h period in which one or more individual PFDFs occurred on a particular burn area. We compiled PFDF events and their associated attributes from scientific literature, agency reports and media. The term 'debris flow' adequately identified potential PFDF events in peer-reviewed literature. When consulting media reports, we expanded our search to include the terms 'mudflow' and 'mudslide'. Each candidate event was evaluated using the following criteria to determine its inclusion in the database:

1. The PFDF event occurred within 5 years of a wildfire in California. Occurrence of runoff-generated debris flows substantially decreases 2–3 years after a wildfire. Debris-flow events more than 3–5 years following wildfire are more likely to have been initiated as shallow landslides (McGuire *et al.* 2024).
2. The PFDF event occurred between the years 2000 and 2024. We selected 2000 as the start year as publications and information become more abundant at approximately this time (McGuire *et al.* 2024).
3. The PFDF event can be constrained to a particular date. This is necessary to conduct analyses of seasonality and storm characteristics.
4. PFDF characteristics were present at the location evaluated. In many cases, the reported PFDF occurs at the basin outlet at a mountain front. In some cases, especially for smaller-volume PFDF, the reported location is a lower-order channel higher up in the basin than the outlet at the mountain front. These are noted and conditions such as impacts are related to the observation location.

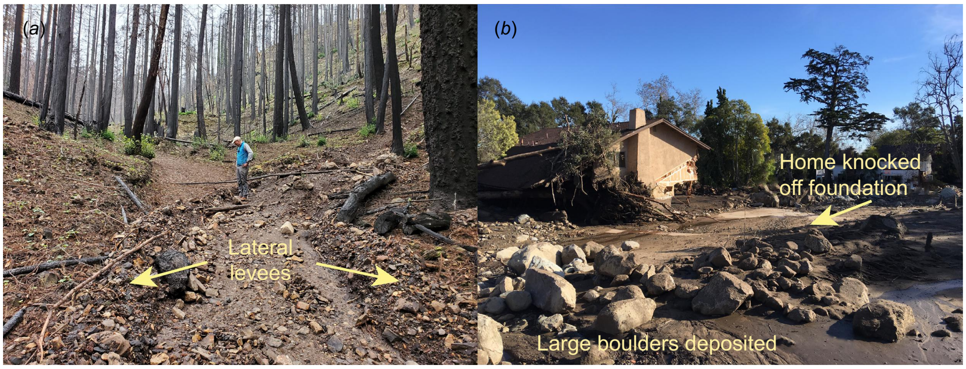

Fig. 1. Examples of PFDFs. (*a*) Deposits from a small PFDF on the 2020 CZU fire that demonstrates lateral levees characteristic of PFDFs. Photo: Matthew Thomas, US Geological Survey (USGS). (*b*) Multiple large PFDFs on the 2017 Thomas Fire caused extensive damage in Montecito and nearby areas. Image shows a location where a home was knocked off its foundation and large boulders of various sizes were deposited by the flow. Photo: Don Lindsay, California Geological Survey.

5. PFDFs reported in peer-reviewed literature and agency reports were assumed to have gone through scientific review and were therefore included. Adjustments made owing to conflicting reports are noted. Where PFDFs were reported in media only, we researched the event and determined flow type based on available evidence.

Candidate post-fire runoff events in the 2000–2024 period that did not meet all criteria were cataloged in a separate database as 'considered', including the rationale for their exclusion. The 'considered' database is not inclusive of all post-fire flood flow events, but rather a subset that were investigated given their potential for classification as PFDF events and allowed us to avoid redundant efforts in PFDF event evaluation. The database presented herein represents a snapshot in time of the best available information; future efforts will add any overlooked events and extend the database into the past and future.

Database fields

The database is available in Supplementary Material S1. This section describes each field of the database. Additional fields, such as rainfall information and sediment yield, were evaluated but are not addressed in this database or analysis (see Supplementary Fig. S1).

Fire information

The database includes the fire name, date of ignition and California counties impacted. These informations are sourced from InciWeb, the federal wildfire incident information system (https://inciweb.wildfire.gov/) and CAL FIRE Incident Information (https://www.fire.ca.gov/incidents).

Resources vary in the level of detail they provide about the locations of individual PFDFs. To provide a consistent representative location across PFDF events for the analysis presented here, we calculate the centroid of the fire perimeter as a reference for the event location (CAL FIRE 2024*b*).

PFDF event timing information

For all events, we record the calendar date (in Pacific Standard Time) on which the PFDF event occurred. When available, we include the start and end time of the window in which the PFDF(s) occurred. If a single time is provided for an event, it is given as the start time of the initiation window.

Each event is given a unique name that includes its fire name and fire ignition year. Some fires experience multiple PFDF events. The event name then includes a letter indicating the order of the event since fire ignition. Additionally, the event number column indicates with numbers whether an event is the first, second, and so on since the fire.

PFDF event flow characteristics

We estimate the number of individual debris flows occurring in each PFDF event. In many instances, there was uncertainly in the number of flows. Given this uncertainty, we bin the count of PFDFs for each event using bins of 1, 2–5, 6–25, 26–100, or >100 and report a minimum estimate of total PFDFs across events. These bins are a slight modification from McGuire *et al.* (2024), who used 0–5 PFDFs as their smallest bin, whereas we create separate bins for one PFDF and two to five PFDFs as we had numerous events where references indicated a single PFDF.

Impacts of PFDF event

We report impacts of each PFDF event, including damage to homes, property, infrastructure, water resources and any reported injuries or deaths. To allow comparison of impacts across events, we assign an impact rating to each event. The ratings are modified from Thomas *et al.* (2023*a*) and described in Table 1.

Meteorological characteristics of PFDF events

We provide a general meteorological context for each PFDF event by classifying events into one of five storm categories,

Table 1. Criteria used to classify impacts of PFDF in database.

Category	Description
Unknown	Impact information not available in resources evaluated
None	Reports and images indicate no impacts or damage occurred
Minor	Minor impairment to infrastructure function (e.g. deposition or erosion along a road that could be re-graded by mechanized earth-moving equipment within a matter of hours, plugged culverts, nuisance mud in yards or shallow mud splash on building walls), minor forms of bodily injury (e.g. abrasions, bruises), short-lived increased sediment in waterways and water quality concerns
Moderate	Moderate structure damage (e.g. repairable damage to structures, mud/debris entered structures but did not cause major damage, structures that were assessed as safe for occupancy or having potential hazards and restricted occupancy), vehicles washed away or damage to vehicles, short-term road closures and light road damage (e.g. roads usable after minor repair), moderate forms of bodily injury (e.g. broken bones), temporary impacts to water quality and fisheries
High	Severe impairment or damage to infrastructure (e.g. road surface washed away and/or prolonged road closures on critical transportation corridors), major structural damage to buildings or irreparably damaged buildings (i.e. assessed as unsafe for occupancy), severe bodily injury (e.g. disfigurement, death), long-lasting, severe impacts to water quality and fisheries (e.g. significant species die-offs)
Extreme	Widespread damage spanning more than 10 km^2. PFDF from several watersheds destroying at a minimum dozens of homes. Numerous deaths. Major damage to critical infrastructure and prolonged closures to major roadways. Very rare events

Table 2. General storm classifications used to categorize each PFDF event.

Category	Description
Cool season storm system (with atmospheric river)	Rainfall events occurring in the cool season (~October–May) driven by mid-latitude cyclone/front systems, shortwaves, cutoff lows, jet disturbances. These rainfall events impact a broad area over a long duration and have embedded convective features or ideal orographic forcing conditions allowing short-duration rainfall intensities conducive to PFDF. Moisture transport for events in this category meets or exceeds atmospheric river criteria.
Cool season storm system (no atmospheric river)	As above, but moisture transport for events in this category does not meet atmospheric river criteria.
Tropical system	Rainfall events associated with moisture from decaying eastern North Pacific tropical cyclones moving into California. Convective storms may be triggered by dynamics associated with the decaying system, surface heating/terrain, or a passing upper-level disturbance.
Monsoon system	Rainfall events associated with moisture transport into California by the North American Monsoon circulation. Convective storms may be triggered by surface heating or terrain or passing upper-level disturbance.
Warm season thunderstorm	Convective storms occurring in the June–September period not associated with North American Monsoon or decaying eastern North Pacific tropical cyclones. These events may be associated with a cold, upper-level disturbance moving over relatively warm, moist low-level air, causing steepening lapse rates and generating localized (or even widespread) thunderstorms. These storms do not produce long-duration, widespread rainfall as in the 'cool season storm system' category.

defined in Table 2. To categorize each event, we consider descriptions of meteorological conditions presented in peer-reviewed literature, National Weather Service Area Forecast Discussions (AFDs) archived at Iowa Environmental Mesonet (IEM) (2025) and review of atmospheric reanalysis products as described below. Additional steps are taken to identify whether a PFDF event features an atmospheric river (AR).

ARs are long, narrow corridors of high water vapor transport that are often associated with impactful precipitation events and flooding in California (Dettinger *et al.* 2011). To identify ARs, we use the Tracking Atmospheric Rivers Globally as Elongated Targets (tARget) algorithm, Version 4 (Guan and Waliser 2024) applied to the global, 1-h, 0.25° × 0.25° horizontal resolution European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5; Hersbach *et al.* 2018). This AR detection (ARDT) algorithm has been applied previously in studies examining the relationship between ARs and geohazards in western North America (e.g. Nash *et al.* 2024). We also calculate the AR scale value for each AR based on the methods of Ralph *et al.* (2019) to provide context on the strength of the AR. The AR scale uses a point-based value of 1–5 based on the duration of AR conditions (Integrated Vapor Transport (IVT) >250 kg m^{-1} s^{-1}) and maximum IVT magnitude during the AR duration at that point.

We evaluate the AR conditions for both tARget and AR scale associated with each PFDF event by examining conditions spanning ±1° in each direction of the centroid of the burn area for the 24 h of the event calendar day (in UTC (Coordinated Universal Time)). If the ARDT identified an AR in the 1° box on the event date, we consider the event to be associated with an AR and assigned the day's maximum observed AR scale value in the box.

To verify our event categorizations, we examine meteorological plots of the ERA5 reanalysis as well as archive weather radar imagery (National Centers for Environmental Information 2025*a*). In some cases, the ARDT incorrectly classifies a monsoon or tropical system event as an AR; this is corrected and noted in the database.

Confidence in PFDF event

Each event is assigned a level of confidence: low, medium, or high. The level of confidence refers to our confidence that the event was a PFDF field-verified by an expert. Confidence is reduced where there is conflicting information on flow type among resources or where reference materials suggest the site may not have been field-verified by subject experts. In cases where there is no information that casts doubt on a PFDF event, 'high' is assigned as a default. Justifications for 'low' and 'medium' confidence are described in database comments. This assessment of confidence is distinct from other inventory work where confidence relates to interpretation of imagery (e.g. Lukashov *et al.* 2019) or where certainty is only achieved through the author's direct verification of physical properties of PFDF at the site (e.g. Neptune *et al.* 2021).

Results

We identified a minimum of 595 PFDFs occurring during 97 PFDF events within 54 unique fires (Supplementary Material S1). Several fires experienced multiple PFDF events (Fig. 2). The 2009 Station Fire in the Transverse Ranges of Los Angeles County experienced the most PFDF events (six), all occurring within the first year following the fire. Three other fires had five PFDF events each, including the 2018 Ferguson Fire in the Sierra Nevada, and the 2016 Fish and 2020 El Dorado Fires in the Transverse Ranges.

Annual variability of PFDF

PFDF count is variable over the 25-year analysis period (Fig. 3). Calendar year 2021 had the greatest number of PFDF events at

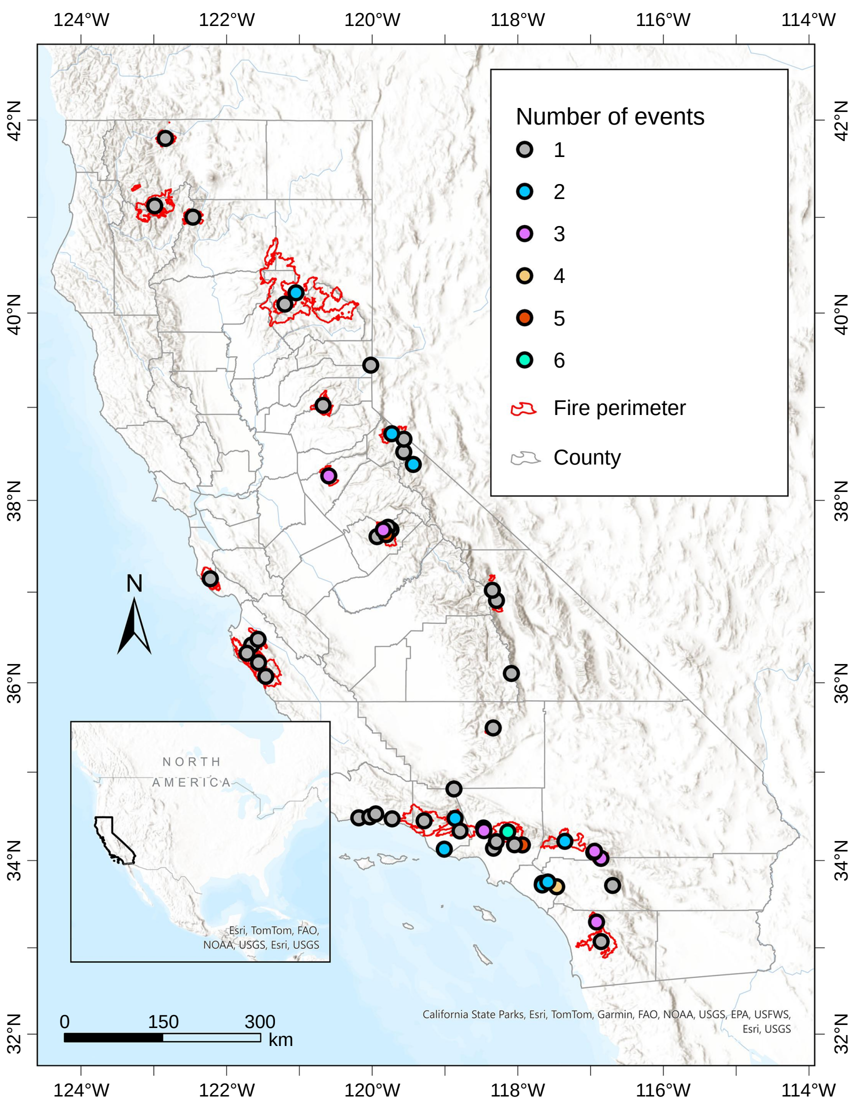

Fig. 2. State of California with county outlines (gray lines), perimeters of 54 fires where PFDF events occurred (red lines) for the 2000–2024 period, and the centroid of each fire colored by the number of PFDF events that occurred (filled circles).

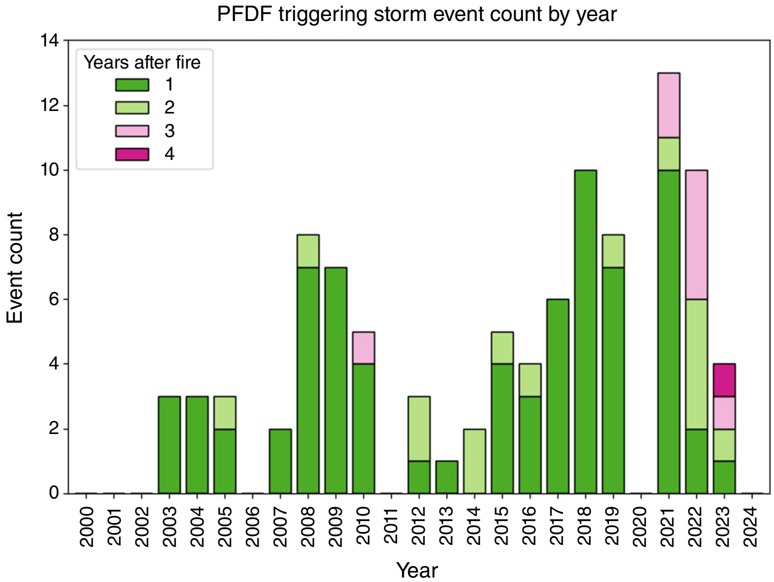

Fig. 3. Count of PFDF events statewide by calendar year. Color fill in bars represents the count in each year that occurred in 1, 2, 3, or 4 years following the fire.

13, followed by 2018 and 2022 with 10 events each. Seven years had no reported PFDF events. The annual average for the study period is 3.88 events. Although PFDF events appear to become more numerous on average in the latter part of the study period, this may be associated with observation bias; we do not evaluate these data for a trend.

Approximately 75% (73) of events occur within 1 year of the fire ignition date, 15% (15) events occur in Year 2, 8% (8) in Year 3, and 1% (1) in Year 4 (Fig. 3). This is as expected as susceptibility to PFDF hazards substantially decreases after the first couple years following a fire (e.g. McGuire *et al.* 2024). Drought conditions may delay a burn area's vegetation recovery, prolonging its susceptibility to PFDF events (e.g. Graber *et al.* 2023). This was the case with the only Year 4 PFDF event in the database on the El Dorado Fire (Swanson *et al.* 2024).

Several factors may influence the interannual variability of PFDFs across California. Here, we examine, by water year (WY, 1 October–30 September), the relationship among PFDF activity and anomalies in area burned and precipitation (Fig. 4). As California's wet season occurs in the winter, the WY approach avoids splitting the winter season across 2 years and more effectively defines 'wet' or 'dry' years in the state. A larger area burned may increase the likelihood that PFDF-susceptible terrain was burned, though large areas may burn that are not susceptible (Staley *et al.* 2016). PFDF are triggered by short-duration, high-intensity rainfall, associated with mesoscale atmospheric processes (of the order of a few to tens of kilometers, with duration of a few hours) that may be embedded within larger storm systems (Oakley *et al.* 2017; Collins *et al.* 2020). Not all storms will have these features, or the features within a particular storm may not affect a PFDF-susceptible area. It is also possible to have an overall dry year but still have high-intensity rainfall intersect with a burn area and trigger PFDFs. Thus, we hypothesize a highly variable relationship between annual precipitation anomaly and PFDF activity.

It is important to note that one storm can produce multiple PFDF events and heavily influence the count for that particular year, creating challenges in evaluating the relationship between seasonal or annual factors and PFDF activity. This was the case in 2021 (Fig. 3) where more than half of the 11 PFDF events occurred in two storms. Four events occurred on 27 January when a narrow cold frontal rainband moved over four burn areas (CZU, River, Carmel and Dolan) in Monterey and Santa Cruz Counties (Zou *et al.* 2023). Three events occurred on 30 July associated with monsoon thunderstorms in the eastern Sierra Nevada and eastern Transverse Ranges. The other four events all occurred in unique storms, and WY 2021 statewide precipitation was 50% of average.

Evaluating by WY, we do not find a strong relationship between anomalies of concurrent or previous year area burned and above-average PFDF count (Fig. 4). Of the 8 years with above-average (>4) PFDF events, 4 had above-average area burned in the preceding year (2018, 2019, 2021, 2022), and 4 had above-average area burned in the concurrent year (2008, 2017, 2018, 2021). Conversely, of the 7 years with above-average area burned in the preceding year, four had above-average PFDF events, 1 at average, and 2 below average. However, the 3 years with the largest PFDF event counts (2019: 12, 2021: 11, 2022: 12) all had preceding years with two to three times average area burned. The only other year with two or more times average area burned in the preceding year was 2009, which had four PFDF events (Fig. 4). Thus, we observe a tendency for years with well above-average area burned in the previous year to have well above-average PFDF activity, though with this small sample size it is difficult to draw conclusions.

From a calendar year perspective (Supplementary Fig. S1), we find that PFDF count tends to be higher in years where the

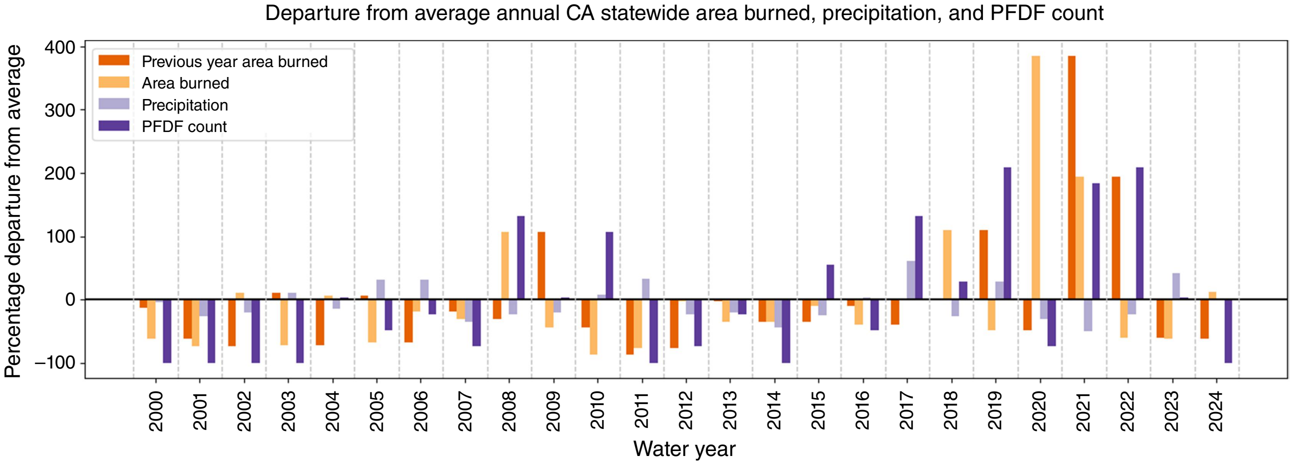

Fig. 4. Previous and current water year area burned departure from average (dark and light orange; CAL FIRE 2024*b*). PFDF count departure from average (dark purple). Statewide precipitation departure from average from California Climate Tracker (Western Regional Climate Center (WRCC) 2025). Water year annual averages are calculated for the period 2000–2024, except precipitation, which is based on 1991–2020, a standard climatological baseline (National Centers for Environmental Information 2025*b*). Vertical dashed gray lines separate each year.

preceding calendar year had above-average area burned. Of the 9 years with above-average (>4) PFDF events, six had above-average area burned in the previous calendar year (2008, 2009, 2018, 2019, 2021, 2022); these were also the 6 years with the greatest number of PFDF events. The only years besides those six to have above-average area burned in the previous calendar year were 2000 and 2004, which had 0 and 3 PFDFs reported, respectively (Supplementary Fig. S1). The relationship between PFDF event count and concurrent calendar year area burned is more variable.

Results indicate there is no clear relationship between annual WY precipitation anomaly and PFDF activity (Fig. 4). We observe a mix of above and below normal precipitation among the 8 above-average PFDF years; 5 of these years have below-normal statewide precipitation and 3 are above. The 3 years with the highest PFDF event counts, 2019, 2021 and 2022, recorded 128, 50 and 77% of WY normal precipitation, respectively. The year in our study with the lowest precipitation, 2021, at 50% of normal, recorded 11 PFDF events, the second-highest annual count in the record. The year with the greatest precipitation, 2017, at 161% of normal, also had an above-average PFDF event count of nine. Taking the calendar year perspective (Supplementary Fig. S1), we observe a mix of above and below-normal precipitation among the 9 above-average PFDF years; 6 of these years have below-normal statewide precipitation and 3 are above. The 3 years with the highest PFDF event counts (2018, 2021, 2022) all had below-average precipitation.

Statewide WY annual average precipitation is a limiting metric in that the precipitation anomaly may be dominated by one region of the state that may or may not coincide with burn areas that have PFDF potential. However, a similar relationship holds at the regional scale for coastal Southern California as seen in the statewide analysis (Supplementary Fig. S2). For this region, of the 9 years in the study period with above-annual average (>2) PFDF events, 3 reported above-average annual precipitation and 6 below. A similar pattern is present when this region is evaluated by calendar year (Supplementary Fig. S3).

Seasonal variability of PFDF

PFDFs occur year-round in California, with 44% of events occurring in the winter months (December–February, Fig. 5*b*). A secondary peak occurs in July and August when 25% of events occurred in those 2 months alone. The autumn season (September–November) is also active, with 23% of events. The spring and early summer (March–June) see the lowest number of events.

The seasonality of PFDF varies by location in the state (Fig. 5*a*). PFDF events in coastal regions often occur in the winter season (December–February), whereas inland locations in the eastern part of the state experience PFDFs predominantly in the summer (June–August) seasons. Autumn (September–November) events occur both in inland and coastal Southern California, as well as in the Sierra Nevada.

We break the PFDF event count by month into Geomorphic Provinces (Fig. 5*b*), a method which groups areas of unique geology, faults, topographic relief and climate (California Geological Survey 2002). Some provinces have PFDF events throughout the year. The Sierra Nevada Province experienced PFDFs in 11 months of the year, and the Peninsular and Transverse Ranges had PFDF events across 9 months. Few events were observed in the Coast Ranges and Klamath Mountains and these were confined to 2–3 months of the year.

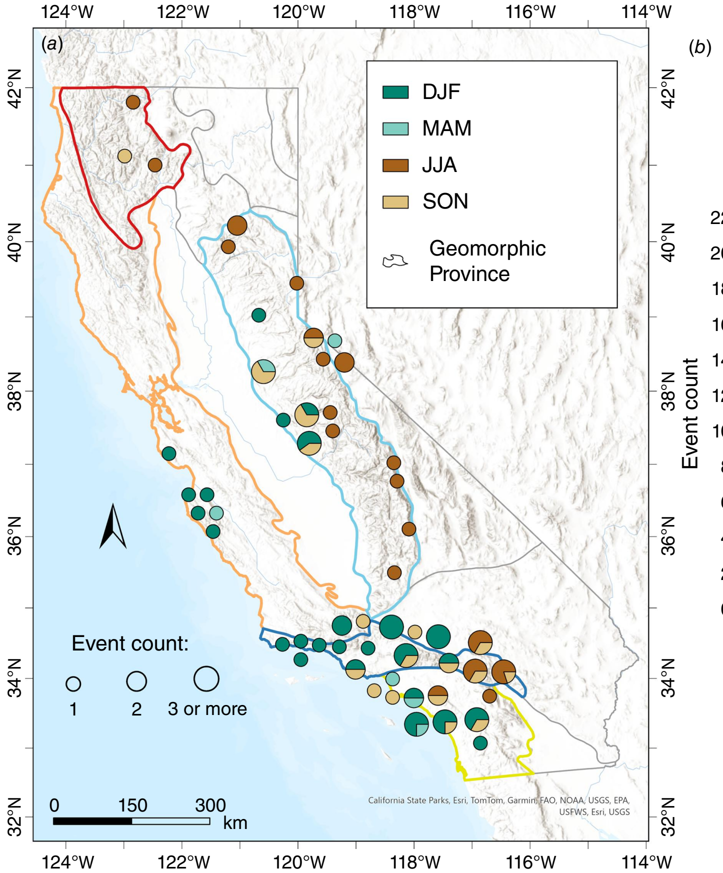

Fig. 5. Panel (*a*) presents the seasonality of PFDF events at each wildfire location. Each wildfire that experienced PFDF events in this study is represented by a pie graph at or near the centroid of the fire perimeter; some are off-centroid for visibility. The size of the pie is proportional to the number of PFDF events that occurred on that fire. The portions of each pie indicate the fraction of PFDF events at that location occurring in each season. The seasons are December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON). The State of California is divided into Geomorphic Provinces (California Geological Survey 2002); colors correspond to labels in panel (*b*). Panel (*b*) provides the count of PFDF events in each month of the year, further grouped by Geomorphic Province.

Spatial variability of PFDF

The spatial distribution of PFDF events in California is influenced by several factors. Areas where steep terrain, vegetation types conducive to moderate-to-high burn severity, frequent wildfire, highly erodible soils and underlying geology, and frequent intense rainfall coincide tend to have a greater likelihood of PFDF events (e.g. Kean and Staley 2021). Although PFDFs occur throughout the mountainous regions of the state, the largest proportion of PFDF events during the study period (42%) was observed in the Transverse Range Geomorphic Province, which has a long history of impactful PFDF events (Cannon *et al.* 2008; Oakley *et al.* 2017). Adjacent to the Transverse Ranges, 18% of events occurred in the Peninsular Ranges. Approximately 30% of events occurred in the Sierra Nevada Province, 7% of events in the Coast Ranges Province and 3% in the Klamath Mountains Province. Several Geomorphic Provinces did not have any PFDFs reported during the study period.

One measure of the severity of a PFDF event is how many individual debris flows occurred within the event. Nearly half (49%) of all PFDF events had only one reported debris flow and 41% had two to five debris flows (Fig. 6*b*). Five PFDF events had 6–25 debris flows. All three PFDF events with 26–100 debris flows were observed in the Transverse Ranges. Only one PFDF event in the study period had >100 debris flows, the 9 January 2018 event on the Thomas Fire in the Transverse Ranges (Swanson *et al.* 2022). This event alone accounts for 41% of the 595 total PFDFs recorded in the database.

Meteorological drivers of PFDF

Storm characteristics influence the spatial distribution and seasonality of PFDF events across the state. The three storm categories prevalent in the June–September period (monsoon system, tropical system and warm season thunderstorm; Table 2) influence PFDF activity in the inland areas of the

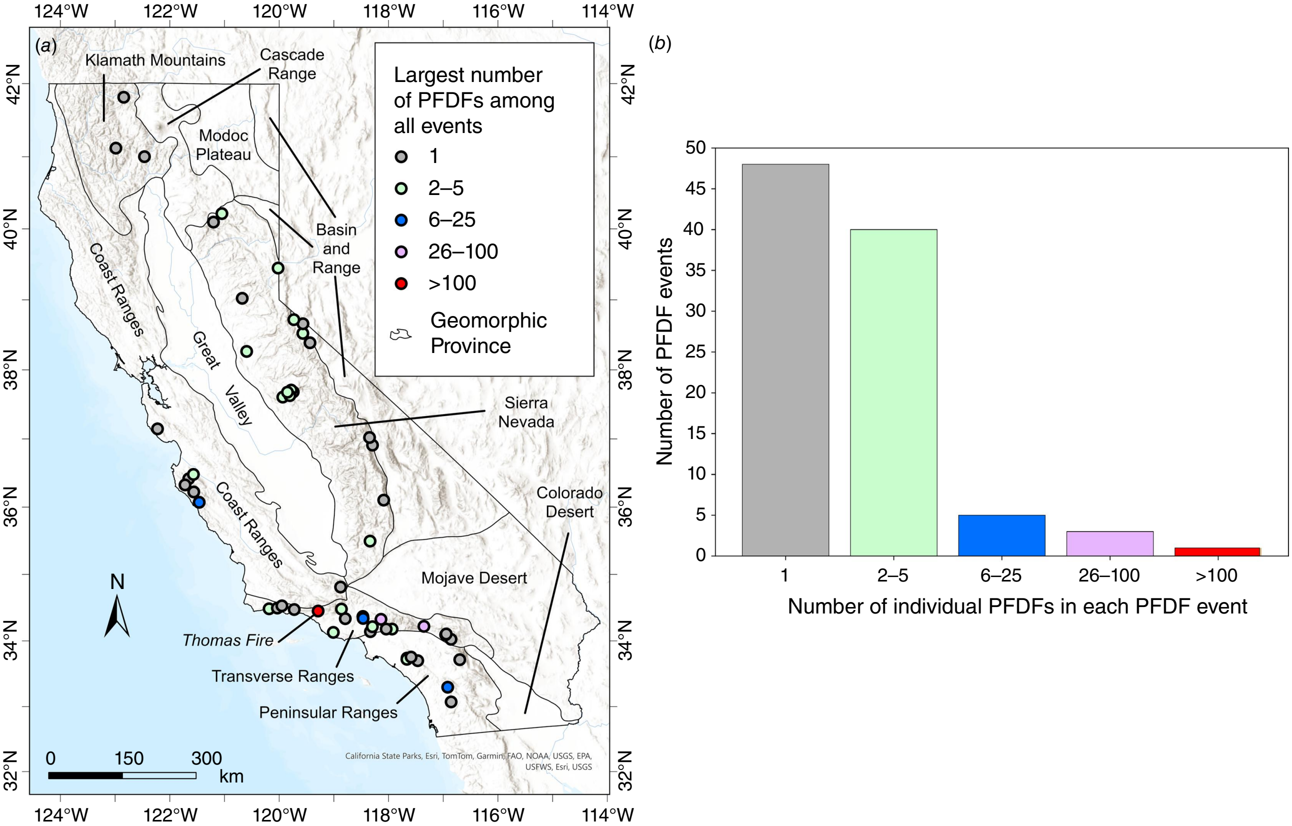

Fig. 6. Panel (*a*) displays centroids of each fire experiencing PFDF events, color filled based on the highest count of individual PFDFs in a PFDF event on that fire. Some fires may have multiple events; only the event with the highest count is displayed. The 2017 Thomas Fire is noted as it was the only burn area with >100 PFDFs in an event. Panel (*b*) shows a histogram indicating the number of individual PFDFs occurring in each PFDF event.

state (Fig. 7*a, c*), and represent 31% of all PFDF events. The poleward paths of decaying eastern North Pacific tropical cyclones often curve eastward over northern Mexico, focusing moisture to the east of the Peninsular Ranges and Sierra Nevada, and typically occur from mid-August through mid-October (Corbosiero *et al.* 2009). Moisture transport and thunderstorm activity associated the North American Monsoon (NAM) often extends poleward along the eastern side of the Peninsular Ranges and Sierra Nevada, resulting in the potential for intense rainfall in these areas from July to September (Adams and Comrie 1997; Becker 2021). Events in the 'warm season thunderstorm' category primarily impact the northeastern portion of the state. Owing to the influence of the cool Pacific Ocean, warm season thunderstorms in coastal regions, especially those producing heavy rainfall, are rare.

PFDF events in the coastal regions and western slope of the Sierra Nevada are primarily associated with cool season storm systems (with and without ARs), making up 69% of all PFDF events in the study period. These systems primarily occur October–May and include mid-latitude cyclone/front systems, among other synoptic features. Convective features embedded within these systems can produce high-intensity rainfall conducive to PFDF (e.g. Oakley *et al.* 2017; Schwartz *et al.* 2021; Zou *et al.* 2023). Under favorable conditions, rainfall rates are enhanced as the system interacts with the terrain, which may also produce rainfall intensities conducive to PFDFs (e.g. Lin *et al.* 2001).

Over half (55%) of PFDF events occur in the context of cool season storm systems with ARs. However, it is important to note that a vast majority of ARs impacting California do not trigger PFDFs. ARs are prevalent in California's cool season, occurring ~18–54 days per year and associated with ~40–60% of annual precipitation (Rutz *et al.* 2014). We do not see evidence that the strength of the AR relates to PFDF occurrence. Events occur with similar frequency across AR1, 2 and 3 conditions (Fig. 7*b*). Of the 53 PFDF events that occurred with moisture transport meeting AR criteria, 16 occurred during AR1 (weak) conditions, 20 during AR2 (moderate) conditions, 15 during AR3 (strong) conditions, and 2 during AR4 (extreme) conditions. No PFDFs were observed with AR5 (exceptional) conditions. Similarly, we do not observe a relationship between AR strength and PFDF impacts (Supplementary Fig. S4). It is possible for a storm featuring a strong AR to lack the atmospheric processes

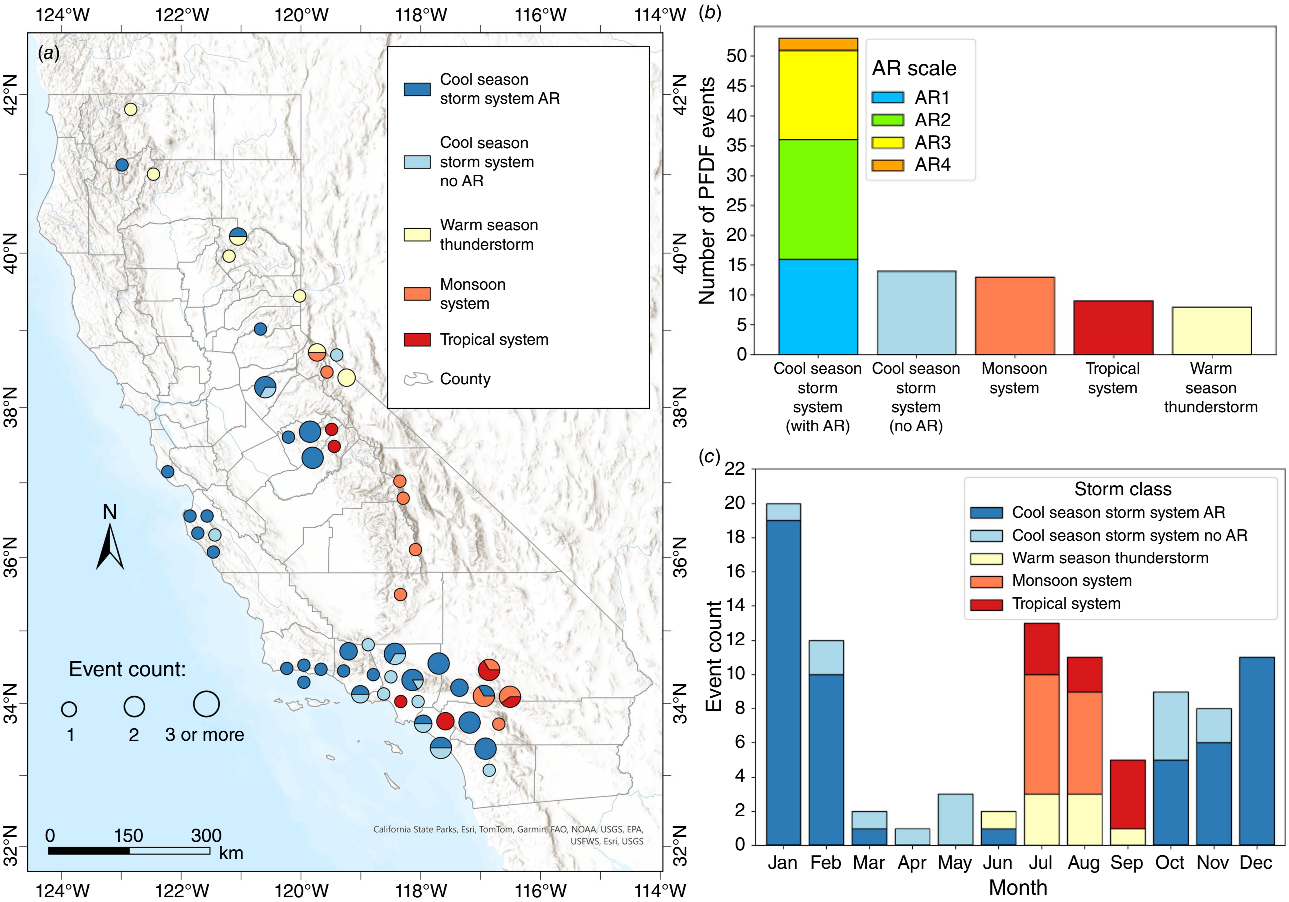

Fig. 7. Panel (*a*) presents the storm category or proportion of storms in each category associated with PFDF events at each wildfire location. Each wildfire that experienced PFDF events in this study is represented by a pie graph at or near the centroid of the fire perimeter; some are off-centroid for visibility. The size of the pie is proportional to the number of PFDF events that occurred on that fire. Panel (*b*) provides the count of PFDF events in each storm category. Panel (*c*) shows the count of PFDF events by month (as in Fig. 5*b*), grouped by storm category.

necessary to produce short-duration, high-intensity rainfall conducive to PFDF (e.g. Thomas *et al.* 2023*b*).

PFDF impacts

Each PFDF event is assigned an impact rating (Table 1) based on the available information. The majority of PFDF events result in no or minor impacts, with only 9% in the high to extreme categories. The only event categorized as 'extreme' in the record was the 2018 PFDF event on the Thomas Fire (Lancaster *et al.* 2021) (Fig. 8).

Impactful events (moderate or higher) are more prevalent in the southern part of the state. This is due to the higher frequency of PFDF events in this area as well as larger populations and development on alluvial fans and in the wildland–urban interface (Federal Emergency Management Agency (FEMA) 1989; Radeloff *et al.* 2018). A caveat to this analysis is that not all impacts were necessarily reported or discovered in our research; thus, there is potential some events are rated low relative to actual impacts. Nevertheless, this analysis provides some insight to spatial patterns and frequency of PFDF impacts.

Discussion

In compiling this PFDF event database, we rely heavily on determinations of flow type made by authors of previous studies. In many cases, there are neither photo evidence nor detailed observations accompanying these determinations, limiting our ability to validate them. Events primarily sourced from media where imagery and reports are limited also present uncertainty and contribute to the potential for under- or over-reporting PFDF occurrence. Future efforts to distinguish between flow types will benefit from quantitative methods such as the Q* method (Cavagnaro *et al.* 2024). This method uses channel cross-section surveys to calculate the ratio of observed peak discharge to the theoretical maximum water discharge from rainfall runoff to make a distinction between flood and debris flows. Additional training for

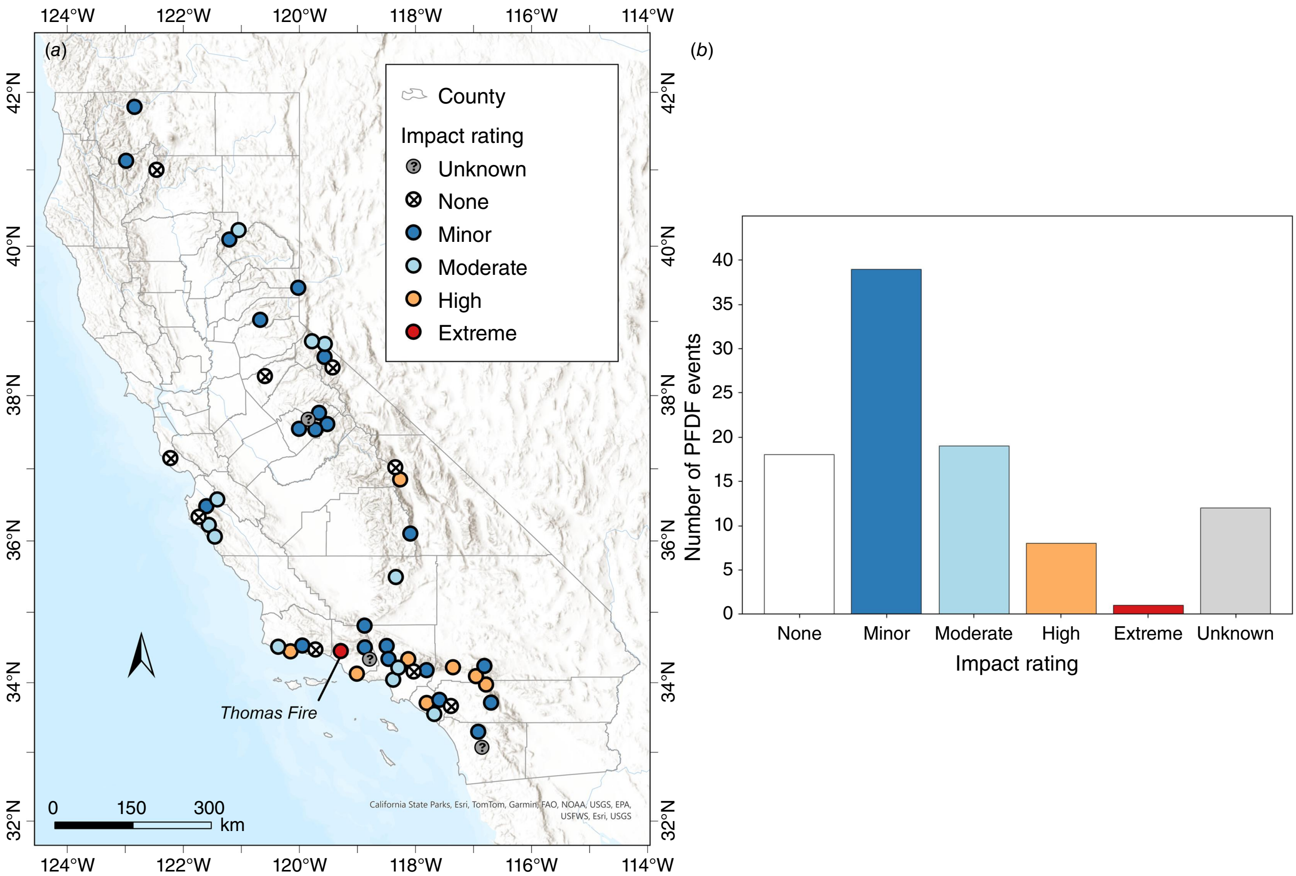

Fig. 8. Panel (*a*) color-filled circles indicate the maximum impact rating among PFDF events at each wildfire location. Each wildfire that experienced PFDF events in this study is represented by a markerat or near the centroid of the fire perimeter; some are off-centroid for visibility. The 2017 Thomas Fire is noted as it was the single event meeting 'extreme' criteria. Panel (*b*) provides the count of PFDF events in each impact category across all PFDF events.

partners frequently in the field (e.g. law enforcement, transportation agencies, public works, rangers) and development of reporting schema may improve reporting and cataloguing of events.

There are two primary sources of bias that may be present in PFDF reporting. First, post-fire runoff events are most likely to be reported where they impact human activity, such as blocking roads or damaging homes. PFDFs in the backcountry out of view of road networks may not be reported, and if reported, may have high uncertainty in date of occurrence. Second, many reported events are associated with intensive monitoring efforts on individual burn areas (e.g. Station Fire, Fish Fire, Ferguson Fire). This may bias the frequency of PFDF events in these areas. Emerging programs focused on burn area hazard evaluation and monitoring (such as the California Geological Survey Burned Watershed Geohazards Program, https://www.conservation.ca.gov/cgs/bwg/program) will allow improved monitoring of post-fire runoff responses and their impacts and may help reduce observation bias over time.

We present a cursory analysis of the relationship among PFDF activity, precipitation and area burned. Future studies can investigate these relationships, or lack thereof, in greater detail with additional metrics such as area burned in susceptible terrain and interannual variability of short-duration intense rainfall. Additional analysis of the mesoscale conditions associated with PFDF activity across the state and the performance of operational mesoscale models in capturing these features and their associated precipitation would support improved forecasting of PFDF events (e.g. Oakley *et al.* 2023).

The 25-year study period is short for drawing conclusions about the spatial and temporal variability of PFDFs in California, though provides a useful starting point to better understand these events. We will build the database stretching back in time and forward as new events occur. A web page is under development that will allow users to access, map and download the PFDF database as well as submit information and observations. This will support improved PFDF monitoring as well as broader efforts to document and quantify the impacts of landslides (Godt *et al.* 2022). A next step in the PFDF database development is to map the basin outlet locations for individual PFDFs where possible. The results of this analysis will support additional efforts such as assessing PFDF-triggering rainfall and evaluating the characteristics of basins producing PFDFs across the state.

Conclusion

We developed a database of post-fire debris flow events (PFDF) occurring in California over a 25-year period (2000–2024) based on scientific literature, media and agency reports and assessed spatial and temporal characteristics of PFDF activity in the state.

We identified 97 PFDF events across the state, comprising a minimum estimate of 595 individual PFDFs. Events primarily occurred in the Transverse Range, Peninsular Range and Sierra Nevada Geomorphic Provinces. There is high interannual variability in PFDF events, with a peak of 13 events in 2021 and 7 years in which no events were recorded. A majority (75%) of events occurred in the first year following a wildfire and only one occurred in the fourth year post-fire. Years with well above-average PFDF events often follow years with well above-average area burned. Above-average annual precipitation does not appear to increase the likelihood of PFDF events.

In terms of seasonality, PFDF event occurrence has a primary peak in the winter season (December–February) and a secondary peak in July–August. The winter peak is associated with cool season storm systems, 55% of which feature atmospheric rivers. Winter season PFDF events predominantly occur in coastal regions and the western slope of the Sierra Nevada. In July–August, events tend to occur in eastern and inland portions of the state, associated with the North American Monsoon, decaying eastern North Pacific tropical cyclones, or other warm season thunderstorms. A majority (72%) of PFDF events had unknown, no, or minor impacts, with the remaining producing moderate to extreme impacts. These range from mud and debris entering structures causing repairable damage and vehicles washed away to widespread damage to dozens of structures and multiple deaths.

This PFDF event database informs California decision makers of where and when these events tend to occur, which supports effective planning and implementation of mitigation strategies. The database is used by the State of California's Watershed Emergency Response Teams in post-fire assessments to assess the likelihood of future PFDF occurrence. The database may also support PFDF model verification. Projections suggest that the frequency and spatial distribution of PFDFs in California is likely to change in a warming climate (Thomas *et al.* 2024). The development of this database and efforts to extend it into the past and future allow us to track changes in PFDF characteristics and support preparedness and resilience for these damaging events.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study are available in the article and accompanying online supplementary material.

Conflicts of interest. N. S. Oakley is a Guest Editor of *International Journal of Wildland Fire* but was not involved in the peer review or decision-making process for this paper. The authors have no further conflicts of interest to declare.

Declaration of funding. Oakley, Cheung and Lindsay were supported by the California Geological Survey. Contributions from Nash used the EXPANSE supercomputer, which was made available by the Atmospheric River Program Phase V, supported by the California Department of Water Resources (award 4600015671) and the Forecast Informed Reservoir Operations Program Phase 3 supported by the US Army Corps of Engineers Engineer Research and Development Center (award W912HZ-15-2-0019).

Acknowledgements. We thank Stefani Lukashov for sharing PFDF records previously compiled that supported the development of this database. We thank David Cavagnaro for support in calculating area burned by year. We also thank the many scientists who produced publications on PFDF events and who provided clarifying information in support of the development of this database.

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