Southern California has a long history of damaging debris flows after wildfire. Despite recurrent loss, forecasts of the frequency and magnitude of postfire debris flows are not available for the region like they are for earthquakes. Instead, debris flow hazards are typically assessed in a reactive manner after wildfires. Such assessments are crucial for evaluating debris flow risk by postfire emergency response teams; however, time between the fire and first rainstorm is often insufficient to fully develop and implement effective emergency response plans like those in place for earthquakes. Here, we use both historical distributions of fire and precipitation frequency and empirical models of postfire debris flow likelihood and volume to map the expected frequency and magnitude of postfire debris flows across southern California. We find that at least small debris flows can be expected almost every year, while major debris flows capable of damaging 40 or more structures have a recurrence interval between 10 and 13 years, a return interval that is comparable to a magnitude 6.7 earthquake. A sensitivity analysis to possible future changes in current fire and precipitation regimes indicates that debris flow activity in southern California is more sensitive to increases in precipitation intensity than increases in fire frequency and severity. Projected increases in rainfall intensity of 18% result in an overall 110% increase in the probability of major debris flows. Our results, in combination with an assessment of exposure, can be used to prioritize watersheds for further analysis and possible prefire mitigation.

Plain Language Summary  Southern California has an especially high risk of debris flows after wildfire. While debris flow hazard assessments are routinely conducted after wildfires, time between the fire and the first rainstorm is seldom enough to use this information to fully develop and implement effective emergency response plans. Here, to identify these hazards before a wildfire occurs, we map the frequency and magnitude of postfire debris flows across southern California in a somewhat similar manner as earthquake hazards are already mapped for the state. The maps are developed using both historical distributions of fire frequency, fire severity, and rainfall intensity and the same models to assess debris flow hazards after real fires. We also evaluate the sensitivity of debris flow frequency and magnitude to possible future changes in fire behavior and precipitation intensity. We find that at least small postfire debris flows can be expected almost every year in southern California, and major debris flows capable of damaging 40 or more structures can be expected about every 10–13 years. We also find that possible future increases in rainfall intensity could substantially increase the frequency of major debris flows.

1. Introduction

Wildfire substantially increases the susceptibility of steep slopes to debris flow, a fast-moving mixture of water, soil, and rock that can cause property damage and loss of life (e.g., Cannon & DeGraff, 2009; Lin et al., 2010; Lukashov et al., 2019; McPhee, 1989). The risk of postfire debris flows is perhaps nowhere greater than in southern California due to the combination of high fire frequency, steep topography, dense population, and recurrent rainstorms delivering high intensity rainfall. Over the last 100 years, major events causing widespread damage (40 or more structures) and/or loss of life have occurred on average every 13 years (Table 1 and Figure 1). Events that cause more localized, yet substantial damage have occurred more frequently (e.g., Abcarian, 2016; Schwarz, 2017; Staley et al., 2013). The loss in southern California has spurred construction of sediment retention basins to mitigate debris flow impacts (e.g., McPhee, 1989; Rantz, 1970; Wohlgemuth & Lilley, 2018), research to understand postfire debris flow processes (e.g., Cannon, 2001; Kean et al., 2011; Lamb et al., 2011; McGuire et al., 2017; Rice & Foggin, 1971; Santi et al., 2008;
Table 1
Major Postfire Debris Flow Events in Southern California

| Date                  | Location (fire)                                                                 | Magnitude   | Impacts                                      | References                                    |
|-----------------------|--------------------------------------------------------------------------------|-------------|----------------------------------------------|----------------------------------------------|
| January 1, 1934       | La Crescenta-Montrose, Los Angeles County (1933 Pickens fire)                   | >500,000 m³ | At least 42 fatalities, 483 homes damaged    | Chawner (1934), Eaton (1935), and Kraebel (1934) |
| January 18–27, 1969   | Azusa and Glendora, Los Angeles County (1968 Canyon fire)                       | >100,000 m³ | 175 Homes damaged                            | Geissner and Price (1971), Kenney (1969), and Scott (1971) |
| February 8–10, 1978   | Hidden Springs, Los Angeles County (1977 Middle fire)                           | 300,000 m³  | 13 Fatalities, all structures destroyed      | Davis (1982) and McPhee (1989)                |
| February 8–10, 1978   | Sunland and La Crescenta-Montrose, Los Angeles County (1975 Mill fire)          | 100,000 m³  | Approximately 50 homes damaged               | Davis (1982) and McPhee (1989)                |
| January 9, 14, 29 and  | San Bernardino, San Bernardino County (1979 Daley fire)                          | 200,000 m³  | 40 Homes damaged                             | Slosson et al. (1991)                         |
| February 16, 1980     |                                                                                |             |                                              |                                              |
| December 25, 2003     | San Bernardino, San Bernardino County (2003 Old and Grand Prix fires)           | >1,000,000 m³ | 16 Fatalities, 52 homes damaged             | Bernard (2007), Cannon et al. (2008), and Chong et al. (2004) |
| February 6, 2010      | La Cañada-Flintridge, Los Angeles County (2009 Station fire)                    | 10,000 m³   | 40 Homes damaged                             | Kean et al. (2012) and Lin et al. (2010)      |
| January 9, 2018       | Montecito, Santa Barbara County (2017 Thomas fire)                              | 700,000 m³  | 23 Fatalities, 408 homes damaged, >0.5 billion USD in direct costs | Kean et al. (2019), Lukashov et al. (2019), and Oakley et al. (2018) |

Figure 1. Photos of damage from major postfire debris flows during the last two decades in southern California: (a) December 25, 2003, Devore, San Bernardino County (Old/Grand Prix fires); (b) February 6, 2010, La Cañada-Flintridge, Los Angeles County (2009 Station fire); (c) and (d) January 9, 2018, Montecito, Santa Barbara County (2017 Thomas fire). Photo credits: USGS.
Importantly, this work has also led to an operational system that provides advance warning of debris flows in recent burn areas based on a comparison of weather forecasts/observations to triggering rainfall intensity thresholds (Cannon et al., 2011; NOAA-USGS, 2005).

Despite support from rapid postfire response teams and an early warning system, emergency managers in southern California are challenged with little time to develop and implement postfire response and evacuation plans between the fire and the first rainstorm. The challenge can be doubly amplified in years with large, late-season fires, which both expand the risk and contract the time window available for planning. This was the case with the 2017 Thomas fire, which started at the end of the fall fire season in December and grew to be, at the time, the largest fire in California history (1,140 km$^2$). There, the first storm of the winter rainy season triggered the fatal debris flows above Montecito on January 9, 2018 before the fire was fully contained and before an evaluation of postfire risk across the extensive burn area could be completed (Table 1 and Figure 1; BAER, 2018; WERT, 2018).

Here, to provide planners and emergency managers in southern California with information to prepare for possible postfire impacts, we combine a set of databases and predictive models to forecast the frequency and magnitude of debris flows across the region. To be consistent with hazard assessments that have been conducted for southern California wildfires over the last 5 years (USGS, 2020), we use the same empirical models for debris flow likelihood (Staley et al., 2017) and volume (Gartner et al., 2014) that were applied in those emergency response situations. These simple models are well suited for application over large regions because of low-computational demands and availability of required input data. Although more complicated physically based models of debris flow initiation have recently been applied to selected small (<1 km$^2$) drainage basins in southern California (McGuire et al., 2017; Rengers et al., 2019; Tang et al., 2019), such models are not yet practical for hazard assessment because they are computationally expensive and require additional input data that are not generally available across large areas (e.g., high-resolution digital elevation data, hillslope and channel sediment grain size distributions, and soil infiltration properties).

Previous studies have used empirical models of postfire debris flow for prefire planning in combination with various methods to define synthetic distributions of burn severity representing wildfire scenarios (Elliot et al., 2012; Hass et al., 2016; Lancaster et al., 2014; Staley et al., 2018; Stevens et al., 2011; Tillery & Haas, 2016; Youberg, 2008). We adopt a similar approach here to assess a larger area, and we emphasize mapping debris flow hazard in a manner similar to well-established models for quantifying earthquake hazards in California (Third Uniform California Earthquake Rupture Forecast, UCERF3, Field et al., 2014, 2015a). Those models have had a major influence on shaping earthquake building codes, insurance, and emergency plans. Just as earthquake hazards vary in time as fault stress is redistributed, postfire debris flow hazards can change in response to changes in fire and precipitation regimes. Accordingly, we develop a predictive framework that not only forecasts the present level of debris flow hazard across the region but can also evaluate the sensitivity of the hazard to possible future changes in the fire and precipitation indices (fire frequency, fire severity, and rainfall intensity) that control debris flow susceptibility. Although we focus here on southern California due its acute postfire risk, our approach can potentially be extended to other areas of the western U.S.

2. Postfire Debris Flow Frequency and Magnitude

2.1. Probability of Postfire Debris Flows

A postfire debris flow involves the intersection of two events: a wildfire occurs, and the rain intensity after the fire exceeds the threshold for triggering a debris flow (Figure 2). The annual probability ($P$) of a postfire debris flow ($DF$) may be expressed as:
If wildfire events and postfire rainfall events are statistically independent, $P(F \cap R > T)$ is equivalent to the product $P(F)P(R > T)$. Several studies have investigated the slightly different correlation between antecedent climate and the severity and extent of subsequent wildfires (e.g., Abatzoglou & Williams, 2016; Keeley, 2004; Westerling et al., 2003). Keeley (2004) showed that, unlike other parts of the western U.S., the area burned by wildfire in southern California is not correlated with antecedent climate indicators because of the long summer-fall dry season and Santa Ana winds, which can quickly dry fuels regardless of previous moisture conditions. The lack of correlation with antecedent climate means that southern California is susceptible to fire in most years, and ignition sources are the primary limit on fire activity (Keeley & Syphard, 2017). Given this fire regime, we assume that warm season fires and subsequent cool season rainfall are uncorrelated and treat $F$ and $R > T$ as statistically independent events.

To evaluate the spatial distribution of debris flow probability across southern California, we divide the region into a grid of over 40,000 1-km² cells and use the methods described below to estimate $P(F)\cap P(R > T)$ for each cell. We do not make estimates for urbanized or low slope areas of southern California, where debris flows are unlikely to initiate. For simplicity, we focus on conditions in the first winter rainy season after the fire when burned bare slopes are most susceptible. Debris flows have been observed to occur in the second winter season after a fire but are less likely because they require greater rainfall intensity to initiate (Cannon et al., 2008). We also do not directly adjust the forecast for areas that have experienced a recent fire. Debris flow hazards in these locations are better addressed with a standard postfire debris flow hazard assessment that is based on an observed map of burn severity (e.g., USGS, 2020).

We estimate $P(F)$ using a California Department of Forestry and Fire Protection (CAL FIRE) database of historical fire perimeters from 1950 to 2018 (CAL FIRE, 2020). Fires in this database generally exceed 4 hectares in size. For a given cell, $P(F)$ can be approximated by calculating the frequency of fires using the equation

$$P(F) \approx \frac{n_{\text{fires}}}{n_{\text{years}}}$$

(2)

where, $n_{\text{fires}}$ is the number of fires that have occurred at that location (center of the cell) over the period of record, $n_{\text{years}}$ (1950–2018). Additional fire perimeters are available for fires before 1950; however, we restrict our analysis to 1950–2018 because the data in this range have received additional review by CAL FIRE and because the perimeters of some fires before 1950 may be missing. We apply a 3 by 3 cell median filter to the grid to smooth the results and provide more realistic estimates for anomalous cells that have not experienced a fire since 1950. Our approach to estimating $P(F)$ assumes that past fires do not substantially influence future fire activity. This assumption is reasonable for southern California given that much of the vegetation is fire adapted (e.g., Keeley, 2000), and the ecosystem has an ignition-limited fire regime (Keeley & Syphard, 2017). We acknowledge this assumption may not be appropriate for other regions.

We estimate $P(R > T)$ using a multistep process that uses an empirical model and databases of historical patterns of fire severity and precipitation frequency. We first estimate the local rainfall intensity threshold ($T$) using a model for debris flow likelihood (Staley et al., 2017) that is calibrated with data from southern California (Staley et al., 2016). This model is routinely applied in an emergency response mode to help assess debris flow hazards in recent burn areas. The model predicts debris flow likelihood as a function of

$$P(DF) = P(F \cap R > T)$$

(1)
basin slope (derived from a 10-m digital elevation model), soil characteristics (from the STATSGO database; Schwartz & Alexander, 1995), 15-min rainfall intensity \( (I_{15}) \), differenced normalized burn ratio \( (dNBR) \), an index of burn severity; Eidenshink et al., 2007], and soil burn severity categorized from dNBR data (Key & Benson, 2006). Specifically, debris flow likelihood increases as (1) 15-min rainfall intensity increases, (2) the fraction of watershed area with slopes greater than 23° and burned at moderate or high-severity increases, (3) the watershed-averaged dNBR increases, and (4) the erodibility index of the fine fraction of the soil \( (K_f) \) factor) increases. Rainfall thresholds for a given catchment in the drainage network are estimated by inverting the model to solve for \( I_{15} \) that corresponds to a likelihood of 50% (Staley et al., 2017). We calculate a representative threshold for each 1-km² cell by taking the median of the thresholds for all stream segments in the cell. Note that stream segments in the model vary slightly in length but are typically about 100 m long.

To apply the model of Staley et al. (2017) across southern California, realistic values of burn severity \( (dNBR) \) and soil burn severity must be constructed. We use the methods of Staley et al. (2018) to construct these maps based on historical patterns of fire severity. The approach uses the database Monitoring Trends in Burn Severity (MTBS) [Eidenshink et al., 2007; https://www.mtbs.gov/)] to define statistical distributions of dNBR for fires between 2001 and 2014. Statistical distributions are defined for each vegetation type mapped across the region by the LANDFIRE project (Rollins, 2009; https://www.landfire.gov/). Soil burn severity classes (low, moderate, and high) are estimated by binning each dNBR distribution by Burned Area Reflectance Classification (BARC4) thresholds reported in MTBS. By linking burn severity to vegetation type, the approach captures the realistic range of potential burn severity across the landscape. We generate two different burn scenarios using this method: one scenario to represent the present fire regime, and a second scenario to represent a hypothetical future fire regime of increased fire severity. The latter scenario is used to assess the sensitivity of debris flow probability to possible changes in fire severity (section 3). Synthetic maps of burn severity for the present and hypothetical fire regimes are constructed using the 50th and 84th percentiles of dNBR distributions, respectively. Corresponding estimates of the rainfall thresholds for each fire scenario \( (T_{50} and T_{84}) \) are then calculated using the model of Staley et al. (2017). Note that our selection of the 84th percentile of dNBR is not based on a specific prediction of future fire severity. It is simply a hypothetical shift used to evaluate the sensitivity debris flow hazards to changes in fire severity.

To evaluate the probability that rainfall will exceed the 15-min threshold at a grid cell, we compare \( T_{50} \) and \( T_{84} \) to gridded National Oceanic and Atmospheric Administration (NOAA) precipitation-frequency data in NOAA Atlas 14 (Perica et al., 2014; https://hdsc.nws.noaa.gov/hdsc/pfds/index.html). At the center of each grid cell, we first spatially interpolate the gridded estimates of \( I_{15} \) corresponding to average recurrence intervals of 1, 2, 5, 10, 25, 50, and 100 years. We then interpolate the recurrence intervals corresponding to rain rates \( T_{50} \) and \( T_{84} \) and use the inverse of these recurrence intervals to represent \( P(R > T_{50}) \) and \( P(R > T_{84}) \).

### 2.2. Probability of Major Postfire Debris Flows

Postfire debris flows generally increase in size and destructive potential as rainfall intensity increases above the threshold for initiation (Cannon et al., 2011). For example, the three most destructive postfire events in the last two decades in southern California were triggered by rainstorms with peak \( I_{15} \) multiple times above established thresholds (Table 1 and Figure 1). Debris flows following the 2003 Old/Grand Prix fire complex had peak \( I_{15} \) between 3.0 and 4.7 times the threshold \( (T = 19 \text{ mm/h}; \text{Cannon et al., 2011}) \). Damaging debris flows after the 2008 Station fire were associated with a peak \( I_{15} \) that was 3.7 times the threshold \( (T = 19 \text{ mm/h}; \text{Staley et al., 2013}) \). The 2018 Montecito debris flows that followed the Thomas fire were triggered by rainfall with a peak \( I_{15} \) between 3.5 and 4.7 times the threshold \( (T = 22 \text{ mm/h}; \text{Kean et al., 2019}) \). To assess the probability of similar major events across southern California, we evaluate equation (1) with a higher rainfall threshold that is representative of major debris flows that escaped the channel and caused damage. Based on the above examples, we define a major debris flow as an event triggered by rainfall intensities of \( 3T \) or greater, which is consistent with events that have damaged 40 or more structures. Accordingly, we use NOAA Atlas 14 to estimate the probability that the higher threshold is exceeded for the two fire scenarios \( \{P(R > 3T_{50}) \text{ and } P(R > 3T_{84}) \} \). It is important to note that we also compute the magnitude (volume) of debris flows, as described in Section 2.3. However, we do not use a volume threshold to define a major event, because a relatively small debris flow that escapes a channel can cause substantial damage.
2.3. Debris Flow Magnitude

As with earthquakes, connecting the potential magnitude of debris flows with their probability of occurrence is important. We use the empirical model of Gartner et al. (2014), which has been calibrated primarily with data from southern California, to estimate the potential volume of postfire debris flows for each of the four cases we are considering: $P(R > T_{50}), P(R > 3T_{50}), P(R > T_{84})$, and $P(R > 3T_{84})$ (the probabilities of at-threshold debris flows and major debris flows in the present and hypothetical more severe fire regimes). The model of Gartner et al. (2014) is used routinely alongside the likelihood model (Staley et al., 2017) for postfire hazard assessments, and similarly estimates debris flow volumes as a function of $I_{15}$, slope (derived from a 10-m digital elevation map), and soil burn severity. We use the two synthetic soil burn severity cov-erages to estimate the volume expected at stream segments given rainfall corresponding to the four sets of rainfall thresholds, $T_{50}, 3T_{50}, T_{84}$, and $3T_{84}$. We then use the stream segment with the maximum volume in each 1-km² grid cell to represent debris flow magnitude for that cell. This step is necessary to synthesize results for the entire region; however, more in-depth analysis using results for individual drainage basins may be required for detailed prefire planning.

3. Sensitivity to Changes in Fire and Precipitation Regimes

The annual probability of debris flow in southern California could shift in the future due to changes in the region’s fire and precipitation regimes. Predicting these changes and their combined effects on debris flow magnitude and frequency is difficult due to complex relations between climate, vegetation, humans, and erosion. While it is not yet possible to accurately quantify future changes in debris flow hazard, it is possible to assess the sensitivity of the hazard to potential changes in fire and precipitation regimes. Here, we briefly summarize trends and projections in relevant fire and precipitation indices and describe how those changes might influence the probability of postfire debris flow. An evaluation of the sensitivity of debris flow hazards to changing fire and precipitation indices is presented in Section 4.2.

Changes in the probability of fire directly affect the probability of debris flow as seen by the approximation to equation 1, $P(DF) = P(F)P(R > T)$. For example, a 5% change in the probability of fire will result in a 5% change in the probability of debris flow. Fire frequency may also indirectly influence the rainfall threshold $T$ through its connection to fire severity. Fire frequency in southern California is primarily controlled by human ignitions (Syphard & Keeley, 2015). While some ignition sources have declined in recent decades, electric power ignitions continue to be a major cause of wildfires (Keeley & Syphard, 2018) including the 2017 Thomas Fire (Serna, 2019). In response, power companies have begun to proactively shut down portions of the electric grid when bad fire weather is expected (e.g., Bogel-Burroughs, 2019). The power outages associated with this plan are controversial, and the effects of this policy on future fire frequency are not clear.

Fire activity (frequency and area burned) is also influenced by climate. The annual area burned has increased in California over the last several decades (e.g., Balch et al., 2018; Dennison et al., 2014; Williams et al., 2019) due primarily to an increase in fire activity in northern California. This trend is driven in part by increased evaporation from warming temperatures, earlier spring, and a reduced length of the winter rainy season (e.g., Abatzoglou & Williams, 2016; Holden et al., 2018; Swain et al., 2018; Westerling et al., 2006). In southern California, the correlation between area burned in summer fires and climate indices is relatively weak (Keeley & Syphard, 2017; Williams et al., 2019). Although wildfire activity associated with Santa Ana wind events may decrease due to projected decreases in the strength of Santa Ana winds (Guzman-Morales & Gershunov, 2019), fall fire activity in southern California could still increase if the onset of cool season precipitation is delayed and evapotranspiration from a warmer climate increases (Swain et al., 2018; Williams et al., 2019). Fire modeling of Mediterranean California ecoregions using established climate projections indicate a 46%–86% increase in the area burned in a typical year by the middle of this century (Hawbaker & Zhu, 2012). However, as mentioned above, the influence of climate on fire activity is not as strong in populated areas like much of southern California due to the strong human influence on fire activity (Syphard et al., 2017).

Burn severity (as measured by dNBR or soil burn severity categories low, moderate, and high) strongly affects debris flow susceptibility, especially when moderate or high burn severity occurs on slopes steeper
than 23° (Staley et al., 2017). Controls on burn severity include fuels, fire weather, long-term climate, and topography (Parks et al., 2018). Burn severity is also related to fire frequency through fire frequency’s control on fuel accumulation. In large parts of the western U.S., the area of high burn severity has increased (e.g., Dillon et al., 2011; Miller et al., 2009; Singleton et al., 2019), but the trend is less clear in southern California. In some parts of southern California, frequent burning of chaparral has converted the vegetation to grass (e.g., Syphard et al., 2018), a vegetation type that tends to burn at lower severity than chaparral. Modeled predictions of fire severity using climate projections suggest that, if vegetation types change naturally with climate change, fire severity may be reduced overall by midcentury across the West but may be slightly increased for some parts of southern California (Parks et al., 2016). While a clear picture of future burn severity is not available, we can assess the sensitivity of burn severity on $P(DF)$ by comparing rainfall thresholds associated with synthetic burn severities corresponding to the 50th and 84th percentiles of historical distributions of dNBR (Section 2.1).

Climate-related changes in precipitation frequency may also affect the probability and magnitude of future postfire debris flows in southern California. Globally, rainfall intensity is expected to increase with warming temperatures from climate change (e.g., Donat et al., 2016). Increases in maximum daily rainfall intensity have been found to scale approximately by the Clausius-Clapeyron (CC) relation of 6–7% per degree Celsius of warming (e.g., Fischer & Knutti, 2016; Trenberth et al., 2003; Westra et al., 2014). Several studies suggest that hourly rainfall intensity in some regions may intensify even more, scaling with a super CC relation up to double that expected for daily maximums (Berg et al., 2013; Huang et al., 2020; Lenderink et al., 2017; Lenderink & Meijgaard, 2010; Panthou et al., 2014; Park & Min, 2017). However, considerable variability in this scaling across climate zones is due to a variety of factors including temperature and moisture availability (e.g., Prein et al., 2017). In southern California, climate models project that precipitation variability will increase this century, making meteorological wet and dry extremes more frequent despite little change in mean precipitation (Swain et al., 2018). Historical precipitation-frequency relations for 1–7 days rainfall totals in southern California are also expected to shift substantially based on climate projections (AghaKouchak et al., 2018). For example, under the Representative Concentration Pathway 8.5 greenhouse gas trajectory (RCP8.5, a high emissions, “business as usual” scenario), AghaKouchak et al. (2018) found that the frequency of what is now a 50 years event in southern California could double by late century 2050–2099.

To evaluate the sensitivity of postfire debris flow hazards to possible changes in precipitation intensity, we investigate a less intense warming projection based on the RCP4.5 emissions trajectory. RCP4.5 is an intermediate emissions scenario described by a peak in emissions in 2040 followed by a decline. We estimate late-century warming (2050–2099) for this scenario using an ensemble of four priority global climate model projections for the South Coast climate region as summarized by Cal-Adapt (2020). That ensemble mean projects 2.5°C of warming by late century, which corresponds to an 18% increase in rainfall intensity based on a CC-rainfall intensity scaling of 7% per degree Celsius of warming. This scaling is consistent with recent modeling results of future hourly precipitation for the Pacific Southwest by Prein et al. (2017). We use the projected 18% increase in rainfall intensity to calculate the change in probability for at-threshold and major debris flows. A summary of all the scenarios of burn severity and rainfall intensity considered in this study is given in Table 2.

4. Results

4.1. Present Forecast

We forecast that at least small postfire debris flow events will be frequent and widespread across southern California given median levels of historical burn severity (Figure 3). A database of results for this and all scenarios can be found in Kean and Staley (2021). The annual probability of debris flows triggered by at-threshold or greater rainfall in the first year after the fire is between 5% and 12% over most of the modeled area (Figure 3a). Locations of past postfire debris flow events contained in the database of Staley et al. (2016) generally align with areas of elevated probability and provide partial qualitative validation of our approach. The corresponding volumes of at-threshold debris flows are generally less than 10,000 m$^3$, except for large drainages, which could produce volumes in excess of 10,000 m$^3$ (Figure 3b). The level and spatial distribution of debris flow probability generally mirrors the frequency of fire across southern California (Figure 4a).
The patterns depend less on the spatial distribution of above threshold rainfall $P(R > T)$ (Figure 4b), because the calculated rainfall thresholds ($T$; median = 33 mm/h) are in many places at or below the rainfall intensity associated with storms with 1-year recurrence intervals. The low thresholds make $P(R > T) = 1$ for a substantial fraction of the susceptible region. This result is supported by a recent analysis of storm recurrence intervals associated with observed postfire debris flows in southern California (Staley et al., 2020), which found the average return interval of rainfall intensity triggering debris flows was 0.9 years.

Although, the probability of debris flow is less than 12% in any specific location, the annual chance of a debris flow occurring somewhere in the entire region is higher, because rainstorms could impact multiple burn areas in southern California in the same year. A crude estimate of the annual regional probability of debris flow $P(DF_{\text{region}})$ can be made by separating the region into appropriate subregions (1 to $n$) and evaluating the probability that none of the subregions experience a debris flow. This estimate is given by the expression $P(DF_{\text{region}}) = 1 - P(DF_1)P(DF_2) \ldots P(DF_n)$, where the overbar indicates the absence of debris flow activity in a sub region. This expression is analogous to the one used to determine the probability of an earthquake along a fault with segments having different probabilities of rupture (WGCEP, 2003). The size of a subregion in our analysis is related to the typical footprint of high intensity rainfall in a storm. We estimate this footprint using the length scale (100 km) and travel distance (100 km) of a narrow cold-frontal rain band, a several kilometer-wide band of intense rainfall associated with a cold front that has triggered many debris flows in southern California, including the 2018 Montecito debris flows (Oakley et al., 2018). Although narrow cold-frontal rain bands can propagate across the entire Bight of southern California (Cannon et al., 2020), we use a shorter 100 km length scale to represent the travel distance because they often do not hold together that far. Using 100 km by 100 km subregions, we estimate $P(DF_{\text{region}}) = 0.7$, suggesting that, at a minimum, small postfire debris flows can be expected almost every year in southern California.

Our forecast for major debris flows (those triggered by rainfall three times above the thresholds associated with median levels of burn severity) shows the most susceptible areas (with probabilities near 0.04) coincide with locations where major events (Table 1) have occurred in the past (Figure 5a). These locations are primarily steep basins in the San Bernardino, San Gabriel, and Santa Ynez Mountains (see also Figure S1 in the supporting information for $P(R > 3T)$). Many of these basins are large, resulting in the potential for volumes greater than 100,000 m$^3$ (Figure 5b). Subdividing the region into 100 km by 100 km subregions, we

| Table 2 | Debris Flow Probability Scenarios |
|-----------------|----------------------------------|
| $P(DF)$ | Conditions | Figures | Description |
| 1 | $P(F)P(R > T_{50})$ | Present | 3 | Probability of debris flow given local precipitation frequency and median of historical burn severity |
| 2 | $P(F)P(R > 3T_{50})$ | Present | 5 | Probability of major debris flow given local precipitation frequency and median of historical burn severity |
| 3 | $P(F)P(R > T_{84})$ | Future w/higher burn severity | 6a | Probability of debris flow given local precipitation frequency and 84th percentile of historical burn severity |
| 4 | $P(F)P(R > 3T_{84})$ | Future w/higher burn severity | 6b | Probability of major debris flow given local precipitation frequency and 84th percentile of historical burn severity |
| 5 | $P(F)P(1.18R > T_{50})$ | Future w/higher rainfall intensity | 7, S4 | Probability of debris flow given median of historical burn severity and 18% increase in precipitation intensity based on RCP4.5 climate projections |
| 6 | $P(F)P(1.18R > 3T_{50})$ | Future w/higher rainfall intensity | 7, 8 | Probability of major debris flow given median of historical burn severity and 18% increase in precipitation intensity based on RCP4.5 climate projections |
Figure 3. Spatial distributions of (a) probability and (b) magnitude (volume) of at-threshold debris flow events across southern California given wildfire with median levels of historical burn severity. Maximum probabilities are close to 0.12 and generally align with locations of high fire frequency. Areas with elevated probability also generally align with locations of observed events (red circles) reported in Staley et al. (2016). Large volumes are expected from larger drainages areas (>1 km²), which typically have more sediment available to be incorporated into the flow.
Figure 4. Spatial distributions of the probability of (a) fire and (b) that rainfall will exceed the threshold for triggering debris flows given wildfire with median levels of historical burn severity. The probability of fire is near 0.15 in some parts of the region, whereas the probability that rainfall will exceed thresholds is nearly 1.0 over large parts of the region because the thresholds are so low.
Figure 5. The (a) probability and (b) magnitude of major debris flow events across southern California given wildfire with median levels of historical burn severity. Elevated probabilities generally align with locations of previous major debris flow events listed in Table 1, which are shown approximately with the yellow circles. Note that the color scale in (a) is different than Figure 3a.
estimate the probability of a major debris flow event somewhere in southern California is 0.1 each year. This corresponds to a frequency (10 years) that is close to the 13 years average interval between major events in the last 100 years (Table 1).

### 4.2. Sensitivity to Changes in Fire and Precipitation Regimes

For simplicity, we separately evaluate the effects of changes in fire frequency and fire severity on debris flow hazards; however, we acknowledge their individual effects cannot be completely disentangled because increases/decreases in fire frequency can lead to decreases/increases in burn severity. All else being equal, changes in fire frequency directly affect postfire debris flow probability, such that a 5% increase or decrease in fire frequency corresponds to a 5% change in debris flow probability. Burn severity, in contrast, has a nonlinear relation to debris flow probability through its effect on rainfall thresholds. We find that for southern California, the probability of debris flows is not strongly sensitive to an increase in burn severity from the median to the 84th percentile of historical burn severity (Figures 3a and 5a vs. Figure 6). See Figure S2 for corresponding maps showing probabilities that rainfall will exceed the thresholds associated with the 84th percentile of burn severity and see Figure S3 for maps showing the expected volumes of at-threshold and major debris flows given wildfire with 84th percentile levels of historical burn severity. Zones of high probabilities for both the 50th and 84th percentile cases remain in the same locations and increase by only 1%–2%. Averaging 1-km² results across the region, we find that an increase in burn severity translates into an increase in the probability of at-threshold debris flows from 0.009 to 0.011 and a rise in the probability of major debris flows from 0.0009 to 0.0015. We also do not expect a substantial change in predicted volumes (Figure S3). The apparent moderate sensitivity of debris flow hazard to burn severity is likely due to the dominant vegetation type in the region (chaparral), which is highly flammable and prone to near complete canopy combustion associated with moderate and high burn severity (e.g., Barro & Conard, 1991).

Changes in precipitation intensity and frequency appear to have a stronger control on debris flow probability in southern California than changes in the fire regime. We find that an 18% increase in rainfall intensity translates into an average 25 years decrease in the return interval of rain rates capable of producing major debris flows. This shift corresponds to a substantial increase in the probability of major debris flows across southern California, with a median of all 1-km² cells showing a 110% increase, and some cells having a greater than 200% increase (Figure 7). The spatial distribution of elevated probability nearly mirrors that for current patterns of precipitation frequency (Figure 8 versus Figure 5a). For at-threshold debris flows, the distribution of change is lower and narrower than for major debris flows, with a median of all 1-km² cells showing a nearly 60% increase (Figure 7). The change is less significant for at-threshold debris flows than major debris flows, because the rainfall thresholds over much of the area are already at or below rain rates with 1-year return intervals in the present climate. As a result, the spatial distribution of probability for at-threshold debris flows (Figure S4) is very similar to the one for the current climate (Figure 3a).

Provided available sediment, increases in precipitation intensity will also translate into larger debris flow volumes. The magnitude of this increase can be estimated using the model of Gartner et al. (2014), in which the natural logarithm of volume increases with the square root of rainfall intensity. This nonlinear scaling is nearly 1-to-1 at relatively high rainfall intensities. For example, an 18% increase in rainfall intensity from 40 to 47 mm/h over a 1 km² basin that is 85% burned at moderate and high severity and has 500 m of relief translates into a 23% increase in volume.

### 5. Discussion

When combined with a local evaluation of values at risk (homes, bridges), our forecast for the probability and magnitude of postfire debris flows can be used to prioritize basins for additional study and/or mitigation. More focused study will require analysis of results for the drainage network of interest, rather than the 1-km² summary presented here. In-depth study could include modeling potential runout paths (e.g., Bessette-Kirton et al., 2019; Iversion & George, 2016; Schraml et al., 2015) and/or geomorphic analysis (e.g., Welsh & Davies, 2010) to plan potential evacuation zones. Modeling debris flow runout paths is generally too time intensive to be completed in the short time window between the fire and the first rainstorm.
Figure 6. The probabilities of (a) at-threshold and (b) major debris flows given wildfire with 84th percentile levels of historical burn severity. In this region, increases in burn severity over median levels slightly increase $P(DF)$. Note that the color scales in (a) and (b) are different to highlight spatial variability in each case. $P$, probability; $DF$, debris flow.
Figure 7. Distributions of potential changes in the probability of at-threshold (black) and major (red) debris flows given an 18% increase in rainfall intensities for the ~40,000 1-km² cells in the study area. The increase in rainfall intensity is based on 2.5°C of projected warming by late century (RCP4.5 scenario) by climate models for the South Coast climate region, and a precipitation intensity scaling of 7% per degree Celsius of warming. Median values of the distributions are shown with the vertical dashed lines. The probability of major debris flows is especially sensitive to changes in rainfall intensity.

Figure 8. The probability of major debris flows given an 18% increase in rainfall intensity based on projections of 2.5°C of warming by late century under a RCP4.5 emissions scenario. See Figure S4 for comparable plot of at-threshold debris flows.
Mitigation could include construction or enlargement of debris basins, fuel reduction through prescribed burning or mechanical thinning to reduce the size and severity of wildfires. This latter strategy, however, may not be as effective for southern Californian chaparral as it is for other vegetation types (e.g., Price et al., 2012).

Additional study is needed to extend these forecasts beyond southern California and will likely reveal different sensitivities to changes in burn severity and precipitation intensity than presented here. Our approach to estimate present fire frequency based on past fire activity will likely need to be adapted for regions whose fire regime is not ignition limited like southern California’s, or for regions where the frequency of fire has recently changed. In these situations, alternative methods such as fire-behavior modeling (e.g., Riley & Loehman, 2016) may be required to estimate fire frequency. Additional work is also needed to evaluate the predictive accuracy of the empirical models for debris flow likelihood and volume in wetter climates like northern California and western Oregon and Washington. To date, little data have been collected on postfire debris flow occurrence outside of semi-arid regions of the western U.S. Emerging physically based numerical models of postfire debris flow initiation may help provide new insights on processes in these areas, but extensive input and computational requirements will likely limit those applications to small study areas. Another barrier to expansion of this approach is that gridded estimates of precipitation frequency (NOAA Atlas 14, Perica et al., 2014) are not available in the northwestern U.S. (Idaho, Montana, Oregon, Washington, and Wyoming). Nongridded estimates of the recurrence intervals of subhourly rain rates are available for parts of this region (Arkell & Richards, 1986); however, an update of this analysis that fills gaps, incorporates new data, and projects future trends is needed to improve understanding of the frequency of geomorphically significant rainfall.

Our attempt to map the probability and magnitude of debris flows in a similar manner as earthquakes invites a comparison between the return intervals of these two southern California hazards. The standard reference example of a major earthquake in this region is the 1994 Northridge earthquake, which had a magnitude of 6.7, killed 57 people, and caused direct losses of at least $25 billion dollars making it the costliest earthquake in U.S. history (Bolin & Stanford, 2006). According to the UCERF3 forecast (Field et al., 2015b), a magnitude 6.7 earthquake has an average repeat time of 12 years, which is about the same recurrence interval of major postfire debris flows observed in southern California and predicted by this forecast. Regrettably, comparing the costs of earthquake and debris flow events with similar return intervals is difficult, because of limited data on debris flow costs. Although major debris flow events have a comparable return interval as major earthquakes in southern California, investment in planning for debris flow hazards has generally been less than for earthquake hazards. Construction of debris basins and other protective measures in some parts of southern California has gone a long way toward mitigating debris flow impacts. However, additional work is needed to plan for their inevitability and possible increase in frequency.

6. Summary and Conclusions

Despite a long history of damaging debris flows after wildfire, southern California lacks a comprehensive regional assessment of postfire debris flow susceptibility needed for advanced planning. This study tried to fill that gap by using a pair of simple models and historical records of fire severity and fire and precipitation frequency to forecast the frequency and magnitude of debris flows across the region. Our results show that postfire debris flows can be expected almost every year in southern California, and major events capable of damaging 40 homes have a return interval of 10–13 years. Predicted locations of high hazard align well with sites of past events and can be used to prioritize basins for mitigation or additional study, such as delineating zones of debris flow inundation and estimating potential impacts.

Changes in southern California’s fire and precipitation regimes could alter the forecast. These changes are difficult to predict given the complex relations between climate, fire, and debris flow. However, an initial analysis of the sensitivity of debris flow probability to increases in fire frequency, fire severity, and precipitation intensity suggest that debris flow activity in southern California is more sensitive to increases in rainfall intensity than increases in fire frequency and burn severity. If warming-related increases in precipitation intensity are realized, the frequency of major postfire debris flows like those in Montecito, California, in 2018,
could increase. This possibility further emphasizes the need for detailed prefire planning and for additional work to outline the trajectory of southern California’s possible changing fire and precipitation regimes.

The recent high numbers of large and severe wildfires across the western U.S. highlights the need to extend this work beyond southern California. While the framework outlined here provides a basis for that extension, adaptations to our approach to estimate fire and precipitation frequency will be required for some regions, and more research is needed to evaluate the efficacy of empirical models of debris flow in regions outside the semi-arid areas where they were developed. In the meantime, this regional forecast of debris flow activity provides a framework to enhance reactive postfire hazard assessments in southern California with proactive prefire planning. Well-constructed prefire plans are likely to be more effective at reducing risk than plans that must be hastily assembled after real wildfires.

Data Availability Statement

The results of this study are in a database (Kean & Staley, 2021).

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