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Post-fire debris flows of 9 January 2018, Thomas Fire, southern California: Initiation areas, precipitation and impacts

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Abstract

The post-fire debris flows of 9 January 2018 killed 23 people, destroyed over 130 homes, and caused severe damage to infrastructure in Montecito and Carpinteria, California. Highway 101 was closed for 13 days, significantly impacting transportation and commerce in the region. Collectively, debris flows from this event are comparable in magnitude to the largest documented post-fire debris flows in the state, inundating over 4 km^2 of land, and costing the Santa Barbara region over half a billion dollars in debris removal and damages to homes and infrastructure. Here, we document the extent and magnitude of inundation areas, debris-flow volumes, and source areas. Additionally, we describe the atmospheric conditions that generated intense rainfall and use precipitation data to compare debris-flow source areas with spatially associated peak 15-minute rainfall depths. We use a compilation of debris-flow damages to summarize economic impacts associated with the event.

Keywords: post-fire; debris flows; alluvial fan; NCFR; rainfall intensity; inundation; Montecito; Thomas Fire; loss estimate

1. Introduction

The Thomas Fire ignited on 4 December 2017 and burned steeply sloping terrain in the western portion of the Transverse Ranges in Santa Barbara and Ventura counties (CAL FIRE, 2018). The fire burned 114,078 ha (281,893 acres), with full containment declared on 12 January 2018. A total of 1,063 structures were destroyed across both counties and 280 additional structures were damaged. A Presidential Disaster Declaration was made on 8 December 2017.

Post-fire debris flows initiated at approximately 3:45 a.m. local time (PST) on 9 January 2018, starting first in the Santa Ynez Mountains and then spreading eastward to watersheds in the Topatopa Mountains. Within the Montecito and Carpinteria area, the debris flows travelled from the canyon mouths on to urbanized alluvial fan areas extending over four kilometers to the Pacific Ocean. The debris flows killed 23 people, destroyed over 130 homes, and caused severe damage to infrastructure. The Thomas Fire Presidential Disaster Declaration was amended on 10 January 2018 to include flooding, mudflows and debris flows.

As storm rainfall runs off on steep hillslopes burned by wildfire, sediment and debris are eroded from hillslopes and subsequently scoured from channels. As sediment and debris are entrained, progressive bulking of runoff may lead to the development of debris flows (Cannon et al., 2003). Debris flows commonly occur in steep watershed areas burned at moderate to high soil burn severity, with the largest events often triggered by the first significant post-fire rainstorm (Cannon et al., 2008; Parise and Cannon, 2012), and in response to short rainfall durations of high intensity (Moody et al., 2008; Kean et al., 2011). As debris flows travel down slope, they strip vegetation, entrain boulders, block drainages, damage structures, and flow in unpredictable directions (Lancaster et al., 2015). The destructive power of boulder-laden surge fronts magnifies the impacts of debris flows to life and property.

Post-fire debris flows have become a common threat to southern California communities due to urbanization of alluvial fans and floodplains downstream of the Transverse Ranges (Lancaster et al., 2015; Oakley et al., 2017). While

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many moderate- to large-sized destructive debris flows have occurred (Cannon et al., 2010; Gartner et al., 2014), documentation of runout distances, areal extent and depth, source areas, triggering rainfall, and damages and costs, are rare in published literature. Quantification of debris-flow damages and costs can be used for risk assessments, planning for future disasters, and in making decisions about allocating money for pre-disaster-mitigation mapping and prevention. However, assignment of post-fire debris-flow costs is challenging as there is no way to quantify the loss of human life and damage costs to physical structures can be difficult to compile where multiple entities are affected (Fleming and Taylor, 1980; Godt, 1999).

We document a large-magnitude, post-fire debris-flow event that occurred a month after the ignition of the Thomas Fire in the southern California counties of Santa Barbara and Ventura and significantly impacted the region. We focus on four aspects of the event: (1) atmospheric conditions and precipitation depth and durations that initiated the event, (2) the distribution of source areas that generated debris flows, (3) the extent of runout and inundation of the debris flows, including debris-flow depths, and (4) damage and costs associated with debris-flow impacts in Santa Barbara County.

2. Debris flow triggering storm event

2.1 Atmospheric conditions

The storm event that produced the high-intensity rainfall responsible for the debris flows featured a weak atmospheric river facilitating moisture transport into the area as well as a strong cold front (Oakley et al., 2018). A narrow band of high-intensity rainfall developed along the cold front (Fig. 1a), a feature referred to as a “narrow cold frontal rainband” (NCFR; Markowski and Richardson, 2010). Between 3:30 and 4:00 a.m. (PST) on January 9, the cold front and associated NCFR moved over the Thomas Fire burn area. One segment of the NCFR intensified within the Santa Barbara Channel as it moved towards Montecito (Fig. 1b). Subsequently, radar and surface-based precipitation observations show the NCFR began to weaken and dissipate to the east near the Santa Barbara-Ventura County line (Oakley et al., 2018).

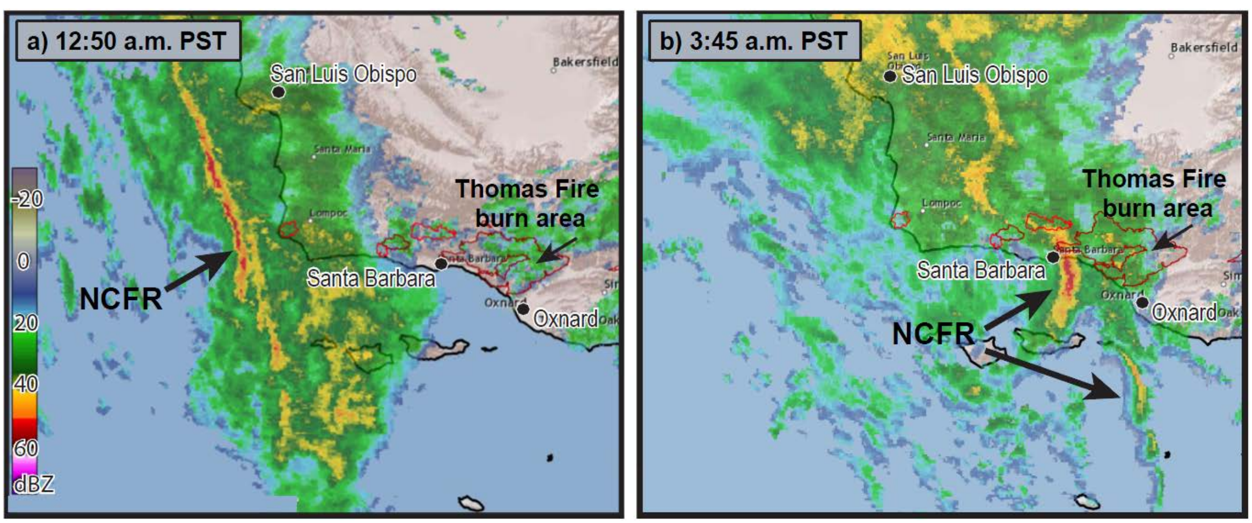

Fig. 1. Panels show radar imagery preceding (a) and at the time of (b) post-fire debris flows in the Thomas Fire burn area. Yellow to red colors indicate progressively higher storm intensity. Figure adapted from Oakley et al. (2018) Radar image source: CNRFC.

2.2 Precipitation observations

Observed rainfall data from Santa Barbara County Public Works Department show the 9 January 2018 storm broke station records but did not exceed the 15-min duration county record of 35.31 mm at San Marcos Pass in 2015, west of the burn area (not shown). Historical 15-min duration records are available for 36 rainfall stations in Santa Barbara County and four of these records were broken during the January 9 event (see Table 1 for summary of data). Two of these stations are within the burn area while two are just south in Montecito and Carpinteria (see Fig. 2 for locations).

Table 1. Summary of 15-min rainfall station records broken during 9 January 2018 storm

Station (abbreviations mark locations in Fig. 2)	*15-min rainfall depth (mm)*	*Precipitation return event in years*	*Average return interval in years (90% confidence)*	*Record (start year – end)*
Doulton Tunnel - DT	26.11	100	25 - 1,000	1965 - present
Jameson Dam - JD	25.15	25	10 - 500	1965 - present
Montecito - M	18.54	50	25 - 1,000	2009 - present
Carpinteria FS - CFS	21.84	50	25 – 1,000	1964 - present

Although 15-min rainfall intensities were not remarkable over Matilija Canyon, this area received the highest total storm precipitation, 164.85 mm, from 04:00 LST 8 January to 0:400 LST 10 January (Oakley et al., 2018; CNRFC, 2018). Peak 15-min rainfall depths from the storm were collected from 46 stations maintained by the Santa Barbara County Public Works Department and Ventura County Watershed Protection District, and depths were interpolated with the Inverse-Weighted Distance method in ArcGIS (Chen et al., 2017) and are shown as contours in Fig. 2.

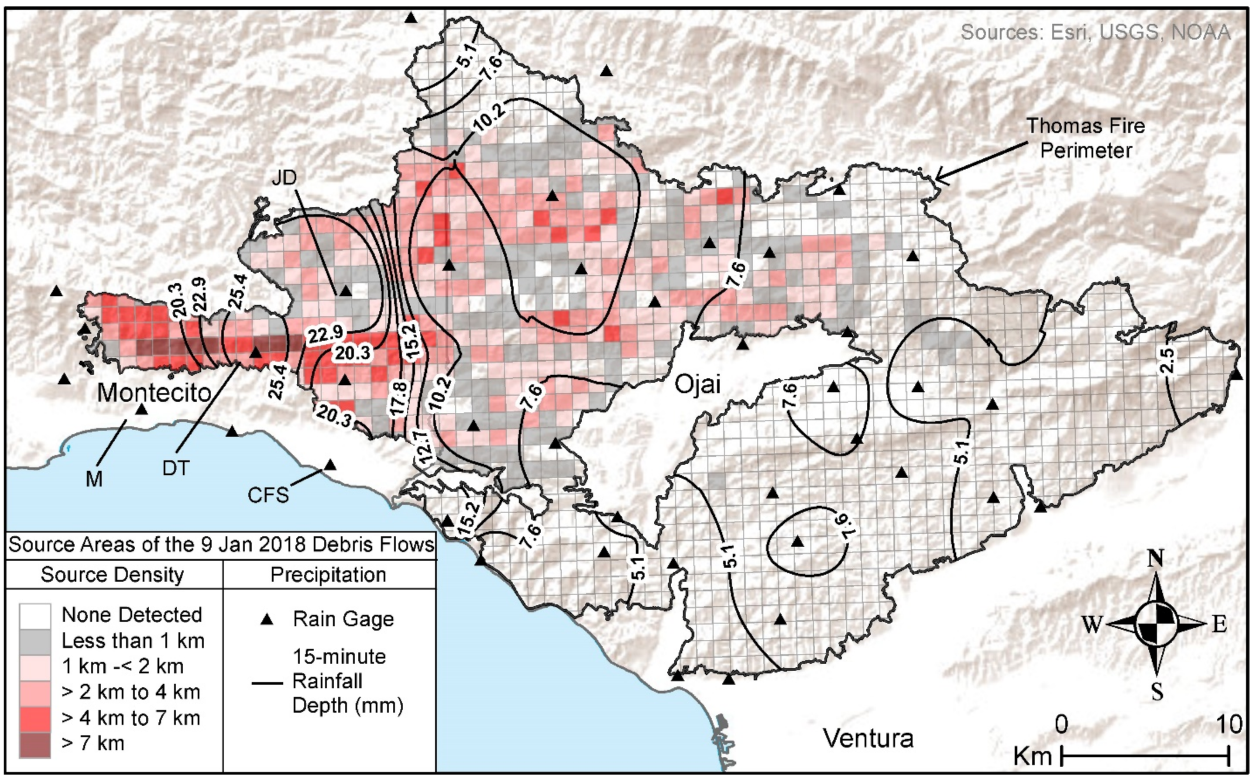

Fig. 2. Maximum 15-min rainfall depths (mm) over a 1 km^2 grid representing the cumulative lineal kilometers of debris-flow source gullies greater than 1.5 m in width; debris flows in gullies less than 1.5 m wide or those interpreted with questionable confidence, are not represented in this figure. The rain gages mentioned above are labeled as follows: DT- Doulton Tunnel, JD- Jameson Dam, M-Montecito, and CFS- Carpinteria.

3. Source areas

Large, destructive debris flows received widespread media coverage in the Montecito area and the extent of these flows and nearby rainfall data have been extensively documented (Kean et al., *in review*, and Oakley et al., 2018). However, identification of the distribution of flows across the rugged Thomas Fire burn area is a challenge owing to the large area impacted and limitations on access and personnel to map the entire area. Therefore, we conducted remote mapping with GIS and standardized identification protocols to assess the entire Thomas Fire area. The results of this mapping were spot checked in the field to validate interpretations and a simplified summary of this work is presented on a 1 km grid in Fig. 2. Corresponding peak 15-min rainfall depths at the source-area grid cells can be interpolated from the contour lines.

3.1. Defining source areas

Debris-flow source areas were identified by interpreting erosional features expressed in post-event 1 m resolution Digital Globe imagery, lidar collected by Towill Inc. processed to a 0.5 m hillshade, and 5 cm resolution aerial photography. Geomorphic interpretation of hillslope and channel source areas was conducted by reviewing hillslope features at a screen scale of between 1:500 and 1:1,250. Geomorphic evidence for identification of source gullies that did or did not issue a debris flow included marginal levees, rills, gullies, extensive scour, mud drapes, boulder fields, and impacts, such as boulders deposited on roads. Marginal levees are considered to be a process unique to debris-flow surge fronts. Levees form along the paths of debris flows as shear stresses increase as slow moving, coarser-grained material is pushed aside at the lateral margins of the flow front by the advancing finer-grained slurry (Sharp and Noble, 1953; Johnson et al., 2012; Iverson, 2014). In contrast, the other geomorphic evidence may be associated with different processes. Progressive erosion and the development of debris flows within eroded gully networks with a minimum width of 1.5 m were determined as the minimum mappable feature, although we recognize debris flows having smaller widths occurred.

A confidence matrix following Wills et al. (2017), was used to classify source areas resulting from debris-flow generation, where, *definite* sources had marginal levees and/or were field verified, *probable* sources had more than one line of evidence, but did not have marginal levees, and *questionable* sources had one line of evidence, but where a process other than debris flow could not be precluded. Debris-flow sources were then intersected with a 1 km^2 grid and weighted by their confidence and summarized for each grid cell. Each confidence type was assigned a weight based on field validation of 184 source gullies across the study area, including 98% for *definite*, 69% for *probable*, and 22% for *questionable* sources (CGS, *in preparation*).

The accuracy of the debris-flow source area map is limited by the different sources and quality of data across the burn area. Lidar data was unavailable for approximately 10% of the burn area, primarily north of the Santa Ynez Mountains (see Fig. 3 for locations of geographic regions). Image quality also varies significantly across the entire burn area, with warping, shadows, and vegetation obscuring the identification and interpretation of erosional features. Confidence assignments are higher in the west where extensive field observations after 9 January validated the occurrence of debris-flow processes.

3.2. Source areas and rainfall

The source-area density map (Fig. 2) shows that the distribution of debris-flow sources varies greatly across the burn area. The highest concentration of source gullies is observed in the Santa Ynez Mountains north of Montecito and Summerland. There is a low-to-moderate concentration of source gullies in the Matilija Creek watershed and the area north and northeast of the Ojai Valley. There is little evidence to support initiation of sizeable debris flows in the southeast portion of the burn area, in Sulphur Mountain and Rincon Point (Fig. 3). Observed burn severity was commonly low in this area and bedrock sources are dominantly fine-grained and generate relatively few boulders for entrainment.

Contoured results of the 15-min duration data indicate the 10.2 mm rainfall contour generally encompasses debris-flow source areas with greater than 4 km/km^2 of source density, while the 5.1 and 7.6 mm contours define what appears to be a triggering precipitation boundary in the north and south of the burn area. The source areas originating at the base of the Topatopa Mountains did not receive rainfall rates as high as the rest of the burn area. The area south of Ojai has rainfall depths of >7.6 mm, but no geomorphic features suggestive of debris-flow generation were identified. The Rincon Point region, along the coast, had rainfall depths exceeding 15.2 mm, but did not have identifiable debris-flow source features. A relatively dense band of debris-flow source gullies in the Santa Ynez Mountains has an east-west trend and appears to correlate with high rainfall depths of up to 17.8 mm.

4. Mapping and evaluating inundated areas

Inundation mapping was conducted in two phases. The first phase was completed as a collaboration between the U.S. Geological Survey and the California Geological Survey in the first twelve days after the event to maximize the observation of perishable features (Kean et al., *in review*). In this phase, field observations were made along the five primary runout paths through Montecito where damage occurred, including from west to east, Cold Spring, Hot Springs, Montecito, Oak, San Ysidro, Buena Vista, and Romero creeks (see Fig. 3). Observations include documentation of limits of inundation, maximum depth of inundation, scour depth, avulsion characteristics, local evidence of flow superelevation, and the distribution, thickness, and grain size of deposits within the inundation zone. In the second phase, additional inundation mapping was conducted using post-event satellite imagery, lidar and aerial photography, supplemented by general field observations (see Fig. 3).

4.1. Extent and depth of inundation

Post-event inundation mapping reveals over 4 km^2 of land was inundated in Santa Barbara and Ventura counties during the January 9 event, collectively. The built environment along the Santa Barbara coastal plain sustained the most inundation, with about 0.2 km^2 of inundation occurring in the canyons north of the Santa Ynez Mountains and west of the Topatopa Mountains. Of the 3.8 km^2 of inundation that occurred in the built environment, 0.6 km^2 of inundation impacted Carpinteria Creek and 3.2 km^2 of inundation impacted the Montecito and Summerland area, from Cold Spring Canyon Creek to Arroyo Paredon. Peak inundation depths of 10 m were recorded near the upper and middle portions of the piedmont, from the channel bottom to mud marks on a tree at Romero Creek at the edge of the burn perimeter, and from the bottom of Montecito Creek to a channel bank near the crossing at SR-192. The maximum debris runout distances, measured from each canyon mouth to the shore, were just over 4 km for Cold Spring Canyon, and 5 km for Romero Creek.

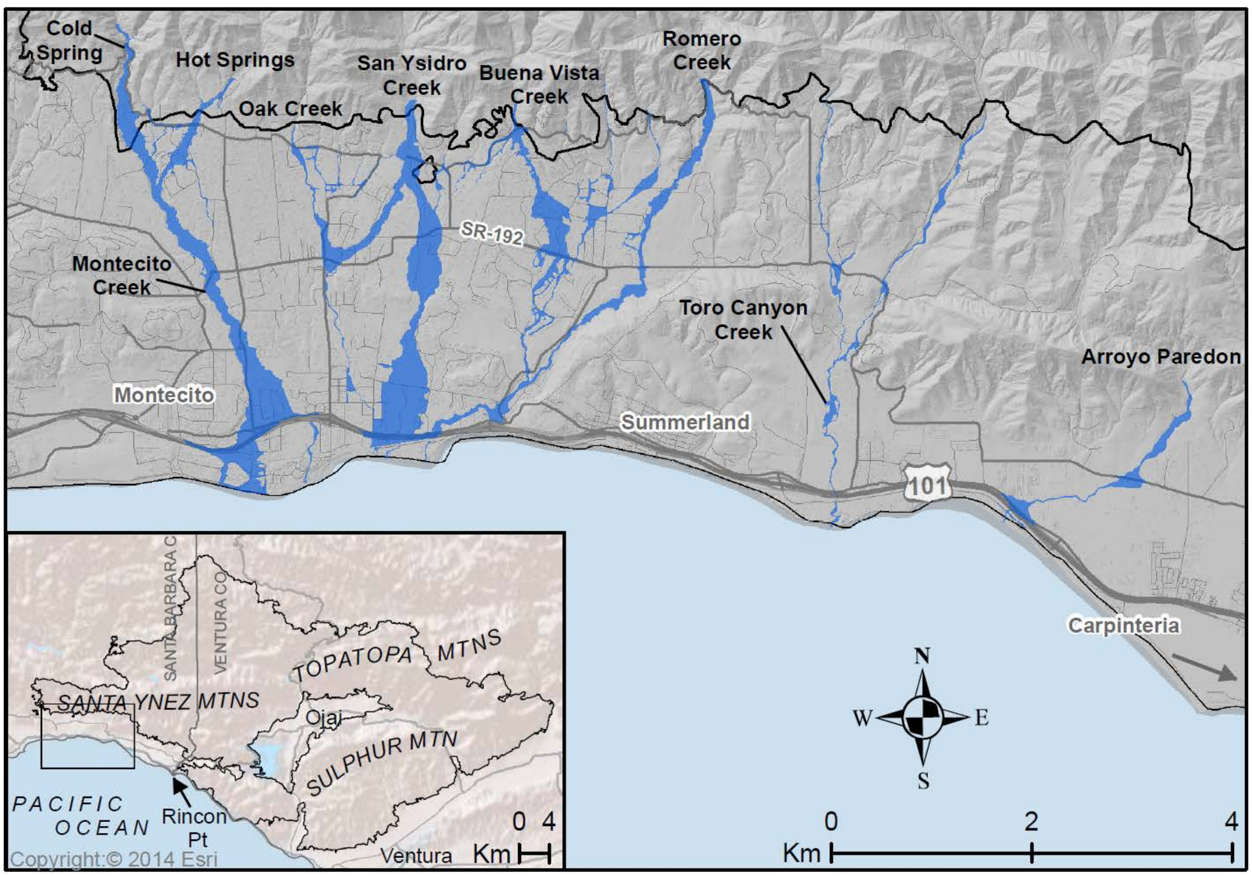

Fig. 3. Mapped inundation (blue) in the Montecito and Summerland region (shown at a 1: 125,000 scale) with an inset map of the Thomas Fire burn perimeter in the Santa Barbara and Ventura counties (shown at a 1: 1,000,000 scale). The primary map extent is shown on the inset map.

4.2. Debris-flow volume estimation

The reported total volume of 9 January 2018 storm material removed in Santa Barbara County from debris basins was 248,000 m^3 and the volume removed from creek channels was 124,000 m^3 (USACE 2018a and 2018b). Recorded sediment thickness at 373 locations, taken during field observations in the Montecito area, were used to estimate the possible debris volume over the inundation area in Montecito and Summerland. The total inundation extent in this area is 3,213,000 m^2. The average deposit depth is 0.3 m with a standard deviation of 0.53 m. Because the data does not have a normal distribution and is heavily skewed by large outliers, the median of 0.2 m is used to estimate deposit volumes (Schiff and D'Agostino, 1996). The median deposit depth multiplied by the inundation area of Montecito and Summerland, gives an estimated deposited debris volume of 643,000 m^3. This estimated volume, combined with the debris volume removed from debris basins and channels amounts to about 1,014,000 m^3.

The calculated inundation area and volume corresponds to a debris-flow magnitude 7 event according to Jakob (2005). Previous large magnitude events affecting similar areas to the January 9 event, include debris flows following the 1964 Coyote Fire and the 1971 Romero Fire; each impacted an estimated area of greater than 2 km^2 for a magnitude 5 classification (Lancaster, 2018; Jakob, 2005).

5. Damages

The compilation of damages and costs follows the general methodology of Fleming and Taylor (1980) and includes direct, indirect, and undetermined debris-flow damages within Santa Barbara County (damages were unavailable for Ventura County as of March 2019). Direct damages include repairs necessary to restore all structures and land sustaining physical damage immediately resulting from the debris flows. Indirect damages include secondary losses from the debris flows like loss of income or measures taken to mitigate additional debris-flow damages. Undetermined damages may be direct or indirect but are inseparable from damages due to the Thomas Fire based on available information. Cost information (Table 2) has been compiled from publicly available documents, such as press releases, presentations to board meetings, and news articles.

Table 2. Summary of damages related to direct and undetermined costs in Santa Barbara County

Direct Damage Costs		
Damage	Cost (USD 2018)	Data Source
U.S. 101 debris removal	$11,250,000	CALTRANS, 2018a
bridge repairs; SR-192	$55,000,000	CALTRANS, 2018b
Property insurance claims	$422,000,000	California Insurance Commissioner, 2018
Debris basin and channel removal	$110,400,000	O'Dell, 2018
Water district	$5,500,000	Montecito Water District, 2019
Indirect Damage Costs		
Lost wages due to U.S. 101 closure	$25,000,000	RDN, 2018
Installation of 6 debris ring nets	$4,000,000	Magnoli, 2019
Undetermined Damage Costs		
County response and recovery	$55,000,000	Santa Barbara County, 2018
Disaster assistance loans	$50,000,000	Small Business Association, 2018

The total estimated cost of the debris flows alone, as of March 2019, is $633,150,000, with possible additional costs of up to $105,000,000 coming from undetermined costs (Table 2). About 64% of the direct costs come from residential property insurance claims. There were insured losses of $388,000,000 from 1,415 residential personal property claims, $27,200,000 from 235 commercial property claims, and $6,700,000 from 388 auto and miscellaneous property claims. Potential damages and costs that cannot be quantified include impacts to the capacity of Gibraltar Reservoir, on the north side of the Santa Ynez Mountains (City of Santa Barbara, 2018), environmental repercussions to local beaches (Molina, 2018), and continued legal action against utility companies for alleged exacerbation of the fire and debris-flow damages (Okada, 2019).

6. Summary and discussion

Large magnitude, post-fire debris flows of 9 January 2018 took 23 lives as a result of extreme precipitation associated with a narrow band of high-intensity rainfall occurring in the vicinity of a cold front, known as a narrow cold frontal rainband (NCFR). The NCFR appears to have controlled the distribution of debris-flow initiation across the burn area. Collectively, the debris flows triggered by the 9 January 2018 event correlate to a magnitude 7 post-fire debris-flow event (Jakob, 2005), with a depositional volume of over 1,000,000 m^3 in the Montecito and Summerland area. Costs associated with this event have exceeded a half billion dollars, as of January 2019.

NCFRs have been previously observed as a trigger for post-fire debris flows in southern California (Oakley et al., 2017), but there are no known studies on the frequency of the occurrence of these features in southern California. A similar damaging NCFR event in the region was the Springs Fire debris flow in Camarillo, CA on 12 December 2014 (Sukup et al., 2016) which also had unremarkable storm totals but high-intensity, short duration rainfall.

Several regions received precipitation in excess of post-fire debris flow triggering thresholds, yet debris flows were not identified as mappable based on our interpretive approach. These include the Sulphur Mountain region and the area around Rincon Point. The lack of debris flows in the Sulphur Mountain area is attributable to relatively lower watershed average slope values as well as generally low soil burn severity. Conversely, the Rincon Point area is typified by steeper sloping terrain and moderate to high soil burn severity, thus it is possible there were finer-scale erosional processes that triggered mudflows lacking levee features, as these areas are underlain by fine-grained sediment sources.

Jakob (2005) classifies boulder debris flows up to magnitude 6, where magnitudes 7-10 are used only for volcanic debris flows. He justified excluding boulder debris flows from larger magnitude classification because only volcanic debris flows were known for having large runouts due to their fluidized nature. The depositional overlap of these debris flows restricts the ability to separate material by watershed, so they are considered here as an aggregate event. The cumulative estimated volume for this event is greater than 1,000,000 m^3, and the inundation area is over double the value used for the magnitude 6. Thus, based on the combined inundation areas, we classify the event as a magnitude 7 debris flow.

We anticipate that our compiled damage estimates will be further refined, but may ultimately underestimate the true cost of the debris flows, as there is no way to quantify the injuries or the loss of life, and documentation of damages to physical structures may never be comprehensive (Fleming and Taylor 1980; Godt, 1999; Taylor and Brabb, 1972). As documentation of economic losses improve with time, we speculate that the cost for this event may exceed $1 billion dollars.

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