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Assessment of a Post-Fire Debris Flow Impacting El Capitan Watershed, Santa Barbara County, California, U.S.A.

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ABSTRACT

In the summer of 2016, the Sherpa Fire burned 30.2 km² in steep terrain in western Santa Barbara County, California. Rainfall events in the subsequent wet season produced damaging post-wildfire flooding and debris flows. This paper presents a case study along a watershed within the burned area, El Capitan Creek, that (1) describes the events and conditions that led to the post-wildfire flooding and debris flow events, and (2) documents the debris flow deposits and inundation zone impacted by the events. Observations compiled after three post-wildfire precipitation events indicate that three distinct flow processes impacted El Capitan Creek between 19 and 22 January 2017. These flow processes included watery flows, hyper-concentrated flows, and debris flows. The velocity and concentrated nature of these flows caused overbanking and channel avulsions that resulted in damaged roads, bridges, pipelines, and major infrastructure damage to the El Capitan Canyon Resort. These events occurred only 1 year prior to the devastating Montecito debris flows of 2018 and call attention to the conditions that produced these impactful flows and highlight the timing and conditions that generate post-wildfire debris flows. Information from case studies such as this can guide decision makers and emergency managers to understand the hazards and risks that floods and debris flows pose on communities below steep mountain drainages and support the development of sound protocols to help reduce the threat to life, property, and infrastructure in downstream communities.

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INTRODUCTION

On the morning of 20 January 2017 at approximately 8:55 a.m. PST an intense rainstorm with a peak 15-minute rainfall intensity rate of 76 mm/hr initiated debris flows and sediment-laden flooding in several watersheds recently burned by the Sherpa Fire: El Capitan Creek, Cañada del Corral Creek, and Las Flores Canyon, Santa Barbara County, California, United States (Figure 1). The flooding and debris flows damaged buildings, property, and infrastructure in the El Capitan Canyon Resort, El Capitan State Beach, and an oil and gas facility located in Cañada Del Corral (Figure 2).

There is a history of post-fire flooding and debris flows in this region (e.g., U.S. Army Corps of Engineers, 1974; Kean et al., 2019). As the climate warms and dries, there is potential for more frequent and/or severe events in Santa Barbara County due to increased fire size and frequency (Barbero et al., 2015; Westerling, 2018) and precipitation intensification (e.g., Prein et al., 2017). Given the potential for future destructive post-fire debris flows to occur along the Santa Ynez Range and other mountainous regions of the southwestern United States, it is valuable to document these types of events with a focus on the conditions that led to their initiation and damage potential to inform the design and development of infrastructure (e.g., culvert size or bridge design), building codes, and land use planning. Case studies also assist decision makers and emergency managers at local, state, and federal levels in understanding and

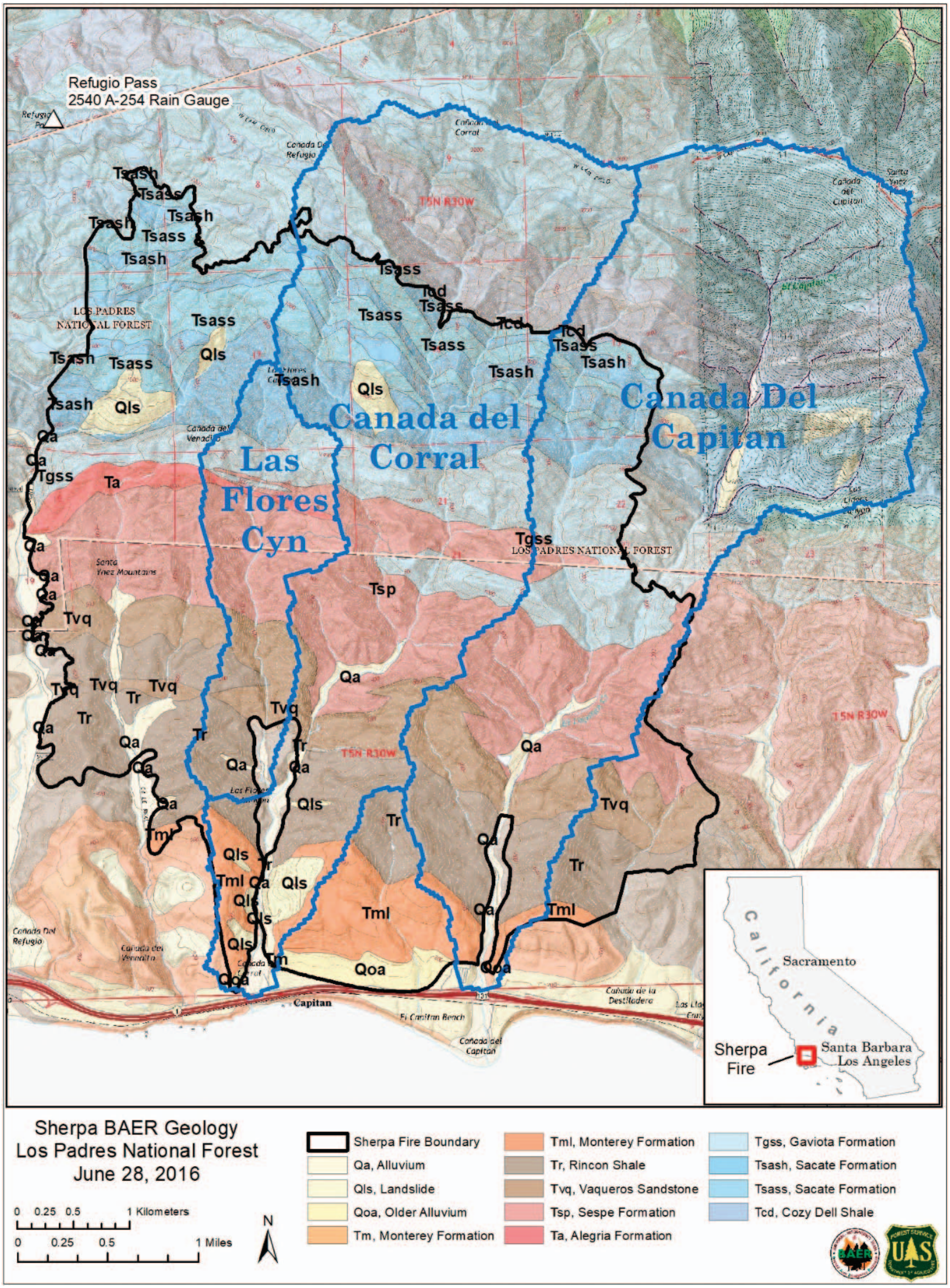

Figure 1. A vicinity and geology map of the watersheds that burned in the Sherpa Fire and were impacted by the 20 January 2017 rainstorm event. Measurement locations and geographic features that are referenced in the paper are denoted on the map.

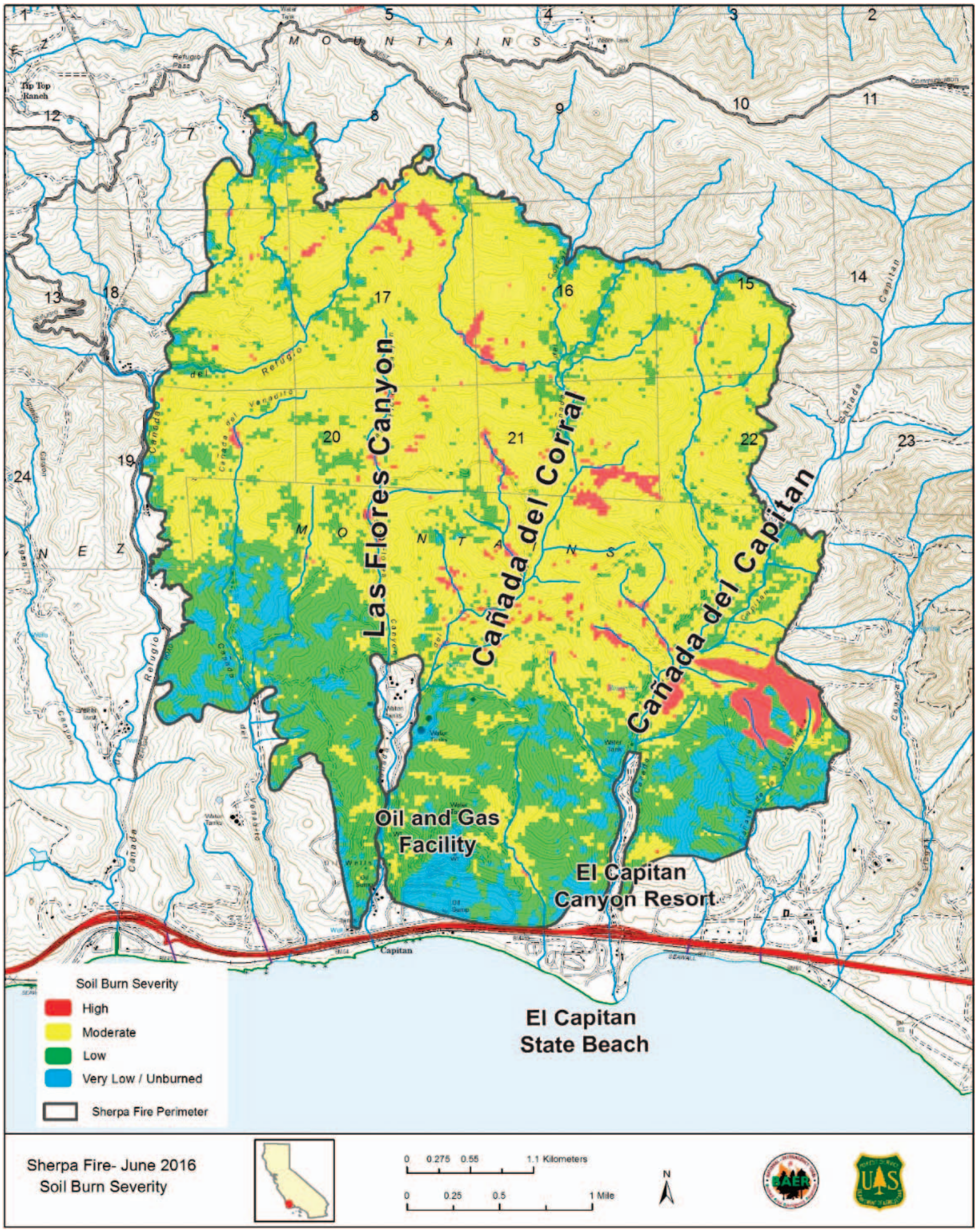

Figure 2. A Sherpa Fire soil burn severity map showing the watersheds impacted by the 20 January 2017 rainstorm event, Santa Barbara County, CA.

mitigating the impacts presented by post-fire flooding and debris flows. Infrastructure design and emergency management protocols that are informed by past events will reduce the threat to life, property, and infrastructure in downstream communities. Additionally, the information presented here can provide input for modeling efforts that will help improve future rapid federal and state post-fire assessments and inform future research on post-fire hazards, including longitudinal studies that look at meteorological triggering events, basin characteristics, soil coverage, and vegetation types across a wide range of events and rock types (e.g., Oakley et al., 2017; Staley et al., 2017; and Dibiase and Lamb, 2020).

Post-Fire Debris Flows

Wildfires dramatically change the hydrological response of watersheds. Higher runoff potential and vegetation loss increase the susceptibility to erosion, flooding, and debris flows (Cannon et al., 2003a, 2003b; Cannon and De Graff, 2009; Kean et al., 2011; De Graff et al., 2015; and Staley et al., 2020). The increase in the hydrological response and susceptibility to erosion is partially related to the soil burn severity (SBS). SBS is classified based on the degree of physical and biological changes to soil surface characteristics, such as char depth, organic matter loss, altered color and structure, and reduced infiltration (Ryan and Noste, 1985; DeBano et al., 1998; Lentile et al., 2006; and Parsons et al., 2010). Wilder et al. (2020) found that other important factors influencing post-fire peak flows include peak rainfall intensity, watershed size, total burned area, and time after fire containment.

Burned watersheds with steep slopes and first order channels that contain significant volumes of stored sediment are likely to experience increases in runoff and erosion from a lack of protective vegetation cover, soil hydrophobicity, and loss in cohesive root strength, which provide the potential to generate debris flows (Kean et al., 2011; Parise and Cannon, 2012; and Kean et al., 2019). In semi-arid landscapes like the southwestern United States, runoff-generated debris flows are the most common and initiate as result of progressive bulking or accumulation of slurry in stream channels (Cannon, 2000, 2001; Cannon et al., 2001a). There are many different mechanisms by which slurry is generated, such as intense rilling on hillslopes, (Meyer and Wells, 1997; Cannon et al., 2001b), saturation and failure of channel bed sediment (Kean et al., 2013), and/or mobilization and mixing of dry ravel accumulations in first-order channels (Dibiase and Lamb, 2020). The increase in slurry production from enhanced runoff is also related to the proportion of the burned area at high and moderate SBS.

Runoff generated slurry typically has high sediment concentrations (40–65 percent) and can scour colluvial and fluvial stream deposits. The flow can then progressively grow in size as it moves downstream by recruiting boulders and woody debris, resulting in destructive debris flows (Iverson, 1997). As debris flows progress down mountain channels at speeds of 30–50 km/h boulders, woody debris, and saturated materials impact drainage infrastructure by clogging culverts, bridges, and underpasses, which can result in a diversion (avulsion) of the flow and destruction of infrastructure built across and along its banks (e.g., Kean et al., 2019; Lukashov et al., 2019; and Lancaster et al., 2020). Other post-fire hydrologic processes, such as hyper-concentrated flooding and debris flows, threaten life, property, and infrastructure. They can destroy houses, block or carve out sections of roads and cause transportation impacts, sever pipelines and damage utilities that cause business disruptions, and add large quantities of sediment to stream channels that impact water resources.

Event Setting

The Sherpa Fire was ignited on 15 June 2016 in the Los Padres National Forest, Santa Barbara County, California, during a strong sundowner wind event. With the strong northerly winds, the fire spread rapidly southward and downslope, propagating over 6 km in 24 hours (Smith et al., 2018). The fire burned a total of 30.2 km², out of which 10.5 km² burned on National Forest lands, 12.6 km² burned on State lands, and 7.4 km² burned on private lands. Within the fire perimeter, 4 percent of the area burned at a high SBS, 60 percent burned at a moderate SBS, 28 percent burned at a low SBS, and 8 percent was either unburned or burned at a very low SBS (Schwartz, 2016) (Figure 2).

The Sherpa Fire occurred on the south slopes of the Santa Ynez Mountains within the east–west-oriented Transverse Ranges of Southern California. The Santa Ynez Mountains parallel the south coast of Santa Barbara County and extend eastward into Ventura County. The Transverse Ranges are some of the most tectonically active mountains in the United States, and with uplift rates of 1–2 mm/yr, they are growing faster than they are eroding (Dibble, 1982; Melosh and Keller, 2013). Unlike the San Gabriel and San Bernardino mountains to the east, this section of the Transverse Ranges is composed almost entirely of un-metamorphosed, mostly marine sedimentary rocks (Figure 1) of Cenozoic age, where shales have a continuous soil mantle and sandstones have low–moderate colluvial coverage (Dibblee, 1988; Keller et al., 2015). Soils in this area are typically shallow and rocky, containing variable soil textures based on age and parent material. Vegetation in the Sherpa Fire burn area is dominated by chaparral with oak woodlands. Conifers exist in small patches along ridgetops and on north-facing slopes. At the bottom of the drainages, narrow riparian corridors contrast sharply with the otherwise dry landscape. Based on U.S. Forest Service fire history data, the last fire that burned this footprint was the Refugio Fire in September 1955. The physiography of the area that was impacted by the

Sherpa Fire is dominated by extremely steep and rugged slopes (30°–45°) with elevations ranging from 60 m above mean sea level (AMSL) by US Highway 101 (Hwy 101) to approximately 760 m AMSL at the northern boundary of the fire. The burned area is drained by five major creeks flowing south to the Pacific Ocean: Cañada del Refugio, Cañada del Venadito, and Las Flores Canyon, which flows into Cañada del Corral and Cañada del Capitan. In the steep, geologically young Santa Ynez Mountains, various forms of storm-driven landsliding, rockfalls, and surface erosion are frequent and occur in unburned settings as well (Alessio, 2019).

The most significant impacts of the 20 January 2017 debris flow event were observed in the Cañada del Capitan watershed. This watershed is situated at the east end of the area burned by the Sherpa Fire, adjacent to and east of the Cañada del Corral watershed. The watersheds impacted by the Sherpa Fire are underlain by alternating sedimentary rock formations of shales and sandstones with some conglomerate, ranging in age from late Eocene to late Miocene, and overlain by Quaternary alluvial, landslide rubble, and surficial sediments (Figure 1); strata of older rock types typically dips (inclines) steeply toward the south or southwest (Dibblee, 1988). Since this area is experiencing rapid uplift, the upper parts of the watershed present deeply incised canyons, which tend to transport high-energy flows, creating steep canyon walls and producing rocky colluvial slopes and stream channel deposits of gravel, sand, and silt.

The area drained by the Cañada del Capitan watershed is 15.8 km^2, out of which 6.42 km^2 (41 percent) were burned in the Sherpa Fire. Of the area burned, 3.6 percent (0.23 km^2) burned at high SBS and 67.9 percent (4.36 km^2) burned at moderate SBS, amounting to 71.5 percent of moderate and high SBS (Figure 2). During the post-fire Burned Area Emergency Response (BAER) assessment conducted by the U.S. Forest Service, a majority of the soils were identified as soil Hydrologic Group D, indicating soils that are shallow and prone to runoff, especially when vegetation is removed. In addition, hydrophobicity testing in numerous plots revealed subsurface hydrophobic layers 2–5 mm thick with moderate to strong hydrophobic severity, lasting 1–5 minutes (Nicita, 2016).

El Capitan State Beach and State Park are located at the mouth of this watershed on the south side of Hwy 101. The El Capitan Canyon Resort is situated above the State Beach, on the north side of Hwy 101, along the floodplain of El Capitan Creek. At the time of the 20 January 2017 post-fire debris flow event, the resort consisted of approximately 160 cabins, yurts, and tent sites, all surrounded by El Capitan State Park lands. To the north and above the El Capitan State Park are the Los Padres National Forest lands.

Based on pre-flooding aerial and ground surveys, it was evident that in the past, mass wasting has occurred in areas dominated by the Sespe Sandstone, Gaviota Sandstone, and Sacate Shale Formations, loading stream channels with boulders, loose debris, and debris flow deposits in the mountain channels. Based on reports from El Capitan Canyon Resort personnel and State Park staff, the unnamed road that traverses through El Capitan Canyon Resort and into the El Capitan State Park lands has been historically impacted multiple times by mass wasting as rockfall and debris slides, even in the absence of wildfires.

Meteorological Triggering Event for Debris Flow

On the morning of 20 January 2017, a storm featuring a weak-to-moderate atmospheric river (Figure 3a) produced rainfall in the Santa Ynez Mountains. This was a very dynamically active and complex storm resulting in the development of several narrow bands of intense rainfall in California, one of which moved over the Sherpa Fire burned area and was enhanced by orographic forcing along the Santa Ynez Mountains (Figure 3b). Similar intense bands of rainfall have previously been associated with post-wildfire debris flows in Southern California (Oakley et al. 2017, 2018).

Rainfall in this storm event began at the Refugio Pass rain gage (Figure 1), which best represents the upper El Capitan watershed, at 0:45 a.m. PST. By 11:55 a.m. PST, 98 mm of rain had fallen, with a maximum 1-hour rainfall accumulation of 52 mm occurring between 8:10 and 9:10 a.m. PST and a peak 15-minute rainfall accumulation of 19 mm occurring between 8:53 and 9:08 a.m. PST, representing a 76 mm/hr rate (Figure 4). Based on NOAA Atlas 14 (NOAA, 2016) using the methods described by Staley et al. (2020), the peak 15-minute accumulation was calculated to an average precipitation return interval frequency of 15.8 years. Kean et al. (2011) and Staley et al. (2013) found that rainfall intensities measured over durations of 60 minutes or less are best correlated with post-fire debris flow initiation. Moreover, the 15-minute duration provides the most accurate prediction of post-fire debris flow generation (Staley et al., 2017).

This triggering event was the second rainfall event in 2 days at this location (Figure 5), following the 19 January rainstorm event that produced 32 mm over a period of 2:45 hours at the Refugio Pass rain gage. The 20 January rainstorm event started 22 hours after the 19 January rainstorm ended. The average annual rainfall (1958–2020) at the Refugio Pass rain gage is 711 mm/yr. From the start of Water Year 2017 (October 1), this rain gage had received 470 mm of

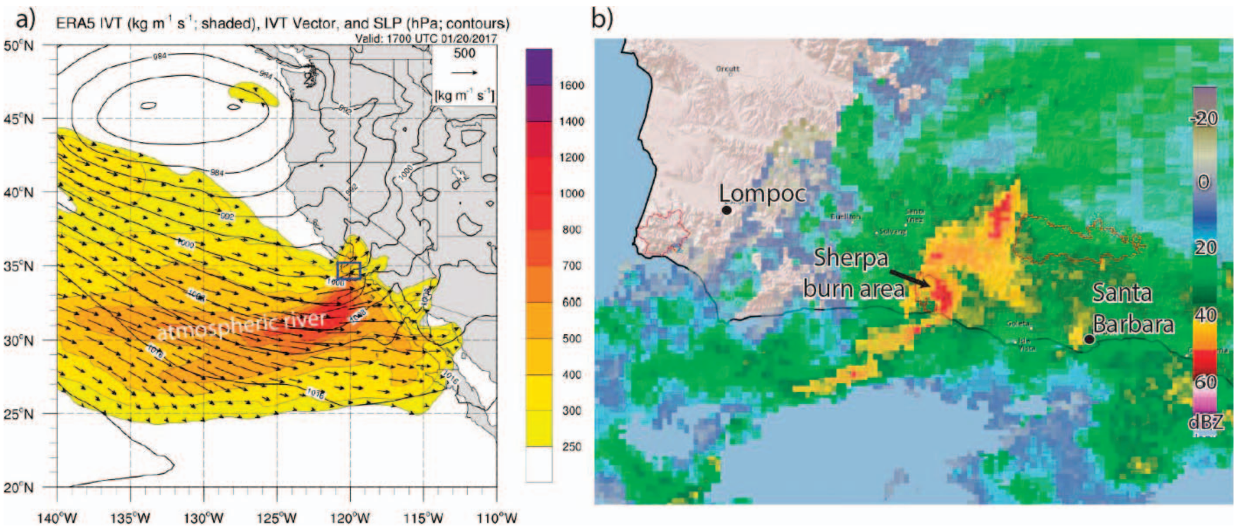

Figure 3. (a) Integrated water vapor transport (IVT; color fill and vectors) and sea level pressure (black contours) for 1000 PST 20 January 2017. Darker/redder colors indicate greater IVT, a measure combining total atmospheric water vapor and wind strength. Data are from the ERA5 atmospheric reanalysis (C3S 2017). (b) Radar reflectivity (dBZ) at 9:15 PST shows intense rainfall (>50 dBZ) over the Sherpa Fire burn area. Intense rain is indicated by yellow-to-red colors and less intense rain is indicated by blue-to-green colors.

precipitation, 66.1 percent of the annual average. Thus, the soil and channel bed moisture were likely elevated, potentially contributing to an increase in surface runoff and mobility of materials (Iverson et al., 2011; Reid et al., 2011; and Kean et al., 2013).

OBSERVATIONS AND DATA COLLECTION

This investigation is based on field observations and data collected during and immediately after the Sherpa Fire, as well as multiple post-flooding field assessments. Field observations and data collected during and immediately after the fire included ground surveys, flight reconnaissance, and aerial photography throughout the burned area. Post-flooding and debris flow event data collection began on 24 January 2017, after the third consecutive rainstorm in 4 days, and was focused on the El Capitan drainage inundation zone. Field work included documentation and measurements of the debris flow inundation extent,

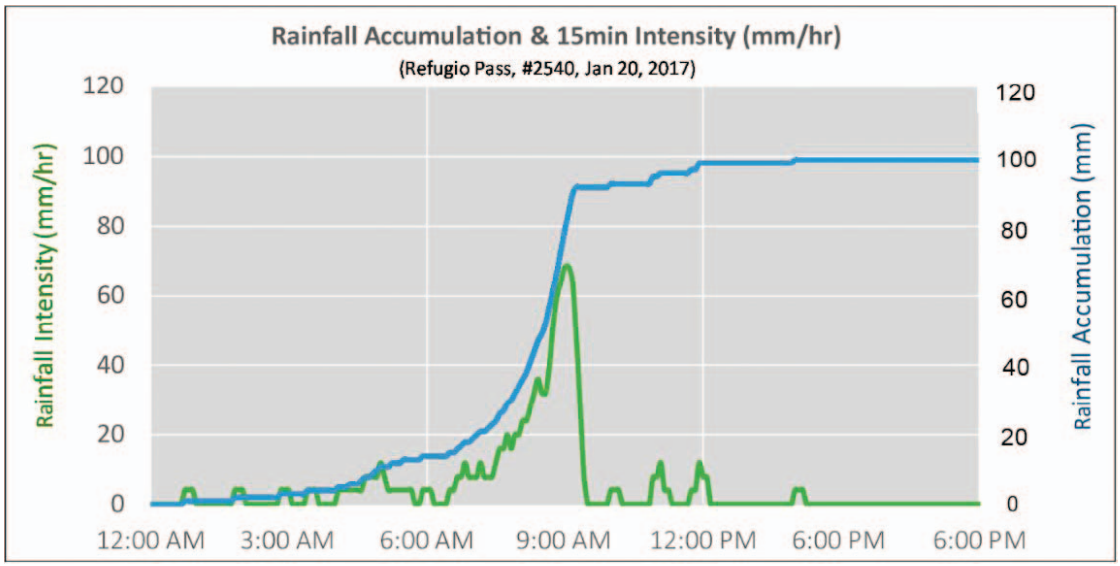

Figure 4. Rainfall accumulation (blue line) and 15-minute intensities (green line) for the storm on 20 January 2017. The peak 15-minute intensity was 76 mm/hr.

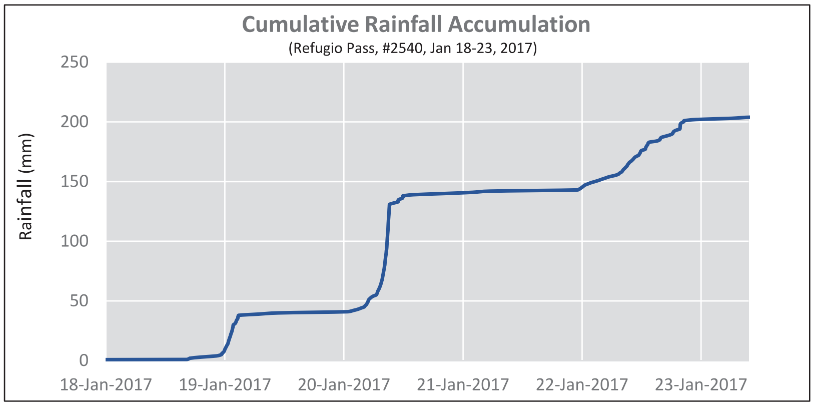

Figure 5. Cumulative rainfall accumulations for the three rainfall events that occurred over a 4-day period, 19–23 January 2017 at Refugio Pass Raingage Station. The El Capitan debris flows occurred during the second consecutive storm on 20 January 2017.

debris flow deposit depth, the type and nature of sediment delivered by the debris flow, scour depths, and the extent of damage caused by the debris flow. In addition to field assessments, observations are supported by eyewitness accounts of the debris flow and flooding events, including photos and videos, which supported reconstruction of these events.

El Capitan Drainage

El Capitan Debris Flow Source Area

Since this post-debris flow investigation focused on the inundation zone, ground assessment and documentation were minimal in the source area. In the limited post-flooding field assessment of the upper portions of the impacted watersheds, rill development and surface erosion were noted on the slopes above the El Capitan Creek and its tributaries channels, but no detailed measurements were taken to document the extent of surface erosion and quantity material delivered from the source area. On 9 July 2017, 6 months after this flooding and debris flow event, the Whittier Fire ignited and burned on both the north and south facing slopes of the Santa Ynez Mountains, adjacent to and overlapping with portions of the Sherpa Fire. Aerial flight reconnaissance conducted during the BAER assessment of the Whittier Fire revealed widespread rilling and surface erosion throughout the steep burned slopes, especially in the shale units. Aerial photography shows the post-fire soil conditions for shale and sandstone units in the Whittier Fire burn area and reveal that many gullies and first-order channels in the Sherpa Fire burn area had been scoured to bedrock (Figure 6).

El Capitan Debris Flow Inundation Zone

The inundation zone associated with the El Capitan debris flow occurred along the El Capitan Creek and floodplain, starting approximately 2 km above and north of Hwy 101 and extending to the ocean. The channel gradients in the upper parts of the watershed where debris flow material was transported ranges from 30° to 10° and decreases to 2°–3° by the upper end of the El Capitan Canyon Resort where debris flow deposits were identified.

Field observations along the stretch of El Capitan Creek between the State Park boundary (upper end of the El Capitan Canyon Resort) and the Mid-Canyon Bridge (Figure 7) revealed that some segments of the stream experienced channel incision and scour depths ranging from 1.2 to 1.5 m. Other segments of the creek, mostly below the Mid-Canyon Bridge, accrued boulders and finer sediment deposition up to 4 m in depth. Lateral bank erosion occurred mostly on the outer banks at channel bends, exposing unsorted, non-stratified, matrix-supported alluvial channel and older debris flow deposits (Figure 8a). Since the field observation for this study began 24 January 2017 after the third consecutive rainstorm in a 4-day period (Figure 5), it is difficult to determine the exact time the scour and deposition took place along these segments of the stream channel. Along segments of the creek that experienced deposition, elongated boulder fields ranging in size from ~60 m to 140 m long, 10 m to 20 m wide were documented in the channel and were comprised of sub-angular to sub-rounded sandstone boulders ranging from 0.3 m to more than 2.5 m in diameter (Figure 9).

Based on eyewitness reports, the debris flow reached the El Capitan Canyon Resort at approximately

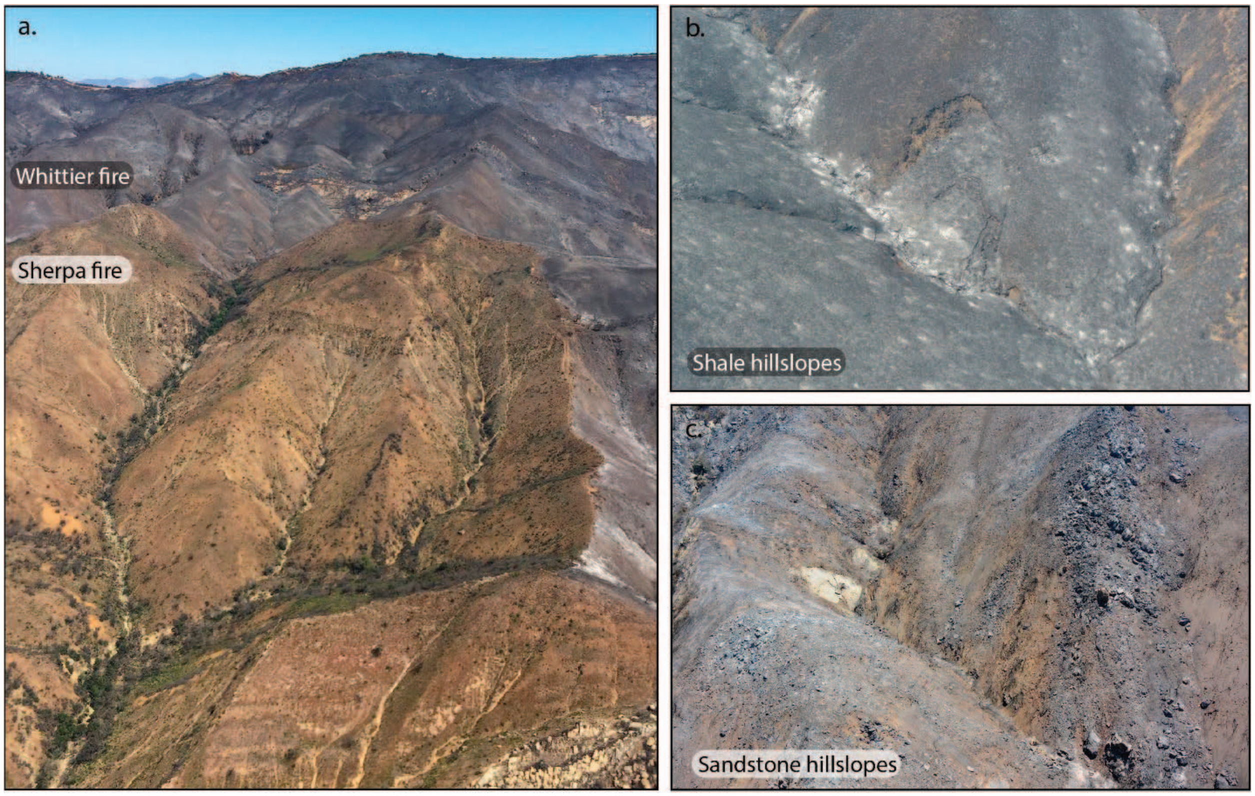

Figure 6. (a) Burned areas of the Sherpa and Whittier fires. This photo was taken a year after the Sherpa Fire, 6 months after the rainstorm and debris flow events, and 2 weeks after the Whittier Fire. Gullies and first-order channels in the Sherpa Fire burn area were scoured to bedrock (photo taken by Kevin Cooper, USFS). (b) Shale hillslopes mantled with thick, continuous fine-grained soil, ash, and charred organic matter. Vegetation is completely incinerated. (c) Sandstone hillslopes composed of thin, patchy soils; bedrock outcrop; ash; charred organic matter; and silt-rich colluvium with grain sizes up to boulders.

9:20 a.m. PST, about 13 minutes after the period of highest 15-minute rainfall intensity. Field evidence and eyewitness reports suggest the debris flow surge front included coarse woody debris that plugged foot and vehicle bridges, culverts, and the Hwy 101 underpass, similar to the 9 January 2018 Montecito debris flows that followed the 2017 Thomas Fire. This coarse woody debris included burned tree limbs and other vegetation transported down the creek from the upper portions of the watershed as well as riparian vegetation that survived the fire but was stripped and transported downstream by the powerful flooding and debris flow. The first bridge to be impacted by the debris flow was the Mid-Canyon Bridge, a large wood deck bridge, approximately 5 m wide and 15 m long. This bridge was supported on both sides of the creek by concrete abutments (Figure 10a). Attached to the top of these abutments and supporting a wooden deck were three metal I-beams 45.72 cm high, 19.05 cm wide, 0.95 cm thick, and 15 m long. The debris flow surge front demolished the bridge, knocking it off its abutments. The metal I-beams were carried downstream and twisted around large standing trees (Figure 10b).

Similar to observations made by Lancaster et al. (2020) in the 9 January 2018 Montecito debris flow, overbank flows and avulsions occurred where the overall flow height exceeded the capacity of the channel bank or at locations where channel constrictions as bridges, bridge abutments, or culverts were present. Ground assessments revealed evidence of dispersed overbank flows as well as debris flow inundation characteristics. At locations where dispersed overbank flows took place, such as below the Mid-Canyon Bridge, high watermarks revealed evidence of up to 1.2 m of flooding that impacted the floodplain above the bankfull discharge. In some locations this flooding impacted an area extending 30 m up each side of the channel. Maximum debris flow inundation depth was determined from mud patinas on structures and tree trunks, broken tree limbs, and fresh scarring on the upstream side of tree trunks. Some structures located on the floodplain were marked on their upstream side by

Figure 7. A map showing the El Capitan Canyon Resort and El Capitan State Beach locations with scale.

mud patinas to heights of up to 2.5 m above the bankfull discharge (Figure 10c). Similarly, along the channel bed, large oak and sycamore trees surviving the flow path were marked by mud patinas and scarring on their upstream side to heights of 2.5 m above bankfull discharge. Boulder deposition in the floodplain consisted of isolated rocks with few boulder fields. In the area below the Mid-Canyon Bridge where avulsions took place, boulder and other debris impacted many cabins located on the floodplain, causing varying

Figure 8. (a) Lateral bank erosion occurred mostly on the outer banks at channel bends, exposing unsorted, non-stratified, matrix-supported, paleo debris flow deposits. (b) Paleo debris flow levees composed of weathered sub-angular boulders were observed on the lateral margins of the active channel in El Capitan Creek.

Figure 9. (a) Large elongated boulder fields that were deposited in the active channel. Boulder fields ranged in size from ~60 m to 140 m long and ~10 m to 20 m wide, and contained (b) sub-angular to sub-rounded sandstone boulders ranging in size from 0.3 m to more than 2.5 m in diameter.

levels of damage (Figure 10d). Nine cabins were forced off their foundations and swept downstream and as many as 21 vehicles were carried away and crushed, some reaching the ocean.

As the debris flow surge front reached this lower area of the El Capitan Canyon Resort, large amounts of coarse woody debris plugged the foot bridge leading to the Canyon Market and the El Capitan Canyon

Figure 10. (a) Damage to the Mid-Canyon Bridge, supported on both sides of the creek by concrete abutments. (b) Twisted metal I-beams that supported the Mid-Canyon Bridge prior to the debris flow event. (c) Structure on the flood plain marked on its up-stream side by mud patinas to a height of up to 2.5 m. (d) Damaged cabins at the El Capitan Canyon Resort.

Figure 11. (a) Large soil-surfaced parking lot near the entrance of the El Capitan Canyon Resort turned into a debris catchment basin as debris flows and flooding impacted the El Capitan watershed and plugged the Hwy 101 underpass. (b) Once the Hwy 101 underpass was clear of debris, the high level of water in the soil-surfaced parking lot area subsided and much of the debris (including cars and cabins) was deposited in the parking lot. (c) In total, four cars, one truck, and one tractor were transported out to the ocean at the mouth of El Capitan Creek. (d) In the Canada Del Corral watershed, woody debris clogged the Hwy 101 underpass, which created a backup that caused mud and boulders to flow overbank onto the floodplain, resulting in damaged historic adobe structures located north of Hwy 101.

Resort Entrée Bridge. As these bridges were completely plugged, the flood was diverted out of the channel and into a large soil-surfaced parking lot (approximately 100 m by 60 m) located below and to the west of the El Capitan Canyon Resort Entrée Bridge and adjacent to Hwy 101 (Figure 7). As debris and flows avulsed the channel, flooding the parking lot area, flows continued toward the Hwy 101 underpass. At this stage, in addition to large amounts of woody debris, mud, rocks and boulders, the debris included cars and cabins that were swept away by the flows. As a result of debris plugging the Hwy 101 concrete underpass (3.6 m wide × 4.6 m high), the large soil-surfaced parking lot turned into a debris catchment basin (Figure 11a). Based on the size of the parking lot and depth of debris estimated from photo documentation of the parking lot during the peak of the event, it is estimated that the volume of debris retained in this "temporary debris basin" ranged from 12,000 m^3 to 16,000 m^3 between 9:20 and 9:45 a.m. PST.

Based on eyewitness reports, at ∼9:45 a.m. PST, when the pressure was high enough, the debris plugging the Hwy 101 underpass broke through and large amounts of debris (including four cars, one truck, and one tractor) were transported out to the ocean (Figure 11c). The estimated distances these vehicles were transported by the event ranged from 1 to2 km depending on their starting point within the resort. Once the Hwy 101 underpass was clear of debris, the water level in the dirt parking lot subsided, depositing much of the debris (including cars and cabins) at this location (Figure 11b). According to Santa Barbara County Fire Department officials, no fatalities or injuries occurred in this event, although 22 people were trapped in cabins in the resort and required immediate rescue from first responders.

El Capitan Canyon State Beach

El Capitan Creek flows under Hwy 101 and continues ~0.75 km before reaching its mouth at El Capitan Beach. On its way to the ocean, the creek flows under a large arch culvert (4.5 m wide × 3.6 m high) located under the entrance road to the State Beach (Figure 7). Reports from staff occupying the State Beach entrance kiosk indicate that at approximately 9:45 a.m. PST, as the surge front of debris came down the creek, large amounts of debris plugged the arch culvert, causing the flows to avulse and divert down the road toward the kiosk. This diversion of the flow persisted for approximately 10 to 15 minutes. Once pressure on the debris plugging the culvert broke through, flows and debris resumed their natural flow path down the creek to the ocean.

Cañada Del Corral and Las Flores Canyon

From eyewitness reports and security camera videos at the Exxon-Mobile oil and gas facility located at the confluence of Cañada Del Corral and Las Flores Canyon, it appears that at the same time El Capitan Creek was impacted by flooding and debris flows, Cañada Del Corral and Las Flores Canyon were experiencing similar events. Video footage demonstrates that the event impacting these drainages was primarily sediment-laden flooding with large amounts of woody debris and smaller quantities of large boulders as compared to the event in El Capitan Creek. The surge front of this sediment-laden flooding reached the oil and gas facility at 9:20 a.m. PST and continued for approximately 25–30 minutes. By 9:50 a.m. PST the high flows in both drainages subsided. As in El Capitan Creek, once the woody debris flowing down Cañada Del Corral reached the Hwy 101 underpass, it clogged the underpass and inundated the floodplain, damaging historic adobe structures located north of Hwy 101 (Figure 11d).

DISCUSSION

The 20 January 2017 flooding and debris flow events that impacted the Cañada del Capitan, Cañada Del Corral, and Las Flores Canyons originated in recently burned watersheds with 64 percent moderate and high SBS, as observed during a post-fire assessment conducted by the U.S. Forest Service BAER Team. The burn area had steep, colluvial-mantled slopes and channels loaded with unsorted, unconsolidated materials, including colluvium and older debris flow deposits, available to be transported(Figure 8b). The parent materials of these watersheds are, for the most part, alternating sandstone and shale units, where shale units provide fine-grained colluvium for slurry production and sandstone units provide coarser colluvium and boulders (Figure 6b and c). In addition, immediately after the Sherpa Fire, ground surveys revealed widespread dry ravel further loading the channels (Schwartz, 2016). Analysis of aerial photography taken from a flight reconnaissance conducted during the BAER assessment of the Whittier Fire (9 July 2017) revealed surface erosion in the form of widespread rilling and sheetwash throughout the steep burned slopes of the Sherpa Fire, especially in the shale units, and first-order channels were scoured to bedrock (Figure 6a). Based on the steep terrain, the underlying geological units, the extensive moderate and high SBS, and the high-intensity rainstorm that triggered this event, we concluded that the steep unstable slopes and channels in the upper portions of these watersheds functioned as major sediment sources for the 20 January 2017 El Capitan flooding and debris flow event.

Observations compiled from the 19–22 January 2017 post-fire storm events indicate that three distinct flow processes occurred in El Capitan Creek throughout these storm events. The three basic flow processes include water flows, hyper-concentrated flows, and debris flows. These flow processes represent a continuum where boundaries between the flow types are not sharp, such that any one flow event may exhibit different flow types at different times and points along the flow path (Pierson, 2005; Wagner et al., 2012). Eyewitness accounts and ground-based observations suggest that the surge front that caused most of the damage in the El Capitan Canyon Resort during the 20 January 2017 storm was related to a debris flow. The velocity and concentrated nature of these flows caused overbanking and channel avulsions that resulted in damaged roads, bridges, pipelines, infrastructure, and cabins in the El Capitan Canyon Resort. Based on observations and analysis done by the U.S. Forest Service BAER Team following the Sherpa Fire, this type of damage was predicted (Schwartz, 2016). Furthermore, in their final report, the U.S. Forest Service BAER Team recommended that during rainstorm events meeting or exceeding 28 mm/hr in the first wet season following the fire, the El Capitan Canyon Resort and El Capitan State Beach should be evacuated.

The physical setting and soil conditions of the source area for the 20 January 2017 El Capitan flooding and debris flow events are similar to those that led to the 9 January 2018 debris flows in Montecito, California. In Montecito, large, channel-clearing debris flows were generated ~3 weeks after the Thomas

Fire that burned in the Santa Ynez Mountains of southern California (Kean et al., 2019). The debris flows were triggered by a high-intensity rainstorm (Oakley et al., 2018) that extensively stripped soil from hillslopes via rilling and scoured boulders and paleo-debris flow deposits from six adjacent mountain catchments, which significantly impacted the community below (Kean et al., 2019). The economic impact from commercial and private property damage alone was ~\$400 million, not including lost wages and impacts from the Hwy 101 closure (RDN, Inc., 2018). In both settings, the source area included steep south-facing slopes along the Santa Ynez Range. In both locations, the underlying geological units consist, for the most part, of alternating sandstone and shale units (Dibble, 1982), and the source area for the debris flows experienced moderate and high SBS (Young et al., 2018), dry ravel, and rilling of hillslopes. Additionally, the storms that initiated these debris flows were short-duration, high-intensity rainstorms in the form of a north–south-oriented narrow band.

Though both events had a similar setup, there are several major differences between the El Capitan and Montecito events that help to explain the differences in their magnitude and impacts. First, the peak 5-minute and 15-minute rainfall intensities were much higher in the Montecito event. For the 20 January 2017 El Capitan debris flows, the peak 5-minute rainfall intensity was 84 mm/hr and the peak 15-minute rainfall intensity was 76 mm/hr, recorded at the Refugio Pass gauge. In the 9 January 2018 Montecito event, the peak 5-minute rainfall intensity was 180 mm/hr and the peak 15-minute rainfall intensity was 106 mm/hr at the Doulton Tunnel ALERT gauge. During the 9 January 2018 event, the most intense rainfall was focused on the eastern half of Santa Barbara County. The Sherpa Fire burn area received much less intense rainfall than the Thomas Fire burn area, with a peak 15-minute rainfall intensity of 20 mm/hr at the Refugio Pass gauge. No impactful hydrologic response was reported on the Sherpa Fire burn area in this event.

Second, Montecito had a greater fraction and total area of the watersheds that burned at moderate and high SBS. In the El Capitan, only 41 percent (6.42 km^2) of the watershed was burned by the Sherpa Fire and the fire did not extend up to the ridge crest, whereas over 90 percent of the area above Montecito and Carpinteria was burned by the Thomas Fire and extended up to the ridge crest. Lastly, the amount and type of development below the mountain front was distinct between the two events. The El Capitan debris flow impacted mostly "soft" structures consisting of about 160 cabins, yurts, and tent sites. In contrast, for the Montecito debris flows, the inundation zone was largely urbanized with houses, paved roads, and essential infrastructure.

Additional key differences between the two events also exist in the physical setting of the inundation zone. In the case of the El Capitan event, the inundation zone impacted by the debris flow and flooding event consists of a narrow floodplain, approximately 100–150 m wide and 2 km long, situated along the El Capitan Creek valley floor. In Montecito, the inundation zone consisted of steeply sloping wide debris flow and alluvial fans, bisected by a fault. The total area inundated in Carpinteria and Montecito in the 9 January 2018 event was 5.56 km^2 (Lancaster et al., 2020), whereas the area inundated in the 2017 El Capitan event was ~0.12 km^2.

CONCLUSIONS

The Montecito and El Capitan events occurred 1 year apart and ~35 km away from one another, with similar physical and climatological settings. Observations presented here in the El Capitan Creek and adjacent watersheds, as well as prior research in other drainages in the Santa Ynez Mountains, demonstrate that hillslopes have ample colluvium to produce slurry from rilling and load channels with dry ravel, channels have ample boulders and coarse material to be mobilized by slurry, and the lithology (alternating sandstone and shale units) produces a favorable setup for post-wildfire debris flow generation. A comparison of the El Capitan and the Montecito debris flow events highlights the potential for future destructive post-wildfire debris flows in this region, especially in a warming climate with projected increases in wildfire activity and precipitation intensity. Information from case studies such as this support decision makers and emergency managers in understanding the hazards and risks that floods and debris flows pose on communities below steep, recently burned drainages and inform the development of sound protocols to reduce the threat to life, property, and infrastructure in downstream communities.

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REFERENCES

Alessio, P., 2019, *Spatial variability of saturated hydraulic conductivity and measurement-based intensity duration thresholds for slope stability*, Santa Ynez Valley, CA: Geomorphology, Vol. 342, pp. 103–116.

Barbero, R.; Abatzoglou, J. T.; Larkin, N. K.; Kolden, C. A.; and Stocks, B., 2015, Climate change presents increased potential for very large fires in the contiguous United States: *International Journal Wildland Fire*, Vol. 24, No. 7, pp. 892–899.

Cannon, S. H., 2000, Debris-flow response of southern California watersheds recently burned by wildfire. In Wieczorek, G. F., and Naeser, N. D. (Editors), *Debris-Flow Hazards Mitigation, Mechanics, Prediction, and Assessment, Proceedings of the Second International Conference on Debris-Flow Hazards Mitigation, Taipei, Taiwan, 16–18 August 2000*: A. A. Balkema, Rotterdam, Netherlands, pp. 45–52.

Cannon, S. H., 2001, Debris-flow generation from recently burned watersheds: *Environmental Engineering Geoscience*, Vol. 7, pp. 321–341.

Cannon, S. H.; Bigio, E. R.; and Mine, E., 2001a, A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico: *Hydrological Processes*, Vol. 15, No. 15, pp. 3011–3023.

Cannon, S. H. and De Graff, J., 2009, *The increasing wildfire and post-fire debris-flows threat in Western USA, and implications for consequences of climate change*. In Sassa, K. and Canuti, P. (Editors), *Landslides – Disaster Risk Reduction*: Springer, Berlin, Germany, pp. 177–190.

Cannon, S., J. Gartner, C. Parret, and M. Parise (2003), Wildfire-related debris-flow generation through episodic progressive sediment bulking processes, western USA, in Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings of the Third International Conference on Debris-Flow Hazards Mitigation, pp. 71–82, Mill press, Rotterdam, Netherlands.

Cannon, S. H.; Gartner, J. E.; Rupert, M. G.; and Michael, J. A., 2003b, *Emergency Assessment of Debris-Flow Hazards from Basins Burned by the Piru, Simi, and Verdale Fires of 2003, Southern California*. U.S. Geological Survey Open-File Report OF-03-481.

Cannon, S. H.; Kirkham, R. M.; and Parise, M., 2001b, Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado: *Geomorphology*, Vol. 39, No. 3–4, pp. 171–188.

DeBano, L. F.; Neary, D.; and Folliott, P., 1998, *Fire's Effects on Ecosystems*: John Wiley and Sons Inc., New York, 333 p.

De Graff, J.; Cannon, S. H.; and Gartner, J. E., 2015, The timing of susceptibility to post-fire debris flows in Western United States: *Environmental Engineering Geoscience*, Vol. 21, No. 4, pp. 277–292. http://doi.org/10.2113/gseegeosci.21.4.277.

Dibblee, T. W., Jr., 1982, Geology of the Santa Ynez - Topatopa Mountains, Southern California. In Fife, D. L., and Minch, J. A., (Editors), *Geology and Minerals Wealth of the California Transverse Ranges: Mason Hill Volume*: Santa Ana, California: South Coast Geological Society, pp. 41–56.

Dibblee, T. W., Jr., 1988, Geology Map of the Santa Ynez / Tajiguas Quadrangles, Santa Barbara County, California: Helmut, E. (Editor), Published by the Thomas W. Dibblee, Jr. Geological Foundation, Map scale 1:24,000.

DiBiase, R. A. and Lamb M. P., 2020, *Dry sediment loading of headwater channels fuels post-wildfire debris flows in bedrock landscapes*: *Geology*, Vol. 48, No. 2, pp. 189–193.

Iverson, R. M., 1997, The physics of debris flows: Reviews Geophysics, Vol. 35, pp. 245–296.

Iverson, R. M.; Reid, M. E.; Logan, M.; LaHusen, R. G.; Godt, J. W.; and Griswold, J. P., 2011, Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment: *Nature Geoscience*, Vol. 4, No, 2, pp. 116–121, available at http://www.nature.com/ngeo/journal/v4/n2/abs/ngeo1040.html#supplementary-information

Kean, J. W.; Staley, D. M.; and Cannon, S. H., 2011, In situ measurements of post-fire debris flows in southern California and soil moisture conditions: *Journal Geophysical Research*, Vol. 116, No. F4, F04019. http://doi.org/10.1029/2011jf002005.

Kean, J. W.; Staley, D. M.; Lancaster, J. T.; Rangers, F. K.; Swanson, B. J.; Coe, J. A.; Hernandez, J. I.; Sigman, A. J.; Allstadt, K. E.; and Lindsay, D. N., 2019, Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA; opportunities and challenges for post-wildfire risk assessment: *Geosphere*, Vol. 15, No. 4, pp. 1140–1163. https://doi.org/10.1130/ges02048.1.

Kean, J. W.; Tucker, G. E.; Staley, D. M.; and Coe, J. A., 2013, Runoff-generated debris flows: Observations and modeling of surge initiation, magnitude and frequency: *Journal Geophysical Research: Earth Surfaces*, 2013JF002796.

Keller, E. A.; Bean, G.; and Best, D., 2015, Fluvial geomorphology of a boulder-bed, debris-flow—Dominated channel in an active tectonic environment: *Geomorphology*, Vol. 243, pp. 14–26.

Lancaster, J. T.; Swanson, B. J.; Lukashov, S. G.; Oakley, N. S.; Lee, J. B.; Spangler, E. R.; Hernandez, J. L.; Olson, B. P. E.; Defrisco, M. J.; Lindsay, D. N.; Schwartz, J. Y.; Mccrea, S. E.; Roffers, P. D.; and Tran, C. M., 2020, Observations and analysis of the 9 January 2018 debris-flow disaster, Santa Barbara County, California: *Environmental Engineering Geoscience*, Vol. XXVI, No. 4, pp. 1–25.

Lentile, L. B.; Holden, Z. A.; Smith, A. M. S.; Falkowski, M. J.; Hudak, A. T.; Morgan, P.; Lewis, S. A.; Gessler, P. E.; and Benson, N. C., 2006, Remote sensing techniques to assess active fire characteristics and post-fire effects: *International Journal of Wildland Fire*, Vol. 15, pp. 319–345.

Lukashov, S. G.; Lancaster, J. T.; Oakley, N. S.; and Swanson, B. J., 2019, Post fire debris flows of 9 January 2018, Thomas Fire, southern California: Initiation areas, precipitation and impacts. In Kean, J. W.; Coe, J. A.; Santi, P. M.; and Guillen, B. K. (Editors), *Debris-Flow Hazards Mitigation: Mechanics, Monitoring, Modeling, and Assessment: Proceedings of the Seventh International Conference on Debris-Flow Hazards Mitigation, June 10–13, 2019*: Association of Environmental and Engineering, Geologists, Golden, CO, pp. 774–781.

Melosh, B. L. and Edward A. Keller, E. A., 2013, Effects of active folding and reverse faulting on stream channel evolution, Santa Barbara Fold Belt, California: *Geomorphology*, Vol. 186, pp. 119–135.

Meyer, G. A. and Wells, S. G., 1997, Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA: *Journal Sedimentary Research*, Vol. 67, No. 5, 776–791.

Nicita, E., 2016, *Sherpa Fire - Soil Resource Assessment - Burned Area Emergency Response (BAER) Report*. USDA Forest Service internal report, 11 p.

NOAA Atlas 14, 2016, *Hydrometeorological Designs Study Center Precipitation Frequency Data Server (PFDS)*: available at http://hdsc.nws.noaa.gov/hdsc/pfds/index.html

Oakley, N. S.; Cannon, F.; Munroe, R.; Lancaster, J. T.; Gomberg, D.; and Ralph, F. M., 2018, Brief communication: Meteorological and climatological conditions associated with the 9 January 2018 post-fire debris flows in Montecito and Carpinteria, California, USA: *Natural Hazards Earth System Sciences*, Vol. 18, No. 11, 3037–3043.

Oakley, N. S.; Lancaster, J. T.; Kaplan, M. L.; and Ralph, F. M., 2017, Synoptic conditions associated with cool season post-fire debris flows in the Transverse Ranges of southern California: *Natural Hazards*, Vol. 88, No. 1, pp. 327–354.

Parise, M. and Cannon, S. H., 2012, Wildfire impacts on the processes that generate debris flows in burned watersheds: *Natural Hazards*, Vol. 61, No. 1, pp. 217–227.

Parsons, A.; Robichaud, P.; Lewis, S.; Napper, C.; and Clark, J. T., 2010, *Field Guide for Mapping Post-fire Soil Burn Severity: Gen. Tech. Rep. RMRS-GTR-243*, Fort Collins, CO, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Pierson, T. C., 2005, *Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds*: U.S. Geological Survey Fact Sheet 2004–3142, available at http://volcanoes.usgs.gov/

Prein, A. F.; Rasmussen, R. M.; Ikeda, K.; Liu, C.; Clark, M. P.; and Holland, G. J., 2017, The future intensification of hourly precipitation extremes: *Nature Climate Change*, Vol. 7, No. 1, pp. 48–52.

Robert D. Niehaus, Inc. (RDN, Inc.), 2018, The Economic Impacts of the Montecito Mudslides: A Preliminary Assessment: Electronic document, available at http://www.rdniehaus.com/rdn/wp-content/uploads/2018/03/RDN_Montecito_Mudslides_Impacts-1.pdf.

Reid, M. E.; Iverson, R. M.; Logan, M.; LaHusen, R. G.; Godt, J. W.; and Griswold, J. P., 2011, Entrainment of bed sediment by debris flows: Results from large-scale experiments. In: Genevois, R.; Hamilton, D. L.; and Prestininzi A. (Eds.), Proceedings of the 5th International Conference on Debris-Flow Hazards: Mitigation, Mechanics, Prediction and Assessment. Italian Journal of Engineering Geology and Environment and Casa Editrice Universita La Sapienza, Rome, pp. 367–374.

Ryan, K. C. and Noste, N. V., 1985, Evaluating prescribed fires; 15–18 November 1983; Missoula, MT. In: Lotan, J. E.; Kilgore, B.M. Fischer, W.C., Mutch, R.W. (Editors), Proceedings of the Symposium and Workshop on Wilderness Fire, Gen. Tech. Rep. INT-GTR-182. Ogden, UT, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: p. 230–238.

Schwartz, J. Y., 2016, *Sherpa Fire - Burn Area Emergency Response (BAER), Geology Report*: *USDA Forest Service internal report, 23* p.

Smith, C. M.; Hatchett, B. J.; and Kaplan, M. L., 2018, Characteristics of sundowner winds near Santa Barbara, California, from a dynamically downscaled climatology: Environment and effects near the surface: *Journal Applied Meteorology Climatology*, Vol. 57, No. 3, pp. 589–606, available at https://journals.ametsoc.org/view/journals/apme/57/3/jamc-d-17-0162.1.xml

Staley, D. M.; Kean, J. W.; Cannon, S. H.; Schmidt, K. M.; and Laber, J. L., 2013, Objective definition of rainfall intensity-duration thresholds for the initiation of post-fire debris flows in southern California: *Landslides*, Vol.10, pp. 547–562. https://doi.org/10.1007/s10346-012-0341-9

Staley, D. M.; Kean, J. W.; and Rangers, F. K., 2020, *The recurrence of post-fire debris-flow generating rainfall in the southwestern United States: Geomorphology*, Vol. 370, pp. 1–10.

Staley, D. M.; Negri, J. A.; Kean, J. W.; Laber, J. L.; Tillery, A. C.; and Youberg, A. M., 2017, Prediction of spatially explicit rainfall intensity–duration thresholds for post-fire debris-flow generation in the western United States: *Geomorphology*, Vol. 278, pp. 149–162.

U.S. Army Corps of Engineers, 1974, *Flood Plain Information, Montecito Streams, Vicinity of Montecito, Santa Barbara County, California*: Electronic document, available a*t* http://www.countyofsb.org/uploadedFiles/pwd/Content/Water/MontStreamsRpt1974.pdf

Wagner, D. L.; Lancaster, J. T.; and DeRose, M. B., 2012, *The Oak Creek Post Fire Debris and Hyperconcentrated Flows of July 12, 2008, Inyo County, California: A Geologic Investigation*: Special Report 225, Version 1.0, California Geological Survey, California Department of Conservation, Sacramento, California, 44 p.

Westerling, A. L., 2018, *Wildfire Simulations for the Fourth California Climate Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate*: Technical report for California's Fourth Climate Change Assessment, Publication No. CCCA4-CEC-2018-014, California Energy Commission, Sacramento, CA.

Wilder BA, Lancaster JT, Cafferata PH, et al. An analytical solution for rapidly predicting post-fire peak streamflow for small watersheds in southern California. Hydrological Processes. 2020;1–14. https://doi.org/10.1002/hyp.13976

Young, D.; Courtney, A.; and Nicita, E., 2018, *Thomas Fire – Burned Area Emergency Response (BAER), Soil Resource Report*: *USDA Forest Service internal report*, 19 p.