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Rainfall intensity–duration thresholds for postfire debris-flow emergency-response planning

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Abstract Following wildfires, emergency-response and public-safety agencies can be faced with evacuation and resource-deployment decisions well in advance of coming winter storms and during storms themselves. Information critical to these decisions is provided for recently burned areas in the San Gabriel Mountains of southern California. A compilation of information on the hydrologic response to winter storms from recently burned areas in southern California steeplands is used to develop a system for classifying magnitudes of hydrologic response. The four-class system describes combinations of reported volumes of individual debris flows, consequences of debris flows and floods in an urban setting, and spatial extents of the hydrologic response. The range of rainfall conditions associated with different magnitude classes is defined by integrating local rainfall data with the response magnitude information. Magnitude I events can be expected when within-storm rainfall accumulations (A) of given durations (D) fall above the threshold $A = 0.4D^{0.5}$ and below $A = 0.5D^{0.6}$ for durations greater than 1 h. Magnitude II events will be generated in response to rainfall accumulations and durations between $A = 0.4D^{0.5}$ and $A = 0.9D^{0.5}$ for durations less than 1 h, and between $A = 0.5D^{0.6}$ and $A = 0.9D^{0.5}$ or durations greater than 1 h. Magnitude III events can be expected in response to rainfall conditions above the threshold $A = 0.9D^{0.5}$. Rainfall threshold-magnitude relations are linked with potential emergency-response actions as an emergency-response decision chart, which leads a user through steps to determine potential event magnitudes and identify possible evacuation and resource-deployment levels. Use of this information in planning and response decision-making process could result in increased safety for both the public and emergency responders.

Keywords Debris flows · Floods · Rainfall thresholds · Wildfires

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1 Introduction

As a consequence of the Station fire (Fig. 1), which burned 160,557 acres of the steep, rugged terrain of the San Gabriel Mountains of southern California in August and September, 2009 (National Interagency Fire Center 2009), postfire floods and debris flows now

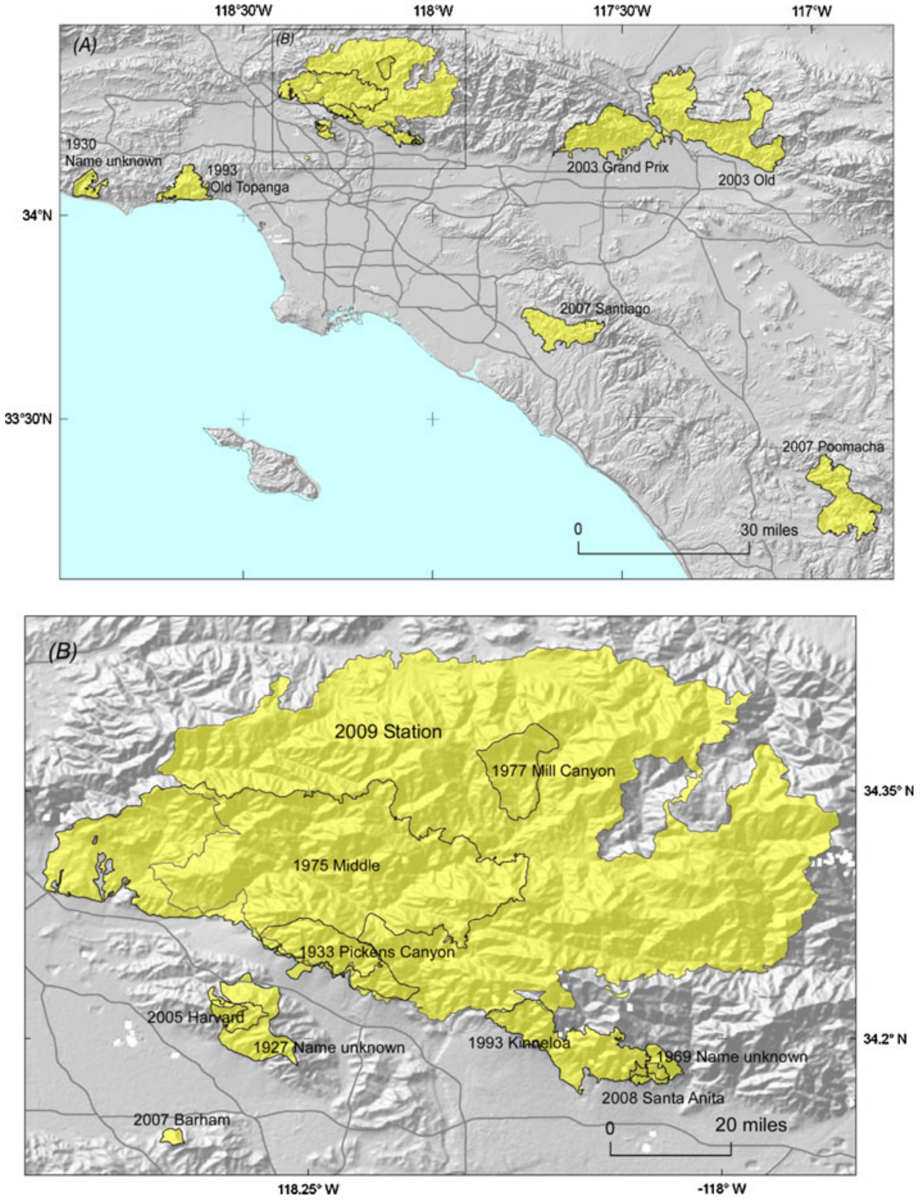


Fig. 1 **a** Map of burned areas (*yellow fill*) and the year of the fire in southern California for which storm rainfall and response magnitude are compiled in this report. **b** Map showing detailed view of northern part of Fig. 1a

pose significant hazards to life and property (Cannon et al. 2009). Emergency-response and public-safety agencies are faced with making evacuation decisions and deploying staff and emergency-response equipment well in advance of each coming winter storm as well as during actual storms themselves. In this report, we provide information that is critical to this decision process. We first describe the information that is included in precipitation forecasts provided by the National Weather Service (NWS) for the San Gabriel Mountains, and the timeframes under which this information is available. Compilations of the hydrologic response to winter storms and measures of the associated rainfall from recently burned steeplands in southern California are used to develop a system for classifying postfire hydrologic event magnitudes and to identify the storm rainfall conditions that have resulted in debris flows and floods in this setting. We then define relations between rainfall conditions and flood and debris-flow magnitudes that are specific to the San Gabriel Mountains. By linking this information to emergency-response actions routinely implemented by fire department and incident command centers, we develop an emergency-response decision chart. This chart can be used to determine potential event magnitudes and identify possible evacuation and resource-deployment levels based on either individual storm forecasts or measured precipitation during storms. The ability to base planning and response decisions on specific storm forecasts, and precipitation measurements may result in significant financial savings and increased safety for both the public and emergency responders.

2 Previous work

2.1 Postfire debris flows

Debris flows, rapidly moving masses of sediment, water, and air, can pose significant hazards to life and property. They can occur with little warning, can exert great impulsive loads on objects in their paths, and can strip vegetation, block drainage ways, damage structures, and endanger human life (Iverson 1997). Debris flows generated from recently burned areas are particularly dangerous because they can be generated in response to very little rainfall and in places where flooding or debris flows have not been observed in the past (Cannon et al. 2008). In recently burned areas, rainfall that normally is captured and stored by vegetation can run off almost instantly, causing creeks and drainage areas to flood much sooner during a storm and with more water than is expected under unburned conditions. Soils in burned areas can be highly erodible, so runoff will contain significant amounts of ash, mud, boulders, and vegetation. Within the burned area and downstream, the powerful force of rushing water, soil, and rock can destroy buildings, roadways, culverts, and bridges and can cause injury or death.

The association between debris flows and floods and wildfires is well established in the San Gabriel Mountains. When the fires that consume the vegetation from the extremely steep, rugged canyons are followed by the high-intensity rain storms that characterize the area, destructive floods and debris flows are a frequent result (e.g., Eaton 1936; Troxell and Peterson 1937; Scott 1971; Scott and Williams 1978; McPhee 1989; Shuriman and Slosson 1992).

Field observations from recently burned basins throughout Southern California indicate that the majority of debris flows that occur within the first 2–3 years following wildfires are generated through the process of progressive entrainment of material eroded from hillslopes and channels by surface runoff, rather than by infiltration-triggered landsliding, as is common in unburned settings (Cannon and Gartner 2005). Exceptions, however, can come about when storm rainfall is sufficient to generate landslides from nearby unburned hillslopes; when this happens, it is not uncommon to also see landslides generated from burned hillslopes (e.g., Scott and Williams 1978).

2.2 Rainfall conditions that lead to postfire debris flows

Empirically derived rainfall intensity–duration or rainfall accumulation–duration thresholds have been widely used to identify rainfall conditions that will lead to the generation of debris flows (see a world-wide compilation of rainfall thresholds at http://rainfallthresholds.irpi.cnr.it). This approach is based on the principle that debris-flow triggering conditions cannot be defined by a total depth of rainfall, or by instantaneous rainfall intensity, but are more accurately characterized as a function of either of these two measures and the time period over which they occur (Caine 1980). In addition, triggering rainfall conditions are best represented by a range of intensities and durations (or rainfall depths and durations) that are specific to particular settings (for example, Caine 1980; Larsen and Simon 1993; Godt et al. 2006; Cannon et al. 2008; Guzzetti et al. 2008). As such, debris flows in a given setting will be triggered by a set of rainfall conditions that may range from high rainfall intensities over short durations to lower rainfall intensities maintained over longer durations. Because rainfall intensity is a measure of rainfall accumulation over a given time period, debris flows also can be considered to be triggered by a range of rainfall conditions between low rainfall accumulations over short durations and higher rainfall accumulations maintained over longer durations. In this case, the slope of the threshold line represents rainfall intensity.

Destructive debris flows from recently burned areas in southern California have been triggered in response to short-duration thunderstorms and longer-duration frontal storms, as well as a combination of these storm types (Cannon et al. 2008). Rain gage and response data from recently burned basins throughout southern California included in Cannon et al. (2008) show that postfire debris flows have been generated after as little as 30 min, and as much as 38 h, of rainfall with intensities between 0.03 and 1.0 inches per hour. In addition, short periods of high-intensity rainfall within lower-intensity storms also have been described as the triggers of postfire debris flows (e.g., Eaton 1936; Scott and Williams 1978). Unusual (or long recurrence-interval) storms are not necessary to generate debris flows from recently burned areas; storms with recurrence intervals of less than 2 years (storms with a greater than 50% probability of occurring during any given year) have triggered destructive debris flows from burned areas in southern California (Cannon et al. 2008).

Rainfall intensity–duration thresholds have been defined for the generation of postfire floods and debris flows for three southern California regions, including the San Gabriel, San Bernardino, and San Jacinto Mountains (Cannon et al. 2008). These regional thresholds are thought to generally reflect the rainfall conditions associated with the occurrence of debris flows and floods, but do not address the conditions that will produce events with varying magnitudes. In addition, debris-flow triggering rainfall will vary with burn severity, basin sizes and gradients, and material properties (Cannon et al. 2010), as well as with local rainfall regimes (Moody and Martin 2009); these fire-specific and local effects are not accounted for in the regional rainfall intensity–duration thresholds.

In this report, we advance from the existing regional definition of storm rainfall conditions that may lead to floods and debris flows from recently burned southern California steeplands as defined in Cannon et al. (2008) by developing information that is specifically relevant to conditions in the San Gabriel Mountains and takes into account the potential magnitudes of debris-flow events. By linking local rainfall information with debris-flow- and flood-magnitude documentation, we are able to define the rainfall conditions that may lead to debris flow and floods of different magnitudes from recently burned areas, thus providing critical information for emergency-response planning. Although this work is of particular relevance for agencies tasked with postfire-emergency planning and response in the San Gabriel Mountains, the approach developed here can be implemented in other settings.

3 Approach

This effort focused on four primary tasks: (1) identifying how information included in precipitation forecasts can be used effectively by public-safety and emergency-response personnel; (2) determining how information about postfire debris flow and flood processes and triggers could be effectively integrated into emergency-response plans; (3) compiling and evaluating rainfall and hydrologic-response data to develop the necessary information for the San Gabriel Mountains; and (4) integrating this information into a form that can be readily implemented by emergency-response personnel.

To start, we held discussions with local and state public-safety and emergency-response agencies charged with protecting people and property that might be affected by debris flows and floods from the 2009 Station fire to identify how they used information included in precipitation forecasts. Existing emergency-response plans were evaluated to identify the types of information routinely included and to determine how to integrate available science-based information on postfire debris-flow processes and triggers.

Rainfall and hydrologic-response information from storms that triggered floods and debris flows from areas recently burned by wildfires in steep, rugged terrain throughout southern California were compiled from published reports and books, written communications, and USGS and NWS monitoring efforts (Fig. 1a, b). This effort focused on those events for which storm rainfall is reported either in terms of within-storm accumulations for varying durations, as rainfall intensities maintained for given durations, and where the potential for, or actual occurrence of, a basin-scale flood or debris-flow response was documented. Available information on the magnitude of the debris-flow or flood response to each storm also was compiled. We documented the number of drainage basins, channels, or locations known to be affected, and when available, reported flow velocities and volumes of deposited material. Information on the impact to the built environment, as it existed at the time of the event, also was compiled.

We found that storm rainfall characteristics were reported in a number of different ways, including total storm rainfall and durations, rainfall accumulations for different time periods within a storm, peak rainfall intensities for different time periods, and 6-min accumulations for the entire storm period. Because the rainfall conditions that lead to postfire debris flows can be described in terms of either rainfall intensities for given durations, or within-storm accumulations for given durations, data reported as rainfall intensities were converted to within-storm totals by multiplying by the given duration, and data reported as within-storm totals were converted to intensities by dividing by the reported duration. These conversions allow for the option to evaluate the dataset in terms of either rainfall intensities or within-storm totals.

Because we do not know exactly what characteristics of a storm control the hydrologic response, we tried to characterize the rainfall in each storm as completely as possible, given the available data. When possible, we calculated measures of within-storm totals for time periods between 5 min and 24 h. With this approach, a single storm is characterized by several different measures of rainfall intensity.

The data included in the compilation represent varying degrees of relevance to recently burned areas within the San Gabriel Mountains. The most relevant information is that collected from the past events in the San Gabriel Mountains themselves and includes data collected at monitoring sites within basins burned by the 2009 Station fire during the winter of 2009–2010. The relevance of additional information from throughout southern California is considered to decrease with distance from the San Gabriel Mountains (Fig. 1a, b).

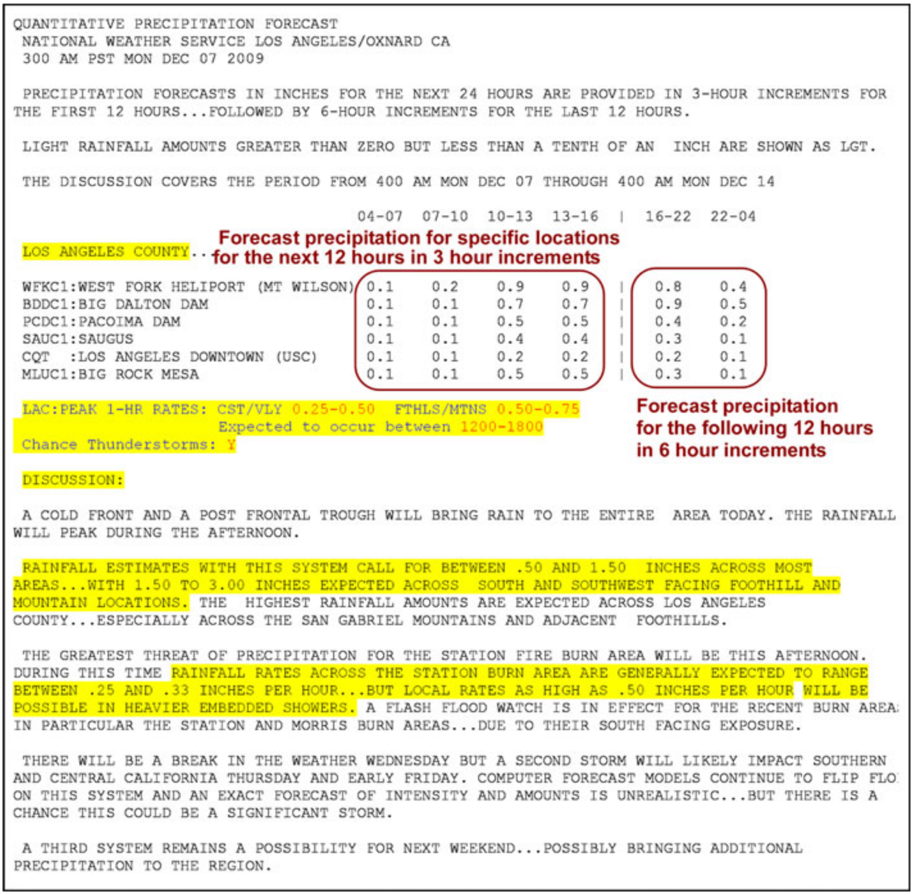
Relations between rainfall conditions and the magnitude of the hydrologic response were defined by first graphing each measure of rainfall intensity as a function of the time period over which it was measured (and its assigned response magnitude) on a log–log scale. The log-scale plot was necessary to discern the closely spaced data associated with short durations. Considerable spatial and temporal variability in rainfall conditions during storms can result in significant overlap between measured rainfall conditions relative to response magnitudes. For example, some rainfall measurements from storms that trigger large and spatially extensive events can also be expected during storms that produced smaller and less extensive events. In addition, it is not known which of the rainfall measures within each storm most strongly correspond to the generation of debris flows. We here assume that those conditions that occurred during storms that did not result in a substantial hydrologic response are not likely to have produced a response during other storms. Following the approach of Gregoretti and Dalla Fontana (2007) and Cannon et al. (2008), where thresholds are defined as the upper limit of the greatest values of rainfall intensities and durations that did not trigger debris flows, we defined the boundaries between rainfall conditions and response magnitudes so as to best separate those conditions that were unique to each response magnitude. In this approach, the boundaries between rainfall conditions associated with each response magnitude were defined by fitting a power law relation to the upper-most rainfall measures within each magnitude class.

In unburned settings, characterization of the rainfall conditions that lead to debris flows requires identification of antecedent rainfall accumulations during the preceding season (e.g., Wieczorek and Glade 2005). In these settings, antecedent rainfall is necessary to increase soil moisture within the soil. In burned settings, however, a quantitative understanding of the role that antecedent rainfall and soil moisture play in the generation of debris flows is largely absent. What we do know is that large debris flows have been generated over extensive areas in response to the first significant storm to impact burned areas (Cannon et al. 2008). This suggests that perhaps drier soils are more susceptible to postfire debris-flow generation, or that the antecedent soil-moisture conditions sufficient to affect debris-flow susceptibility in burned settings may be attained within individual storms. At this time, we do not know what these conditions might be. However, evaluation of soil-moisture data collected during and after rainstorms in recently burned areas in southern California by Staley et al. (2008) indicated that hillslope soil moisture returns to prestorm conditions after approximately 8 h without rainfall. We also have learned that soil-moisture conditions in materials over which a debris-flow travels will strongly influence the volume of material that is incorporated into the flow itself (Reid et al. 2009). This finding is important for recently burned areas in that most of the materials in postfire debris flows are entrained from along the drainage network (Santi et al. 2008), and thus, larger debris flows may be produced when the channel materials are wetter. Given the quantitative uncertainties with antecedent rainfall or soil-moisture conditions in recently burned areas, we have taken the approach of considering each storm that starts after approximately 8 h with no rainfall as a single entity. Continuous or back-to-back storms without intervening dry periods of at least 8 h are considered to indicate an increased potential for the production of large debris flows.

4 Results

4.1 National weather service precipitation forecasts for the San Gabriel Mountains

NWS issues quantitative precipitation forecasts (QPFs) for the San Gabriel Mountains twice a day, at approximately 4 a.m. and at 4 p.m., along with unscheduled updates when conditions change such that the existing forecast no longer is representative. Forecasts are provided for each county for the following 24-h period and include estimates of the expected rainfall totals in 3-h increments for the first 12-h period and in 6-h increments for the second 12-h period for specific locations (Fig. 2). In addition, the anticipated 1-h rainfall intensities, and the time period during which these can be expected, are provided for coastal and valley areas and foothills and mountains for each county. The forecasts also



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QUANTITATIVE PRECIPITATION FORECAST
 NATIONAL WEATHER SERVICE LOS ANGELES/OXNARD CA
 300 AM PST MON DEC 07 2009

 PRECIPITATION FORECASTS IN INCHES FOR THE NEXT 24 HOURS ARE PROVIDED IN 3-HOUR INCREMENTS FOR
THE FIRST 12 HOURS...FOLLOWED BY 6-HOUR INCREMENTS FOR THE LAST 12 HOURS.

 LIGHT RAINFALL AMOUNTS GREATER THAN ZERO BUT LESS THAN A TENTH OF AN  INCH ARE SHOWN AS LGT.

 THE DISCUSSION COVERS THE PERIOD FROM 400 AM MON DEC 07 THROUGH 400 AM MON DEC 14

                                    04-07  07-10  10-13  13-16  |  16-22  22-04

 LOS ANGELES COUNTY..

 WFKC1:WEST FORK HELIPORT (MT WILSON) 0.1    0.2    0.9    0.9  |  0.8    0.4
 BDDC1:BIG DALTON DAM                 0.1    0.1    0.7    0.7  |  0.9    0.5
 PCDC1:PACOIMA DAM                    0.1    0.1    0.5    0.5  |  0.4    0.2
 SAUC1:SAUGUS                         0.1    0.1    0.4    0.4  |  0.3    0.1
 CQT  :LOS ANGELES DOWNTOWN (USC)     0.1    0.1    0.2    0.2  |  0.2    0.1
 MLUC1:BIG ROCK MESA                  0.1    0.1    0.5    0.5  |  0.3    0.1

 LAC:PEAK 1-HR RATES: CST/VLY 0.25-0.50  FTHLS/MTNS 0.50-0.75
                      Expected to occur between 1200-1800
 Chance Thunderstorms: Y

 DISCUSSION:

 A COLD FRONT AND A POST FRONTAL TROUGH WILL BRING RAIN TO THE ENTIRE  AREA TODAY. THE RAINFALL
WILL PEAK DURING THE AFTERNOON.

 RAINFALL ESTIMATES WITH THIS SYSTEM CALL FOR BETWEEN .50 AND 1.50  INCHES ACROSS MOST
AREAS...WITH 1.50 TO 3.00 INCHES EXPECTED ACROSS  SOUTH AND SOUTHWEST FACING FOOTHILL AND
MOUNTAIN LOCATIONS. THE  HIGHEST RAINFALL AMOUNTS ARE EXPECTED ACROSS LOS ANGELES
COUNTY...ESPECIALLY ACROSS THE SAN GABRIEL MOUNTAINS AND ADJACENT  FOOTHILLS.

 THE GREATEST THREAT OF PRECIPITATION FOR THE STATION FIRE BURN AREA WILL BE THIS AFTERNOON.
DURING THIS TIME RAINFALL RATES ACROSS THE STATION BURN AREA ARE GENERALLY EXPECTED TO RANGE
BETWEEN .25 AND .33 INCHES PER HOUR...BUT LOCAL RATES AS HIGH AS .50 INCHES PER HOUR WILL BE
POSSIBLE IN HEAVIER EMBEDDED SHOWERS. A FLASH FLOOD WATCH IS IN EFFECT FOR THE RECENT BURN AREA:
IN PARTICULAR THE STATION AND MORRIS BURN AREAS...DUE TO THEIR SOUTH FACING EXPOSURE.

 THERE WILL BE A BREAK IN THE WEATHER WEDNESDAY BUT A SECOND STORM WILL LIKELY IMPACT SOUTHERN
AND CENTRAL CALIFORNIA THURSDAY AND EARLY FRIDAY. COMPUTER FORECAST MODELS CONTINUE TO FLIP FLO
ON THIS SYSTEM AND AN EXACT FORECAST OF INTENSITY AND AMOUNTS IS UNREALISTIC...BUT THERE IS A
CHANCE THIS COULD BE A SIGNIFICANT STORM.

 A THIRD SYSTEM REMAINS A POSSIBILITY FOR NEXT WEEKEND...POSSIBLY BRINGING ADDITIONAL
PRECIPITATION TO THE REGION.
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Forecast precipitation for specific locations for the next 12 hours in 3 hour increments

Forecast precipitation for the following 12 hours in 6 hour increments

Fig. 2 Example of Quantitative Precipitation Forecast (QPF) issued by National Weather Service (NWS) for burned areas within Los Angeles County, including the San Gabriel Mountains indicate whether thunderstorms or convective cells embedded in larger-scale systems are expected within the 24-h rainfall forecast period to highlight the potential for localized heavy rainfall and associated high rainfall intensities. The final discussion covers the following 7-day period and includes information about specific burned areas and if watches or warnings have been issued. Precipitation forecasts are available at http://www.wrh.noaa.gov/lox/scripts/getprodplus.php?wfo=lox&prod=laxqpslox, with additional forecast discussions at http://www.wrh.noaa.gov/lox/scripts/getprodplus.php?sid=lox&pil=afd&back=yes.

Although estimates of rainfall intensities can be included in precipitation forecasts, there is considerable uncertainty with these values. Forecast rainfall totals usually arrive as a series of waves of high-intensity rainfall separated by periods of less intense rain. Methods for forecasting the rainfall intensity variability associated with these waves are not well developed. During a storm itself, however, the NWS can report rainfall intensities either measured at rain gages located within and upstream of the burned area or indicated as by radar data.

Because debris flows and floods from recently burned areas are frequently triggered by periods of high-intensity rainfall, NWS forecasters pay particular attention to conditions that can lead to the generation of thunderstorms or convective cells embedded in larger-scale storm systems. NWS forecasters look for cold fronts that can provide additional lift, upslope-wind flow that may enhance rain intensities, and any instability along or behind a front that can lead to convective cells. In these cases, the entire projected rainfall amount could affect an area in a short-time period and at high intensities. In addition, convective cells can move rapidly, hitting one area and not another, and varying considerably in intensity.

NWS issues flash flood watches between 12 and 24 h in advance of heavy rain to provide notification about the threat of predicted rainfall accumulations that could lead to floods and debris flows from recently burned areas. Flash flood advisories are issued for recently burned areas when measured rainfall accumulations are approaching conditions defined by the thresholds. Flash flood warnings are issued when debris-flow and flood-triggering rainfall conditions are imminent or taking place based on information from real-time rain gages located both upstream of and within the burn perimeter, nearby storm spotter reports, and interrogation of the Doppler Radar Flash Flood Monitoring and Prediction (FFMP) system and 1-h precipitation estimates. Given the immediacy of runoff and debris-flow activity, warning lead times vary from just a few minutes up to about 45 min.

4.2 Debris-flow and flood magnitudes

Our search resulted in information on the hydrologic response to 23 storms and two full winter seasons from 16 different burned areas in southern California (Table 1). Based on the range of information available on the spatial extent and size of postfire debris flows and floods in southern California, reviews of existing size classifications for debris flows (e.g., Jakob 2005), and Los Angeles Department of Public Works Event Level definitions (Los Angeles Department of Public Works, written communication, 2009), we defined criteria for classifying each known hydrologic response as one of four possible magnitudes (Table 2). This system for classifying the magnitude of the hydrologic response incorporates the volumes of individual debris flows, consequences of debris flows and floods in an urban setting (such as that along the San Gabriel Mountain Front), and the spatial extent of the hydrologic response to the triggering storm.

Table 1 Storm ID and date, fire name and date, hydrologic response, information sources, and assigned debris flow and flood magnitude

Storm ID	Storm date	Fire name and date	Hydrologic response	Information sources	Event magnitude
1	Dec. 7, 2009	Station fire; Aug.–Sept., 2009	Ash-laden flow in Arroyo Seco and some minor hillslope erosion. No impact to built environment	USGS and citizen field observations; http://watershednews.blogspot.com/2009/12/arroyo-negro.html	0
2	Jan. 19, 2010	Station fire; Aug.–Sept., 2009	Minor erosion and sediment movement on hillslopes and in channels	USGS and citizen field observations	0
3	Feb. 9, 2010	Station fire; Aug.–Sept., 2009	Minor erosion and sediment movement on hillslopes and in channels	USGS field observations	0
4	Oct. 13–14, 2009	Station fire; Aug–Sept., 2009	Small debris flows and sediment-laden floods in several tributary channels to Big Tujunga River and Arroyo Seco. No impact to built environment	USGS and citizen field observations	I
5	Nov. 12, 2009	Station fire; Aug.–Sept., 2009	Localized storm produced minor hillslope and channel erosion in some areas and sediment-laden flood in Arroyo Seco	USGS field observations	I
6	Jan. 20, 2010	Station fire; Aug.–Sept., 2009	Minor hillslope and channel erosion and some sediment movement throughout burned area	USGS field observations	I
7	Winter 1993–1994	Kinneloa fire; 1993	2,000 yds^3 of material collected in Kinneloa debris retention basin over winter. No rainfall reported from any gages in Sierra Madre on the Sunday in March when debris flow occurred in Bailey Canyon	Van de Water (2000) and Collins (2008)	I
8	May 22, 2008	Santa Anita fire; 2008	Small debris flow and sediment-laden flood from one watershed	NWS observations and web reports	I
9	Nov. 13–14, 1928	Unnamed; Dec. 3–5, 1927	Debris flows from Sunset and Brand Canyons above Burbank and Glendale; 27,000 yds^3 of material produced from Brand Canyon	Eaton (1936)	II
10	Jan. 7, 1931	Unnamed: Oct. 29–Nov. 6, 1930	Debris flows from Arroyo Sequis traveled to Pacific Ocean at velocities between 5 and 9 ft per second	Eaton (1936)	II

Table 1 continued

Storm ID	Storm date	Fire name and date	Hydrologic response	Information sources	Event magnitude
11	Oct. 17, 2005	Harvard fire; 2005	Debris flows produced from four burned watersheds. 39,000 yds^3 of material collected in Verdugo debris retention basin and 12,000 yds^3 in Wildwood basin	USGS and NWS field observations	II
12	Winter of 1993–1994	Old Topanga fire; 1993	Large debris flow produced from Big Rock Creek	Collins (2008)	II
13	Sept. 22, 2007	Barham fire; 2007	Debris flow from one burned watershed overtopped debris retention basin and damaged cars parked along road	USGS and NWS field observations	II
14	Nov. 30, 2007	Poomacha fire; Fall 2007	Debris flows and sediment-laden floods produced from four watersheds	USGS field observations	II
15	Jan. 27, 2008	Poomacha fire; Fall 2007	Debris flows and sediment-laden floods produced from five watersheds	USGS field observations	II
16	May 22, 2008	Santiago fire; Fall 2007	Debris flows from two watersheds, damaging houses and inundating yards; volumes estimated to be $<10,000$ yds^3	USGS field observations	II
5	Nov. 12, 2009	Station fire; Aug.–Sept., 2009	Localized storm produced debris flows and sediment-laden floods from several watersheds; 9,500 yds^3 of material filled Mullally debris retention basin; Halls and Snover Canyon basins near capacities of 93,800 yds^3 and 24,800 yds^3, respectively; debris flows and sediment-laden floods in neighborhoods damaged houses and closed Highway 2	USGS field observations	II

Table 1 continued

Storm ID	Storm date	Fire name and date	Hydrologic response	Information sources	Event magnitude
17	Dec. 11–13, 2009	Station fire; Aug.–Sept, 2009	Localized storm produced debris flows and sediment-laden floods from several watersheds; 70 cars trapped in mud and debris on Highway 2, debris flow and sediment-laden floods closed several streets in La Canada-Flintridge and damaged homes. Reaches of Arroyo Seco scoured to bedrock, others aggraded with up to 6 ft of material	USGS field observations, citizen reports	II
18	Dec. 31, 1933–Jan. 1, 1934	Pickens fire; Nov. 21–24, 1933	Debris flows and floods produced from watersheds between, and including, Blanchard and Snover Canyons; Total material volume of 660,000 yds^3 reported by Eaton (1936); Chawner (1934), measured 700,000 yds^3 from Halls and Pickens Canyons alone; 50,000 yds^3 of material collected in Haines debris retention basin; debris-flow and flood deposits mapped from mountain front to Verdugo Wash. 51 deaths reported by Eaton 1936	Eaton (1936) and Chawner (1934, 1935)	III
19	Feb. 8–10, 1978	Mill Creek fire; July 24, 1977	Community of Hidden Springs destroyed by debris flow resulting in 13 deaths	Graham, Shuriman, Slosson, Yoakum, written commun. (2009); Shuriman and Slosson (1992)	III
19	Feb. 8–10, 1978	Middle fire; Nov. 2, 1975	Debris flows and floods produced from watersheds between and including Zachau and Shields Canyons; 3,000 yds^3 collected in Zachau debris retention basin, which overtopped. Material deposited over 0.5 mi^2, blocking streets, and damaging houses and other facilities	Bruington (1982)	III

Table 1 continued

Storm ID	Storm date	Fire name and date	Hydrologic response	Information sources	Event magnitude
20	Jan. 18–27, 1969	Unnamed; July and Aug., 1968	Debris flows produced from seven watersheds above Glendora; 25,000 yds^3 of material into East Hook Canyon debris retention basin, 45,000 yds^3 into Englewild Canyon basin, 52,000 yds^3 into Harrow Canyon basin, and 18,000 yds^3 of material produced from Rainbow Drive watershed and 24,000 yds^3 from Glencoe Heights watershed	Scott (1971), Scott and Williams (1978) and Bruington (1982)	III
21	Dec. 25, 2003	Grand Prix and Old fires; Nov. 2003	Debris flows and floods produced from nearly every burned watershed (>100). Between 8,900 yds^3 and 800,000 yds^3 of material collected in debris retention basins at mouths of larger watersheds. 16 people killed by debris flows at two locations	USGS field observations; US Army Corps of Engineers (2005)	III
22	Jan. 18, 2010	Station fire; Aug–Sept, 2009	Debris flows and floods produced from many burned watersheds including tributaries to Big Tujunga Canyon and Arroyo Seco and along the San Gabriel Mountain Front	USGS field observations	III
23	Feb. 6, 2010	Station fire; Aug–Sept, 2009	Debris flows and floods produced from any burned watersheds including tributaries to Big Tajunga Canyon and Arroyo Seco and along the San Gabriel mountain front. Homes destroyed or damaged on Manistee and Ocean View Drive below Mullally debris basin	USGS field observations	III

USGS U.S. geological survey, *yd*^{3} Cubic yards, *mi*^{2} Square miles, *ft* feet

Note that the same storm may trigger different magnitude events in different areas, more than one burned area may be affected by the same storm, and conditions in the same storm may be represented by more than one rain gage

Table 2 Magnitude classification for debris-flow and flood events

Event classification	Criteria potential consequences
Magnitude 0	Negligible response
Magnitude I	Small (<1,000 cubic yards) debris flows or flooding produced from one or two drainages basins or in one or two locations Some culverts and storm drains may be blocked, streets may be partially flooded or blocked by debris, and cars may be partially buried Houses may be damaged, and small wooden buildings may be destroyed. Few, if any, larger buildings will be threatened
Magnitude II	Two to five moderately sized (1,000–10,000 cubic yards) debris flows or one large (>10,000 cubic yards) event produced from two to five drainage basins which impact the built environment Several culverts and storm drains may be blocked, several streets may be flooded or completely blocked by debris, several cars may be buried Several homes, buildings, streets, and bridges may be damaged
Magnitude III	Widespread and abundant debris flows and flooding with volumes in excess of 10,000 cubic yards produced from more than five drainage basins resulting in a significant impact to the built environment Many culverts, storm drains, and streets may be completely blocked by debris, making many streets unsafe for travel Several large buildings (including homes), sections of infrastructure corridors, and bridges may be destroyed

Modified from Jakob (2005) and Los Angeles Department of Public Works Event Level definitions (Los Angeles Department of Public Works, written communication 2009)

Each debris flow and flood for which data were available was classified as one of four possible magnitudes (Table 2). Ten of the storms triggered magnitude II debris flows or floods, and six triggered magnitude III events (Table 1). Note that the same storm may trigger different magnitude events in different areas, more than one burned area may be affected by the same storm, and more than one rain gage may provide data for a given storm.

4.3 Storm rainfall data

Because the NWS places more confidence in its forecasts of storm rainfall totals for different time periods than forecasts of rainfall intensities, we focused our assessment on storm rainfall totals (Tables 3, 4). The 16 storms included in the data compilation that triggered Magnitude II or III events ranged between 45 min and 56 h in duration, with storm rainfall totals between 0.5 and 15.50 inches (Tables 3, 4). These data are consistent with the finding of Cannon et al. (2008) that postfire debris flows can be triggered by a range of short-duration, high-intensity rainfall, and longer duration, lower-intensity storms.

4.4 Relations between storm rainfall data and debris-flow and flood magnitudes

The rainfall conditions in storms associated with magnitude 0, I, II, and III events are shown in Fig. 3. The different color zones identify the range of rainfall conditions associated with each magnitude. The boundaries between the event-magnitude zones each define threshold rainfall accumulation–duration conditions between which postfire debris flows and floods of a given magnitude may be generated. As is typical of many thresholds

Table 3 Storm ID and response magnitude, storm date, fire name, and storm rainfall data including storm total, storm duration, peak 5-, 10-, 15-, 30-min, and 1- and 2-h rainfall (–, no value)

Storm ID, response magnitude	Storm date	Fire name	Storm total (inches)	Storm duration (hours)	Peak 5-min rainfall (inches)	Peak 10-min rainfall (inches)	Peak 15-min rainfall (inches)	Peak 30-min rainfall (inches)	Peak 1-h rainfall (inches)	Peak 2-h rainfall (inches)
1, 0	Dec. 7, 2009	Station	0.92	13.80	0.06	0.08	0.09	0.11	0.17	–
1, 0	Dec. 7, 2009	Station	0.80	13.00	0.04	0.05	0.06	0.09	0.16	–
1, 0	Dec. 7, 2009	Station	1.38	12.90	0.08	0.11	0.11	0.16	0.27	–
1, 0	Dec. 7, 2009	Station	1.04	14.00	–	–	–	–	0.25	0.41
1, 0	Dec. 7, 2009	Station	0.79	16.00	–	–	–	0.10	0.13	–
1, 0	Dec. 7, 2009	Station	0.97	16.00	–	–	0.08	0.13	0.25	–
2, 0	Jan. 19, 2010	Station	0.48	7.00	–	–	0.09	0.12	0.22	–
2, 0	Jan. 19, 2010	Station	0.68	7.00	–	–	0.13	0.17	0.31	–
2, 0	Jan. 19, 2010	Station	0.44	7.00	–	–	0.09	0.13	0.21	–
3, 0	Feb. 9, 2010	Station	0.38	6.00	–	–	0.07	0.14	0.24	–
3, 0	Feb. 9, 2010	Station	0.32	1.60	0.06	0.11	0.13	0.17	0.28	–
3, 0	Feb. 9, 2010	Station	0.61	5.10	0.06	0.07	0.10	0.16	0.23	–
3, 0	Feb. 9, 2010	Station	0.87	5.20	0.11	0.20	0.24	0.30	0.32	
3, 0	Feb. 9, 2010	Station	0.80	7.00	–	–	–	–	0.29	0.44
3, 0	Feb. 9, 2010	Station	0.65	6.00	–	–	0.17	0.20	0.22	–
4, I	Oct. 13–14, 2009	Station	2.82	41.70	0.05	0.08	0.11	0.18	0.29	0.50
4, I	Oct. 13–14, 2009	Station	2.50	29.00	–	–	0.09	0.15	0.26	0.40
5, I	Nov. 12, 2009	Station	0.07	0.67	0.06	0.06	0.07	0.07	–	–
5, I	Nov. 12, 2009	Station	0.03	1.67	–	–	0.02	0.02	0.03	–
6, I	Jan. 20, 2010	Station	1.75	16.00	–	–	–	–	0.35	0.69
6, I	Jan. 20, 2010	Station	1.67	15.00	–	–	0.11	0.22	0.41	–
6, I	Jan. 20, 2010	Station	1.26	15.00	–	–	0.08	0.15	0.28	–
6, I	Jan. 20, 2010	Station	1.18	13.90	0.03	0.06	0.08	0.14	0.27	–

Table 3 continued

Storm ID, response magnitude	Storm date	Fire name	Storm total (inches)	Storm duration (hours)	Peak 5-min rainfall (inches)	Peak 10-min rainfall (inches)	Peak 15-min rainfall (inches)	Peak 30-min rainfall (inches)	Peak 1-h rainfall (inches)	Peak 2-h rainfall (inches)
6, I	Jan. 20, 2010	Station	1.82	15.30	0.06	0.11	0.15	0.20	0.38	–
6, I	Jan. 20, 2010	Station	1.11	15.00	–	–	0.09	0.11	0.2	–
6, I	Jan. 20, 2010	Station	0.97	15.00	–	–	0.09	0.12	0.2	–
7, I	Winter 1993–1994	Kinneloa	–	–	–	–	–	–	–	–
8, I	May 22, 2008	Santa Anita	0.39	1.07	0.08	–	0.15	0.08	0.36	–
9, II	Nov. 13–14, 1928	Unnamed	2.00	12.00	–	0.06	–	–	0.43	–
10, II	Jan. 7, 1931	Unnamed	1.28	3.00	–	0.23	–	0.54	0.75	–
11, II	Oct. 17, 2005	Harvard	–	–	–	0.24	0.24	0.28	0.39	0.44
12, II	Winter 1993–1994	Old Topanga	–	–	–	–	–	0.25	–	–
13, II	Sept. 22, 2007	Barham	–	–	–	0.16	0.20	0.28	0.39	0.56
14, II	Nov. 30, 2007	Poomacha	6.85	34.00	–	0.29	0.28	0.43	0.71	0.98
14, II	Nov. 30, 2007	Poomacha	–	–	–	0.16	0.20	0.31	0.47	0.78
15, II	Jan. 27, 2008	Poomacha	4.24	–	–	0.12	0.14	0.22	0.34	0.62
15, II	Jan. 27, 2008	Poomacha	5.26	–	–	0.19	0.26	0.41	0.50	0.82
16, II	May 22, 2008	Santiago	0.50	0.75	–	0.37	0.42	–	–	–
5, II	Nov. 12, 2009	Station	0.76	1.00	–	–	–	–	–	–
5, II	Nov. 12, 2009	Station	1.12	1.10	0.21	0.32	0.45	0.61	–	–
5, II	Nov. 12, 2009	Station	1.12	1.33	–	–	0.43	0.65	1.11	–
5, II	Nov. 12, 2009	Station	1.12	1.33	0.27	0.40	0.43	0.65	1.11	–
17, II	Dec. 11–13, 2009	Station	2.92	38.00	–	–	–	–	0.51	0.79
17, II	Dec. 10–13, 2009	Station	2.44	35.40	0.08	0.10	0.13	0.20	0.31	–
17, II	Dec. 10–13, 2009	Station	3.95	56.00	–	–	0.13	0.24	0.38	–
17, II	Dec. 10–13, 2009	Station	2.96	54.80	0.05	0.07	0.09	0.16	0.26	–
17, II	Dec. 10–13, 2009	Station	6.87	53.00	0.14	0.22	0.27	0.46	0.68	–

Table 3 continued

Storm ID, response magnitude	Storm date	Fire name	Storm total (inches)	Storm duration (hours)	Peak 5-min rainfall (inches)	Peak 10-min rainfall (inches)	Peak 15-min rainfall (inches)	Peak 30-min rainfall (inches)	Peak 1-h rainfall (inches)	Peak 2-h rainfall (inches)
17, II	Dec. 10–13, 2009	Station	1.87	56.00	–	–	0.11	0.15	0.26	–
17, II	Dec. 10–13, 2009	Station	2.36	56.00	–	–	0.13	0.21	0.28	–
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	13.40	28.00	–	–	–	–	1.28	–
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	14.03	–	–	0.34	–	0.84	1.33	2.14
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	12.00	–	–	0.27	–	0.50	0.94	1.64
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	11.04	–	–	0.30	–	0.50	0.88	1.34
19, III	Feb. 8–10, 1978	Mill Creek	11.60	–	–	–	–	–	1.60	–
19, III	Feb. 8–10, 1978	Mill Creek	14.50	–	–	–	–	–	1.50	–
19, III	Feb. 8–10, 1978	Mill Creek	15.50	–	–	–	–	–	1.10	–
19, III	Feb. 8–10, 1978	Mill Creek	12.30	–	–	–	–	–	0.60	–
19, III	Feb. 8–10, 1978	Middle	10.90	32.50	0.40	–	–	1.40	–	–
19, III	Feb. 8–10, 1978	Middle	–	–	1.50	–	–	–	1.60	–
20, III	Jan. 18–27, 1969	Unnamed	–	–	–	–	–	–	1.30	–
21, III	Dec. 25, 2003	Grand Prix and Old	–	–	–	0.87	0.87	0.95	0.95	0.96
21, III	Dec. 25, 2003	Grand Prix and Old	–	–	–	0.20	0.28	0.36	0.60	1.00
21, III	Dec. 25, 2003	Grand Prix and Old	5.64	–	0.14	0.25	0.33	0.56	1.09	1.94
22, III	Jan. 18, 2010	Station	3.47	49.30	0.17	0.86	0.32	0.60	1.03	–
22, III	Jan. 18, 2010	Station	2.74	23.00	–	–	0.18	0.35	0.51	–
22, III	Jan. 18, 2010	Station	2.28	23.80	0.11	0.16	0.21	0.39	0.59	–
22, III	Jan. 18, 2010	Station	4.06	32.90	0.14	0.24	0.35	0.61	1.02	–
22, III	Jan. 18, 2010	Station	2.13	23.00	–	–	0.17	0.29	0.51	–
22, III	Jan. 18, 2010	Station	3.24	31.60	–	0.09	0.11	0.15	0.20	0.35
23, III	Feb. 6, 2010	Station	2.09	15.90	0.17	0.27	0.34	0.46	0.69	–
23, III	Feb. 6, 2010	Station	3.08	25.00	–	–	0.37	0.53	0.73	–

Table 3 continued

Storm ID, response magnitude	Storm date	Fire name	Storm total (inches)	Storm duration (hours)	Peak 5-min rainfall (inches)	Peak 10-min rainfall (inches)	Peak 15-min rainfall (inches)	Peak 30-min rainfall (inches)	Peak 1-h rainfall (inches)	Peak 2-h rainfall (inches)
23, III	Feb. 6, 2010	Station	2.79	30.80	0.17	0.28	0.36	0.53	0.71	–
23, III	Feb. 6, 2010	Station	4.56	35.20	0.34	0.54	0.68	0.83	1.07	
23, III	Feb. 6, 2010	Station	3.27	25.00	–	–	0.22	0.3	0.35	–
23, III	Feb. 6, 2010	Station	3.02	25.00	–	–	0.22	0.29	0.33	–

Note that storms are often represented by more than one gage record, the same storm may trigger different magnitude events in different areas, and more than one burned area may be affected by the same storm

Table 4 Storm ID and response magnitude, storm date, fire name, and storm rainfall data including peak 3-, 6-, 12-, 18-, and 24-h rainfall and data source

Storm ID, response magnitude	Storm date	Fire name	Peak 3-h rainfall (inches)	Peak 6-h rainfall (inches)	Peak 12-h rainfall (inches)	Peak 18-h rainfall (inches)	Peak 24-h rainfall (inches)	Source
1, 0	Dec. 7, 2009	Station	0.42	0.64	0.88	–	–	USGS Dunsmore Channel Site 1 rain gage
1, 0	Dec. 7, 2009	Station	0.39	0.57	0.78	–	–	USGS Dunsmore Channel Site 2 rain gage
1, 0	Dec. 7, 2009	Station	0.63	0.93	1.35	–	–	USGS Arroyo Seco Channel rain gage
1, 0	Dec. 7, 2009	Station	0.52	0.71	1.03	–	–	Jet Propulsion Laboratory rain gage
1, 0	Dec. 7, 2009	Station	0.36	0.50	0.77	–	–	USGS Arroyo Seco Hillslope rain gage
1, 0	Dec. 7, 2009	Station	0.58	0.84	0.91	–	–	USGS Dunsmore Hillslope Site 1 rain gage
2, 0	Jan. 19, 2010	Station	0.41	0.48	–	–	–	USGS Dunsmore Hillslope Site 1 rain gage
2, 0	Jan. 19, 2010	Station	0.60	0.68	–	–	–	USGS Arroyo Seco Channel rain gage
2, 0	Jan. 19, 2010	Station	0.39	0.44	–	–	–	USGS Arroyo Seco Hillslope rain gage
3, 0	Feb. 9, 2010	Station	0.37	0.38	–	–	–	USGS Dunsmore Hillslope Site 1 rain gage
3, 0	Feb. 9, 2010	Station	0.64	0.82	–	–	–	USGS Dunsmore Channel Site 1 rain gage
3, 0	Feb. 9, 2010	Station	0.46	0.6	–	–	–	USGS Dunsmore Channel Site 2 rain gage
3, 0	Feb. 9, 2010	Station	0.76	0.94	–	–	–	USGS Arroyo Seco Channel rain gage
3, 0	Feb. 9, 2010	Station	0.66	0.79	–	–	–	Jet Propulsion Laboratory rain gage
3, 0	Feb. 9, 2010	Station	0.53	0.65	–	–	–	USGS Arroyo Seco Hillslope rain gage
4, I	Oct. 13–14, 2009	Station	0.67	1.01	1.91	2.45	2.71	USGS Dunsmore Channel Site 1 rain gage
4, I	Oct. 13–14, 2009	Station	0.70	0.88	1.66	2.14	2.39	USGS Dunsmore Hillslope Site 1 rain gage
5, I	Nov. 12, 2009	Station	–	–	–	–	–	USGS Dunsmore Channel Site 1 rain gage
5, I	Nov. 12, 2009	Station	–	–	–	–	–	USGS Dunsmore Hillslope Site 1 rain gage
6, I	Jan. 20, 2010	Station	0.85	1.35	1.60	–	–	Jet Propulsion Laboratory rain gage
6, I	Jan. 20, 2010	Station	0.91	1.31	1.39	–	–	USGS Dunsmore Channel Site 1 rain gage
6, I	Jan. 20, 2010	Station	0.59	0.80	1.18	–	–	USGS Dunsmore Hillslope Site 1 rain gage
6, I	Jan. 20, 2010	Station	0.59	0.89	1.10	–	–	USGS Dunsmore Channel Site 2 rain gage

Table 4 continued

Storm ID, response magnitude	Storm date	Fire name	Peak 3-h rainfall (inches)	Peak 6-h rainfall (inches)	Peak 12-h rainfall (inches)	Peak 18-h rainfall (inches)	Peak 24-h rainfall (inches)	Source
6, I	Jan. 20, 2010	Station	0.85	1.45	1.71	–	–	USGS Arroyo Seco Channel rain gage
6, I	Jan. 20, 2010	Station	0.50	0.83	1.00	–	–	USGS rain gage 1160877
6, I	Jan. 20, 2010	Station	0.45	0.77	0.96	–	–	USGS Arroyo Seco Hillslope rain gage
7, I	Winter 1993–1994	Kinneloa	–	–	–	–	–	ALERT rain gage network
8, I	May 22, 2008	Santa Anita	–	–	–	–	–	Santa Anita Dam ALERT rain gage
9, II	Nov. 13–14, 1928	Unnamed	–	–	–	–	–	Eaton (1936)
10, II	Jan. 7, 1931	Unnamed	1.28	–	–	–	–	Eaton (1936)
11, II	Oct. 17, 2005	Harvard	–	–	–	–	–	USGS rain gage
12, II	Winter 1993–1994	Old Topanga	–	–	–	–	–	Collins (2008)
13, II	Sept. 22, 2007	Barham	–	–	–	–	–	Brand Park ALERT rain gage
14, II	Nov. 30, 2007	Poomacha	1.29	2.10	3.48	–	–	La Jolla Amago ALERT rain gage
14, II	Nov. 30, 2007	Poomacha	1.02	1.44	2.16	2.34	–	Rincon Springs ALERT rain gage
15, II	Jan. 27, 2008	Poomacha	0.93	1.38	0.84	1.80	–	USGS rain gage 1160877
15, II	Jan. 27, 2008	Poomacha	0.84	1.02	1.32	1.80	–	USGS rain gage 1160878
16, II	May 22, 2008	Santiago	–	–	–	–	–	USGS rain gage 1175619
5, II	Nov. 12, 2009	Station	–	–	–	–	–	Citizen rain gage in La Cresenta
5, II	Nov. 12, 2009	Station	–	–	–	–	–	USGS rain gage 1184896
5, II	Nov. 12, 2009	Station	–	–	–	–	–	USGS Arroyo Seco Hillslope rain gage
5, II	Nov. 12, 2009	Station	–	–	–	–	–	USGS Arroyo Seco Channel rain gage
17, II	Dec. 11–13, 2009	Station	0.92	1.27	1.78	2.16	2.52	Jet Propulsion Laboratory rain gage
17, II	Dec. 10–13, 2009	Station	0.78	1.09	1.68	2.52	3.77	USGS Dunsmore Channel Site 1 rain gage
17, II	Dec. 10–13, 2009	Station	0.70	1.21	1.88	2.45	2.92	USGS Dunsmore Hillslope Site 1 rain gage
17, II	Dec. 10–13, 2009	Station	0.54	0.89	1.41	2.44	2.79	USGS Dunsmore Channel Site 2 rain gage

Table 4 continued

Storm ID, response magnitude	Storm date	Fire name	Peak 3-h rainfall (inches)	Peak 6-h rainfall (inches)	Peak 12-h rainfall (inches)	Peak 18-h rainfall (inches)	Peak 24-h rainfall (inches)	Source
17, II	Dec. 10–13, 2009	Station	1.53	2.68	3.94	–	–	USGS Arroyo Seco Channel rain gage
17, II	Dec. 10–13, 2009	Station	0.49	0.71	1.31	1.50	1.75	USGS rain gage 1184896
17, II	Dec. 10–13, 2009	Station	0.62	0.92	1.35	1.36	–	USGS Arroyo Seco Hillslope rain gage
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	3.21	5.22	9.24	11.88	–	Eaton (1936)–Flintridge Fire Station rain gage
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	–	–	9.21	–	13.19	Chawner (1935)–Flintridge Fire Station rain gage
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	–	–	6.69	–	8.17	Chawner (1935)–Haines Canyon rain gage
18, III	Dec. 31, 1933–Jan. 1, 1934	Pickens Canyon	–	–	5.30	–	8.07	Chawner (1935)–Sister Elsie Peak rain gage
19, III	Feb. 8–10, 1978	Mill Creek	–	–	–	–	9.90	Shuriman and Slosson (1992)–Big Tujunga Dam rain gage
19, III	Feb. 8–10, 1978	Mill Creek	–	–	–	–	12.30	Shuriman and Slosson (1992)–Clear Creek School rain gage
19, III	Feb. 8–10, 1978	Mill Creek	–	–	–	–	11.50	Shuriman and Slosson (1992)–Colbys rain gage
19, III	Feb. 8–10, 1978	Mill Creek	–	–	–	–	11.00	Shuriman and Slosson (1992)–Camp Hi Hill rain gage
19, III	Feb. 8–10, 1978	Middle	2.00	2.20	–	–	–	Bruington (1982)
19, III	Feb. 8–10, 1978	Middle	–	3.90	–	–	9.00	Graham, written commun 2009–Haines Canyon rain gage
20, III	Jan. 18–27, 1969	Unnamed	–	–	–	–	4.50	Scott (1971), Scott and Williams (1978)
21, III	Dec. 25, 2003	Grand Prix and Old	0.96	1.32	1.92	–	–	USGS rain gage 2840
21, III	Dec. 25, 2003	Grand Prix and Old	1.44	2.22	–	–	–	USGS rain gage 2842

Table 4 continued

Storm ID, response magnitude	Storm date	Fire name	Peak 3-h rainfall (inches)	Peak 6-h rainfall (inches)	Peak 12-h rainfall (inches)	Peak 18-h rainfall (inches)	Peak 24-h rainfall (inches)	Source
21, III	Dec. 25, 2003	Grand Prix and Old	2.72	4.71	5.52	–	5.59	Lytle Creek Fire Station ALERT rain gage
22, III	Jan. 18, 2010	Station	1.48	1.66	2.02	2.22	–	USGS Dunsmore Channel Site 1 rain gage
22, III	Jan. 18, 2010	Station	0.66	0.90	1.50	1.77	–	USGS Dunsmore Hillslope Site 1 rain gage
22, III	Jan. 18, 2010	Station	1.39	1.54	1.76	2.00	–	USGS Dunsmore Channel Site 2 rain gage
22, III	Jan. 18, 2010	Station	2.25	2.87	3.35	3.92	–	USGS Arroyo Seco Channel rain gage
22, III	Jan. 18, 2010	Station	1.13	1.42	1.61	2.56	–	USGS Arroyo Seco Hillslope rain gage
22, III	Jan. 18, 2010	Station	0.48	0.61	1.09	1.41	–	USGS Big Tujunga rain gage
23, III	Feb. 6, 2010	Station	1.42	1.80	2.08	–	–	USGS Dunsmore Channel Site 1 rain gage
23, III	Feb. 6, 2010	Station	1.46	2.26	2.73	2.96	3.08	USGS Dunsmore Hillslope Site 1 rain gage
23, III	Feb. 6, 2010	Station	1.35	2.09	2.43	2.60	2.70	USGS Dunsmore Channel Site 2 rain gage
23, III	Feb. 6, 2010	Station	2.15	3.24	3.67	1.53	–	USGS Arroyo Seco Channel rain gage
23, III	Feb. 6, 2010	Station	0.67	0.76	1.04	–	–	USGS rain gage 1184896
23, III	Feb. 6, 2010	Station	0.61	0.69	0.94	–	–	USGS Arroyo Seco Hillslope rain gage

–, No value; *USGS* U.S. geological survey, *ALERT* automatic local evaluation in real time

Note that storms are often represented by more than one gage record, the same storm may trigger different magnitude events in different areas, and more than one burned area may be affected by the same storm

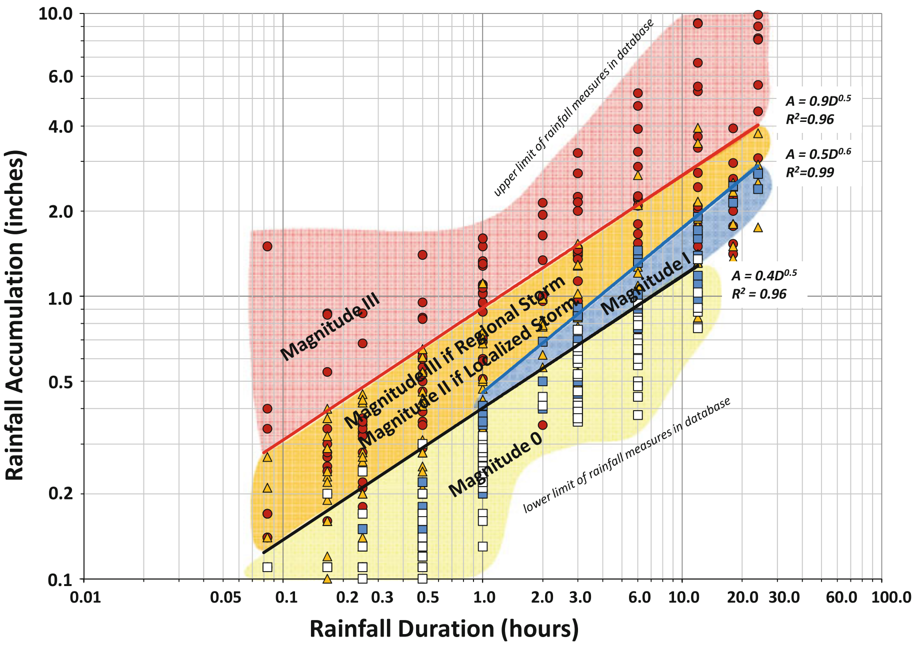


Fig. 3 Within-storm rainfall accumulations for different durations measured from storms that triggered magnitude 0, I, II, III debris flows and floods. *Open squares*, measures of rainfall conditions within storms associated with a negligible response; *blue squares*, measures of rainfall conditions within storms associated with magnitude I events; *orange triangles*, measures of rainfall conditions within storms that triggered magnitude II events; *red circles*, measures of rainfall conditions within storms associated with magnitude III events. *Threshold lines* are the power law relation through the upper rainfall value at each duration within each assigned magnitude class. Note that each storm can be characterized by several measures of peak rainfall from more than one rain gage. Data points on Tables 3 and 4 that fall beyond the graph area are not included to optimize presentation

that define rainfall conditions associated with landslide failures (e.g., Larsen and Simon 1993; Godt et al. 2006), these thresholds can be represented by power law relations between rainfall accumulation and duration, as shown in Fig. 3.

Our data and observations of the storms affecting the Station fire indicate that magnitude I events have occurred in response to storms with low peak rainfall accumulations ($<$ 0.31 inches) for durations less than about 1 h, but comparable values also occurred in storms that did not show any response (Fig. 3). In keeping with our assumption that those conditions that occurred during storms that did not result in a substantial hydrologic response are not likely to produce a response during other storms, we conclude that peak rainfall accumulations for durations less than 1 h do not indicate a propensity for magnitude I events. Conversely, the peak rainfall accumulations associated with magnitude I events exclusively are those with greater than 1 h durations.

Storms that impact only two to five drainage basins, and thus result in a magnitude II event, may also be capable of triggering a magnitude III event if they affect a larger area. In Fig. 3, the rainfall conditions associated with magnitude II events are intermixed with those from magnitude III events. Many of the magnitude II data are from storms on November 12 and December 10–13, 2009, which dropped significant amounts of rain over just a few drainage basins within the area burned by the Station fire and triggered damaging debris flows and floods within those drainage basins that received the highest rainfall (Tables 1, 2). Because debris flows and floods were produced from only a few drainage basins, the responses to these storms were classified as magnitude II events. The overlap of these data with those from magnitude III events indicates that had the storms impacted a larger area, the rainfall conditions associated with these storms may have triggered a magnitude III event. We thus identified the portion of Fig. 3 occupied by storm rainfall conditions measured from both magnitude II and III storms as those storm rainfall conditions that will result in a magnitude III event if associated with a broad, regional storm and will result in a magnitude II event if associated with a localized storm.

Note that the potential for postfire debris flows and floods will decrease with time as revegetation stabilizes hillslopes and material is removed from canyons (e.g., Cannon and Gartner 2005). As a result, the rainfall accumulation–duration relations shown in Fig. 3 will indicate an increasingly conservative estimate of the rainfall conditions that may lead to the generation of debris flows and floods with time.

In addition to rainfall totals for given time periods, the NWS provides estimates of hourly rainfall intensities. Values for the rainfall accumulation–duration thresholds (Fig. 3) are presented in Table 5, along with values for the equivalent rainfall intensity–duration thresholds.

4.5 Emergency-response decision chart

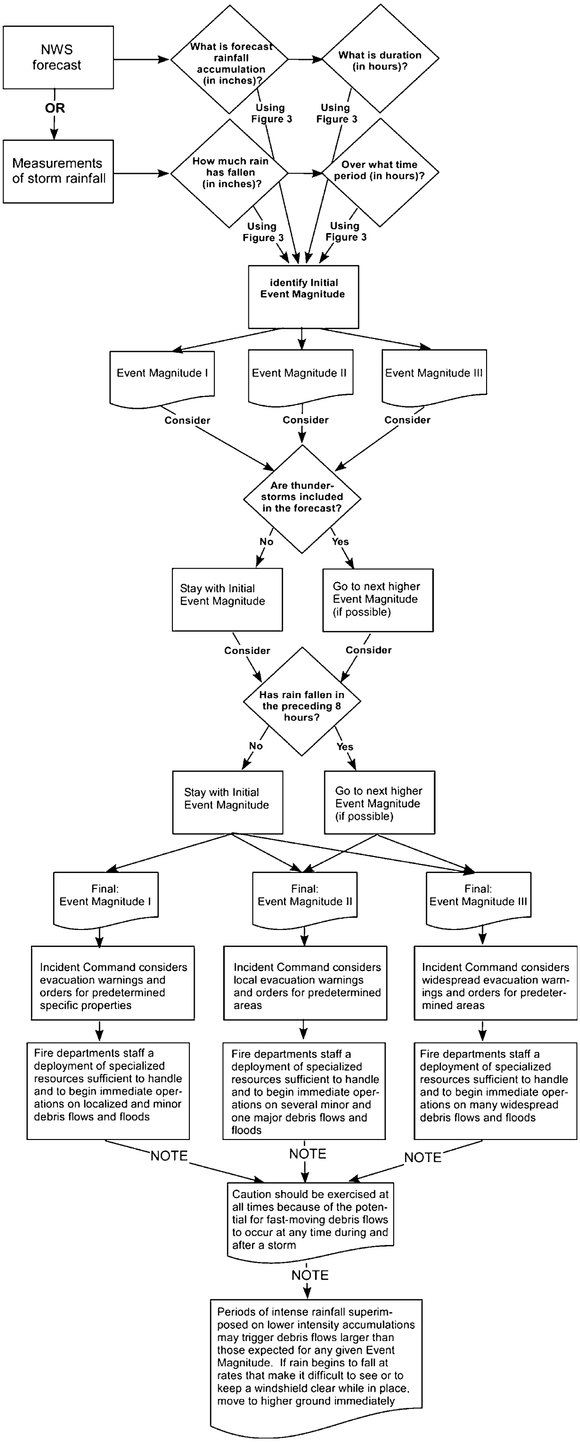
We incorporated the information developed above for postfire debris-flow hazards to develop an emergency-response decision chart for recently burned areas within the San Gabriel Mountains (Fig. 4). The decision process starts with either evaluation of rainfall totals and durations included in a NWS precipitation forecast, or with measurements of actual storm rainfall accumulations over different time periods, to identify an initial estimate of the possible event magnitude. Additional factors that may affect event magnitudes, including the high-intensity rainfall associated with thunderstorms and convective cells and the recency of preceding rainfall, are then evaluated to identify a final event magnitude for which to plan. Potential response actions for each event magnitude are then identified (L. Collins, Los Angeles County Fire Department, personal communication), as are particular caveats for personnel implementing a postfire debris-flow emergency-response plan.

To illustrate the use for the decision chart (Fig. 4) and Fig. 3, we first consider a storm forecast for up to 4.0 inches of rain falling in the next 12-h period. These rainfall conditions

Table 5 Values for storm rainfall accumulation–duration intensity–duration thresholds between which different magnitude events can be expected (from Fig. 3) (–, no value)

Duration	Rainfall accumulation (inches, in) Peak rainfall intensity (inches/hour, in/h)						
	15 min	30 min	1 h	3 h	6 h	12 h	24 h
Magnitude I	– –	– –	0.4 in 0.4 in/h	0. 7 in 0.2 in/h	0.9 in 0.2 in/h	1.3 in 0.1 in/h	1. 8 in 0.1 in/h
Magnitude II if local storm, Magnitude III if regional storm	0.2 in 0.8 in/h	0.3 in 0.6 in/h	0.5 in 0.5 in/h	0.9in 0.3 in/h	1.3 in 0.2 in/h	1.9 in 0.2 in/h	2.9 in 0.1 in/h
Magnitude III	0.5in 1.9 in/h	0.7 in 1.3 in/h	0.9 in 0.9 in/h	1.5 in 0.5 in/h	2.1 in 0.4 in/h	2.9 in 0.2 in/h	4.0 in 0.2 in/h

Fig. 4 Emergency-response decision chart



fall clearly within the range of conditions that have triggered magnitude III events in the past (Fig. 3), and decision makers should plan their response accordingly (Fig. 4). In contrast, should the forecast be for the same amount of rain but over a 24-h period, and thunderstorms or periods of high-intensity rainfall are included in the forecast, or if there was appreciable rainfall in the preceding 8 h, a magnitude III event is also possible, and a potential response is suggested in Fig. 4. Should neither thunderstorms, convective cells, nor previous rainfall be issues, the possibility of a magnitude II event can be considered.

A forecast of one inch of rain for any period less than approximately 1 h indicates the possibility of a magnitude III event and should be planned for accordingly (Fig. 4). A forecast of one inch of rainfall in 2 h and the absence of thunderstorms or preceding rainfall indicates the possibility of a magnitude III response if a regional scale storm is forecast, or a magnitude II event should the forecast be for a more localized impact. A forecast of one inch of rain in 3 to 6 h, and the absence of thunderstorms and preceding rainfall, indicates that planning should be appropriate for a magnitude I event, and a forecast of one inch of rain during any time period greater than about 6 h indicates a negligible effect (Fig. 4).

As a practical illustration of the utility and function of the decision chart (Fig. 4) and Fig. 3, please consider the information provided in the example forecast shown in Fig. 2. The forecast calls for between 1.5 and 3.0 inches of rain to fall over a 24-h period. If we locate the rainfall accumulation of 1.5 inches over the 24-h duration on Fig. 3, we will see that these values fall within the area characterized as a magnitude 0, or that the expected response would be negligible. However, given the range in the forecast of 1.5 to 3.0 inches in a 24-h period, a magnitude I, II, or III events may also be in the making. Such ambiguity should not be surprising in any effort to predict natural hazards, and points to the need for examining additional information, as follows.

The example forecast (Fig. 2) also provides estimates of rainfall expected for specific locations within Los Angeles County for the next 12-h period in 3-h increments, for the subsequent 12 h in 6-h increments, as well as potential peak 1-h rainfall rates. The forecast indicates that approximately 2.0 inches of rain will fall during the first 12 h, followed by 1.0 inch in the subsequent 12 h. Again, 2.0 inches of rain in a 12-h period suggests the possibility of either a Magnitude II or III response, while the 1.0 inch of rain in the subsequent period should not generate much of a hydrological response. Potential peak 1-h rainfall rates between 0.25 and 0.50 inches per hour indicate the same response. However, an important piece of information provided in the forecast is that thunderstorms, and their associated high-intensity rainfall, are expected with this storm. This indicates that in response to the rainfall forecast, a magnitude II or III event is certainly in the making, and decision makers should plan their response accordingly.

Figures 3 and 4 also can be used during a storm to identify a potential event magnitude in an area with rain gage coverage and thus contribute to an appropriate emergency-response decision (Fig. 4). Should a rainfall accumulation of 2 inches in a 1-h period be reported from within a recently burned area, a magnitude III response can certainly be expected (Fig. 3), and an appropriate emergency response will be necessary (Fig. 4). Similarly, measured rainfall accumulations of 0.5 inch over any time period less than about 1 h indicate that a magnitude III event may be underway if the rain is falling across the entire region, and a magnitude II event may be occurring if the storm is localized (Fig. 3). Similarly, measured rainfall accumulations of less than 1.0 inch over any time period between about 3 and 6 h would indicate that a magnitude I event was occurring in the area of the gage.

5 Limitations of approach

Keep in mind that weather forecasting is not an infallible science; actual storm conditions may differ from weather forecasts and conditions either more or less severe than those forecast may occur at any time during a storm. In addition, the boundaries between the event magnitudes were located based on interpretation of the available data and should be considered both wide and flexible to allow for the personal judgment and experience of decision makers. In addition, the potential for postfire debris flows and floods will decrease with time as revegetation stabilizes hillslopes, and material is removed from canyons by debris flows and floods. As a result, the estimates of the rainfall conditions that may lead to the generation of debris flows and floods will become increasingly conservative with time and would thus benefit from continued assessment and adjustment based on site-specific analyses. And last, considerable uncertainty is associated with relying exclusively on rainfall conditions as the basis of emergency-response decisions for recently burned areas; debris-flow magnitude and timing also will depend on factors such as burn severity, material properties and hillslope gradients, in addition to rainfall. Additional assessments, such as those presented in Cannon et al. (2009; 2010), are necessary to indicate areas that can be impacted by postfire debris flows and floods.

6 Summary and conclusions

As a consequence of the Station fire, which burned 160,557 acres of the San Gabriel Mountains of southern California in August and September, 2009 (National Interagency Fire Center 2009), postfire floods and debris flows now pose significant hazards to life and property (Cannon et al. 2009). Emergency-response and public-safety agencies are faced with making evacuation decisions and deploying staff and emergency-response equipment both well in advance of each coming winter storm and during actual storms. In this paper, we provide information critical to this process. The NWS issues Quantitative Precipitation Forecasts (QPFs) for the San Gabriel Mountains twice a day, at approximately 4 a.m. and at 4 p.m., along with unscheduled updates when conditions change. QPFs are for the following 24-h period and include estimates of the expected rainfall totals in 3-h increments for the first 12-h period and in 6-h increments for the last 12-h period. Estimates of 1-h rainfall intensities can be provided in the forecast narrative, along with probable peak intensities and timing, although with less confidence than values provided for rainfall totals.

A compilation of the hydrologic response to winter storms from recently burned areas in southern California was used to develop a system for classifying the postfire hydrologic response by magnitude. The four-magnitude classification system incorporates information on the volumes of individual debris flows, the consequences of these events in an urban setting (such as that along the San Gabriel Mountain Front), and the spatial extent of the response to the triggering storm. Each hydrological event was assigned one of four event magnitudes.

Measures of triggering storm rainfall associated with each hydrologic response indicate that significant debris flows and floods (Magnitude II or III events) have been produced from recently burned, southern California steeplands in response to storms that lasted between 45 min and 56 h, with storm rainfall totals between 0.5 and 15.50 inches.

Relations between triggering rainfall conditions and flood and debris-flow magnitudes specific to the San Gabriel Mountain setting were defined by three rainfall accumulation–duration thresholds between which postfire debris flows and floods of a given magnitude may be generated. Magnitude I events can be expected when within-storm rainfall accumulations (A) of given durations (D) fall above the threshold $A = 0.4D^{0.5}$ and below $A = 0.5D^{0.6}$ for durations greater than 1 h. Magnitude II events will be generated in response to rainfall accumulations and durations between $A = 0.4D^{0.5}$ and $A = 0.9D^{0.5}$ for durations less than 1 h, and between $A = 0.5D^{0.6}$ and $A = 0.9D^{0.5}$ for durations greater than 1 h. And last, magnitude III events can be expected in response to rainfall conditions above the threshold $A = 0.9D^{0.5}$.

By linking rainfall and event-magnitude information with emergency-response actions routinely implemented by fire departments and incident command centers, we developed an emergency-response decision chart that can be used to (1) determine potential event magnitudes as a function of precipitation forecasts or measurements, the occasion of high-intensity rainfall associated with thunderstorms, and the recency of preceding rainfall and (2) identify possible evacuation and resource-deployment levels based on individual storm forecasts and measured precipitation during storms. The ability to base planning and response decisions on specific storm forecasts, and precipitation measurements may result in significant financial savings and increased safety for both the public and emergency responders.

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