Joint NOAA/NWS/USGS Prototype Debris Flow Warning System for Recently Burned Areas in Southern California

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In the United States, landslides result in an estimated 25–50 deaths and damages between $1 and $3 billion annually. Debris flows are gravity-driven mixtures of sediment and water that are intermediate between coherent landslides and water floods, most commonly initiated when heavy rainfall or rapid snowmelt mobilizes soil on steep slopes, sending a slurry of rocks, soil, and organic debris downhill with tremendous force. The public often calls these mudslides (Fig. 1). Because of their close link with precipitation, debris flows are more predictable than most other types of landslides. The weather conditions that trigger them can be the same as those monitored for flash-flood warnings, although the critical precipitation warning thresholds and areas vulnerable to debris flow may differ considerably from those of conventional flash floods. Within the United States, rainfall intensity and duration thresholds, above which debris flows are likely to occur, have been defined for some canyons, coastal areas, and mountain regions. Meanwhile, the ability to monitor and forecast precipitation and issue timely weather hazard warnings is a well-established and ever-improving capability of the NOAA's National Weather Service (NWS).

FIG. 1. St. Sophia Church Camp in upper Waterman Canyon near San Bernardino, California. In December 2003, a debris flow triggered from recently burned hillslopes traveled from the bottom to top of this view, leaving deposits and only the foundation of the caretaker's residence. (PHOTO: Jerry DeGraff, USDA Forest Service)

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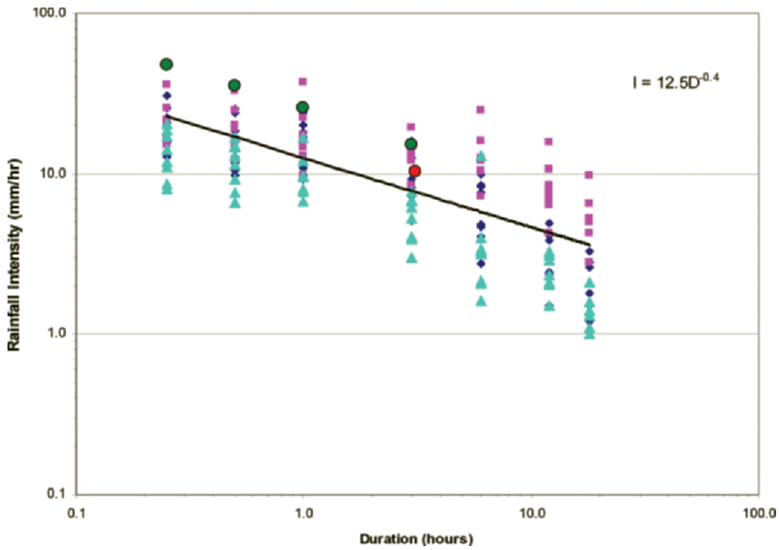

Fig. 2. Rainfall intensity–duration threshold for recently burned areas in Ventura County, CA. Blue diamonds represent measures of storm rainfall from rain gauges near basins that produced debris flows in response to a storm on 25 December 2003; magenta squares represent measures of storm rainfall from gauges near basins that produced debris flows and floods in response to a storm on 25 February 2004; cyan triangles represent measures of storm rainfall from gauges near basins that showed a minimal response to a storm on 2 February 2004. Note that each storm is represented by several data points representing peak intensities of different durations within the storm. Measurements from different storms can occupy the same location, but at least one measure of storm rainfall from the debris flow and flood-producing storms lies above the threshold line. Red dot indicates the average storm intensity leading up to known time of debris-flow occurrence from the 2005 Gorman Fire in response to a storm on 17 October 2005, and green dots are the peak intensities preceding the event. The threshold line is located to identify the upper limit of measurements made from storms known not to have produced floods or debris flows.

In 2004, the U.S. Geological Survey (USGS) and NOAA established a task force to evaluate the feasibility of establishing a debris-flow warning system that links the complementary expertise and capabilities of the two agencies. These scientists issued their report to both agencies in September 2005; this report recommended that a prototype debris-flow warning system be established in areas recently burned by wildfires in Southern California. The ongoing prototype project has now completed three years of operation. We present results here from the first rain season of operations, which occurred during the fall and winter of 2005/2006.

DEBRIS FLOWS. Debris flows are composed of approximately equal parts sediment and water, have mechanical characteristics that are distinct from either landslides or floods, and are commonly described as resembling flowing wet concrete. As described by Costa (1984), debris flows can travel through steep channels, over open hillslopes, and across gently sloping surfaces, where they are known to build their own channels. Flow properties vary with water and clay content, and sediment size and sorting. Debris flows commonly travel as a series of waves or surges and can have apparent viscosities that are 5–6 orders of magnitude greater than water, and fluid densities almost twice as great. As a consequence of the high fluid densities and shear strengths of debris flows, large rocks can be transported and cause considerable damage. In this report, the term "debris flow" includes mudflows (slurries containing mostly fine-grained material).

Debris flows originate when added moisture mobilizes poorly sorted rock and soil debris on hillslopes and in channels. Prerequisites for most debris flows include an abundant source of unconsolidated regolith, steep slopes, and a source of water. The most common water sources are intense or prolonged rainfall or snowmelt, or some combination of the two. Debris flows can be triggered by a variety of mechanisms. Commonly, debris flows occur when landslides transform into rapidly flowing masses. However, in landscapes disturbed by wildfire or volcanic eruptions, hillslope runoff or flood surges can erode and entrain channel sediment. Cannon and Gartner (2005) document that this is the prevalent condition in recently burned areas.

Debris flows have issued from burned basins in response to short-duration convective thunderstorms and to longer-duration winter frontal storms. Rainfall intensity–duration thresholds identified by Cannon et al. (2008) for recently burned areas in Southern California (Fig. 2) are considerably lower than those identified for unburned settings. This is a result of the considerably larger proportion of surface runoff in burned areas (runoff dominated) when compared with nonburned areas (infiltration dominated) for identical storms. Similar thresholds exist for the San Bernardino, San Gabriel, and San Jacinto Mountains and for the Peninsular Ranges. Because vegetation regrowth and sediment erosion can affect triggering rainfall conditions, a separate threshold has been defined for burned areas following one year of recovery.

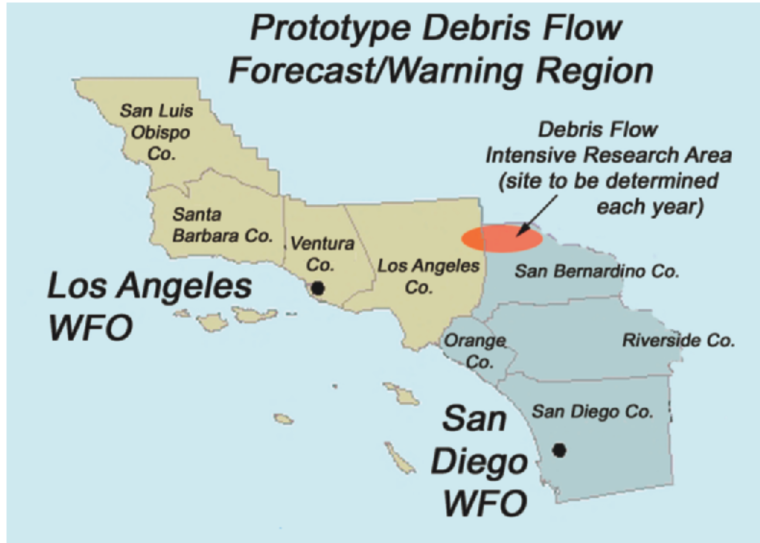

Fig. 3. Areas of debris-flow watch and warning responsibilities for the NWS offices in Southern California. The location of a debris-flow Intensive Research Area, which moves each year within the eight-county area, is also indicated in general terms.

DEBRIS-FLOW WARNING SYSTEMS. Rainfall intensity–duration thresholds have been linked with rainfall forecasts and real-time rainfall measurements to form the basis of operational debris-flow warning systems throughout the world. Rainfall thresholds, usually empirically derived, by themselves simply identify combinations of rainfall intensities and durations that can trigger debris flows during a storm, and can vary with previous accumulations of rainfall during the rainy season. With the premise that additional information on the hydraulic properties of the hillslope material and its initial moisture can improve the predictive effectiveness of rainfall intensity–duration thresholds, Baum et al. (2005) proposed a comprehensive warning system that consists of field measurements of precipitation, soil wetness, and pore-water pressures coupled with rainfall forecasts and time-dependent infiltration models for unsaturated soils, in addition to intensity–duration thresholds.

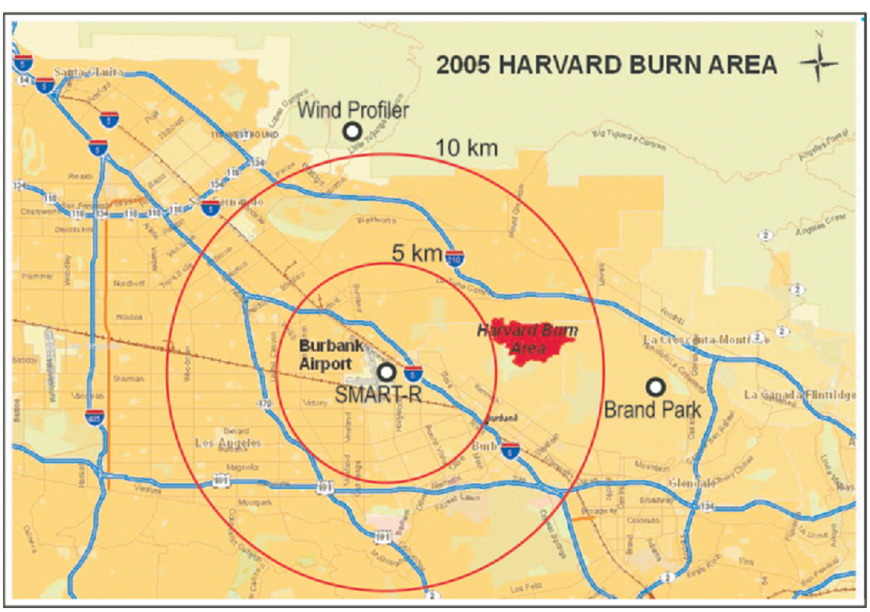

Fig. 4. Location of the Harvard burn area (in red) northeast of Burbank, California. The SMART-R radar was sited at the Burbank airport. Brand Park is the location of a nearby rain gauge used for radar QPE comparisons. The NOAA wind profiler site is also shown.

ELEMENTS OF THE DEBRIS-FLOW WARNING SYSTEM PROTOTYPE. *Scope.* After considering several alternatives, the Task Force recommended that a prototype debris-flow warning system be implemented in areas burned by wildfire (within two years of the fire) in the warning areas of the NWS Los Angeles–Oxnard and San Diego Weather Forecast Offices (WFOs) (Fig. 3). The area is characterized by an annual sequence of a very dry season followed by a rainy season. During the dry season, wildfires commonly burn mountainous terrain adjoining urban areas. During the

Table 1. Debris Flow Project instrumentation for the Intensive Research Area in and near the Harvard Burn, Winter 2005–06.

Instrument	Location	Parameters measured	Operator
5.6-GHz portable scanning radar	Burbank	Radar reflectivity > rain intensity, Doppler velocity	NOAA/NSSL
915-MHz wind-profiling radar	San Fernando	Vertical profile of winds, reflectivity, fall speeds aloft	NOAA/ESRL
Radio Acoustic Sounding System	San Fernando	Vertical profile of virtual temperature aloft	NOAA/ESRL
GPS-Met station	San Fernando	Precipitable water vapor	NOAA/ESRL
Surface meteorology station	San Fernando	T, RH, P, WS, WD, IR and solar radiation, rain intensity	NOAA/ESRL
Tipping buckets	Harvard Burn Area	Rainfall intensity, duration	USGS
Surface runoff sensors	Harvard Burn Area	Surface runoff	USGS
Soil moisture probes	Harvard Burn Area	Soil moisture	USGS
Pressure transducers	Harvard Burn Area	Flow depth	USGS
LIDAR	Harvard Burn Area	Finescale topography and channel cross sections	USGS

wet season, even storms with a two-year or less recurrence interval can trigger debris flows that threaten lives and property in and near recently burned areas. In contrast, debris-flow triggering mechanisms in unburned and not-recently-burned areas require accumulations of soil moisture throughout a rainy season and typically require more intense storms with longer recurrence intervals. Therefore, recently burned areas are prone to debris flows in response to even relatively modest storms.

Products. The debris-flow warning system uses the same terminology as in NWS hazardous weather messages ("outlook," "watch," and "warning"). An outlook indicates that a hazardous weather or hydrologic event may develop. Debris-flow outlooks are issued soon after a fire is contained and before the onset of winter storms. They include general information about potential hazards from burned areas, and identify areas that could potentially be impacted by floods or debris flows. An outlook is intended to provide information to those who need considerable lead time to prepare for an event. A watch is issued when the risk of a hazardous weather or hydrologic event has increased considerably, but its occurrence, location, and/or timing is still uncertain. Debris-flow watches are issued when forecast precipitation approaches the threshold lines. Watches are intended to provide enough lead time so that those who need to set their plans in motion can do so. Lead times are at most three days, and can be as short as a few hours. A warning is issued when a hazardous weather or hydrologic event is occurring, is imminent, or has a very high probability of occurring. A debris-flow warning is used for conditions

Table 2. Statistical performance of the Southern California prototype debris-flow warning system for the rain season of 2005/2006.

WFO	Total warnings issued	Events verified	POD (%)	FAR (%)
LOX (Los Angeles–Oxnard)	20	8	89	60
SGX (San Diego)	19	3	100	84
Total	**39**	**11**	**92**	**72**

that pose a threat to life or property, and are issued when precipitation estimates, either from observations or forecasts, exceed or will exceed the threshold lines. Desired lead times for debris-flow warnings are within one day, but developing conditions might cause them to be issued with lead times as short as 30 minutes.

Forecasting operations. The existing NWS Flash Flood Monitoring and Prediction (FFMP) operational tool, which automatically compares precipitation forecasts and measurements with threshold guidance for individual drainage basins, was adapted to bring the prototype debris-flow system online by November 2005. The ability of the WFOs to operate on a 24-hour, 7-days-a-week basis provided the opportunity for continuous monitoring. Additionally, the NWS infrastructure for dissemination of watches and warnings allowed for efficient communication with emergency managers and the public.

Research. Every year, a recently burned location, called the Intensive Research Area (IRA), has been identified for focused research activities to augment the forecasting operations of the prototype project (Fig. 3). Conditions in and near the IRA are monitored with instrument arrays to measure overland flow, soil moisture, sediment transport, channel changes, and numerous meteorological parameters, including rainfall (Table 1). In addition, NOAA's National Severe Storms Laboratory has deployed a portable C-band Doppler weather radar to collect spatially detailed precipitation measurements. Data from the IRA are used to improve our understanding of the meteorological, hydrologic, and geomorphic processes that operate in burned areas, with a specific focus on debris-flow triggering mechanisms.

FIRST YEAR OF OPERATION. The NWS tracks warning successes and false alarms to evaluate the efficacy of the debris-flow warning system (statistics for watches are not kept). Following a dry season that saw severe burns, the winter of 2005/2006 in Southern California brought below-normal precipitation, and only a handful of storms threatened the area; most only marginally approached the debris-flow thresholds. A total of 39 warnings were issued, 11 of which were verified to have generated debris flows. The ratio of verifications to warnings translates to a 92% probability of detection (POD) and 72% false-alarm rate (FAR). Table 2 shows how those numbers were computed from each of the two Weather Forecast Offices. For comparison, Table 3 shows the corresponding statistics for nondebris-flow warnings. It is important to note that debris flows triggered high in a watershed can stop upstream of the watershed outlet, which makes event verification difficult. Furthermore, debris flows may be harmlessly contained by debris basins specifically built to catch them. Debris flows that do not threaten life or property are considered "nonverified" by NWS standards, even if they have occurred. These complexities conspire to produce lower PODs and higher FARs than are typical for flash floods. We used the NWS standard for consistency with the WFO reporting.

Despite the lower POD and higher FAR achieved by the debris-flow warning system when compared to the performance of flash-flood warnings in the same areas, the prototype debris-flow warning system was received enthusiastically as a step forward by the emergency management community. Some emergency managers in other parts of the country have requested that the system be extended to their communities.

Table 3. Statistical performance of the Southern California flash-flood warning system for the rain season of 2005/2006.

WFO	Total warnings issued	Events verified	POD (%)	FAR (%)
LOX (Los Angeles–Oxnard)	10	3	100	70
SGX (San Diego)	28	6	100	79
Total	**38**	**9**	**100**	**76**

RESEARCH TO IMPROVE THE WARNING SYSTEM. Accurately measuring rainfall over potential debris-flow basins is one of the more difficult challenges associated with applying intensity–duration thresholds. Given the mesoscale character of convective rainfall in Southern California, a few widely spaced rain gauges cannot adequately capture the true threat. Radar-observed quantitative precipitation estimates (QPE) provide one way to estimate the areal coverage of precipita-

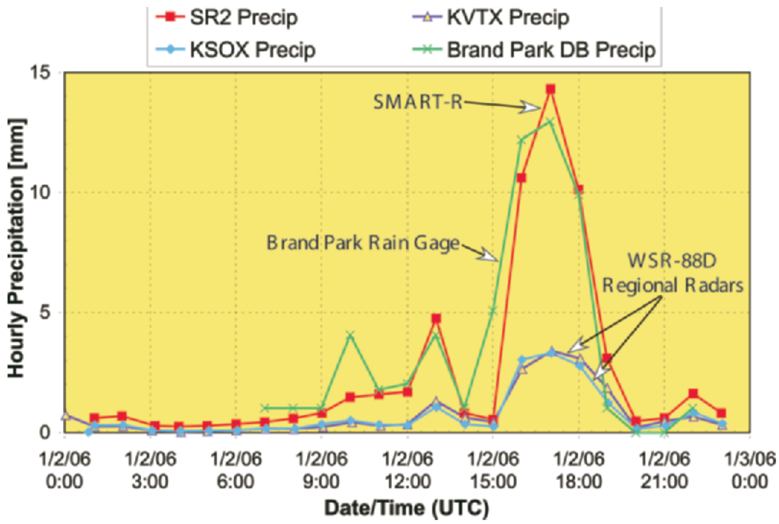

Fig. 5. Time series of basin average rainfall estimates from SMART-R radar and NWS network radars (KSOX and KVTX) for the 2 January 2006 Burbank, California, storm. The time series of measured rainfall is from the Brand Park rain gauge (see Fig. 4).

tion, if the radar is properly sited and calibrated. The 2005/2006 IRA was the Harvard burn area in the Verdugo foothills near Burbank, California (Fig. 4). As part of the IRA instrumentation, a transportable C-band Doppler weather radar was sited within 10 km of the basin to demonstrate the utility of close-up radar measurements to augment rain gauges. The radar was one of the Shared Mobile Atmospheric Research and Teaching Radars (SMART-R) operated by NOAA's National Severe Storms Laboratory (NSSL) and the University of Oklahoma. This research radar was much closer to the burned area than the NWS's operational WSR-88D surveillance radars and produced finescale unobstructed observations of the precipitation immediately above it. Radar reflectivity (R) was converted to rainfall estimates (Z) using the NWS "convective" empirical relationship $Z=300R^{1.4}$.

For a storm on 2 January 2006, estimates of basin-average precipitation from the NWS WSR-88D radars (KSOX and KVTX) are compared with measurements from a rain gauge at Brand Park near the burned area and with estimates from the nonbias-corrected SMART-R unit. As shown in Fig. 5, the closer proximity of the portable radar to the burn area yielded data that matched the point-measurements of the gauge much more accurately than the more distant NWS radars and, thus, provides greater confidence in its area-wide rain estimations.

Several other important meteorological and hydrological sensors were deployed in and near the IRA, as indicated in Table 1. NOAA's Earth System Research Laboratory operated a 915-MHz wind profiler with Radio Acoustic Sounding System (RASS) near San Fernando about 11 km north of the SMART-R site. The profiler site also included a surface meteorological station and a GPS probe for measuring the vertically integrated amount of water vapor overhead. These observations are particularly useful to forecasters in deciding to issue watches, whereas the SMART-R measurements are more appropriate for issuing warnings. USGS-operated networks of overland flow detectors, soil moisture sensors, and rain and stream gauges installed on the hillslopes and in the channels burned by the Harvard fire provided data on postfire infiltration and runoff processes and are presently being analyzed.

LESSONS LEARNED. Evaluation of the inaugural year of operation of the prototype debris-flow warning system in Southern California indicates that:

- Watches provide valuable information that allows for adequate lead time for preparation, road closures, and posting of emergency vehicles in hazardous areas.
- Precipitation measurements from the Automated Local Evaluation in Real Time (ALERT) rain-gauge network, and forecaster experience, are necessary to augment both forecasting models and operational radar precipitation data.
- Small, portable radars can augment observations from the fixed-site operational radar network with highly accurate, finer-scale estimates of precipitation.
- Rainfall thresholds provide a very conservative estimate of hazardous rainfall conditions throughout an entire burned area. As a given storm approached threshold conditions, it proved worthwhile to contact local authorities or observers regarding event verification.
- More detailed information on areas of potential debris-flow impact or inundation as functions

of burn severity, material properties, and basin morphology would be useful.

- Separate watch and warning products, specific to debris flow, are necessary to adequately characterize potential hazards posed by the distinct flow processes and triggers of debris flows, and to allow for a quantitative verification of the warning system.

CONCLUSIONS. The joint NOAA–USGS prototype debris-flow warning system established in Southern California in 2005 has provided valuable information to emergency managers in affected communities. Future plans include development of new or improved methods for defining and testing rainfall thresholds, estimating probabilities of debris-flow occurrence and volumes of events relative to basin conditions, and linking real-time monitoring of precipitation and hillslope and channel conditions with physical models for postfire debris-flow occurrence. Although the potential exists for enhancing and expanding the warning system to unburned settings throughout the United States, considerable effort and scientific advancements are necessary to realize this potential.

FOR FURTHER READING

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