Impact of Recent Extreme Arizona Storms

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Heavy rainfall on 27–31 July 2006 led to record flooding and triggered an historically unprecedented number of debris flows in the Santa Catalina Mountains north of Tucson, Ariz. The U.S. Geological Survey (USGS) documented record floods along four watercourses in the Tucson basin, and at least 250 hillslope failures spawned damaging debris flows in an area where less than 10 small debris flows had been documented in the past 25 years. At least 18 debris flows destroyed infrastructure in the heavily used Sabino Canyon Recreation Area (http://wwwpaztcn.wr.usgs.gov/rsch_highlight/articles/200611.html). In four adjacent canyons, debris flows reached the heads of alluvial fans at the boundary of the Tucson metropolitan area. While land-use planners in southeastern Arizona evaluate the potential threat of this previously little recognized hazard to residents along the mountain front, an interdisciplinary group of scientists has collaborated to better understand this extreme event.

Prior to this event, researchers from the University of Arizona (UA), the U.S. Department of Agriculture's Agricultural Research Service (ARS), the U.S. National Weather Service (NWS), the USGS, and the Arizona Geological Survey (AZGS) had independently instrumented much of the southern side of the Santa Catalina Mountains. Researchers distributed rainfall and streamflow gages throughout the watershed to study, among other things, the hydrologic response to the 2003 Aspen Fire on the Santa Catalina Mountains. A NWS Doppler weather radar (Weather Surveillance Radar 88 Doppler, WSR-88D) located 50 kilometers to the southeast has an unimpeded view of the atmosphere above the mountains. These resources have provided a unique opportunity to study the unusual sequence of strong thunderstorms that crossed the region in late July 2006.

Atmospheric Physics of the Storm

Southeastern Arizona receives about 55% of its annual precipitation during the North American Monsoon, when incursions of moist, tropical air from the south promote localized convective thunderstorms. During the last week of July 2006, an upper-level disturbance stalled over northwestern New Mexico. Combined with a humid air mass, the low pressure generated widespread, early morning thunderstorms over southeastern Arizona during a 5-day period.

On 31 July, heavy rainfall began shortly after midnight and lasted 6–8 hours. A strong complex of thunderstorms developed over central Arizona on the back side of the upper-level disturbance. The moist atmosphere, coupled with cooling aloft, generated two mesoscale thunderstorm complexes that moved southeast into the Tucson basin. Simultaneously, a strong, low-level southwesterly jet (30–35 kilometers per hour) developed with an orographic upslope component over the southern face of the Santa Catalina Mountains.

Mesoscale thunderstorms are well-organized convective complexes typically affecting areas larger than 50,000 square kilometers. The first of the mesoscale thunderstorms had a cold cloud top structure (heavy, intense rainfall) and passed through the region around 1000 GMT (3:00 A.M. local time). A second mesoscale thunderstorm with a warmer cloud top structure (less intense, yet longer-lasting rainfall) developed near dawn and persisted past 1500 GMT (8:00 A.M. local time). The low-level, southwesterly jet provided lifting and fed additional moisture into the southwest trending canyons along the mountain range. This atmospheric combination sustained heavy rainfall for several hours.

Rainfall and Hydrologic Response

Rainfall amounts estimated from WSR-88D data for the morning of 31 July, the fifth consecutive day of widespread rainfall, showed totals up to 150 millimeters on the south side of the Santa Catalina Mountains, a semi-arid region that receives 350–400 millimeters of rainfall per year. Six rainfall gages operated by Pima County Regional Flood Control District and 13 rainfall gages operated by UA were either within the Sabino Creek watershed or nearby (Figure 1). The largest-measured 6-hour rainfall totaled 105 millimeters at the Middle Sabino gage (1126-meter elevation). According to U.S. National Oceanic and Atmospheric Administration precipitation statistics, this 6-hour rainfall had a recurrence interval of 250 years. More telling in terms of hydrogeomorphic response, the 3-day total precipitation at this gage was 265 millimeters, a rainfall depth with an estimated 1000-year recurrence interval.

Two streamflow gaging stations were in operation along Sabino Creek. Though multiple debris flows entered the flood in Sabino Creek, sediment-rich water flow (i.e., not debris flow) passed each gaging station for the duration of the flood. At the lowermost gaging station (USGS 09484000), the 31 July flood had four separate peaks, the largest having a provisional discharge estimate (based on a USGS indirect calculation) of 445 cubic meters per second from

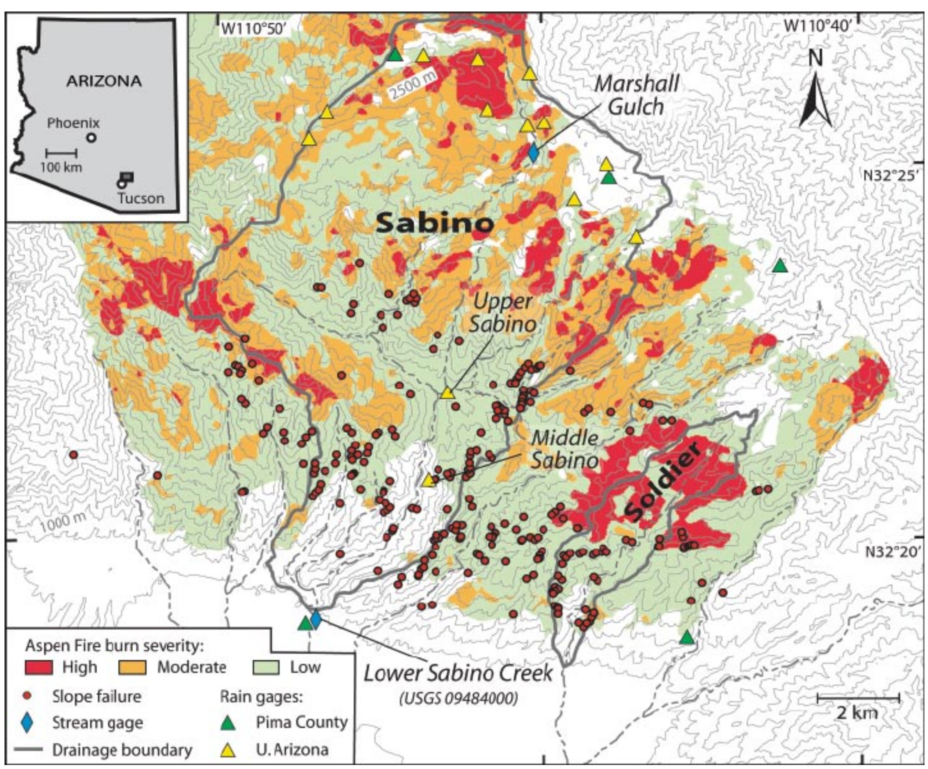

Fig. 1. Map of hillslope failures, rainfall gages, and stream gages within the Santa Catalina Mountains north of Tucson, Ariz. The elevation contour interval is 100 meters. Locations of hillslope failures were mapped with helicopter-based and ground-based reconnaissance.

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the 91-square-kilometer drainage (Figure 2). This flow represents the largest flood in the 75-year gaging record (1932–2006) and followed flood peaks of 181 and 225 cubic meters per second on 29 and 30 July, respectively. On 31 July, the gaging station higher in the watershed recorded a smaller flood, commensurate with rainfall data that indicated the 31 July storm was focused in the middle elevations of the catchment.

Flood-frequency analysis, based on USGS gage data excluding the 2006 peak, determined the recurrence interval of the 31 July flood on Sabino Creek to be 100+ years. While the flood of 31 July is significant, the sequence of large floods on three consecutive days is exceptional. Analyzing the three floods with a stationary log-Pearson type III distribution, the USGS recommended technique for flood frequency analysis, and including the 2006 peak, the consecutive floods of 29–31 July would have respective recurrence intervals of 10, 20, and 90 years.

Before the 31 July storm, collaborative research among the NWS, UA, and ARS led to development of a prototype flood-forecasting model based on WSR-88D and KINEROS, a distributed kinematic rainfall-runoff-erosion model developed by ARS; Sabino Creek watershed was one of the test watersheds. Hydrologic parameters were estimated using geospatial data and were refined by calibrating the model's response to modest runoff events from 2004 and 2005. For the 31 July storm, the model calibration process showed the soils became saturated during the first thunderstorm, behaving as impermeable surfaces. By adjusting the model parameters of soil depth and antecedent moisture, the predicted results matched the reported flood peak to within 5% (Figure 2).

Slope Failures and Debris Flows

The southern flanks of the Santa Catalina Mountains consist of many near-vertical bedrock outcrops. Steep talus slopes below these outcrops are covered by thin colluvium, of the order of 50 centimeters. The more than 250 shallow slope failures from July 2006 occurred at elevations of 1200–1800 meters. Most documented failures initiated in steep colluvium or beneath bedrock cliffs, and mobilized into debris flows in steep chutes leading to valley axes.

Within Sabino Canyon, most debris flows traveled short distances down chutes and stopped upon reaching Sabino Creek. Numerous large boulders were entrained, adding mass to debris flows and compounding damage to roads, bridges, and structures in Sabino Canyon. The large flood in Sabino Creek diluted the incoming debris flows, preventing mass movements farther downstream. In five adjacent canyons having smaller drainage areas and no antecedent floods, debris flows coalesced in the main channels and traveled several kilometers toward the mountain front. For example, in Soldier Canyon, several kilometers east of Sabino Canyon, at least 35 slope failures coalesced into multiple debris-flow pulses that exited the mountain front, choked the stream channel with coarse sediment, and forced recessional flow to spill across the alluvial fan, flooding several homes.

The Aspen Fire

In 2003, the Aspen Fire, the largest historical wildfire in the Santa Catalina Mountains, burned 343 square kilometers of forest and shrubland on a mountain range spanning 900–2800 meters in elevation. Burn severity was highest near the top of the range. On 31 July 2006, three years after the fire, 86% of the slope failures were either in unburned or low-severity-burn areas corresponding to middle-elevation regions exposed to heavy rainfall (the high-severity-burn areas at the top of the range had moderate rainfall on 31 July). *Cannon and Gartner* [2005] found that enhanced debris-flow potential on hillslopes affected by forest fires decreased to prefire levels in about 2 years; they also found the great majority of postfire debris flows were initiated through a process of progressive sediment bulking rather than through discrete hillslope failures, the dominant failure mode found in this study. Preliminary analysis suggests therefore that the 2006 Catalina Mountain debris flows were not strongly related to the Aspen Fire; instead, they were caused by an extreme precipitation event.

Geologic Hazard

The alluvial fans skirting the mountains of the Tucson basin are popular for expensive homes and resorts. Few of these property owners realize the role debris flows play in building these fans. While geologists long recognized the processes responsible for alluvial fan building, most had assumed debris flows moved onto the fans during the late Pleistocene or early Holocene (approximately 8000 to 12,000 years ago). Late Holocene debris flows were thought not to occur. Supporting this assumption, historical records in the Tucson basin in the past 150 years report no instances of debris flows affecting areas downslope of the mountains.

In the small, steep watersheds of the Santa Catalina Mountains, surface water from each individual July 2006 thunderstorm drained quickly (Figure 2). Other than increased soil moisture, the 29 July flood had little effect on the 30 July flood, and the 30 July flood had little effect on the 31 July flood. Though the integrated volume of water released from the Sabino Creek drainage from 29 to 31 July was significant, the largest individual peak discharge represented a 100-year event. The hydrogeomorphic response of the hillslopes, however, was sensitive to the multiday storm. Accumulated soil moisture from 3 days of heavy rainfall led to multiple hillslope failures and damaging debris flows.

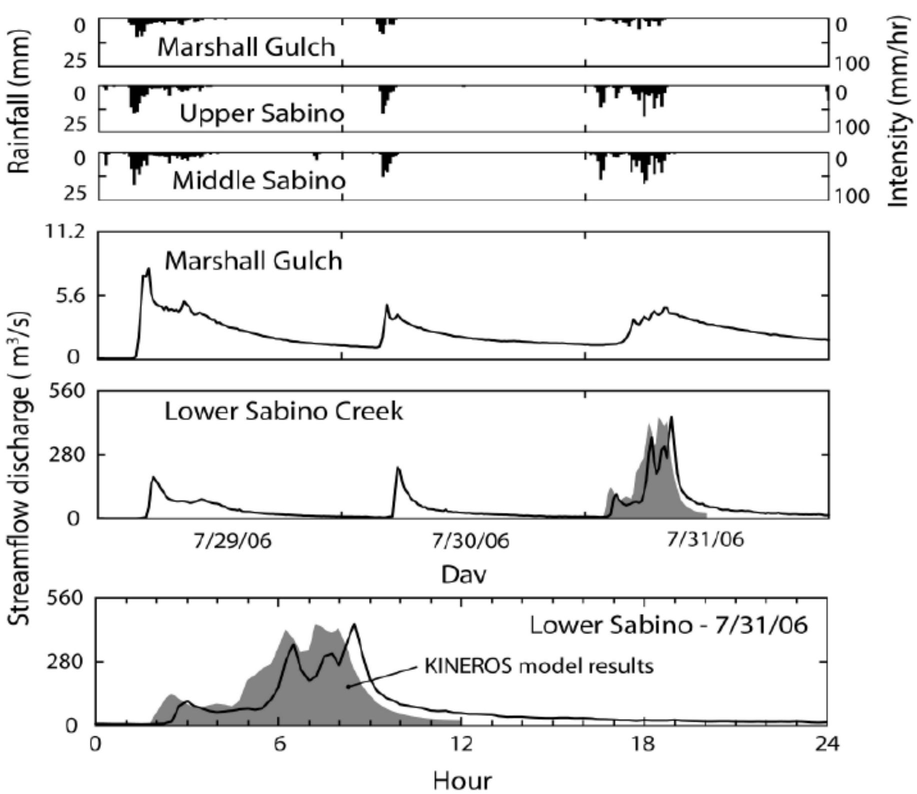

Fig. 2. Hyetographs (i.e., plots of rainfall versus time) and hydrographs from three rainfall gages and two stream gages located throughout the Sabino Creek watershed. The rainfall is shown in 15-minute increments. Rainfall intensity during the storm was as high as 66 millimeters per hour—heavy, though not uncommon for convective thunderstorms in the Southwest U.S.—and lasted several hours. Results of the KINEROS model are represented by the gray-fill region at the Lower Sabino Creek gage. The bottom graph is the expanded hydrograph from 31 July.

Analysis suggests that the 3-day depth of rainfall in the middle elevations of the Catalinas for the July 2006 storms would occur once every 1000 years or so.

Further spatial analysis of multiday precipitation patterns at initiation sites is planned for the coming year to better evaluate hillslope-failure potential and debris-flow return frequency. Older debris-flow deposits along the mountain front will be dated using cosmogenic isotopes. More research also is planned to understand spatial extent of debris-flow runout potential in southern Arizona. Finally, detailed analysis is under way to assess the impact of abundant fine-grained sediment released by the hillslope failures on flood-control infrastructure designed without accommodation for rapid aggradation. These data will enable land-use planners to better protect people and property located near steep, mountainous watersheds in the arid West.

Acknowledgments

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NEWS

In Brief

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Satellite repositioned to monitor South American region The NOAA geostationary operational environmental satellite GOES-10 has been repositioned to provide coverage of atmospheric conditions in South America, the agency announced on 10 April. In its new position, the satellite will provide coverage of the region around South America nearly to the South Pole, imaging it once every 15 minutes. Further, coverage will no longer be interrupted during hurricanes and other severe weather events in the United States. Continual satellite coverage of the region should provide better advanced warning of natural disasters, such as storms, cyclones, mudslides, and flooding. Shifting the satellite was part of the U.S. contribution to the Global Earth Observation System of Systems (GEOSS), a global monitoring network.

Russian volcano warnings reinstated The Kamchatka Volcanic Eruption Response Team (KVERT) is again issuing warnings for aviation during periods of activity by Kamchatkan volcanoes. KVERT had stopped issuing warnings on 1 March due to a loss of funding by the Federal Unitary Enterprise State Air Traffic Management Corporation of Russia (see *Eos 88*(12), 2007). The funding for this work has now resumed. KVERT is a collaborative project of scientists from the Russian Institute of Volcanology and Seismology, the Kamchatka Experimental and Methodical Seismological Department, and the Alaska Volcano Observatory.

Report details climate change effects on cultural sites A new report from UNESCO (United Nations Educational, Scientific, and Cultural Organization) details how 26 World Heritage sites could be affected by coming climate changes. The 26 examples, which are meant to be representative of the range of threats to the 830 sites inscribed in the World Heritage List, are divided into five types: archaeological sites, glaciers, historic cities and settlements, marine biodiversity, and terrestrial biodiversity. Some of the examples include the Great Barrier Reef, which is expected to experience more frequent episodes of coral bleaching; Timbuktu in Mali, threatened by desertification; and the Chavín Archaeological Site in the Peruvian Central Andes, one of the earliest and best-known pre-Columbian sites, which flooding. The report, "Case Studies on Climate Change and World Heritage," is available at http://whc.unesco.org/documents/publi_climatechange.pdf

Computer failure caused loss of Mars spacecraft A computer error that occurred 5 months before NASA lost contact with the Mars Global Surveyor on 2 November 2006 led to the spacecraft's eventual battery failure and subsequent loss of orientation. This is according to a 13 April preliminary report from an internal NASA review board. The report, "Mars Global Surveyor Spacecraft Loss of Contact," is available at http://www.nasa.gov/mission_pages/mgs/

Ozone sensor restored to weather satellite A sensor for measuring ozone will be included on the National Polar-Orbiting Environmental Satellite System (NPOESS) Preparatory Project (NPP) satellite, NASA and NOAA announced on 11 April. The Ozone Mapping and Profiler Suite (OMPS) Limb will measure the vertical distribution of ozone in the atmosphere. A U.S. National Academies committee recommended the restoration of the OMPS Limb to the NPOESS program earlier this year in its Earth science decadal survey (see *Eos 88*(13), 2007). Restoration of the OMPS Limb to the NPOESS program is contingent upon the cost of the instrument. The NPP satellite is scheduled to launch in 2009, and the first NPOESS satellite is scheduled for 2013.

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