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Debris Flows and Record Floods from Extreme Mesoscale Convective Thunderstorms over the Santa Catalina Mountains, Arizona

by Christopher S. Magirl [1], Craig Shoemaker [2], Robert H. Webb [1], Mike Schaffner [2], Peter G. Griffiths [1], and Erik Pytlak [2]

[1]US Geological Survey; 520 North Park; Tucson, Arizona 85719; magirl@usgs.gov

[2]National Weather Service, Tucson, Arizona; craig.shoemaker@noaa.gov

ABSTRACT

Ample geologic evidence indicates early Holocene and Pleistocene debris flows from the south side of the Santa Catalina Mountains north of Tucson, Arizona, but few records document historical events. On July 31, 2006, an unusual set of atmospheric conditions aligned to produce record floods and an unprecedented number of debris flows in the Santa Catalinas. During the week prior to the event, an upper-level area of low pressure centered near Albuquerque, New Mexico generated widespread heavy rainfall in southern Arizona. After midnight on July 31, a strong complex of thunderstorms developed over central Arizona in a deformation zone that formed on the back side of the upper-level low. High atmospheric moisture (2.00" of precipitable water) coupled with cooling aloft spawned a mesoscale thunderstorm complex that moved southeast into the Tucson basin. A 15-20 knot low-level southwesterly wind developed with a significant upslope component over the south face of the Santa Catalina Mountains advecting moist and unstable air into the merging storms. National Weather Service radar indicated that a swath of 3-6" of rainfall occurred over the lower and middle elevations of the southern Santa Catalina Mountains. This intense rain falling on saturated soil triggered over 250 hillslope failures and debris flows throughout the mountain range. Sabino Canyon, a heavily used recreation area administered by the U.S. Forest Service, was the epicenter of mass wasting, where at least 18 debris flows removed structures, destroyed the roadway in multiple locations, and closed public access for months. The debris flows were followed by streamflow floods which eclipsed the record discharge in the 75-year gaging record of Sabino Creek. In five canyons adjacent to Sabino Canyon, debris flows approached or exited the mountain front, compromising flood conveyance structures and flooding some homes.

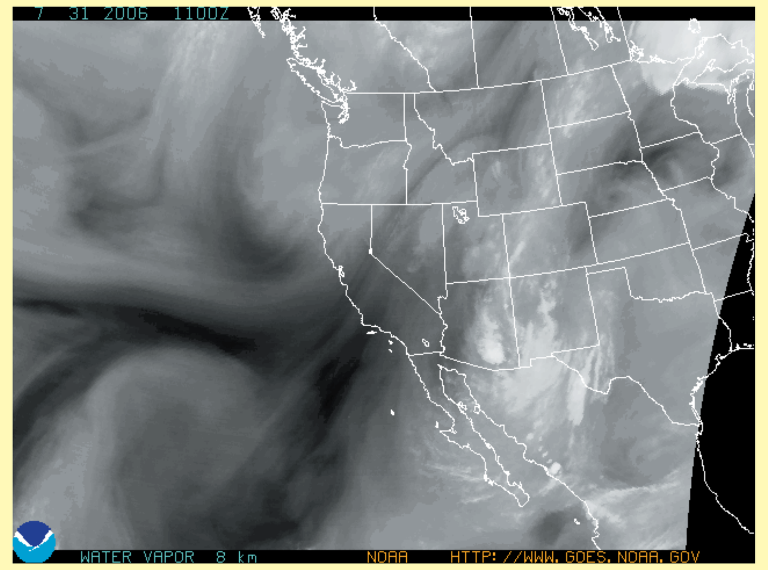

Figure 1. GOES water-vapor imagery of Arizona in the early morning of July 31 showing the humid air mass over the Southwest and the low pressure over New Mexico.

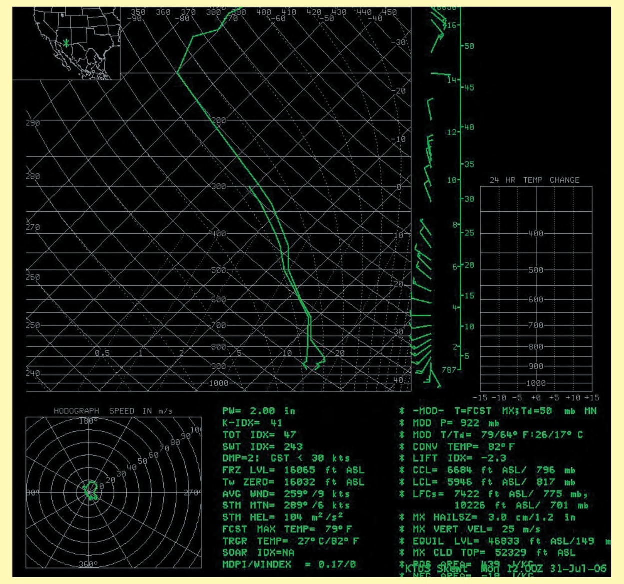

Figure 2. Rawinsonde sounding from the Tucson International Airport from July 31 showing the low-level southwesterly jet and high precipitable water.

1) Atmospheric Physics of the Storm

The heaviest rainfall began shortly after midnight on July 31 and lasted 6-8 hrs. An unusually moist atmosphere coupled with cooling aloft generated two mesoscale thunderstorm complexes that moved southeast into the Tucson basin (Figure 1). Simultaneously, a relatively strong, low-level southwesterly inflow jet (15-20 knots) developed with an orographic upslope component over the south face of the Santa Catalina Mountains (Figure 2). The first of the mesoscale thunderstorms had a cold cloud-top structure (-72° C) and passed through the region from 2:00-4:00 AM (MST). A second mesoscale thunderstorm with a warm cloud-top structure (-60° C) developed near dawn and persisted until about 8:00 AM (MST), bringing heavy, sustained rainfall. The low-level, southwesterly jet provided lifting and fed additional moisture directly into the southwest-trending canyons on the southern side of the mountains. This atmospheric combination sustained convective activity for several hours over a number of mountain watersheds.

2) Precipitation

Rainfall amounts estimated from NWS radar (WSR-88D) data for the morning of July 31, the fifth consecutive day of widespread rainfall, showed totals up to 6" on the south side of the Santa Catalina Mountains (Figure 3). The peak 6-hour rainfall at the Molino Basin gage, operated by Pima County Regional Flood Control District, 5 mi east of Sabino Canyon (3,840 ft elevation), was 3.82" on July 31; the storm total was 4.64" and the 3-day total was 8.30". Based on NOAA precipitation statistics [Bonnin et al., 2003], the 6-hour and 3-day recurrence intervals at this station were 175 and 1200 years, respectively (Figure 4). Similar multiday rainfall recurrence intervals occurred at the Sabino Dam gage; recurrence intervals on Mount Lemmon were more modest (Figure 4).

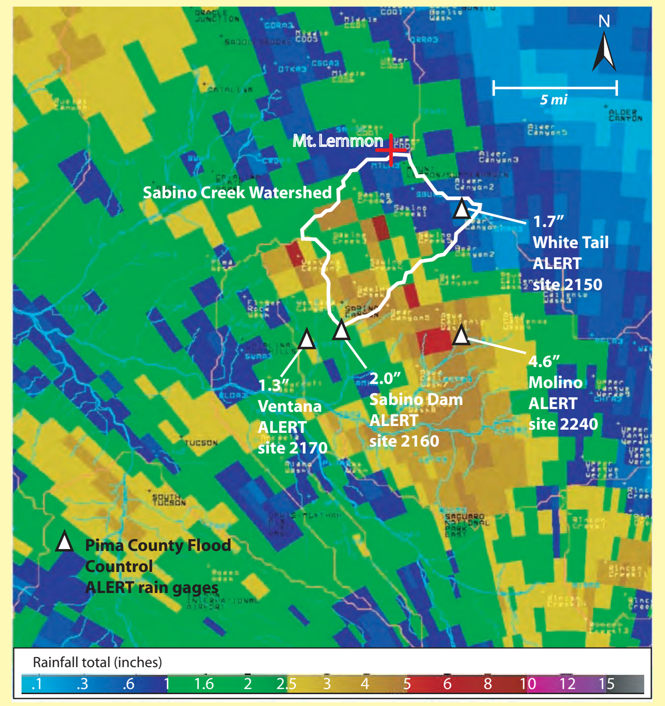

Figure 3. Cumulative precipitation from July 31 based on WSR-88D data with select ALERT raingage data.

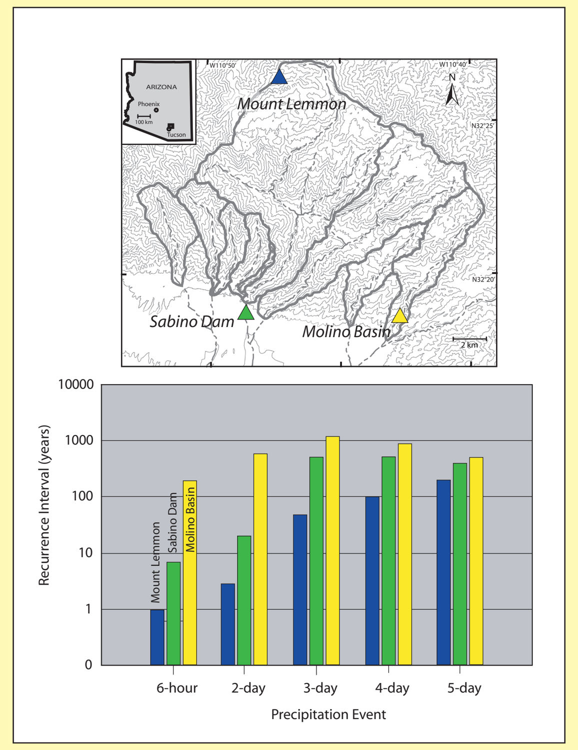

Figure 4. Calculated return period of rainfall for three sites on the Santa Catalina Mountains.

3) Flooding

A U.S. Geological Survey streamflow gaging station on Sabino Creek (USGS 09484000) showed the July 31 flood had four separate peaks, the largest having a provisional discharge estimate of 15,700 cfs from 35.5 mi² (Figure 5). This flow represents the largest flood in the 75-year gaging record (1932-2006), and followed flood peaks of 6,390 and 7,930 cfs on July 29 and 30, respectively. Flood-frequency analysis, based on gage data excluding the 2006 peak, determined the recurrence interval of the July 31 flood on Sabino Creek to be 100+ years. Including this flood in the analysis lowered the recurrence interval to about a 90-year event.

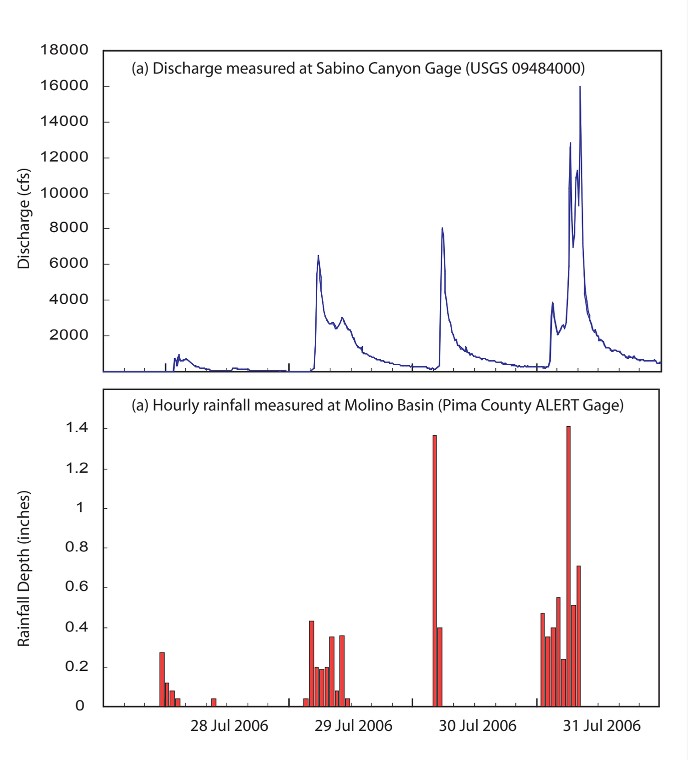

Figure 5. Provisional streamflow data in Sabino Creek and rainfall at Molino Basin over the last four day in July 2006.

Figure 6. Roadway damaged by debris flow in Sabino Canyon Recreation Area. The largest boulders on edge of channel were deposited by a prehistoric debris flow.

4) Hillslope Failures

Many of the hillslope failures initiated in steep colluvium or beneath bedrock cliffs near ridgelines, mobilizing debris flows in steep chutes leading to the valley axes (Figures 6-8). At least two modes of failure were observed: (1) failures occurring in a relatively small area at the base of a cliff or steep slope leading into a steep chute, and (2) a broad swath of failed colluvium creating a series of closely spaced rills and gullies coalescing into a single chute. More than 250 slope failures occurred, concentrated at elevations between 4,000 - 6,000 ft, on the southern slope of the Santa Catalina Mountains (Figure 9).

Figure 7. Hillslope scar and debris-flow chute in Sabino Canyon.

5) Debris Flows

Within Sabino Canyon, most debris flows moved short distances down chutes and stopped upon reaching the flood waters in Sabino Creek (Figure 6). Although many chutes were scoured to bedrock, some chutes – particularly below broad hillslope failures – had considerable exposure of barren colluvium or regolith, increasing the likelihood of additional slope failures in the future. In five adjacent canyons, debris flows coalesced in the main channel and traveled several kilometers to the mountain front (Figure 10). In Rattlesnake Canyon at least 24 slope failures coalesced into a debris flow that traveled 2.5 mi, depositing large boulders (Figure 11) and destroying a roadway crossing. Where the debris flow entered Sabino Creek, about 20 ft of vertical aggradation occurred over a width of about 100-150 ft (Figure 12). Bear Canyon experienced at least 41 slope failures that coalesced into a valley axis debris flow that reached the mountain front, clearing out a dense corridor of riparian vegetation. In Soldier Canyon at least 35 slope failures coalesced into multiple pulses of debris flow that exited the mountain front. Where this debris flow encountered a low bridge, deposition choked the stream channel with coarse sediment and forced recessional flow into a broad area across the alluvial fan (Figure 13). Several homes on this fan were flooded with sheet flow as a result of channel aggradation. In an unnamed canyon between Bear and Soldier Canyons, at least 7 hillslope failures coalesced into a debris flow that traveled onto the alluvial fan nearly 0.5 mi from the mountain front. A roadway was washed out and several homes were flooded.

Figure 8. Hillslope scars on western side of Sabino Canyon. Rattlesnake Canyon is in the background.

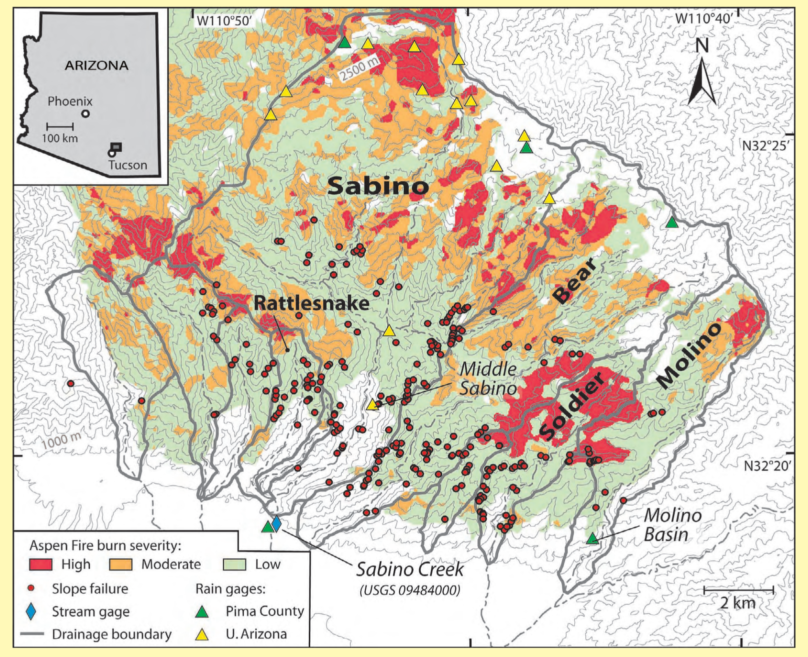

Figure 9. Over 250 hillslope failures occured in the Santa Catalina Mountains, most between 4,000 - 6,000 ft elevation. The extent of the 2003 Aspen Fire is indicated with the orange line.

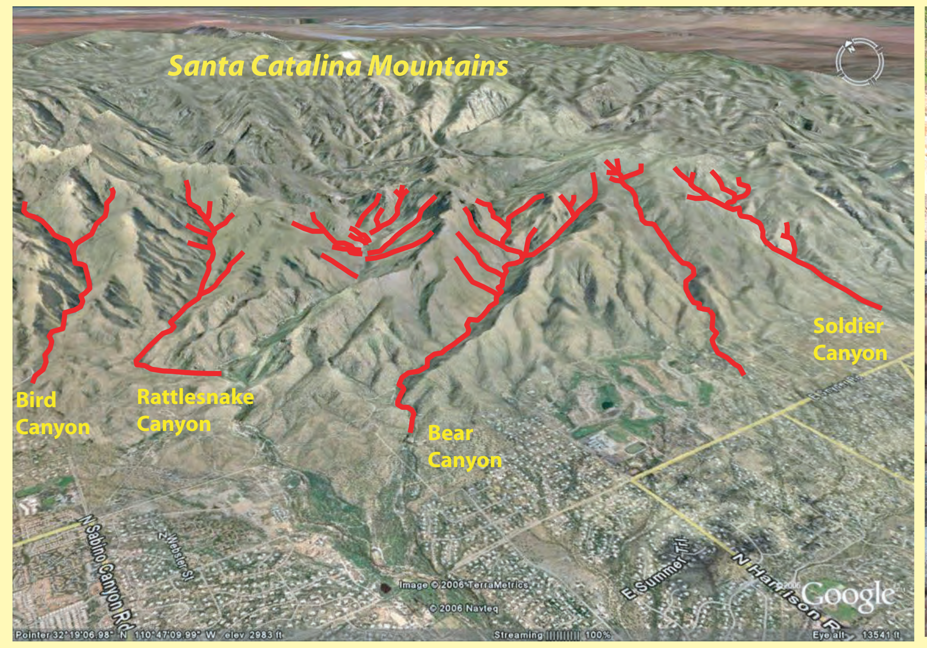

Figure 10. Debris flows traveled several miles down streambeds approaching or exiting the mountain front in five canyons.

Figure 11. Deposit of a debris-flow snout in Rattlesnake Canyon.

6) The Aspen Fire

In 2003, the Aspen Fire, the largest historical wildfire in the Santa Catalina Mountains, burned 85,000 acres of forest and shrubland on a mountain range that varies in elevation from 3,000-9,157 ft (Figure 9). Fire intensity was highest near the top of the range. On July 31, three years after the fire, 85% of the slope failures were either in unburned or low-intensity fire areas. Coupled with the conclusions of Cannon and Gartner [2005] that enhanced debris-flow potential on hillslopes impacted by forest fires decreases to pre-fire levels two years after the event, preliminary analyses suggest that debris-flow occurrence was not strongly related to the Aspen Fire. Instead, an extreme precipitation event, with a return period ranging from hundreds to about one thousand years, was responsible for the flooding and debris flows.

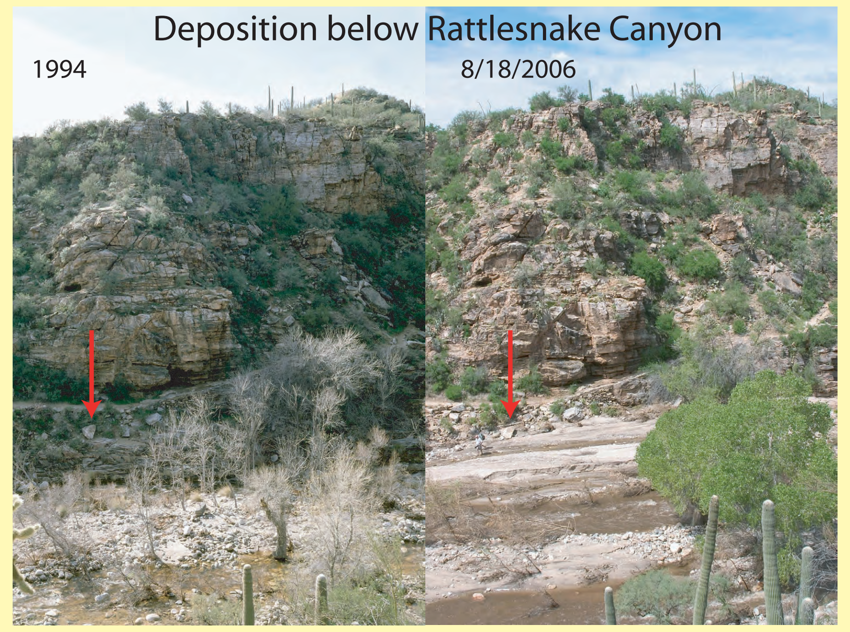

Figure 12. Net vertical aggradation of the Sabino Creek channel below its confluence with Rattlesnake Canyon was about 20 ft.

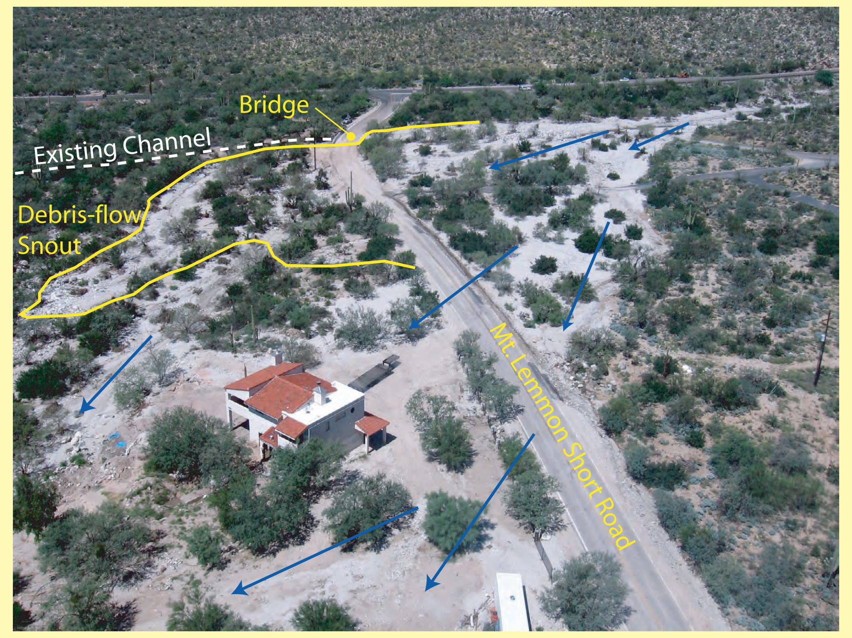

Figure 13. The debris flow in Soldier Canyon filled the existing channel near the Mt. Lemmon Short Road bridge and caused sheet flow

Acknowledgements

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