Western Region Technical Attachment
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Evaluation of Post-Burn Hydrologic Recovery of a Small Mountainous Watershed: Upper Campo Bonito Wash in Southern Arizona

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I. Introduction

Research conducted on burned watersheds throughout the Rockies indicates hydrologic recovery to near pre-burn conditions within 3 to 5 years (Morris and Moses 1987, Martin and Moody 2001). This study looks at hydrologic recovery for a small basin in southern Arizona (Figure 1). Two significant flow events are studied in the Campo Bonito watershed. The initial event occurred during the summer immediately following the fires. This event was first documented in National Weather Service (NWS) Western Region Technical Attachment 03-10 (Schaffner 2003). The second event occurred two years later in 2005.

This work builds upon the 2003 technical attachment. Improvements include GIS analysis of burn severity, a more detailed look at rainfall frequency, and topographic influence on peak discharge.

II. Watershed Description

Campo Bonito is a 1.5 square mile watershed located on the northeast flank of the Santa Catalina Mountains (Figure 2). The upper portion of the basin will be evaluated for watershed recovery (Figure 3). The Oracle Hill Fire burned about 40% of the upper basin in 2002: the Aspen Fire burned the other 60% in 2003 (Figure 4). Burn severity was 42% high, 38% moderate, and 20% low/unburned. The contributing area of the basin burned by the Oracle Hill Fire was slightly lower in mean basin elevation and basin relief ratio (i.e. less steep) than the contributing area burned by the Aspen Fire (Table 1). The vegetation community of Campo Bonito watershed is primarily scrub oak, shrubs, and grasses.

Basin	Drainage Area (sq mi)	Mean Basin Elevation (feet)	Basin Relief Ratio
Upper Campo Bonito Basin	1.50	5,250	n/a
Oracle Hill Fire Contributing Area	0.60	5,170	0.08
Aspen Fire	0.90	5,310	0.17

Contributing Area			

Table 1: Topographic information for the upper Campo Bonito basin and its two fire burned contributing areas. Basin relief ratio is the basin relief divided by the total channel length.

III. Data Description

A. Rainfall Data

Rainfall data comes from several sources. The NWS WSR-88D KEMX radar located 46 miles to the south-southeast covers the area. Pima County Flood Control operates a rain gage on Oracle Ridge located 2 miles south-southwest of the watershed. The NWS has several rainfall observers located within or near the basin. One observer was located within the headwaters in the upper basin and another near the outlet of the lower basin (Figure 5).

Radar estimated rainfall data can be contaminated by hail during the summer convective season. As a result, the estimates are usually compared to rain gage data to see if the data is reasonable. If the comparison is reasonable, radar rainfall pixels that fall within the basin can be averaged to yield the basin average rainfall. If the radar rainfall differs significantly from rain gage data, rain gage data is relied upon assuming an adequate number of rainfall observations.

B. Discharge Data

The US Geological Survey (USGS) estimated the discharge from flow events in 2003 and 2005 using the slope-area method. The slope-area measurement makes use of the energy equation for computing streamflow. The energy equation makes use of the physical characteristics of the channel, water-surface elevations at time of peak discharge, and channel roughness coefficients. The data required for a slope-area measurement is obtained in a field survey of a reach of the channel. The survey includes the elevation and location of high-water marks corresponding to the peak stage, cross sections of the channel along the reach, and selection of a roughness coefficient.

C. Precipitation Frequency Data

Precipitation frequency was obtained using the NOAA Atlas 14 for Arizona:

http://hdsc.nws.noaa.gov/hdsc/pfds/sa/az_pfds.html

An areal estimate of precipitation frequency was used in this study (Table 2). A single point value for precipitation frequency can be misleading. Areal estimates of precipitation frequency incorporate the entire drainage area and not just one or two points where rainfall observations were taken. Areal estimates work best where basin size is small and the storm event covered the entire watershed with relatively uniform precipitation.

To make sure that the basin precipitation frequency is truly areal, the average precipitation frequency estimate (depth) over the basin typically has the appropriate Areal Reduction Factor (ARF) applied. ARFs show reductions approaching zero as the basin size decreases dramatically below 10 square miles (NWS Hydro-40 1984). As a result, an ARF was not applied due to the small basin size.

Average Recurrence Interval (years)	**30 min**	**45 min***	**60 min**	**120 min**
2	0.98	1.11	1.21	1.38
5	1.28	1.44	1.58	1.79
10	1.50	1.70	1.86	2.10
25	1.81	2.05	2.24	2.54
50	2.04	2.31	2.52	2.89
100	2.27	2.57	2.81	3.25

Table 2: Areal precipitation estimates from NOAA Atlas 14, Volume 1, Version 3 for upper Campo Bonito basin at a basin average elevation of 5,250 feet. * The 45 min precipitation frequency estimates were determined by logrithmic interpolation between 30 and 60 min values.

D. Flood Frequency Data

Return flows for upper Campo Bonito were calculated using the USGS National Flood Frequency program (NFF). NFF estimates magnitude and frequency of flood-peak discharges based on USGS developed and published regression equations for the United States (see http://water.usgs.gov/software/nff.html). NFF is a simple tool to obtain flood frequencies in non-regulated ungaged basins. A wide range of data from gaged basins of various drainage areas are used to develop the regression equations. The USGS Arizona Region 13 regression equation (that includes the study watershed) used basin data for watersheds as small as 0.01 square miles and as large as 1,782 square miles. Average standard error of 37% is assigned for a 10-year event for Region 13.

E. Hydrologic Recovery

Hydrologic recovery is a condition in which post-disturbance watershed response corresponds to pre-disturbance watershed response. It is assumed that a rainfall of a given rainfall frequency should yield the corresponding peak discharge of similar return period. In this case, a 10-year rainfall event falling on a pre-burn or fully recovered watershed should produce approximately the 10-year NFF discharge.

Hydrologic Recovery is computed using the following formula:

$$\Psi = 100\left(1 - \frac{Q_{current} - Q_{\Pr e-Burn}}{Q_{Post-Burn} - Q_{\Pr e-Burn}}\right)$$

Where:

Ψ = Hydrologic Recovery (%)
$Q_{Pre\text{-}Burn}$ = the pre-burn peak discharge (from NFF)
$Q_{Post\text{-}Burn}$ = the peak discharge (usually first occurrence) immediately following the burn
$Q_{Current}$ = the current or most recent discharge measurement

IV. August 14, 2003 Event

A. Rainfall

The August 14, 2003 event had a basin average rainfall of 1.51 inches within 30 minutes. Basin average rainfall was determined by averaging radar rainfall pixels that fell within the basin. A Pima County Flood Control rain gage located on Oracle Ridge 2 miles south-southwest of the basin headwaters recorded 1.54 inches. This rainfall report as well as one received further north in the town of Oracle from the NWS rainfall observer were in good agreement with radar estimates (Figure 6). This amounts to a 10-year 30-minute rainfall frequency. No rainfall reports were received within the basin since rainfall observers had not yet been established.

B. Discharge

The USGS documented the event by performing a slope-area measurement at the upper reach. USGS reported 1,900 cfs +/- 20%. This amounts to at least a 100-year pre-burn flow event (Table 3).

Return Period	Pre-Burn Return Flow
2-year	155 cfs
5-year	375 cfs
10-year	585 cfs
25-year	935 cfs
50-year	1,240 cfs
100-year	1,640 cfs
500-year	2,750 cfs

Table 3: Return flows for upper Campo Bonito watershed using the USGS National Flood Frequency Program methodology for Southern Arizona Region 13 for a drainage basin size of 1.5 square miles.

V. September 1, 2005 Event

A. Rainfall

Hail reports were received from storms that had developed earlier in the day in southern Arizona. Reports varied from three-quarter inch to near golf ball-sized. As a result, radar rainfall estimates were likely overestimated (Figure 7).

Initial storm development began with a small cell that persisted from 11:45 AM MST to 12:45 PM MST. The Pima County Flood Control gage on Oracle Ridge recoded 0.39 inches. It is assumed that this rainfall helped to satisfy soil storage requirements and did not produce significant in-channel flow. From 1:08 PM MST to 1:52 PM MST, a cell merger occurred over the watershed and produced 1.93 inches according to the gage on Oracle Ridge. Of this 45-minute amount, 1.61 inches fell within 30 minutes. A NWS rainfall observer at High Jinks Ranch reported 2.02 inches for the entire event and 1.83 inches over a 45-minute timeframe. A NWS rainfall observer near the outlet of the lower watershed recorded a storm total precipitation of 1.80 inches.

Assuming that the rainfall rate recorded at the Oracle Ridge gage was representative of the entire watershed, rainfall amounts for timeframes less than those recorded at the two NWS rainfall-reporting sites and across the basin as a whole can be extrapolated. Basin average precipitation values for this event and the corresponding basin average areal precipitation frequency can be found in Table 4. Although this was a longer duration storm than in August 14, 2003, the 30-minute precipitation totals were nearly identical.

Timeframe of Rainfall (minutes)	Basin average rainfall (inches)	Average Recurrence Interval (years)
120	2.05	9
45	1.85	15
30	1.51	10

Table 4: Basin average rainfall values and average recurrence intervals for 30, 45, and 120-minute rainfall durations on September 1, 2005.

B. Discharge

USGS documented peak discharge by performing another slope-area measurement at the same reach as the 2003 slope-area for the upper basin. USGS reported 680 cfs +/- 20%. Both this highwater mark and that from the 2003 flow event were well preserved (Figure 8). Another new highwater mark was evident 0.5 feet below the 2005 highwater mark. The USGS reported 520 cfs +/- 20% for this second peak. The second peak was preserved in many, but not all cross sections. It was preserved best on the left bank in gently sloping grass-covered slopes.

C. Dual Hydrograph Signals

The origin of the second peak in 2005 was likely due to different source areas within the basin. The basic idea is that different source areas create unique hydrograph signals (i.e. peaks). The literature has examples of double peaks where there is an urban component to the watershed. Sheeder, et. al. (2002) examined dual urban and rural hydrograph signals in small watersheds. The percent of urban component was directly related to the size of the respective urban-component peak. For burn areas, they function analogous to impervious urban areas due to their hydrophobic soils and reduced ground vegetation.

The larger first peak for the 2005 event likely originated from the Aspen Fire contributing area and the second smaller peak for the 2005 event likely originated from the Oracle Hill Fire contributing area. The area burned by the Aspen Fire is about 1.5 times larger than that burned by the Oracle Hill Fire. Additionally, the Aspen Fire's basin has had one less year to recover, has a basin relief ratio twice as steep as the Oracle Hill burn area, has a slightly greater mean basin elevation, and has a higher maximum topographic point.

In August 2002, only one flow peak was observed. Since the Aspen Fire was only two months old and the Oracle Hill burn area only had one year to recover, both burn areas contributed significant quantities of water to produce the 1,900 cfs peak flow.

The second peak does not appear to be storm dependent. The small size of the watershed, relatively equal distribution of rainfall, and no preferred direction of storm motion support this.

VI. Conclusions

Based on the peak of 680 cfs, the upper Campo Bonito watershed had 93% percent recovery between the 2003 and 2005 event.

$$Hydrologic\,Recovery = 100\left(1 - \frac{680cfs - 585cfs}{1900cfs - 585cfs}\right) = 93\%$$

It is believed that upon full recovery, a 10-year rainfall event, such as was observed on September 1, 2005, should produce a flow of 585 cfs. If the second peak had occurred simultaneously with the first peak, then only 53% hydrologic watershed recovery would have occurred. This represents the least possible recovery. The peaks coinciding would have produced approximately 1,200 cfs that is in the range of a 50-year pre-burn return flow.

Based on the peak of 680 cfs alone, hydrologic watershed recovery at upper Campo Bonito was nearly complete after two full growing seasons and three winters for the Aspen Fire and three full growing seasons and four winters for the Oracle Hill Fire. This recovery time period is consistent with other researched burn areas in the semi-arid west. Pierson, et. al. (2003) found that after two growing seasons and three winters on the Denio Fire, Nevada that 50% vegetation and litter ground cover had returned after 95% ground cover removal immediately following the fire. This amounts to 80% recovery based on 60% ground cover that was cited as adequate to gauge hydrologic protection of a site. Canfield (2005) found that modeled hillslope roughness (a primary factor in accounting for hillslope runoff from burned basins) returned to forested conditions at Starmer Canyon, Los Alamos, New Mexico three years later.

Recovery to this point in the Campo Bonito watershed was likely due to growth of grasses that helped to breakup hydrophobic soils, increased surface roughness, and intercepted a percentage of rainfall. Full recovery of the watershed will likely require growth of higher order ground cover (i.e. shrubs and trees) other than grasses. As a result, remaining recovery is likely to transpire over a slower rate.

Hydrologic recovery does occur. At some point after a burn, conditions do return to what approximates pre-burn hydrologic conditions. At that point, extra vigilance is no longer needed on the part of NWS forecast staff. Burn-specific flash flood guidance thresholds can be returned to standard flash flood guidance. It should be emphasized that since the Campo Bonito watershed has not fully recovered; some degree of added vigilance is still needed.

One area requiring further study is that upon 100% recovery of the Aspen Fire burn area, will the watershed produce a single peak. The authors speculate that the dual hydrograph signal will disappear upon full recovery.

Acknowledgements

Special thanks to the USGS for performing slope-area measurements at Campo Bonito in August 2003 and September 2005. To Jeff Phillips of the USGS and Ann Youberg of the Arizona Geological Survey for their review comments. WFO Tucson Science and Operations Officer Erik Pytlak for reviewing the final paper. Barry Scott from Arizona Division of Emergency Management for GIS analysis of drainage area and burn severity. Pima County Flood Control for operating the Oracle Hill rain gage and the NWS rainfall observers in the Oracle and Campo Bonito area.

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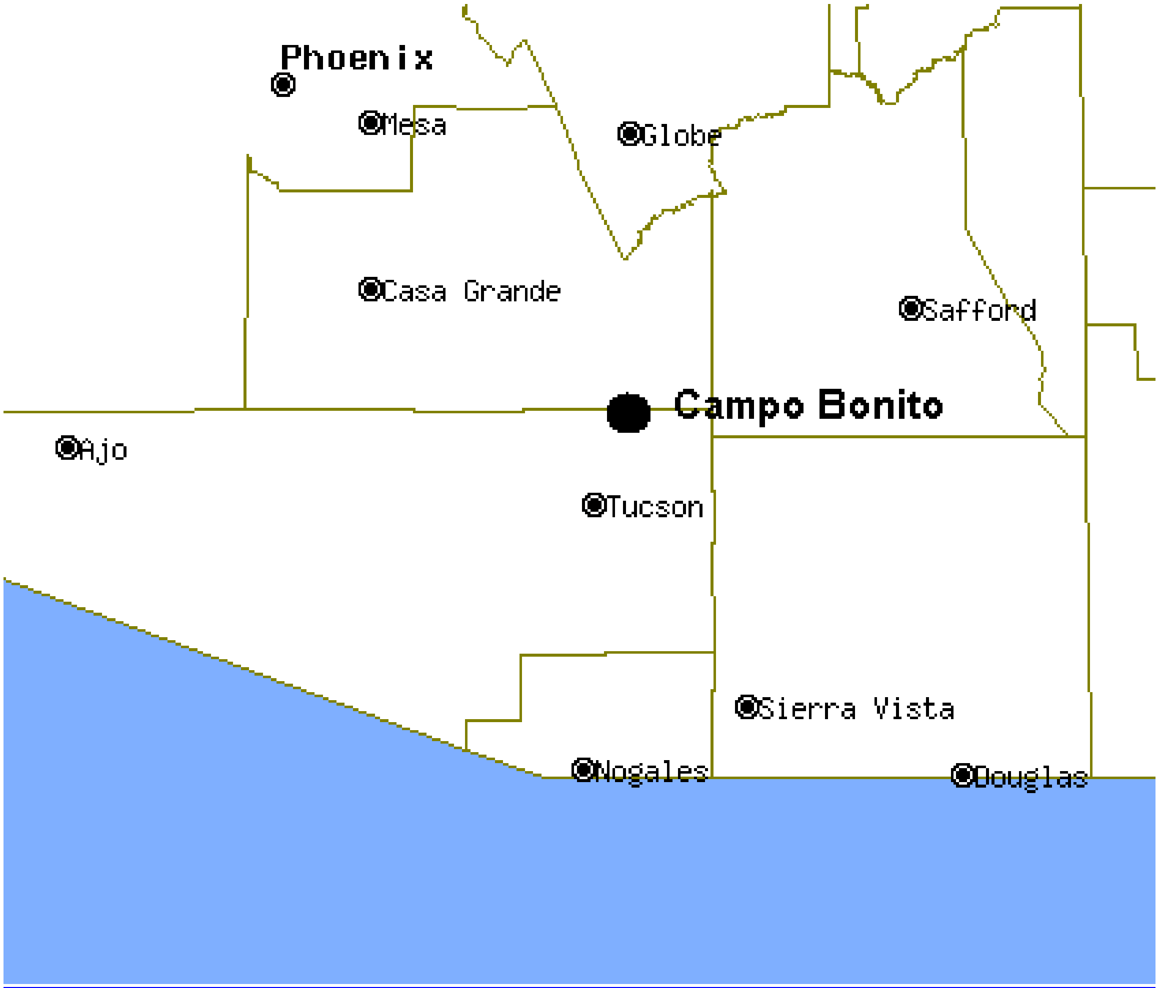

Figure 1: Location map of Campo Bonito watershed. Map modified from U.S. Census Bureau Tiger Map Server: http://tiger.census.gov/cgi-bin/mapbrowse-tbl

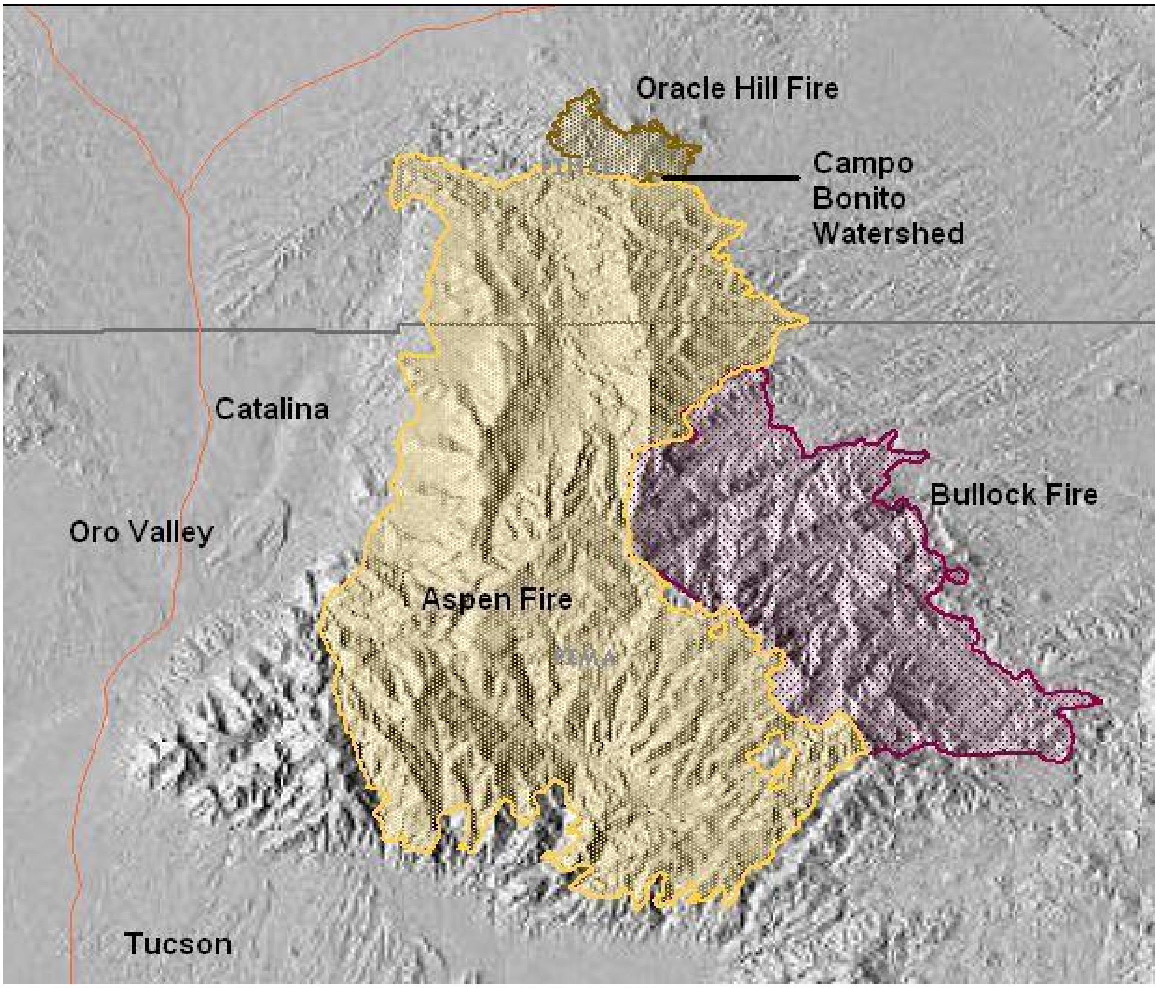

Figure 2: Hillshade image of Santa Catalina Mountains overlaid with shapefiles from 2002 Oracle Hill and Bullock fires and 2003 Aspen Fire. Line pointing to location of Campo Bonito watershed. Original image courtesy of Pima County Flood Control District. Scale is one inch equals 4 miles.

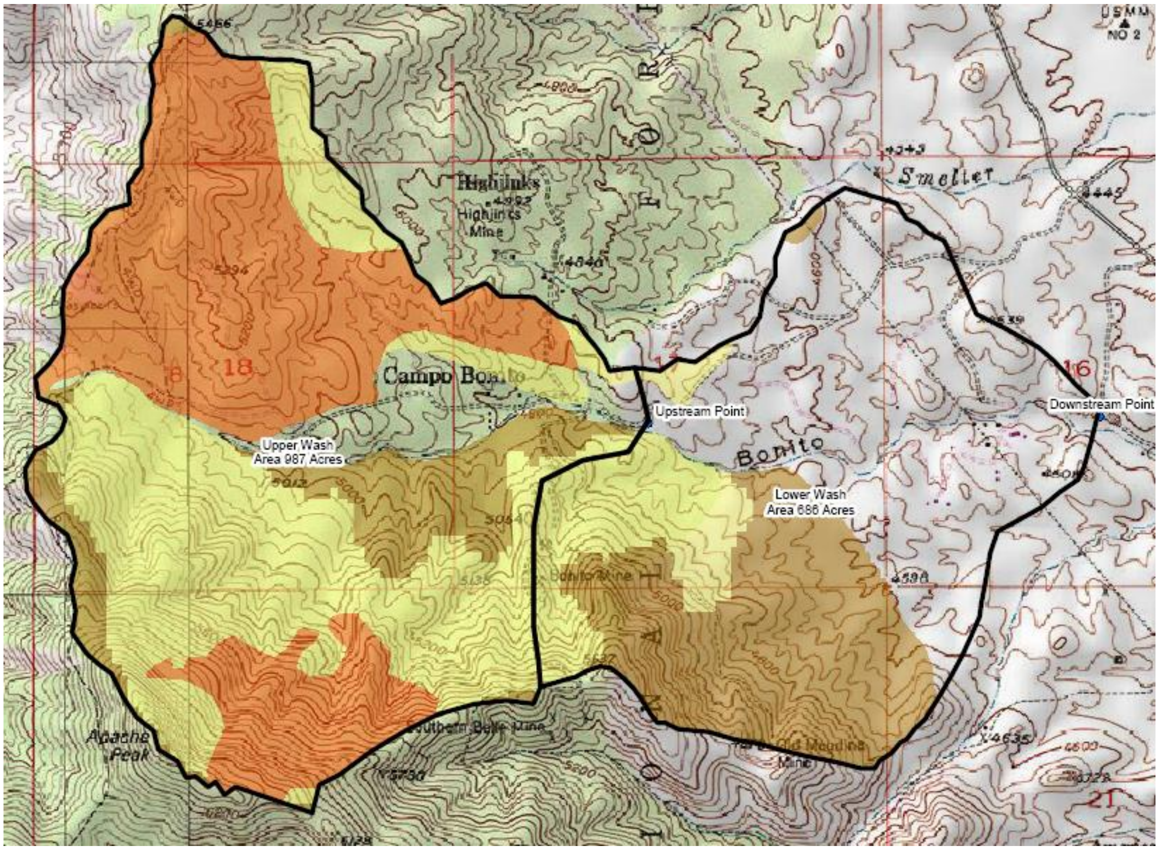

Figure 3: Map of Campo Bonito watershed prepared by AZ Division of Emergency Management. The study watershed of 1.50 square miles is labeled Upper Wash in the image. Burn severity data provided by Coronado National Forest. High burn severity in orange, moderate burn severity in yellow, and low burn severity in brown. Scale is one inch equals 0.33 miles.

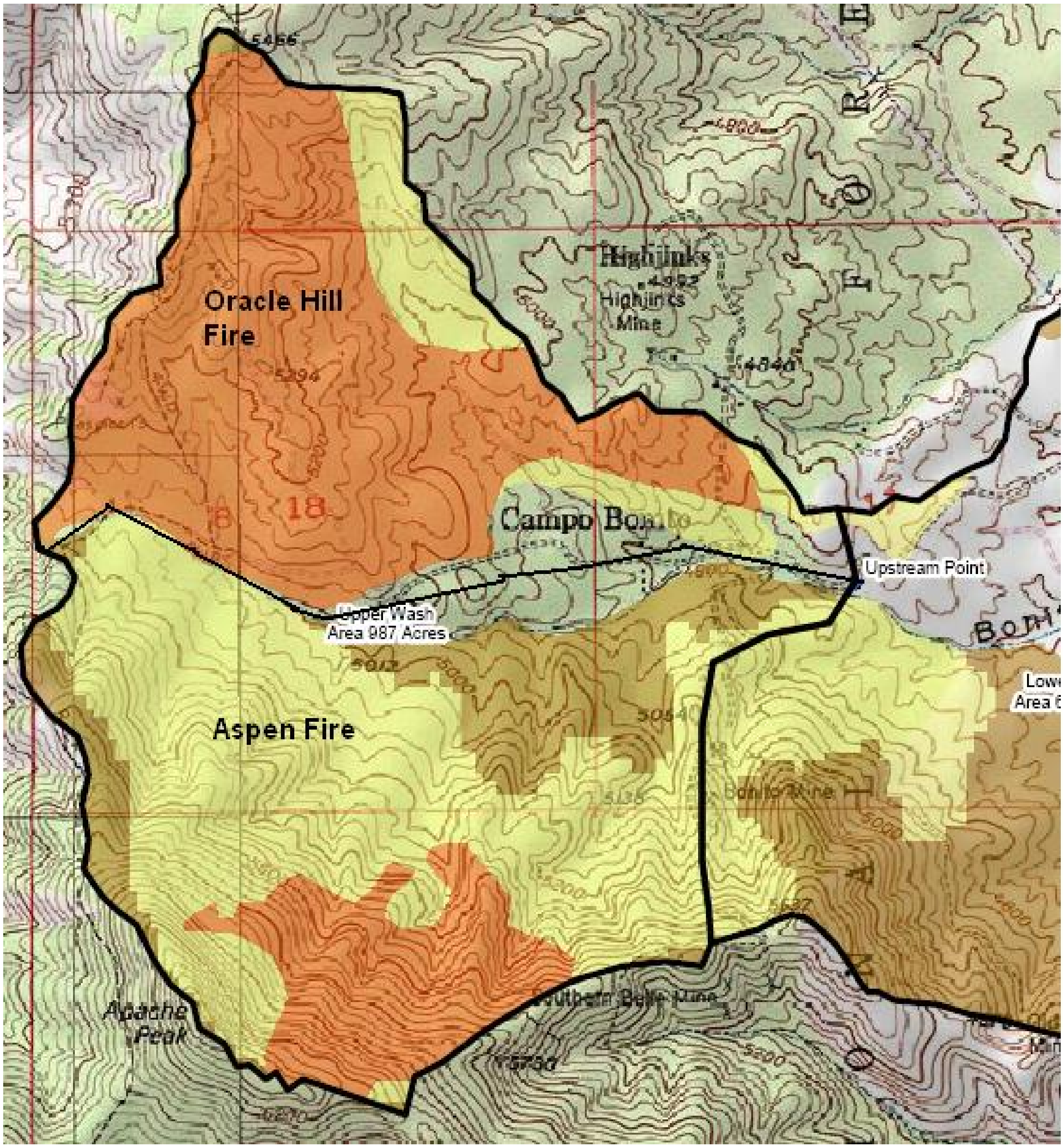

Figure 4: Upper Campo Bonito watershed with Oracle Hill Fire and Aspen Fire contributing areas displayed. Oracle Hill fire is from 2002 and the Aspen Fire is from 2003. Scale is one inch equals 0.25 miles.

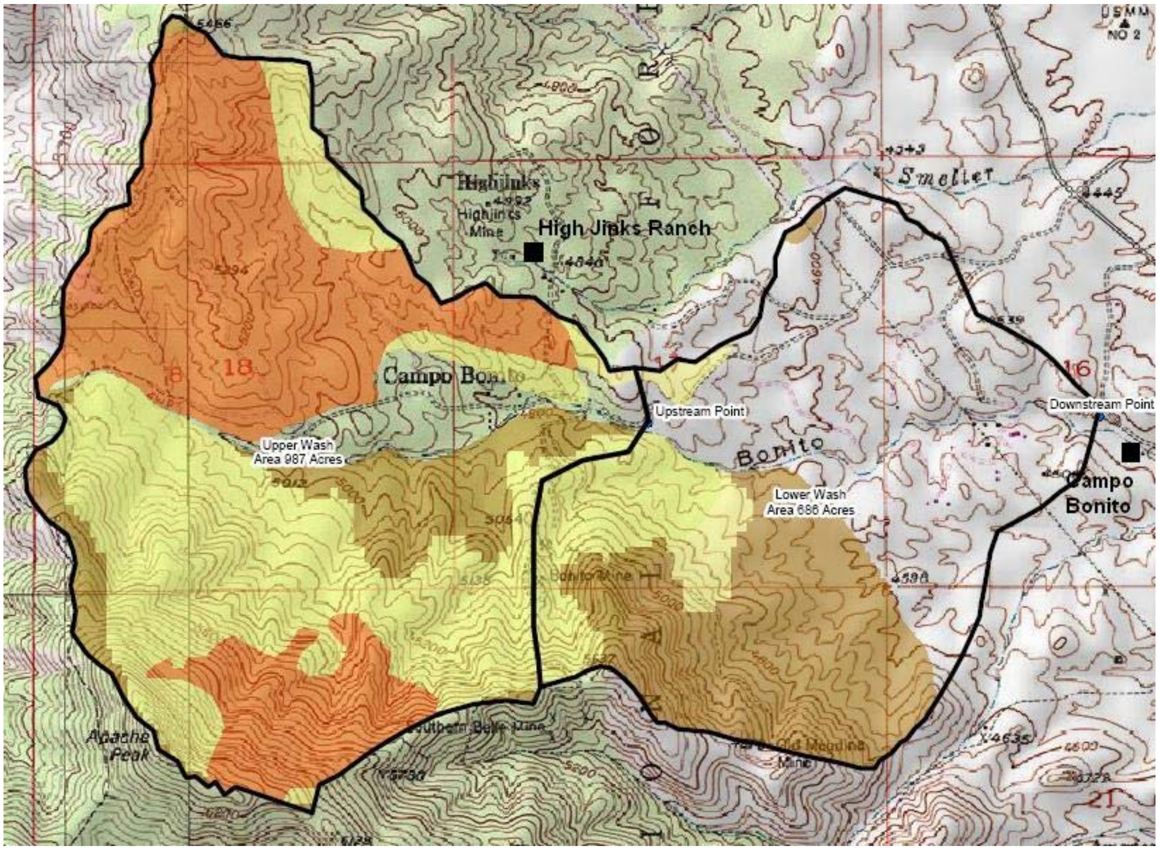

Figure 5: Campo Bonito watershed with locations of NWS rainfall observers at Hi Jinks Ranch and Campo Bonito. Scale is one inch equals 0.33 miles.

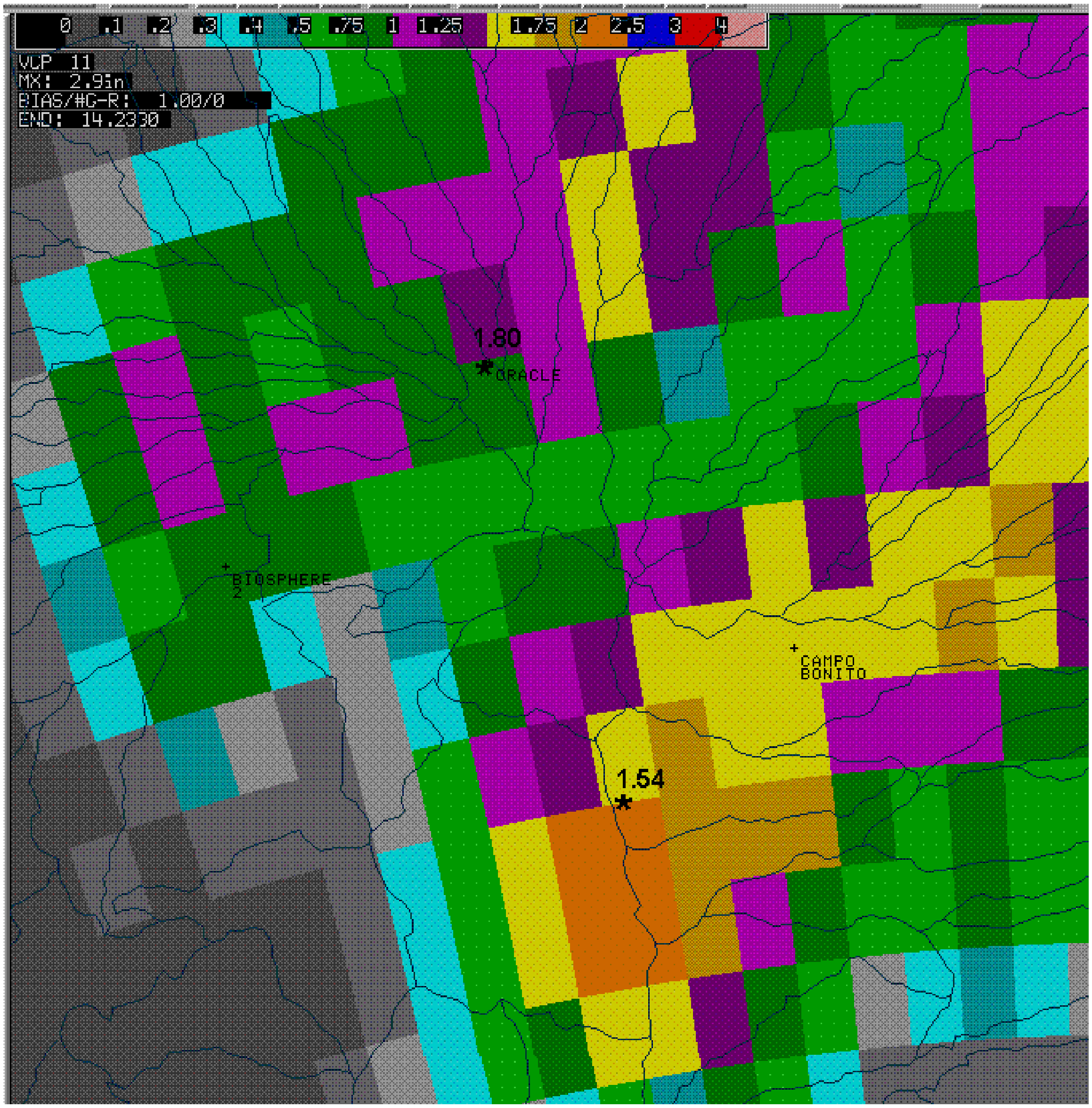

Figure 6: KEMX one-hour precipitation estimate for August 14, 2003 ending at 4:28 PM MST. Overlaid with storm total precipitation values from Oracle Ridge Pima County Flood Control gage (1.54 inches) and Oracle NWS rainfall observer (1.80 inches).

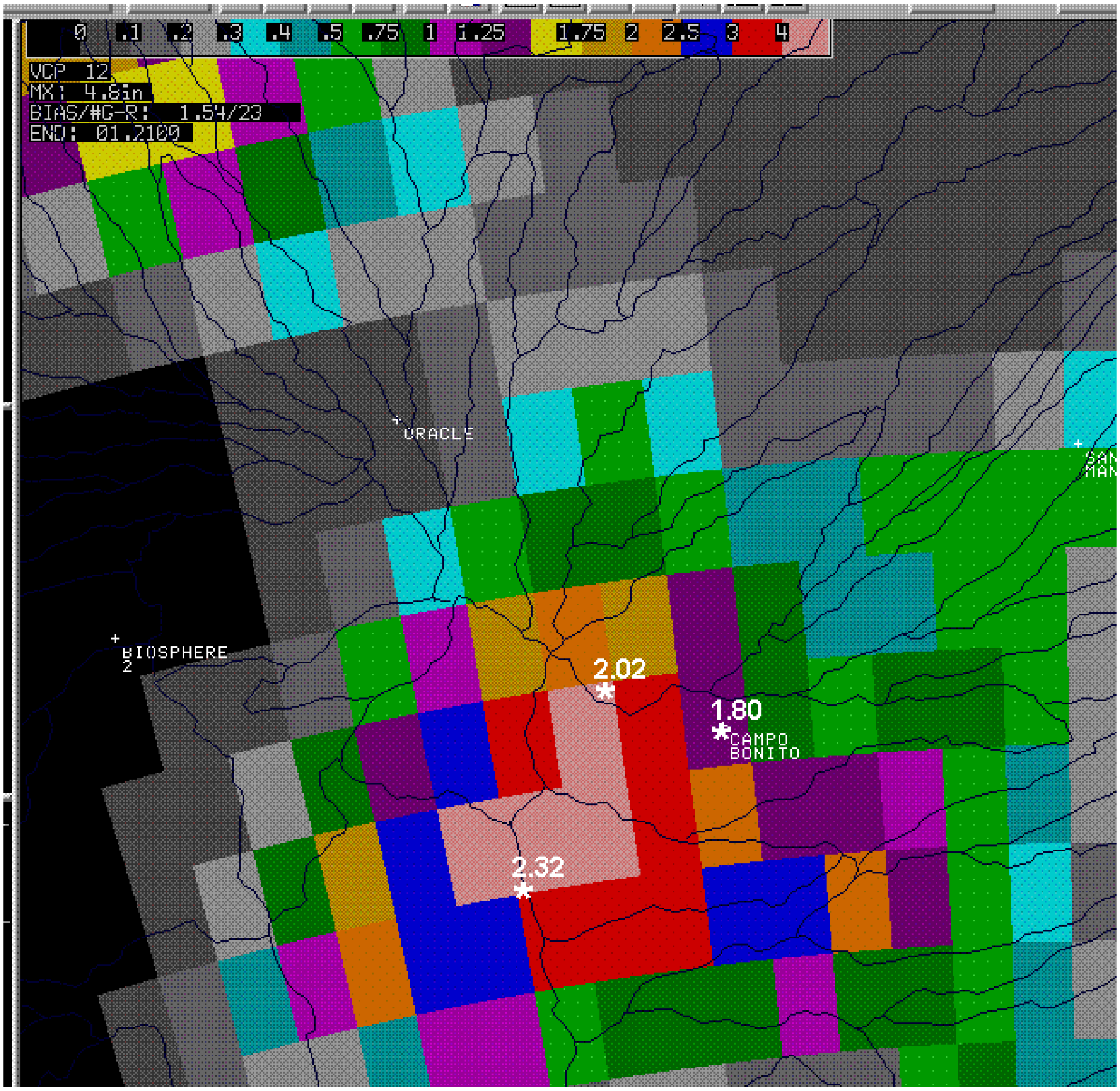

Figure 7: KEMX three-hour precipitation estimate for September 1, 2005 ending at 2:00 PM MST. Overlaid with storm total precipitation values from Oracle Ridge Pima County Flood Control gage (2.32 inches), Hi Jinks Ranch NWS rainfall observer (2.02 inches), and Campo Bonito NWS rainfall observer (1.80 inches).

Figure 8: Image of slope-area reach taken by USGS on September 15, 2005. Image is looking upstream from left bank. Standing on the August 14, 2003 highwater mark is the author on the upper right-hand corner of the picture. Standing on the September 1, 2005 highwater mark is Ann Youberg from the Arizona Geological Survey. Highwater mark from the second peak on September 1st is located about a half foot below Ann.