Effects of Wildfire in the Mountainous Terrain of Southeast Arizona: Post-Burn Hydrologic Response of Nine Watersheds

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ABSTRACT:

This paper documents the hydrologic response of nine watersheds in Southeast Arizona within the first two years of a wildfire. These watersheds are within the forested steep terrain of the Santa Catalina and Pinaleno Mountains. Frequent flash floods and occasional debris flows occurred. A few of the flash floods were particularly severe resulting in one fatality, several evacuations of flood prone areas, and the destruction of four stream gaging sites. Post-burn flows were 1.3 to 6.5 times pre-burn flows in the Santa Catalina Mountains. Post-burn flows in the Pinaleno Mountains, where the average channel gradients are 2 to 3 times steeper, were 27 to 154 times pre-burn flows.

1. INTRODUCTION

Southeast Arizona has been impacted by several large wildfires. These include the Oracle Hill Fire (2002), Bullock Fire (2002), and Aspen Fire (2003) on the Santa Catalina Mountains (figure 1) and the Nuttall Fire (2004) on the Pinaleno Mountains (figure 2). After these wildfires, significantly increased runoff from the burn areas has occurred. Rainfall amounts and intensities that normally would have caused little if any flooding now have the potential to produce dangerous flash floods.

In Southeast Arizona there are over a dozen mountain ranges. Each range is unique and exhibits its own complex terrain and geomorphologic diversity. This paper documents the hydrologic response of nine watersheds in Southeast Arizona within the first two years after the occurrence of wildfire.

2. METHODS

Basin average precipitation used in this paper was obtained by taking an aerial pixel average from the NWS WSR-88D radar located on Empire Mountain to the southeast of Tucson, AZ. Due to limitations with radar precipitation estimation, rain gauges located within each basin were used to "ground truth" these values. All rainfall amounts reported are basin average precipitation obtained from radar unless referenced to a particular rain gauge.

Burn severity percentages for each basin were obtained:

1) from GIS analysis by Barry Scott of Arizona Division of Emergency Management (AZ DEM) using U.S. Forest Service data for Campo Bonito, Cañada del Oro Wash, Frye Creek, Deadman Canyon, Marijilda Canyon, Noon Creek, and Wet Canyon;
2) using gridded overlay analysis for Alder Canyon;
3) estimated by U.S. Forest Service for Sabino Creek (Personal communication, Coronado National Forest, Robert Lefevre, September 23, 2004)

The pre-burn return flows used in this paper where obtained:

1) (when available) from USGS Water-Resources Investigations Report 98-4225 (Pope, G., et. al., 1998);
2) using a multiplier (basin size ratio) times reported values for a similar or downstream site;
3) using the method in USGS Water-Supply Paper 2433 (Thomas, B., et. al., 1997); or
4) using the USGS National Flood Frequency Program software (Ries and Crouse, 2002).

The post-burn return flows were obtained from the pre-burn return flows; after a multiplier was determined from an evaluation of the post-burn flood events documented in Sections 3 and 4 of this report.

Antecedent precipitation was not considered. For recent burns (e.g. 1 to 2 years following wildfire), water repellent soils are intact. Dyrness (1976) found that recovery of water repellent soils is not noticeable until the 3rd year and some degree of water repellency persisted until the 5th year. All events evaluated by the authors were within 15 months of their respective burns. The wettable layer is confined to the surface of the soil. The wettable layer is typically 1 to 2 inches thick (Bashir, 1969). In rare cases the wettable layer can be up to 6 inches thick. Such thin wettable layers typically are of limited consequence when evaluating the rainfall-runoff process. Under such circumstances, all rainfall can be considered in excess of soil moisture requirements. In addition, no significant precipitation fell on the study watersheds in the 24 hours prior to the event.

3. SANTA CATALINA MOUNTAINS

Campo Bonito

On August 14, 2003, a rainfall event and resultant flash flood occurred on the upper Campo Bonito watershed (figure 3). The upstream site drains a 1.5 square mile watershed, has a mean basin elevation of 5,600 feet, and contains 42% high severity and 38% moderate severity burn. The peak discharge was estimated, by the USGS using the slope area method, at 1,900 cfs +/- 20%. This equates to a 100-year pre-burn flood. This amounts to a burn area post-burn runoff 2.5 times greater than runoff during pre-burn conditions (table 1).

Further details on the watershed, flash flood event, and USGS slope area measurement can be found in a NWS Western Region Technical Attachment entitled *The Campo Bonito Wash Flash Flood of August 14, 2003: A Heavy Rain Event on a Recent Burn* (Schaffner, 2003).

Sabino Creek near Mount Lemmon

On August 7, 2003, 1.25 inches fell within an hour in the Sabino Creek near Mount Lemmon watershed. This is a 3.4 square mile watershed with a mean basin elevation of 7,900 feet, which is estimated to contain 30% high severity and 25% moderate severity burn. Unlike other burn area watersheds in southeast Arizona which are mostly undeveloped, Sabino Creek contains the community of Summerhaven. This community is composed of several hundred summer homes and cabins. A Pima County Flood Control ALERT stream gauge located on Sabino Creek near Mt. Lemmon recorded 350 cfs. This was a former USGS stream-gaging site (table 2). According to the NOAA Atlas 14 (2004), the rainfall had a frequency of a 2-year one-hour event. The resultant flash flood equates to approximately a 10-year pre-burn flood. This amounts to a burn area post-burn runoff 3 times greater than runoff during pre-burn conditions.

Cañada del Oro Wash near Coronado Camp

On July 23, 2004, 1.14 inches fell within an hour in the Cañada del Oro near Coronado Camp watershed (figure 4). This is a 21.6 square mile watershed with a mean basin elevation of 6,675 feet, which contains 56% high severity and 19% moderate severity burn. A Pima County Flood Control ALERT stream gauge located on Cañada del Oro near Coronado Camp recorded 1,450 cfs (table 3). According to the NOAA Atlas 14 (2004), the rainfall had a frequency of a 2-year one-hour event. The resultant flash flood equates to approximately a 40-year pre-burn flood. This amounts to a burn area post-burn runoff 6.5 times greater than runoff during pre-burn conditions.

Alder Canyon near Ventana Windmill

Alder Canyon near Ventana Windmill is a 15 square mile watershed with a mean basin elevation of 5,980 feet. On July 29, 2003, 1.60 inches fell in about an hour. The authors conducted a slope conveyance along Alder Canyon near Ventana Windmill (figure 5). A slope conveyance is a simple indirect discharge measurement. Unlike a slope-area measurement where multiple cross sections are used, slope conveyance utilized one cross section and the slope of the channel. The survey was conducted on November 2, 2004. The peak flow was calculated as 3,103 cfs +/- 10 percent. According to the NOAA Atlas 14 (2004), the rainfall had a frequency of a 5-year one-hour event. The resultant flash flood equates to approximately a 25-year pre-burn flood (table 4). This amounts to a burn area post-burn runoff 2.5 times greater than runoff during pre-burn conditions.

4. PINALENO MOUNTAINS

During late June and early July 2004, the Nuttall and Gibson Fires began on the Pinaleno Mountains in Graham County. They merged into what is known as the Nuttall Complex Fire that burned 29,725 acres (table 5). The Nuttall Complex burned the majority of four watersheds (figure 6) and the upper reach of Wet Canyon south of Noon Creek. All of these are relatively small watersheds and are located on a northward facing flank of the Pinaleno Mountains. Burn severity is a patchwork with moderate burn severity dominating (table 6).

Frye Creek

Frye Creek is a 4.02 square mile watershed with a USGS stream gauge situated at an elevation of 5,580 feet (figure 7 and 8). It has a mean basin elevation of 8,400 feet. Close to its headwaters is an automated rain gauge at Emerald Park situated at an elevation of 10,350 feet. Events occurred on July 27, 2004, August 4, 2004, and August 17, 2004 (table 7). These events were characterized by a significant amount of debris entrainment and characteristic dark grey to black color from ash (figure 9 and 10). Analysis of precipitation frequencies for each event in comparison to USGS return flows shows that events with rather typical precipitation frequencies are capable of producing significant return flows many orders of magnitude greater than would have been expected in pre-burn conditions (table 8 and 9).

Post-burn peak discharge increase was computed by dividing the peak flow for each event by the USGS return flow for the basin average precipitation frequency for each event. The 5-year post-burn flood is estimate to be > 6,264 cfs---perhaps as high as 8,700 cfs---using the July 27 event; 4,640 cfs using the August 4 event, and 1,508 cfs using the August 17 event. The July 27th event likely reflects the extreme flow possible from the first flush after a burn.

Deadman Canyon

Deadman Canyon is a 4.78 square mile watershed with a discontinued USGS stream gauge situated at an elevation of 4,950 feet (figure 11 and 12). It has a mean basin elevation of 7,500 feet. The site was reoccupied as an ALERT stream and rain gauge following the fires.

On August 17, 2004, 1.00 inch basin average precipitation fell within about 30 minutes on the Deadman Canyon watershed upstream from the USGS site. The rain gauge at Deadman Canyon reported 1.64 inches within 21 minutes. The resultant flash flood destroyed the USGS stilling well and the ALERT gauge (figure 13). High water marks were at least 8 feet high (Personal communication, JE Fuller Hydrology, Brian Iserman, October 25, 2004). Based on the old USGS rating for the site, this would amount to a flow of 5,000-5,500 cfs. Such a flow would be in the range of a 300-year return flow (table 10). Basin average precipitation frequency for Deadman Canyon amounts to 3-year event. This is a post-burn peak discharge increase of at least 75 times greater than pre-burn peak discharge.

Marijilda Canyon

Marijilda Canyon is an 11.00 square mile watershed with a discontinued USGS stream gauge site situated at an elevation of 4,400 feet (figure 14). It has a mean basin elevation of 6,500 feet. An ALERT stream and rain gauge was placed several hundred feet downstream of this site following the fires. An ALERT rain gauge was placed in the headwaters at Pinaleno Park situated at an elevation of 10,117 feet.

On August 17, 2004, 1.25 inch basin average precipitation fell on the Marijilda Canyon watershed within about 30 minutes. The rain gauge at Marijilda Canyon reported 1.16 inches within 41 minutes. The rain gauge at Pinaleno Park reported 0.24 inches in 32 minutes. The resultant flash flood damaged the ALERT stream gauge pressure transducer.

Shortly after the flash flood event, NWS Tucson partnered with the USGS to perform a slope-area measurement. Slope-area is an indirect discharge measurement used by the USGS when it is impractical to directly measure peak discharge. Slope-area has been used before, by the USGS, to document post-burn flow events in southeast Arizona (Schaffner, 2003). The slope-area reach was located a quarter mile downstream from the ALERT gauge at an elevation of 4,200 feet (figure 15).

The drainage area is approximately the same since ridges border the canyon on either side with no significant tributaries in between. The reach selected was about 300 feet long and contained five surveyed cross-sections. The channel is steep and rocky with 15 to 20 feet of fall within it. Numerous trees were bent over by the force of the flow. Several trees withheld and collected debris. At least one tree was removed by flood waters. Only the stump remains. High water marks were generally well defined by debris. The main channel contained 8 to 10 feet water depth. An overflow channel on right bank was up to three feet deep. Those cross sections that had both main channel and an overflow channel were subdivided. Another quarter mile downstream from the slope-area reach, an impressive pile of boulders was seen (figure 16). In the same area, large debris piles were noticed.

Slope-area results indicate a peak discharge between 8,470 cfs +/- 20% (Written communication from USGS, (Tadayon 2004)). Being conservative, the flow would be a minimum of a pre-burn 100-year event (table 11). Basin average precipitation frequency for Marijilda Canyon amounts to 5-year event. This is a post-burn peak discharge increase of at least 27 times greater than pre-burn peak discharge.

Noon Creek

Noon Creek is a 2.99 square mile watershed with an ALERT stream gauge situated at an elevation of 5,202 feet (figure 17). It has a mean basin elevation of 7500 feet. The ALERT site is located along Highway 366 where two 8-foot diameter culverts convey flow under the road (figure 18). A rain gauge is located at Noon Creek as is another one at Heliograph Peak near the headwaters.

On August 3, 2004, 0.69 inch basin average precipitation fell on the Noon Creek watershed within about 30 minutes. The rain gauge at Noon Creek reported 0.48 inches within 26 minutes. The resultant flash flood overtopped the highway leaving behind several large logs.

On August 17, 2004, 0.94 inch basin average precipitation fell on the Noon Creek watershed within about 30 minutes. The rain gauge at Noon Creek reported 0.92 inches within 25 minutes. The resultant flash flood overtopped the highway leaving behind debris and roadway damage. Overtopping of the highway, with significant debris left behind, would have resulted from a flow of 1,400 cfs +/- 25% (Personal communication, JE Fuller Hydrology, Brian Iserman, September 1, 2004). Such a flow would be in the range of a 100-year return flow (table 12).

On October 26, 2004, 0.30 inch basin average precipitation fell over a period of about an hour. The rain gauge at Noon Creek reported 0.28 inches over an hour and 20 minutes. The resultant flow was 137 cfs according to the rating table developed for the site by JE Fuller Hydrology. This amounted to 2 feet of flow through the highway culverts. Base flow for the event was in the range of 50 cfs.

Basin average precipitation frequency for Noon Creek amounts to 1-year and a 2-year event for August 3rd and 17th respectively. This is a post-burn peak discharge increase of at least 55 times using the August 17th event.

Wet Canyon

Wet Canyon is a 1.57 square mile watershed where it crosses Highway 366 at an elevation of 6,170 feet (figure 19). On August 17, 2004, 0.80 inch basin average precipitation fell in about an hour. On November 4, 2004, the authors conducted a slope conveyance where Wet Canyon crosses Highway 366. The peak flow for the August event was calculated as 1,490 cfs +/- 10 percent. Such a flow would be in the range of a 100-year return flow (table 13). Basin average precipitation frequency for Wet Canyon event amounts to a 2-year event. This is a post-burn peak discharge increase of at least 146 times greater than pre-burn peak discharge.

5. ROLE OF MOUNTAINOUS TERRAIN

Other than the obvious factors in peak discharge generation from burn areas, such as burn severity, basin size, rainfall amount and intensity, terrain can play a key role. A review of the hydrologic responses documented in this study indicates that channel gradient is a geomorphologic indicator of peak discharge in mountainous terrain. In general, peak discharge will tend to increase as channel gradient increases. An increase in channel gradient results in decreased time of concentration and less infiltration. Post-burn flows originating from the Pinaleno Mountains had greater increases in runoff than those observed in the Santa Catalina Mountains. This is likely due to significant differences in the channel gradient (table 14). The difference between individual basins and between mountain ranges is illustrated in graph 1. The Santa Catalina Mountains have an average post-burn basin response 3.8 times greater than pre-burn conditions. The Pinaleno Mountains have an average post-burn basin response 77.2 times greater than pre-burn conditions. The Santa Catalina Mountains have values similar to those reported by Reed (2002) for the White Mountains in Arizona and the Pinaleno Mountains have values similar to those reported by Jack E. Veenhuis, U.S. Geological Survey for the Jemez Mountains in New Mexico (Veenhuis, 2002).

Mean basin elevation is also an important variable for mountainous terrain. In addition to being an indicator of rainfall variability and local climate, mean basin elevation in mountainous terrain is indirectly an indication of vegetation coverage and type (Brown, 1982); and perhaps to a lesser degree, of soil depth and type.

6. CONCLUSIONS AND DISCUSSION

Rainfall events, with rather common precipitation frequencies, tend to produce post-burn peak flows that are at a minimum several orders of magnitude greater than what they would have been in pre-burn conditions. This was observed in various watersheds in the Santa Catalina Mountains. When comparing watersheds in the Santa Catalina Mountains with those in the Pinaleno Mountains, they are quite similar in terms of mean basin elevation and vegetation type. They differ in that average channel gradients are 2 to 3 times greater for the watersheds in the Pinaleno Mountains. This has produced post-burn flows originating from the Pinaleno Mountains 5 to 18 times greater than those of the Santa Catalina Mountains (graph 1).

Burn areas yield an increase in debris and sediment as compared to pre-burn conditions (Robichuad, 2000). This study and its associated indirect discharge measurements do not take into account added bulking of the flow.

The authors have prepared a second paper providing an empirical formula to estimate peak discharge from small watersheds during burn recovery. The resultant equations use the hydrologic responses of the nine watersheds documented here. These equations (envelope curve and best-fit) seem to be representative of the conditions prevalent during the first two years of recovery; and therefore, are expected to be useful for initial post-burn planning. These equations are for small watersheds less than 25 square miles; and include, sites with mean basin elevations from 5600 to 8400 feet above mean sea level. After several tries to fit the data, the authors found that weighing the burned area heavily, in this case using the high and moderate burn area as the only contributing area (the hyper-effective drainage area), and using average channel gradient as an indicator of basin steepness provided a reasonable fit. Also, mean basin elevation was found to be useful for these post-burn equations; i.e., the R-square values improved when mean elevation data were used. This second paper will be submitted to Hydrologic Processes for publication in Spring 2005.

7. ACKNOWLEDGEMENTS

To the USGS for their conducting a slope-area measurement of Marijilda Canyon as well as providing preliminary flow information for Frye Creek. Special thanks to Arizona Division of Emergency Management, for their GIS analysis of the various watersheds in the Pinaleno Mountains and Santa Catalina Mountains. For USFS for providing burn severity shapefiles for the Nuttall Fire and burn severity estimates for Sabino Creek near Mount Lemmon watershed. Helpful comments provided by Dave Brandon, Steve Shumate, and Kevin Werner.

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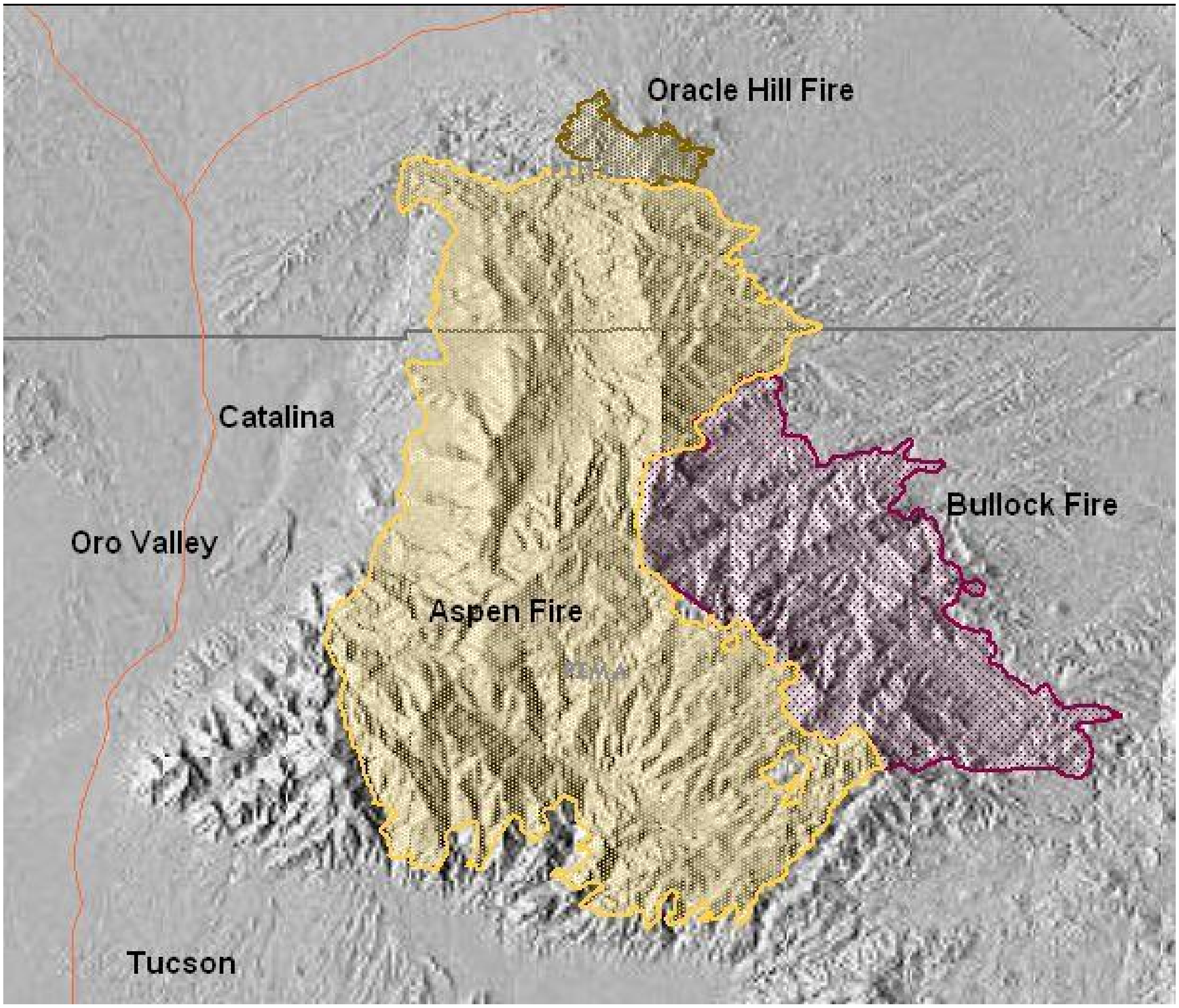


Figure 1: Hillshade image of the Santa Catalina Mountains overlaid with fire shapefiles. Image courtesy of Pima County Flood Control.

Figure 2: Map displaying locations of Santa Catalina and Pinaleno Mountains in southeast Arizona.

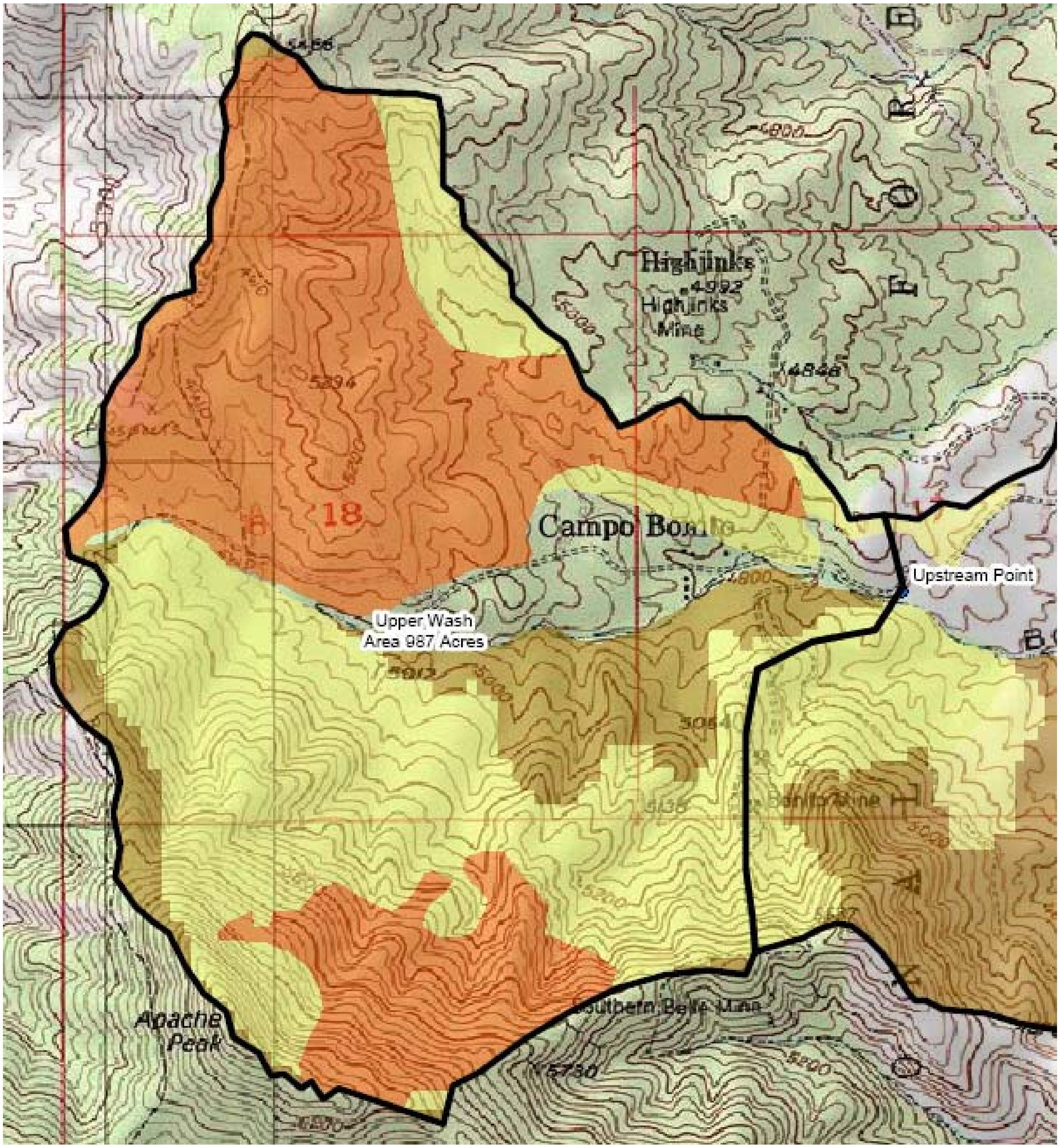


Figure 3: Upper Campo Bonito Watershed. Watershed shown with their burn severity and location of upstream slope-area reach. Image created on October 8, 2004 and courtsey of Barry Scott of AZ DEM using data from US Forest Service.

	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	155 cfs	499 cfs
5-year	375 cfs	1,219 cfs
10-year	585 cfs	1,872 cfs
25-year	935 cfs	2,988 cfs
50-year	1,240 cfs	3,968 cfs
100-year	1,640 cfs	5,248 cfs
500-year	2,750 cfs	8,800 cfs

Table 1. Return Flows for Upper Campo Bonito Watershed. The maximum flow calculated from Crippen and Bue (1977) method is 12,900 cfs.

Table 2. Sabino Creek near Mt. Lemmon Return Flows.

Return Period	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	119 cfs	350 cfs
5-year	278 cfs	834 cfs
10-year	431 cfs	1,293 cfs
25-year	685 cfs	2,055 cfs
50-year	922 cfs	2,766 cfs
100-year	1,200 cfs	3,600 cfs
500-year	5,316 cfs	15,948 cfs

Table 2: Sabino Creek near Mt. Lemmon return flows. The pre-burn flows were calculated using a multiplier, basin size ratio, (0.10) applied to the values reported for Sabino Creek near Tucson, AZ (the next downstream USGS gaging station). The maximum flow calculated from Crippen and Bue (1977) method is 26,400 cfs.

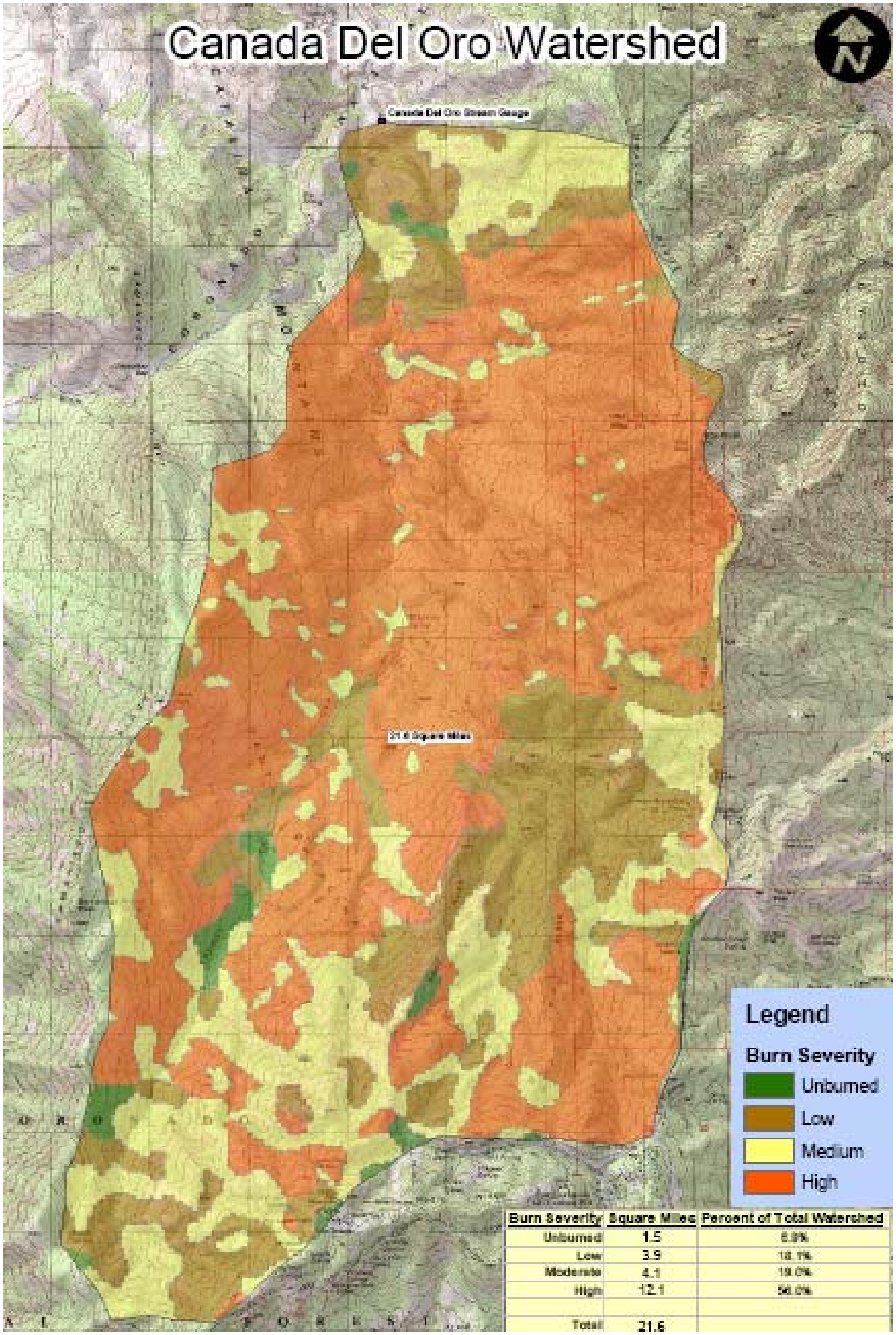


Figure 4: Cañada del Oro Watershed. Watershed shown with their burn severity and location of Pima County Flood Control stream gauge at outlet. Image created on October 7, 2004 and courtsey of Barry Scott of AZ DEM using data from US Forest Service.

Table 3. Cañada del Oro near Coronado Camp Return Flows.

Return Period	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	230 cfs	1,495 cfs
5-year	530 cfs	3,445 cfs
10-year	810 cfs	5,265 cfs
25-year	1,245 cfs	8,095 cfs
50-year	1,625 cfs	10,565 cfs
100-year	2,065 cfs	13,425 cfs
500-year	2,731 cfs	17,750 cfs

Table 3: Cañada del Oro near Coronado Camp return flows. The pre-burn flows were calculated using a multiplier, basin size ratio, (0.0864) applied to the values reported for Cañada del Oro near Tucson. The maximum flow calculated from Crippen and Bue (1977) method is 112,000 cfs.

Figure 5: Alder Canyon near Ventana Windmill. Photo taken in center of channel in slope conveyance cross section looking upstream. William Reed holding survey rod 100 feet upstream for scale.

Table 4. Alder Canyon near Ventana Windmill Return Flows.

Table 4. Alder Canyon near Ventana Windmill Return Flows.

Return Period	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	523 cfs	1,308 cfs
5-year	1,260 cfs	3,103 cfs
10-year	1,990 cfs	4,975 cfs
25-year	3,200 cfs	8,000 cfs
50-year	4,290 cfs	10,725 cfs
100-year	5,710 cfs	14,275 cfs
500-year	9,820 cfs	24,550 cfs

Table 4: Alder Canyon near Ventana Windmill return flows. The pre-burn flows were calculated using the National Flood Frequency (NFF) method for Southern Arizona Region 13. The maximum flow calculated from Crippen and Bue (1977) method is 85,900 cfs.

Table 5. Approximate burn severity acreages. Data from Nuttall Complex Fire BAER Team.

Burn Severity	Approximate Acreages
Unburned/Low	15,700
Moderate	11, 350
High	2,675
Total	29,725

Table 5: Approximate burn severity acreages. Data from Nuttall Complex Fire BAER Team.

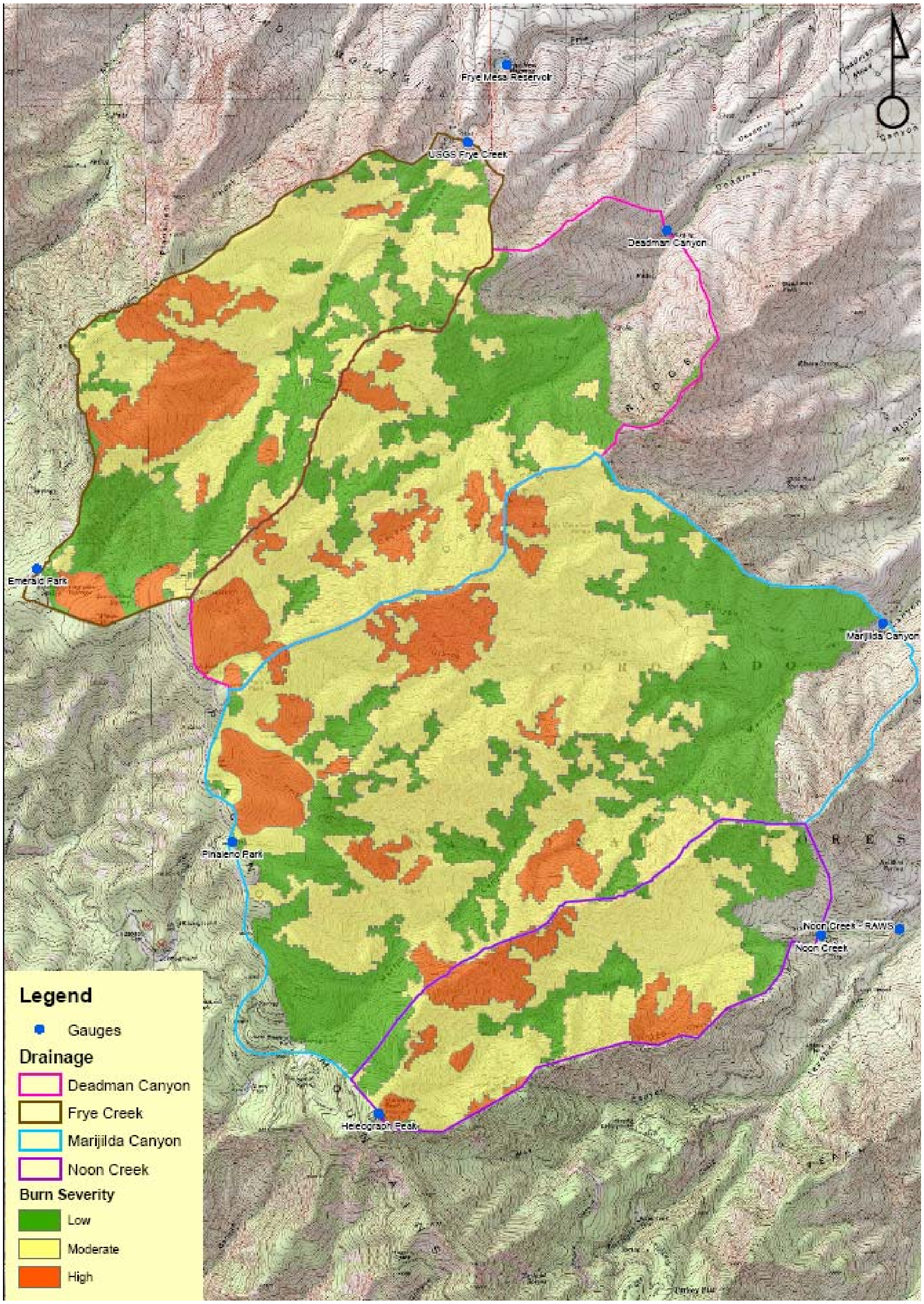


Figure 6: Southern half of the Nuttall Complex burn area. Several study watersheds are shown with their burn severity and gauge locations. Image created on September 21, 2004 and courtsey of Barry Scott of AZ DEM using data from US Forest Service.

Table 6. Drainage Area and Area Burned for Nuttall Burn Area Study Watersheds.

	FRYE	DEADMAN	MARIJILDA	NOON	WET
Total drainage area	4.02	4.78	11.00	2.99	1.58
Drainage area of high burn severity	0.76	0.57	1.21	0.52	0.22
Drainage area of moderate burn severity	1.69	1.86	5.28	1.79	0.47
Drainage area unburned or low burn severity	1.57	2.34	4.51	0.68	0.89

Table 6: Drainage area (in square miles) and area burned (in square miles) for Nuttall burn area study watersheds above stream gauge, slope conveyance, or slope-area reach. Burn severity figures provided by Barry Scott of AZ DEM using data from US Forest Service.

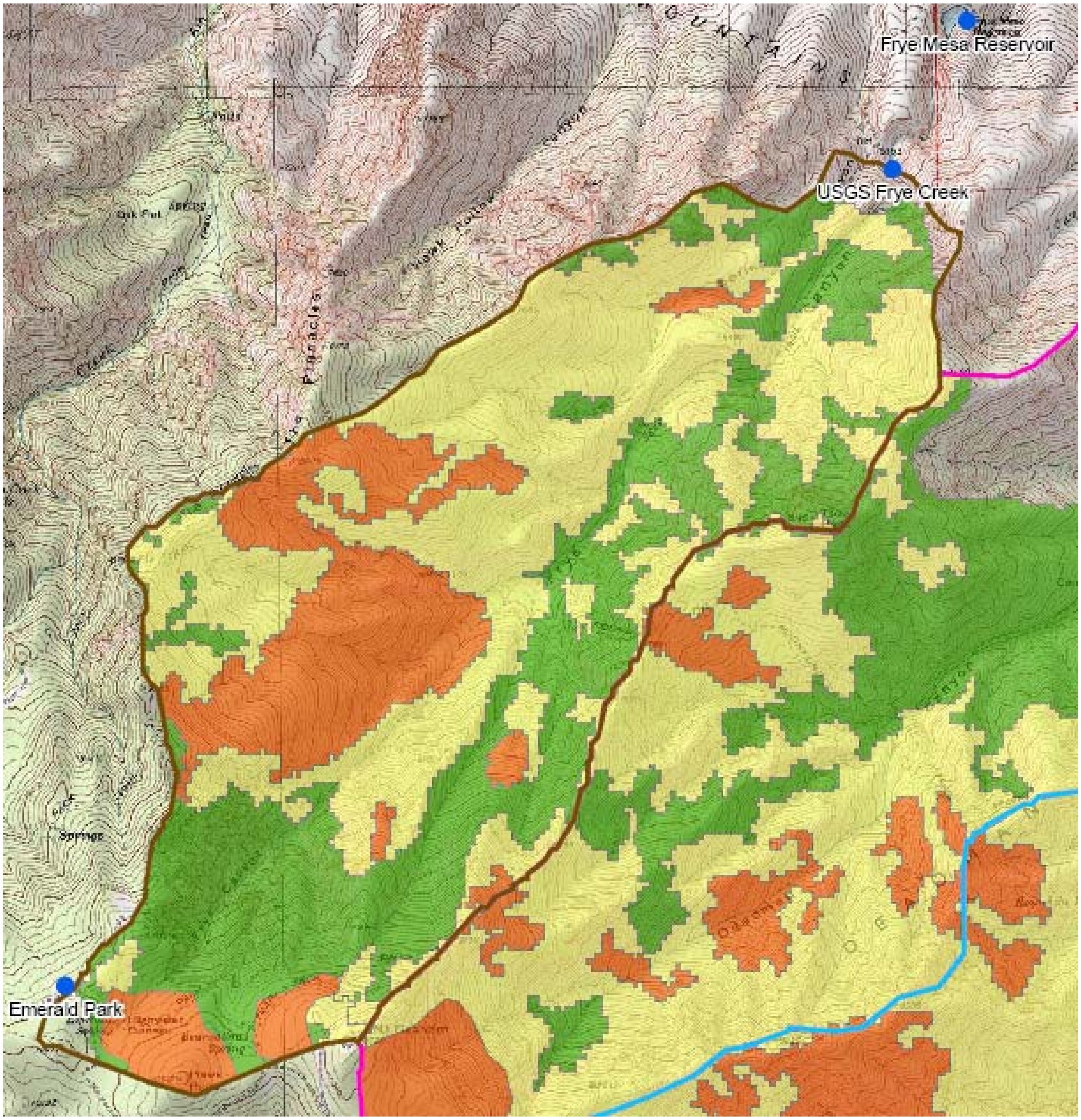


Figure 7: Close-up of Frye Creek watershed outlined in brown. Location of Emerald Park rain gauge and USGS stream and rain gauge shown as blue dots.

Figure 8: View above gauge looking upstream towards headwaters. Rugged and steep terrain of the Pinaleno Mountains is clearly visible. Photo taken prior to fires in 2003.

Table 7. Rainfall and Flow Data for Frye Creek for 2004 Monsoon.

Date of event	Basin average precipitation	Rainfall at USGS Frye Creek	Flow at USGS Frye Creek
July 27, 2004	0.40 inches in 30 minutes	0.19 inches in 30 minutes	1,400 cfs
August 4, 2004	1.00 inch in 60 minutes	Not reporting.	1,040 cfs
August 17, 2004	1.30 inches in 30 minutes	1.20 inches in 30 minutes	2,260 cfs

Table 7: Rainfall and flow data for Frye Creek for 2004 monsoon. Due to problems with stream gauge, flow amounts are estimated from high water marks by USGS using slope-area techniques (Personal communication, USGS, Dan Evans, October 28, 2004).

Figure 9: Frye Creek just downstream of gauge. Photo taken on the morning of August 4, 2004 prior to flow event. Note clear water. Photo courtesy of USGS.

Figure 10: Frye Creek just downstream of gauge. Photo taken during August 4, 2004 flow event. Note black color of water due to ash. Photo courtesy of USGS.

Table 8. Return Flows for Frye Creek.

Return Period	Return Flow	30-minute basin average precipitation estimate (inches)	60-minute basin average precipitation estimate (inches)
1-year	n/a	0.69	0.80
2-year	26 cfs	0.92	1.11
5-year	116 cfs	1.22	1.48
10-year	254 cfs	1.45	1.67
25-year	581 cfs	1.74	2.13
50-year	986 cfs	1.97	2.41
100-year	1,580 cfs	2.20	2.70
500-year	7,000 cfs	n/a	n/a

Table 8: Return flows for Frye Creek for 2-year through 100-year taken from USGS Water-Resources Investigations Report 98-4225. 500-year return flow was estimated by curve fitting data and assuming the maximum flow calculated from Crippen and Bue (1977) method, 30,400 cfs, to be equal to about a 2000-year event. 30 and 60-minute basin average precipitation values estimated by taking averaging point frequency amounts for lower, middle, and upper portions of the watershed from NOAA Atlas 14.

Table 9. Approximate Pre-Burn Return Flow and Basin Average Frequencies and Post-Burn Peak Discharge Increase for Frye Creek.

Date of event	Approximate pre-burn return flow frequency	Basin average precip. frequency	Approximate post-burn peak discharge increase
July 27, 2004	~90 year	< 1 year	> 54 times
August 4, 2004	~50 year	~2 year	40 times
August 17, 2004	150 year	7 year	13 times

Table 9: Approximate pre-burn return flow and basin average frequencies and post-burn peak discharge increase for Frye Creek.

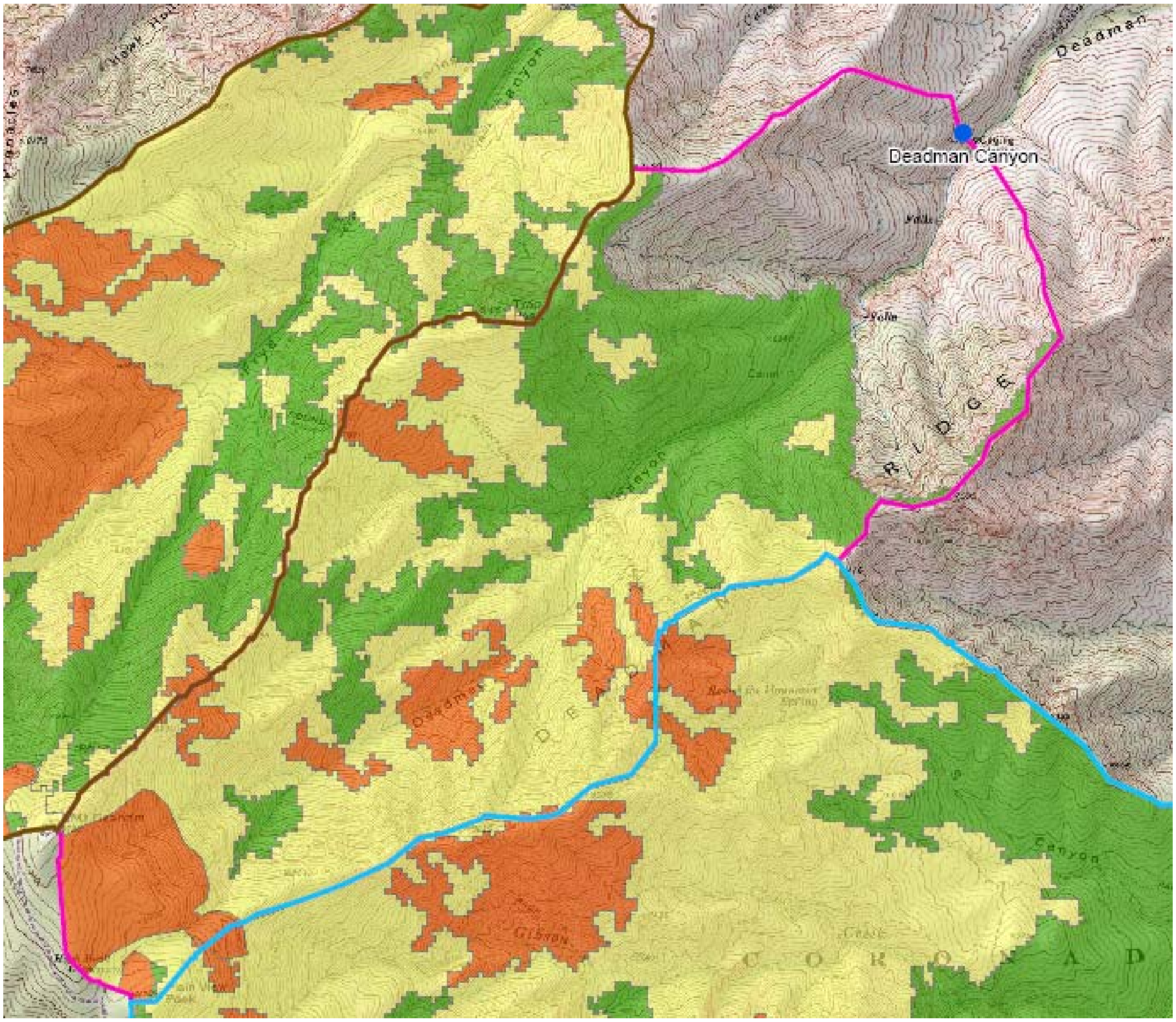


Figure 11: Close-up of Deadman Canyon watershed outlined in pink. Location of ALERT stream gauge shown as blue dot.

Figure 12: Discontinued USGS site on Deadman Canyon being reactivated as an ALERT gauge. Photo taken on June 26, 2004. Photo courtesy of JE Fuller Hydrology.

Figure 13: Looking up Deadman Canyon from USGS gauge site. One right is portion of the stilling well. Photo taken on August 27, 2004. Photo courtesy of JE Fuller Hydrology.

Table 10. Return Flows for Deadman Canyon at Old USGS site.

Return Period	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	31 cfs	2,325 cfs
5-year	137 cfs	10,275 cfs
10-year	300 cfs	22,500 cfs
25-year	686 cfs	51,450 cfs
50-year	1,163 cfs	n/a
100-year	1,864 cfs	n/a
500-year	8,260 cfs	n/a

Table 10: Return flows for Deadman Canyon at old USGS site. Due to USGS return flows not being available, the Frye Creek return flows were multiplied by a factor of 1.18, which is the ratio of the drainage areas. The post-burn return flows for periods greater than the 25-year period are not reported since they would far exceed the maximum flow calculated from Crippen and Bue (1977), which is 35,100 cfs.

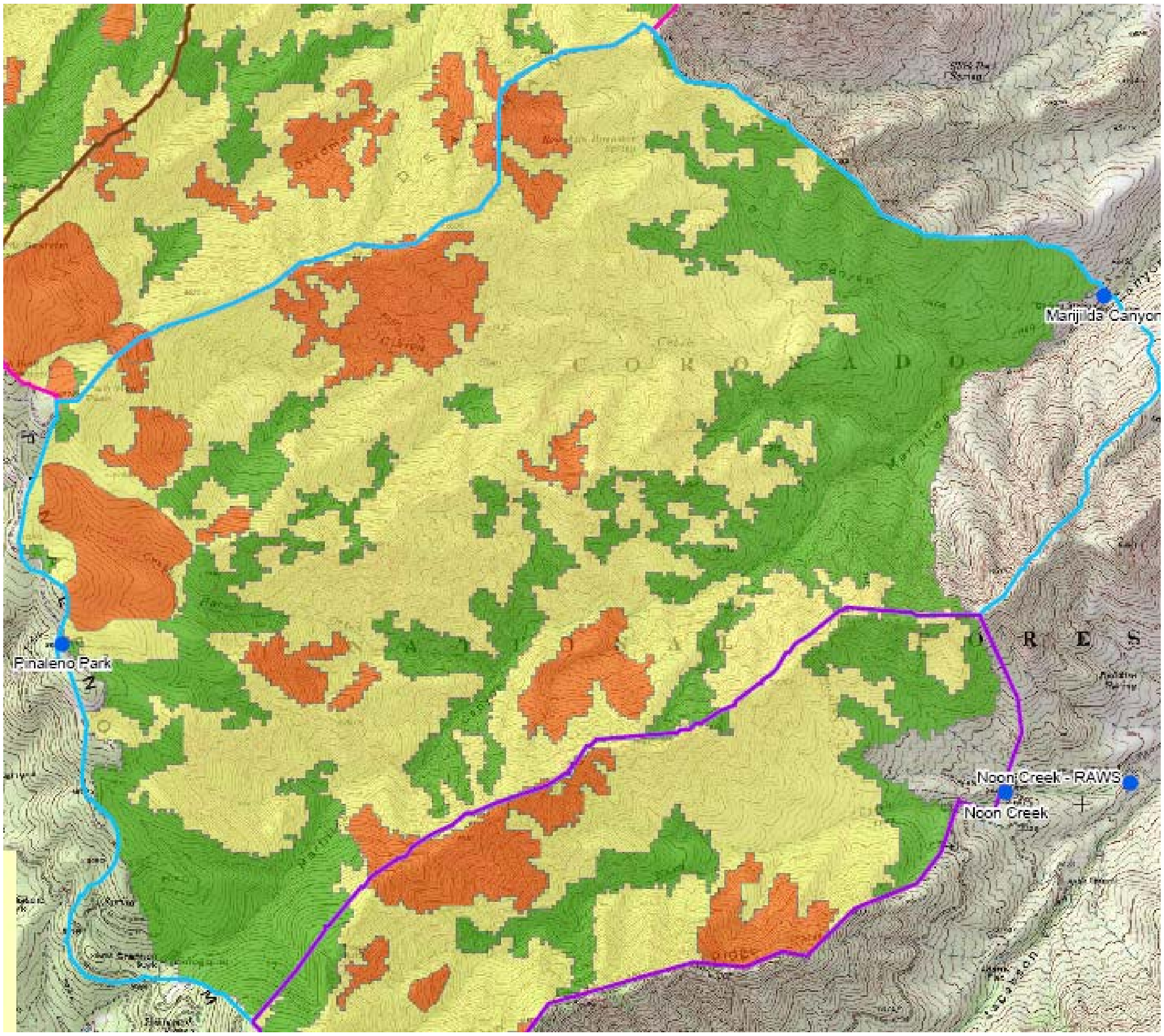


Figure 14: Close-up of Marijilda Canyon watershed outlined in light blue. Location of ALERT stream gauge and former USGS site shown as blue dot labeled Marijilda Canyon. Pinaleno Park is an ALERT rain gauge located at the headwaters.

Figure 15: Marijilda Canyon slope area reach looking upstream. Photo taken on August 31, 2004 and courtesy of USGS.

Figure 16: View of boulder deposit in Marijilda Canyon about a quarter mile downstream from slope area reach. Photo taken on August 30, 2004 and courtesy of USGS. Tucson WFO Service Hydrologist, Mike Schaffner, for scale.

Table 11. Return Flows for Marijilda Canyon at Slope-Area Reach.

Return Period	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	70 cfs	1,890 cfs
5-year	313 cfs	8,470 cfs
10-year	686 cfs	18,522 cfs
25-year	1569 cfs	42,363 cfs
50-year	2662 cfs	71,874 cfs
100-year	4266 cfs	n/a
500-year	18900 cfs	n/a

Table 11: Return flows for Marijilda Canyon at slope-area reach. Due to USGS return flows not being available; the Frye Creek return flows were multiplied by a factor of 2.70, which is the ratio of drainage areas. The post-burn return flows for periods greater than the 50-year period are not reported since they would far exceed the maximum flow calculated from Crippen and Bue (1977), which is 68,100 cfs.

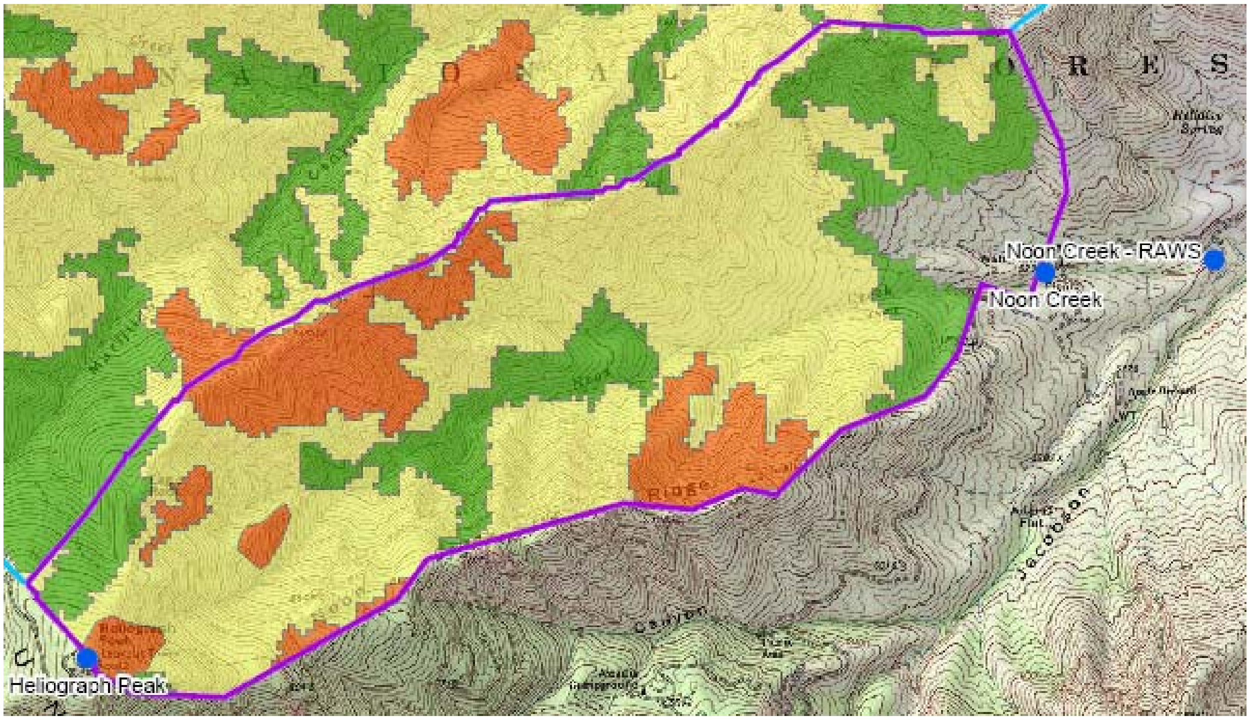


Figure 17: Close-up of Noon Creek watershed outlined in purple. Location of ALERT stream gauge shown as blue dot labeled Noon Creek. Heliograph Peak is an ALERT rain gauge located at the headwaters.

Figure 18: Noon Creek at Highway 366. ALERT pressure transducer located near base of right culvert.

Table 12. Return Flows for Noon Creek at Highway 366.

Return Period	Pre-Burn Return Flow	Post-Burn Return Flow
2-year	19 cfs	1,045 cfs
5-year	86 cfs	4,730 cfs
10-year	188 cfs	10,300 cfs
25-year	430 cfs	23,650 cfs
50-year	730 cfs	n/a
100-year	1169 cfs	n/a
500-year	5180 cfs	n/a

Table 12: Return flows for Noon Creek at Highway 366. Due to return flows not previously calculated for this site; the Frye Creek flows were multiplied by a factor of 0.74, which is the ratio of drainage areas. The post-burn return flows for periods greater than the 25-year period are not reported since they would far exceed the maximum flow calculated from Crippen and Bue (1977), which is 23,700 cfs.

Figure 19: Wet Canyon at Highway 366. Photo taken upstream on left bank looking downstream towards Highway 366 bridge.

Table 13. Return flows for Wet Canyon at Highway 366.

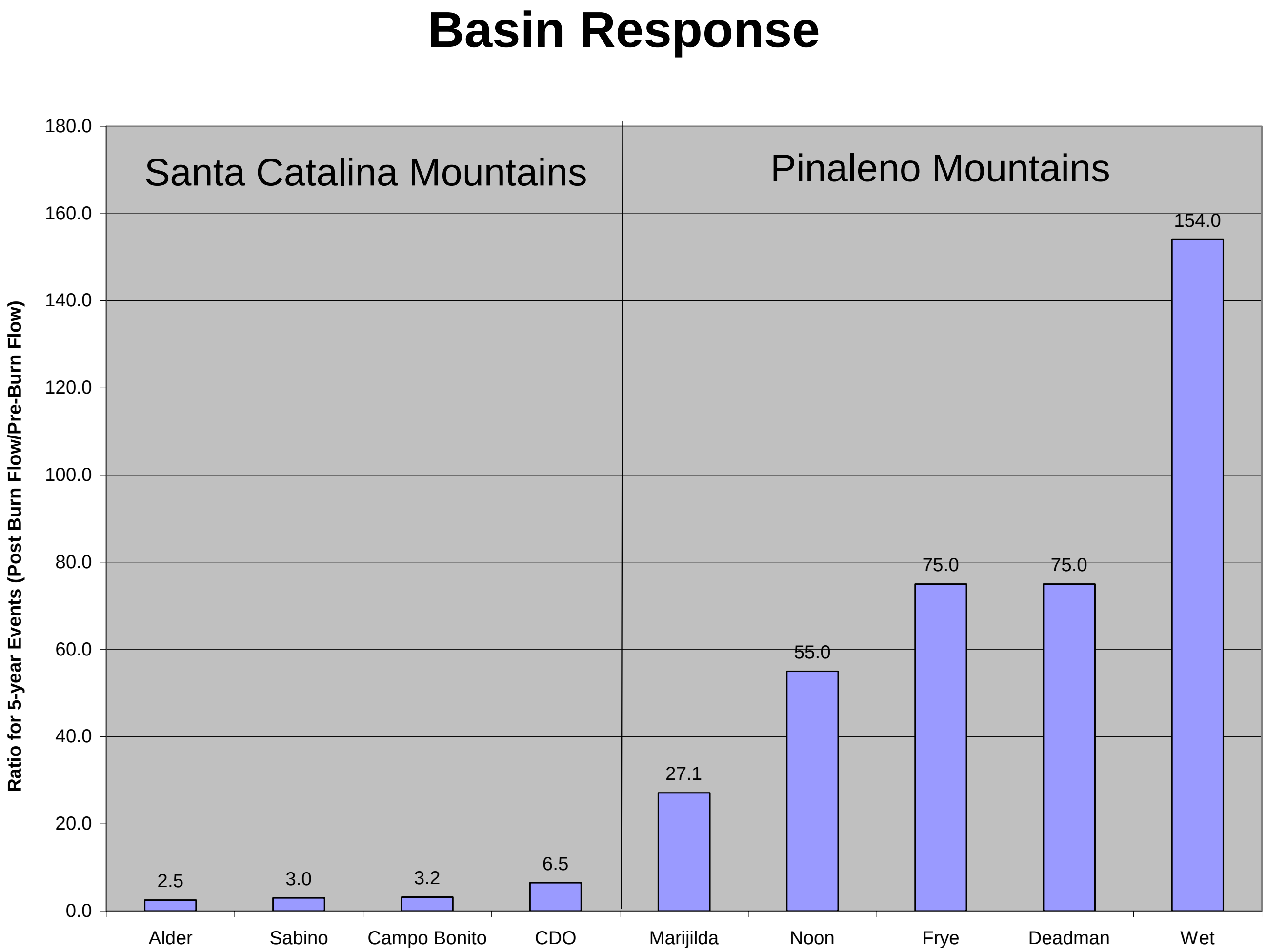
Return Period	**Pre-Burn Return Flow**	**Post-Burn Return Flow**
2-year	10.2 cfs	1,490 cfs
5-year	45.5 cfs	6,643 cfs
10-year	100 cfs	14,600 cfs
25-year	228 cfs	n/a
50-year	387 cfs	n/a
100-year	620 cfs	n/a
500-year	2,748 cfs	n/a

Table 13: Return flows for Wet Canyon at Highway 366. Due to return flows not previously calculated for this site; the Frye Creek flows were multiplied by a factor of 0.329, which is the ratio of drainage areas. The post-burn return flows for periods greater than the 10-year period are not reported since they would far exceed the maximum flow calculated from Crippen and Bue (1977), which is 13,500 cfs.

Table 14. Channel Gradient for Study Watersheds in the Pinaleno and Santa Catalina Mountains.

Watershed	**Location**	**Average channel gradient (ft/ft)**
Frye Canyon	Pinaleno Mountains	0.21
Deadman Canyon	Pinaleno Mountains	0.23
Marijilda Canyon	Pinaleno Mountains	0.16
Noon Creek	Pinaleno Mountains	0.23
Wet Canyon	Pinaleno Mountains	0.26
Upper Campo Bonito	Santa Catalina Mountains	0.07
Sabino Creek near Mount Lemmon	Santa Catalina Mountains	0.08
Cañada del Oro near Coronado Camp	Santa Catalina Mountains	0.09
Alder Canyon at Ventana Windmill	Santa Catalina Mountains	0.09

Table 14: Channel gradient for study watersheds in the Pinaleno and Santa Catalina Mountains. Represents the average gradient from headwaters to point of observation.



Graph 1: Basin Response under burn conditions for various watersheds in the Santa Catalina and Pinaleno Mountains.