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Effects of Wildfire in the Mountainous Terrain of Southeast Arizona: An Empirical Formula to Estimate 5-Year Peak Discharge from Small Post-Burn Watersheds

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Coauthor Mike Schaffner viewing a boulder deposit in Marijilda Canyon (photo courtesy of USGS).

Effects of Wildfire in the Mountainous Terrain of Southeast Arizona: An Empirical Formula to Estimate 5-Year Peak Discharge from Small Post-Burn Watersheds

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Abstract. This paper presents the new fundamental concept of the *hyper-effective drainage area*, the area of the high severity burn plus the area of the moderate severity burn, and provides an empirical formula to estimate the 5-year peak discharge from small post-burn watersheds to demonstrate the use of the concept. The equation uses the documented hydrologic response within the first two years after the occurrence of wildfire of ten watersheds in Southeast Arizona. These watersheds are within the forested steep terrain of the Santa Catalina, Santa Rita, and Pinaleno Mountains. After the burns, frequent flash floods and occasional debris flows have 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. To predict the “likely” peak flow that can be expected before a given burned watershed is back to conditions that resemble pre-burn hydrology, an empirical equation was devised to estimate the post-burn 5-year peak flow. The developed equation works reasonably well (cross validation adjusted coefficient of determination of 0.90) for the documented watersheds. Its ability to deal with topographic and geomorphologic diversity lies in the use of a multivariate runoff index that utilizes the hyper-effective drainage area (determined from burn severity), average basin elevation, and an objective modified channel relief ratio.

Additional keywords: Arizona; Post-Burn Hydrology; Forest Hydrology; Peak Flows; Flash Floods; Modified Channel Relief Ratio; Hyper-Effective Drainage Area.

Introduction

Southeast Arizona has recently been impacted by several wildfires. These include the Oracle Hill Fire (2002), Bullock Fire (2002), and Aspen Fire (2003) in the Santa Catalina Mountains; the Nuttall Fire (2004) in the Pinaleno Mountains; and the Florida Fire (2005) in the Santa Rita Mountains (Figure 1). After these wildfires, significantly increased runoff from the burn areas has occurred. Rainfall amounts and intensities, which normally would have caused little if any, flooding, have produced dangerous flash floods during watershed recovery.

Often the National Weather Service is faced with predicting post-burn peak flows shortly after a fire, and sometimes, while the fire is still burning. This urgency for forecasts does not allow for the use of the tools currently available to Burned Area Emergency Rehabilitation (BAER) teams for post-burn hydrologic analysis because these methods are either too data intensive, or too time consumptive, for use in a real-time operational setting. Although burn severity information is usually not available in near real time, for operational purposes, a worst-case scenario could be assumed until the data became available. The outlet of the basin would be selected based upon potential damage to life or property, e.g., a bridge crossing or nearby housing.

This study presents the new fundamental concept of *hyper-effective drainage area*, the area of the high severity burn plus the area of the moderate severity burn, and provides an empirical formula to estimate the 5-year peak discharge (Q_5) from small watersheds, watersheds less than 15 square miles (38.8 square kilometers), during post-burn recovery to demonstrate the use of the concept. Determining the 5-year return interval has proven an effective approach for similar burn studies (Reed 2002). This is perhaps because research conducted on burned watersheds throughout the Rocky Mountains indicates hydrologic recovery to near pre-burn conditions within 3 to 5 years (Morris and Moses 1987, Martin and Moody 2001).

A series of equations for different return intervals (e.g., 2-year and 10-year) also could be developed but was beyond the scope of this paper. The 5-year peak discharge equation was developed by evaluating the hydrologic response within the first two years after the occurrence of wildfire of ten watersheds in Southeast Arizona: Frye Canyon, Deadman Canyon, Marijilda Canyon, Noon Creek, Wet Canyon, Upper Campo Bonito, Sabino Creek near Mount Lemmon, Alder Canyon at Ventana Windmill, (these first eight documented in Schaffner and Reed 2005a), Madera Canyon (described below), and Romero Canyon (also described below). Additionally the information for Upper Campo Bonito was updated in Schaffner and Reed (2005b). The methodology used to determine the 5-year post-burn flow for all ten basins was similar. Pertinent data are presented in Figures 2, 3, and 4.

Cañada del Oro near Coronado Camp documented in Schaffner and Reed (2005a) was not used because it was a second year event likely preceded by undocumented first year events of larger magnitude. Additionally, this basin at 21.6 square miles (55.9 square kilometers) is perhaps too large for the methodology used. A cursory examination of the data for the downstream gage, Cañada del Oro at Rancho Solano, suggests that post-burn runoff from basins of this size (21.6 square miles) and larger may be better modeled using a technique that considers maximum rainfall rates rather than basin averages. Another approach that may be worth evaluating is to use only the basin average for the hyper-effective drainage area.

Eight of the ten basins are smaller than 10 square miles (25.9 square kilometers). When considering only the hyper-effective drainage area, eight of the ten basins are smaller than 2.5 square miles (6.5 kilometers). Therefore, the spatial distributions of the entire storms were not generally considered important to this analysis. However, what may have been important was for the storm core to have moved over at least a portion of the hyper-effective drainage area. This was common to all ten events. Additionally, the importance of storm motion is evaluated.

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

Role of Mountainous Terrain

Factors in peak discharge generation from burn areas, such as burn severity, basin size, terrain, rainfall amount, and storm intensity, can all play a key role. In this study, an objective Southeast Arizona specific modified channel relief ratio¹ was selected as an important indicator

¹ The modified channel relief ratio was defined by the authors so as not to include the relief from the upper most area of the mountainous terrain of Southeast Arizona, which often is void of well defined channels. The modified channel relief ratio is an objective measurement unlike the traditional channel relief ratio. Additionally, the authors defined the modified channel relief ratio so as to include the channel relief in the vicinity of the basin outlet where flooding occurred.

of topographic diversity in the mountainous terrains evaluated. The *modified channel relief ratio* is the average slope of the basin along the first order channel measured from 1,250 feet (381 meters) below the ridge to the basin outlet. For small impervious areas, peak discharge will tend to increase as channel slope increases. An increase in channel slope can result in decreased time of concentration and less infiltration. This may be especially true for areas recently denuded or with new hydrophobic soils. Post-burn flows originating from the Pinaleno Mountains had greater increases in runoff than those observed in the Santa Catalina Mountains. This was initially believed by the authors to be due to significant differences in the channel relief. However, the Santa Rita Mountains with modified channel relief ratio similar to the Pinaleno Mountains had an increase in runoff similar to the Santa Catalina Mountains. But the actual channel slope through the slope conveyance cross-section measured for the Santa Rita flood is similar to the modified channel relief of the Santa Catalina Mountains. Therefore future studies may want to evaluate using channel slope through flooded reach rather than the modified channel relief ratio. Modified channel relief ratio and other basin values are presented in Figure 3. Average basin elevation was also selected as an important variable for mountainous terrain. The *average basin elevation* is the average altitude above mean sea level using the elevation of the highest point of the basin and the elevation of the basin outlet. In addition to being an indicator of rainfall variability and local climate, average basin elevation in mountainous terrain is indirectly an indication of vegetation coverage and type (Brown 1982); and perhaps to a lesser degree, indirectly an indicator of soil depth and predominant soil characteristics (Hendricks 1985). Initially, the authors thought the usefulness of the average basin elevation could also be because the higher organic matter in the higher elevation soils (in contrast to lower elevation soils with less organic matter) played a key role in the likelihood of the higher elevation soils developing hydrophobic conditions. Yet for very high elevations there may be: 1) more exposed bedrock, 2) no channel development, 3) less natural vegetation, and 4) where soils occur they may tend to be shallow; such conditions would likely result in an inverse relationship between elevation and increased post-burn runoff. Simply put if you burn rock it is still rock, resulting in very little—if any—change in hydrologic response. Other indicators evaluated by the authors but not selected included the traditional channel relief ratio, main channel slope index, basin relief ratio, average channel elevation, mean main channel elevation, and traditional drainage area.

Methodology

The methodology used to determine the 5-year post-burn flow for all ten basins was similar. The details for Frye Creek, Deadman Canyon, Marijilda Canyon, Noon Creek, Wet Canyon, Upper Campo Bonito, Sabino Creek near Mount Lemmon, and Alder Canyon at Ventana Windmill are documented in Schaffner and Reed (2005a). The information for Upper Campo Bonito was updated in Schaffner and Reed (2005b). The details for Madera Canyon and Romero Canyon are provided below.

To create the empirical formula the first step was to determine the 5-year post-burn flow for the basins. The steps required were 1) calculate the basin average precipitation for events known to have caused floods from the burned basins (an attempt was made to use the first major flush after a burn) and document storm duration, 2) determine the return period of these rain events, 3) determine the peak flow of the flood event, 4) calculate the pre-burn peak flow for the corresponding return period of the precipitation event, 5) calculate the pre-burn 5-year peak

flow, 6) calculate the ratio of pre-burn peak flow to post-burn peak flow², and 7) multiply the pre-burn 5-year peak flow for a basin (determined in step 5) by the corresponding ratio (determined in step 6). For the two cases, Marijilda and Alder, where the return period of the precipitation event was a 5-year event, steps 4 through 7 were not necessary but were done for consistency and display purposes. Results of steps 1 through 4 are presented in Figure 2. Results of step 5 are presented in Figure 4. Results of Steps 6 and 7 are presented in Figure 3.

The t-year rainfall is commonly used in applied hydrology to calculate a t-year flood, for example this is a major input of the rational method, as well as the model TR55 (Natural Resources Conservation Service, 1986) commonly used by the Forest Service to estimate post-burn runoff response. For the rational method a rainfall intensity for a duration equal to the time of concentration is used. For TR55 a rainfall with a duration of 24-hours is used with a rainfall time distribution designed to contain the intensity of any duration of rainfall for the frequency of the event chosen. Or as stated by Natural Resources Conservation Service (1986): “That is, if the 10-year frequency, 24-hour rainfall is used, the most intense hour will approximate the 10-year, 1-hour rainfall volume.”

For this paper, it was assumed that a short-term thunderstorm with a duration approximately equal to or greater than the time of concentration for the burned basin, of a particular frequency, produces a peak flood discharge of the same frequency. Whereas this may be an oversimplification, it will always be a conservative one that overestimates the t-year flow for relatively impervious burned basins in the mountainous terrain of Southeast Arizona. In the United States, it is a common assumption made by land management agencies when trying to calculate t-year flows for ungaged basins in arid and semi-arid regions.

Time of concentration for the ten studied basins range from 0.3 to 1.2 hours (Figure 2). Duration of the event storms ranged from 0.5 to 1 hours (Figure 2). For all but one case, the duration of the flood-causing storm was approximately (within 0.2 hours) equal to or greater than the time of concentration. The exception was Romero Canyon. For Romero Canyon, the duration of the storm was approximately 0.5 hours while time of concentration is 1.1 hours. Therefore, the post-burn 5-year peak flow may have been slightly underestimated for this basin. However, it has also been observed that time to peak can be shorter for burned basins (Neary and others, 2003), if so, even Romero Canyon’s case study storm duration could have been approximately equal to the time of concentration for the then existing post-burn watershed conditions.

Another possible oversimplification of this paper was the use of the same ratio of pre-burn to post-burn flow for return intervals different than the 5-year storm (e.g. 2-year) to calculate post-burn 5-year flow from the corresponding pre-burn 5-year flow. The authors felt that this assumption was acceptable because half of the events were close to a five-year event, i.e., five of the ten events were 2-year, 3-year or 5-year events. Additionally, of the remaining five events, three had return intervals less than the 2-year event (they were approximately 1-year events) and two had return intervals greater than the 5-year event (both were 10-year events). Whereas the ratios likely are different for smaller events than larger events, it was felt that this clustered “balanced” distribution would reasonably offset the tendency for an unacceptable over- or-under estimation.

Another way to look at the relationship of pre-burn to post-burn flows (resulting in the same values as above) is to assume that the ratio of the magnitude of the pre-burn t-year event to the magnitude of pre-burn 5-year event would remain essentially the same for post-burn events

² This ratio is calculated by dividing the result of step 3 by the result of step 4.

of the same respective return intervals. Once again, this seems a reasonable approach when return intervals equal to or less than the 10-year return interval are used.

Madera Canyon

Madera Canyon is a 4.00 square mile (10.35 square kilometers) watershed. On August 8, 2005, 0.70 inches (17.78 millimeters) fell in about 45 minutes. The basin average precipitation frequency for Madera Canyon event was less than a 1-year event using NOAA Atlas 14 Volume 1 (Bonnin and others, 2004). On January 23, 2006, the authors conducted a field survey of the high water mark and associated channel geometry for Madera Creek near the U.S. Forest Service amphitheater. The high water mark was 7 feet (2.13 meters) above the channel thalweg. The cross section perpendicular to the direction of the flood flow was trapezoidal with a top width of 38.2 feet (11.64 meters) and a base of 15 feet (4.57 meters) resulting in a cross sectional area of 186.2 square feet (17.3 square meters). Channel slope through this cross section was 0.094 feet/feet (0.094 meters/meters). Manning's "n" was estimated at 0.15. The velocity of the peak flow was calculated to be 8.20 feet/sec (2.50 meters/sec). The peak flow was calculated as 1526 cfs (43.22 cubic meters per second) +/- 10 percent. Such a flow would be in the range of a 20-year pre-burn flow (Figure 5). This is a post-burn peak discharge increase of at least 6.8 times greater than pre-burn peak discharge. The 5-year post-burn flood is therefore estimated using this ratio to be greater than 4,476 cfs (126.76 cubic meters per second).

Romero Canyon

Romero Canyon is a 7.25 square mile (18.78 square kilometers) basin located on the southwest side of the Santa Catalina Mountains. At 6:00 PM MST of July 24, 2003, a north-south line of thunderstorms developed in the San Pedro River Valley to the east and pushed westward over the Santa Catalina Mountains at 15 mph (24.14 kilometers per hour). Rain fell on the Romero Canyon basin from about 6:30 to 7:30 PM. Tucson's KEMX WSR-88D radar as well as five Pima County Flood Control rain gages sampled the thunderstorms. Storm motion during the event was generally up to down-stream over Romero Canyon. This likely added to the magnitude of the peak; perhaps resulting in a peak flow up to 3.0 times greater than other storm motions.

A basin average rainfall value was obtained for the Romero Canyon event by averaging radar bins that fell within the basin from the one-hour precipitation product. A basin average 1-hour rainfall value of 2.35 inches (59.69 millimeters) was obtained. Since radar rainfall can be overestimated in the desert southwest due to hail contamination and dry air at the low levels, it is desirable to adjust the radar values if there is significant variation from rain gage totals. While no rain gages are located within the Romero Canyon basin, two are located within 2 miles (3.22 kilometers) of the basin boundary. These two gages show that only 63 percent of the radar indicated rainfall reached the ground.

Satellite imagery, radar, and lightning data remained consistent as the storm progressed from east to west across the Santa Catalina Mountains. As a result, there is confidence to use a regional approach to determine the best possible radar correction factor to compute an adjusted basin average rainfall. Using the above-mentioned rain gages, a radar correction factor of 0.85

was obtained. As a result, 2.00 inches (50.8 millimeters) was the adjusted basin average 1-hour rainfall.

Because the majority of rainfall from summer convective storms tends to fall in a timeframe less than an hour, it is advantageous to examine precipitation frequency with respect to peak rainfall. The five rain gages showed 80 percent of the rain fell within 30 minutes. Values ranged from 78 – 83 percent of rain fell within 30 minutes. Due to the narrow range of values between individual gages, the regional approach is once again valid. Thus 80 percent of the adjusted basin average 1-hour rainfall yields a 1.60 inches (40.64 millimeters) adjusted basin average 30-minute rainfall. According to NOAA Atlas 14 Volume 1, this amounts to a 10-year 30-minute basin average precipitation frequency.

Ann Youberg of the Arizona Geological Survey estimated the resultant flash flood at 9,500 cfs (269.04 cubic meters per second) +/- 15 percent. This estimate was derived by Ann Youberg using the HEC-RAS step backwater model with 5 cross sections. Such a flow would be greater than a 500-year pre-burn flow (Figure 6). This is a post-burn peak discharge increase of 6.7 times greater than pre-burn peak discharge. The 5-year post-burn flood is therefore estimated using this ratio to be 6,035 cfs (170.90 cubic meters per second).

Frye Creek Multiple Events Considered

The multiple events for Frye Creek documented in Schaffner and Reed (2005a) and presented in Figure 7 can be used to demonstrate the importance of using the first major hydrologic flush from the basin after the burn for calculating the maximum likely post-burn 5-year response. If the post-burn response calculated for each subsequent event were used, the calculated post-burn 5-year peak flow would be approximately half of the post-burn 5-year peak flow calculated using the preceding event (see Figure 8). Therefore an attempt was made to use only the first hydrologic flush from the ten basins after the burns to determine the maximum likely 5-year post-burn peak flow. Therefore, for Frye Creek, July 27, 2004 is used.

General Basin Response

The basin response differences between individual basins and between mountain ranges are illustrated in Figure 4. The Santa Catalina Mountains have an average post-burn basin response 3.8 times greater than pre-burn conditions. The Santa Rita Mountains have a post-burn basin response 6.8 times greater than pre-burn condition. The Pinaleno Mountains have an average post-burn basin response 106.6 times greater than pre-burn conditions. The Santa Catalina and Santa Rita Mountains have values similar to those reported by Reed (2002), NOAA National Weather Service for the White Mountains in Arizona and the Pinaleno Mountains have values similar to those reported by Veenhuis (2002), U.S. Geological Survey for the Jemez Mountains in New Mexico.

An Empirical Formula to Estimate 5-Year Peak Discharge from Small Post-Burn Watersheds

Because it takes 3-5 years or in some cases longer (Livingston, R. K. and others, 2005) for a watershed to recover from high and moderate severity burns, an empirical equation for predicting post-burn runoff for the 5-year return interval is presented here (Figure 9). The

presented equations (envelope curve and best-fit) are representative of the conditions prevalent during the first two years of recovery; and therefore, are expected to be useful for initial burn recovery planning as well as operational forecasting. These equations use a multivariate runoff index defined as

$$x = 1000(\alpha\psi)^{0.54} \beta^2 \phi^{-1.28} \quad (1)$$

where

x = multivariate runoff index

α = high severity burn + moderate severity burn as a fraction of total watershed (square miles/square miles);

ψ = total drainage area (square miles);

β = modified channel relief ratio (feet/feet); and

ϕ = average basin elevation above mean sea level (thousands of feet).

The envelope curve equation is

$$Q_5 = 4114(x)^{0.65} \quad (2)$$

and the best-fit equation is

$$Q_5 = 1993x \quad (3)$$

where

Q_5 = post-burn runoff for the 5-year return interval (cfs).

The adjusted R-square value for the best-fit curve is 0.96. The envelope curve was developed by adding 25% (the largest reported flow measurement error) to the values for Deadman, Romero, and Marijilda Canyons; and then fitting a power curve to these data points. A power function was used to insure the curve went through the origin, (0,0).

These equations are for small watersheds less than 15 square miles (38.8 square kilometers); and include sites with average basin elevations from 5500 to 8100 feet (1676.4 to 2469 meters) above msl. 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 area³, using modified channel relief ratio as an indicator of basin steepness, and using average basin elevation as an indicator of predominant vegetation and soil characteristics, provided a reasonable fit. The best-fit equation neither significantly overestimates nor significantly underestimates the post-burn runoff for any watershed.

Storm Motion Considered

To evaluate the possible influence of storm motion, Romero Canyon, the only storm that moved from upstream to downstream (see Figure 2), was temporarily removed. The new envelope curve equation for the remaining 9 data points is

$$Q_5 = 5293(x)^{0.56} \quad (4)$$

and the corresponding best-fit equation is

$$Q_5 = 1949x \quad (5)$$

where

Q_5 = post-burn runoff for the 5-year return interval (cfs).

³ The hyper-effective drainage area, α times ψ in the first equation or the area of the high severity burn (square miles) plus the area of the moderate severity burn (square miles).

The adjusted R-square value for the new best-fit curve is 0.97. The new envelope curve was developed by adding 25% (the largest reported flow measurement error) to the values for Noon and Deadman Canyons; and then fitting a power curve to these data points. As can be seen, equations 3 and 5 are essentially the same. The relationship between envelope equations is

$$y = 0.1963(x)^{1.1605} \quad (6)$$

where

y = equation 2; and
x = equation 4.

Equations 4 and 5 are presented here for comparison with equations 2 and 3 only. To allow direct comparison the definition of the multivariate runoff index has been held constant. Since the best-fit equations are essentially the same, and the difference between envelope curves is within the reported error of observations, the continued use of equations 2 and 3 are recommended.

Validation of Equation

The leave-one-out cross validation technique was used to test the regression equation ability to predict Q_5 . This technique allows each data point to be treated, one at a time, as independent data (Wilks 2006, see page 215 for a more detailed description of this method). Using this process a cross validation adjusted R-square value of 0.81 was obtained with a corresponding cross validation standard error of 1757 cfs (49.8 cubic meters per second). This yields a cross validation adjusted coefficient of determination (adjusted correlation coefficient) of 0.90. This is considered by the authors to represent an acceptable forecast precision, and therefore, the authors feel confident in the use of the equations operationally to predict the “likely” peak flow that can be expected before a given burned watershed is back to conditions that resemble pre-burn hydrology. However, as more data becomes available, these equations should be updated and their usefulness further tested.

Discussion

The USGS equations for estimating flood-frequency relations in USGS Water-Supply Paper 2433 (Thomas 1997) specifically the relationships for the 5-year event in Southeast Arizona do not use an elevation measurement for Region 13 (this region includes the Santa Catalina and Santa Rita Mountains); and uses an inverse relationship for elevation for Region 14 (this region includes the Pinaleno Mountains). In order to have a reasonable data set for post burn events, we had to evaluate these regions lumped together. An analysis of the data separated into these regions hints that an inverse relationship for average basin elevation would be significant for the post-burn Region 13 basins but perhaps not for the post-burn Region 14 basins. This is likely because all the basins had a relatively high average basin elevation regardless of what region they were in, and perhaps because neither region had enough data for a more rigorous analysis. An equation using just the hyper-effective drainage area and the modified channel relief ratio, i.e., an equation that does not use an elevation measurement, was found to have an adjusted R-square value of 0.93. Therefore, a bivariate equation could be developed with essentially the same success as the multivariate approach. However, average basin elevation was considered useful to help discern between different mountain ranges and was retained. As more data becomes available it may become possible to develop separate equations

for these regions. At that time it may be that a multivariate approach will work best for post-burn Region 13 and a bivariate approach will work best for post-burn Region 14.

It is interesting to note that the USGS equations do not use a relief ratio or other measurement of slope for these regions. Also as would be expected for pre-burn equations, the USGS equations use the entire drainage basin (not a portion of the basin, i.e., hyper-effective drainage area). Perhaps these differences between the pre-burn equations and those presented here underscores that post-burn hydrology can be significantly different from normal conditions.

The direct relationship between 5-year peak flow and basin size does not necessarily pertain to burned watersheds (Figure 10). Noon Creek, with the largest value for the Post-Burn runoff, has neither the steepest modified channel relief ratio nor the highest average basin elevation; neither the largest burned area nor the largest basin size. Yet Noon Creek does have the highest multivariate runoff index. As can be seen in Figure 10, the best-fit equation value (light blue/fourth bar) underestimates (although not significantly) the target post-burn value⁴ (blue/third bar) for Wet, Frye, Romero, and Alder Canyons. However, as intentionally developed, the envelope curve values (burgundy/fifth bar) are greater than target post-burn values for all ten sites. Additionally, the envelope curve begins to “flatten” faster than the best-fit curve (Figure 9), and thus displays the curve shape expected for larger basins (generally larger index values). Therefore, for conservatively estimating 5-year post-burn runoff in Southeast Arizona watersheds, the envelope curve (equation 2) should be used. For situations where post-burn hydrology is not significantly different than normal conditions (when the hyper-effective drainage area is a small portion of the total drainage area) the results of the post-burn envelope curve and a pre-burn 5-year equation should be compared and the higher result used.

Conclusions

Common rainfall events can cause large peak flows in basins recently burned. Peak flows from post-burn mountainous terrain may be several orders of magnitude greater than what they would have been for pre-burn conditions. This was observed for various watersheds in the Santa Catalina, Santa Rita, and Pinaleno Mountains. Since 3 to 5 years is a reasonable rule of thumb for recovery of burned watersheds, a 5-year rainfall event should be expected during the recovery period. The probability of occurrence of one or more events equal to or greater than the 5-year event in 5 years is 67%. In order to evaluate the minimum peak flow that can be expected before a given burned watershed is back to conditions that resemble pre-burn hydrology, an empirical equation was devised to predict the 5-year peak flow. This equation works reasonably well for the recently burned watersheds of the Santa Catalina, Santa Rita, and Pinaleno Mountains. Its ability to deal with such topographic and geomorphologic diversity lies in the use of a multivariate runoff index that utilizes the hyper-effective drainage area (determined from burn severity), average basin elevation, and an objective (Southeast Arizona specific) modified channel relief ratio. The hyper-effective drainage area approach may be representative of two contrasting runoff conditions: 1) significant runoff from burn areas with hydrophobic soils, under such circumstances all rainfall can essentially be considered in excess of soil moisture needs; and 2) little runoff from dry non-burned areas where there may have been little if any excess.

⁴ The target values are those values determined by Schaffner and Reed (2005a) and were updated as shown in furthest right column of Figure 3.

In light of the difficulty in estimating increased peak flow from burned areas, empirical equations represent a significant tool for estimating peak flow. Several flow events from various watersheds are required for the geographic area in question. If a different probability of occurrence is desired, a curve could be developed for a different return interval using the methods described above. However, for return intervals greater than the 10-year return interval, the method to calculate post-burn peak flow would have to be modified to take into account that the ratio of pre-burn to post-burn would not be the same for large magnitude events.

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A Few Words Regarding the Cover Photograph

This boulder levee is an interesting feature of our studies. Such levees are characteristic of debris flows. From USGS Open File Report 97-136 by Susan H. Cannon: "Debris-flow deposits are characterized by significant relief and sharp, well-defined flow boundaries. Levees lining the flow path, or a veneer of mud coating the channel sidewalls, as well as steep, lobate deposits of matrix-supported material at the path terminus are characteristic of this flow process." We tend to believe that the levee was the result of a debris flow prior to a water flow and that the peak flow was a water flow that did over topped the levee as evidenced by the "debris" against the tree and the lack of mud stained walls. So a possible order of the events is 1) debris flow, 2) levee deposited, 3) frontal lobe of debris / hyperconcentrated flow, 4) overtopping of levee by water flow with floating debris, 5) wrapping of floating debris against tree, 6) peak flow, 7) retreat of water flow to channel during falling limb of hydrograph. Note: steps 1-5 would occur during rising limb of hydrograph. Perhaps steps 1 and 2 would be considered a separate geo-hazard event, followed by a second hydrological event consisting of steps 3 through 7. Of course this is all conjecture. Finally it seems to us that the levee was washed clean of any mud coating due to the overtopping by water or perhaps subsequent rain.

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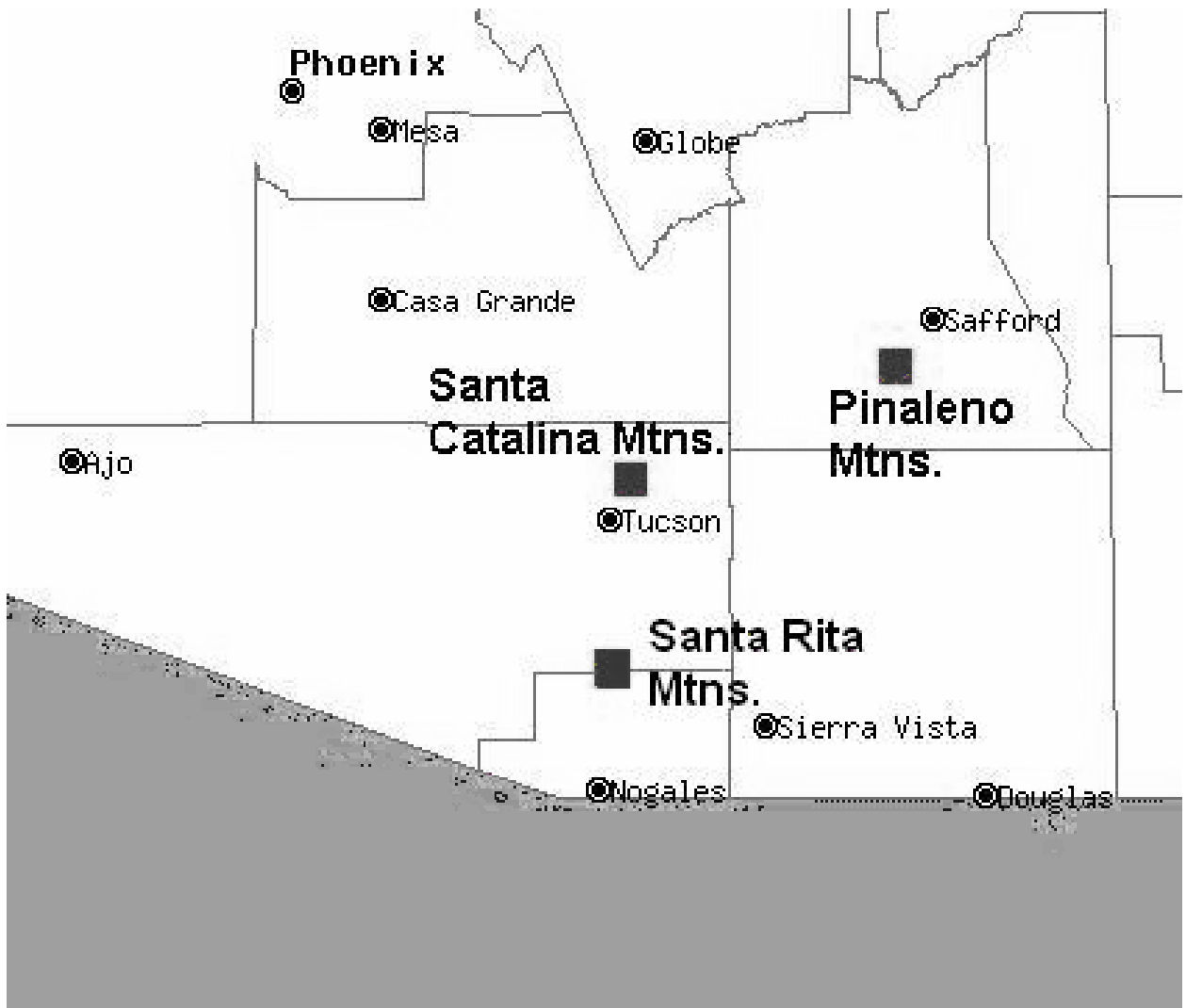


Figure 1: Map displaying locations of Santa Catalina, Santa Rita, and Pinaleno Mountains in southeast Arizona.

SOUTHEAST ARIZONA POST-BURN FLOOD DATABASE FOR TEN BASINS

Watershed	Basin Average Precipitation (inches)	Storm Duration (hours)	General Storm Motion	Time of Concentration (hours)	Rainfall Return Interval (t-years)	Peak Flow of Flood (cfs)	Pre-Burn Peak Flow of Rainfall Return Interval (cfs)
Frye Creek	0.40	0.5	across	0.6	< 1-year	1400 [~]	18.5
Deadman Canyon	1.00	0.5	across	0.5	3-year	5500	67.2
Marijilda Canyon	1.25	0.7	across	0.8	5-year	8470 [♦]	313
Noon Creek	0.94	0.4	across	0.4	2-year	2684 [#]	19
Wet Canyon	0.8	0.7	across	0.3	1-year	1490	7.2
Upper Campo Bonito	1.51	0.5	stationary	0.3	10-year	1900	586
Sabino Creek near Mount Lemmon	1.25	1	stationary	0.6	2-year	350	119
Alder Canyon at Ventana Windmill	1.60	1	down to up	1.2	5-year	3103	1260
Madera Canyon	0.70	0.75	stationary	0.4	< 1-year	1526	224
Romero Canyon	1.60	0.5	up to down	1.1	10-year	9500	1420

Figure 2: Southeast Arizona post-burn flood database for ten basins.

[~] July 27, 2004.

[♦] Value updated based upon October 6, 2004 written communication from USGS (Tadayon, 2004) providing a new peak flow estimate for the flood of August 17, 2004.

[#] Value updated based upon January 24, 2006 survey of high water marks by authors and subsequent slope conveyance.

ADDITIONAL SELECTED BASIN VALUES

Watershed	Location	Modified channel relief ratio (ft/ft)	High severity burn + Moderate severity burn (%)	Average basin elevation above mean sea level (ft/1000)	Drainage area (sq mi)	Pre-burn 5-year peak discharge (cfs)	Post-burn 5-year discharge (cfs)
Frye Creek	Pinaleno Mountains	0.19	61	8.1	4.02	116	8778
Deadman Canyon	Pinaleno Mountains	0.22	51	7.7	4.78	137	11213
Marijilda Canyon	Pinaleno Mountains	0.15	59	7.1	11	313	8470 [♦]
Noon Creek	Pinaleno Mountains	0.24	77	7.7	2.99	86	12149 [#]
Wet Canyon	Pinaleno Mountains	0.26	44	8.1	1.58	45.5	9416 [*]
Upper Campo Bonito	Santa Catalina Mountains	0.07	80	5.5	1.5	376	1219 ^{**}
Sabino Creek near Mount Lemmon	Santa Catalina Mountains	0.07	55	8.2	3.4	278	818
Alder Canyon at Ventana Windmill	Santa Catalina Mountains	0.08	35	6.1	14	1260	3103 ^{***}
Madera Canyon	Santa Rita Mountains	0.22	15	7.2	4	657	4476
Romero Canyon	Santa Catalina Mountains	0.12	34	5.7	7.25	902	6035

Figure 3: Additional selected basin values for study watersheds in the Pinaleno, Santa Catalina, and Santa Rita Mountains. Note: Madera and Romero Canyons recently added and documented in this paper.

[♦] Value updated based upon October 6, 2004 written communication from USGS (Tadayon, 2004) providing a new peak flow estimate for the flood of August 17, 2004.

[#] Value updated based upon January 24, 2006 survey of high water marks by authors and subsequent slope conveyance.

^{*} This value corrected to reflect that event storm was actually a 1-year event.

^{**} This value corrected to reflect Region 13.

^{***} This value corrected to reflect that event storm was actually a 5-year event.

Basin Response
Ratio for 5-Year Events (Post-Burn vs Pre-Burn Flow)

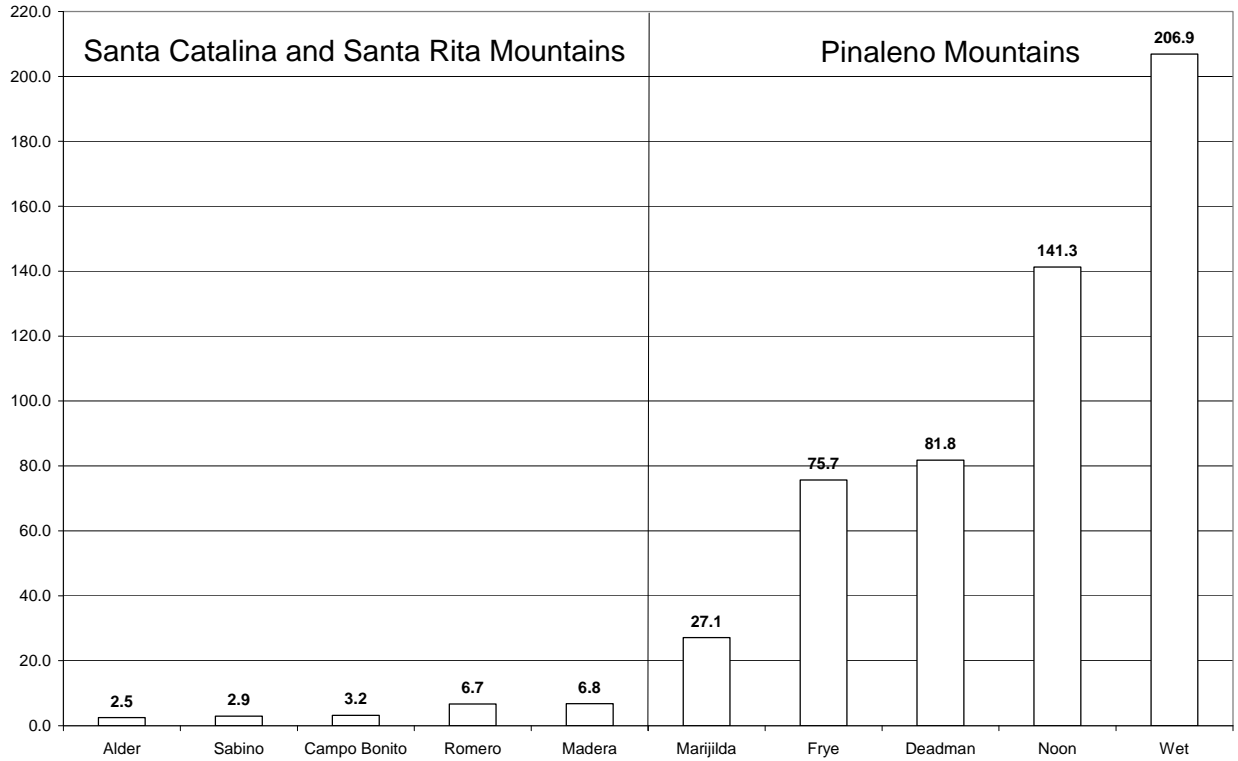


Figure 4: Basin Response under burn conditions for various watersheds in the Santa Catalina, Campo Bonito, Sabino, Alder, and Romero), Santa Rita (Madera), and Pinaleno Mountains (Marijilda, Frye, Noon, Deadman, and Wet).

Madera Creek		
Return Period	Pre-Burn Flow	Post-Burn Flow
2-year	271 cfs (7.67 m ³ /sec)	1846 cfs (52.25 m ³ /sec)
5-year	657 cfs (18.61 m ³ /sec)	4476 cfs (126.67 m ³ /sec)
10-year	1030 cfs (29.17 m ³ /sec)	7017 cfs (198.59 m ³ /sec)
25-year	1660 cfs (47.01 m ³ /sec)	11310 cfs (320.06 m ³ /sec)
50-year	2220 cfs (62.87 m ³ /sec)	15125 cfs (428.03 m ³ /sec)
100-year	2960 cfs (83.83 m ³ /sec)	20166 cfs (570.71 m ³ /sec)
500-year	5040 cfs (142.73 m ³ /sec)	34338 cfs (971.75 m ³ /sec)

Figure 5: Peak flows for Madera Creek. The pre-burn flows were calculated using the National Flood Frequency (NFF) method for Southern Arizona Region 13 (Ries and Crouse, 2002). The maximum flow calculated from Crippen and Bue (1977) method is 30,300 cfs (858.10 m³/sec). Note: The Post-Burn Flow values for events greater than the 10-year event are not considered as reliable as those for the return intervals equal to or less than the 10-year event. These less reliable values were not used in the development of the empirical equation.

Romero Canyon		
Return Period	Pre-Burn Flow	Post-Burn Flow
2-year	372 cfs (10.54 m ³ /sec)	2490 cfs (70.52 m ³ /sec)
5-year	902 cfs (25.54 m ³ /sec)	6035 cfs (170.90 m ³ /sec)
10-year	1420 cfs (40.21 m ³ /sec)	9515 cfs (269.46 m ³ /sec)
25-year	2290 cfs (64.85 m ³ /sec)	15340 cfs (434.43 m ³ /sec)
50-year	3070 cfs (86.94 m ³ /sec)	20600 cfs (583.39 m ³ /sec)
100-year	4090 cfs (115.83 m ³ /sec)	27400 cfs (775.97 m ³ /sec)
500-year	7020 cfs (198.81 m ³ /sec)	47000 cfs (1331.04 m ³ /sec)

Figure 6: Peak flows for Romero Canyon. The pre-burn flows were calculated using the National Flood Frequency (NFF) method for Southern Arizona Region 13 (Ries and Crouse, 2002). The maximum flow calculated from Crippen and Bue (1977) method is 49,200 cfs (1393.34 m³/sec). Note: The Post-Burn Flow values for events greater than the 10-year event are not considered as reliable as those for the return intervals equal to or less than the 10-year event. These less reliable values were not used in the development of the empirical equation.

FRYE CREEK MULTIPLE EVENTS

Date	Basin Average Precipitation	Storm Duration	Rainfall Return Interval	Peak Flow of Flood	Pre-Burn Peak Flow of Rainfall Return Interval	Ratio	Pre-burn 5-year peak discharge	Post-burn 5-year discharge
	Step 1 (inches)	Step 1 (hours)	Step 2 (t-years)	Step 3 (cfs)	Step 4 (cfs)	Step 5 (cfs/cfs)	Step 6 (cfs)	Step 7 (cfs)
2004								
July 27	0.40	0.5	< 1-year	1400	18.5	75.7	116	8778
August 4	1.00	1.0	2-year	1040	26	40	116	4640
August 17	1.30	0.5	5-year	2260	116	19.5	116	2260

Figure 7: Multiple Events For Frye Creek.

Multiple Frye Creek Events

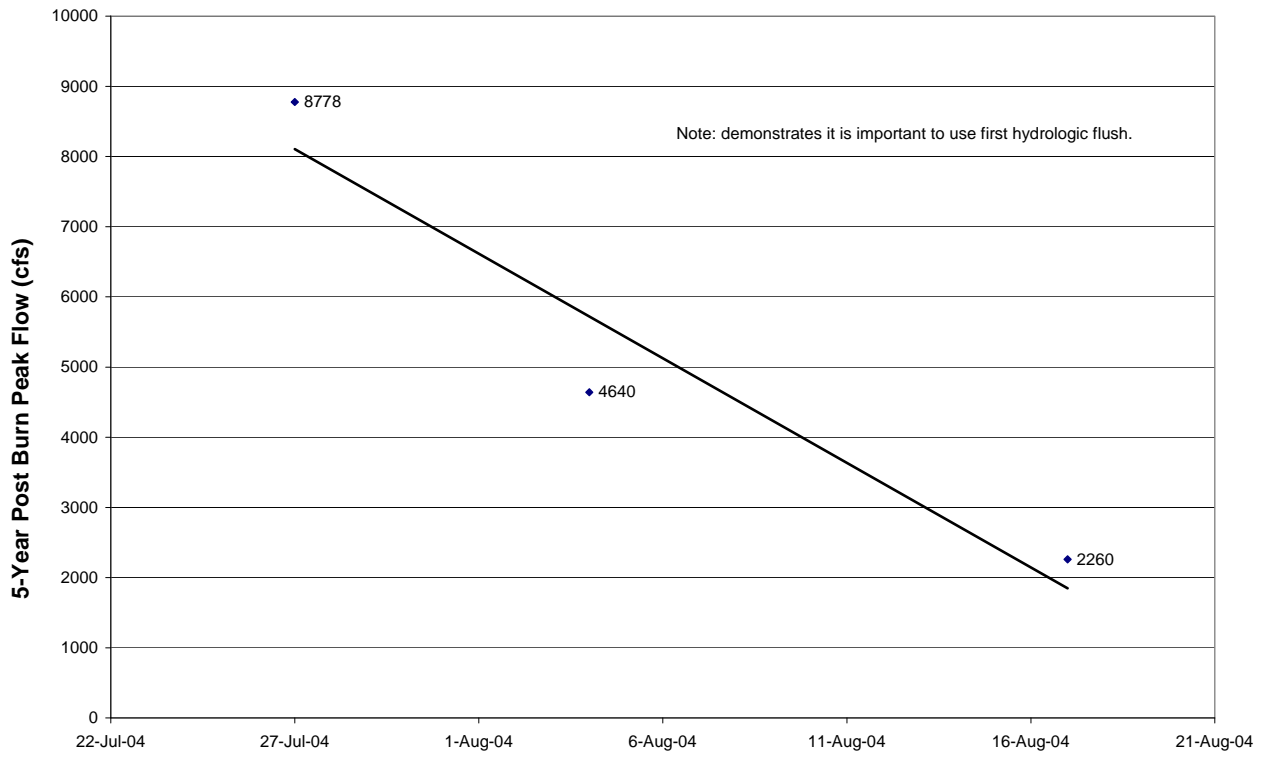


Figure 8: Calculated 5-Year Peak Flows For Sequential Events on Frye Creek.

An Empirical 5-Year Post-Burn Runoff Equation for Southeast Arizona Watersheds

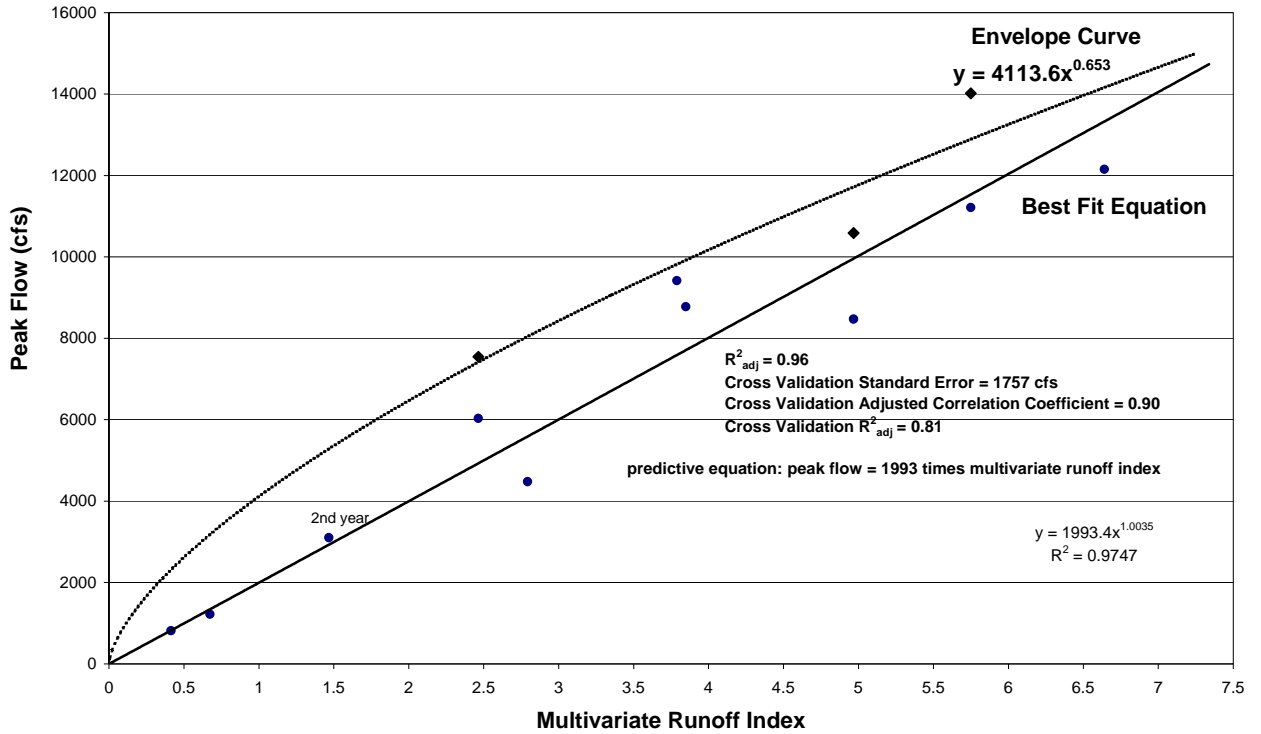


Figure 9: An empirical equation to estimate post-burn runoff during recovery (Southeast Arizona Watersheds). 2nd year = those events that occurred during the second year after the burn; the other 9 events occurred during the first year after the burn. These equations are for small watersheds less than 15 square miles (38.8 square kilometers); and include sites with average basin elevations from 5500 to 8100 feet (1676.4 to 2469 meters) above msl. Multivariate runoff index = $1000(\alpha\psi)^{0.54} \beta^2 \phi^{-1.28}$; where α = high severity burn + moderate severity burn as a fraction of total watershed (square miles/square miles); ψ = total drainage area (square miles); β = modified channel relief ratio (feet/feet); and ϕ = average basin elevation above mean sea level (thousands of feet). Note: α times ψ in above equation = hyper-effective drainage area.

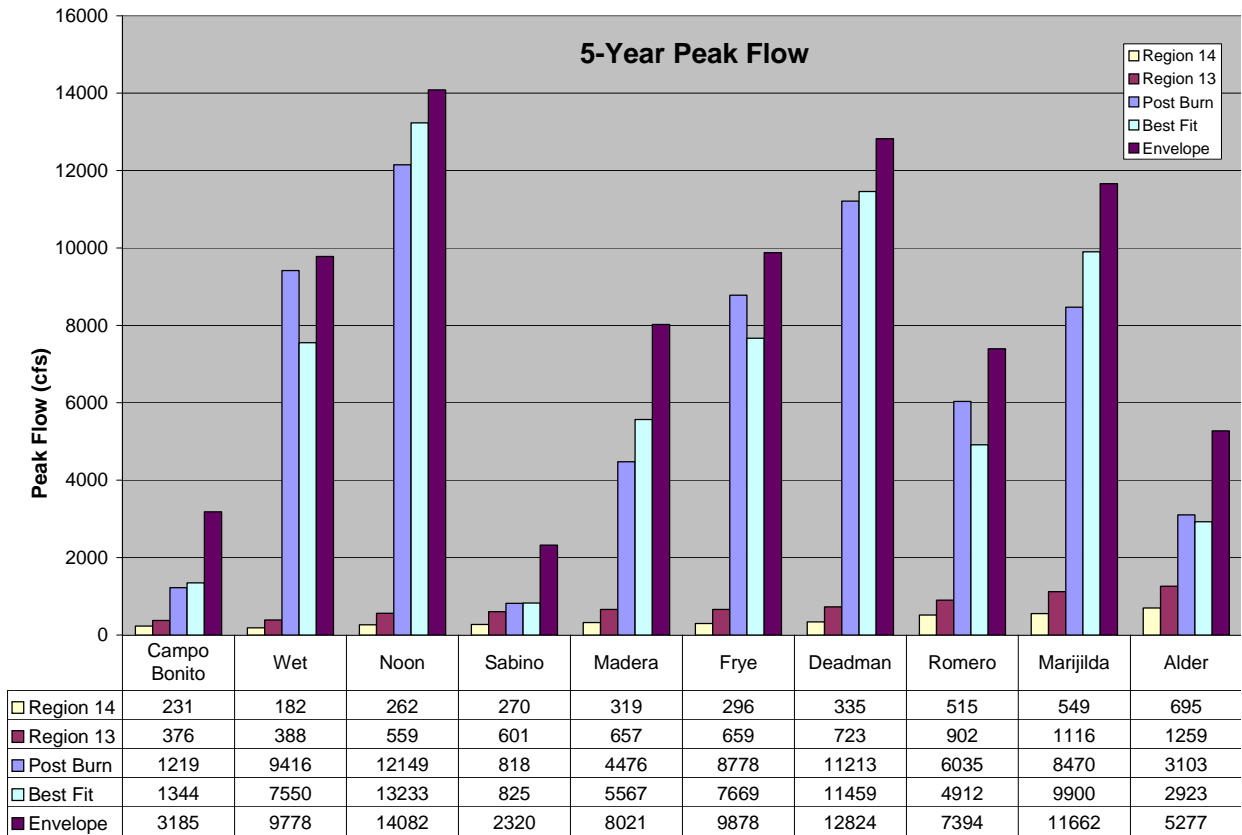


Figure 10: As basin size increases from left to right, the peak flow generally increases using pre-burn equations (yellow/first bar & red/second bar). The Post-Burn equations results are very different (light blue/fourth bar & burgundy/fifth bar). The target post-burn value is shown in blue/third bar. Peak flows are shown in cubic feet per second (cfs).



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