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2011 Wildfire in the Mountainous Terrain of Southeast Arizona: Verification of Empirical Formulas used to Estimate from 1-Year through 10-Year Peak Discharge from Post-Burn Watersheds and Associated Increased Flash Flood Potential of Post-Burn Hyper-Concentrated Flows

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May 2012

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Page iii photograph: Old Sawmill Creek Channel Reach Looking Upstream of the Cross Section. Note: for this basin only one cross section was surveyed.

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Abstract:

In the desert southwest of the United States, wildfire alters the hydrologic response of watersheds greatly increasing the magnitudes and frequency of flash floods. The NOAA National Weather Service is tasked with the issuance of flash flood warnings to save life and property. Tools that allow the weather forecast offices to quickly access the peak flow magnitude and flood potential from burned areas are highly desirable. The application of readily available topographic and burn severity data make this possible through a series of empirical equations.

In studies of post-burn peak flows throughout southeast Arizona, Reed and Schaffner have demonstrated that future peak flows can be estimated for burned basins using a multivariate runoff index defined by several watershed characteristics. Therefore, a series of empirical equations were developed to estimate peaks flows with 1-year through 10-year recurrence intervals from both small and larger sized burned basins. The basin properties used are 1) the hyper-effective drainage area (the area of the basin with moderate and high severity burn, in square miles); 2) the modified channel relief ratio; and 3) the mean basin elevation, in thousands of feet above mean sea level. The modified channel relief ratio in feet/feet is the average slope of the basin along the first order channel measured from 1,250 feet below the ridge to the basin outlet.

Five basins in Cochise County, Arizona burned by either the 2011 Horseshoe II Fire or the 2011 Monument Fire are used to evaluate the usefulness of the Reed-Schaffner Equation 12 to forecast post-burn peak flows and associated increased flash flood potential. An estimate of post-burn peak flows for these basins with an emphasis on the first significant flash flood that occurred were evaluated. It is the experience of the authors that these "first flush" peak flows are often hyper-concentrated flows. Thus often peaks from post-burn basins are essentially sediment-carrying water flows with entrained post-burn debris. Indirect measurement of observed peak flows are compared to the values obtained from Equation 12 for five basins using the return interval of the causative rainfall events. Additionally, the values obtained from Equation 13 are evaluated for special circumstances. This report provides the first verification for this southeast Arizona Sky Island Complex post-burn flood forecasting technique.

Three basins burned by the 2011 Wallow Fire are also used to evaluate the usefulness of the Reed-Schaffner Equation 12 to forecast post-burn peak flows and associated increased flash flood potential. Additionally, the values obtained from Equation 13 are evaluated for special circumstances. For this burned area the channel relief ratio was used unmodified. This modification of Equations 12 and 13 was done because the Wallow Fire occurred within the Central Arizona Highlands outside of the area for which the original equations were developed (the Sky Island Complex of southeastern Arizona). This report provides the first verification for this Central Arizona Highlands post-burn flood forecasting technique.

INTRODUCTION

Shortly after three Arizona fires in 2011 (Horseshoe II, Monument, and Wallow, Figure 1) three reports were written by Reed, Schaffner, and Kahler (2011a, b, & c) to provide an estimate of post-burned increased flash flood risk. These fires occurred within the Colorado Basin River Forecast Center area of responsibility (Figure 2). The 5-year increased flash flood risk determined in those studies is shown in Figures 3-7. The Wallow Wildfire basins are grouped by HEC-RAS (Figure 5), Apache County (Figure 6), and WILDCAT 5 (Figure 7). The BAER teams and staff of the Arizona Water Science Center, United States Geological Survey provided necessary data on the burned basins required to complete these analyses. This report provides verification for the initial use of these post-burn flood forecasting techniques for the Sky Island[5] Complex of southeastern Arizona (within the Basin and Range) and the Central Arizona Highlands (Figure 1).

The eight Arizona basins studied in this report were burned by the 2011 Horseshoe II Fire (Figure 8), the 2011 Monument Fire (Figure 9), or the 2011 Wallow Fire (Figure 10). This report provides an estimate of post-burn peak flows for these basins with an emphasis on the first significant flash flood that occurred. It is the experience of the authors that these "first flush" peak flows are often hyper-concentrated flows. Thus the peaks from each basin are essentially sediment-carrying water flows with entrained post-burn debris. Indirect measurement of observed peak flows are compared to the values obtained from Reed-Schaffner Equation 12 for the eight basins using the return interval of the causative rainfall events. Reed-Schaffner (2008) suggested using this envelope curve[6] for most applications. However, Equation 13[7], the corresponding best-fit curve, may work best for drainage areas less than 1 square mile and/or storm events with return intervals less than 1 year. Therefore, Equation 13 will be evaluated for these limited special circumstances.

METHODOLOGY

In studies of post-burn hyper-concentrated flows throughout southeast Arizona, Reed and Schaffner (2007 and 2008) have demonstrated that peak flows can be estimated for burned basins using a multivariate runoff index defined by several watershed characteristics. Therefore, a series of empirical equations were developed by Reed to estimate peaks flows with 1-year through 10-year recurrence intervals from both small and larger sized burned basins. The basin properties used are 1) the hyper-effective drainage area, the area of the basin with moderate and high severity burn, in square miles, 2) the modified channel relief ratio, and 3) the mean basin elevation, in thousands of feet above mean sea level. The modified channel relief ratio in feet/feet is the average slope of the basin along the first order channel measured from 1,250 feet below the ridge to the basin outlet. However, for basins less than 1 square mile, the channel relief ratio was used unmodified. For such small basins the authors have found the modified channel relief ratio too unstable to use (i.e., sometimes it would work and sometimes it would not), and the channel relief ratio more reliable (i.e., always worked). This is perhaps due to the modified channel relief ratio approaching zero or becoming negative for such small basins when 1,250 feet is subtracted from the basin's rise or due to a calculated slope based on a very short

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[5] Sky Island ranges of Arizona, New Mexico, and adjacent Sonora and Chihuahua are shown on Figures 11 and 94.

[6] Equation 12 is an envelope curve that provides the largest estimate, i.e., Equation 12 values are greater than equation 13 values. Equation 13 is a best-fit curve.

[7] Equation 3 (mentioned in other reports by the authors) and Equation 13, although derived independently and numbered differently, are the same equation

unrepresentative run. Additionally, for the three basins in the Wallow Fire burned area, the channel relief ratio was used unmodified. This was done because the Wallow Fire occurred within the Central Arizona Highlands outside of the area for which the original equations were developed (the Sky Island Complex of southeastern Arizona).

Increased Flash Flood Risk

As described in Reed, Schaffner, and Kahler (2011c) to evaluate the increase in flash flood risk, the basins are ranked by post-burn yield (cfs per square mile) and assigned an increased flash flood risk. Flash floods pose a significant threat to life and property in and downstream of burned areas. Although often the impacts of post-burn flash floods are documented at the wilderness or wildland urban interface, this methodology does not seek to determine if a given structure is at risk of damage or destruction. Such a determination is beyond the scope of this methodology or the expertise of the authors. Any statements about increases in post-burn flash flood risks are general in nature and based on a comparison of pre- and post-burn peak flows. As defined for the purpose of this report, variables affecting increased flash flood risk are size of basin, percent of basin with high and moderate burn severity, magnitude of storm, modified channel relief ratio, and mean basin elevation.

The first attempt by the authors to use the previous work of Reed and Schaffner (2007 and 2008) and the work of Schaffner and Reed (2005a & b) to assign flash flood risk for post-burn basins was done shortly after the Horseshoe II Fire. The technique was then refined after each subsequent 2011 burn as more data became available. As described in Reed, Schaffner, and Kahler (2011c) basins with yields greater than 2000 cfs per square mile are assigned extreme increased flash flood risk, basins between 2000 and 1000 cfs per square mile are assigned high increased flash flood risk, basins between 1000 and 100 cfs per square mile are assigned moderate increased flash flood risk, and basins below 100 cfs per square mile are assigned low increased flash flood risk. This method can be used for 1-year, 2-year, 5-year, and 10-year events. Event specific figures, like Figures 3-7, can then be developed.

In the ranking of the basins, it was the intent of the authors that the risk categories would correspond to the following possible conditions: low would include flows within banks; moderate would include flows near bankfull, both within and out of banks; high would include flood flows; and extreme would include record flows. Therefore, as more data becomes available, breaking points between these categories made need to be refined.

Post Burn Flash Flood Rainfall Thresholds

Rainfall thresholds are usually based on either return interval of causative events or are related to a previously determined threshold stage (such as bankfull or flood). When a stage is used it is converted to flow for modeling. For ungaged streams the stage-discharge relationship is often not known thus a return interval is used. The post-burn flash flood rainfall thresholds for the Chiricahua, Huachuca & White Mountains will be calculated using the increased flash flood risk of the 8 documented events. The values should be considered speculative and should be modified as more events are documented within these mountain ranges.

Survey

Three basins that burned in the Monument Fire and two basins that burned in the Horseshoe II Fire were surveyed using a Leica Rugby 100LR Leveling Laser[8]. The surveying was done to produce cross sections for each basin to calculate post-fire peak discharge. The surveyed reach was selected by locating a relatively

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[8] The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the National Weather Service.

straight channel reach, with visible high water marks on at least one of the two banks, and flow contained within only one channel. The length of the reaches surveyed equaled approximately the sum of the total distance of the cross sections. All basins had three cross sections surveyed, except Old Sawmill Creek a tributary of Carr Canyon. A suitable reach within Carr Canyon that met the criteria for surveying multiple cross sections could not be located. At each cross section elevation readings were taken across the channel at increments to best represent the channel morphology. Also measured was the channel width, the wetted perimeter, distance between cross sections, and slope of surveyed reach. At each survey location a 100 foot datum was set using a semi-permanent object, such as large tree or boulder, that could be located if there was a need to resurvey the reach.

Slope-Area Method

Unless noted otherwise, the survey data was used to calculate the flow indirectly by the slope-area method. The slope-area method is a common technique for determining discharge indirectly (Rantz and others, 1982). The water slope through the channel reach was determined from the surveyed high water marks. The Manning flow equation was used:

$$Q = 1.486/n\ A\ R^{2/3}\ S^{1/2}$$

Where: Q = flow, cfs

n = roughness coefficient, a.k.a., Manning’s n

A = cross-sectional area of wetted channel, ft^2

R = hydraulic radius A/wp, ft

wp = wetted perimeter, ft

S = water surface slope.

Geographical Information Systems

The application of readily available topographic and burn severity data make the use of empirical equations possible. The use of GIS information is essential to 1) basin delineation, 2) determination of basin characteristics, and 3) use of radar precipitation data.

Basin Delineation: Initial data for previous reports were provided by the USFS BAER Teams. For this report, basins were delineated using stream cross-sections provided by the NWS Forecast Office in Tucson, AZ, as the basin outlets. In addition to the basin outlets, Digital Elevation Models (DEM) were acquired from the USGS and used within the USDA's Automated Geospatial Watershed Assessment Tool (AGWA) and ESRI's ArcGIS software to delineate basin perimeter along with stream channels.

Basin Characteristics: Basin perimeters were used to calculate the total basin area along with the total area of the moderate and high burn severity area (e.g. Hyper-Effective Drainage Area) within the specified basin. A maximum and minimum basin elevation was calculated using Google Earth and cross-referenced against the USGS DEM file. The basin's stream length was also calculated using Google Earth with AGWA/ArcGIS delineated stream channels overlaid. The basin elevation difference and stream length were used to calculate the unmodified or modified channel relief ratio where appropriate.

Basin Precipitation: Where radar precipitation data was available, a grid was generated over the basin that aligned with the radar grid. The centroid of each precipitation grid cell was used to retrieve precipitation return intervals from the NOAA Atlas website.

Rainfall

Rainfall estimates, for the basins burned by the Horseshoe II and the Monument Fires, were taken from the NWS WSR-88D radar located in the Empire Mountains southeast of Tucson. The rainfall estimates were derived using the legacy radar precipitation processing algorithms since the events all took place prior to the installation of dual-pol radar in Tucson. Radar rainfall estimates are most commonly computed in 4-minute increments while in precipitation mode. The radar rainfall closest to the time of concentration[9] for the basin in question was used. For example, if a given basin has a 29-minute time of concentration and radar rainfall totals are 28- and 32-minute, then the 28-minute radar rainfall total would be used. Likewise, if the radar rainfall totals were 26- and 30-minute, then the 30-minute would be used. Rain gage data if available in or nearby was included in the paper to locally compare to the radar rainfall estimates.

Basins burned by the Wallow Fire, could not utilize radar rainfall estimates since the area in question is too far from any of the NWS radars in Arizona or New Mexico and either has 1) no precipitation coverage or 2) precipitation coverage of poor quality. As a result, rain gage data was used. The rain gage used was either within the study basins or in close proximity in that the three studied Wallow Fire basins were contiguous (Figure 10) and North Fork and South Fork of Thomas Creek had basins less than 1 square mile.

Return Intervals

Precipitation frequency was obtained using NOAA's Precipitation Frequency Data Server (http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=az). The server provides point precipitation frequency estimates based on a user provided latitude and longitude. The dataset is NOAA Atlas 14, volume 1, version 5. Precipitation frequency estimates provided include both a single value for each average recurrence interval as well as the upper and lower bounds for the 90% confidence interval. Precipitation frequency like the rainfall corresponded to the time of concentration for the basin in question. For the basins burned by the Horseshoe II and the Monument Fires, precipitation frequency was obtained for each grid. For the basins burned by the Wallow Fire, precipitation frequency was obtained for the basin centroid and outlet.

Reed-Schaffner Equations 12 and 13

Equations 12 and 13 were developed using 11 post-burn watersheds in 3 mountain ranges within the Sky Island Complex of Southeastern Arizona (Figure 11). Both equations are plotted on Figure 12. The equations begin to quickly converge below 1,100 cfs (i.e., when mvi values are low).

Equation 12 is an envelope curve with the following form:

$$\mathbf{Q_t = 55.819(mvi_1)^2 + 2138.9(mvi_1)}.$$

Where the multivariate runoff index (mvi) for 1 to 10 year events is

$$\mathbf{(\mathit{mvi_1}) = 1000(\alpha\psi)^{0.51}\beta^{1.91}\varphi^{-1.99}\lambda^{0.78}}$$

and α = fraction of total watershed with moderate or greater burn severity (square miles/square miles); ψ = total drainage area (square miles); β = modified channel relief ratio (feet/feet); φ = average basin elevation above mean sea level (thousands of feet); and λ = recurrence interval of rainfall (t-years). Equation 12 applies where: 1) the storm duration is greater or equal to the basin's time of concentration, *the time of concentration is the time it takes for water to travel from the most distant point of a watershed to the outlet or other point of interest (Chow, 1964)*; 2) the event is the first major flush after the fire; 3) water repellent soils are present; and 4) the core of the storm moves over at least a portion of the hyper-effective drainage area. Caution should be used when applying Reed-Schaffner Equation 12 to watersheds with 1) drainage area less than 1 square mile[10], 2) drainage area greater than 20 square miles, 3) elevation change less than 1500 feet, 4) lower mean basin

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[9] Calculated using the formula: $T_C = 60(L^{1.15}/7700H^{0.38})$, where L= basin stream length in feet, H = basin elevation change in feet, and T_C = time of concentration in minutes.

[10] For basins with drainage areas less than 1 square mile, the channel relief ratio should be used unmodified.

elevations where vegetation recovery may occur quickly, and 5) higher mean basin elevations with predominately shallow soils and impermeable rock outcrops. The range of watersheds used to develop equations 12 and 13 is 1.5 square miles to 21.6 square miles.

Equation 13 is the best-fit equation corresponding to Equation 12 and has the following form:

$$\mathbf{Q_t = 1422.5(mvi_1)^{0.998}}.$$

Equation 13 may work best for drainage areas less than 1 square mile[8] and/or storm events with return intervals less than 1 year. However, caution should be used when applying any Reed-Schaffner equation to these conditions. If the basin is greater than 1 square mile and the return interval of the storm is <u>known</u> then Equation 12 should be used.

MILLER CANYON - JULY 10, 2011

On July 10, 2011 rainfall started at 19Z and ended at 23Z (Figure 13 is a USFS image of rain falling over Miller Canyon on July 10, 2011). The 4-hour storm total ranged from 0.5 to 3.0 inches over this Huachuca Mountains basin (see Figure 14) resulting in debris flows (reported upstream of studied reach at bed and breakfast) and flash flooding (observed downstream of studied reach). See Youberg and Pearthree (2011) for additional discussion of post-fire floods and debris flows. On October 18, 2011 to assess the magnitude of the flooding on July 10, high water marks and cross section information were collected by USGS and NWS approximately 1 mile upstream of several Broken Arrow Road homes that were flooded during the event. Figure 15 is a summary of channel characteristics. Figure 16 shows the channel upstream of the surveyed reach. Flood depth ranged from 4.5 to 5.6 feet within the three surveyed cross sections. The USGS used the collected data in U.S. Army Corps of Engineers HEC-RAS step-backwater model to estimate the peak flood flow as 4,900 cfs +/- 20%. This method is a standard indirect technique for estimating a peak flow for an ungaged stream for reaches with steep slopes and mixed flow regimes. Within the studied reach supercritical conditions occurred (Froude number ranged from 1.01 to 1.82). Within the reach the velocity ranged from 11.6 to 17.2 ft/sec. A GIS analysis of the basin above the surveyed cross sections provided the basin characteristics shown in Figure 17. The time of concentration for the basin was calculated from these data to be 29 minutes.

Impact of 2011 Flash Flood

There were many impacts due to the flooding in Miller Canyon. Several homes within Miller Canyon and downstream of the canyon east of Highway 92 were flooded. The evidence of high flows in Miller Canyon can be seen in Figure 18; notice the debris on the car port roof and highwater mark stain on the two shown sides of the building. This photo was provided courtesy of BAER team and was taken the day after the lower Miller Canyon flash flood. The Tombstone water pipeline in Miller Canyon was damaged, including the spring collection basins. Cochise County Highway and Floodplain Department documented having to clear roads due to flooding. For the basin above the surveyed site, the increased flash flood risk was high.

Verification for Miller Canyon

Figure 19 is a burn severity map for the basin and Figure 20 provides the raw radar for the highest 30 minute rainfall during the 4-hour storm. The core of the storm moved over grids 1A-C, 2A-D, 3B-D, 4C, 5C and 6B. The median 30-minute raw radar storm amount for the basin (1.25 inches) is within the range provided for the 2-year 30-minute return interval storm (Figure 20). For determining the median only those grids with moderate and high severity burns were used. For this basin all grids shown on Figure 19 met this criterion. The centroid grid received 1.50 inches in 30 minutes (a strong 2-year 30-minute event). Within grid 1B, but outside of the basin, a gage reported 1.22 inches for the same time period as the radar image. The raw radar is 1.45 inches for grid 1B. The authors decided not to adjust the radar values using this gage because: 1) the gage is outside the basin, 2) it was unclear how many grids to adjust, and 3) tipping bucket rain gages are known to underestimate total rainfall during high intensity rainfall events. Using Equation 12, the expected flow from the hyper-effective drainage area is 3,964 cfs. This accounts for the runoff from 78% of the basin. To obtain the runoff from the entire basin we need to add 22% of the basins pre-burn 2-year runoff. The basins pre-burn runoff is 254 cfs calculated using USGS Region 13 equations for Southern Arizona (Thomas, 1997). The resulting runoff for the entire basin is 3,964 cfs plus 56 cfs = 4,020 cfs +/- 25%.

Equation 12 Method: A comparison of the Equation 12 method and the indirect method values is provided in Figures 21 and 22. The amounts shown in Figures 21 and 22 indicate that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported for both values. Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

Increased Flash Flood Risk: The observed post-burn hyper-concentrated peak flow of 4,900 cfs was 19 times greater than the pre-burn 2-year peak flow of 254 cfs. As shown in Figure 4 the 5-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011b) to be extreme for the lower portion of Miller Canyon. The corresponding 2-year increased flash flood risk was determined to be high by Reed, Schaffner, and Kahler (2011b). Using 4,900 cfs / 3.57 square miles = 1,373 cfs/sq. mi., the 2-year increased flash flood risk for the Miller Canyon basin above the cross sections would be high.

Return Interval: Using Equation 12 (the preferred equation), to obtain a mean value of 4,900 cfs a return interval of approximately 2.6 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

EAST TURKEY CREEK - AUGUST 15, 2011

On August 15, 2011 rainfall occurred over essentially the upper two-thirds of this Chiricahua Mountains basin (Figure 23). This area of rainfall roughly corresponds to the area with moderate and high severity burn (Figure 24). Figure 23 is from 2103 to 2145Z with rainfall amounts of 0.10 to 0.75 inches in 42 minutes. On November 7, 2011 to assess the magnitude of the flooding on August 15, high water marks and cross section information were collected by the NWS approximately 0.75 mile upstream of homes at the southern edge of Paradise, AZ. Figure 25 is a summary of channel characteristics and calculated values. Figure 26 shows the surveyed channel reach looking upstream of cross section 2 towards cross section 1. Flood depth ranged from 2.2 to 4.6 feet within the three surveyed cross sections. The NWS used the collected data and the slope-area method to estimate the peak flood flow as 470 cfs +/- 30%. Within the reach the average velocity was 8.4 ft/sec. A GIS analysis of the basin above the surveyed cross sections provided the basin characteristics shown in Figure 27. The time of concentration for the basin was calculated from these data to be 41 minutes.

Impact of 2011 Flash Flood

The authors found no reports of damage from this event. This was likely due to Cochise County and the Natural Resource Conservation Service working with residents to install flood mitigation measures, such as sandbags and K-rails (NRCS, 2011). From notes made during Chiricahua surveys: East Turkey Creek did seem to experience high flows, but that was downstream of the survey location on private land. We surveyed just upstream of Paradise on Forest Service Land… East Turkey Creek has several side canyons entering into the main channel within the Paradise area. For the basin above the surveyed site, the increased flash flood risk was low/moderate.

Verification for East Turkey Creek

Figure 24 is a burn severity map for the basin and Figure 28 provides the raw radar for the highest 42 minute rainfall during the storm. The core of the storm moved over grids 6B-D and 7B. The median 42-minute raw radar storm amount for the basin (0.20 inches) is less than the range provided for the 1-year 30-minute return interval storm (Figure 28). For determining the median only those grids with non-zero precipitation amounts were used. As previously stated, these grids were essentially the same as those grids with moderate and high severity burn. The grids that received 0.75 inches in 42 minutes were still less than the corresponding 0.81 inches lower estimate for the 1-year 30-minute return interval. For return intervals less than 1 year, the 1-year return interval is to be used (Reed and Schaffner, 2008). Using Equation 12, the expected flow from the hyper-effective drainage area is 852 cfs. This accounts for the runoff from 33% of the basin. This can be assumed the runoff from the entire basin since the remaining portion of the basin received either no rainfall or very little. The resulting runoff for the entire basin is therefore 850[11] cfs +/- 25%. Using the same procedure for Equation 13 the resulting runoff for the entire basin is 560 cfs +/- 25%.

Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 29. The amounts shown in Figure 29 show that the Equation 12 method would overestimate by 30 cfs the indirectly observed peak flow from this post-burn basin if a 1-year return interval is used. Since the event was less than a 1-year 40-minute storm we would expect Equation 12 method to overestimate the storm. However, the values are close and therefore, Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 30. The amounts shown in Figure 30 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The mean Equation 13 method value for the 1-year storm is greater than the mean indirect method value and less than the higher indirect method value. Also the lower Equation 13 method value is greater than the lower indirect method value. Equation 13 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin when storm events have return intervals less than 1 year.

Increased Flash Flood Risk: If we assume a 1-year event with a pre-burn peak flow half the pre-burn 2-year peak flow of 103 cfs[12], then the post-burn hyper-concentrated peak flow of 470 cfs was 9 times greater than the pre-burn 1-year peak flow of 51.5 cfs. The authors realize that this assumption is an oversimplification of the relationship between 1-year and 2-year peaks; however, such an assumption seemed reasonable for the illustrative purposes of this report. As shown in Figure 3 the 5-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011a) to be high for East Turkey Creek. A 1-year increased flash flood risk was not previously determined. Using 470 cfs / 4.38 square miles = 107 cfs / sq. mi., the 1-year increased flash flood risk for this East Turkey Creek basin would be moderate. Using 470 cfs / 1.43 square miles (the area that received rainfall) = 329 cfs / sq. mi., the 1-year increased flash flood risk for this East Turkey Creek basin would be moderate.

Return Interval: Using Equation 12 (the preferred equation), to obtain a mean value of 470 cfs a return interval of 0.475 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

ASH CANYON - AUGUST 23, 2011

On August 23, 2011 rainfall occurred over this Huachuca Mountains basin (Figure 31). See Youberg and Pearthree (2011) for discussion of post-fire floods and debris flows. The area of the basin with moderate and high severity burn is shown in Figure 32. Figure 31 is from 0057Z to 0124Z with rainfall amounts of 0.20 to 1.40 inches in 27 minutes. On November 28, 2011 to assess the magnitude of the flooding on August 23, high water marks and cross section information were collected by the NWS. Figure 33 is a summary of channel characteristics and calculated values. Figure 34 shows the surveyed channel reach looking upstream of cross section 3. Flood depth ranged from 1.5 to 4.1 feet within the three surveyed cross sections. The NWS

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[11] By convention rounded down from 852.

[12] Calculated using USGS Region 14 equations for Upper Gila Basin (Thomas, 1997).

used the collected data and the slope-area method to estimate the peak flood flow as 1,070 cfs +/- 30%. Within the reach the average velocity was 11.0 ft/sec. A GIS analysis of the basin above the surveyed cross sections provided the basin characteristics shown in Figure 35. The time of concentration for the basin was calculated from these data to be 26 minutes.

Impact of 2011 Flash Flood

According to Cochise County the only flooding impacts in Ash Canyon was damage to roads. Cochise County Highway and Floodplain Department documented having to fix washouts alongside of culverts caused by flooding. They said most of the homes were burned so there was no flooding of occupied structures. For the basin above the surveyed site, the increased flash flood risk was moderate.

Verification for Ash Canyon

Figure 32 is a burn severity map for the basin and Figure 36 provides the raw radar for the highest 27 minute rainfall during the storm. The core of the storm moved over grids 3C-E, 4B-E and 5B-D. The median 27-minute raw radar storm amount for the basin (0.75 inches) is less than the range provided for the 1-year 30-minute return interval storm (Figure 36). For determining the median only those grids with moderate and high severity burns were used. For this basin all grids shown on Figure 31 met this criterion. The grids that received 1.20 to 1.40 inches in 27 minutes (approximately a third of the basin centered over the south fork of Ash Creek) were greater than the corresponding upper estimate for the 1-year 30-minute return interval. However, the peak flow was estimated below the confluence of the north and south forks. As stated previously, the median for the total basin was less than the lower value for the 1-year storm. For return intervals less than 1 year, the 1-year return interval is to be used (Reed and Schaffner, 2008). Using Equation 12, the expected flow from the hyper-effective drainage area is 2,881 cfs. This accounts for the runoff from 91% of the basin. To obtain the runoff from the entire basin we need to add 9% of the basins pre-burn 1-year runoff. The basins pre-burn runoff is 136 cfs calculated using USGS Region 13 equations for Southern Arizona (Thomas, 1997). Since there are no 1-year equations half of the 2-year value of 272 cfs was used. The resulting runoff for the entire basin is 2,881 cfs plus 12 cfs = 2,895 cfs +/- 25%. Using the same procedure for Equation 13 the resulting runoff for the entire basin is 1,865 cfs +/- 25%.

Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 37. The amounts shown in Figure 37 shows that the Equation 12 method would overestimate by 780 cfs the indirectly observed peak flow from this post-burn basin if a 1-year return interval is used. However, since the event was less than a 1-year 26-minute storm we would expect the Equation 12 method to overestimate the storm.

Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 38. The amounts shown in Figure 38 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower Equation 13 method value for the 1-year storm is essentially the same as the higher indirect method value (within a 10 cfs rounding error). The Equation 13 method is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin when storm events have return intervals less than 1 year.

Increased Flash Flood Risk: If we assume a 1-year event with a pre-burn peak flow half the pre-burn 2-year peak flow of 272 cfs, then the post-burn hyper-concentrated peak flow of 1,070 cfs was 8 times greater than the pre-burn 1-year peak flow of 136 cfs. As shown in Figure 4 the 5-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011b) to be extreme for Ash Canyon. The corresponding 2-year increased flash flood risk was also determined to be extreme by Reed, Schaffner, and Kahler (2011b). A 1-year increased flash flood risk was not previously determined. Using 1,070 cfs / 4.04 square miles = 265 cfs/sq. mi., the 1-year increased flash flood risk for this Ash Canyon basin would be moderate.

Return Interval: Using Equation 12 (the preferred equation), to obtain a mean value of 1,070 cfs a return interval of 0.285 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

OLD SAWMILL CREEK - JULY 10, 2011

On July 10, 2011 rainfall occurred over this Huachuca Mountains basin (Figure 40). See Youberg and Pearthree (2011) for discussion of post-fire floods and debris flows. The area of the basin with moderate and high severity burn is shown in Figure 39. Figure 40 is from 2:00 PM to 2:18 PM MST with rainfall amounts of 0.10 to 1.25 inches in 18 minutes. Old Sawmill Creek is a tributary of Carr Canyon and is adjacent to Miller Canyon (Figure 9). On November 28, 2011 to assess the magnitude of the flooding on July 10, high water marks and cross section information were collected by the NWS. Figure 41 is a summary of channel characteristics. The figure on page iii of this report is the surveyed channel reach looking upstream of the cross section. Figure 42 shows the surveyed channel reach looking downstream of the cross section. For this basin only one cross section was surveyed because it was difficult finding high water marks and an area without split flow. Average flood depth was 5.8 feet at cross section. The NWS used the collected data and the slope-area method to estimate the peak flood flow as 1,620 cfs +/- 30%. Within the cross section the average velocity was 10.4 ft/sec. A GIS analysis of the basin above the surveyed cross section provided the basin characteristics shown in Figure 43. The time of concentration for the basin was calculated from these data to be 18 minutes.

Impact of 2011 Flash Flood

There were reports of a bed and breakfast being flooded and several other homes in the canyon having damage to yards (Arizona Daily Star Article: Water floods area denuded by fire, damaging 4 homes, July 12, 2011). Cochise County Highway and Floodplain Department documented having to clear roads due to flooding. Figure 44 shows flood debris at the bridge in Carr Canyon approximately 0.2 mile upstream of the cross section. This photo was provided courtesy of BAER team and was taken the day after the Carr Canyon flash flood. The increased flash flood risk was high in this isolated area.

Verification for Old Sawmill Creek

Figure 40 is a burn severity map for the basin and Figure 45 provides the raw radar for the highest 18 minute rainfall during the storm. The core of the storm moved over grids 6A-D, 7A-D, and 8A-B. The median 18-minute raw radar storm amount adjusted for 15 minutes for the basin (0.95 inches) is within the range provided for the 2-year 15-minute return interval storm (Figure 45). For determining the median only those grids with moderate and high severity burns were used. For this basin grids 3A, 3C, 4A-C, 5A-D, 6A-E, 7A-D, and 8A-B shown on Figure 40 met this criterion. The centroid grid received 0.79 inches in 15 minutes (a weak 2-year 15-minute event). Within grid 5D, but outside of the basin, a gage reported 1.03 inches for the same time period as the radar image. The raw radar is 0.95 inches for grid 5D. The authors decided not to adjust the radar values using this gage because: 1) the gage is outside the basin, and 2) it was unclear how many grids to adjust. Using Equation 12[13], the expected flow from the hyper-effective drainage area is 4,010 cfs. This accounts for the runoff from 59% of the basin. To obtain the runoff from the entire basin we need to add 41% of the basins pre-burn 2-year runoff. The basins pre-burn runoff is 107 cfs calculated using USGS Region 13 equations for Southern Arizona (Thomas, 1997). The resulting runoff for the entire basin is 4,010 cfs plus 44 cfs = 4,055 cfs +/- 25%. Using the same procedure for Equation 13[10] the resulting runoff for the entire basin is 2,590 cfs +/- 25%.

Equation 12 Method: A comparison of the Equation 12 method and the indirect method values is provided in Figure 46. The amounts shown in Figure 46 shows that the Equation 12 method would overestimate the indirectly observed peak flow from this post-burn basin if a 2-year return interval is used. The lower Equation 12 method value for the 2-year storm is greater than the higher indirect method value by 935 cfs. The amounts shown in Figure 46 indicate that Equation 12 can not be successfully used to predict the indirectly observed peak flow from this post-burn basin with a drainage area less than 1 square mile.

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[13] For basins with drainage areas less than 1 square mile, the channel relief ratio should be used unmodified.

Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 47. The amounts shown in Figure 47 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower Equation 13 method value for the 2-year storm is greater than the mean indirect method value and less than the higher indirect method value. Equation 13 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin with a drainage area less than 1 square mile.

Increased Flash Flood Risk: The observed post-burn hyper-concentrated peak flow of 1,620 cfs was 15 times greater than the pre-burn 2-year peak flow of 107 cfs. As shown in Figure 4 the 5-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011b) to be extreme for the upper portion of Carr Canyon. The corresponding 2-year increased flash flood risk was determined to be high by Reed, Schaffner, and Kahler (2011b). Using 1,620 cfs / 0.79 square miles = 2,051 cfs/sq. mi., the 2-year increased flash flood risk for this Carr Canyon basin would be high.

Return Interval: Using Equation 13 (the preferred equation for basins less than 1-square mile), to obtain a mean value of 1,620 cfs a return interval of 1.12 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

CAVE CREEK - JULY 26, 2011

On July 26, 2011 rainfall occurred over this Chiricahua Mountains basin (Figure 48). The area of the basin with moderate and high severity burn is shown in Figure 49. Figure 48 is from 1801Z to 1919Z with rainfall amounts of 0.10 to 1.55 inches in 1.3 hours. On November 7, 2011 to assess the magnitude of the flooding on July 26, high water marks and cross section information were collected by the NWS approximately 0.5 mile upstream of homes at the southern edge of the Portal area. Figure 50 is a summary of channel characteristics and calculated values. Figure 51 shows the surveyed channel reach looking downstream of cross section 3. Flood depth ranged from 4.0 to 5.6 feet within the three surveyed cross sections. The NWS used the collected data and the slope-area method to estimate the peak flood flow as 880 cfs +/- 30%. Within the reach, the average velocity was 7.0 ft/sec. A GIS analysis of the basin above the surveyed cross sections provided the basin characteristics shown in Figure 52. The time of concentration for the basin was calculated from these data to be 77 minutes.

Impact of 2011 Flash Flood

"I heard that the water was getting near or up against one building at Cave Creek Ranch, but people re-sandbagged it. The flood came down South Fork, not the main fork, and for a time it was over the South Fork Bridge, leaving a layer of silt on the roadbed." This quote is from a local resident and real estate agent (Helen Snyder).

There were no reports of damage to buildings due to flooding. This was likely due to Cochise County and the Natural Resource Conservation Service working with residents to install sandbags, K-rails, and other flood mitigation measures. Cochise County Highway and Floodplain Department documented having to clean out creek crossing due to flooding. The increased flash flood risk was high for the South Fork but low/moderate for the larger area downstream of the confluence. Therefore, for the basin above the surveyed site, the increased flash flood risk was low/moderate.

Verification for Cave Creek

Figure 49 is a burn severity map for the basin and Figure 53 provides the raw radar for the highest 78 minute rainfall during the storm. The core of the storm moved over grids 4F-G and 5D-F. The median 78-minute raw radar storm amount for the basin, 0.25 inches, is less than the range provided for the 1-year 60-minute return interval storm (Figure 53). The grids that received 1.25 inches to 1.55 inches in 78 minutes (the core of the storm), adjusted for 60 minutes, were within the corresponding range of values for the 1-year 60-

minute return interval; however, this was true for only 17% of the basin. For return intervals less than 1 year, the 1-year return interval is to be used (Reed and Schaffner, 2008). Using Equation 12, the expected flow from the hyper-effective drainage area is 1,035 cfs. This accounts for the runoff from 24% of the basin. To obtain the runoff from the entire basin we need to add 76% of the basins pre-burn 1-year runoff. The basins pre-burn runoff is 190 cfs calculated using USGS Region 14 equations for Upper Gila Basin (Thomas, 1997). Since there are no 1-year equations, half of the 2-year value of 381 cfs was used. The resulting runoff for the entire basin is 1,035 cfs plus 145 cfs = 1,180 cfs +/- 25%. Using the same procedure for Equation 13 the resulting runoff for the entire basin is 825 cfs +/- 25%.

Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 54. The amounts shown in Figure 54 shows that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower Equation 12 method value for the 1-year storm is greater than the mean indirect method value and less than the higher indirect method value. Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 55. The amounts shown in Figure 55 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower and mean Equation 13 method values for the 1-year storm are greater than the lower indirect method value and less than the mean indirect method value. Also the higher Equation 13 method value is less than the higher indirect method value. Equation 13 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin when storm events have return intervals equal to or less than 1 year.

Low Intensity Rainfall: For Cave Creek both Equation 12 and 13 methods were useful in determining the magnitude of the post-burn observed event. This would also be true if only the runoff from the burn area calculated by these equation were used, 1035 cfs and 681 cfs, respectively. If we use Equation 12 for only 17% of the basin, we calculate a mean runoff value of 870 cfs; this is essentially the same as the mean indirect method value of 880 cfs. The authors speculate that for such a low intensity rainfall, runoff may have been only from the burn area or only from the 17% of the basin that received a 1-year storm.

Increased Flash Flood Risk: If we assume a 1-year event with a pre-burn peak flow half the pre-burn 2-year peak flow of 381 cfs, then the post-burn hyper-concentrated peak flow of 880 cfs was 5 times greater than the pre-burn 1-year peak flow of 190 cfs. As shown in Figure 3 the 5-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011a) to be moderate for Cave Creek. Increased flash flood risks for 2-year and 1-year storms were not previously determined. Using 880 cfs / 39.4 square miles = 22 cfs/sq. mi., the 1-year increased flash flood risk for this Cave Creek basin would be low. Using 880 cfs / 6.7 square miles (17% of the basin) = 131 cfs/sq. mi., the 1-year increased flash flood risk for this cave creek basin would be moderate.

Return Interval: Using Equation 12 (the preferred equation), to obtain a mean value of 880 cfs a return interval of 0.820 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

NORTH FORK THOMAS CREEK - JULY 11, 2011

On July 11, 2011 rainfall started at 14:30 MST and ended at 16:15 MST. The 1 hour 45 minute storm total was 1.66 inches over this White Mountains basin (see Figure 56) resulting in flash flooding at the USFS weir at the basin outlet. The site is reported in real-time as USGS 09489082, North Fork Thomas Creek near Alpine, AZ. The rain data are from a Salt River Project gage at the North Fork Thomas Creek weir. The area of the basin with moderate and high severity burn is shown in Figure 57. Figure 58 shows the channel looking downstream at weir. From high water marks at the weir, the USFS estimated the observed flow to be 186 cfs +/- 10% (Joe Wagenbrenner, USFS, personal communication, 2/23/2012 9:10 AM). Joe Wagenbrenner says, "*The North Thomas creek flow stayed within the compound weir, but we maintained the assumption that the flow in the v-notch section had an open surface (whereas it was actually 'overlain' by the flow in the rectangular weir). Still, I'd say the North Thomas value is a little better, maybe +/- 10%"* (personal communication, 2/23/2012 11:17 AM). A GIS analysis of the basin above the weir provided the basin characteristics shown in Figure 59. The time of concentration for the basin was calculated from these data to be 19 minutes.

Impact of 2011 Flash Flood

The authors found no reports of damage other than overtopping of weir. The increased flash flood risk is assumed moderate.

Verification for North Fork Thomas Creek

Figure 56 shows there was 0.62 inches in 15-minutes at the basin outlet. The gage amount of 0.62 inches at the basins outlet (Figure 60) falls into the range for both the 1-year 15-minute and the 2-year 15-minute storms. Therefore both return intervals will be evaluated.

1-Year 15-Minute Storm: Using Equation 12[14], the expected flow from the hyper-effective drainage area is 195 cfs. This accounts for the runoff from 45% of the basin. To obtain the runoff from the entire basin we need to add 55% of the basins pre-burn 1-year runoff. The basins pre-burn runoff is 17 cfs calculated using USGS Region 12 equations for central Arizona (Thomas, 1997). Since there is no 1-year equation, half the of the 2-year value of 33 cfs was used. The resulting runoff for the entire basin is 195 cfs plus 9 cfs = 205 cfs +/- 25%. Using the same procedure for Equation 13[11] the resulting runoff for the entire basin is 140 cfs +/- 25%.

1-Year 15-Minute Storm Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 61. The amounts shown in Figure 61 shows that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The mean Equation 12 method value for the 1-year storm is the same as the higher indirect method value. The amounts shown in Figure 61 indicate that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin with a drainage area less than 1 square mile and assuming a 1-year 15-minute storm.

1-Year 15-Minute Storm Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 62. The amounts shown in Figure 62 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The higher Equation 13 method value for the 1-Year Storm falls halfway between the lower and mean indirect method values. Assuming a 1-year 15-minute storm, Equation 13 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential of this post-burn basin with a drainage area less than 1 square mile.

2-Year 15-Minute Storm: Using Equation 12, the expected flow from the hyper-effective drainage area is 335 cfs. This accounts for the runoff from 45% of the basin. To obtain the runoff from the entire basin we need to add 55% of the basins pre-burn 2-year runoff. The basins pre-burn runoff is 33 cfs calculated using USGS Region 12 equations for central Arizona (Thomas, 1997). The resulting runoff for the entire basin is 334 cfs plus 18 cfs = 350 cfs +/- 25%. Using the same procedure for Equation 13 the resulting runoff for the entire basin is 240 cfs +/- 25%.

2-Year 15-Minute Storm Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 63. The amounts shown in Figure 63 shows that the Equation 12 method can not be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower Equation 12 method value for the 2-year storm is greater than the higher indirect method value by 55 cfs. This is to be expected since the basin has a drainage area less than 1 square mile. Although close, the amounts shown in Figure 63 indicate that Equation 12 method can not be successfully used to predict the indirectly observed peak flow from this post-burn basin with a drainage area less than 1 square mile.

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[14] Channel slope used unmodified (basin less than 1 square mile and also in Central Arizona Highlands).

2-Year 15-Minute Storm Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 64. The amounts shown in Figure 64 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower Equation 13 method value for the 2-year storm is essentially the same as the mean indirect method value. Assuming a 2-year 15-minute storm, Equation 13 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin with a drainage area less than 1 square mile.

Increased Flash Flood Risk: If we assume a 1-year event with a pre-burn peak flow half the pre-burn 2-year peak flow of 33 cfs, then the post-burn hyper-concentrated peak flow of 186 cfs was 11 times greater than the pre-burn 1-year peak flow of 17 cfs. This is in good agreement with Wagenbrenner, J., P. Robichaud, and R. Brown (2011). The observed post-burn hyper-concentrated peak flow of 186 cfs was 5.6 times greater than the pre-burn 2-year peak flow of 33 cfs. North Fork of Thomas Creek is within the Upper Beaver Creek drainage shown on Figure 5. The 2-year, 5-year (Figure 5), and 10-year increased flash flood risk were previously determined by Reed, Schaffner, and Kahler (2011c) to be low for the larger drainage. This illustrates that the increased flash flood risk for a 37 square mile basin cannot be applied to a nested headwater basin less than 1 square mile. However, independently the Reed-Schaffner equations can be used successfully for smaller and larger size basins. Using 186 cfs / 0.70 square miles = 265 cfs/sq. mi., the 1-year increased flash flood risk for this North Fork Thomas Creek basin would be moderate. Or using 186 cfs / 0.70 square miles = 265 cfs/sq. mi., the 2-year increased flash flood risk for this North Fork Thomas Creek basin also would be moderate.

Return Interval: Using Equation 13 (the preferred equation for basins less than 1-square mile) to get a mean value of approximately 186 cfs, a return interval of 1.62 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

SOUTH FORK THOMAS CREEK- JULY 11, 2011

On July 11, 2011 rainfall started at 14:30 MST and ended at 16:15 MST. The 1 hour 45 minute storm total was 1.66 inches over this White Mountains basin (see Figure 65) resulting in over topping of the USFS weir at the basin outlet. This site is very close to the North Fork Thomas Creek weir. The rain data are from a Salt River Project gage at the North Fork Thomas Creek weir. The area of the basin with moderate and high severity burn is shown in Figure 66. Figure 67 shows the channel looking downstream at weir. From high water marks at the weir, the USFS estimated the observed flow to be 308 cfs +/- 20% (Joe Wagenbrenner, USFS, personal communication, 2/23/2012 9:10 AM). Joe Wagenbrenner says, "*The South Fork Thomas Creek estimate was more complicated because the flow also overtopped the compound weir, so +/- 20% would be a good error estimate for that value*" (personal communication, 2/23/2012 11:17 AM). A GIS analysis of the basin above the weir provided the basin characteristics shown in Figure 68. The time of concentration for the basin was calculated from these data to be 30 minutes.

Impact of 2011 Flash Flood

The authors found no reports of damage other than overtopping of weir. The increased flash flood risk is assumed to be moderate.

Verification for South Fork Thomas Creek

Figure 65 shows there was 1.07 inches in 30-minutes at the basin outlet. The gage amount of 1.07 inches at the basins outlet (Figure 69) falls into the range for both the 2-year 30-minute and the 5-year 30-minute storms. Therefore both return intervals will be evaluated.

2-Year 30-Minute Storm: Using Equation 12[15], the expected flow from the hyper-effective drainage area is 234 cfs. This accounts for the runoff from 81% of the basin. To obtain the runoff from the entire basin

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[15] Channel slope used unmodified (basin less than 1 square mile and also in Central Arizona Highlands).

we need to add 19% of the basins pre-burn 2-year runoff. The basins pre-burn runoff is 38 cfs calculated using USGS Region 12 equations for central Arizona (Thomas, 1997). The resulting runoff for the entire basin is 234 cfs plus 7 cfs = 240 cfs +/- 25%. Using the same procedure for Equation 13[12] the resulting runoff for the entire basin is 165 cfs +/- 25%.

2-Year 30-Minute Storm Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 70. The amounts shown in Figure 70 shows that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The higher Equation 12 method value for the 2-year storm is essentially the same as the mean indirect method value (within 10 cfs). Also the mean Equation 12 method value is essentially the same as the lower indirect method value (within 5 cfs). Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

2-Year 30-Minute Storm Equation 13 Method: A comparison of Equation 13 method and indirect method results are provided in Figure 71. The amounts shown in Figure 71 shows that Equation 13 method can not be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The higher Equation 13 method value for the 2-year storm is less than the lower indirect method value by 40 cfs. Equation 13 is not useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin with a drainage area less than 1 square mile. Since Equation 13 does not work, it is likely that the return interval of the storm was greater than 2 years.

5-Year 30-Minute Storm: Using Equation 12, the expected flow from the hyper-effective drainage area is 479 cfs. This accounts for the runoff from 81% of the basin. To obtain the runoff from the entire basin we need to add 19% of the basins pre-burn 5-year runoff. The basins pre-burn runoff is 101 cfs calculated using USGS Region 12 equations for central Arizona (Thomas, 1997). The resulting runoff for the entire basin is 479 cfs plus 19 cfs = 500 cfs +/- 25%. Using the same procedure for Equation 13 the resulting runoff for the entire basin is 335 cfs +/- 25%.

5-Year 30-Minute Storm Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 72. The amounts shown in Figure 72 shows that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The lower Equation 12 method value for the 5-year storm is essentially the same as the greater indirect method value (within 5 cfs). Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

5-Year 30-Minute Storm Equation 13 method: A comparison of Equation 13 method and indirect method results are provided in Figure 73. The amounts shown in Figure 73 shows that the Equation 13 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The mean Equation 13 method value for the 5-year storm is greater than the mean indirect method value and less than the higher indirect method value. Also the lower Equation 13 method value is greater than the lower indirect method value. Equation 13 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin with a drainage area less than 1 square mile.

Increased Flash Flood Risk: The observed post-burn hyper-concentrated peak flow of 308 cfs was 8.1 times greater than the pre-burn 2-year peak flow of 38 cfs. This is in fair agreement with Wagenbrenner, J., P. Robichaud, and R. Brown (2011). The observed post-burn hyper-concentrated peak flow of 308 cfs was 3 times greater than the pre-burn 5-year peak flow of 101 cfs. South Fork of Thomas Creek is within the Upper Beaver Creek drainage shown on Figure 5. The 2-year, 5-year (Figure 5), and 10-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011c) to be low for the larger drainage. This illustrates that the increased flash flood risk for a 37 square mile basin cannot be applied to a nested headwater basin less than 1 square mile. However, independently the Reed-Schaffner equations can be used successfully for smaller and larger size basins. Using 308 cfs / 0.89 square miles = 346 cfs/sq. mi., the 2-year increased flash flood risk for this South Fork Thomas Creek basin would be moderate. Or using 308 cfs / 0.89 square miles = 346 cfs/sq. mi., the 5-year increased flash flood risk for this South Fork Thomas Creek basin also would be moderate.

Return Interval: Using Equation 12 to get a mean value of approximately 308 cfs, a return interval of 2.8 years would have to be used. Using Equation 13 (the preferred equation for basins less than 1-square mile) to get a mean value of approximately 308 cfs, a return interval of 5 years would have to be used. This is using only the hyper-effective drainage area since the runoff from the remaining area would be minimal.

HANNAGAN CREEK AT HIGHWAY 191 - JULY 11, 2011

This White Mountains basin is very close to the North Fork Thomas Creek weir (Figure 74). The rain data are from a Salt River Project gage at the North Fork Thomas Creek weir. On July 11, 2011 rainfall started at 14:30 MST and ended at 16:15 MST. The 1 hour 45 minute storm total was 1.66 inches (Figure 75). The area of the basin with moderate and high severity burn is shown in Figure 76. Figure 77 shows the channel looking upstream of culvert under US Highway 191. Figure 78 shows the channel looking downstream of the culvert under US Highway 191. Figure 79 shows the area above the culvert where Hannagan Creek flowed over the road during the event. Channel characteristics for these sites are shown in Figure 80. Using the channel characteristics and high water marks from Figures 77-79 and depth of flow over road reported by AZDOT (4-8 feet), the authors estimated the flow to be 1,430 cfs +/- 60%. A GIS analysis of the basin above the culvert provided the basin characteristics shown in Figure 81. The time of concentration for the basin was calculated from these data to be 73 minutes.

Impact of 2011 Flash Flood

Joe Wagenbrenner of USFS says regarding the July 11, 2011 storm, “A debris flow occurred from the same storm just to the south of South Fork Thomas Creek, but we did not estimate flow rate for that drainage (personal communication, 2/2/2012 4:00 PM). The Hannagan Creek basin is located just south of South Fork Thomas Creek.

As estimated from several figures provided by AZDOT and as reported by AZDOT in several personal communications: A box culvert (10 feet x 6 feet and about 40 feet long) under US Highway 191 became blocked at mile marker 235.9 causing Hannagan Creek to flow over US Highway 191 (see Figure 79). Flow was 4-8 feet deep over road above culvert (near where person is standing in photo). Perpendicular to direction of flow, from highwater mark to highwater mark, was a distance of 980 feet (in photo you can see far highwater mark near yellow sign). The flow over the road was primarily due to the culvert being blocked by a debris flow. The increased flash flood risk was moderate/high.

Verification for Hannagan Creek at Highway 191

Figure 75 shows there was 1.60 inches in 75-minutes at the basin outlet. The gage amount of 1.60 inches at the basins outlet (Figure 82) falls into the range for both the 5-year 75-minute and the 10-year 75-minute storms. Therefore both return intervals will be evaluated.

5-Year 75-Minute Storm: Using Equation 12[16], the expected flow from the hyper-effective drainage area is 233 cfs. This accounts for the runoff from 28% of the basin. To obtain the runoff from the entire basin we need to add 72% of the basins pre-burn 5-year runoff. The basins pre-burn runoff is 302 cfs calculated using USGS Region 12 equations for central Arizona (Thomas, 1997). The resulting runoff for the entire basin is 233 cfs plus 217 cfs = 450 cfs +/- 25%.

5-Year 75-Minute Storm Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 83. The amounts shown in Figure 83 shows that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The higher Equation 12 method value for the 5-year storm is essentially the same as the lower indirect method value (within 5 cfs). Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

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[16] Channel slope used unmodified (basin is in Central Arizona Highlands).

10-Year 75-Minute Storm: Using Equation 12, the expected flow from the hyper-effective drainage area is 400 cfs. This accounts for the runoff from 28% of the basin. To obtain the runoff from the entire basin we need to add 72% of the basins pre-burn 10-year runoff. The basins pre-burn runoff is 539 cfs calculated using USGS Region 12 equations for central Arizona (Thomas, 1997). The resulting runoff for the entire basin is 400 cfs plus 388 cfs = 790 cfs +/- 25%.

10-Year 75-Minute Storm Equation 12 Method: A comparison of Equation 12 method and indirect method results are provided in Figure 84. The amounts shown in Figure 84 shows that the Equation 12 method can be successfully used to predict the indirectly observed peak flow from this post-burn basin within the error reported. The higher Equation 12 method value for the 10-year storm is less than the mean indirect method value and greater than the lower indirect method value. Also the mean Equation 12 method value is greater than the lower indirect method value and the lower Equation 12 method value is essentially the same as the lower indirect method value (within 20 cfs). Equation 12 is useful in determining the magnitude of the post-burn observed event; and therefore, the increased post-burn flash flood potential for this basin.

Increased Flash Flood Risk: The observed post-burn hyper-concentrated peak flow of 1,430 cfs was 4.7 times greater than the pre-burn 5-year peak flow of 302 cfs. The observed post-burn hyper-concentrated peak flow of 1,430 cfs was 2.7 times greater than the pre-burn 10-year peak flow of 535 cfs. Hannagan Creek is within the Upper Beaver Creek drainage shown on Figure 5. The 2-year, 5-year (Figure 5), and 10-year increased flash flood risk was previously determined by Reed, Schaffner, and Kahler (2011c) to be low for the larger drainage. This illustrates that the increased flash flood risk for a 37 square mile basin cannot be applied to a nested headwater basin with a drainage area of 4.37 square miles. However, independently the Reed-Schaffner equations can be used successfully for smaller and larger size basins. Using 1,430 cfs / 4.37 square miles = 327 cfs/sq. mi., the 5-year increased flash flood risk for this Hannagan Creek basin would be moderate. Or using 1,430 cfs / 4.37 square miles = 327 cfs/sq. mi., the 10-year increased flash flood risk for this Hannagan Creek basin would also be moderate.

Return Interval: Because of the storm size (likely a 10-year return interval[17]); the runoff from the non-hyper-effective area is not minimal. Therefore, the return interval can not be calculated by using Equation 12 and assuming runoff from only the hyper-effective drainage area. If we assume that 990 cfs (Figure 82) is correct, then the return interval needed for a storm over just the hyper-effect drainage area (1.21 square miles) would be 30 years. If we assume that 990 cfs is correct, then the return interval needed over the entire basin (4.37 square miles) prior to it being burned is 25-years. However, a 10-year return interval storm will result in a runoff of 990 cfs from a mixture of hyper-effect and pre-burn, i.e., the method used in this report (Figure 82).

VERIFICATION SUMMARY

The use of the Reed-Schaffner Equations 12 and 13 verified for the Central Arizona Highlands and the Sky Island Complex of southeastern Arizona (Figure 85). For peak flows less than 1,100 cfs, Equations 12 and 13 begin to converge (Figure 12) and provide essentially the same answer. As expected, because the Central Arizona Highlands are outside of the area for which the original equations were developed (the Sky Island Complex of southeastern Arizona) the equations had to be slightly modified. For the Central Highlands the channel relief ratio was used rather than the modified channel relief ratio. Equation 13 was used for storms with return intervals less than 1 year and for basins with drainage areas less than 1 square mile. If the flow is known, Equation 12 can be used to determine the return intervals for those events with return intervals less than 1.

Once the flow has been determined directly or indirectly by another method, Equation 12 and 13 can be solved for any variable, including the return interval of the causative storm, using only the hyper-effective drainage area. Figures 86 (Sky Island Basins) and 87 (Central Highland Basins) show the calculated return

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[17] The 10-year return interval storm has a 41% chance of being equaled or exceeded one or more times during the assumed burn recovery period of five years for the three 2011 Arizona fires studied.

intervals for the seven of the eight basins assuming the runoff from the non-hyper-effective drainage area to be minimal. Equation 12 was used for the basins with drainage areas equal to or greater than 1 square mile. However, since South Fork of Thomas Creek was almost completely burned and has a drainage area close to 1 square mile, the storm return interval is consider closer to 2.8 years than 5 years.

As shown on Figure 88, using the Equation 12 and calculated return intervals, Miller Creek has the highest multivariate runoff index and highest 2011 peak flow for these Sky Island and Central Highland basins with drainage areas equal to or greater than 1 square mile. As shown on Figure 89, using Equation 13 and calculated return intervals, Old Sawmill Canyon has the highest multivariate runoff index and highest 2011 peak flow for these Sky Island and Central Highland basins with drainage areas less than 1 square mile. For these basins, the channel relief ratio was used unmodified. On these figures, basin parameters are ranked by flow and only mvi_1 increases the same as flow (see Figures 88-90**)**. It is this observation in previous studies by Reed and Schaffner that led us to the definition of the hyper-effective drainage area and the development of the multivariate runoff index. Figure 91 shows the resulting new curves if the new 8 basins are added to the data used in Figure 12. Figure 92 shows the equations using only those basins with mvi values less than 1. However, because of the large reported error for several of the new basins, it is recommended that the original equations continue to be used at this time.

Basin Specific 5-year Post-Burn to Pre-Burn Peak Flow Ratio

The 5-year return interval storm calculated post-burn peaks have a 67% chance of being equaled or exceeded one or more times during the assumed burn recovery period of five years for the three 2011 Arizona fires studied. Figure 93 shows the 5-year total watershed peak flow response under burn conditions in the Santa Catalina (Sabino, Alder, Campo Bonito, Romero, Cañada del Oro), Santa Rita (Madera), Chiricahua (Cave, East Turkey), Huachuca (Miller, Ash, Old Sawmill), White (South Fork Thomas, North Fork Thomas, Hannagan Creek at Highway 191), and Pinaleno Mountains (Marijilda, Frye, Deadman, Noon, Wet). Numerical values are the ratio of Equation 13 post-burn values to pre-burn values. Post-burn response is up to 107.6 times greater than pre-burn peak flow. Equation 13 was used because the data were readily available, if Equation 12 was used, the ratios would be higher. The ratio of post to pre can be grouped into three categories: 1) Santa Catalina, Santa Rita, Chiricahua, and White; 2) Huachuca; and 3) Pinaleno Mountains. The studied mountain ranges from north to south are: White Mountains, Pinaleno Mountains, Santa Catalina Mountains, Chiricahua Mountains, Santa Rita Mountains, and Huachuca Mountains. Within the Sky Island Complex, the north most (Pinaleno) and south most (Huachuca) mountains have the greatest response (Figures 93).

The five Sky Island mountain ranges studied by Reed and Schaffner are indicated by red stars on Figure 94. Figure 95 shows the biotic communities of White, Pinaleno, and Huachuca Mountains. All the Sky Island Mountains have the pine-woodland biotic community (Marshall 1957). Because of their relief and vegetation similarities, the Equation 12 and 13 methods can likely be applied to all of the Sky Islands of Arizona and New Mexico. The White Mountains are in the Central Highlands, a biotic community transition zone and do not have the pine-oak woodlands common to the Sky Islands. Because of their relief and vegetation similarities, the modified Equation 12 and 13 methods can likely be applied to all of the Central Highlands basins.

Grouping the basins by geophysical provinces and utilizing a post-burn multivariate runoff index allows the complex nature of these basins to be simplified to the use of four variables: 1) hyper-effective drainage area, 2) average basin elevation, 3) channel relief ratio or modified channel relief ratio, and 4) the return interval of the causative storm event. The resulting empirical equations allow the basin specific post-burn to pre-burn peak flow ratio to be calculated for 1 year to 10 year events, and with less accuracy for events less than 1 year.

5-Year Post-Burn to 2011 Observed Peak Flow Ratio and Increased Flash Flood Risk

The 5-year return interval storm calculated post-burn peaks have a 67% chance of being equaled or exceeded one or more times during the assumed burn recovery period of five years for the three 2011 Arizona fires studied. Figure 96 shows the ratio of 5-year post-burn to 2011 observed peak flows. Hannagan Creek at Highway 191 is not shown because the 2011 event had a return interval greater than 5 years. Although the 2011 flows in Miller Canyon were significant, the basin can experience 5-year peak flows twice the magnitude of the 2011 observed peak. The increased relative flash flood risk for 2011 post-burn and 5-year post-burn peak flows are shown in Figure 97. For these specific basins, the Monument Fire basins are at greater post-burn 5-year risk than the Horseshoe II Fire and Wallow Fire basins. The 2011 observed impacts and calculated increased flash flood risk are shown in Figure 98. For all sites with observations, the impacts are in agreement with the calculated risks. For East Turkey Creek and Cave Creek initial impacts may have been reduced by flood proofing. For Hannagan Creek at Highway 191 initial impacts may have been increased by infrastructure failure or blockage. Figure 99 shows a comparison of observed and calculated peak flows for mean values only.

Projected Recovery for 5-Year Post-Burn Peak Flows (Assuming Linear Recovery over 5-Year Period)

The 5-year return interval storm calculated post-burn peaks have a 67% chance of being equaled or exceeded one or more times during the assumed burn recovery period of five years for the three 2011 Arizona fires studied. Figure 100 shows the projected hydrologic recovery for 5-year return interval peak flows (cfs) assuming a linear recovery rate. Figure 101 shows the projected hydrologic recovery for 5-year return interval peak flows (cfs/sq mi) assuming a linear recovery rate and the associated increased flash flood risk.

Precipitation Thresholds

Precipitation thresholds for different levels of flash flood impacts can be determined from the 8 basins and utilizing return interval estimations to fill in the remaining matrix. Figure 102 shows the White Mountain thresholds. Figure 103 shows the Chiricahua and Huachuca Mountains thresholds. Figure 104 shows post-burn precipitation thresholds for moderate impacts. Figure 105 shows post-burn precipitation thresholds for high impacts. Figure 105 shows post-burn precipitation thresholds for extreme impacts. The basins shown on each graph are the ones used to develop the thresholds shown and the return intervals of those events were used to fill in the remaining values. To fill in the extreme values, the precipitation associated with the next higher than high impact return intervals were used in Figure 106. The estimated thresholds should be considered preliminary and replace as more data become available, i.e., with those based on future observed impacts.

DISCUSSION

Immediately after the fires, rainfall events with return periods from less than 1 year to 10 years caused hyper-concentrated flows in the 8 basins documented here. During the 2012-2015 monsoon seasons the chance for post-burn increased flash flood risk continues to be a concern for these areas as documented in Reed, Schaffner, and Kahler (2011a, b, & c). This is especially true if large return interval events occur.

The 2011 Reed, Schaffner, and Kahler reports (2011a, b, & c) demonstrated that the increased flash flood potential for post-burn basins impacted by the Horseshoe II, Monument, or Wallow Fires could be determined shortly after the burns. The method was developed based upon previous reports by Reed and Schaffner (2007 and 2008) and Schaffner and Reed (2005a & b). This report verifies the method used in these earlier reports in that two Reed-Schaffner equations are shown to successfully predict the peak flows for the eight post-burn basins documented in this report. Equation 12 is shown to be usefully for post-burn basins with drainage areas equal to or greater than 1 square mile when storm events have return intervals equal to or greater than 1 year. Equation 13 is shown to be usefully for post-burn basins with drainage areas less than 1 square mile and/or when the storm return interval is less than 1 year. For basins with drainage areas less than 1 square mile or for those located in the Central Arizona Highlands, the channel relief ratio should be used unmodified. For basins with drainage areas equal to or greater than 1 square mile and located in the Sky Island Complex of southeastern Arizona, the channel relief ratio should be used as defined in Reed and Schaffner (2008).

As documented in this report, it is possible for:

1. Storm events with return intervals less than 1 year to cause local flooding in post-burn basins (East Turkey Creek, Ash Creek, and Cave Creek),
2. Post-burn basins with drainage areas less than 1 square mile to experience local flooding (Old Sawmill Creek, North Fork Thomas Creek, and South Fork Thomas Creek),
3. Post-burn basins greater than 1 square mile with 2-year storms to experience significant flooding (Miller Canyon) in the Huachuca Mountains, and
4. Post-burn basins greater than 1 square mile with 10-year storms to experience moderate flooding (Hannagan Creek at Highway 191) in the White Mountains.

As documented in this report, Reed-Schaffner equations can be used to successfully estimate the hyper-concentrated peak discharge from post-burned basins in the Sky Island Complex of southeastern Arizona and the Central Arizona Highlands.

As documented in this report, Reed-Schaffner equations can be used to successfully estimate the increased flash flood risk associated with the hyper-concentrated peak discharge from post-burned basins in the Sky Island Complex of southeastern Arizona and the Central Arizona Highlands. For the eight post-burn basins evaluated the increased flash flood risk ranged from moderate to high.

CONCLUSIONS

- Reed-Schaffner equations can be used successfully to predict the post-burn increased flash flood risk for basins in the Sky Island Complex of southeastern Arizona.
- Modified Reed-Schaffner equations can be used successfully to predict the post-burn increased flash flood risk for basins in the Central Arizona Highlands.
- The methodology used in Reed, Schaffner, and Kahler (2011a, b, & c) is valid until such time as a more sophisticated method becomes readily available.
- During the 2012-2015 monsoon seasons the chance for post-burn increased flash flood risk continues to be a concern for these areas as documented in Reed, Schaffner, and Kahler (2011a, b, & c).

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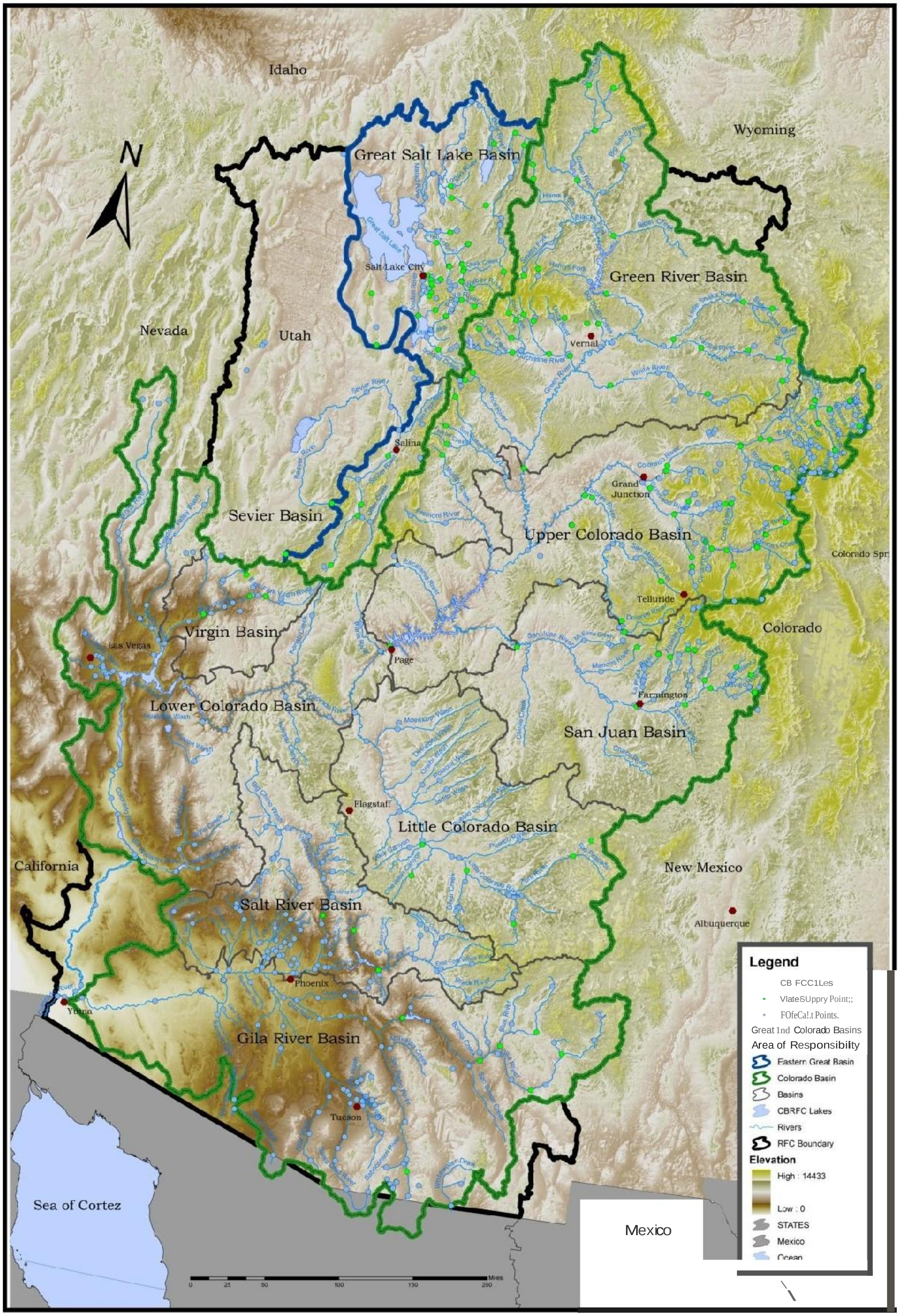
Figure 1. **Location of 2011 Fires and Physiographic Provinces of Arizona (including the Sky Island Complex of southeastern Arizona within the Basin and Range Province).**

Colorado Basin River Forecast Center, Salt Lake City, Utah



www.cbrfc.noaa.gov

Figure 2. Colorado Basin River Forecast Center Area of Responsibility.

Increased Flash Flood Risk

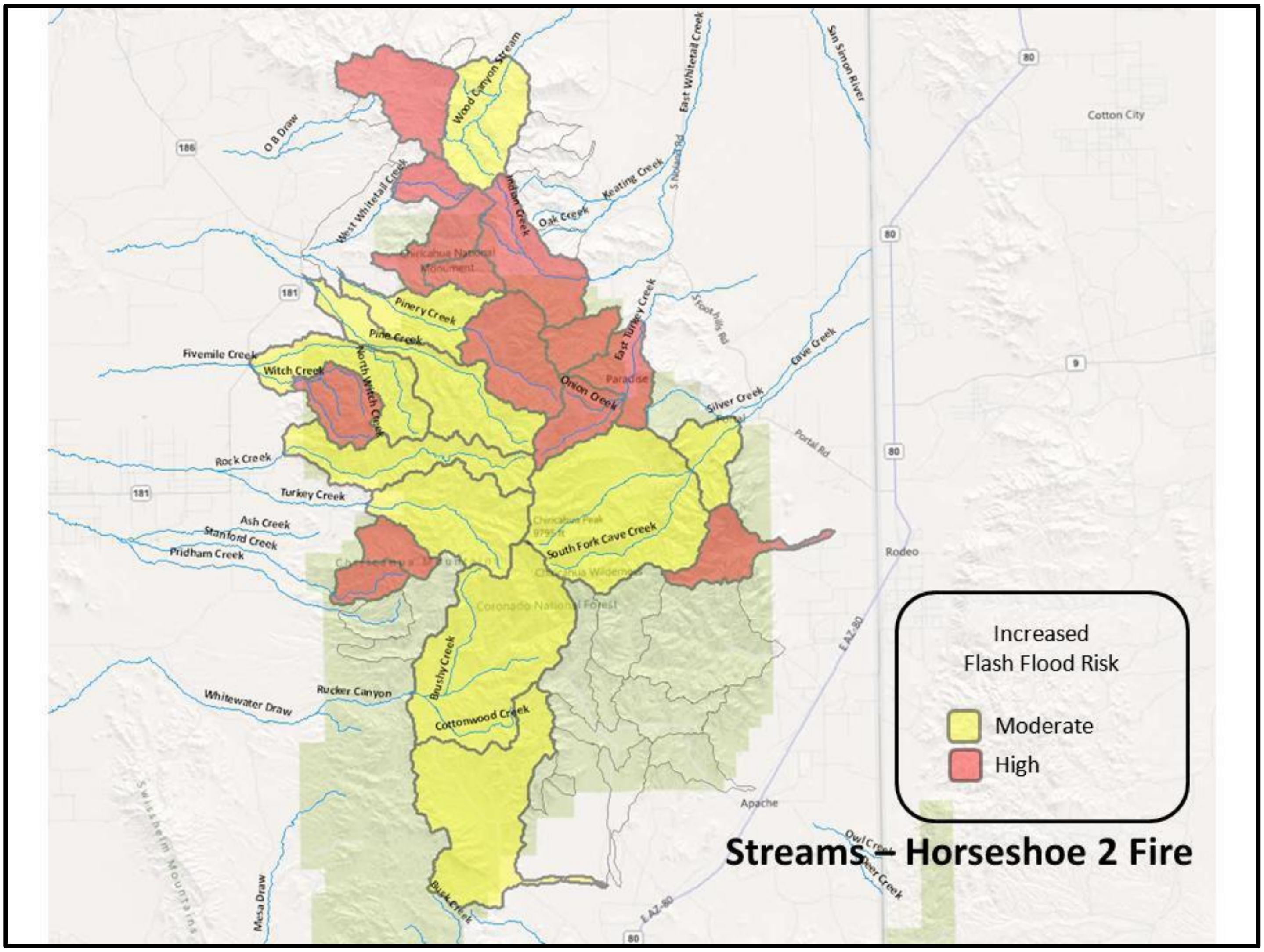


Figure 3. Horseshoe II Wildfire: Increased 5-Year Storm Flash Flood Risk.

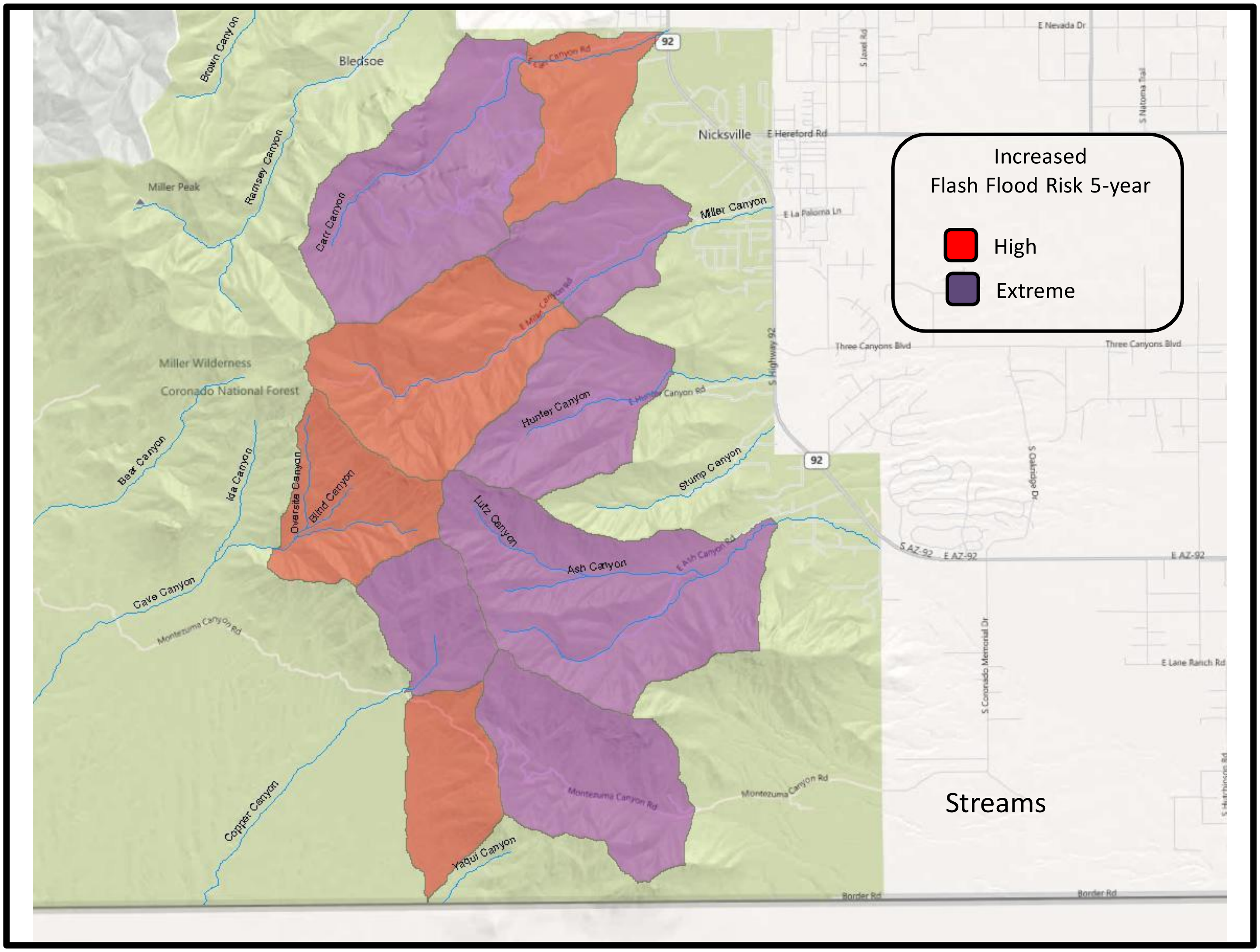


Figure 4. Monument Wildfire: Increased 5-Year Storm Flash Flood Risk.

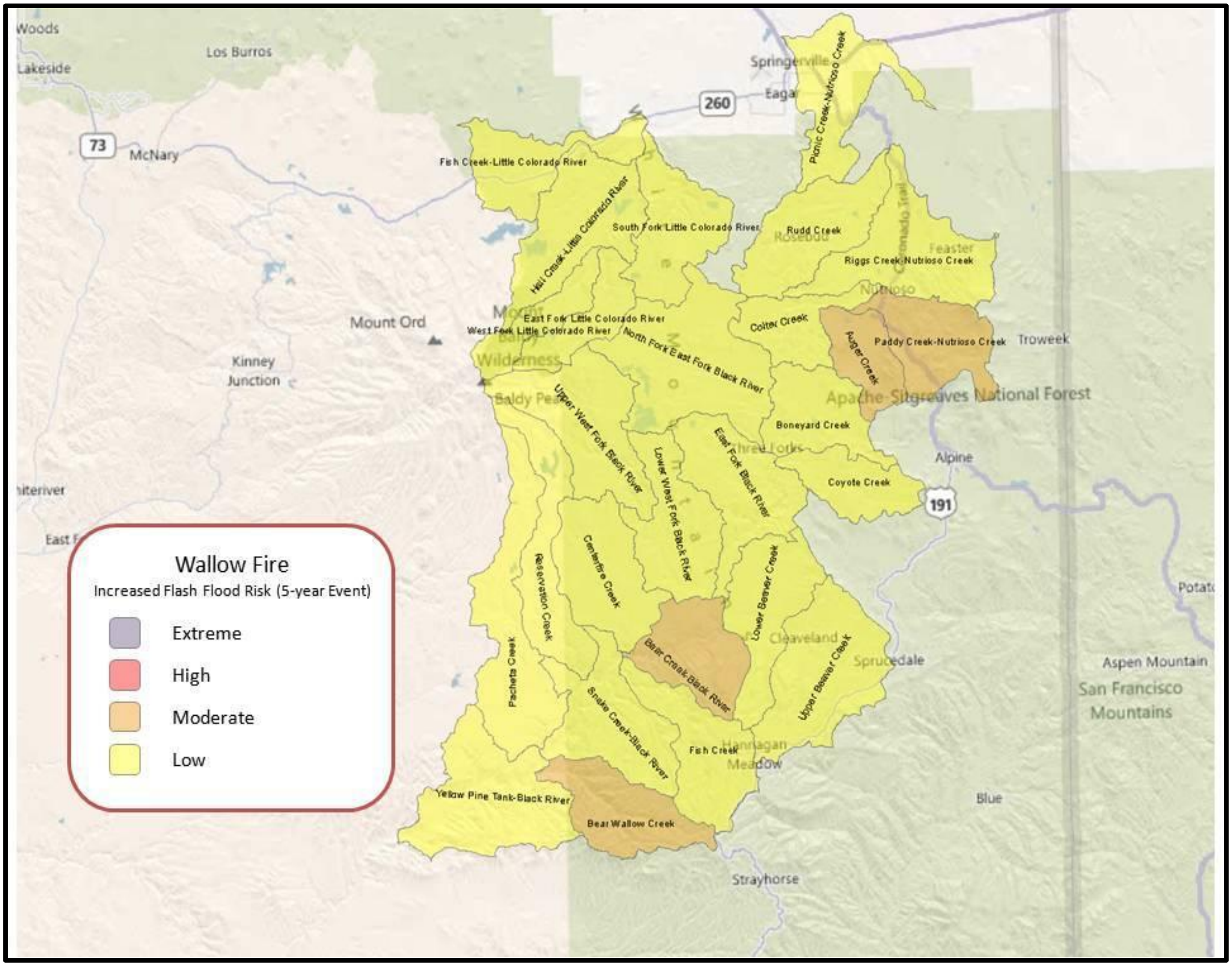


Figure 5. Wallow Wildfire: Increased 5-Year Storm Flash Flood Risk – HEC-RAS Basins.

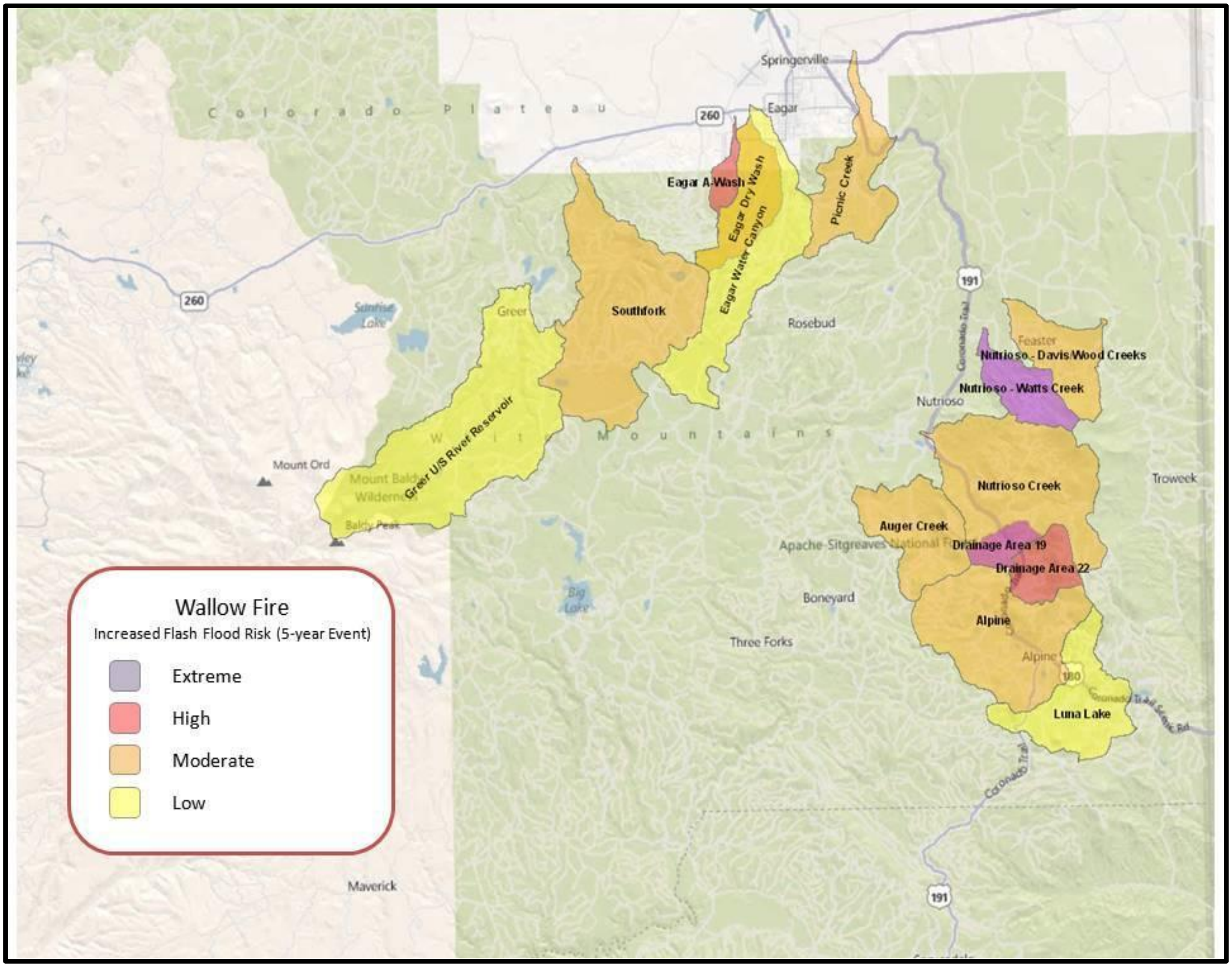


Figure 6. Wallow Wildfire: Increased 5-Year Storm Flash Flood Risk – Apache County Basins.

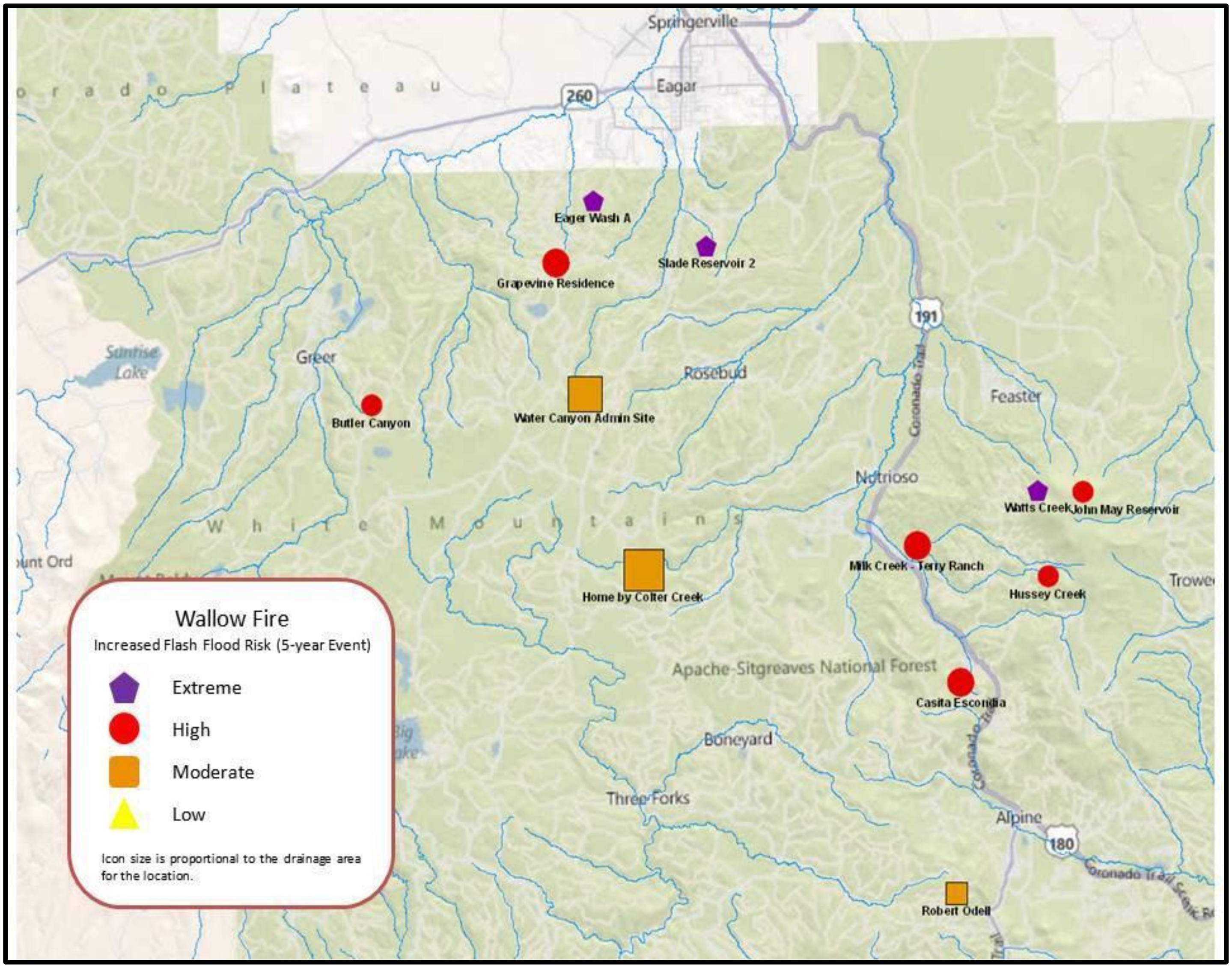


Figure 7. Wallow Wildfire: Increased 5-Year Storm Flash Flood Risk – WILDCAT 5 Basins.

Verification Basins

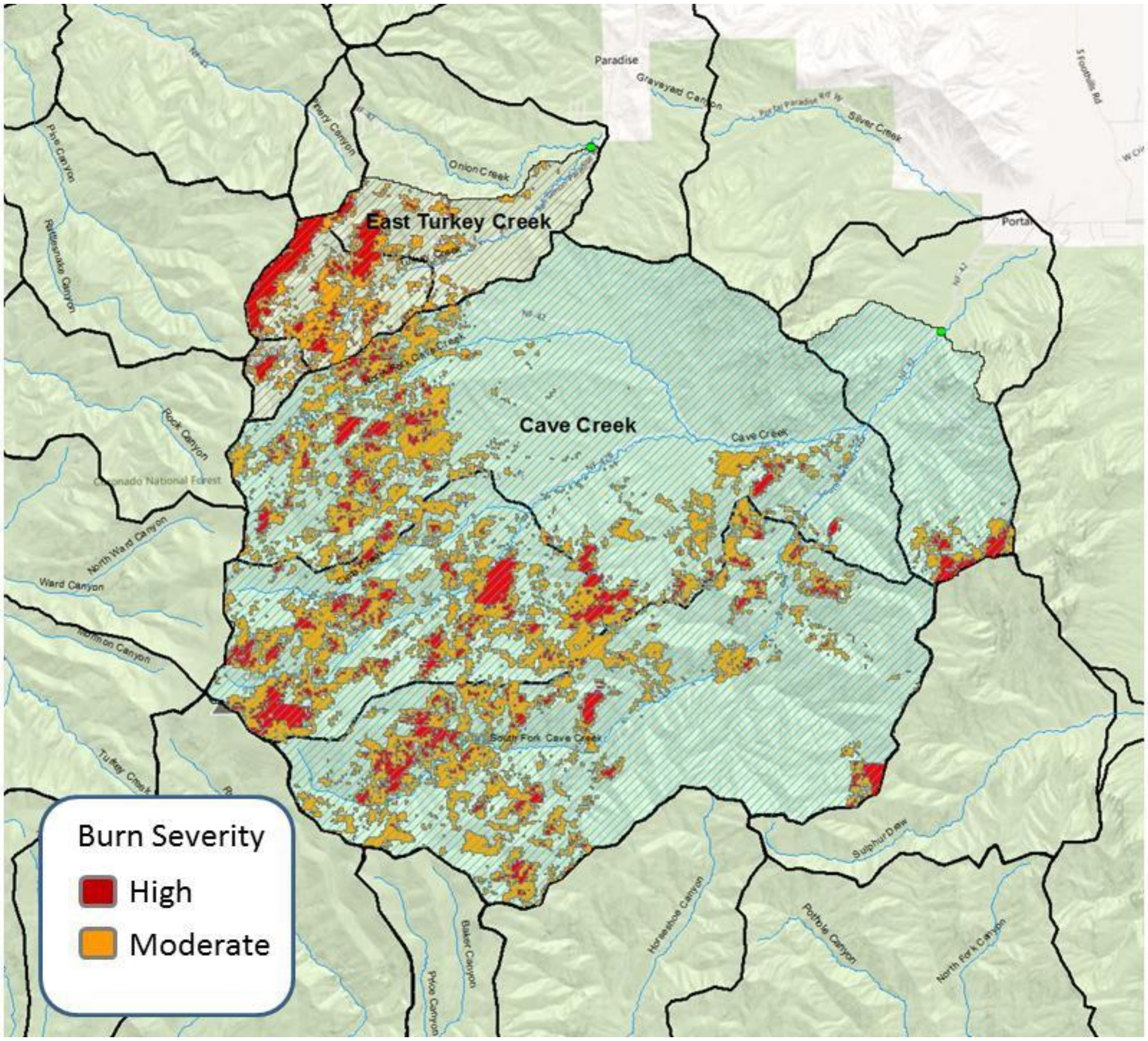


Figure 8. Horseshoe II Wildfire: Two Verification Basins (East Turkey Creek and Cave Creek).

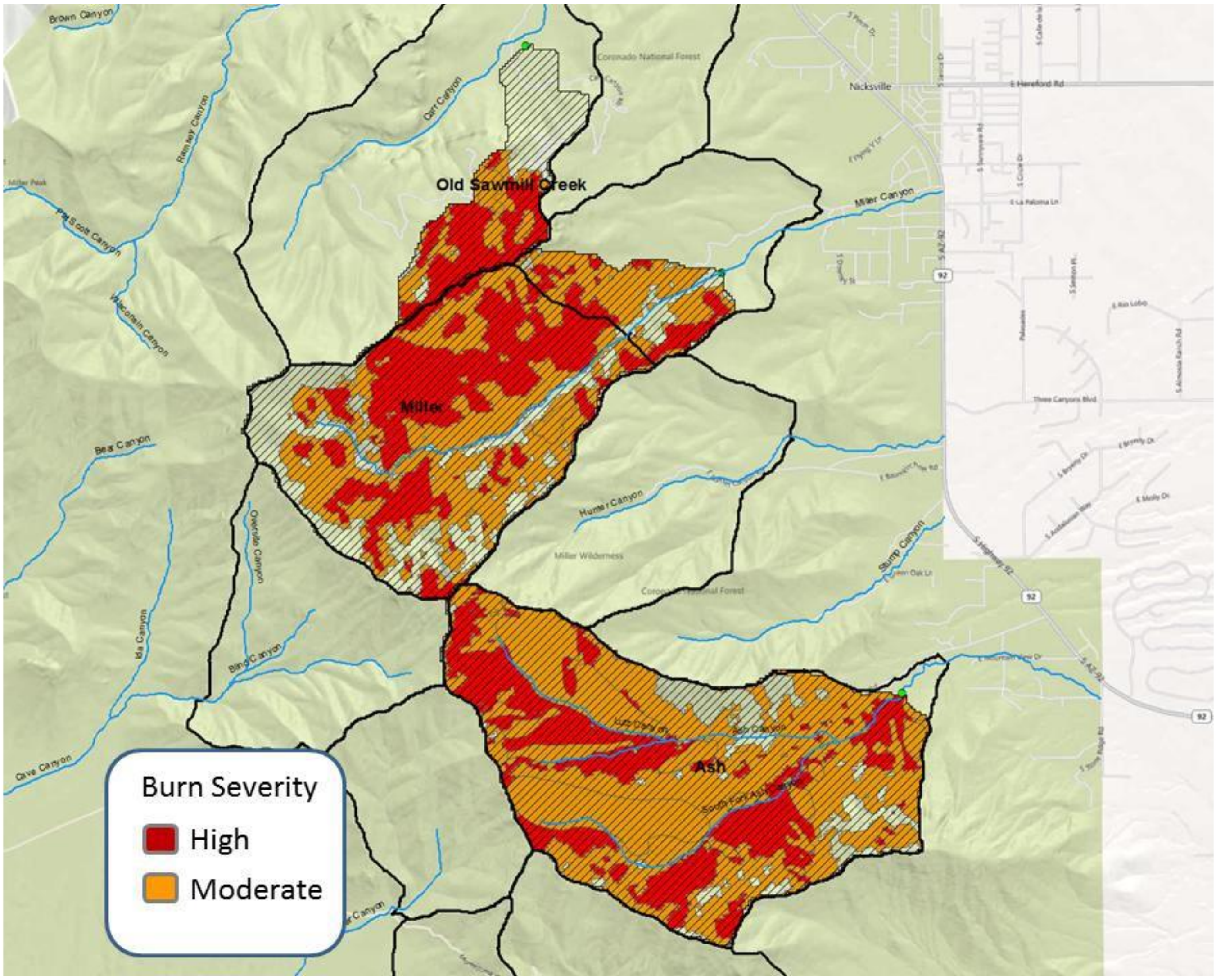


Figure 9. Monument Wildfire: Three Verification Basins (Miller Canyon, Old Sawmill Creek and Ash Canyon).

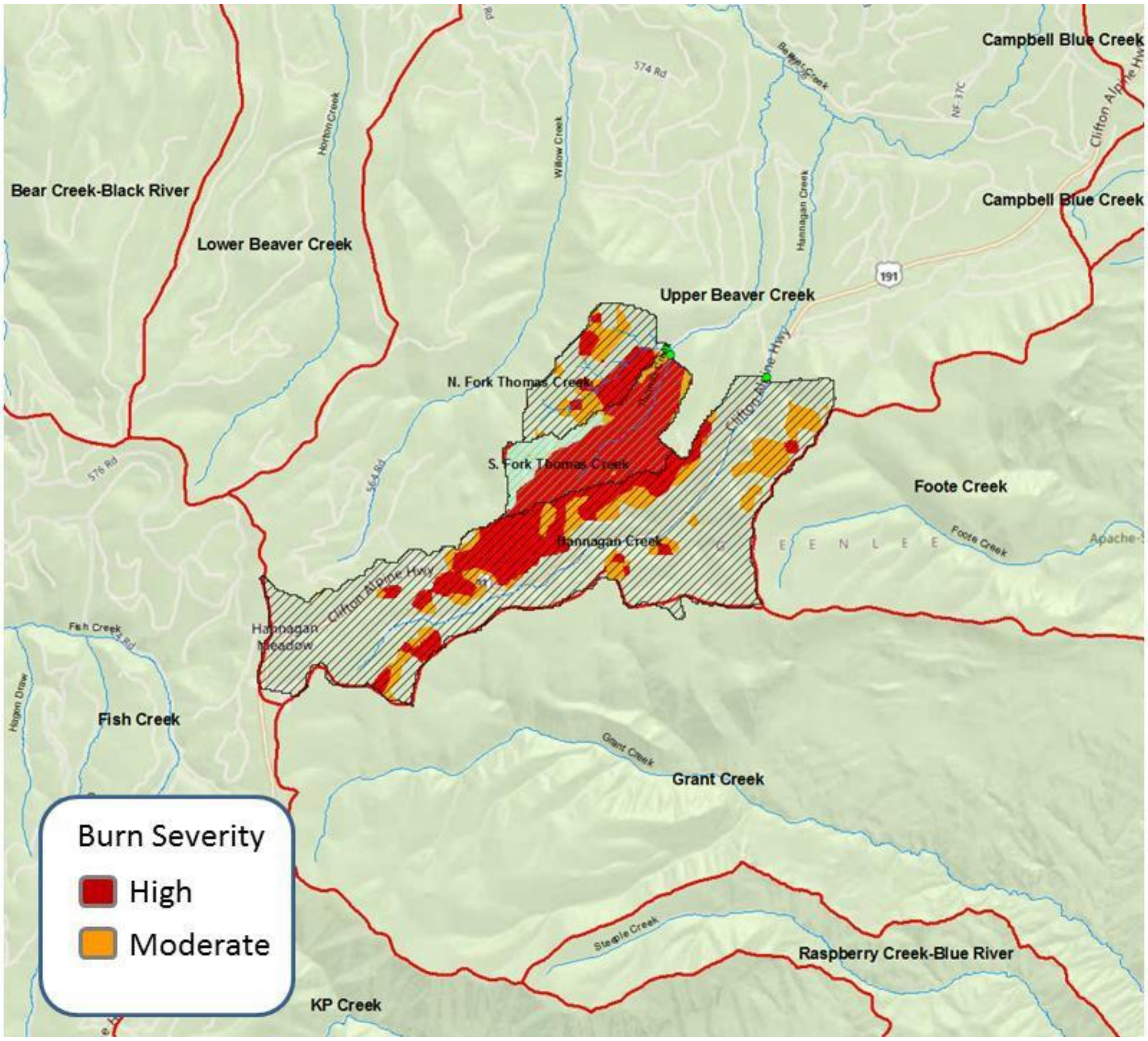
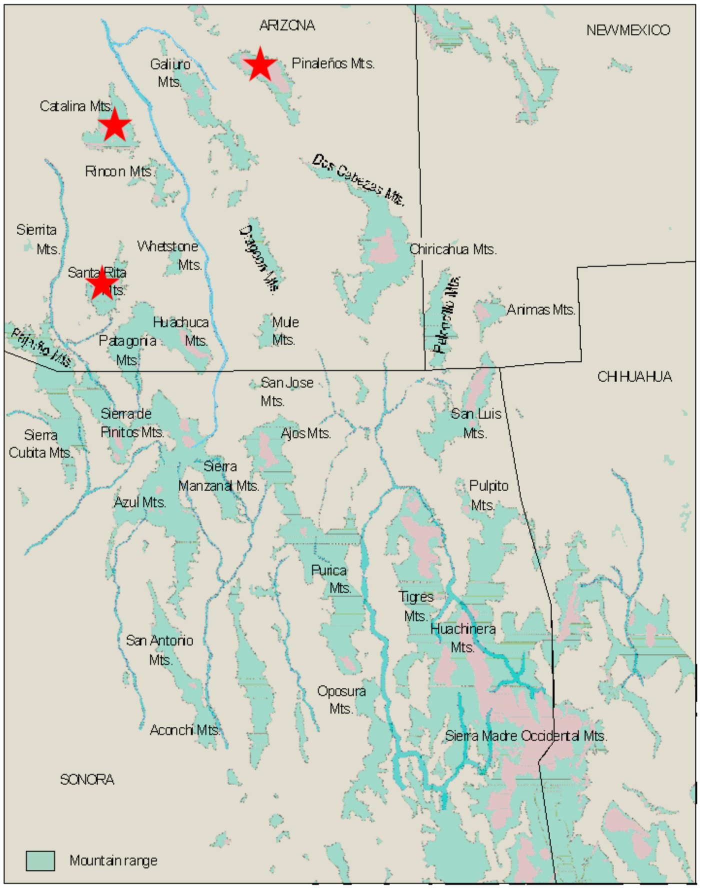


Figure 10. Wallow Wildfire: Three Verification Basins (North Fork Thomas Creek, South Fork Thomas Creek, and Hannagan Creek Basin at Highway 191).

Reed - Schaffner Equations 12 and 13



PREVIOUS WORK SKY ISLAND BASINS

Santa Catalina

- Sabino
- Alder
- Campo Bonito
- Romero
- Cañada del Oro

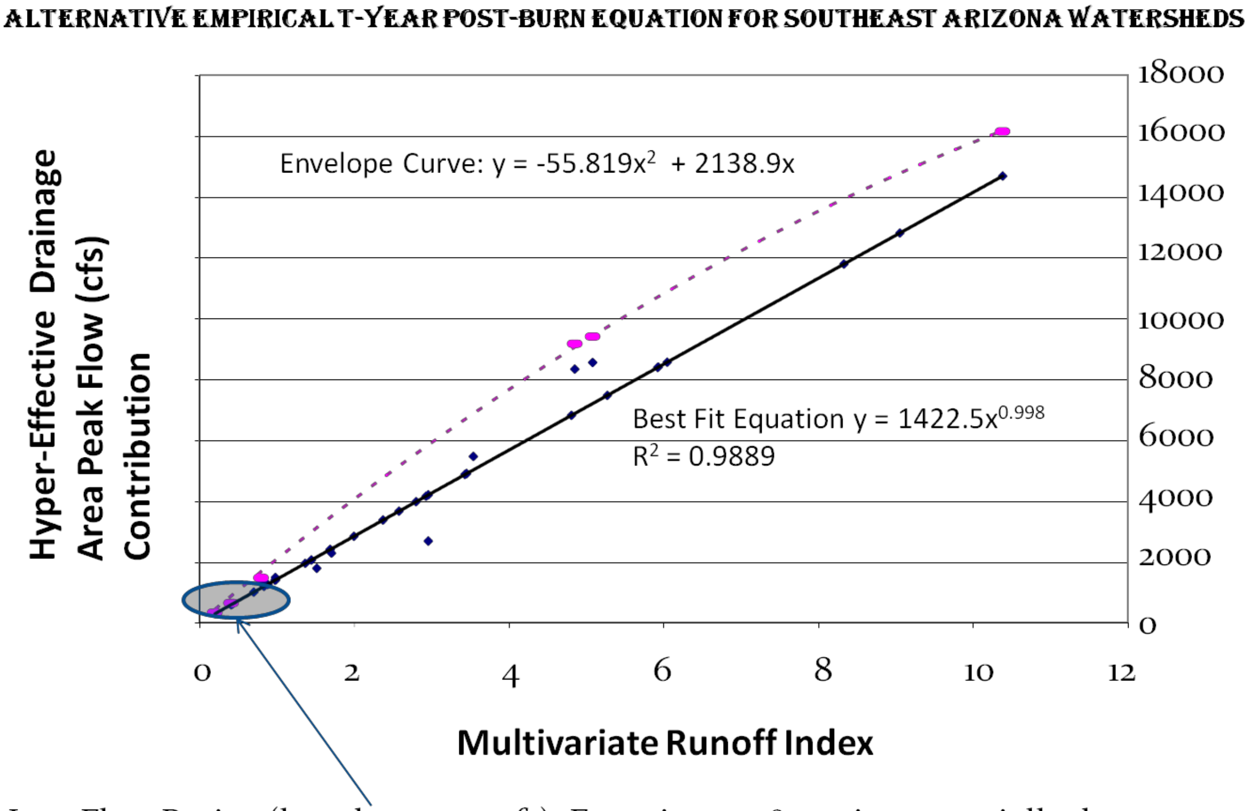
Santa Rita

- Madera

Pinaleno Mountains

- Marijilda,
- Frye
- Deadman
- Noon
- Wet

Figure 11. Previously 11 basins in the Sky Island Complex of Southeastern Arizona were studied. These basins are in the Santa Catalina, Santa Rita, and Pinaleno Mountains.



For Low Flow Basins (less than 1,100 cfs): Equations 12 & 13 give essentially the same answer.

Figure 12. **Equation 12 and 13 were generated from a data set of 37 values developed from the original data set of 11 basins to better define the envelope curve. The best fit equation (Equation 13) stayed the same as Equation 3 that used only 11 data points. For low flows (less than 1,100 cfs), Equations 12 & 13 converge.**

Miller Canyon

Figure 13. USFS Image of rain falling over Miller Canyon, Monument Fire Burn Area, on July 10, 2011 (used with permission).

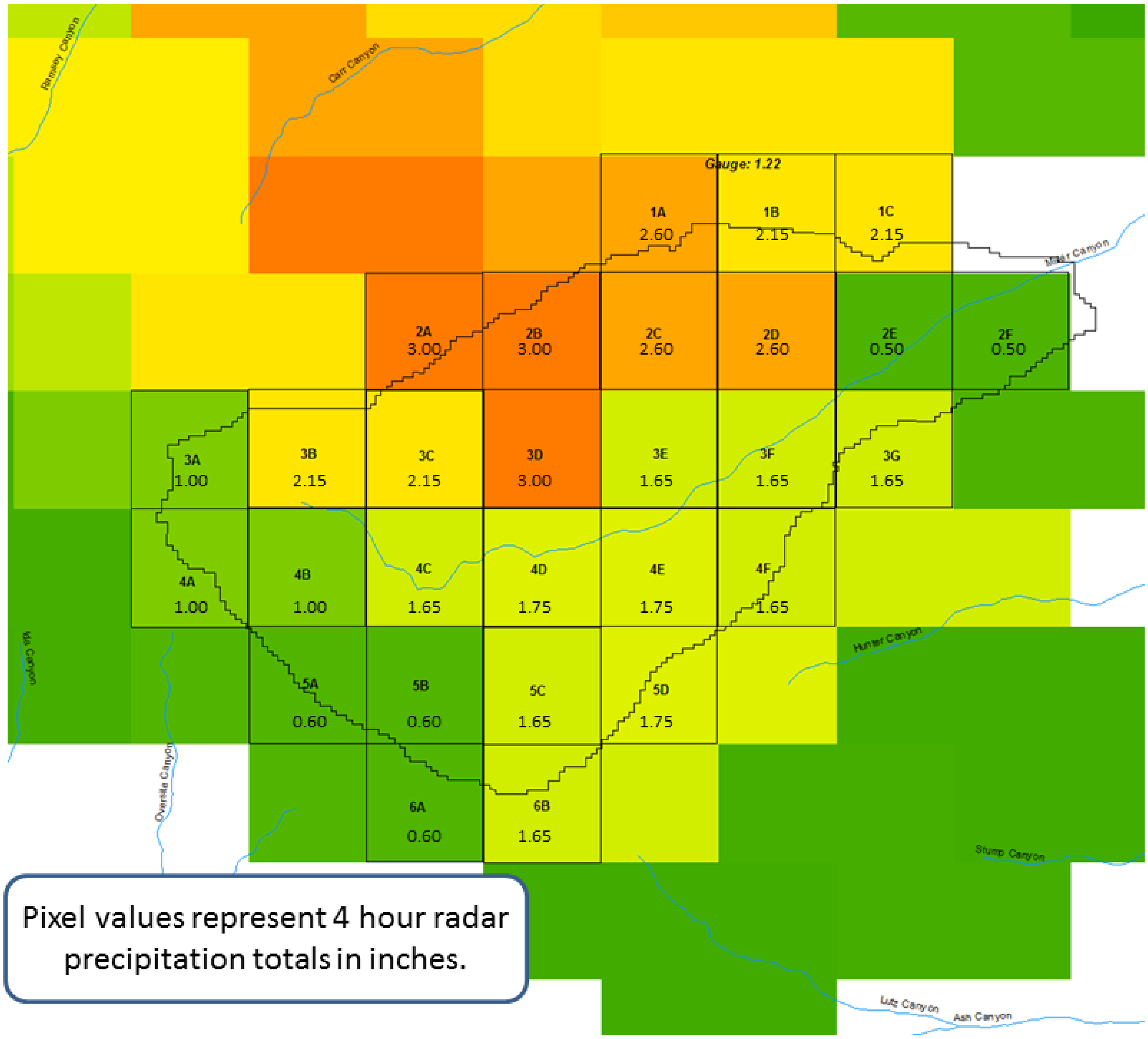


Figure 14. Miller Canyon 4-Hour Storm Total (inches), the Centroid of the Basin Lies within Grid 3D.

Miller Canyon Channel Characteristics						
Cross Section #	n	Area (square feet)	Wetted Perimeter (feet)	slope	Q (cfs)	Velocity (ft/sec)
1	0.075	425	107	0.084	6,115	14.4
2	0.056	295	114	0.084	4,275	14.5
3	0.055	275	109	0.084	3,990	14.5
				avg	**4,795**[18]	**14.5**

Figure 15. Miller Canyon Channel Characteristics and Calculated Values.

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[18] USGS calculated 4,900 cfs using a different method. Two methods are within 105 cfs, i.e., are within 2%.

Figure 16. Miller Canyon Channel Upstream of Surveyed Reach: Manning's n = 0.050 - 0.055.

Miller Basin – TWC[19]	
Lat:	**31.25.16 N**
Long:	**110.15.52 W**
Total Area (sq. mi.)	**3.57**
High Burn Severity (sq. mi.)	**1.26**
Moderate Burn Severity (sq. mi.)	**1.55**
Post-Burn Hyper-effective Area (sq. mi.)	**2.80**
Modified Channel Relief Ratio	**0.1671**
Modified Elevation Difference (ft)	**2,824**
Modified Stream Length (ft)	**16,900**
Mean Basin Elevation (ft)	**7,407**
Basin Elevation Difference (ft)	**4,074**
Stream Length (ft)	**19,680**
Time of Concentration (min)	**29**

Figure 17. Miller Canyon Basin Characteristics.

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[19] Basin is above cross sections surveyed by Tucson Weather Forecast Office (TWC).

Figure 18. Notice the debris on the car port roof and highwater mark stain on the two shown sides of the building. This photo was provided courtesy of BAER team and was taken the day after the lower Miller Canyon flash flood.

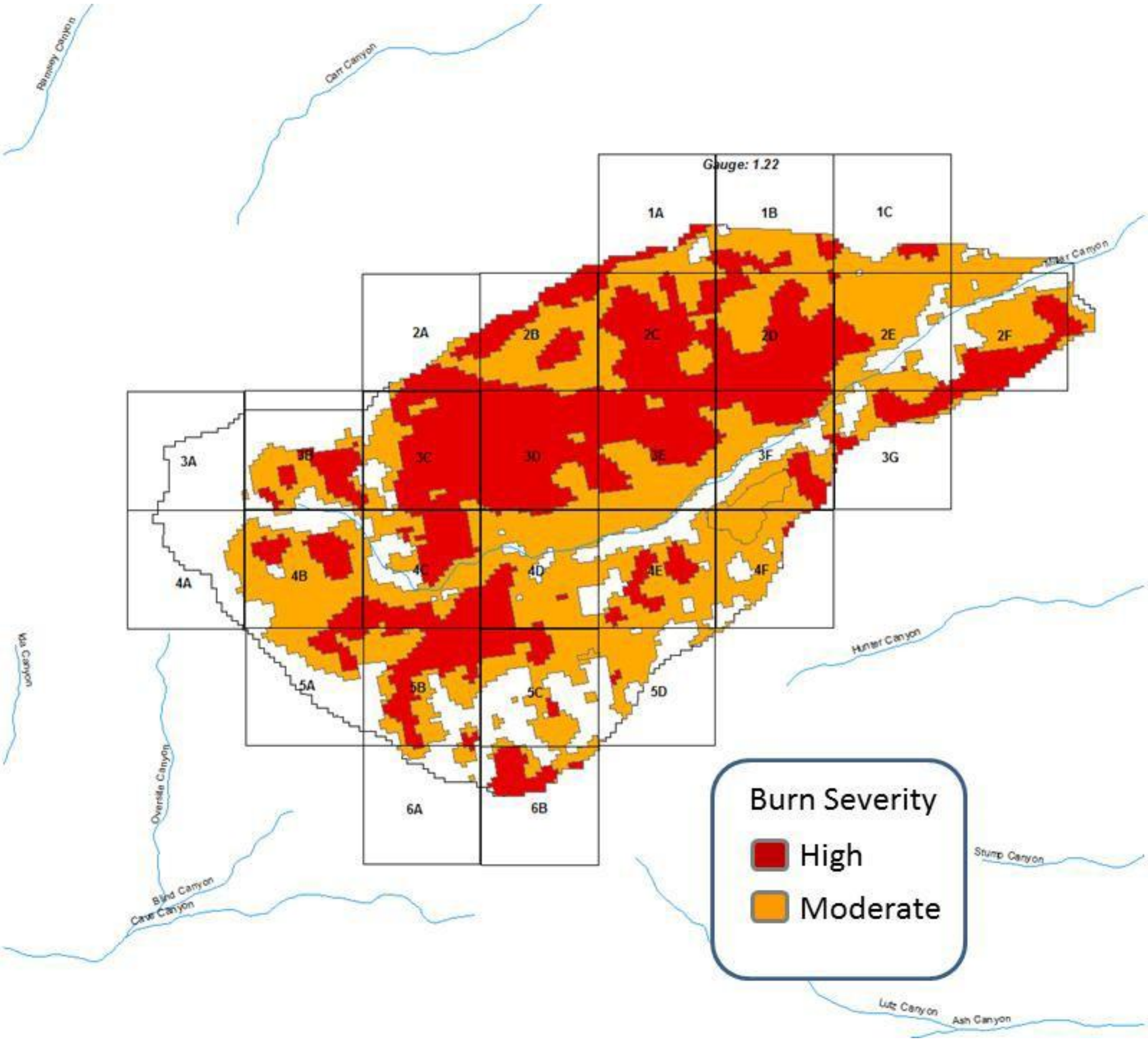

Figure 19. Miller Canyon Burn Severity Map, the Centroid of the Basin Lies Within Grid 3D.

MILLER BASIN									
					1yr 30min			2yr 30min	
ID	LAT	LON	RAW RADAR	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER
1A	31.424	-110.288	1.50	0.88	0.99	1.13	1.13	1.28	1.45
1B	31.424	-110.281	1.45	0.84	0.95	1.08	1.08	1.22	1.39
1C	31.424	-110.275	1.45	0.80	0.90	1.03	1.02	1.16	1.31
2A	31.417	-110.301	1.50	0.95	1.07	1.22	1.22	1.38	1.56
2B	31.417	-110.294	1.50	0.92	1.03	1.18	1.17	1.33	1.51
2C	31.417	-110.288	1.50	0.92	1.03	1.18	1.17	1.33	1.51
2D	31.417	-110.281	1.50	0.88	0.99	1.12	1.12	1.27	1.44
2E	31.417	-110.275	0.40	0.83	0.93	1.06	1.06	1.20	1.36
2F	31.417	-110.268	0.40	0.78	0.88	1.00	1.00	1.13	1.28
3A	31.41	-110.314	1.25	1.00	1.13	1.28	1.28	1.45	1.65
3B	31.41	-110.308	1.60	0.99	1.11	1.26	1.26	1.43	1.62
3C	31.41	-110.301	1.60	0.97	1.09	1.24	1.24	1.40	1.59
3D	**31.41**	**-110.294**	**1.50**	**0.94**	**1.05**	**1.20**	**1.20**	**1.36**	**1.54**
3E	31.41	-110.288	1.10	0.94	1.05	1.20	1.20	1.36	1.54
3F	31.41	-110.281	1.10	0.89	1.01	1.15	1.15	1.30	1.47
3G	31.41	-110.275	1.10	0.84	0.95	1.08	1.08	1.23	1.39
4A	31.404	-110.314	1.25	0.99	1.12	1.27	1.27	1.44	1.63
4B	31.404	-110.308	1.25	0.98	1.11	1.26	1.26	1.43	1.62
4C	31.404	-110.301	1.35	0.97	1.09	1.24	1.24	1.41	1.59
4D	31.404	-110.294	1.25	0.94	1.06	1.21	1.21	1.37	1.55
4E	31.404	-110.288	1.25	0.94	1.06	1.21	1.21	1.37	1.55
4F	31.404	-110.281	1.10	0.91	1.02	1.16	1.16	1.31	1.49
5A	31.397	-110.308	0.40	0.98	1.11	1.26	1.26	1.43	1.62
5B	31.397	-110.301	0.40	0.97	1.09	1.24	1.24	1.41	1.59
5C	31.397	-110.294	1.35	0.94	1.06	1.21	1.21	1.37	1.55
5D	31.397	-110.288	1.25	0.94	1.06	1.21	1.21	1.37	1.55
6A	31.391	-110.301	0.40	0.97	1.09	1.24	1.24	1.40	1.59
6B	31.391	-110.294	1.35	0.95	1.07	1.22	1.22	1.38	1.56
		MEAN	**1.18**	0.92	1.04	1.18	**1.18**	1.34	1.52
		MEDIAN	**1.25**	0.94	1.06	1.21	**1.21**	1.37	1.55

Figure 20. Miller Canyon by Grid Time of Concentration (30-Minute) Raw Radar Storm Amounts (inches) and 1-Year and 2-Year Return Interval Amounts (inches). These Grids Match Those Shown on Figure 18.

Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
3,015	4,020	5,025	3,920	4,900	5,880

Figure 21. Miller Canyon Comparison of Results for Peak Flow: The Higher Equation 12 Value for the 2-Year Storm is Greater Than the Mean Indirect Method Value and Less Than the Higher Indirect Method Value. Also the Mean Equation 12 Value is Greater Than the Lower Indirect Method Value.

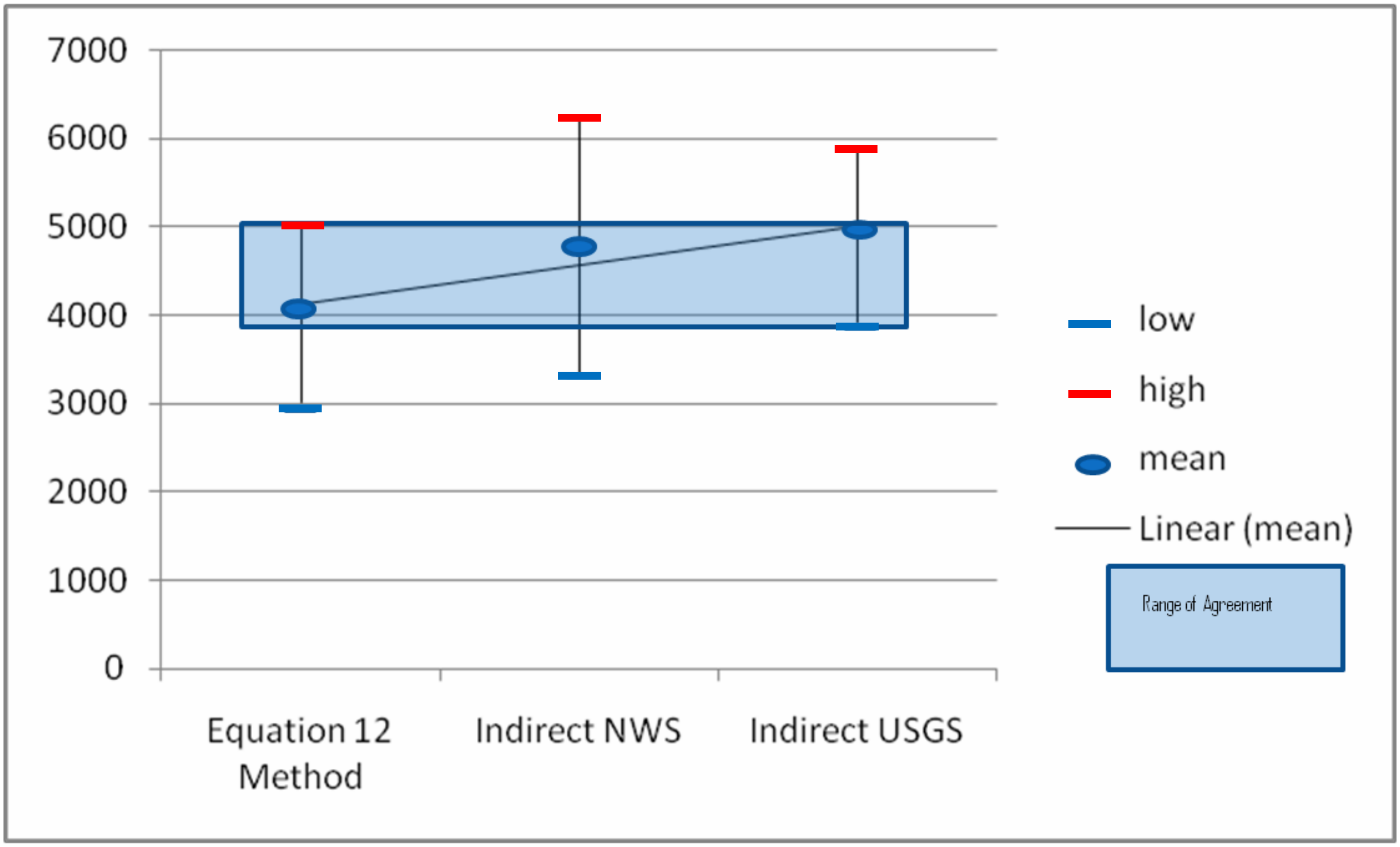

Figure 22. Miller Canyon Comparison of Results for Peak Flow: Range of Agreement.

East Turkey Creek

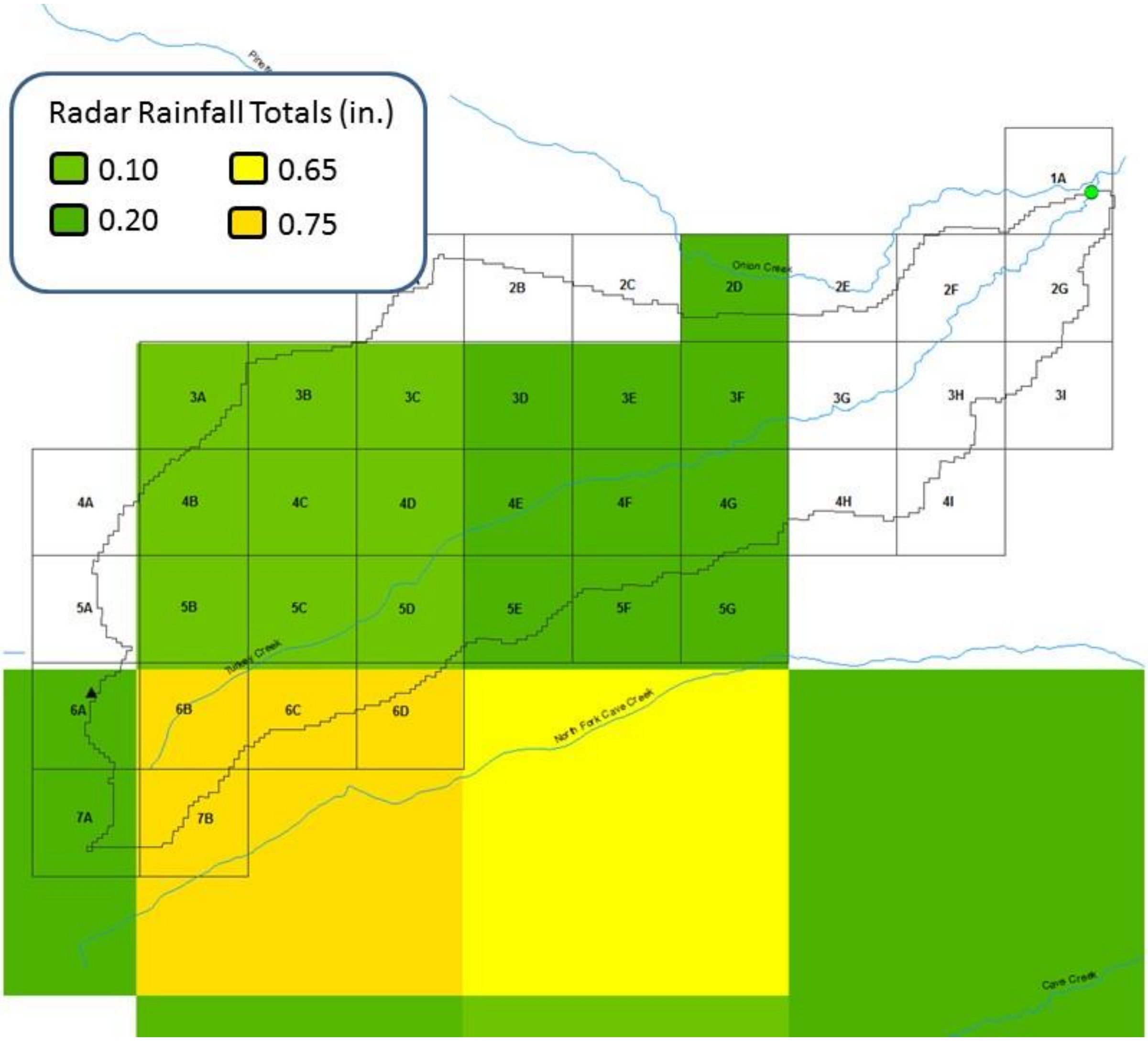

Figure 23. East Turkey Creek August 15 Rainfall Total from 2103-2145Z: the Centroid of the Basin lies within Grid 4E.

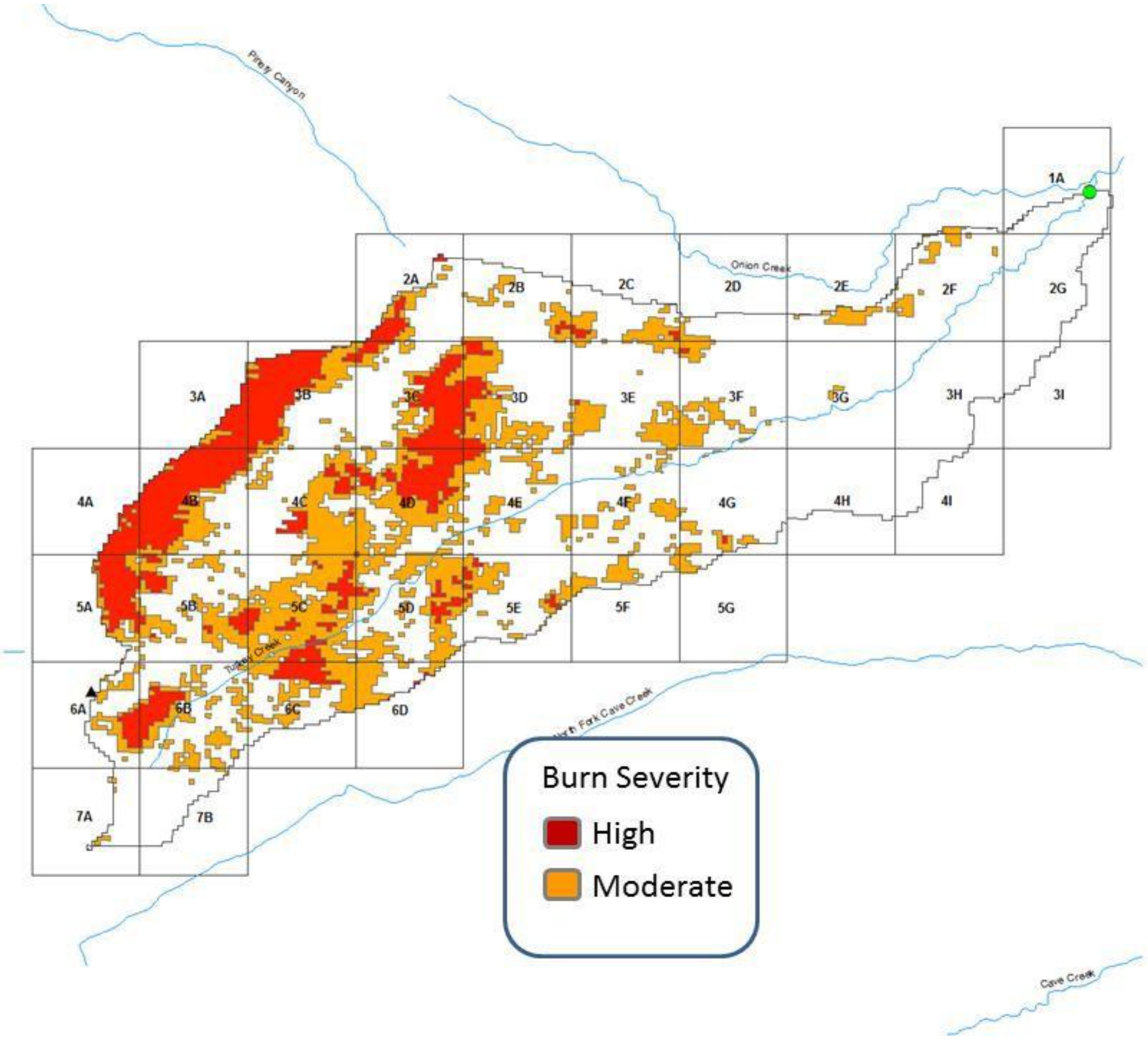

Figure 24. East Turkey Creek Burn Severity Map.

East Turkey Creek Channel Characteristics						
Cross Section #	n	Area (square feet)	Wetted Perimeter (feet)	slope	Q (cfs)	Velocity (ft/sec)
1	0.055	70	35.0	0.0298	520	7.4
2	0.037	40	26.6	0.0298	365	9.1
3	0.045	60	31.0	0.0298	530	8.8
				avg	470	8.4

Figure 25. East Turkey Creek Channel Characteristics and Calculated Values.

Figure 26. East Turkey Creek Looking Upstream From Cross Section 2 towards Cross Section 1: Manning's n = 0.045 - 0.050.

East Turkey Creek - TWC[20]	
Lat:	**31.55.36 N**
Long:	**109.13.20 W**
Total Area (sq. mi.)	**4.38**
High Burn Severity (sq. mi.)	**0.50**
Moderate Burn Severity (sq. mi.)	**0.93**
Post-Burn Hyper-effective Area (sq. mi.)	**1.43**
Modified Channel Relief Ratio	**0.1210**
Modified Elevation Difference (ft)	**2,396**
Modified Stream Length (ft)	**19,794**
Mean Basin Elevation (ft)	**7,410**
Basin Elevation Difference (ft)	**3,646**
Stream Length (ft)	**25,876**
Time of Concentration (min)	**41**

Figure 27. East Turkey Creek Basin Characteristics.

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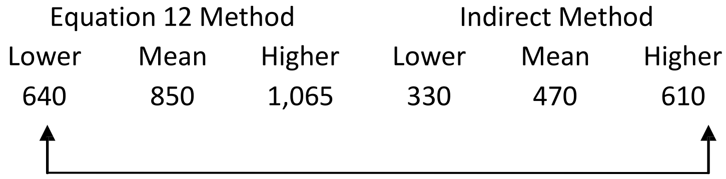
[20] Basin is above cross sections surveyed by Tucson Weather Forecast Office (TWC).

East Turkey Creek - August 15, 2011 2:03 PM - 2:45 PM MST

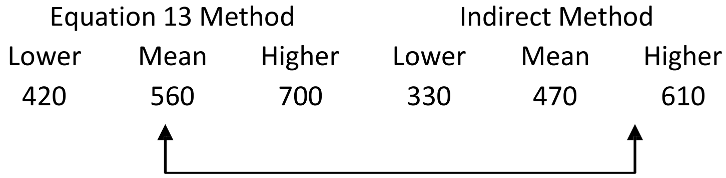
					1yr 30min	
ID	LAT	LON	RAW RADAR	LOWER	MEAN	UPPER
1A	31.927	-109.224	0.00	0.73	0.86	1.02
2A	31.921	-109.264	0.00	0.79	0.93	1.09
2B	31.921	-109.257	0.00	0.78	0.92	1.08
2C	31.921	-109.251	0.00	0.77	0.91	1.07
2D	31.921	-109.244	0.10	0.76	0.89	1.05
2E	31.921	-109.238	0.00	0.76	0.89	1.05
2F	31.921	-109.231	0.00	0.75	0.88	1.04
2G	31.921	-109.224	0.00	0.73	0.86	1.02
3A	31.914	-109.277	0.20	0.81	0.95	1.12
3B	31.914	-109.271	0.20	0.81	0.95	1.12
3C	31.914	-109.264	0.20	0.80	0.94	1.11
3D	31.914	-109.257	0.10	0.79	0.93	1.10
3E	31.914	-109.251	0.10	0.78	0.91	1.08
3F	31.914	-109.244	0.10	0.77	0.90	1.07
3G	31.914	-109.238	0.00	0.76	0.90	1.07
3H	31.914	-109.231	0.00	0.76	0.89	1.05
3I	31.914	-109.224	0.00	0.74	0.87	1.03
4A	31.908	-109.284	0.00	0.82	0.96	1.13
4B	31.908	-109.277	0.20	0.81	0.95	1.12
4C	31.908	-109.271	0.20	0.82	0.95	1.12
4D	31.908	-109.264	0.20	0.80	0.94	1.11
4E	**31.908**	**-109.257**	**0.10**	**0.80**	**0.93**	**1.10**
4F	31.908	-109.251	0.10	0.78	0.92	1.09
4G	31.908	-109.244	0.10	0.77	0.91	1.07
4H	31.908	-109.238	0.00	0.77	0.91	1.07
4I	31.908	-109.231	0.00	0.76	0.89	1.06
5A	31.901	-109.284	0.00	0.82	0.96	1.12
5B	31.901	-109.277	0.20	0.81	0.95	1.12
5C	31.901	-109.271	0.20	0.81	0.95	1.12
5D	31.901	-109.264	0.20	0.81	0.94	1.11
5E	31.901	-109.257	0.10	0.80	0.93	1.10
5F	31.901	-109.251	0.10	0.79	0.92	1.09
5G	31.901	-109.244	0.10	0.77	0.91	1.07
6A	31.895	-109.284	0.10	0.81	0.95	1.11
6B	31.895	-109.277	0.75	0.81	0.95	1.11
6C	31.895	-109.271	0.75	0.81	0.95	1.11
6D	31.895	-109.264	0.75	0.80	0.94	1.11
7A	31.888	-109.284	0.10	0.81	0.95	1.11
7B	31.888	-109.277	0.75	0.81	0.95	1.11
		MEAN (w/o zero)	**0.24**	**0.80**	0.93	1.10
		MEDIAN (w/o zero)	**0.20**	**0.80**	0.94	1.11

Figure 28. By Grid Time of Concentration (42-Minute) Raw Radar Storm Amounts (inches) and 1-Year Return Interval Amounts (inches). (These Grids Match Those Shown on Figures 23 and 24.)



Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
640	850	1,065	330	470	610

Figure 29. East Turkey Creek Comparison of Results for Peak Flow: The Lower Equation 12 Value for a 1-Year Storm is Greater Than the Higher Indirect Method Value by 30 cfs. (This is to be expected since the storm had a return interval less than 1-Year.) However, since the numbers are so close this can be considered a match.



Equation 13 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
420	560	700	330	470	610

Figure 30. East Turkey Creek Comparison of Results for Peak Flow: The Mean Equation 13 Value for the 1-Year Storm is Greater Than the Mean Indirect Method Value and Less Than the Higher Indirect Method Value. Also the Lower Equation 13 Value is Greater Than the Lower Indirect Method Value.

Ash Canyon

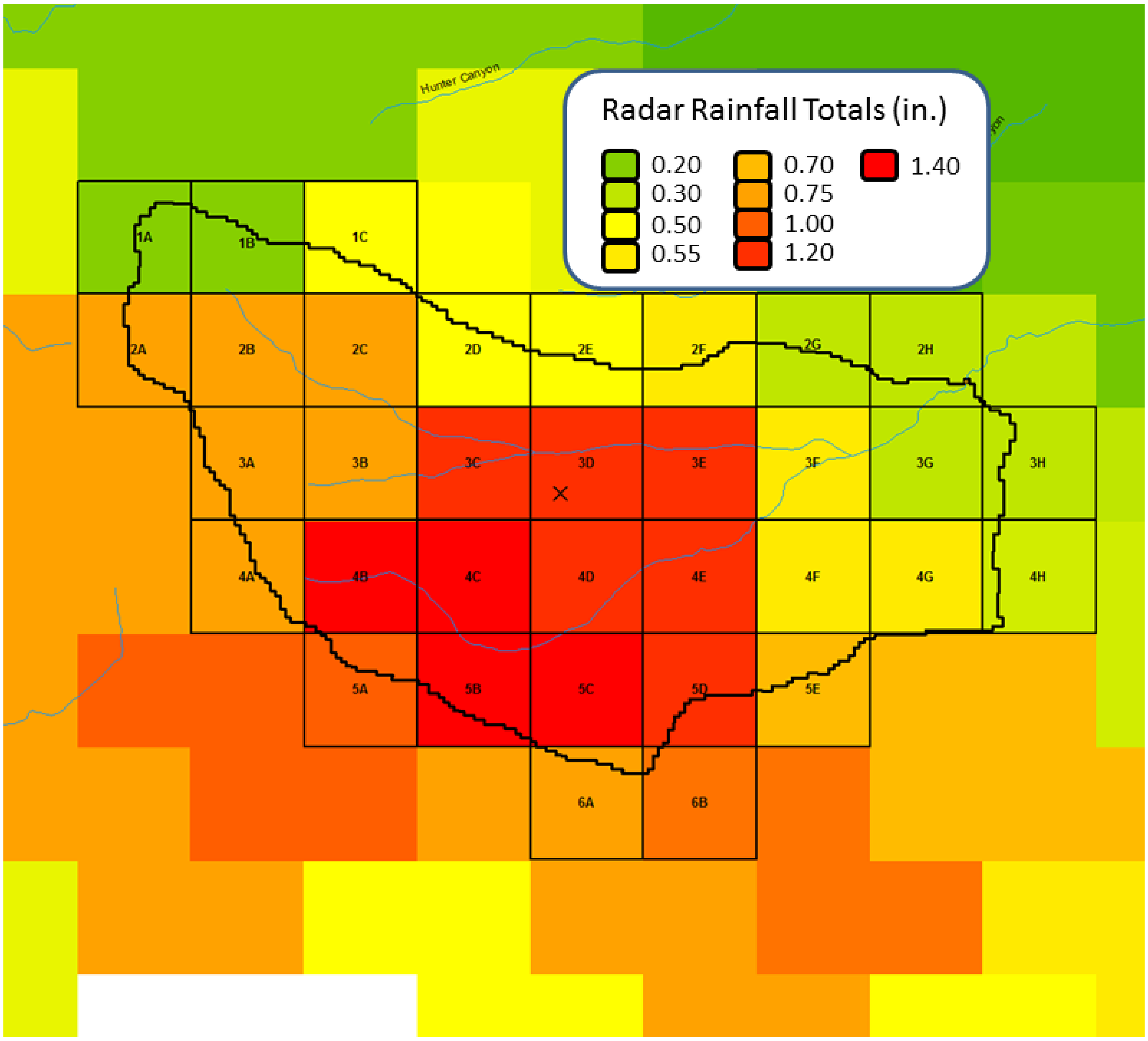


Figure 31. Ash Basin August 23 Rainfall Total from 0057-0124Z: the "X" in Grid 3D Marks the Centroid of the Basin.

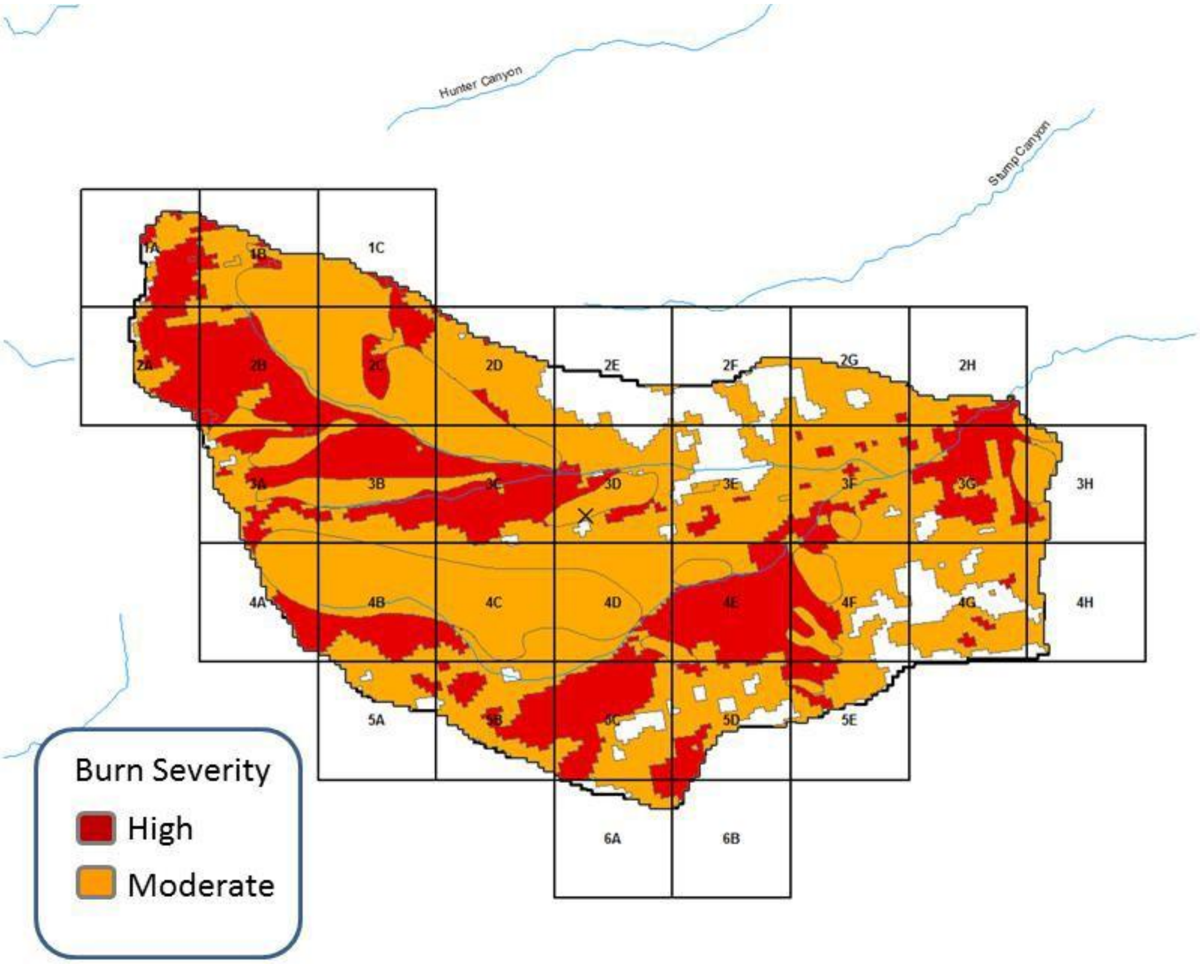
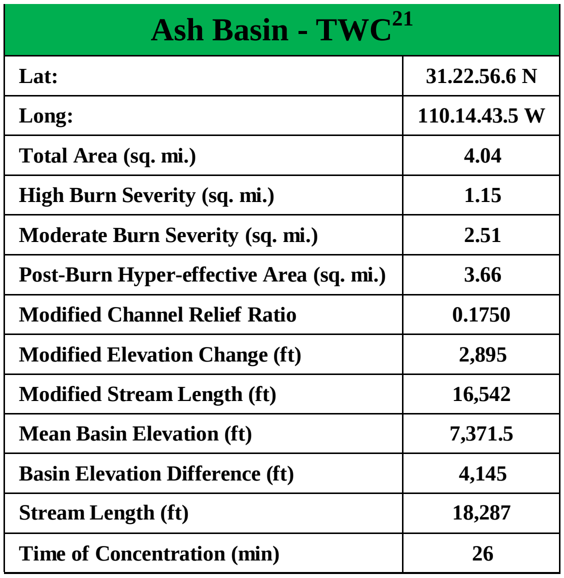


Figure 32. Ash Basin Burn Severity Map.

Ash Basin Channel Characteristics						
Cross Section #	n	Area (square feet)	Wetted Perimeter (feet)	slope	Q (cfs)	Velocity (ft/sec)
1	0.055	129	53.5	0.0527	1440	11.1
2	0.045	83	47.5	0.0527	910	11.0
3	0.045	80	47.5	0.0527	860	10.7
				avg	1070	11.0

Figure 33. Ash Canyon Channel Characteristics and Calculated Values.

Figure 34. Ash Canyon Channel Upstream of Cross Section 3: Manning's n = 0.045-0.050.



Ash Basin - TWC[21]	
Lat:	**31.22.56.6 N**
Long:	**110.14.43.5 W**
Total Area (sq. mi.)	**4.04**
High Burn Severity (sq. mi.)	**1.15**
Moderate Burn Severity (sq. mi.)	**2.51**
Post-Burn Hyper-effective Area (sq. mi.)	**3.66**
Modified Channel Relief Ratio	**0.1750**
Modified Elevation Change (ft)	**2,895**
Modified Stream Length (ft)	**16,542**
Mean Basin Elevation (ft)	**7,371.5**
Basin Elevation Difference (ft)	**4,145**
Stream Length (ft)	**18,287**
Time of Concentration (min)	**26**

Figure 35. Ash Canyon Basin Characteristics.

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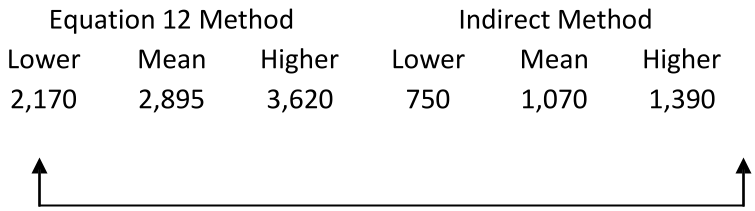
[21] Basin is above cross sections surveyed by Tucson Weather Forecast Office (TWC).

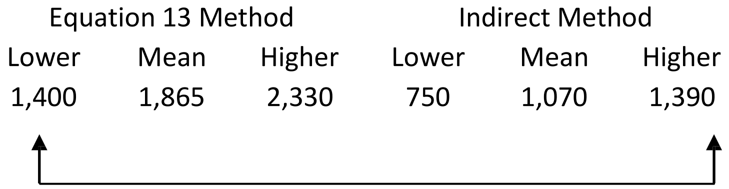
Ash Canyon - August 22, 2011 5:57 PM - 6:24 PM MST						
					1yr 30min	
ID	LAT	LON	RAW RADAR	LOWER	MEAN	UPPER
1A	31.391	-110.294	0.20	0.95	1.07	1.21
1B	31.391	-110.288	0.20	0.95	1.07	1.21
1C	31.391	-110.281	0.50	0.92	1.04	1.18
2A	31.384	-110.294	0.75	0.95	1.07	1.21
2B	31.384	-110.288	0.75	0.95	1.07	1.22
2C	31.384	-110.281	0.75	0.92	1.04	1.19
2D	31.384	-110.274	0.50	0.89	1.01	1.14
2E	31.384	-110.268	0.50	0.85	0.96	1.10
2F	31.384	-110.261	0.55	0.82	0.92	1.05
2G	31.384	-110.255	0.30	0.82	0.92	1.05
2H	31.384	-110.248	0.30	0.79	0.89	1.01
3A	31.377	-110.288	0.75	0.95	1.07	1.22
3B	31.377	-110.281	0.75	0.92	1.04	1.19
3C	31.377	-110.274	1.20	0.90	1.01	1.15
3D	**31.377**	**-110.268**	**1.20**	**0.86**	**0.98**	**1.11**
3E	31.377	-110.261	1.20	0.83	0.94	1.07
3F	31.377	-110.255	0.55	0.83	0.94	1.07
3G	31.377	-110.248	0.30	0.80	0.90	1.03
3H	31.377	-110.242	0.30	0.76	0.86	0.98
4A	31.371	-110.288	0.75	0.92	1.04	1.18
4B	31.371	-110.281	1.40	0.92	1.04	1.18
4C	31.371	-110.274	1.40	0.89	1.01	1.14
4D	31.371	-110.268	1.20	0.86	0.97	1.10
4E	31.371	-110.261	1.20	0.83	0.94	1.06
4F	31.371	-110.255	0.55	0.83	0.94	1.06
4G	31.371	-110.248	0.55	0.80	0.90	1.03
4H	31.371	-110.242	0.35	0.77	0.87	0.99
5A	31.364	-110.281	1.00	0.92	1.04	1.18
5B	31.364	-110.274	1.40	0.89	1.01	1.14
5C	31.364	-110.268	1.40	0.86	0.97	1.10
5D	31.364	-110.261	1.20	0.83	0.94	1.06
5E	31.364	-110.255	0.70	0.83	0.94	1.06
6A	31.357	-110.268	0.75	0.84	0.95	1.08
6B	31.357	-110.261	0.90	0.81	0.92	1.05
		MEAN	**0.77**	**0.87**	**0.98**	**1.11**
		MEDIAN	**0.75**	**0.86**	**0.97**	**1.10**

Figure 36. By Grid Time of Concentration (27-Minute) Raw Radar Storm Amounts (inches) and 1-Year Return Interval Amounts (inches). (These Grids Match Those Shown on Figures 31 and 32.)



Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
2,170	2,895	3,620	750	1,070	1,390

Figure 37. Ash Canyon Comparison of Results for Peak Flow: The Lower Equation 12 Value for the 1-Year Storm is Greater Than the Higher Indirect Method Value. (This is to be expected since the storm had a return interval less than 1-Year.)



Equation 13 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
1,400	1,865	2,330	750	1,070	1,390

Figure 38. Ash Canyon Comparison of Results for Peak Flow: The Lower Equation 13 Value for the 1-Year Storm is essentially the same as the Higher Indirect Method Value.

Old Sawmill Creek

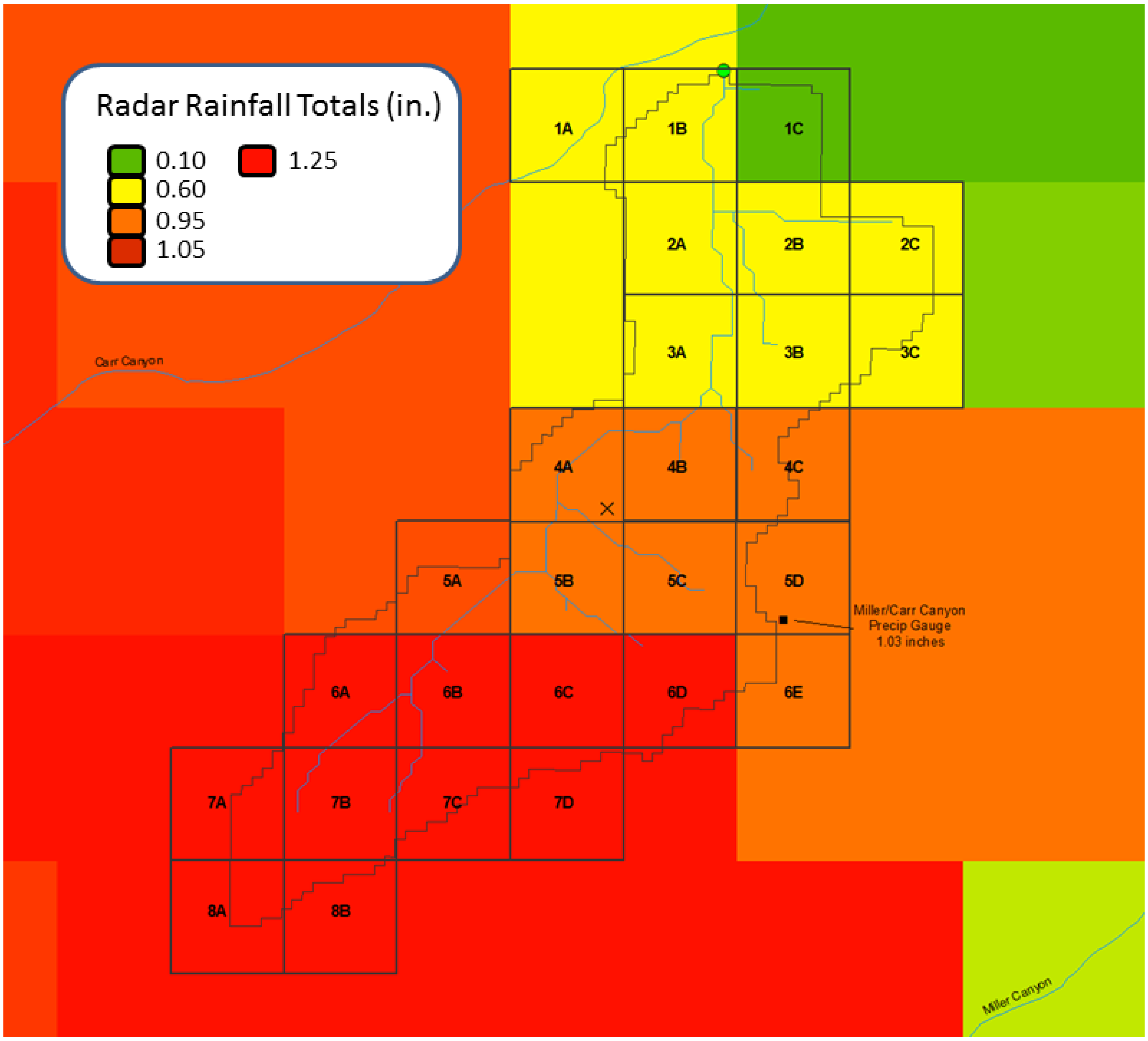


Figure 39. Old Sawmill Creek 18-Minute Rainfall Total: the "X" in Grid 4A Marks the Centroid of the Basin.

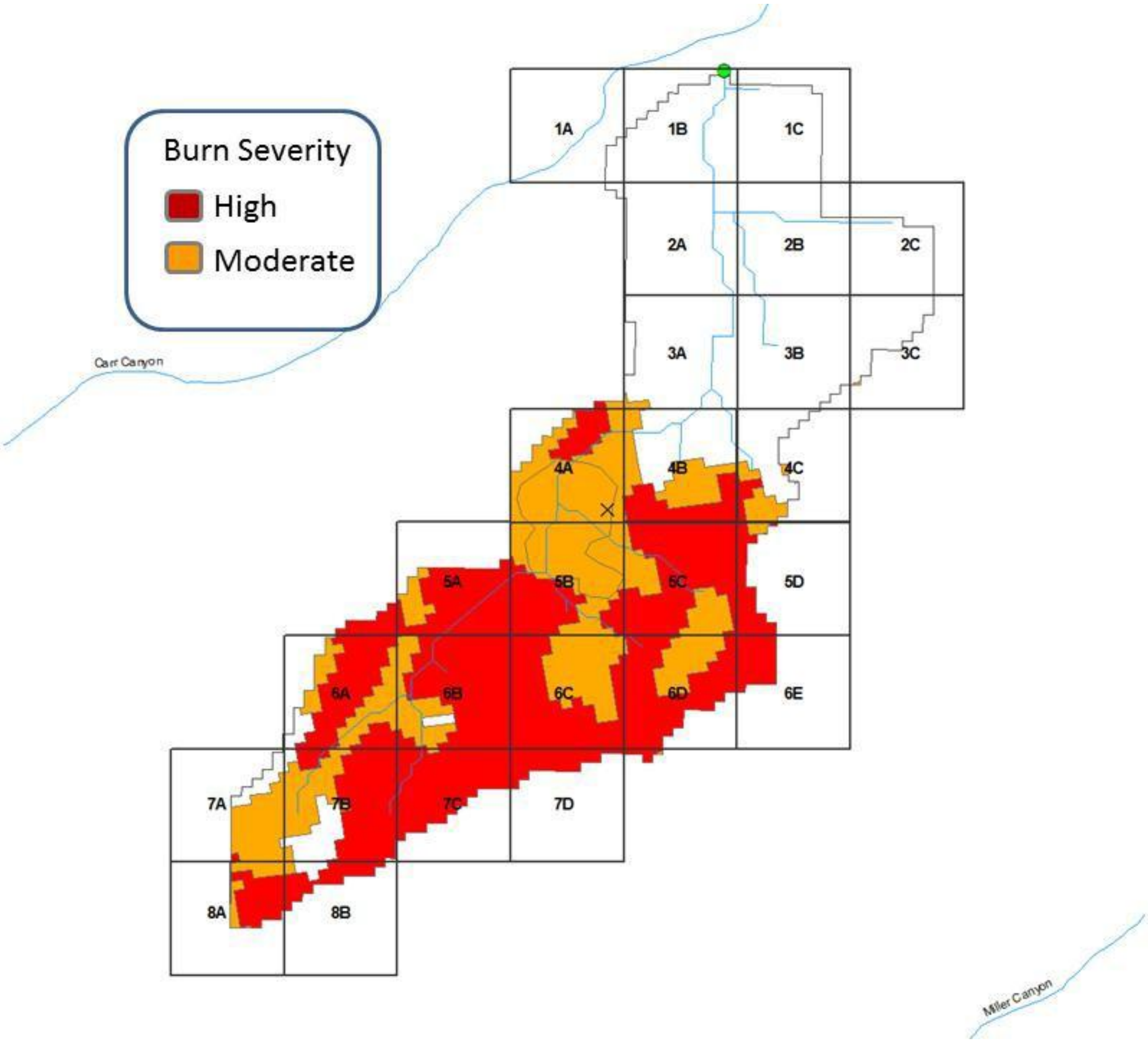


Figure 40. Old Sawmill Creek Burn Severity Map: burn area is essential the upper 60% of the basin within grids 4A-8B. The "X" in Grid 4A marks the Centroid of the Basin.

Old Sawmill Creek Channel Characteristics						
Cross Section #	n	Area (square feet)	Wetted Perimeter (feet)	slope	Q (cfs)	Velocity (ft/sec)
1	0.070	156	70	0.0823	1,620	10.4

Figure 41. Old Sawmill Creek Channel Characteristics and Calculated Values.

Figure 42. Old Sawmill Creek Looking Downstream at Cross Section): Manning's n = 0.070-0.075.

Sawmill Creek Basin - TWC[22]	
Lat:	**31.26.31.6 N**
Long:	**110.17.7.2 W**
Total Area (sq. mi.)	**0.79**
High Burn Severity (sq. mi.)	**0.29**
Moderate Burn Severity (sq. mi.)	**0.17**
Post-Burn Hyper-effective Area (sq. mi.)	**0.46**
Channel Relief Ratio	**0.2522**
Mean Basin Elevation (ft)	**6,889.5**
Basin Elevation Difference (ft)	**2,937**
Stream Length (ft)	**11,647**
Time of Concentration (min)	**18**

Figure 43. Old Sawmill Creek Basin Characteristics.

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[22] Basin is above cross section surveyed by Tucson Weather Forecast Office (TWC).

Figure 44. Bridge in Carr Canyon: bridge is approximately 0.2 mile upstream of the cross section (figure 39). This photo was provided courtesy of BAER team and was taken the day after the Carr Canyon flash flood.

Old Sawmill Creek - July 10, 2011 2:00 PM - 2:18 PM MST

					2yr 15min			5yr 15min		
ID	LAT	LON	RAW RADAR	Adjusted for 15 min	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER
1A	31.441	-110.289	0.60		0.74	0.84	0.95	0.95	1.08	1.23
1B	31.441	-110.286	0.60		0.71	0.81	0.92	0.92	1.05	1.19
1C	31.441	-110.283	0.10		0.71	0.81	0.92	0.92	1.05	1.19
2A	31.437	-110.286	0.60		0.76	0.86	0.97	0.98	1.11	1.26
2B	31.437	-110.283	0.60		0.76	0.86	0.97	0.98	1.11	1.26
2C	31.437	-110.279	0.60		0.72	0.82	0.93	0.93	1.06	1.20
3A	31.434	-110.286	0.60	0.50	0.76	0.86	0.97	0.98	1.11	1.26
3B	31.434	-110.283	0.60		0.76	0.86	0.97	0.98	1.11	1.26
3C	31.434	-110.279	0.60	0.50	0.72	0.82	0.93	0.93	1.06	1.20
4A	**31.431**	**-110.289**	**0.95**	**0.79**	**0.79**	**0.89**	**1.01**	**1.01**	**1.16**	**1.31**
4B	31.431	-110.286	0.95	0.79	0.76	0.86	0.97	0.98	1.11	1.26
4C	31.431	-110.283	0.95	0.79	0.76	0.86	0.97	0.98	1.11	1.26
5A	31.427	-110.293	1.05	0.87	0.84	0.95	1.07	1.08	1.23	1.39
5B	31.427	-110.289	0.95	0.79	0.84	0.95	1.07	1.08	1.23	1.39
5C	31.427	-110.286	0.95	0.79	0.80	0.91	1.03	1.03	1.18	1.33
5D	31.427	-110.283	0.95	0.79	0.80	0.91	1.03	1.03	1.18	1.33
6A	31.424	-110.296	1.25	1.04	0.87	0.98	1.11	1.11	1.27	1.43
6B	31.424	-110.293	1.25	1.04	0.84	0.95	1.07	1.08	1.23	1.39
6C	31.424	-110.289	1.25	1.04	0.84	0.95	1.07	1.08	1.23	1.39
6D	31.424	-110.286	1.25	1.04	0.80	0.91	1.03	1.03	1.18	1.33
6E	31.424	-110.283	0.95	0.79	0.80	0.91	1.03	1.03	1.18	1.33
7A	31.421	-110.299	1.25	1.04	0.87	0.98	1.11	1.11	1.27	1.43
7B	31.421	-110.296	1.25	1.04	0.87	0.98	1.11	1.11	1.27	1.43
7C	31.421	-110.293	1.25	1.04	0.84	0.95	1.07	1.08	1.23	1.39
7D	31.421	-110.289	1.25	1.04	0.84	0.95	1.07	1.08	1.23	1.39
8A	31.417	-110.299	1.25	1.04	0.90	1.02	1.16	1.16	1.32	1.49
8B	31.417	-110.296	1.25	1.04	0.90	1.02	1.16	1.16	1.32	1.49
		MEAN	0.93	**0.89**	0.80	**0.91**	1.02	1.03	1.17	1.33
		MEDIAN	0.95	**0.95**	0.80	**0.91**	1.03	1.03	1.18	1.33

Figure 45. By Grid Time of Concentration (18-Minute) Raw Radar Storm Amounts (inches) and 1-Year and 2-Year 15-Minute Return Interval Amounts (inches). (These Grids Match Those Shown on Figures 39 and 40.)

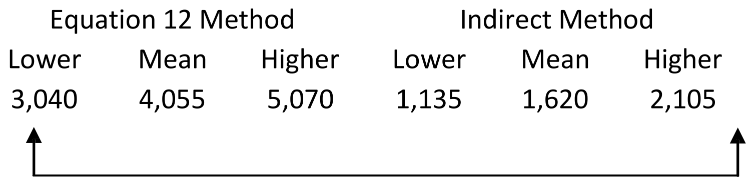


Figure 46. Old Sawmill Creek Comparison of Results for Peak Flow: Equation 12 (Using Unmodified Channel Relief Ratio); the Lower Equation 12 Value for the 2-Year Storm is Greater Than the Higher Indirect Method Value by 935 cfs. (This is to be expected since the basin has a drainage area less than 1 square mile.)

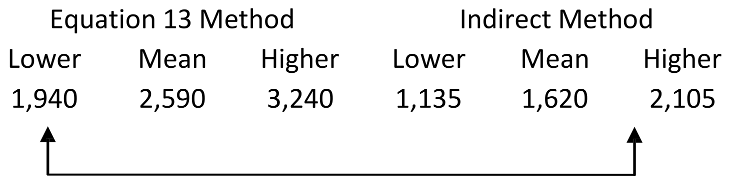
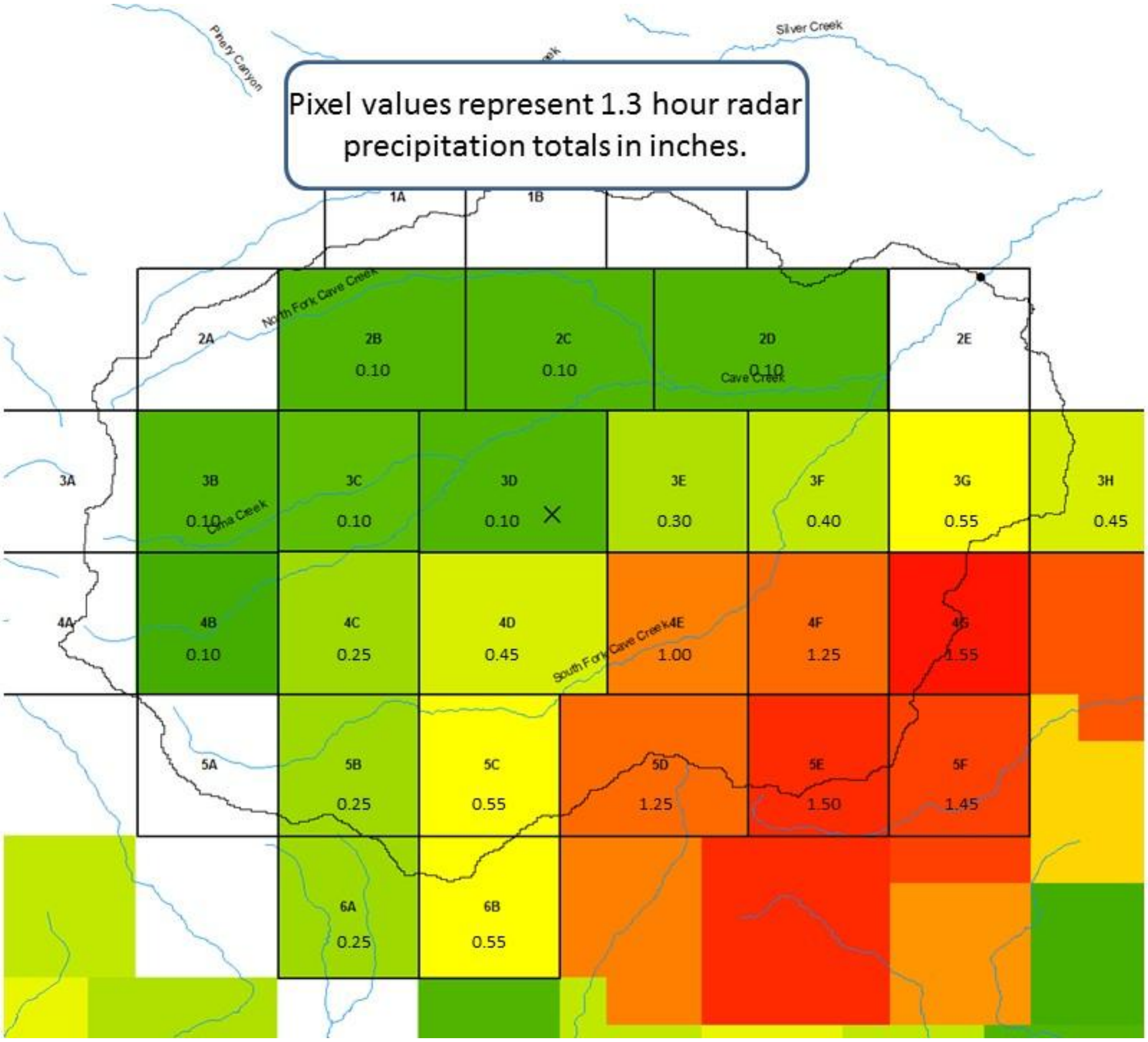


Figure 47. Old Sawmill Creek Comparison of Results for Peak Flow: Equation 13 (Using Unmodified Channel Relief Ratio); the Lower Equation 13 Value for the 2-Year Storm is Greater Than the Mean Indirect Method Value and Less Than the Higher Indirect Method Value.

Cave Creek



Pixel values represent 1.3 hour radar precipitation totals in inches.

Figure 48. Cave Creek Rainfall Total from 1801 to 1919: the "X" in Grid 3D Marks the Centroid of the Basin.

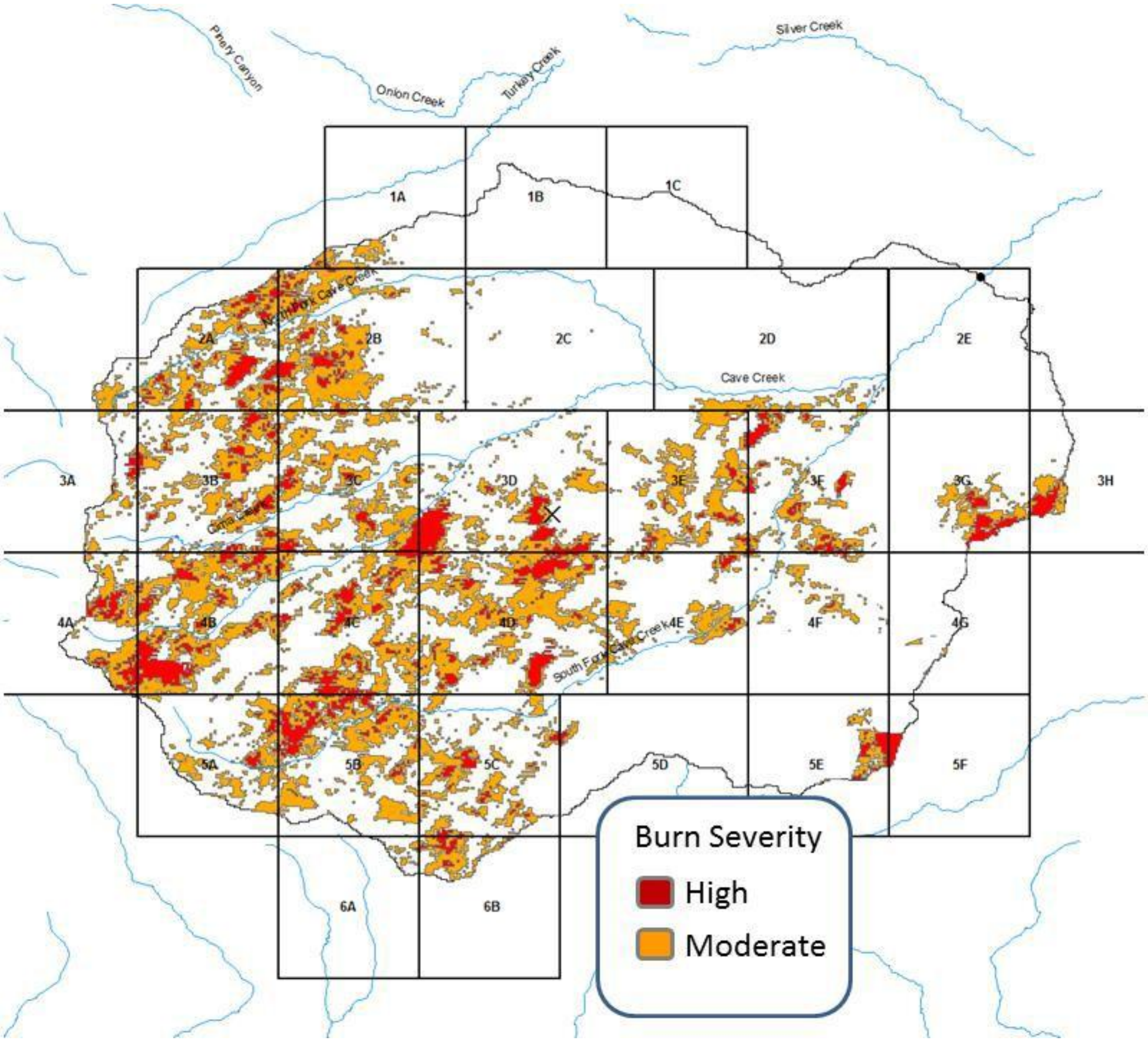


Figure 49. Cave Creek Burn Severity Map.

Cave Creek Channel Characteristics						
Cross Section #	n	Area (square feet)	Wetted Perimeter (feet)	slope	Q (cfs)	Velocity (ft/sec)
1	0.070	134	49.0	0.030	965	7.2
2	0.065	127	57.0	0.030	860	6.8
3	0.065	115	47.5	0.030	820	7.1
				avg	880	7.0

Figure 50. Cave Creek Channel Characteristics and Calculated Values.

Figure 51. Cave Creek Looking Downstream of Cross Section 3: Manning’s n = 0.065 - 0.070.

Cave Creek - TWC[23]	
Lat:	31.53.53 N
Long:	109.09.40 W
Total Area (sq. mi.)	39.40
High Burn Severity (sq. mi.)	1.98
Moderate Burn Severity (sq. mi.)	7.40
Post-Burn Hyper-effective Area (sq. mi.)	9.38
Modified Channel Relief Ratio	0.0799
Modified Elevation Difference (ft)	3,467
Modified Stream Length (ft)	43,396
Mean Basin Elevation (ft)	7,314.5
Basin Elevation Difference (ft)	4,717
Stream Length (ft)	48,757
Time of Concentration (min)	77

Figure 52. Cave Creek Basin Characteristics.

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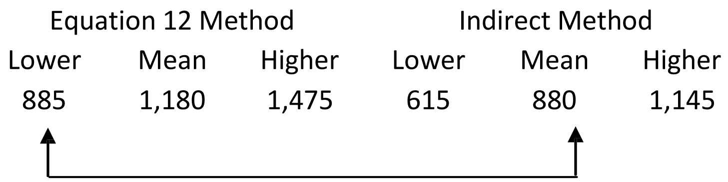
[23] Basin is above cross sections surveyed by Tucson Weather Forecast Office (TWC).

Cave Creek - July 26, 2011 11:01 AM - 12:19 PM MST

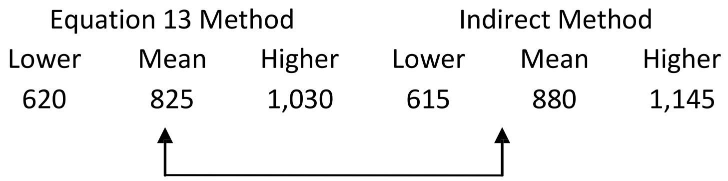
					1yr 60min		
ID	LAT	LON	Adjusted for 60 Minutes	RAW RADAR	LOWER	MEAN	UPPER
1A	31.909	-109.244		0.00	0.96	1.12	1.33
1B	31.909	-109.224		0.00	0.92	1.09	1.29
1C	31.909	-109.204		0.00	0.88	1.03	1.23
2A	31.889	-109.271		0.00	1.00	1.17	1.38
2B	31.889	-109.247		0.10	0.97	1.14	1.35
2C	31.889	-109.221		0.10	0.91	1.06	1.26
2D	31.889	-109.191		0.10	0.88	1.03	1.23
2E	31.889	-109.164		0.00	0.84	1.00	1.19
3A	31.869	-109.29		0.00	0.99	1.15	1.35
3B	31.869	-109.271		0.10	0.99	1.16	1.37
3C	31.869	-109.25		0.10	0.98	1.15	1.36
3D	31.869	-109.227		0.10	0.92	1.08	1.29
3E	31.869	-109.204		0.30	0.90	1.06	1.26
3F	31.869	-109.185		0.40	0.91	1.07	1.27
3G	31.869	-109.164		0.55	0.89	1.06	1.26
3H	31.869	-109.144		0.45	0.83	0.98	1.18
4A	31.85	-109.29		0.00	1.00	1.16	1.36
4B	31.85	-109.271		0.10	1.00	1.17	1.38
4C	31.85	-109.25		0.25	1.00	1.17	1.38
4D	31.85	-109.227		0.45	0.95	1.12	1.33
4E	31.85	-109.204		1.00	0.93	1.10	1.31
4F	31.85	-109.185	0.97	1.25	0.93	1.10	1.31
4G	31.85	-109.164	1.21	1.55	0.91	1.07	1.28
5A	31.829	-109.271		0.00	1.01	1.18	1.39
5B	31.829	-109.25		0.25	1.01	1.18	1.40
5C	31.829	-109.231		0.55	1.00	1.17	1.38
5D	31.829	-109.207	0.97	1.25	0.97	1.14	1.36
5E	31.829	-109.185	1.17	1.50	0.95	1.12	1.33
5F	31.829	-109.164	1.13	1.45	0.91	1.08	1.29
6A	31.809	-109.25		0.25	0.99	1.15	1.36
6B	31.809	-109.231		0.55	0.98	1.15	1.36
		MEAN	1.09	0.41	0.95	**1.11**	**1.32**
		MEDIAN	1.13	0.25	0.95	1.12	**1.33**

Figure 53. By Grid Time of Concentration (77-Minute) Raw Radar Storm Amounts (inches) and 1-Year 60-Minute Return Interval Amounts (inches). (These Grids Match Those Shown on Figures 48 and 49.)



Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
885	1,180	1,475	615	880	1,145

Figure 54. Cave Creek Comparison of Results for Peak Flow: The Lower Equation 12 Value for the 1-Year Storm is Greater Than the Mean Indirect Method Value and Less Than the Higher Indirect Method Value.



Equation 13 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
620	825	1,030	615	880	1,145

Figure 55. Cave Creek Comparison of Results for Peak Flow: The Lower and Mean Equation 13 Values for the 1-Year Storm are Greater Than the Lower Indirect Method Value and Less Than the Mean Indirect Method Value. Also the Higher Equation 13 Value is less Than the Higher Indirect Method Value.

North Fork Thomas Creek

USGS Precipitation Data

North Fork Thomas Creek Near Alpine, Arizona (07/11/2011)

		Totals			
Time	**Zone**	**15-Minute**	**30-Minute**	**75-Minute**	**Storm Total**
14:45:00	MST	0.08			
15:00:00	MST	0.16	0.24		
15:15:00	MST	0.45	0.61		
15:30:00	MST	**0.62**	**1.07**		
15:45:00	MST	0.29	0.91	**1.60**	
16:00:00	MST	0.05	0.34	1.57	
16:15:00	MST	0.01	0.06	1.42	**1.66**

Figure 56. North Fork Thomas Creek – July 11 Rainfall Totals: Storm Duration 1 hour 45 minutes.

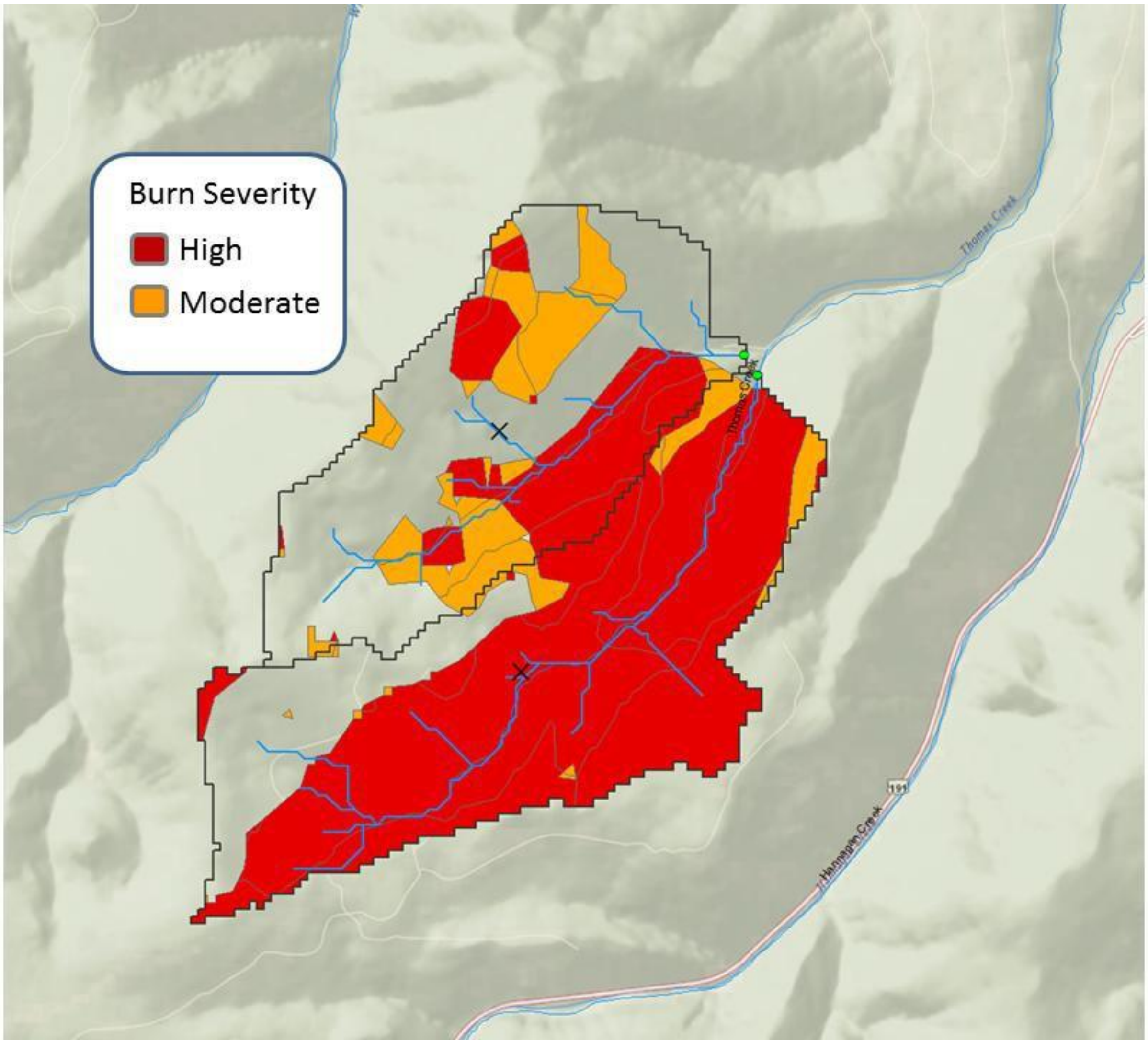


Figure 57. North Fork and South Fork Thomas Creek Burn Severity Map.

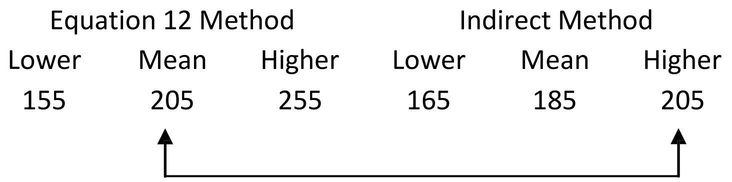
Figure 58. North Fork Thomas Creek Looking Downstream at Weir (photo provided by USFS). From High Water Marks July 11 Flow was 186 cfs +/- 10% at Weir (flow depth was 1.64 feet).

North Fork Thomas Creek - USFS	
Lat:	**33.40.31 N**
Long:	**109.16.15 W**
Total Area (sq. mi.)	**0.70**
High Burn Severity (sq. mi.)	**0.17**
Moderate Burn Severity (sq. mi.)	**0.14**
Post-Burn Hyper-effective Area (sq. mi.)	**0.31**
Channel Relief Ratio	**0.1005**
Mean Basin Elevation (ft)	**8,774**
Basin Elevation Difference (ft)	**798**
Stream Length (ft)	**7,943**
Time of Concentration (min)	**19**

Figure 59. North Fork Thomas Creek Basin Characteristics.

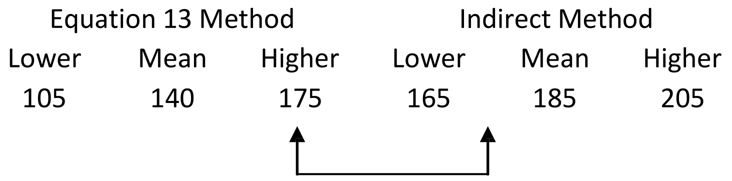
North Fork Thomas Creek - July 11, 2011 3:15 PM - 3:30 PM MST									
			Gage	1yr 15min			2yr 15min		
ID	LAT	LON	15-Minute	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER
Outlet	33.675	-109.271	**0.62**	0.48	0.55	0.63	0.61	0.70	0.81
Centroid	33.672	-109.281	N/A	0.48	0.55	0.64	0.62	0.71	0.82
		MEAN	N/A	0.48	0.55	**0.64**	**0.62**	0.71	0.82
		MEDIAN	N/A	0.48	0.55	**0.64**	**0.62**	0.71	0.82

Figure 60. Outlet Time of Concentration 15-Minute Storm Amount (0.62 inches) and 1-Year and 2-Year 15-Minute Return Interval Amounts (inches). The Gage Amount of 0.62 Inches Falls into the Range for Both the 1-Year 15-Minute and the 2-Year 15-Minute Storms.



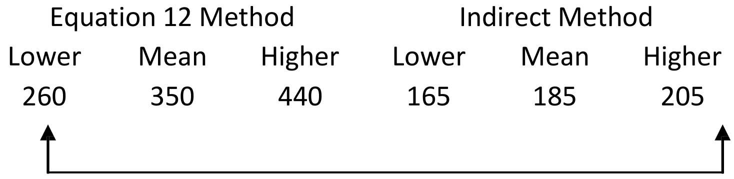
Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
155	205	255	165	185	205

Figure 61. North Fork Thomas Creek Comparison of Results for Peak Flow: The Mean Equation 12 Value for the 1-Year Storm is Essentially the Same as the Higher Indirect Method Value.



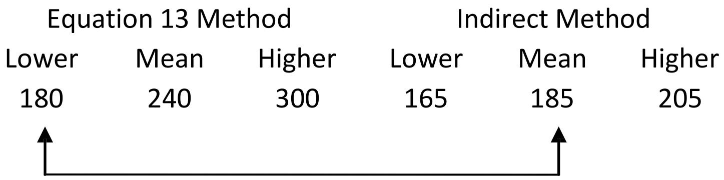
Equation 13 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
105	140	175	165	185	205

Figure 62. North Fork Thomas Creek Comparison of Results for Peak Flow: The Higher Equation 13 Value for the 1-Year Storm falls halfway between the Lower and Mean Indirect Method Values.



Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
260	350	440	165	185	205

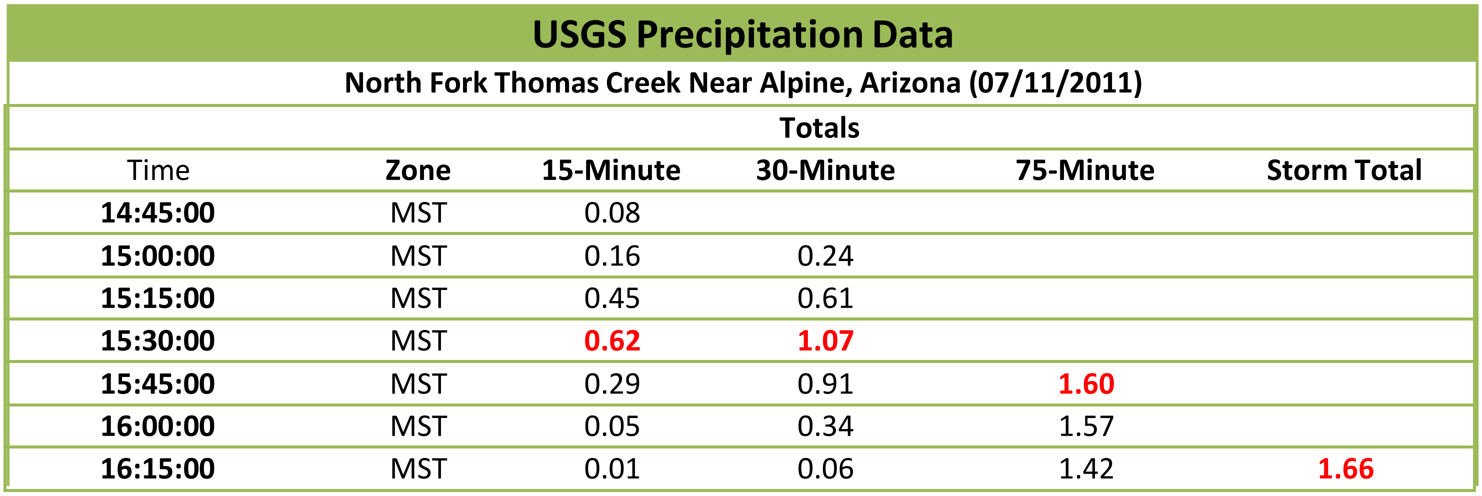
Figure 63. North Fork Thomas Creek Comparison of Results for Peak Flow: The Lower Equation 12 Value for the 2-Year Storm is Greater Than to the Higher Indirect Method Value by 55 cfs. (This is to be expected since the basin has a drainage area less than 1 square mile.)



Equation 13 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
180	240	300	165	185	205

Figure 64. North Fork Thomas Creek Comparison of Results for Peak Flow: The Lower Equation 13 Value for the 2-Year Storm is Essentially the Same as the Mean Indirect Method Value.

South Fork Thomas Creek



USGS Precipitation Data

North Fork Thomas Creek Near Alpine, Arizona (07/11/2011)

		Totals			
Time	**Zone**	**15-Minute**	**30-Minute**	**75-Minute**	**Storm Total**
14:45:00	MST	0.08			
15:00:00	MST	0.16	0.24		
15:15:00	MST	0.45	0.61		
15:30:00	MST	**0.62**	**1.07**		
15:45:00	MST	0.29	0.91	**1.60**	
16:00:00	MST	0.05	0.34	1.57	
16:15:00	MST	0.01	0.06	1.42	**1.66**

Figure 65. South Fork Thomas Creek – July 11 Rainfall Totals (used North Fork Thomas Creek Near Alpine, Arizona, USGS Rain Gage).

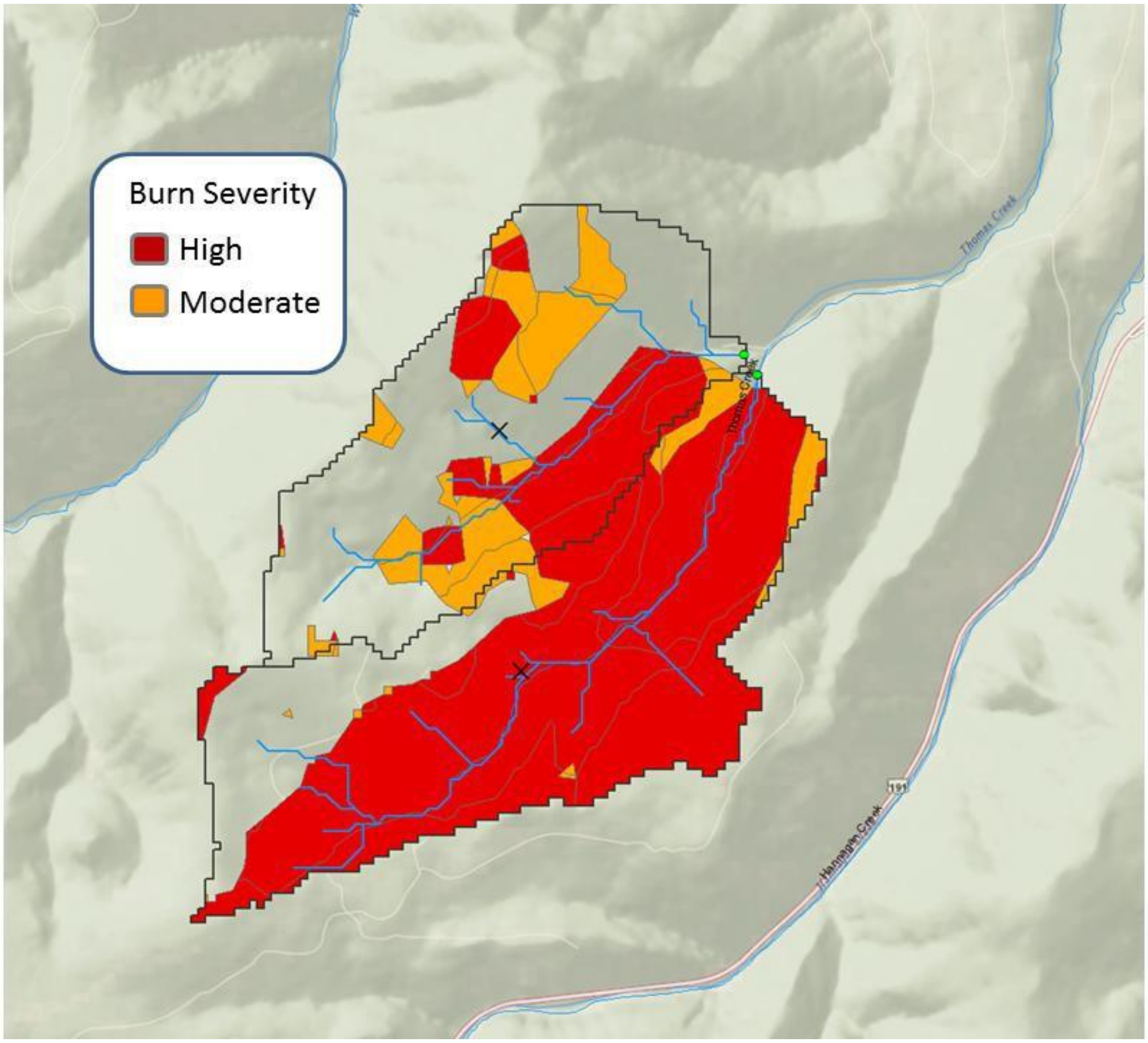


Figure 66. North Fork and South Fork Thomas Creek Burn Severity Map.

Figure 67. South Fork Thomas Creek Looking Downstream at Weir (photo provided by USFS). From High Water Marks July 11 Flow was 308 cfs +/- 20% at Weir (overtopped rectangular section by 0.67 ft).

South Fork Thomas Creek – USFS	
Lat:	33.40.27 N
Long:	109.16.11 W
Total Area (sq. mi.)	0.89
High Burn Severity (sq. mi.)	0.68
Moderate Burn Severity (sq. mi.)	0.04
Post-Burn Hyper-effective Area (sq. mi.)	0.72
Channel Relief Ratio	0.0666
Mean Basin Elevation (ft)	8,774.5
Basin Elevation Difference (ft)	797
Stream Length (ft)	11,974
Time of Concentration (min)	30

Figure 68. South Fork Thomas Creek Basin Characteristics.

South Fork Thomas Creek - July 11, 2011 3:00 PM - 3:30 PM MST

			Gage	2yr 30min			5yr 30min		
ID	LAT	LON	30-MINUTE	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER
Outlet	33.674	-109.270	1.07	0.82	0.94	1.09	1.05	1.22	1.4
Centroid	33.664	-109.280	N/A	0.84	0.96	1.11	1.08	1.24	1.42
		MEAN	N/A	0.83	0.95	1.10	1.07	1.23	1.41
		MEDIAN	N/A	0.83	0.95	1.10	1.07	1.23	1.41

Figure 69. Outlet Time of Concentration 30-Minute Storm Amount (inches) and 2-Year and 5-Year 30-Minute Return Interval Amount (inches). The Gage Amount of 1.07 Inches Falls into the Range for Both the 2-Year 30-Minute and 5-Year 30-Minute Storms.

Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
180	240	300	245	310	370

Figure 70. South Fork Thomas Creek Comparison of Results for Peak Flow: The Higher Equation 12 Value for the 2-Year Storm is Essentially the Same as the Mean Indirect Method Value (within 10 cfs). Also the Mean Equation 12 Value is essentially the same as the Lower Indirect Method Value (within 5 cfs).

Equation 13 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
125	165	205	245	310	370

Figure 71. South Fork Thomas Creek Comparison of Results for Peak Flow: The Higher Equation 13 Value for the 2-Year Storm is less Than the Lower Indirect Method. This indicates that the storm's return interval was greater than 2 years.

Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
375	500	625	245	310	370

Figure 72. South Fork Thomas Creek Comparison of Results for Peak Flow: The Lower Equation 12 Value for the 5-Year Storm is Essentially the Same as the Higher Indirect Method Value (within 5 cfs).

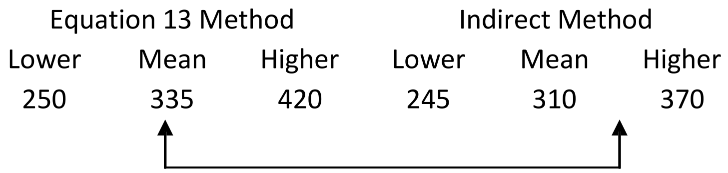
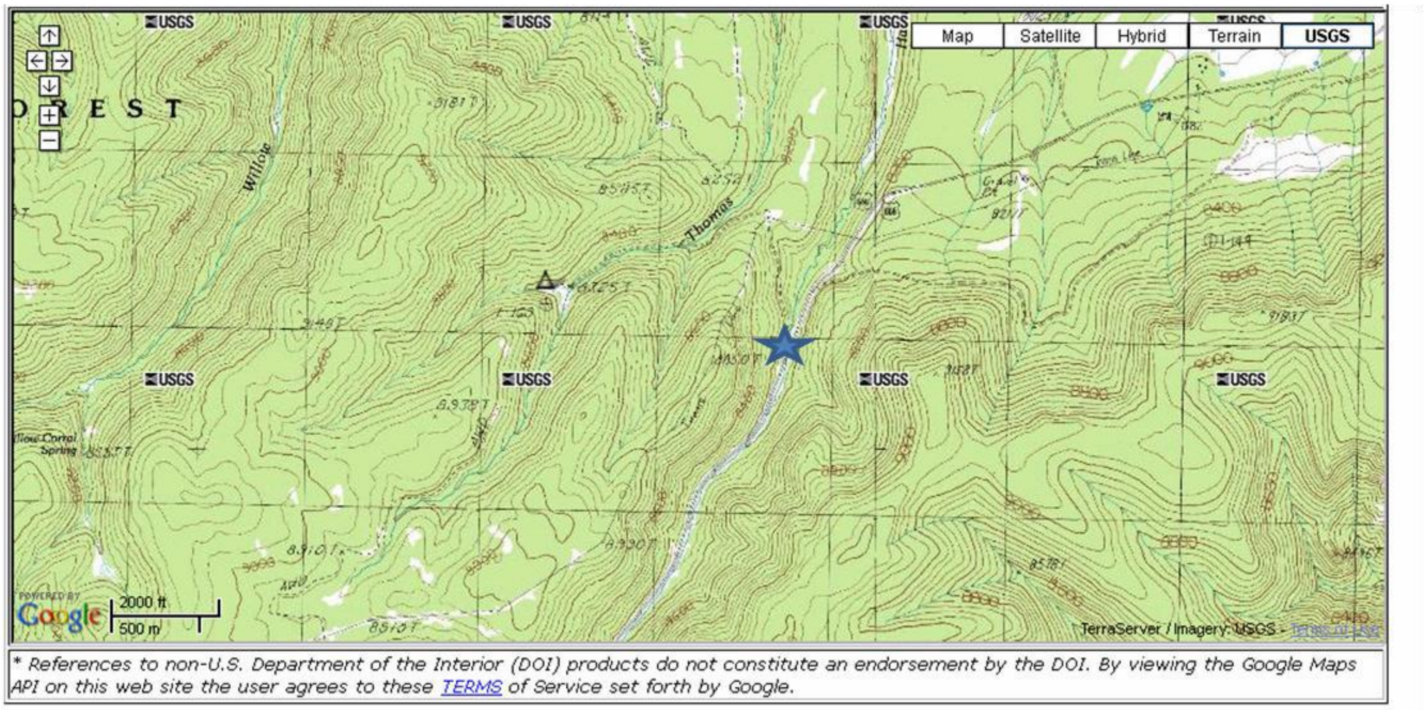


Figure 73. South Fork Thomas Creek Comparison of Results for Peak Flow: The Mean Equation 13 Value for the 5-Year Storm is Greater Than the Mean Indirect Method Value and Less Than the Higher Indirect Method Value. Also the Lower Equation 13 value is Greater Than the Lower Indirect Method value.

Hannagan Creek Basin at Highway 191



* References to non-U.S. Department of the Interior (DOI) products do not constitute an endorsement by the DOI. By viewing the Google Maps API on this web site the user agrees to these TERMS of Service set forth by Google.

Figure 74. Location of Hannagan Creek at Highway 191 (star) and North Fork Thomas Creek USGS Precipitation Gage (triangle).

USGS Precipitation Data					
North Fork Thomas Creek Near Alpine, Arizona (07/11/2011)					
		Totals			
Time	**Zone**	**15-Minute**	**30-Minute**	**75-Minute**	**Storm Total**
14:45:00	MST	0.08			
15:00:00	MST	0.16	0.24		
15:15:00	MST	0.45	0.61		
15:30:00	MST	**0.62**	**1.07**		
15:45:00	MST	0.29	0.91	**1.60**	
16:00:00	MST	0.05	0.34	1.57	
16:15:00	MST	0.01	0.06	1.42	**1.66**

Figure 75. Hannagan Creek at Highway 191 – July 11 Rainfall Totals (used North Fork Thomas Creek Near Alpine, Arizona, USGS Rain Gage).

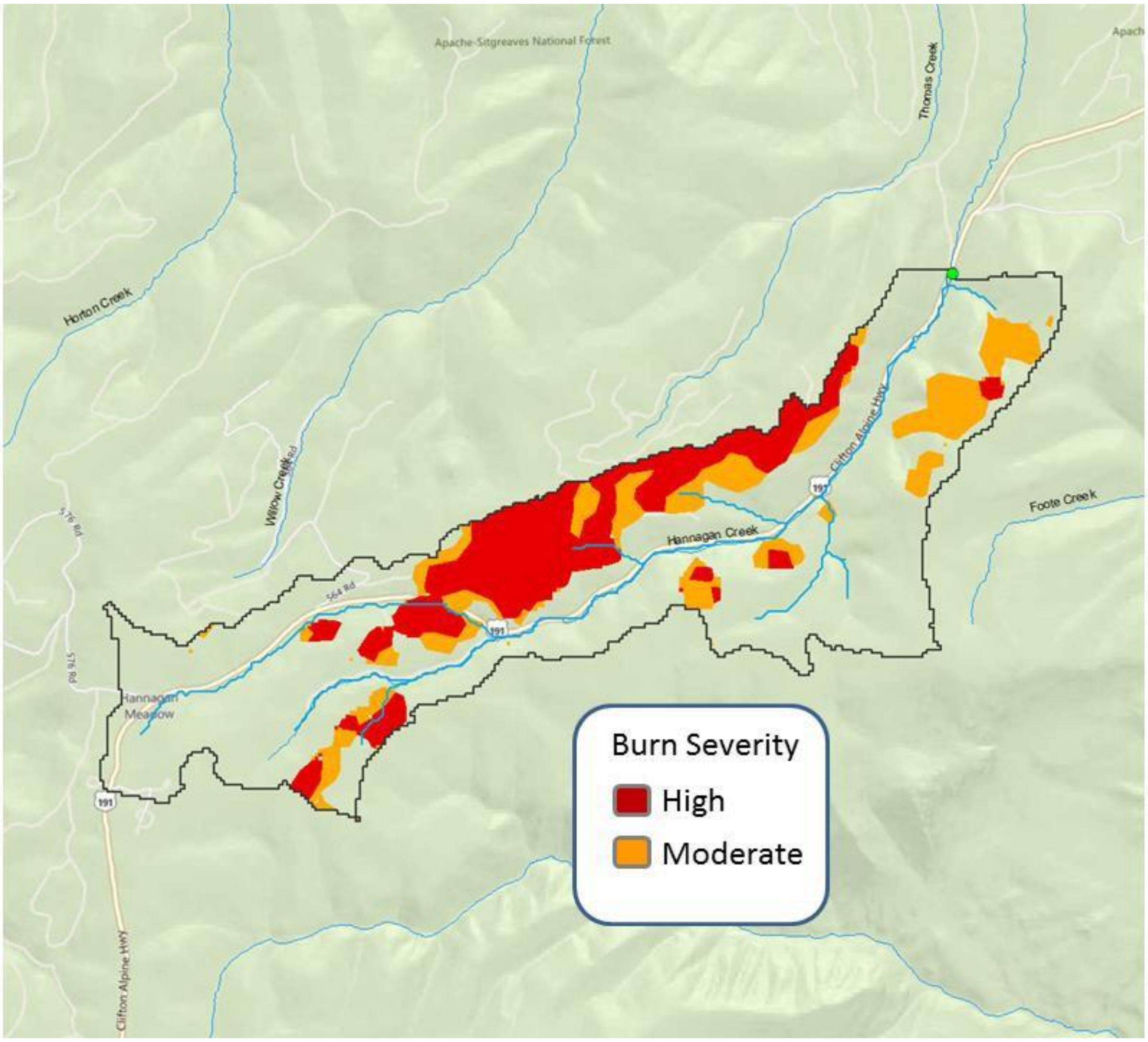


Figure 76. Hannagan Creek Basin at Highway 191 Burn Severity Map.

Figure 77. Looking upstream (photo provided by AZDOT, this picture was not taken on the day of storm): Cross Section #1; Channel at far end of pullout estimated as 18 feet wide at base, trapezoid shape with 30 feet wide at top, flow 6 feet deep (estimated from right bank highwater marks), wetted perimeter of 35 feet, and n value of 0.066 prior to cleaning. Slope is estimated as 0.0395 from topographic map. Estimated flow = 1,655 cfs. Mean velocity = 11.5 ft/sec.

Figure 78. Looking downstream (photo provided by AZDOT, this picture was not taken on the day of the storm): This channel is below road culvert. Cross Section #3; The channel width is estimated as 20 feet wide at base, box shape with flow 6 feet deep (estimated from left bank highwater marks), wetted perimeter of 32 feet, and n value of 0.066 prior to cleaning. Slope is estimated as 0.0395 from topographic map. Estimated flow = 1,295 cfs. Mean velocity = 10.8 ft/sec.

Figure 79. Hannagan Creek Basin at Highway 191 (photo provided by AZDOT). Culvert became blocked and Hannagan Creek flowed over Highway 191. Flow was 4-8 feet deep over road above culvert (near where person is standing in photo). Perpendicular to direction of flow, from highwater mark to highwater mark, was a distance of 980 feet (in photo you can see far highwater mark near yellow sign). The highwater marks were likely not made at the same time. Also, the flow across the road may have at times been braided or the direction of flow may have not always been perpendicular to the road. Cross Section #2; Main watercourse over road estimated as 30 feet wide, 6 feet deep, having a shape of half a ellipse, a wetted perimeter of 36 feet, a n value of 0.055, and a slope of 0.022. Estimated flow = 1,405 cfs. Mean velocity = 10 ft/sec. [Estimated flow = 1,360 cfs using a broad crested weir equation[24] with hydraulic head (H) = 6 feet, weir length (L) = 30 feet, and discharge coefficient (C) = 3.09.]

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[24] $Q=CLH^{1.5}$

Hannagan Creek Channel Characteristics						
Cross Section #	n	Area (square feet)	Wetted Perimeter (feet)	slope	Q (cfs)	Velocity (ft/sec)
1	0.066	144	35	0.0395	1,655	11.5
2	0.055	141	36	0.022	1,405	10.0
2[25]	-	180	-	-	1,360	7.6
3	0.066	130.5	32	0.0395	1,295	10.8
				avg	1,430	10.0

Figure 80. Hannagan Creek Channel Characteristics and Calculated Values.

Hannagan Creek Basin at Highway 191 - AZDOT[26]	
Lat:	**33.40.16 N**
Long:	**109.15.22 W**
Total Area (sq. mi.)	**4.37**
High Burn Severity (sq. mi.)	**0.70**
Moderate Burn Severity (sq. mi.)	**0.51**
Post-Burn Hyper-effective Area (sq. mi.)	**1.21**
Channel Relief Ratio	**0.0395**
Mean Basin Elevation (ft)	**8719**
Basin Elevation Difference (ft)	**1142**
Stream Length (ft)	**28938**
Time of Concentration (min)	**73**

Figure 81. Hannagan Creek Basin at Highway 191 Basin Characteristics.

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[25] Broad Crested Weir Method, with hydraulic head (H) = 6 feet, weir length (L) = 30 feet, and discharge coefficient (C) = 3.09; and $Q=CLH^{1.5}$.

[26] Basin is above Highway 191 as reported by AZDOT.

Hannagan Creek - July 11, 2011 2:30 PM - 3:45 PM MST

			Gage	5yr 60min			5yr 75min			5yr 120min		
ID	LAT	LON	75-MINUTES	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER
Outlet	33.671	-109.256	**1.60**	1.30	1.50	1.72	1.33	1.53	1.76	1.41	1.63	1.87
Centroid	33.651	-109.285	N/A	1.33	1.54	1.76	1.36	1.58	1.80	1.46	1.69	1.93
		MEAN	**N/A**	**1.32**	**1.52**	**1.74**	**1.35**	**1.56**	**1.78**	**1.44**	**1.66**	**1.90**
		MEDIAN	**N/A**	**1.32**	**1.52**	**1.74**	**1.35**	**1.56**	**1.78**	**1.44**	**1.66**	**1.90**

Hannagan Creek - July 11, 2011 2:30 PM - 3:45 PM MST

			Gage	10yr 60min			10yr 75min			10yr 120min		
ID	LAT	LON	75-MINUTES	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER	LOWER	MEAN	UPPER
Outlet	33.671	-109.256	**1.60**	1.50	1.74	1.99	1.54	1.79	2.04	1.65	1.92	2.19
Centroid	33.651	-109.285	N/A	1.54	1.79	2.04	1.58	1.84	2.10	1.70	1.98	2.26
		MEAN	**N/A**	**1.52**	**1.77**	**2.02**	**1.56**	**1.81**	**2.07**	**1.68**	**1.95**	**2.23**
		MEDIAN	**N/A**	**1.52**	**1.77**	**2.02**	**1.56**	**1.81**	**2.07**	**1.68**	**1.95**	**2.23**

Figure 82. Outlet Time of Concentration 75-Minute Storm Amount (inches) and 5-Year and 10-Year 75-Minute Return Interval Amount (inches). The Gage Amount of 1.60 Inches Falls into the Range for Both the 5-Year 75-Minute and 10-Year 75-Minute Storms.

Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
340	450	565	570	1,430	2,290

Figure 83. Hannagan Creek at Highway 191Comparison of Results for Peak Flow: The Higher Equation 12 Value for the 5-Year Storm is essentially the same as the Lower Indirect Method Value (within 5 cfs). Note that the indirect method has a high degree of uncertainty (+/- 60%) because depth over the road was reported with a range from 4 to 8 feet and channel cross sections upstream and downstream of culvert were estimated from photos.

Equation 12 Method			Indirect Method		
Lower	Mean	Higher	Lower	Mean	Higher
590	790	990	570	1,430	2,290

Figure 84. Hannagan Creek at Highway 191Comparison of Results for Peak Flow: The Higher Equation 12 Value for the 10-Year Storm is Less Than the Mean Indirect Method Value and Greater Than the Lower Indirect Method Value. Also the Mean Equation 12 Value is Greater Than the Lower Indirect Method Value and the Lower Equation 12 Value is Essentially the Same as the Lower indirect Method Value (within 20 cfs). Note that the indirect method has a high degree of uncertainty (+/- 60%) because depth over the road was reported with a range from 4 to 8 feet and channel cross sections upstream and downstream of culvert were estimated from photos.

Verification Summary

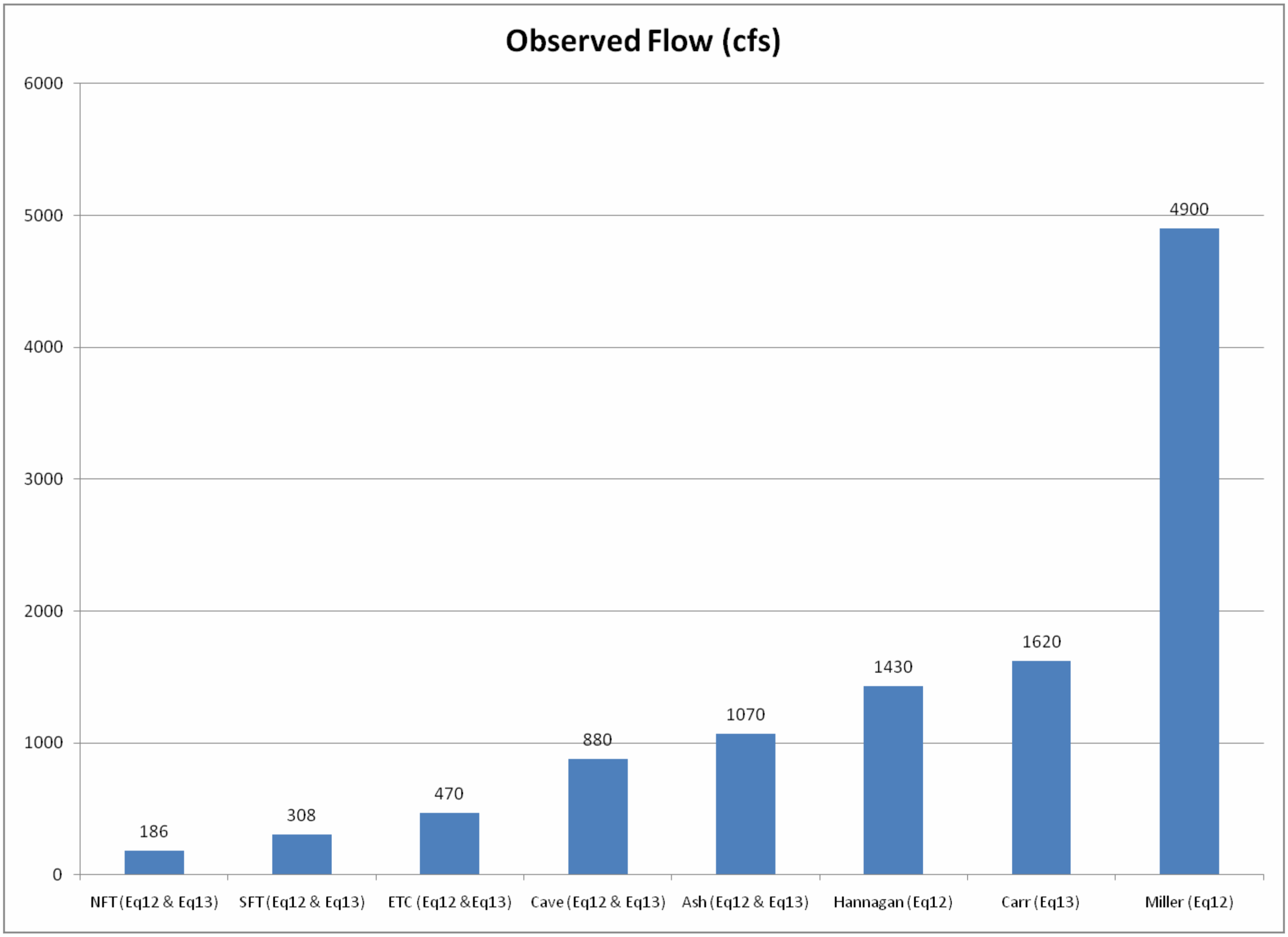

Figure 85. Next to basin name in parenthesis are equations that verified for following conditions: 1) NFT and SFT (Central Highlands, drainage area less than 1 square mile); 2) ETC, Cave, and Ash (Sky Islands, return interval less than 1 year); 3) Hannagan (Central Highlands, return interval greater than 1 year and drainage area greater than 1 square mile), 4) Old Sawmill[27] (Sky Islands, drainage area less than 1 square mile); and 5) Miller (Sky Islands, return interval greater than 1 year and drainage area greater than 1 square mile). The above assumes you know the return interval when they are less than 1 (in practice use Equation 13). For flows less than 1100 cfs, Equations 12 & 13 converge.

---

[27] Old Sawmill is labeled Carr in this figure.

Verification Summary Sky Islands				
Basin	Hyper-effective Drainage Area (sq. mi.)	Calculated Return Interval (years)	Equation 12 (cfs)	Equation 13 (cfs)
Miller	2.80	2.60	4,913 (4,900)	
East Turkey Creek	1.43	0.475	475 (470)	
Ash	3.66	0.285	1,060 (1,070)	
Old Sawmill[28]	0.46	1.12		1,621 (1,620)
Cave	9.38	0.82	885 (880)	
Cave	9.38	1.40		886 (880)

Figure 86. Sky Islands Basins: Calculated Return Interval and Equation Used (numbers in blue used). Calculated Value Using Calculated Return Interval (Indirect Value).

Verification Summary Central Highlands				
Basin	Hyper-effective Drainage Area (sq. mi.)	Calculated Return Interval (years)	Equation 12 (cfs)	Equation 13 (cfs)
North Fork Thomas	0.31	1.62		189 (186)
North Fork Thomas	0.31	0.95	187(186)	
South Fork Thomas	0.72	5.00		318 (308)
South Fork Thomas[29]	0.72	2.80	304 (308)	
Hannagan[30]	4.37	n/a	n/a	n/a

Figure 87. Central Highlands Basins: Calculated Return Interval and Equation Used (numbers in blue used). Calculated Value Using Calculated Return Interval (Indirect Value). For these calculations only the hyper-effective drainage area was used.

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[28] Total drainage area is also less than 1 square mile.

[29] Total drain area of 0.89 square miles is close to 1 square mile.

[30] The runoff from the non-hyper-effective drainage area is not minimal. Therefore, the return interval can not be calculated by using Equation 12 and assuming runoff from only the hyper-effective drainage area.

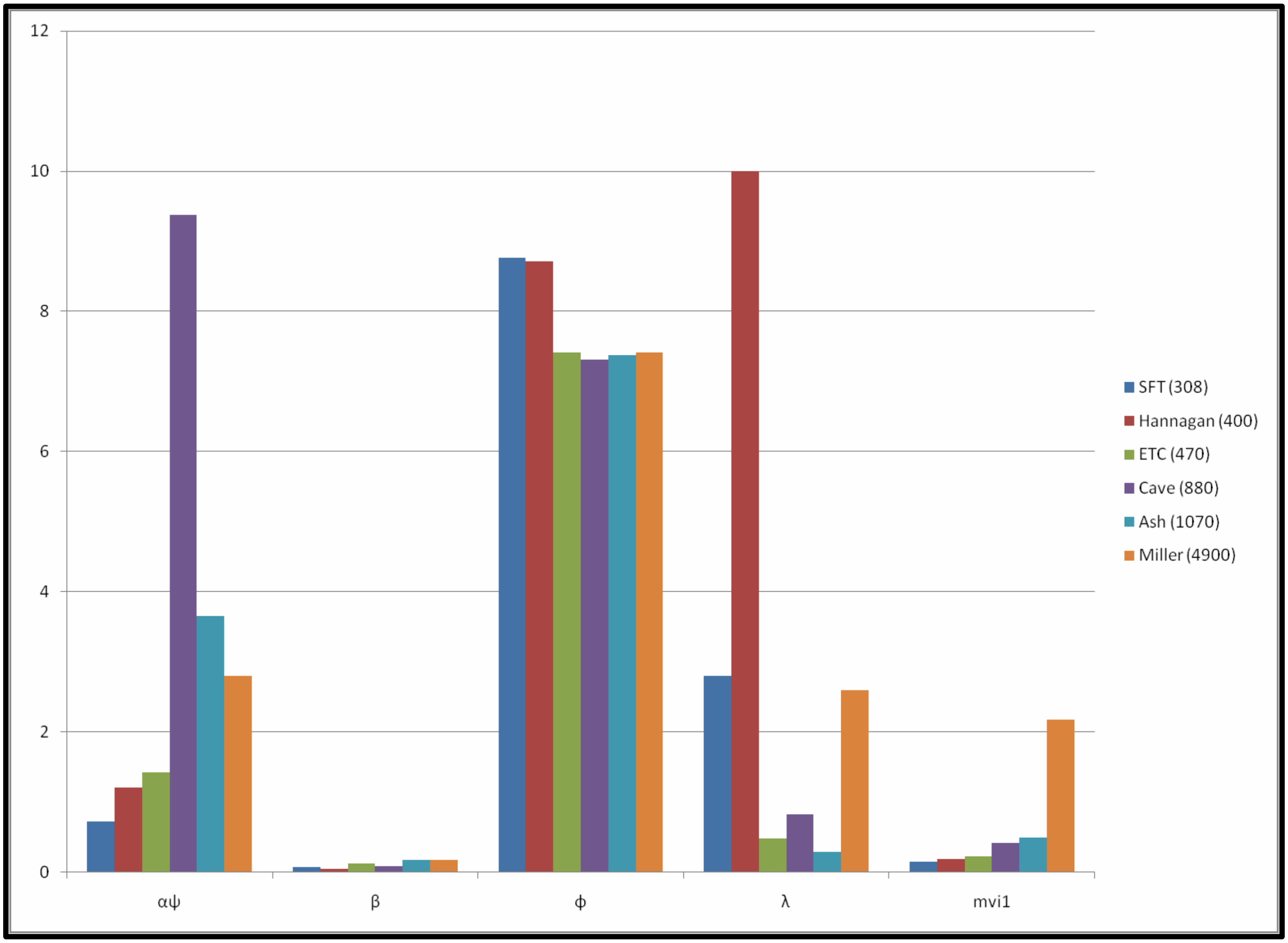

Figure 88. **Sky Island and Central Highlands Equation 12 (basin parameters ranked by flow, note that only mvi$_1$ increases the same as flow). For Sky Island basins, β = modified channel relief ratio (feet/feet). For Central Highlands basin, β = channel relief ratio (feet/feet). A return interval of 2.8 years was used for South Fork of Thomas Creek. A return interval of 10 years was used for Hannagan Creek at Highway 191. For Hannagan Creek only the runoff from the hyper-effective area was used.**

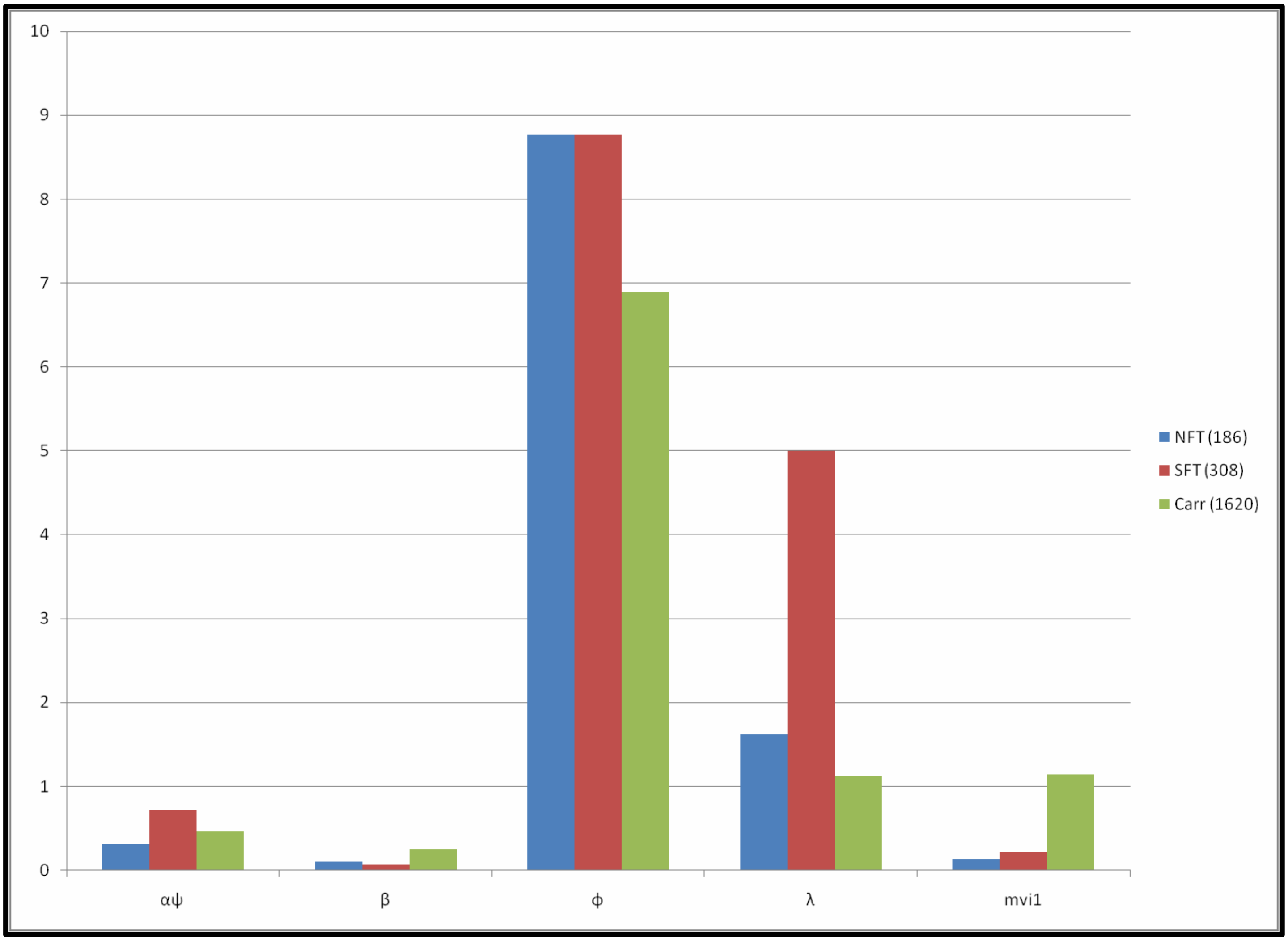

Figure 89. Sky Island and Central Highlands Equation 13 (basin parameters ranked by flow, note that only mvi_1 increases the same as flow). For these basins[31], channel relief ratio was used unmodified. β = channel relief ratio (feet/feet). A return interval of 5 years was used for South Fork of Thomas Creek.

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[31] Old Sawmill is labeled Carr in this figure.

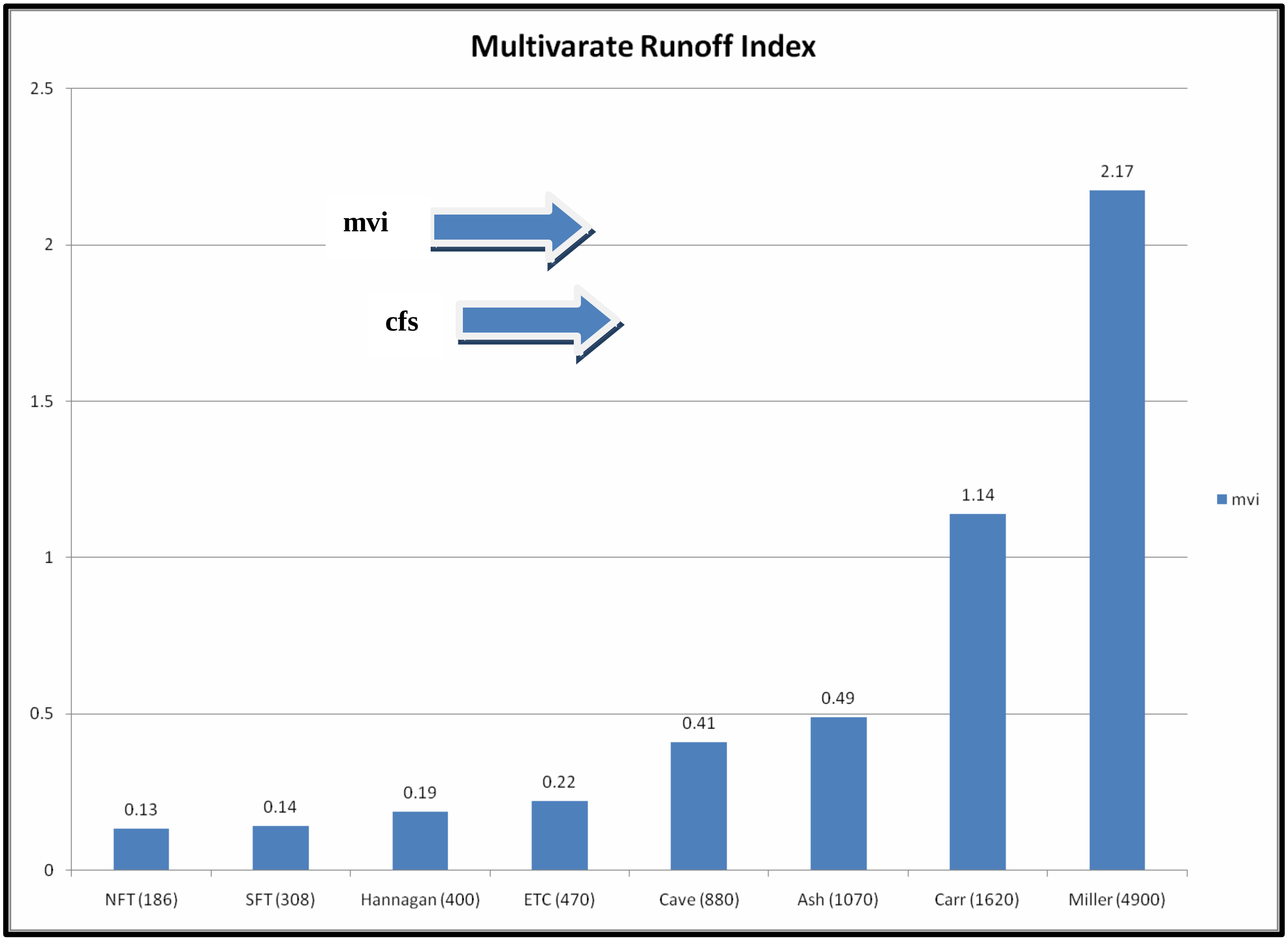

Figure 90. Sky Island and Central Highlands Equation 12 or 13 mvi$_1$ increases the same as flow (flow in cfs is in parenthesis next to basin name). A return interval of 2.8 years was used for South Fork of Thomas Creek. A return interval of 10 years was used for Hannagan Creek at Highway 191. For Hannagan Creek only the runoff from the hyper-effective area was used. Equation 12 was used for South Fork Thomas Creek, Hannagan Creek at Highway 191, East Turkey Creek, Cave Creek, Ash Creek, and Miller Creek. Equation 13 was used for North Fork of Thomas Creek and Old Sawmill Creek[32].

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[32] Old Sawmill is labeled Carr in this figure.

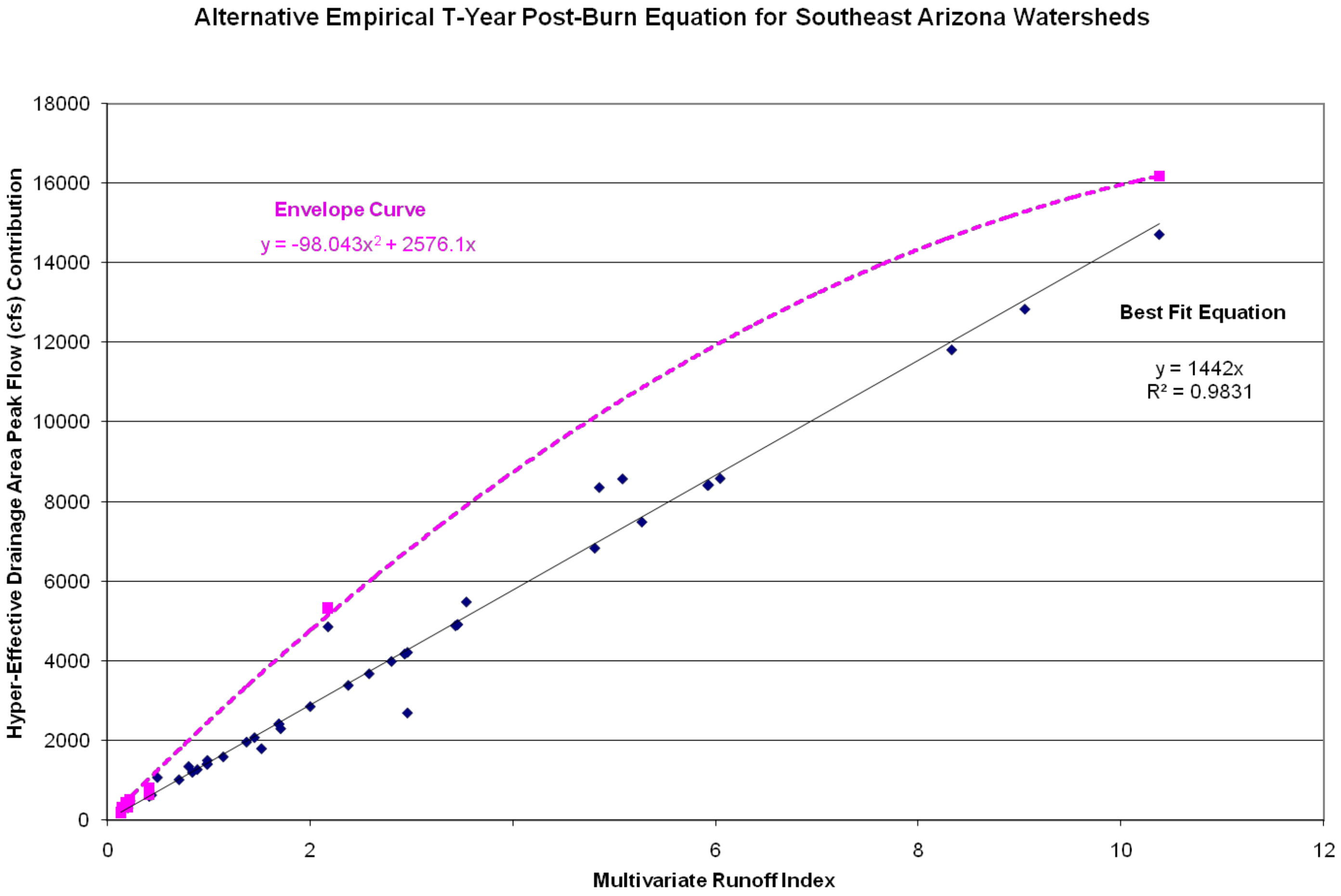

Figure 91. Adding the 8 new basins to the data used in Figure 12 the best fit equation (Equation 13) is now linear but essentially the same. The envelope curve (Equation 12) is of the same form yet slightly different, the shape is more bowed in the central section defined by Miller Canyon. For low flows (less than 1,100 cfs), the envelope curve and best-fit curve continue to converge. However, because of the large reported error for several of these basins, it is recommended that the original equations continue to be used at this time.

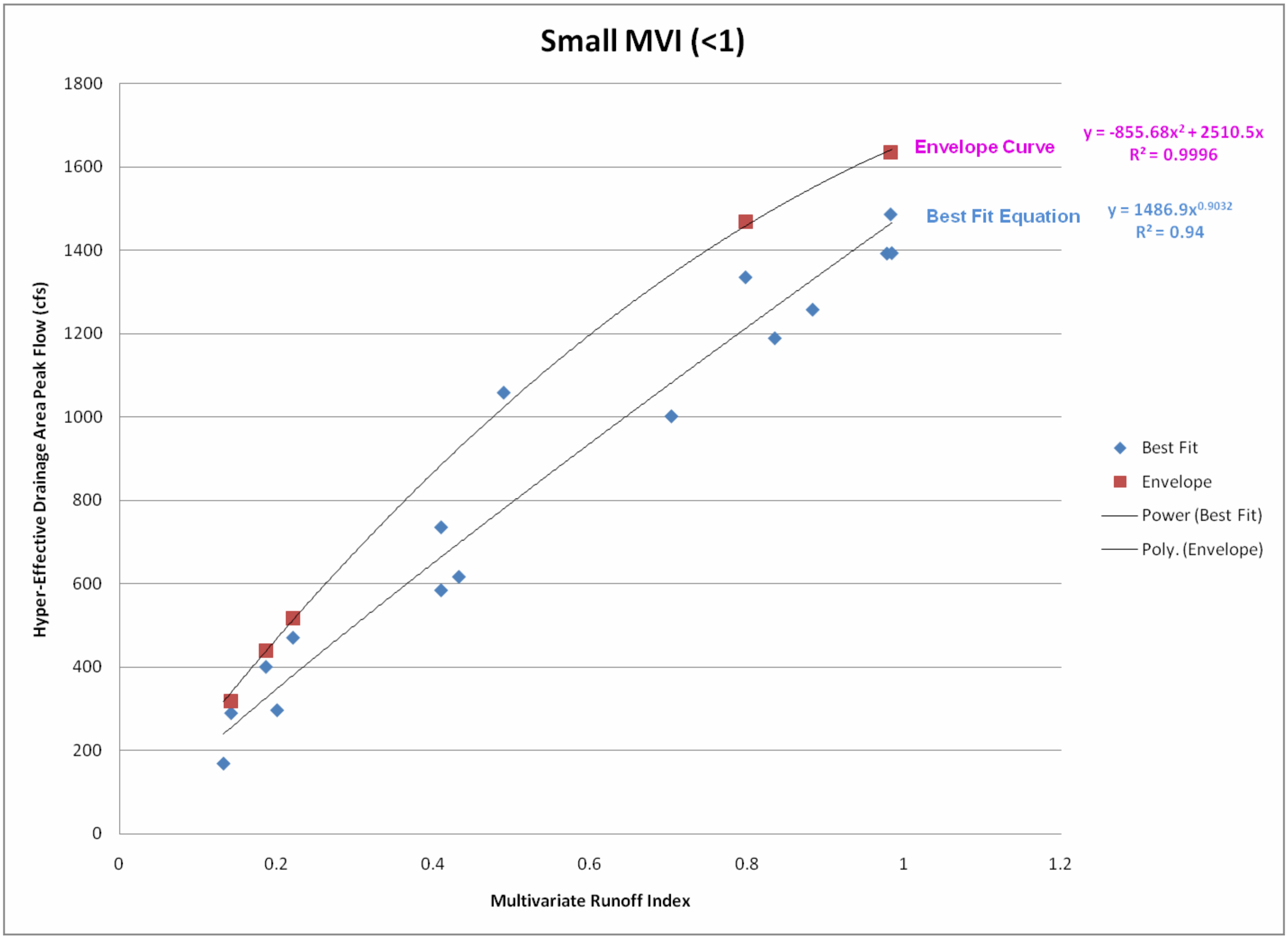

Figure 92. The above equations use those basins with mvi values less than 1. This data set includes 6 of the new basins for the best-fit curve. The envelope curve data set includes 3 of the new basins. However, because of the large reported error for several of these basins, it is recommended that the original equations continue to be used at this time.

Basin Specific 5-Year Post-Burn to Pre-Burn Peak Flow Ratio

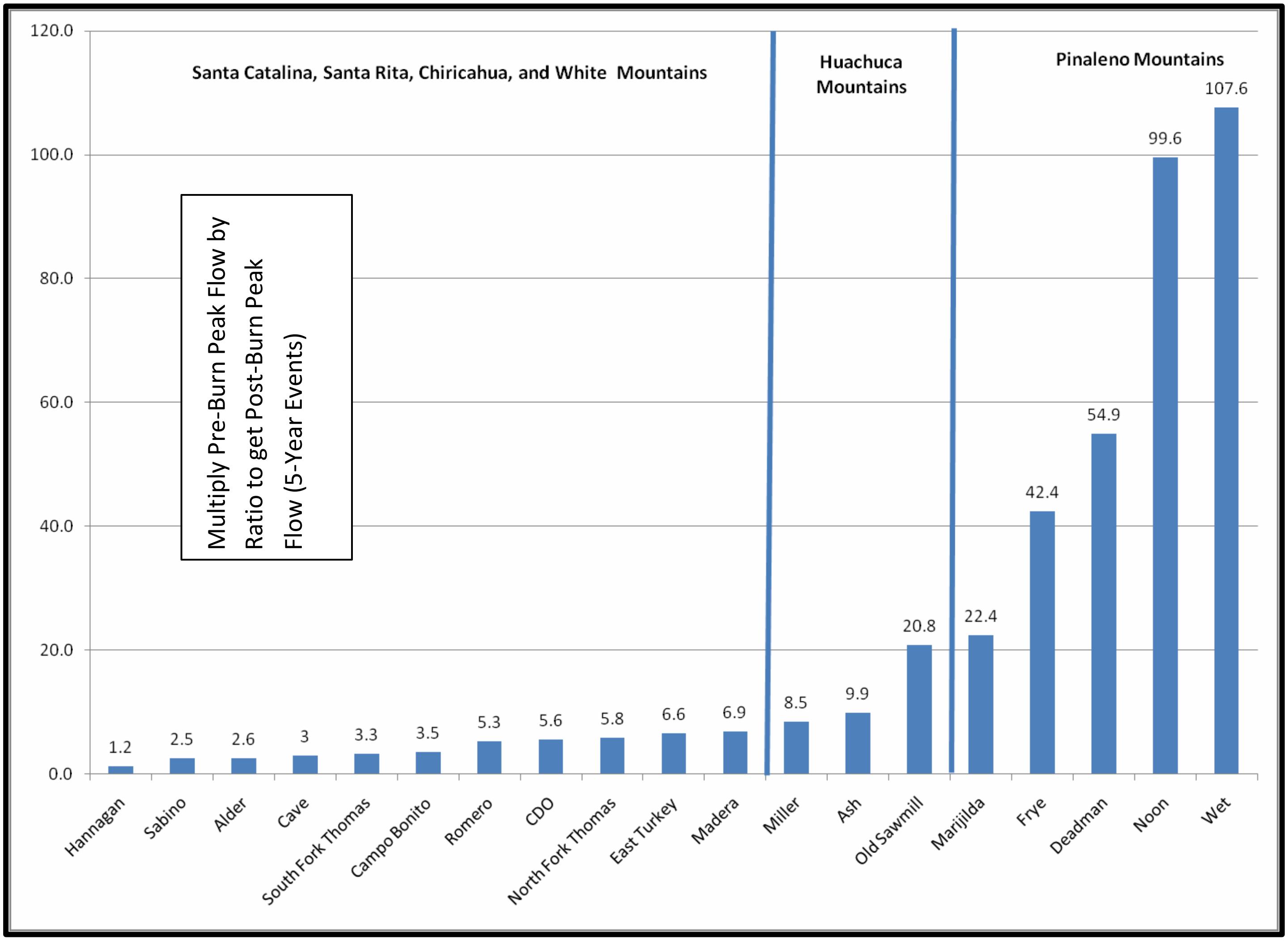

Figure 93. The 5-year total watershed peak flow response under burn conditions in the Santa Catalina (Sabino, Alder, Campo Bonito, Romero, and Cañada del Oro), Santa Rita (Madera), Chiricahua (Cave and East Turkey), Huachuca (Miller, Ash, and Old Sawmill), White (South Fork Thomas, North Fork Thomas, and Hannagan Creek at Highway 191), and Pinaleno Mountains (Marijilda, Frye, Deadman, Noon, and Wet). Numerical values are the ratio of Equation 13 post-burn values to pre-burn values. Post-Burn Response is up to 107.6 times greater than Pre-Burn Peak Flow. Ratios would be higher if Equation 12 post-burn values were used. Although debris flows may have also occurred within the same basin, the sites selected for this and previous studies were locations of hyper-concentrated flows.

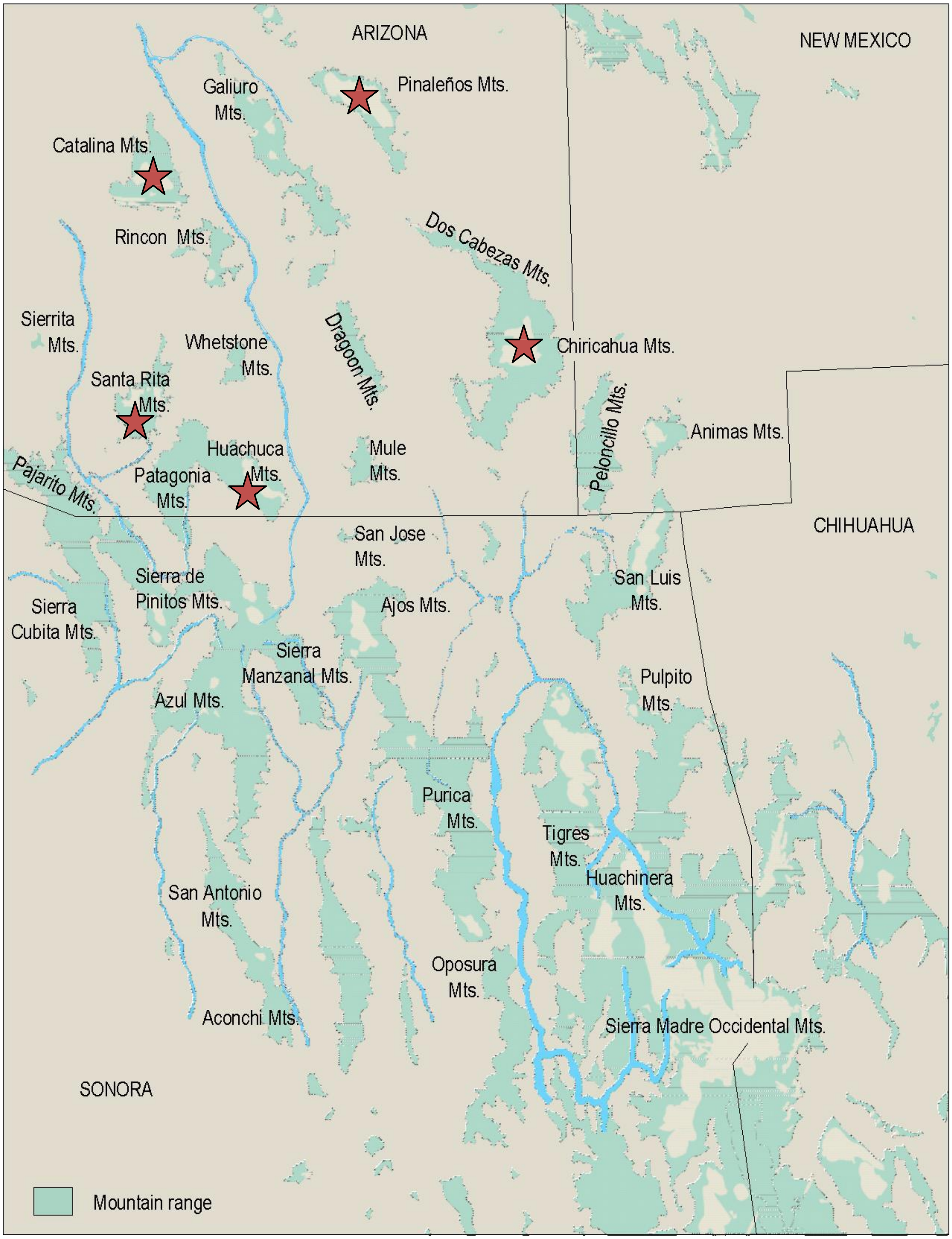

Fig. 94. **Sky island mountain ranges of Arizona, New Mexico, and adjacent Sonora and Chihuahua (Marshall 1957). All of the labeled mountain ranges have pine-oak woodland. Source: LaRoe, E.T., G.S. Farris, C.E. Puckett, P.D. Doran, and M.J. Mac, eds. 1995. The red stars have been added by the authors to indicate the 5 mountain ranges in the Sky Island complex of southeastern Arizona studied by Reed and Schaffner.**

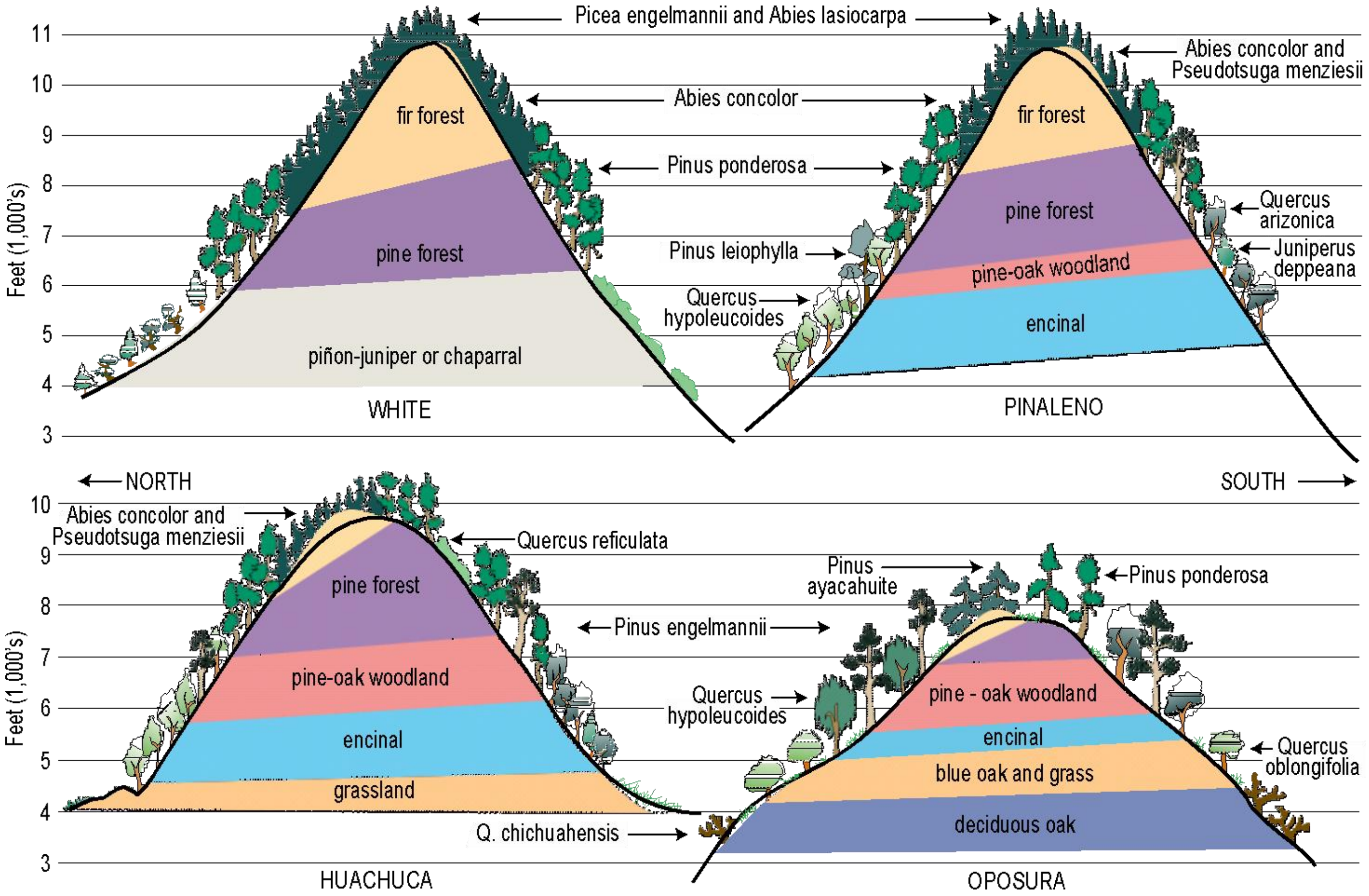

Fig. 95. Cross-sections of three sky islands showing the "stacked" biotic communities varying with latitude. The White Mountains are close to the Rocky Mountain flora and fauna. The Oposura Mountains begin to show the full development of the Sierra Madre communities (Marshall 1957). Source: LaRoe, E.T., G.S. Farris, C.E. Puckett, P.D. Doran, and M.J. Mac, eds. 1995.

5-Year Post-Burn to 2011 Observed Peak Flow Ratio and Increased Flash Flood Risk

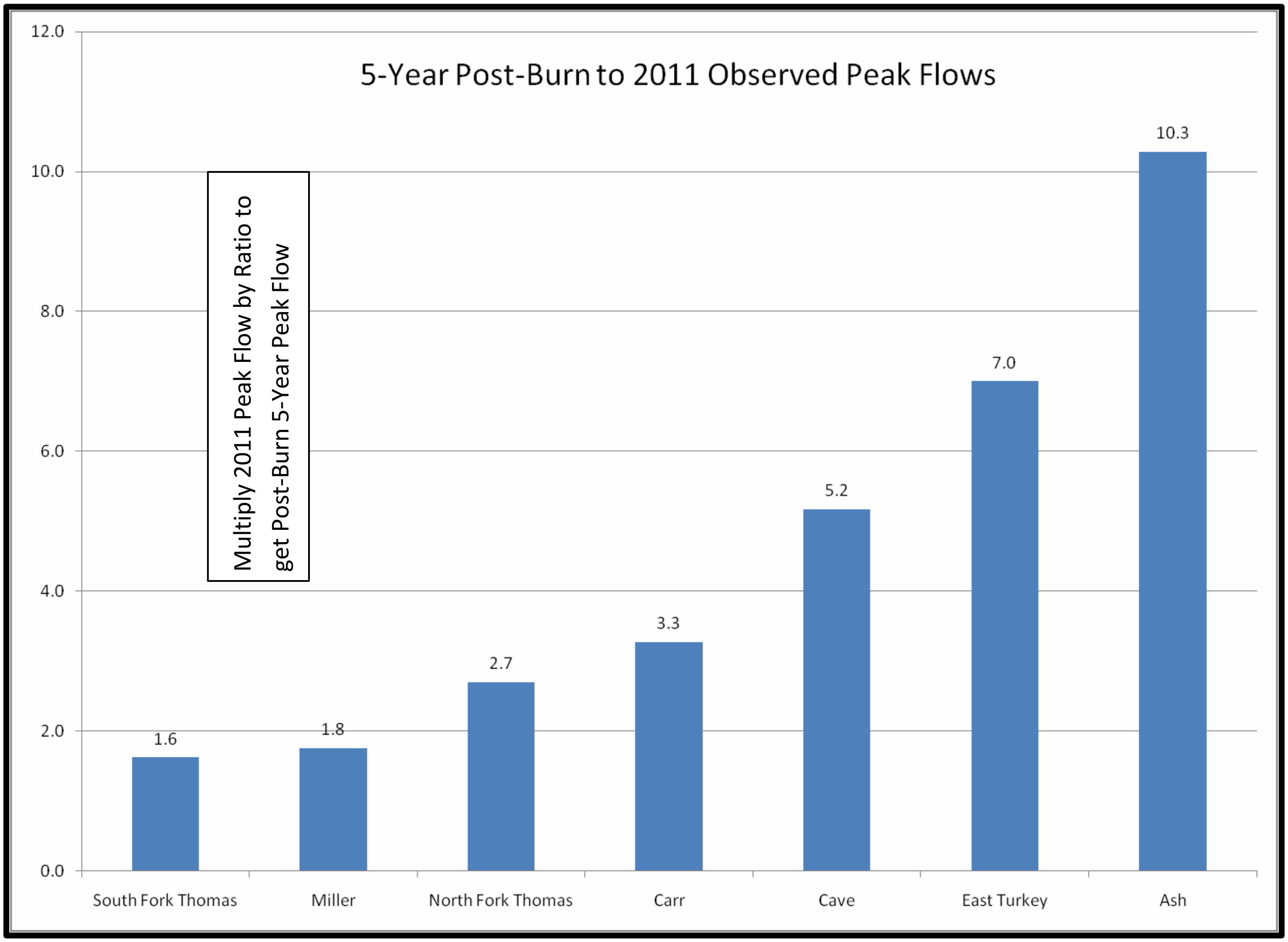

Figure 96. The Ratio of 5-Year Post-Burn to 2011 Observed Peak Flows[33]. Although the 2011 Flows in Miller Canyon were Significant, the Basin can Experience 5-Year Peak Flows Twice the Magnitude of 2011. (The 5-year return interval storm calculated post-burn peaks have a 67% chance of being equaled or exceeded one or more times during the assumed burn recovery period of five years for the three 2011 Arizona fires studied.) Hannagan Creek at Highway 191 is not shown because the 2011 event had a return interval greater than 5 years.

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[33] Old Sawmill is labeled Carr in this figure.

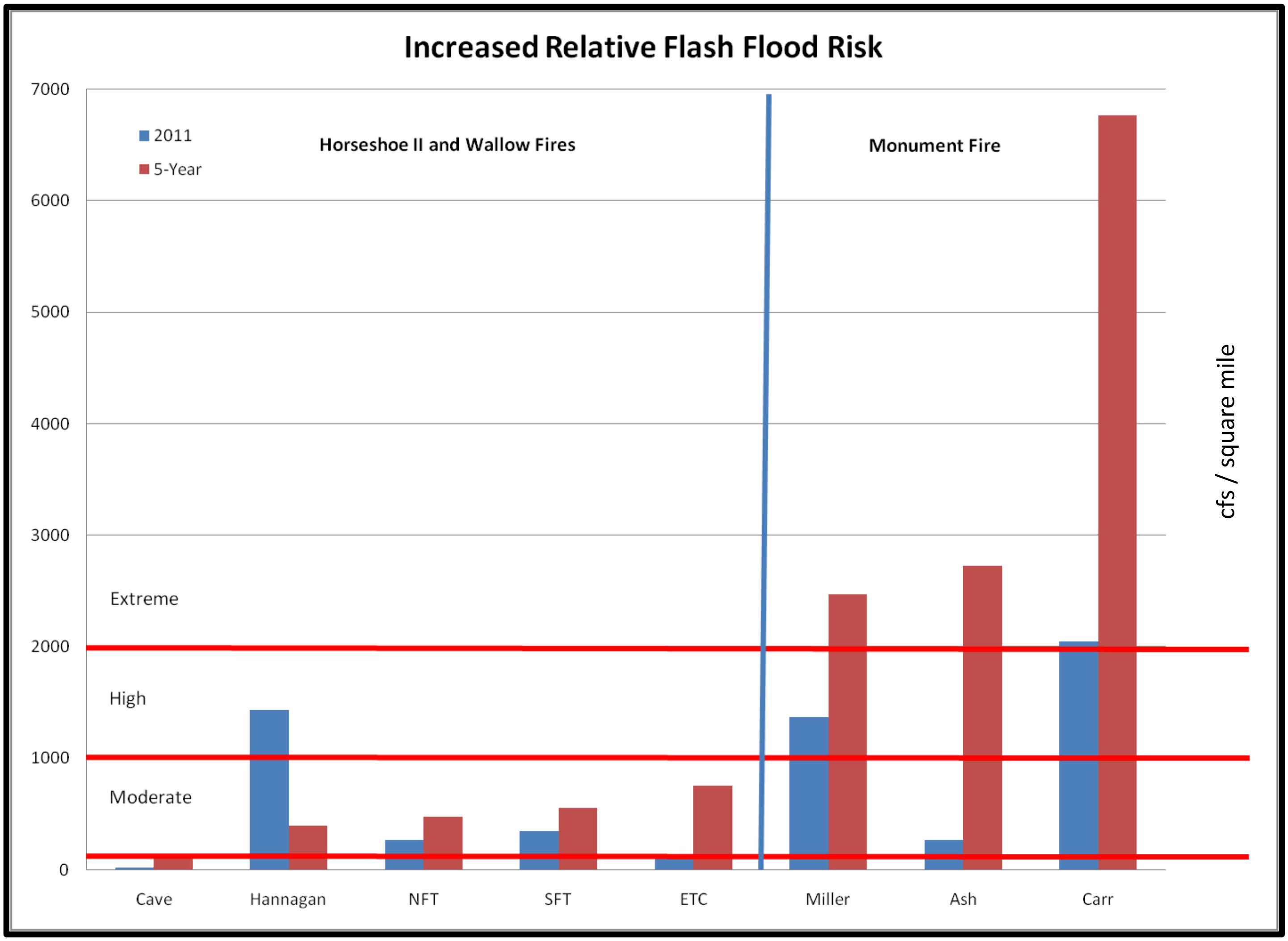

Figure 97. The Flash Flood Risk for 2011 Post-Burn and 5-Year Post-Burn Peak Flows[34]: for these Specific Basins, the Monument Fire Basins are at Greater Post-Burn 5-Year Risk than the Horseshoe II Fire and Wallow Fire Basins. The y axis is in units of cfs per square mile. The 2011 Hannagan Creek storm was greater than a 5-year storm.

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[34] Old Sawmill is labeled Carr in this figure.

Comparison of Observed and Calculated Increased Flash Flood Risk

Basin	Observed	Equation	Calculated	Agreement
Miller	High	12	High	yes
East Turkey	**Low/Moderate**	12 & 13	Moderate	yes
Ash	Moderate	12	Moderate	yes
Old Sawmill	High	13	High	yes
Cave	**Low/Moderate**	12 & 13	Moderate	yes
NF Tomas	Moderate	12 & 13	Moderate	yes
SF Thomas	Moderate	12 & 13	Moderate	yes
Hannagan	**Moderate/High**	12	Moderate	yes

Figure 98. Comparison of Observed and Calculated Increased Flash Flood Risk: All sites where an impact could be documented are in agreement with the calculated risk. The above assumes you know the return interval when they are less than 1 (in practice use Equation 13 for these situations). For flows less than 1000 cfs, Equations 12 & 13 converge. For East Turkey Creek and Cave Creek initial impacts may have been reduced by flood proofing. For Hannagan Creek at Highway 191 initial impacts may have been increased by infrastructure failure or blockage.

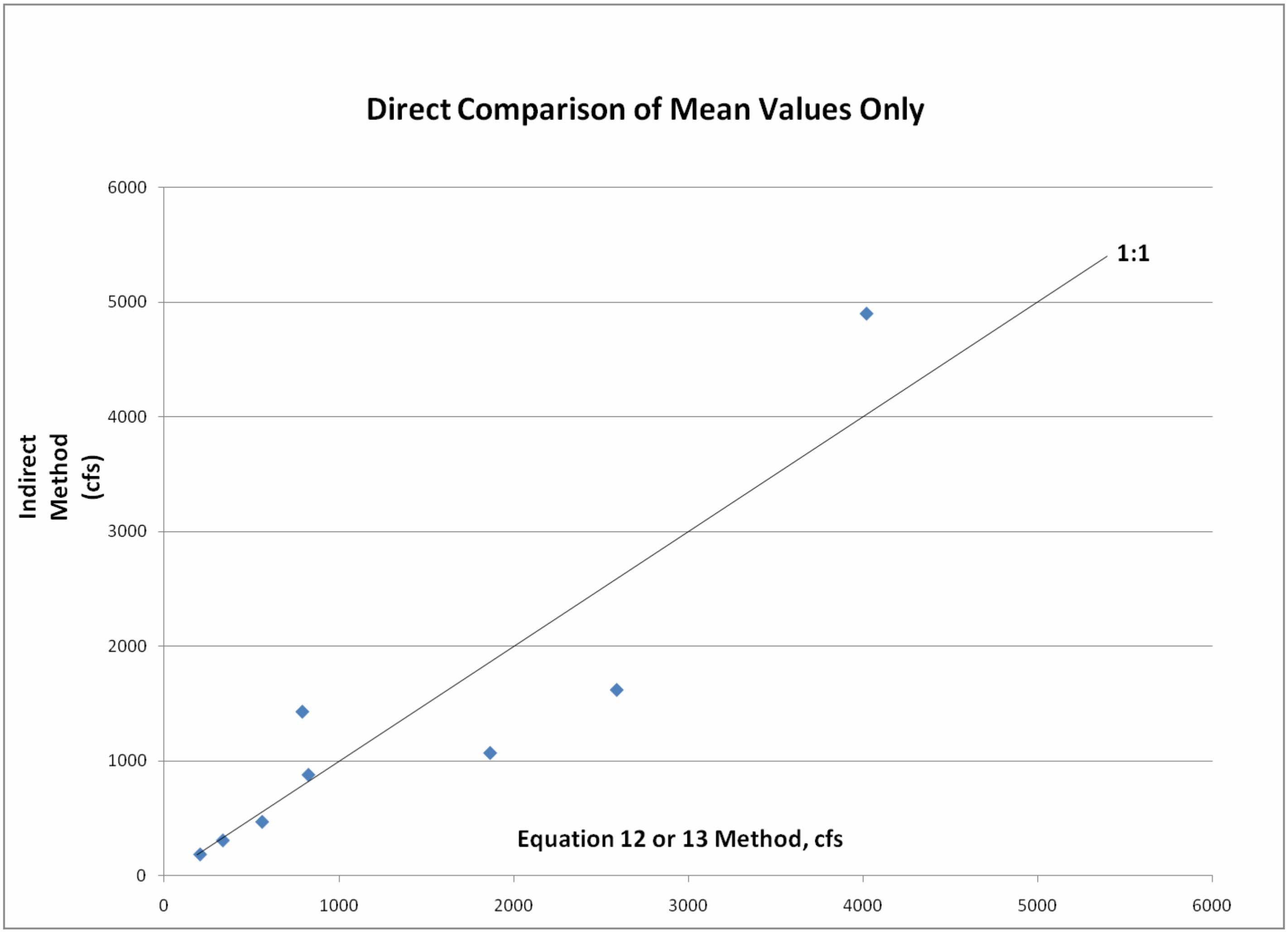

Figure 99. Comparison of Observed and Calculated Peak Flows for Mean Values Only. The four lowest observed peak flow basins (NFT, SFT, ETC, and Cave) line up almost directly with the 1:1 line. The four highest observed peak flow basins (Ash, Hannagan, Old Sawmill, and Miller) are likely outliers either because the return interval was different than that used or because of the uncertainty associated with the indirect method value.

Projected Recovery for 5-Year Post-Burn Peak Flows (Assuming Linear Recovery over 5-Year Period)

PROJECTED RECOVERY FOR 5-YEAR RETURN FLOWS (cfs)

	Year 2011 (cfs)	Year 2012 (cfs)	Year 2013 (cfs)	Year 2014 (cfs)	Year 2015 (cfs)	Year 2016 (cfs)
East Turkey	3290	2698	2106	1514	922	330
Cave	4548	3849	3150	2451	1751	1052
Miller	8608	7010	5412	3814	2216	618
Old Sawmill	5301	4292	3282	2273	1264	255
Ash	11007	8938	6868	4799	2730	660
North Fork Thomas	502	418	335	252	169	86
South Fork Thomas	499	419	340	260	181	101
Hannagan	451	421	391	362	332	302

Figure 100. Projected Recovery for 5-year return flows (cfs).

PROJECTED RECOVERY FOR 5-YEAR RETURN FLOWS (cfs/sq mi) and Increased Flash Flood Risk

	Year 2011 (cfs/sq mi)	Year 2012 (cfs/sq mi)	Year 2013 (cfs/sq mi)	Year 2014 (cfs/sq mi)	Year 2015 (cfs/sq mi)	Year 2016 (cfs/sq mi)
Old Sawmill	6724	5444	4164	2884	1604	323
Miller	2408	1961	1514	1067	620	173
Ash	2724	2212	1700	1188	676	163
North Fork Thomas	717	598	479	360	241	122
South Fork Thomas	560	471	382	292	203	113
East Turkey	752	616	481	346	211	75
Hannagan	103	96	90	83	76	69
Cave	115	98	80	62	44	27

Figure 101. Projected Recovery for 5-year return flows (cfs/square mile): Red Boxes indicate extreme increased risk, Yellow-Orange Boxes indicate high increase risk, Yellow Boxes indicate moderate increase risk and White Boxes indicate low increased risk.

Precipitation Thresholds

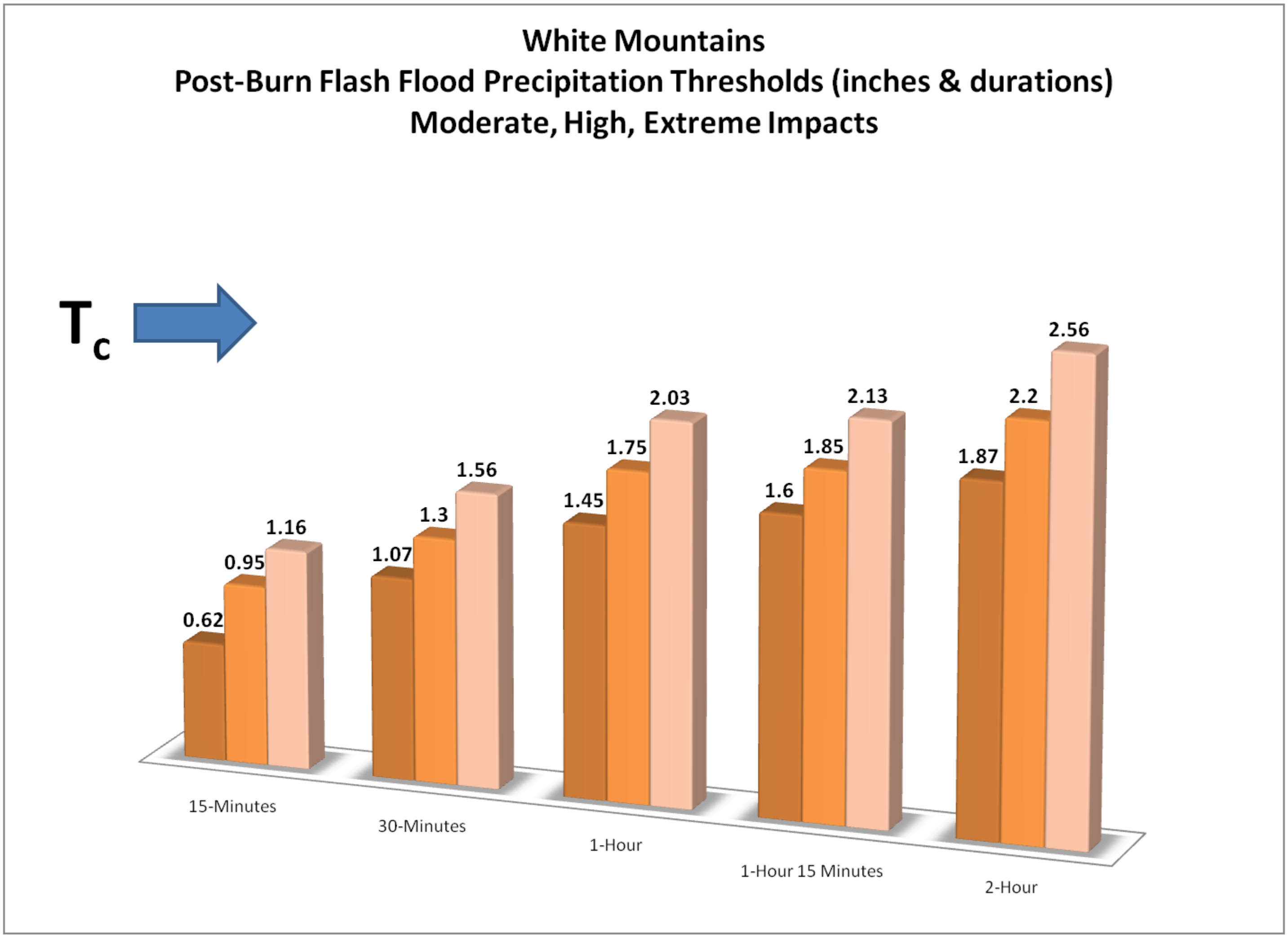

Figure 102. White Mountain Post-Burn Flash Flood Precipitation Thresholds. North Fork Thomas Creek, South Fork Thomas Creek, and Hannagan Creek in the White Mountains had Moderate Impacts in 2011.

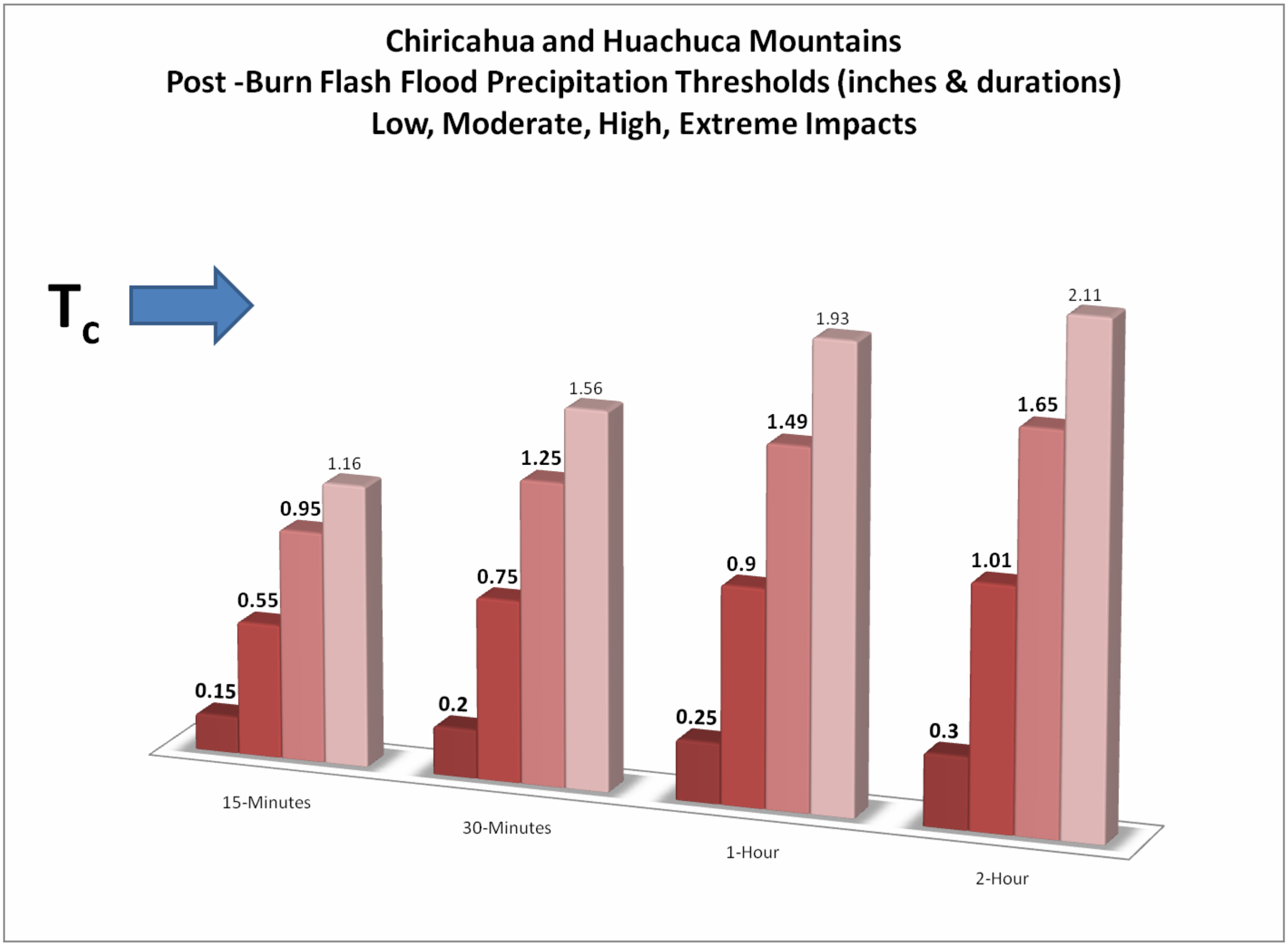

Figure 103. Chiricahua and Huachuca Mountains Post-Burn Flash Flood Precipitation Thresholds. East Turkey Creek and Cave Creek in the Chiricahua Mountains had Low Impact Events in 2011. Ash Basin in the Huachuca Mountains had a Moderate Impact Event in 2011. Old Sawmill and Miller Basins in the Huachuca Mountains had High Impact Events in 2011.

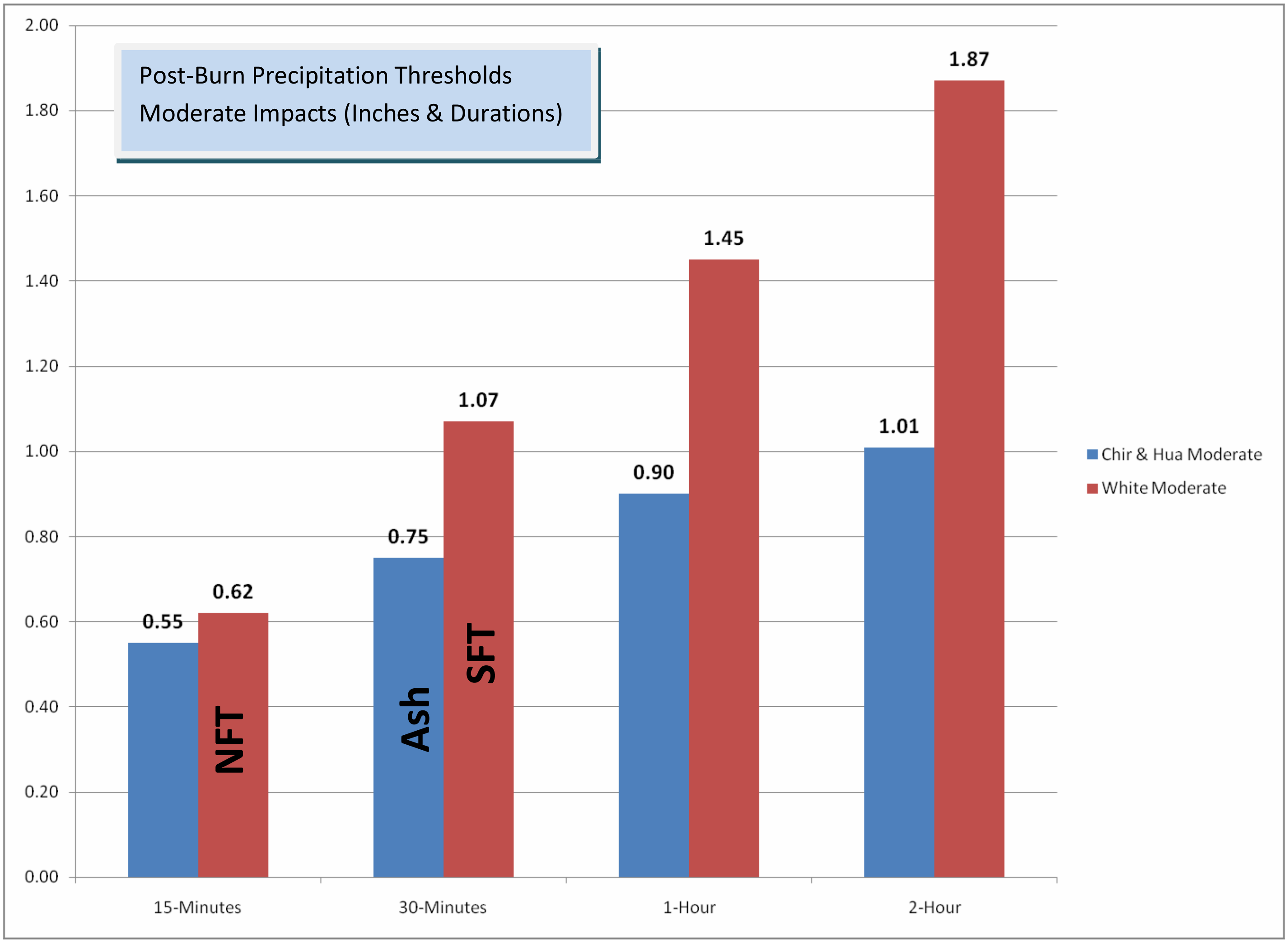

Figure 104. Post-Burn Precipitation Thresholds for Moderate Impacts. North Fork Thomas Creek, South Fork Thomas Creek, and Hannagan Creek in the White Mountains had Moderate Impacts in 2011. Hannagan Creek is not shown because it was a 1 hour 15 minute event. Ash Basin in the Huachuca Mountains had Moderate Impact Events in 2011.

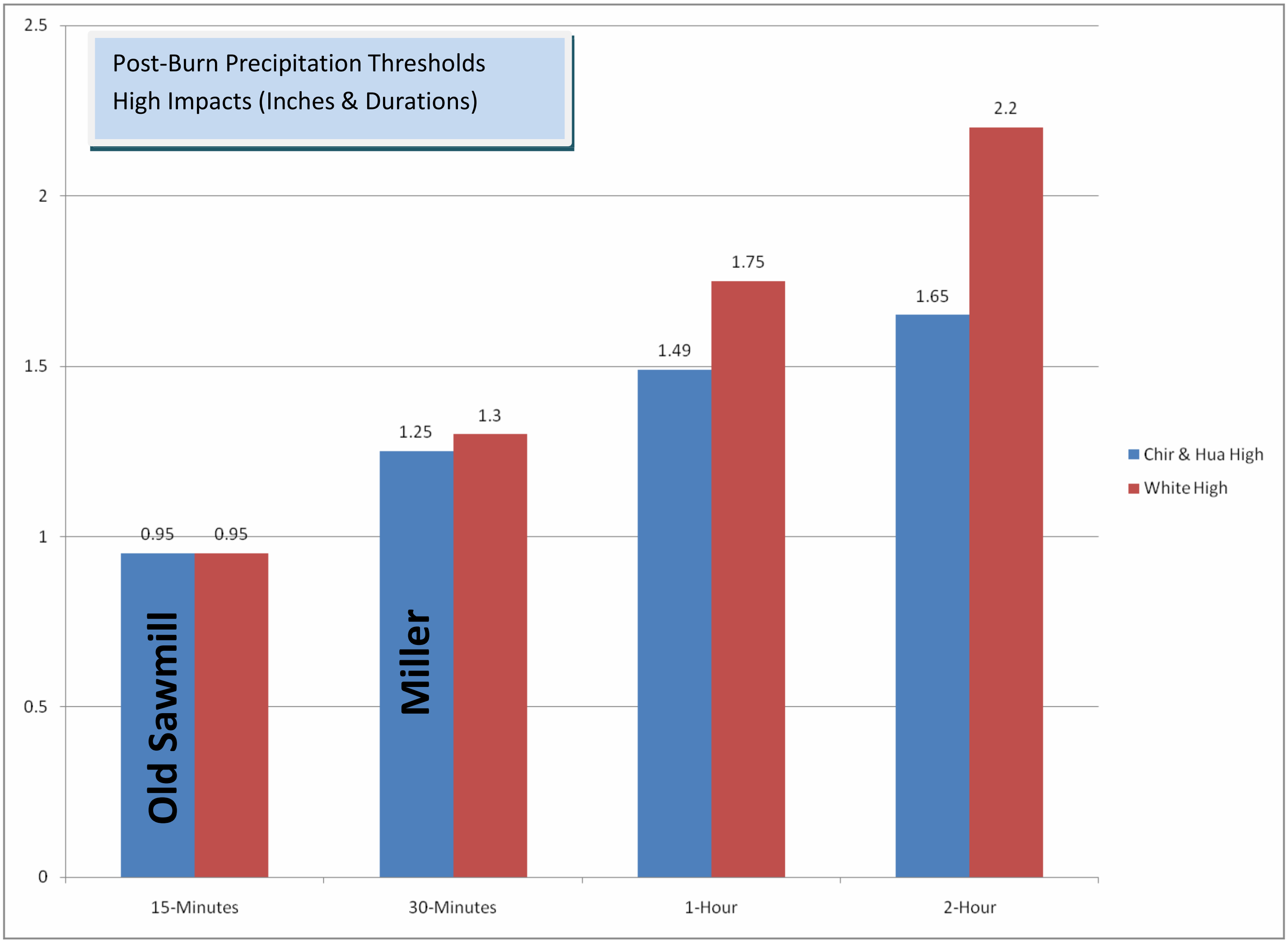

Figure 105. Post-Burn Precipitation Thresholds for High Impacts. Old Sawmill and Miller Basins in the Huachuca Mountains had High Impact Events in 2011.

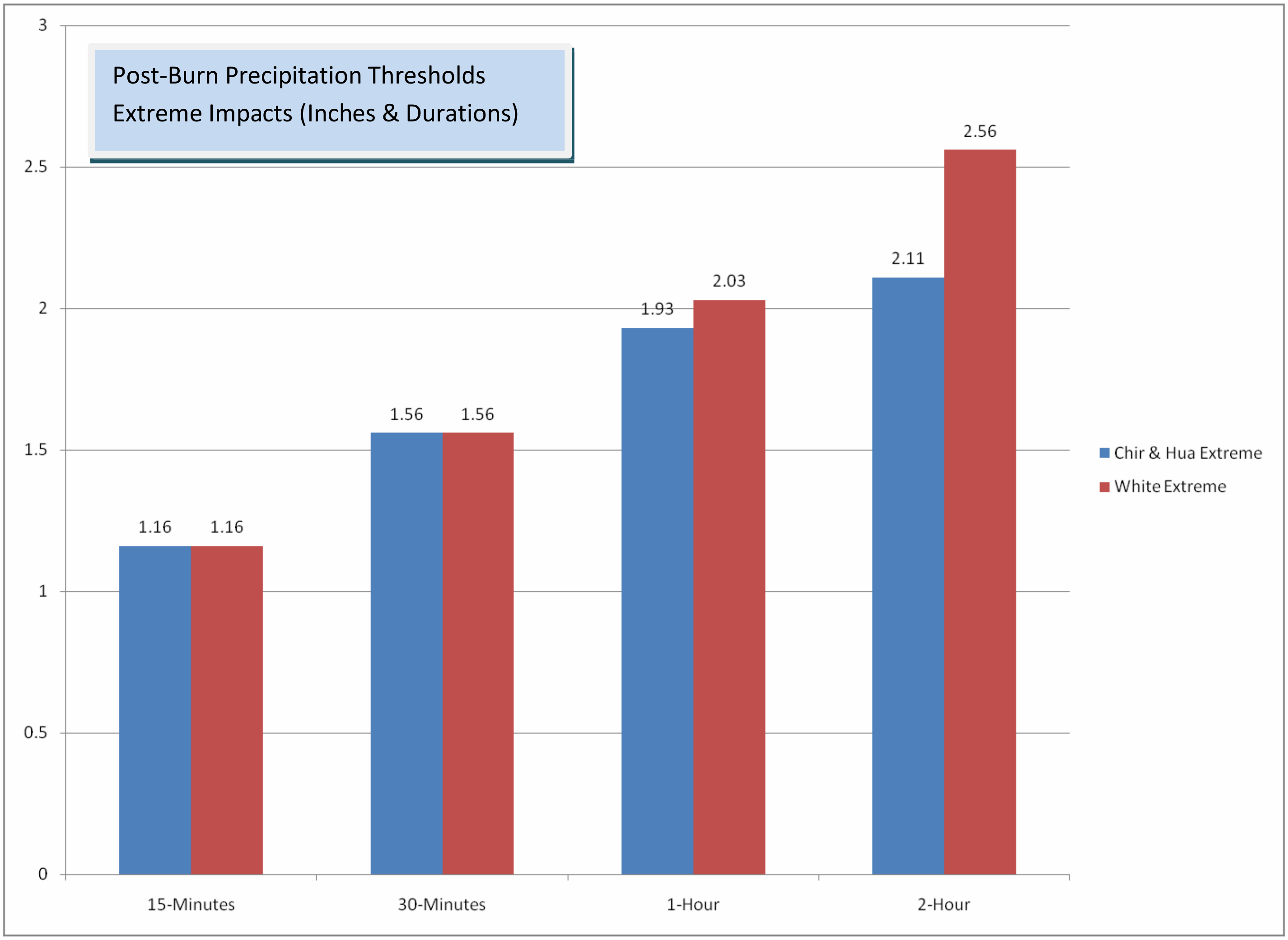

Figure 106. Post-Burn Precipitation Thresholds for Extreme Impacts. In 2011 there were no documented extreme impact events in these mountain ranges.