# McNally Post-Fire Discharge and the Relationship of Sierra Nevada-wide Flood Frequency Curves and Local Kern River Discharge Curves

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The analysis tool recommended to USDA Forest Service Burned Area Emergency Rehabilitation (BAER) team hydrologists to determine design flow in ungaged systems is defined in *Magnitude and frequency of floods in California* by Waananen and Crippen (1977). These authors provide discharge equations for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year recurrence interval storms for six regions in California based on 703 streamflow stations. Stream channel discharge relationships were developed from tributaries and USGS gage stations in the Kern River basin in response to the need to develop local hydro-physiographic discharge relationships for BAER assessment. Kern River hydro-physiographic channel geometry and discharge relationships versus drainage area were developed from this effort. This information was used to determine pre-fire stream design flow for the 2002 McNally fire. Comparison of discharge using local Kern River hydro-physiographic relationships and those derived from Waananen and Crippen (1977) yielded interesting results. With the exception of the 5-year recurrence interval, discharges derived from field measurements and local data are at least a magnitude of order higher for most of the recurrence intervals studied than those derived from Waananen and Crippen. Discharge relationships for the 5-year recurrence interval have the closest relationship using these two methods. Since the 2002 McNally fire, the response of fire-affected watersheds to winter and summer thunderstorm events has been studied. Rattlesnake Creek and Tobias Creek watersheds were surveyed in 2002 either prior to or immediately after the fire, and again in 2003 and 2004. Parameters measured include cross-sections, longitudinal profiles, bank stability, and particle distribution. Discharge estimates were calculated using resistance equations, which base discharge on bankfull depth, bankfull cross-sectional area, wetted perimeter, hydraulic radius bed material, and slope. The results of this study suggest that post-fire runoff may provide the means to estimate actual post-fire discharge by a watershed and thus be useful in validating adjusted design flows calculated during BAER assessment.

Keywords: *hydrology/water, watershed, hydrologic processes, hydrologic modeling, physiographic processes, streamflow*

## Introduction

Wildfires result in increased runoff commensurate with burn severity. Burned Area Emergency Rehabilitation (BAER) teams use burn severity to estimate runoff increases resulting from fires. This increase is calculated as adjusted design flow – the flow increase expected to occur as a result of decreased infiltration and interception following a wildfire. This discharge value is used to evaluate the need to increase the capacity of drainage structures such as culverts and bridges, and provides an estimate of flooding potential to nearby communities.

Before an adjusted design flow can be determined, the pre-fire design flow must be calculated. This is the flow expected to occur prior to the fire, responsible for forming present day channel conditions, and used to estimate proper performance of culverts and other drainage structures. BAER teams are directed to determine design flow from related storm duration and magnitude (design storm) estimates from U.S. Geological Survey data, or to calculate it from a regional analysis for an equivalent design recurrence interval (Forest Service Handbook 2509.13,40 [USDA FS 1993]). These estimates assume pre-fire ground infiltration and ground cover conditions. The analysis tool recommended to BAER team hydrologists to determine design flow in ungaged systems is defined in *Magnitude and frequency of floods in California* by Waananen and Crippen (1977).

Adjusted design flow is calculated using the same relationships as design flow; however, runoff response is estimated by assuming increased runoff commensurate with burn severity, in terms of recurrence interval. This recurrence interval estimates the response of the newly burnt landscape to an average annual storm. For example, a pre-fire landscape would respond with a discharge associated with a 1.5- to 2-year storm given an average rainfall event, while post-fire, the same landscape may

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respond as if the discharge were associated with a 5- or 10-year event. The increased discharge associated with predicted recurrence interval is then prorated across the watershed by burn severity level to yield the post-fire discharge or the adjusted design flow. Watershed area above infrastructure and communities at risk from post-fire erosion-related damage (flooding, debris flows, culvert failures and washouts) often determines the size of watershed chosen for analysis.

This paper will demonstrate how *Magnitude and frequency of floods in California*, Waananen and Crippen (1977), the recommended method used to analyze both design and adjusted design flows, underestimates discharge for most rainfall response conditions when compared to discharge relationships determined from gaged and ungaged sites in the vicinity of the Kern River, in the southern Sierra Nevada. In addition, post-fire discharge calculations based on channel characteristics may provide hydrologists with a process to measure actual post-fire adjusted design flow and monitor BAER design flow predictions.

## Calculation Methods for Emergency Runoff Response

The most widely used publication for calculation of design flow in California is U.S. Geological Survey Water-Resources Investigation Report 77-21, *Magnitude and frequency of floods in California*, by A.O. Waananen and J.R. Crippen (1977). This investigation provides analysis of 703 stream flow stations across California, with records ranging in length from 5 to 85 years and provides a method for evaluating magnitude and frequency of floods at gaged and ungaged sites. Because climatic and topographic conditions create a variety of watershed responses to precipitation events, these authors have divided California into six regions: North Coast, Northeast, Sierra, Central Coast, South Coast, and South Lahontan-Colorado Desert regions. Each region has a set of discharge equations developed for the flows from a 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year storm event. Equations for the Sierra Region are as follows:

$$Q_2 = 0.24(A^{0.88})(P^{1.58})(H^{-0.80}) \quad (1)$$

$$Q_5 = 1.20(A^{0.82})(P^{1.37})(H^{-0.64}) \quad (2)$$

$$Q_{10} = 2.63(A^{0.80})(P^{1.25})(H^{-0.58}) \quad (3)$$

$$Q_{25} = 6.55(A^{0.79})(P^{1.12})(H^{-0.52}) \quad (4)$$

$$Q_{50} = 10.4(A^{0.78})(P^{1.06})(H^{-0.48}) \quad (5)$$

$$Q_{100} = 15.7(A^{0.77})(P^{1.02})(H^{-0.43}) \quad (6)$$

where Q = discharge, subscript indicates recurrence interval in years; A = drainage area in square miles; P = mean precipitation in inches; H = altitude index in thousands of feet. (Altitude index is computed as the average of the altitudes at points along the main channel of the stream 10 and 85 percent of the distance from the site to the basin divide as outlined on a topographic map.) These authors also provide references to water resource investigations for other areas within the United States.

The method set forth in Waananen and Crippen (1977) was initially applied to the 2002 McNally fire to determine design flow and adjusted design flow. The McNally fire affected roughly 150,000 acres (60,750 ha) on the Sequoia National Forest in the North Fork Kern River basin, which is located in the Sierra Region as defined by Waananen and Crippen (1977). Figure 1 shows the relationship of flows by recurrence interval to drainage area using the equations for the Sierra Region defined by these authors. The equations used drainage area, mean annual precipitation, and altitude values for the North Fork Kern watershed.

The North Fork Kern River is roughly an 1100-square mile (2820-km$^2$) watershed, as measured from north of Mount Whitney to Lake Isabella. The North Fork Kern River is located within the Kern River basin. The area defined as the Sierra Region by Waananen and Crippen (1977) ranges from Mt. Shasta to Bakersfield and encompasses roughly 47,000 square miles (122,000 km$^2$). Figure 2 shows the contrast in size between North Fork Kern and Sierra Region as well as gage stations located in the Kern River vicinity. The Sierra Region crosses numerous hydro-physiographic areas and is significantly larger than the North Fork Kern River watershed, which is located within a single hydro-physiographic area.

Design flows (pre-fire flows) for watersheds in the North Fork Kern River were calculated using the equation for the 2-year recurrence discharge from Waananen and Crippen (1977). Adjusted design flows (post-fire flows) were based on expected runoff response by burn severity. The McNally burn severity map was used to determine relative percentages of high, moderate, and low burn severity, and unburned areas in each watershed. Runoff response calculations used the 2-year recurrence discharge equation for unburned and low severity areas, the 20-year recurrence discharge equation for moderate severity areas, and the 50-year recurrence discharge equation for high severity burn areas (Figure 1).

## Development of Discharge Curves for the Kern River

During the summers of 2000, 2001, 2002, and 2003, stream channel geometry and flow relationships were developed using Kern River tributary streams and USGS

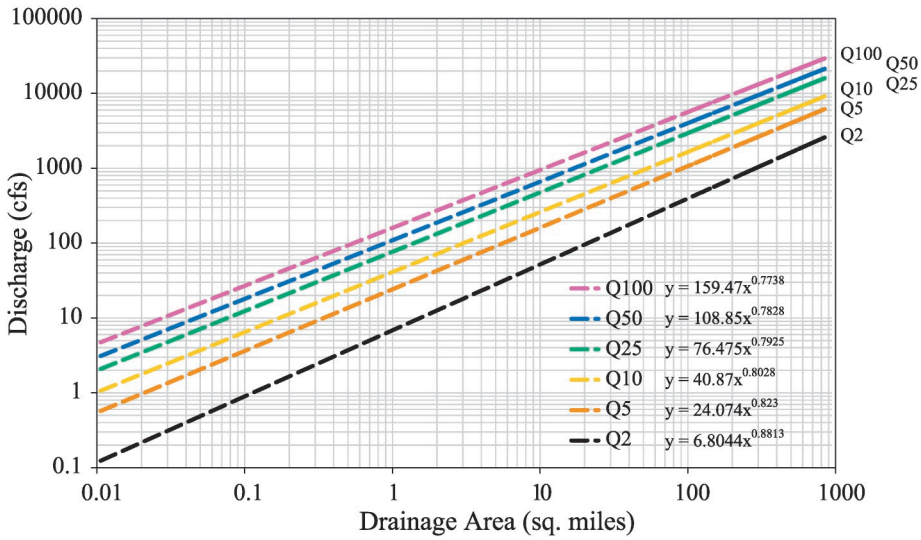
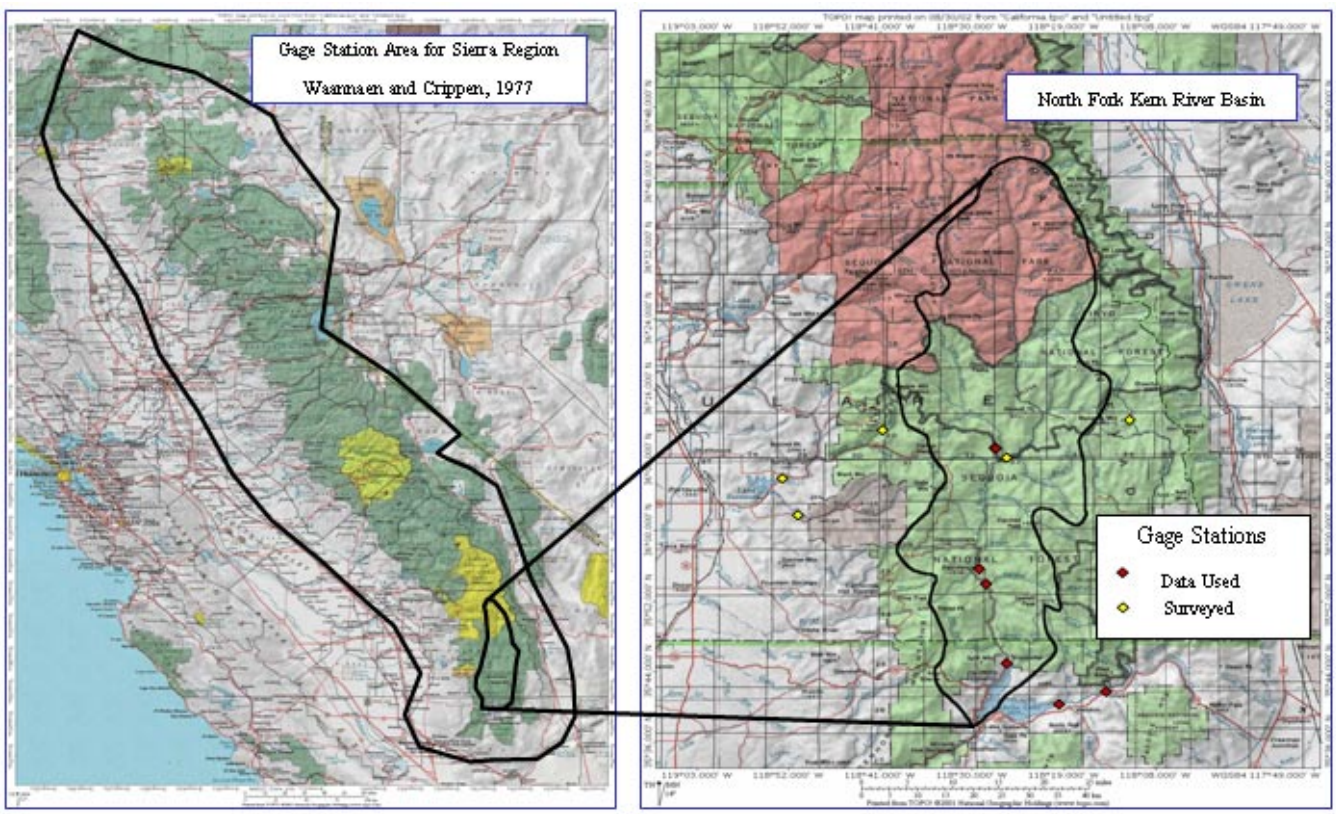



*Figure 1. Sierra Nevada Region flood frequency curves from Waananen and Crippen (1977) using drainage area, mean annual precipitation and altitude index values from the North Fork Kern River.*

*Figure 2. Contrast and location of the Sierra Region and the North Fork Kern River basin. (below)*




gage stations. Field crews collected data from cross sections, longitudinal profiles, and pebble counts following the protocol from Harrelson et al. (1994). Staff plate readings were taken at gage sites for bankfull discharge. Bankfull discharges were determined from station rating curves or USGS flow records. A protocol modified by McCandless and Everett (2002) was used for field surveys at gage stations. Modification of the protocol involved surveying only riffle habitats, and bed and bank material for most sites was characterized from reach-averaged pebble counts and riffle pebble counts. Stream bank material was not analyzed in this study.

Flow from most tributary streams was calculated using the Darcy-Weisbach with friction factor method after Hey (1979). Darcy-Weisbach uses hydraulic slope, cross-sectional area, mean depth, and the specific gravity of water in the following relationship:

$$U = \left(\frac{8gdS}{f}\right)^{1/2} \qquad (7)$$

where U = velocity, g = specific gravity of water, d = mean depth, S = hydraulic slope, and f is the friction factor defined by Hey (1979).

The friction factor, after Hey (1979), employs maximum depth, hydraulic radius and $D_{84}$ of the bed material as follows:

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{aR}{3.5D_{84}}\right) \qquad (8)$$

where f = friction factor, $D_{84}$ is the fraction of the bed material that 84% is finer than, R = hydraulic radius, and a is a function of channel cross section shape that varies between 11.1 and 13.46 and can be approximated as:

$$a = 1.11\left(\frac{R}{d_{max}}\right)^{-0.314} \qquad (9)$$

Manning's equation was used to calculate flow for channels with extremely low gradients and sand-size bottom material. Cross-sectional area, wetted perimeter, and slope were used to solve Manning's equation:

$$Q = \left(\frac{1.486}{n}\right)(A)(R^{2/3})(S^{1/2}) \qquad (10)$$

where: Q = discharge in cubic feet/second, A = cross-section area in square feet, R = hydrologic radius in feet (area/wetted perimeter), S = water surface slope, n = Manning's roughness coefficient.

For those tributary streams with low gradient (slope between 0.001 and 0.02) and sand-size bed material Jarrett's resistance equation (1984) was used to calculate Manning's 'n'. Manning's 'n' is calculated as a function of slope and hydraulic radius (area divided by wetted perimeter). Jarrett's equation for Manning's 'n' is:

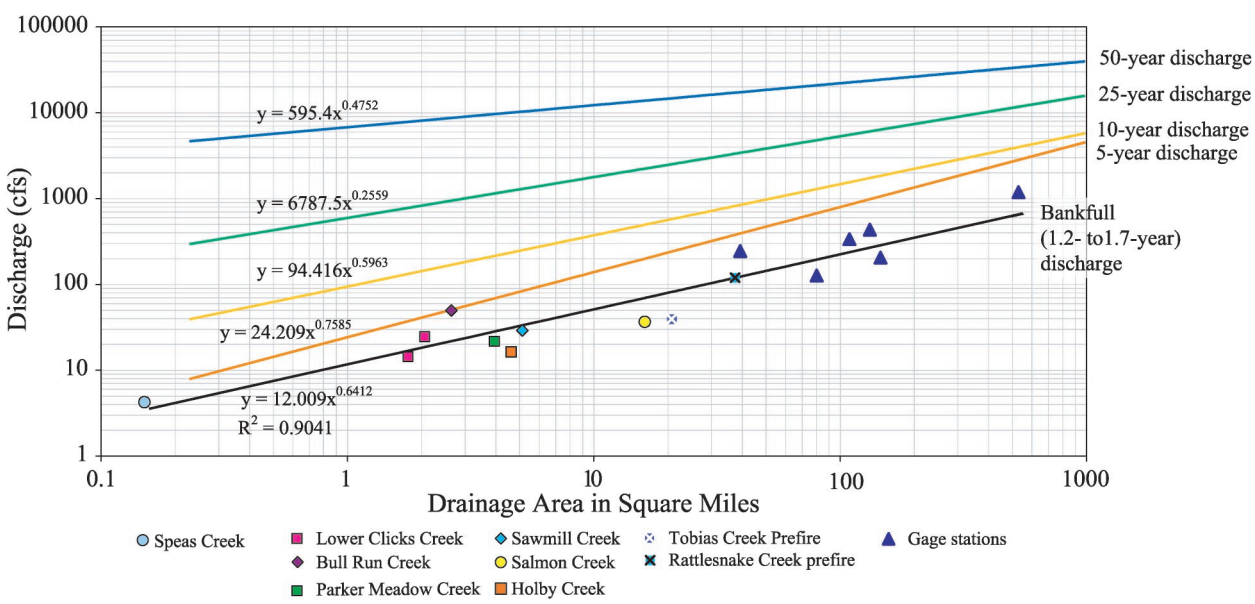
$$n = 0.39S^{0.38}R^{-0.16} \qquad (11)$$

where: n = Manning's n value, S = hydraulic gradient, and R = hydraulic radius.

Field surveys and discharge measurements within the Kern River provided data to develop discharge versus drainage area relationships with a 1.2 to 1.7-year flood frequency (the lower-most [black] line in Figure 3). Actual data points for surveyed stations are also shown. The recurrence interval of 1.2 to 1.7 years is derived from discharge measurements either calculated as described above, or measured at gage stations then compared to annual peak flow frequency analysis at gage stations. Frequency analysis for gage stations determined the 2-year, 5-year, 10-year, 25-year, and 50-year return interval curves (Figure 3).

Comparison of Sierra Region discharge curves using the relationships defined by Waananen and Crippen (1977) to local Kern River hydro-physiographic curves derived from field measurements provided surprising results. There is a large discrepancy between the sets of curves, even though many of the same gage stations evaluated in the Kern River were also used by Waananen and Crippen (1977). This is especially interesting since there is a very strong correlation between gage station sites and discharge data from non-gaged sites within the Kern River area, with an $R^2$ value of 0.9. Figure 4 displays the relationship of Sierra Region flood frequency curves to local Kern River hydro-physiographic discharge curves by recurrence calculated using Waananen and Crippen (1977). It is interesting

*Figure 3. Local Kern River hydrologic physiographic discharge relationships for bankfull, 5-year, 10-year, 25-year and 50-year recurrence interval. The 1.2- to 1.7-year discharge data were derived from field surveys; 5-, 10-, 25-, and 50-year discharges were acquired from USGS gage station discharge records.*



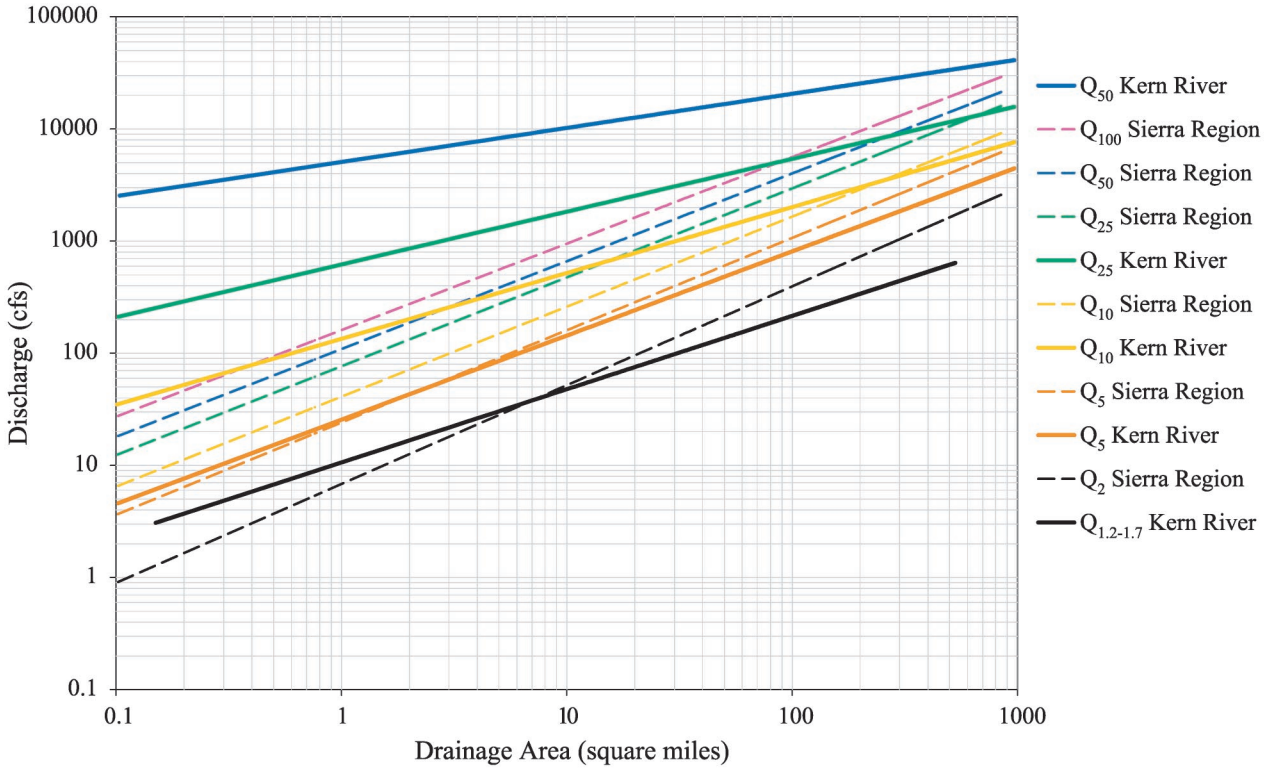



*Figure 4. Relationship of Sierra Region flood frequency curves after Waananen and Crippen (1977) to local Kern River hydrologic physiographic flood frequency curves.*

to note that for all frequency curves except the 5-year flood frequency curve there is an order of magnitude difference between locally calculated discharge and that calculated using Waananen and Crippen (1977). Discharge calculations using Waananen and Crippen (1977), for recurrence intervals greater than 5 years, are substantially lower than the measured discharge from the Kern River area. The 5-year flood frequency curve is reasonably similar to Kern River discharge relationships, while the 2-year flood frequency curve from Waananen and Crippen is lower for watersheds of roughly less than 5 square miles (13 $km^2$) and greater for watersheds greater than 10 square miles (26 $km^2$). This suggests that the Sierra Region equations provided by Waananen and Crippen (1977) provide reasonable estimates of discharge for 5-year recurrence interval estimates for any size watershed, and 2-year recurrence interval estimates for watersheds of roughly 5 to 10 square miles (13 to 26 $km^2$) within the Kern River area.

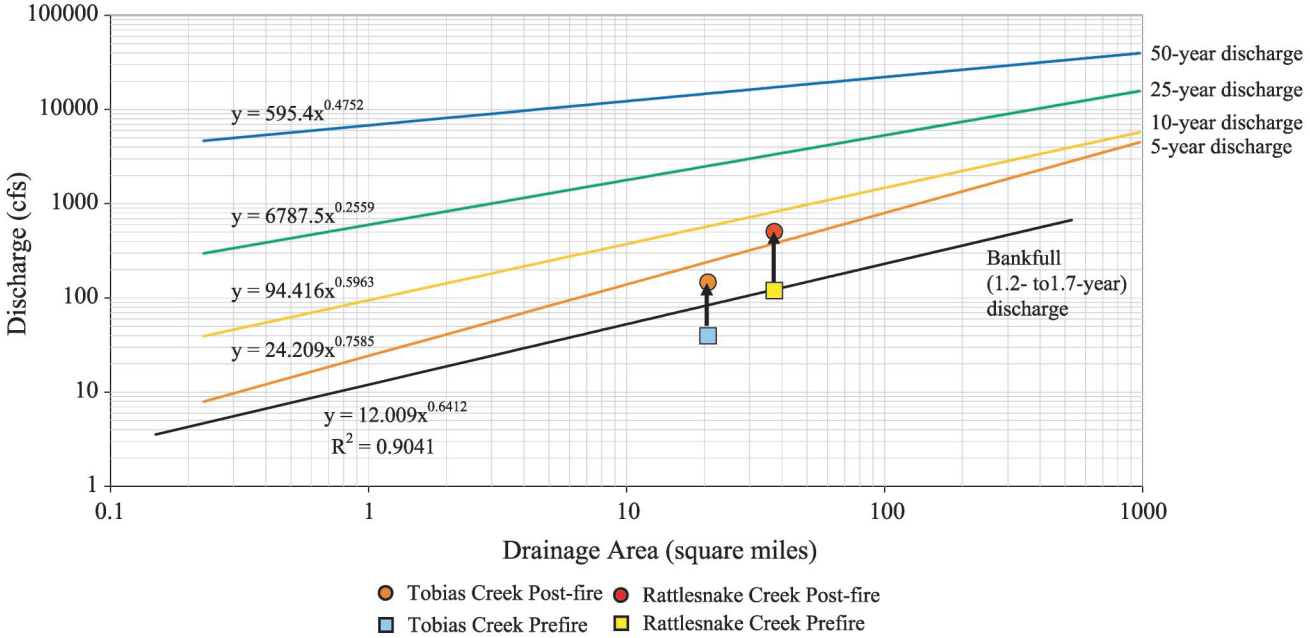
Just why this occurs could be related to application of state-wide gage station data across the Sierra Region to develop equations which were then applied to much smaller watersheds. The large variation in climate from north to south would be expected to account for some of the differences. Discharge relationships determined from local data (Figure 4) suggest that the equations from Waananen and Crippen grossly underestimate discharge for the North Fork Kern River, and it is clear that using data outside the immediate area provides substantially lower discharge for adjusted design flows. This could have serious implications in the case of BAER runoff determinations, which have the potential to affect life, property, and resources.

The data used to develop the Kern River hydro-physiographic discharge relationships (Figures 3, 4 and 5) are displayed in three groups (Appendix 1). The first group of figures represents field data collected at non-gaged sites along with discharge, velocity, and friction or n values used for resistance calculations. The second group is field data collected at gage stations and discharge information from station rating curves or USGS records. The third group is information used to develop discharge at the various recurrence intervals by watershed size derived from frequency analysis of peak flow data from the identified USGS gage stations.

## Monitoring of Predicted Adjusted Design Flows in the McNally Fire Area

The author is responsible for the selection of recurrence interval relative to burn severity and runoff rate estimates used in the McNally fire. Monitoring results suggest that

*Figure 5. Shift in post-fire discharge for Rattlesnake and Tobias Creeks as compared to local Kern River hydrologic physiographic discharge.*



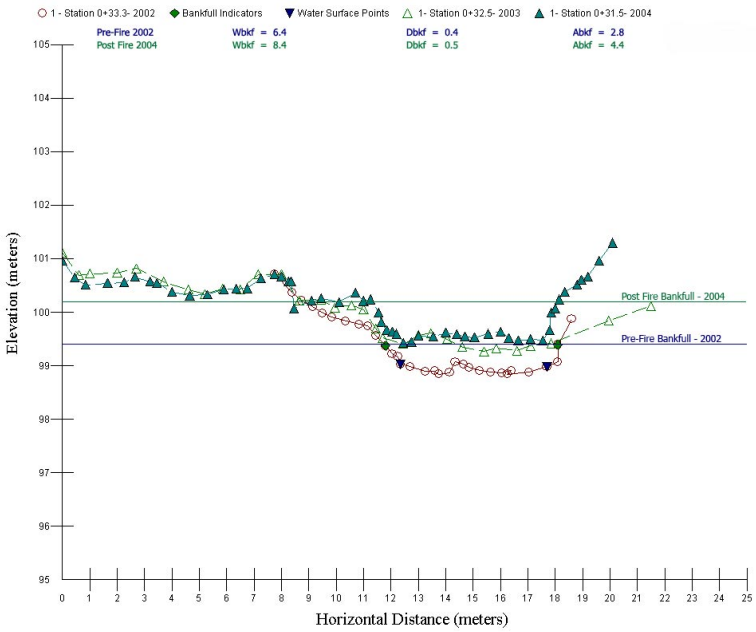



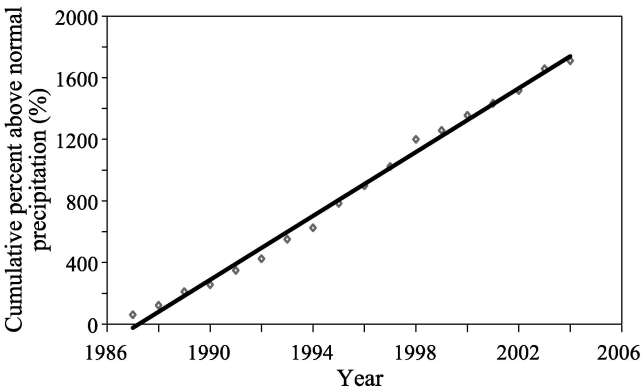

*Figure 6. Rattlesnake Creek cross section 0+31.5 (2000-2004).*

selected recurrence interval and discharge response for burn severity was grossly over-estimated, with the exception of those lands burned at low severity. This does not alleviate concern surrounding variance between Sierra Regional Flood Frequency curves versus local Kern River hydro-physiographic discharge curves. It only suggests that monitoring and follow up investigations of post-fire runoff rates is important so hydrologists can better estimate adjusted design flows in an emergency.

Monitoring of ungaged stream channels within the McNally fire area continued following the fire. And, serendipitously, the Tobias Creek watershed was surveyed just days prior to the fire. Rattlesnake Creek watershed was surveyed immediately after the fire prior to seasonal rains. These surveys were used in the creation of the bankfull hydro-physiographic discharge curves (Figure 3). Continued post-fire surveys have provided information on channel geometry following the wildfire.

Following the fire, channels of Tobias Creek and Rattlesnake Creek developed a new floodplain in response to increased runoff. Cross-sections and longitudinal profiles surveyed in 2003 and 2004 provided data on the channel geometry response to rainfall events. One of the cross sections taken on Rattlesnake Creek provides a good

*Figure 7. Cumulative percent above average precipitation in the vicinity of the McNally fire at KR3 Intake, 1986-2004. (below)*




example of floodplain development after the fire (Figure 6). Three years of data are overlaid in this figure. The newly formed floodplain provides bed and geometry information that was used to estimate discharge as previously discussed. When discharge values were plotted on Kern River hydro-physiographic discharge curves, they occurred between 5-year and 10-year recurrence curves. Rattlesnake Creek sustained higher burn severity and showed a higher recurrence than Tobias Creek. The post-fire discharge values have been plotted as circular points immediately above their square pre-fire points (Figure 5).

Rainfall events included the winter storm of November 2002 and numerous average annual thunderstorm events of July and August 2003. However, a study of 1987 to 2004 cumulative annual percent-above-normal rainfall by year did not show anomalous or unusually intense rainfall post-fire (Figure 7). This suggests that the increased runoff after the fire rather than an unusually high runoff season is responsible for the change in channel geometry. Furthermore, field investigations at Osa Meadow between August 2003 thunderstorms provide visual support that post-fire runoff is responsible for the creation of new floodplain in Rattlesnake and Tobias Creeks. Osa Meadow is located at the eastern edge of the McNally fire. The upstream section of the meadow was not affected by the fire; however the lower section of the meadow received increased runoff generated by a low severity burn in the headwaters of a tributary channel. The series of summer thunderstorms responsible for development of a new floodplain in Rattlesnake and Tobias Creeks was responsible for flooding in the lower portion of Osa Meadow. The portion of the meadow upstream where burning did not occur in tributary streams was unaffected by the storm. Figures 8a and 8b show Osa Meadow above and below the flooding caused by the McNally fire. The distribution of organic material defining the high water in upper Osa Creek meadow has a width of roughly three feet

*Figure 8. (a) Osa Meadow upstream of fire effects. (b) Osa Meadow downstream of fire effects.*

(0.9 m) commensurate with bankfull width, suggesting a storm responsible for a discharge of 1.2 to 1.7 years. The lower meadow had an accumulated flood width of roughly thirty-three feet (10 m) resulting from the same storm event. As evidenced in these two photos, the two sections of creek responded differently to the same event. These two areas are no more than 200 feet (61 m) apart.

## Summary

The results of this study suggest that local flow relationships provide the basis for design and adjusted design flow for emergency evaluations. However, when local information is unavailable the use of the 5-year flood frequency equation from Waananen and Crippen (1977) provides reasonably good estimates for watersheds of all sizes, while the 2-year flood frequency curves provide reasonable estimates of discharge for watersheds of roughly two to ten square miles (5 to 26 km$^2$) within the Kern

River area. Other recurrence interval discharge equations from Waananen and Crippen (1977) grossly underestimate discharge for the North Fork Kern River area. This could have serious consequences in the case of BAER runoff determinations which have the potential to affect life, property, and resources.

Comparison of post-fire effects to predicted adjusted design flow may provide managers with a way to predict discharge following fire, based on channel geometry. Currently there are only two locations with data available, so the concept is based on professional judgment and limited data. With additional study it may be possible to develop a dataset based on local fires and their effect on post-fire channel discharge. This study suggests that post-fire channel geometry may provide information on runoff rates following wildfires when compared to a set of recurrence interval discharge curves developed for the physiographic region associated with the wildfire event.

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*Appendix 1. Data used for development of local hydrologic physiographic relationships.*

| Ungaged Creeks | Drainage Area ($mi^2$) | X-Sectional Area ($ft^2$) | Discharge (cfs) | Velocity ($ft\ s^{-1}$) | Friction factor *or "n" value | Resistance Equation Used |
|---|---|---|---|---|---|---|
| Speas | 0.15 | 1.20 | 4.24 | 2.97 | 0.39 | Darcy-Weisbach |
| Lower Clicks Creek | 1.76 | 8.60 | 14.32 | 1.53 | 0.07* | Jarrett |
| Lower Clicks Creek | 2.06 | 11.80 | 24.49 | 2.21 | 0.06* | Jarrett |
| Bull Run Creek | 2.64 | 10.66 | 49.63 | 4.44 | 0.03 | Darcy-Weisbach |
| Parker Meadow Creek | 3.95 | 7.21 | 21.7 | 2.04 | 0.16 | Darcy-Weisbach |
| Holby Creek | 4.62 | 10.76 | 16.25 | 1.15 | 0.02* | Jarrett |
| Sawmill Creek | 5.13 | 8.50 | 29.02 | 2.87 | 0.08 | Darcy-Weisbach |
| Salmon Creek | 16.10 | 13.99 | 36.62 | 3.73 | 0.12 | Darcy-Weisbach |
| Tobias Creek 2002 Pre-fire | 20.70 | 26.91 | 39.5 | 1.46 | 3.50 | Darcy-Weisbach |
| Tobias 2003 Post-fire | 20.70 | 39.83 | 146.34 | 3.75 | 0.44 | Darcy-Weisbach |
| Rattlesnake 2002 Pre-fire | 37.42 | 23.36 | 119.5 | 5.99 | 0.24 | Darcy-Weisbach |
| Rattlesnake 2003 Post-fire | 37.42 | 77.50 | 503 | 6.55 | 0.22 | Darcy-Weisbach |

| Gage Stations | | Drainage | X-Sectional | Bankfull | Bankfull Return |
|---|---|---|---|---|---|
| Name | Number | Area ($mi^2$) | Area ($ft^2$) | Discharge | Interval in Years |
| Wishon Fork Tule River | 11202000 | 39 | 37 | 243.7 | 1.69 |
| Tule River Near Springville | 11204000 | 80 | 60.7 | 127.15 | 1.2 |
| South Fork Tule River | 11204500 | 109 | 63.2 | 337 | 1.31 |
| Little Kern River Near Quaking Aspen Camp | 11185400 | 132 | 74.00 | 435.00 | 1.53 |
| SF Kern River Near Olancha | 11188200 | 146 | 50.00 | 205.00 | 1.55 |
| Kern River Near Quaking Aspen Camp | 11185350 | 530 | 230.00 | 1186.00 | 1.21 |

| Gage Stations | | Drainage | Discharge Values at Associated Return Intervals from Gage Records | | | |
|---|---|---|---|---|---|---|
| Name | Number | Area ($mi^2$) | 5-Year | 10-Year | 25-Year | 50-Year |
| Salmon Creek | 11186380 | 0.23 | 7.00 | 50 | 300 | 3000 |
| Salmon Creek | 11186360 | 0.30 | 12.00 | 90 | 700 | 7000 |
| Salmon Creek | 11186340 | 0.45 | 10.00 | 40 | 175 | 1000 |
| Wishon Fork Tule River | 11202000 | 39 | 1548 | 5333 | 11530 | 15049 |
| Tule River Near Springville | 11204000 | 80 | 1360 | 2280 | not available | not available |
| South Fork Tule River | 11204500 | 109 | 3084 | 4466 | 6857 | 12075 |
| Little Kern River Near Quaking Aspen Camp | 11185400 | 132 | 2010 | 7370 | 14000 | 57200 |
| SF Kern River Near Olancha | 11188200 | 146 | 1000 | 1314 | 3500 | 20000 |
| Kern River Near Quaking Aspen Camp | 11185350 | 530 | 4053 | 7867 | 15000 | 30000 |
| Kern River Near Onyx | 11189500 | 530 | 2389 | 3576 | 6784 | 17196 |
| Kern River near Kernville river only | 11186000 | 846 | 5241 | 10533 | 27076 | 46510 |
| Kern River at Isabella | 11190000 | 982 | 1788 | 3612 | 10000 | 40000 |