Evaluation of Regional Calibration Parameters using a Distributed Rainfall-Runoff Model: Borrego Palm Canyon near Borrego Springs, California

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ABSTRACT

Flash flood prone canyons pose a significant threat to recreational users in the semi-arid western United States. This is in particular the case for ungaged locations where stream and rain gage observations are not available to assist National Weather Service (NWS) forecasters. The application of an event based distributed rainfall-runoff model forced with radar data to fast-responding basins is one such solution. The KINematic runoff and EROsion model (KINEROS2) has been successfully calibrated for Fish Creek in Anza Borrego Desert State Park, California for the prediction of the magnitude and timing of flash flood peak flows. Due to the uncertainties in simulating peak flows for ungaged locations, the output from KINEROS2 will be only used for categorical forecasting (no flooding, minor flooding, moderate flooding, major flooding, and record flooding). This paper presents the results of the application of the calibration parameters derived for Fish Creek to a nearby basin, Borrego Palm Canyon near Borrego Springs, California. Borrego Palm Canyon is located 27 miles northwest of Fish Creek in Anza Borrego Desert State Park. The goal was to evaluate if the Fish Creek calibration parameters could be used as the basis of a regional calibration. A regional calibration could be applied to similar basins and would reduce the resources needed to field the model to additional locations. Four storm events of different areal average rainfalls and maximum areal average rainfall intensities were required for evaluation of a regional calibration. Additional events were evaluated, but not used in the evaluation due to their being influenced by post wildfire watershed response or being classified by the USGS as a debris flow. Model calibration simulations fell within or in close proximity to the flood category that corresponded to the observed USGS or estimated peak flow and the null event did not produce any flow. The results show promise that a regional calibration has been created for the greater Anza Borrego Desert State Park and potentially for other regions of the semi-arid West.

Introduction

Borrego Palm Canyon is a popular hiking destination. It is the third largest palm oasis in California. The Borrego Palm Canyon Trail takes hikers from the Borrego Palm Campground over an alluvial fan at the mouth of the canyon and then into a v-shaped canyon gorge. Most hikers travel 1.5 miles to the first palm oasis and waterfall, while some hikers choose to hike further upstream. Further upstream, boulders and increasingly dense vegetation make hiking more difficult. Flooding impacts hikers in the canyon as well as points further downstream of the mouth of the canyon including a campground and the De Anza Country Club.

Despite good radar coverage from the Yuma (KYUX) WSR-88D (Weather Surveillance Radar 88 Doppler) and fair coverage from the San Diego (KNKX) WSR-88D, forecasting floods within the watershed is challenging. The forecaster must compare radar quantitative precipitation estimates (QPE) totals and rates with flash flood guidance and integrate that with their knowledge of the local area. Most forecasters have never visited the basin and may not have the tools or conceptual model to translate accumulated rainfall totals into a level of flooding. Determining if flash flooding is going to occur is the first step in this process. After that has been completed, hydrologic Decision Support Services (DSS) requires high resolution basin information to properly determine the degree of impact. For example, the determination of a peak flow reaching a minor, moderate, or major flooding stage and its time of occurrence is critical.

The modeling of Borrego Palm Canyon was built upon work previously accomplished for modeling Fish Creek (Schaffner et al., 2014). Fish Creek is an ungaged watershed located 27 miles southeast of Borrego Palm Canyon (Figure 1). Fish Creek was modeled with the KINEROS2 model. The model integrates rainfall and basin response to produce a useful prediction tool for forecasters. It is a distributed model tool that runs using real-time radar data at every volume scan to compute a forecast hydrograph. When calibrated, it can accurately translate rainfall into guidance for the forecaster on the magnitude and timing of a peak flow. The forecast flash flood warning and other DSS provided could then include, in addition to the basin being impacted by flash flooding, the category of flooding (i.e. minor, moderate, or major flooding). A premise from modeling Fish Creek was that calibration of a distributed model for one basin can be applied to similar basins in efforts to effectively provide advanced warning with greater specificity and longer lead time. If calibration parameters for one basin could be applied to other nearby basins in the hydrologic region, it would streamline setting up the model elsewhere. The primary objective of this work was to evaluate the calibration parameters for Fish Creek in Borrego Palm Canyon. If the calibration showed skill, it is likely it can be used throughout the greater Anza Borrego Desert State Park region.

The calibration parameters created for Fish Creek, namely a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00 for events with a maximum basin average rainfall intensity less than 1.80 inches/hour and a saturated hydrologic conductivity multiplier of 1.00 and a channel length multiplier of 1.00 for events with a maximum basin average rainfall intensity equal or greater than 1.80 inches/hour were evaluated in this study. KINEROS2 computes the maximum basin average rainfall and automatically applies the appropriate calibration parameters if the value is less than or equal to or greater than 1.80 inches/hour.

Borrego Palm Canyon Watershed Information

Borrego Palm Canyon basin is 21.8 square miles above the outlet point selected for this study. This location is located in Hydrologic Unit 18100200. The outlet point was selected to correspond to a discontinued USGS stream gage that was active through 2004. This point corresponds to the reach of the river near the first palm oasis where most visitors complete their hike.

Mammoth Pines Fire

The Mammoth Pines Fire burned portions of the watershed during the summer of 2002. The watershed contained mature chaparral and high desert vegetation at the time of the fire (Figure 2). The fire burned 77.9% of the watershed. The dominant vegetation type was chaparral and scrub which covers 86.4% of the watershed and 90.3% of the area the fire burned within the watershed.

Burn severity and post-fire watershed response depend heavily on the fuel load, fire conditions, and the rainfall following the fire. A burn severity map was not created for the fire. A Burned Area Reflectance Classification (BARC) image was made available by the USGS Earth Resources Observation and Science Center (EROSC). As a result, the effects of the fire on the ground surface, soil condition, and extent of water repellency was assessed solely from the BARC image. Ideally Burn Area Emergency Response (BAER) team members, including hydrologists, would verify the BARC in the field and modify it as needed. Figure 3 displays a burn severity map of the watershed derived solely from the BARC image. Of the 77.9% of the watershed burned, 1.8% was high burn severity, 31.6% moderate burn severity, 51.0% low burn severity, and 15.6% unburned. This amounts to 33.4% of the watershed having high + moderate burn severity and 66.6% of the watershed being low burn severity + unburned. From a post-fire response perspective, high and moderate burn severity tend to elicit an increase in runoff and peak flows while low burn severity is essentially equivalent to an unburned condition.

USGS Stream Gage Record

USGS operated a stream gage at the modeled location from October 1950 through September 10, 2004. The stream gage was destroyed by the September 10th flood event. The USGS refers to this event as a debris flow in their 2007 Water Year Report for this gaging station (USGS, 2007). The USGS recorded the high water mark for this flood, but did not conduct a slope-area indirect measurement to determine the discharge. After September 10, 2004, the USGS continued to take field measurements at the site though May 10, 2007. All of these measurements were low flow; generally less than 1 cfs. The USGS rates the records for this stream gage as being poor. No regulation or diversions are located upstream from the gage location.

Development of Peak Flow Rating Curve

The KINEROS2 graphical user interface (GUI) requires a rating curve to convert modeled discharge to stage. A rating curve was developed using peak streamflow data provided by the USGS (USGS, 2014). The USGS rating curve extends from zero flow upward to a stage of 10.17 feet which corresponded to the USGS peak flow of record of

2990 cfs. This peak flow was calculated by the USGS in a slope-area measurement, using high water marks, from a flow event on August 20, 2013.

The rating curve was extended upward to the 50-year return flow event. The rating curve along with peak flow events used to develop it and USGS peak streamflow statistics can be viewed in Figure 4. Peak flow statistics for the basin were calculated using the USGS California StreamStats program (http://water.usgs.gov/osw/streamstats/california.html). StreamStats uses published USGS regression equations to compute peak streamflow statistics for ungaged locations. Regression equations differ by region. Borrego Palm Canyon falls 94% within the USGS Southern Great Plains Region and 6% within the South Coast Region. The peak streamflow statistics presented here are an area-averaged value based on the percentage of the watershed that falls within each USGS regression equation region. This is the default calculation method provided by USGS StreamStats.

The USGS California Water Science Center provided a copy of the last rating curve for the discontinued stream gage. The USGS rating curve compares well with the peak flow curve developed for the model (Figure 5).

The modeling approach is semi-quantitative where the simulated hydrograph will be used for categorical forecasting of the peak flow. Categorical forecasting provides binary output of flood or no flood, and if it does flood the determination of a relative category of flooding (e.g. minor, moderate, or major) is provided. Furthermore, the rating curve is a peak flow rating curve and does not need to account for changes in the stage-discharge relationship on the rising and falling limbs of the hydrograph to the degree of specificity that might otherwise be required. The rating curve will not be used to forecast daily or instantaneous flows. As a result, the rating curve will be mostly left alone and should be considered maintenance free. Exceptions would be to update the upper end of the rating curve should the USGS document flood events exceeding the USGS peak flow of record; or should the USGS place the discontinued stream gage back into operation and develop a new rating curve; or if a debris flow would substantially alter channel cross-section or slope characteristics.

Determination of Flood Thresholds

Modeling Borrego Palm Canyon required the determination of action, minor, moderate and major flood stages. For most of the country, flood stages begin above bankfull. Since Borrego Palm Canyon is in a dry wash canyon landscape, flood impacts begin at stages below bankfull so the flood stages selected are within-bank flooding, rather than traditional out of bank flows.

Flood stages generally apply to the reach of the Borrego Palm Canyon within 500 feet upstream and downstream of the model outlet point. The flood stages become a less reliable indicator of flood impacts as one progresses away from the outlet point. This is particularly true downstream due to tributary creeks entering the mainstem channel and resultant widening of the channel. The first tributary is encountered 800 feet downstream of the outlet point. This results in roughly a doubling of the width of the channel and the channel becoming braided. The next and last significant tributary creek enters the mainstem channel about 2100 feet further downstream or about 2900 feet from the outlet point. Shortly after this last tributary, the channel encounters the mouth of Borrego Palm Canyon and spreads out onto the alluvial fan located at the mouth of the canyon. Much of the flow as it exits the canyon ultimately flows in a northeast direction and impacts the De Anza Country Club (Figure 6).

Setting flood stages for a location like Borrego Palm Canyon is challenging since conditions vary spatially along the wash due to changes in channel width, deposition, and erosion. Changes take place temporally from one flood event to another that cannot possibly be accounted for without a stream gage or active on the ground monitoring program.

Action Stage was set at 4.0 feet which corresponds to an estimated peak discharge of 355 cfs. This equates to greater than a 2-year peak flow and less than a 5-year peak flow. At Action Stage, water is within the low flow channel and does not impact any of the overbank area.

Minor Flood Stage was set at 5.5 feet which correspond to an estimated peak discharge of 882 cfs. This equates to greater than a 5-year peak flow and less than a 10-year peak flow. At Minor Flood Stage, water begins to exceed the low flow channel in sections. Portions of Borrego Palm Canyon Trail closest to the channel would be inundated (Figure 7).

Moderate Flood Stage was set at 6.5 feet which correspond to an estimated peak discharge of 1330 cfs. This equals the 10-year peak flow. More significant damage of the Borrego Palm Canyon Trail occurs above Moderate Flood Stage. Flooding is likely beyond the mouth of the canyon and at the De Anza Country Club if there is additional rainfall downstream of the model outlet point.

Major Flood Stage was set at 9.0 feet which correspond to an estimated peak discharge of 2400 cfs. This equated to greater than a 10-year peak flow and less than a 25-year peak flow. Major flood events, such as occurred in 2003 and 2013, caused significant flooding of De Anza Country Club (homes, streets, and golf course). Both events also caused significant damage to the Borrego Palm Canyon trail. Even without additional rainfall downstream of the model outlet point, flooding at De Anza County Club is likely during major flood events.

Flood stages in context to historical USGS water year peak flows and peak flow statistics can be viewed in Figure 4.

<u>Model Calibration Events</u>

A total of five events were evaluated to create an initial calibration. A sixth event was run through the model, but the results were not used to create the calibration since it was a debris flow event. It would have been ideal to have additional events, but these were not available. The basin seems to flood less frequently as compared to Fish Creek. Fish Creek had additional flood events for calibration (Schaffner et al., 2014). Borrego Palm Canyon is about half the drainage area of Fish Creek. The smaller drainage area allows for fewer rainfall events to be captured. In addition, visitation to Borrego Palm Canyon is entirely on foot while Fish Creek allows vehicle access. The ease of access and hence the number of visitors likely plays some role in the number of flood reports that get reported for Fish Creek vs Borrego Palm Canyon. Several of the events evaluated for Borrego Palm Canyon were from the 2003 and 2004 summers. These events were captured by the USGS while the stream gage was still in operation. After 2004, there is little evidence of flood events until the summer of 2013 when another significant flash flood impacted the area. San Diego County Flood Control District maintains a rain gage at Borrego Palm Canyon (Figure 8). Their rainfall data confirms the general lack of summer time rainfall during the 8-year timeframe of 2005 to 2012.

August 20, 2003

The USGS recorded a peak flow of 2,990 cfs (10.17 feet) at 4:30 PM. This places the flow for this event into the major flood category. Unit values record a flow of 0.33 cfs at 3:45 PM, 1.6 cfs at 4:00 PM, and 4.0 cfs at 4:15 PM. The water rose from low flow to peak flow in a time-frame of 15-minutes or less. USGS unit values are instantaneous values of stage collected at specified time intervals (for this site, every 15-minutes).

August 27, 2003

The USGS recorded a peak flow of 1,240 cfs (6.31 feet) at 1:30 PM. This places the flow for this event into the minor flood category. Unit values record a flow of 0.86 cfs at 13:00 local time and 5.3 cfs at 1:15 PM. As with the August 20, 2003 flow event, the water rose very rapidly from low flow to peak flow.

September 10, 2004

The USGS stream gage was destroyed during this event. The USGS recorded the high water mark at the gage for this event, but did not conduct a slope-area indirect discharge measurement since they deemed the event a debris flow. The high water mark was 18.03 feet. The USGS California Water Science Center provided all available reports and documentation related to the flood event. This included an e-mail from Supervisory Hydrologic Technician Al Caldwell who was the first USGS employee to visit the site of the stream gage after the flood on morning of September 11, 2004 (USGS, 2004) and field notes of a 3-person USGS survey crew for an indirect discharge measurement (USGS, 2004). Supervisory Hydrologic Technician Caldwell wrote there "was no indication that this was a debris-flow event". He mentioned that he "was able to flag a fair reach for a slope-area or slope-conveyance survey." He noted this flood event "easily eclipses that of August 20, 2003" which was a significant event from the prior water year. The field notes from the indirect discharge measurement simply have the words "debris flow" written down and later state that there was a "debris pile" making up the high water mark.

The final unit value reported by the stream gage was 3:30 PM. Based on the rapid rise seen in the two events from 2003, the gage was destroyed or damaged such that it could no longer transmit shortly thereafter. Media reports mention a wall of water, mud, and debris upwards of 20 to 25 feet high upstream and the campground at the mouth of the canyon was obliterated (UT San Diego, 2004). Media attribute the time of flooding at Borrego Palm Canyon and other nearby canyons at just before 5:00 PM. Several dozen homes in the Sun Gold and De Anza Country Club areas of Borrego Springs were flooded with one home filled with 4-feet deep of mud. The first palm grove located a short distance upstream of the model outlet point was estimated to have lost approximately 80% of its large palm tree individuals (Chester et al., 2010).

July 21, 2013

The Borrego Palm Canyon tipping bucket rain gage operated by San Diego County Flood Control District recorded 2.01 inches of rain on the 21st. There were no reports of flooding in Borrego Palm Canyon proper. There was a reference of flooding along Palm Canyon Drive from a blog posting made by the innkeeper at the Borrego Valley Inn (Marie, 2013). Portions of Palm Canyon Drive were covered by 7 to 8 inches of water, but flood damage was minimal. Palm Canyon Drive is located 2.3 miles southeast of the model outlet point for Borrego Palm Canyon (Figure 9).

August 25, 2013

The Borrego Palm Canyon tipping bucket rain gage operated by San Diego County Flood Control District recorded 1.78 inches of rain on the 25th. Flooding impacted the De Anza Country Club where about 40 homes were damaged and the waterline reached as high as two feet above the ground level (UT San Diego, 2013). Brick walls surrounding the backyard of one home were reported to have broken apart. Media attribute the time of flooding at De Anza Country Club at about 3:30 PM. Given the magnitude of the event, the authors have assigned this as a 25-year event or 2920 cfs. This places the estimated flow for this event into the major flood category. In addition to damage at the country club, the Borrego Palm Canyon trail sustained significant damage.

August 26, 2013

The Borrego Palm Canyon tipping bucket rain gage operated by San Diego County Flood Control District recorded 0.51 inches of rain on the 26th. While no reports of flooding were found for this date, most of the media attention was focused on the major flood event on the prior day. This will be used as a null event to test the model to make sure it does not over-simulate.

Model Calibration Assumptions

The model was run for all events using a constant default convective Z-R relationship for QPE ($Z = aR^b$ where a = 300 and b = 1.4). For the best calibration and operational real-time model results, it is best to select the most appropriate Z-R relationship. Rain gages have commonly been compared with radar rainfall to determine the most appropriate Z-R relationship. Borrego Palm Canyon is remote and lacks any rain gages within its watershed boundaries and only has one rain gage situated nearby, but outside of the watershed boundary. The convective Z-R relationship was assumed to be reasonable since all flood events modeled were during the warm monsoon convective season. The selected Z-R relationship should be viewed as being conservative in nature since the more intense rainfall events may have had significant warm rain processes occurring and as such may have required a Z-R relationship with a lower Z and R coefficient or exponent. Furthermore, the convective Z-R relationship was applied to all events used in the calibration of the nearby Fish Creek basin and produced good results.

The height of the radar beam, from the KYUX WSR-88D, is approximately 10,000 MSL feet and experiences no beam blockage. Since the base of most thunderstorms in the Borrego Palm Canyon area are near 700 mb, or 10,000 feet, the radar captures the important layers needed for proper processing of radar QPE.

The user provides the initial flow rate in cfs at the start of each event to be modeled. The assumption was that the Borrego Palm Canyon channel was dry at the start of each event. While there is some base flow most of the year this amount is generally less than 1 cfs. For events modeled where there has been a flow event within a week prior, the initial soil moisture state was increased as opposed to trying to estimate an initial flow value. Any flow value would likely be small compared to flood flows and as such would be relatively insignificant from a modeling standpoint.

Setting up the Model

The Automated Geospatial Watershed Assessment (AGWA – www.tucson.ars.ag.gov/agwa) tool was used to develop the input parameter file for the KINEROS model (Miller et al., 2007; Goodrich et al., 2012). AGWA uses nationally available standardized spatial datasets that are readily obtained via the Internet free of charge. These include the USGS Digital Elevation Model (DEM), North American Landscape Characterization (NALC), Multi-Resolution Land Characteristics Consortium (MLRC) land cover, and STATSGO, SSURGO, and Food and Agriculture Organization (FAO) soil data. AGWA is maintained by the USDA Agricultural Research Service.

AGWA allows the user to delineate the watershed boundary upstream of a user defined outlet point. AGWA was used to discretize the internal model elements within the watershed (contributing hillslope elements and open channel elements). Refer to Figure 10 for an image of the model elements AGWA created for the KINEROS2 model for Borrego Palm Canyon. As a default setting, AGWA assigns a uniform Manning's roughness of 0.035 to all open channel elements. AGWA estimates channel widths at the upstream and downstream end of each open channel element based on upstream contributing area. Calibration and modeling results are generally improved when the user can customize the open channel element widths and Manning's roughness.

Google Earth was used to measure channel widths for each channel element, and was used to evaluate the Manning's roughness coefficient by viewing pictures that were geocoded based on their latitude and longitude. Google Earth imagery dated from 2010 and 2011. Manning's roughness values of 0.043 to 0.045 were assigned to the main channel sections of Borrego Palm Canyon (mainstem, South Fork, and Middle Fork). Smaller headwater tributary streams were given roughness values as high as 0.046. The authors view the Manning's roughness values as some of the highest they have ever seen (Figure 11).

Figure 12 displays a summary of the channel widths and Manning's roughness coefficient assigned to each open channel element.

Calibrating the Model

Calibration was accomplished by adjusting global parameter multipliers. A parameter multiplier allows the user to proportionally adjust the parameters for all model elements without having to edit the parameter value for each element individually. For example, a multiplier of 1.5 for the saturated hydrologic conductivity would increase by 50% the original parameter value for each overland flow model element. This is based on the assumption that the soils and DEM data used to derive the initial model parameters accurately reflect the spatial variability in a relative sense.

The model was calibrated manually for each event to match the observed timing and magnitude of the peak flow. Lengths of open channel elements were scaled by a multiplier to obtain a best fit for the timing of the peak flow, and the saturated hydrologic conductivity of overland planes was adjusted to obtain a best fit for the magnitude of the peak flow. It is often necessary to have a parameter multiplier of greater than 1 for channel length since DEMs often do not fully capture the channel sinuosity. In order to preserve the elevation drop when the length of a channel element is adjusted by a multiplier, the channel slope is also adjusted accordingly. If saturated hydrologic conductivity is adjusted by a multiplier, the soil capillary potential is also adjusted based on a linear regression between the two parameters (Goodrich 1990).

<u>Model Calibration Simulations</u>

A. August 20, 2003

The August 20th event had full rainfall coverage over the basin with the heaviest being over the southern portion of the Middle Fork of Borrego Palm Canyon (Figure 13), an areal average rainfall of 2.45 inches from the start of the rainfall event to the time of the simulated peak flow, and a maximum areal average rainfall intensity of 3.60 inches/hour. This amounted to the largest rainfall event and the most intense rainfall rate used in the calibration. The model simulated a flow of 3856 cfs (11.45 feet) at 5:11 PM using the Fish Creek calibration parameters of 1.00 for the saturated hydrologic conductivity multiplier and 1.00 for the channel length multiplier. The simulated flow exceeded the USGS flow of 2990 cfs (10.17 feet), but was within the same flood category of major flooding. Major flooding begins at 2400 cfs (9.00 feet). Timing of the peak flow reported by the USGS was 4:30 PM. The model was able to match with USGS observed peak flow when a saturated hydrologic conductivity multiplier of 1.15 and a channel length multiplier of 1.00 were used. This resulted in a simulated peak flow of 2957 cfs (10.15 feet) with no change in the simulated time of peak flow. An initial soil moisture condition of super dry was used based on the lack of antecedent rainfall in the weeks prior to the event.

B. August 27, 2003

The August 27th event had full rainfall coverage over the basin with the heaviest rainfall being over the headwaters of the Middle Fork of Borrego Palm Canyon (Figure 14), an areal average rainfall of 0.89 inches from the start of the rainfall event to the time of the simulated peak flow, and a maximum areal average rainfall intensity of 1.70 inches/hour. The model did not simulate any flow using the Fish Creek calibration parameters of 0.50 for the saturated hydrologic conductivity multiplier and 2.00 for the channel length multiplier. In order for the model to produce a peak flow that matched the USGS observed flow of 1240 cfs (6.31 feet), a saturated hydrologic conductivity multiplier of 0.10 and a channel length multiplier of 1.20 were used. This resulted in a simulated peak flow of 1227 cfs (6.28 feet) and a peak flow time at 1:29 PM compared to the observed peak flow time of 1:30 PM. An initial soil moisture condition of dry was used based on the antecedent rainfall from the August 20th event.

C. September 10, 2004

The September 10th event had rainfall that covered greater than 90% of the basin with the heaviest rainfall being along the North Fork of Borrego Palm Canyon (Figure 15). Running this event through the model for calibration was complicated by the fact that an hour and 15-minutes worth of radar DHR data was not archived. The missing DHR data began at 3:55 PM which is the estimated time that the USGS stream gage stopped reporting data before it was destroyed. The available DHR data created an areal average rainfall of 1.21 inches and a maximum areal average rainfall intensity of 2.95 inches/hour. The model simulated a flow of 117 cfs (3.22 feet) at 6:05 PM using the Fish Creek calibration parameters of 1.00 for the saturated hydrologic conductivity multiplier and 1.00 for the channel length multiplier. The model was able to simulate a more significant flow using a saturated hydrologic conductivity multiplier of 0.25 and a channel length multiplier of 1.00. These parameters simulated a flow of 2262 cfs (8.07 feet).

Due to the dual complexity with this event being classified by the USGS as a debris flow event and the lack of a complete set of DHR data, this event was not be included in the calibration. The authors however point out that the areal average rainfall intensity over the basin was so intense that a debris flow of a magnitude significant enough to destroy the USGS stream gage was not a surprise even after 2-years of post-fire recovery. The rainfall exceeded the USGS developed California Flash Flood and Debris Flow Rainfall Thresholds where a year-2 threshold is 0.90 inches within 1-hour.

D. July 21, 2013

The July 21st event has an areal average rainfall of 0.58 inches from the start of the rainfall event to the time of the simulated peak flow, and a maximum areal average rainfall intensity of 0.62 inches/hour. The model simulated a flow of 823 cfs (5.36 feet) using the Fish Creek calibration parameters of 0.50 for the saturated hydrologic conductivity multiplier and 2.00 for the channel length multiplier. An initial soil moisture condition of super dry was used based on the lack of antecedent rainfall in the weeks prior to the event. The simulated flow is a high end Action Stage event falling below Minor Flood Stage of 6.00 feet (Figure 16). While no flooding was reported in Borrego Palm Canyon proper, an in-bank rise of the magnitude simulated is entirely possible given the rainfall total, intensity, and nearby flooding reported along Palm Canyon Drive. It is possible that in-bank rises that fail to exceed flood stage, do not cause significant trail damage, or flood downstream homes at the country club fail to make it into media and other reports.

E. August 25, 2013

The August 25th event had rainfall coverage over the lower one-third the basin (Figure 17), an areal average rainfall of 0.72 inches from the start of the rainfall event to the time of the simulated peak flow, and a maximum areal average rainfall intensity of 0.70 inches/hour. There was significant rainfall downstream of the model outlet point and upstream of the De Anza Country Club. This additional downstream rainfall likely contributed to the magnitude of flooding reported at the country club. The model simulated a flow of 2270 cfs (8.12 feet) at 5:15 PM using the Fish Creek calibration parameters of 0.50 for the saturated hydrologic conductivity multiplier and 2.00 for the channel length multiplier. The simulated flow exceeded Moderate Flood Stage, but failed to exceed Major Flood Stage (Figure 18). In order for the model to produce a peak flow that matched the 25-year event of 2920 cfs (10.12 feet), a saturated hydrologic conductivity multiplier of 0.25 and a channel length multiplier of 2.00 were used (Figure 19). This resulted in a simulated peak flow of 2860 cfs (10.06 feet) and no change in peak flow time. Considering the rainfall downstream of the model's outlet point and upstream of the De Anza Country Club, uncertainties in setting flood stages and estimating the magnitude of the event's peak flow without a stream gage record or indirect discharge estimate, the peak flow simulated using the Fish Creek calibration parameters (i.e. an upper end moderate flood event) seems reasonable. An initial soil moisture condition of super dry was used based on the lack of antecedent rainfall in the weeks prior to the event.

F. August 26, 2013

The August 26th event has an areal average rainfall of 0.42 inches from the start of the rainfall event at 4:00 AM to the end at 8:00 AM, and a maximum areal average rainfall intensity of 0.50 inches/hour. The model did not simulate any flow using the Fish Creek calibration parameters of 0.50 for the saturated hydrologic conductivity multiplier and 2.00 for the channel length multiplier. An initial soil moisture condition of wet was used based on the antecedent rainfall from the day before. An initial soil moisture condition of very wet was tried and the model did not simulate any flow under those conditions either. This was viewed as a successful null event.

Modeling Post Wildfire Events

Modeling post wildfire events are complicated for several reasons. Post fire debris can block and bulk up channel flows and impact peak flow magnitudes. The BARC image used in this study is assumed to approximate a burn severity map produced by a BAER team. The watershed response changes temporarily and spatially as recovery takes place. The 2003 events were 1-year post fire. It is difficult to estimate the amount of recovery that would have taken place within this timeframe.

The larger of the two events modeled from August 20, 2003, had a maximum basin average rainfall intensity of 3.60 inches per hour. This is the highest maximum basin average rainfall intensity value of not only all of the events in the study, but during the 10-year timeframe from 2003 to 2013. Furthermore, the saturated hydrologic conductivity multiplier had to be increased from 1.00 used in the Fish Creek calibration to 1.15. This represents a 15% increase in infiltration on overland flow planes needed to match the USGS peak flow of 2990 cfs. This may seem counterintuitive for a post wildfire extreme flow event when one might expect to have to reduce the infiltration to approximate post wildfire conditions dominated by hydrophobic soils.

The authors view this event's peak flow magnitude as a result of the extreme nature of the rainfall event. The contribution from the wildfire was muted by the excessive rainfall rates over the watershed. Even without a wildfire, this event likely would have exceeded Moderate Flood Stage. In addition, the authors postulate a number of potential reasons for an increase in hydrologic conductivity with increasing rainfall intensity. High levels of hydrophobicity are not likely to persist for an entire year after the fire. This depends on the nature of vegetation regrowth after the fire. If the ground received released nutrients from the fire, there could have been relatively rapid growth of ground cover grasses, small trees, and shrubs. Ground vegetation cover can have a significant effect on hydraulic conductivity. Another phenomena observed in rainfall simulator plot studies is that larger events typically result in a larger back calculated effective hydrologic conductivity (Stone et al., 2008). This occurs when a greater area is inundated resulting in larger wetted areas that are subjected to ponded infiltration. In this environment dominated by ephemeral channels, this large flow will inundate more channel cross-sectional area, also resulting in higher infiltration losses.

The smaller of the two events modeled from August 27, 2003, had a maximum basin average rainfall intensity of 1.70 inches per hour and an areal average rainfall of 0.89 inches from the start of the rainfall event to the time of the simulated peak flow. This equates to 47% of the August 20, 2003 maximum basin average rainfall intensity and 36% of its areal average rainfall. The peak flow recorded by the USGS was 1240 cfs or 41% of the August 20th event's peak flow. For this event, the Fish Creek calibration did not create any flow. A dramatic reduction in the saturated hydrologic conductivity multiplier was needed in order to simulate the observed peak flow. The Fish Creek calibration had a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00 while values of 0.10 and 1.20 respectively were needed to match the USGS peak flow. Due to the much lower rainfall intensities and basin average rainfall, the influence of the burn area likely contributed more to the peak flow.

Hence, considerably lower saturated hydrologic conductivity was needed to simulate a peak flow that was heavily influenced by the burn area.

While limited to two events, there does seem to be a relationship between maximum basin average rainfall intensity, areal average rainfall, runoff contribution from burn area, and resultant peak flow magnitude. The greater the maximum basin average rainfall intensity and areal average rainfall, the smaller the overall contribution from the burn area in terms of peak flow. Conversely, the smaller the maximum basin average rainfall intensity and areal average rainfall, the greater the contribution from the burn area to peak flow (Sidman et al., in-review). From an operational forecasting standpoint, there may be a need to vary model parameter multipliers as a function of maximum basin average rainfall intensity. Events with higher maximum basin average rainfall intensity may require a greater saturated hydrologic conductivity multiplier due to a smaller relative contribution from the burn area. Model parameter multipliers could be varied automatically by KINEROS2 and would not require forecaster intervention.

<u>Lead Time Provided by KINEROS2</u>

KINEROS2 provided noticeable simulated lead time for action, minor flood, moderate flood, and major flood stage (Figure 20). The average lead time provided for minor flood stage, based on the three events, was 38 minutes. This was less than the national flash flood lead time goal of 58 minutes. The lead times for moderate and major flooding were 28 and 20 minutes respectively based on a smaller sampling of events. Action stage, having the lowest flow threshold, had an average lead time of 46 minutes and was more in line with national lead time goal. Lead times are limited by both the time of concentration of the basin and the fact the model is forced by radar data only and no forecast precipitation. The lead times provided by the model were still of added value when compared to tools currently available at the Weather Forecast Office (WFO) for flash flood forecasting such as the Flash Flood Monitoring and Prediction Program (FFMP).

All lead times were using the Fish Creek calibration parameters. Lead times were calculated with respect to the simulated peak flow times when they differed from USGS peak flow data.

<u>Evaluation of a Regional Calibration</u>

A consideration in applying a distributed model to multiple flash flood prone basins in an office's County Warning Area is the time needed to set up and calibrate each location. For example, if there were 10 high-impact basins that could benefit from running a distributed model to aid the flash flood program and DSS, this would be a significant effort likely over a multiple year period. The effort could be reduced and basins prepared more quickly if a regional calibration was available. A regional calibration is based on the notion that somewhat identical basins respond in a similar manner. Basin similarity might include basin size, topography, dominant vegetation type, land use, soils type, and annual rainfall. This study tested if the calibration created for Fish Creek could be applied to similar flash flood prone catchments nearby in the greater Anza Borrego State Park area. While Borrego Palm Canyon is not identical it is about half the size, has steeper terrain, channels with considerably greater Manning's roughness coefficients, and contains several palm oasis's, it was a close enough analog for the purpose of this study. If the Fish Creek calibration parameters work reasonably well for Borrego Palm Canyon, then an assumption could be made that other basins in the region could be run with the same parameters.

For evaluating the regional calibration, the August 27, 2003 event was excluded due to significant contribution from the burn area. The events of August 20, 2003, July 21, 2013, August 25, 2013, and the null event of August 26, 2013 were used. The regional calibration produced 129% of the USGS peak flow for the August 20, 2003 event. For the August 25, 2013 event, the regional calibration produced 78% of the estimated peak flow. The August 20, 2003 event fell within the correct category of major flood. The August 25, 2013 event fell within the neighboring category of moderate flooding as opposed to major flooding, but was simulated a high-end moderate flood. As previously stated, the July 21, 2013 event simulated a peak flow in the Action Stage category using the regional calibration. Considering the rainfall for this event and the minor flood damage in Borrego Springs, this seemed like a reasonable simulated peak flow. Finally, the null event of August 26, 2013 did not produce any flow using the regional calibration. The regional calibration was able to correctly simulate the correct category of flooding or in the case of the August 25, 2013 event fell close to the correct category.

Discussion and Conclusions

The ability to provide categorical guidance in terms of the magnitude of a flash flood and its timing is an important step forward beyond currently available tools at the WFO including FFMP and River Forecast Center flash flood guidance. The application of a local model in the form of a real-time distributed model forced by radar data is a potential solution. The guidance provided by the model, in particular for ungaged locations with frequent recreational use, is essential in the provision of hydrologic DSS. Advances with applications of distributed modeling for small basins throughout the semi-arid west would provide the guidance needed for WFOs to add greater impact-based detail to flash flood warnings and increase warning precision for flash flood prone locations.

This study shows that it is possible to create calibration parameters that can be applied to a hydrologic region. The calibration parameters created for Fish Creek, a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00 for events with a maximum basin average rainfall intensity less than 1.80 inches/hour and a saturated hydrologic conductivity multiplier of 1.00 and a channel length multiplier of 1.00 for events with a maximum basin average rainfall intensity equal or greater than 1.80 inches/hour, were successfully applied to Borrego Palm Canyon.

While the authors see the value of a regional calibration and as an avenue to field the model to a larger number of basins, this does not negate the importance of model calibration. If resources allow, flow events of various magnitudes should still be used in setting up new basins. In this situation, the regional calibration can be used as a first guess or starting point for the calibration simulations.

The results of the study are constrained by several factors. This includes limited stream gage record, a few events being influenced by post burn hydrologic conditions, and fewer warm season convective events and hence streamflow events for validation of the regional calibration.

Future work could include developing KINEROS2 at additional flash flood prone locations in the greater Anza Borrego Desert State Park region which the regional calibration would have greatest application. This includes several canyons situated between Fish Creek to the south and Borrego Palm Canyon on the north end which represents the most likely area for application of the regional calibration. Basins of potential application of KINEROS2 include, but are not limited to Hellhole Canyon and Vallecito Wash.

Acknowledgements

The authors would like to thank William Reed, retired NWS hydrologist, for providing his insights into the development of a conceptual model for the rating curve and flood stages for Borrego Palm Canyon. The authors recognize Shea Burns, USDA-ARS, for setting up the model using AGWA and San Diego County Flood Control for providing rainfall data for their Borrego Palm Canyon rain gage.

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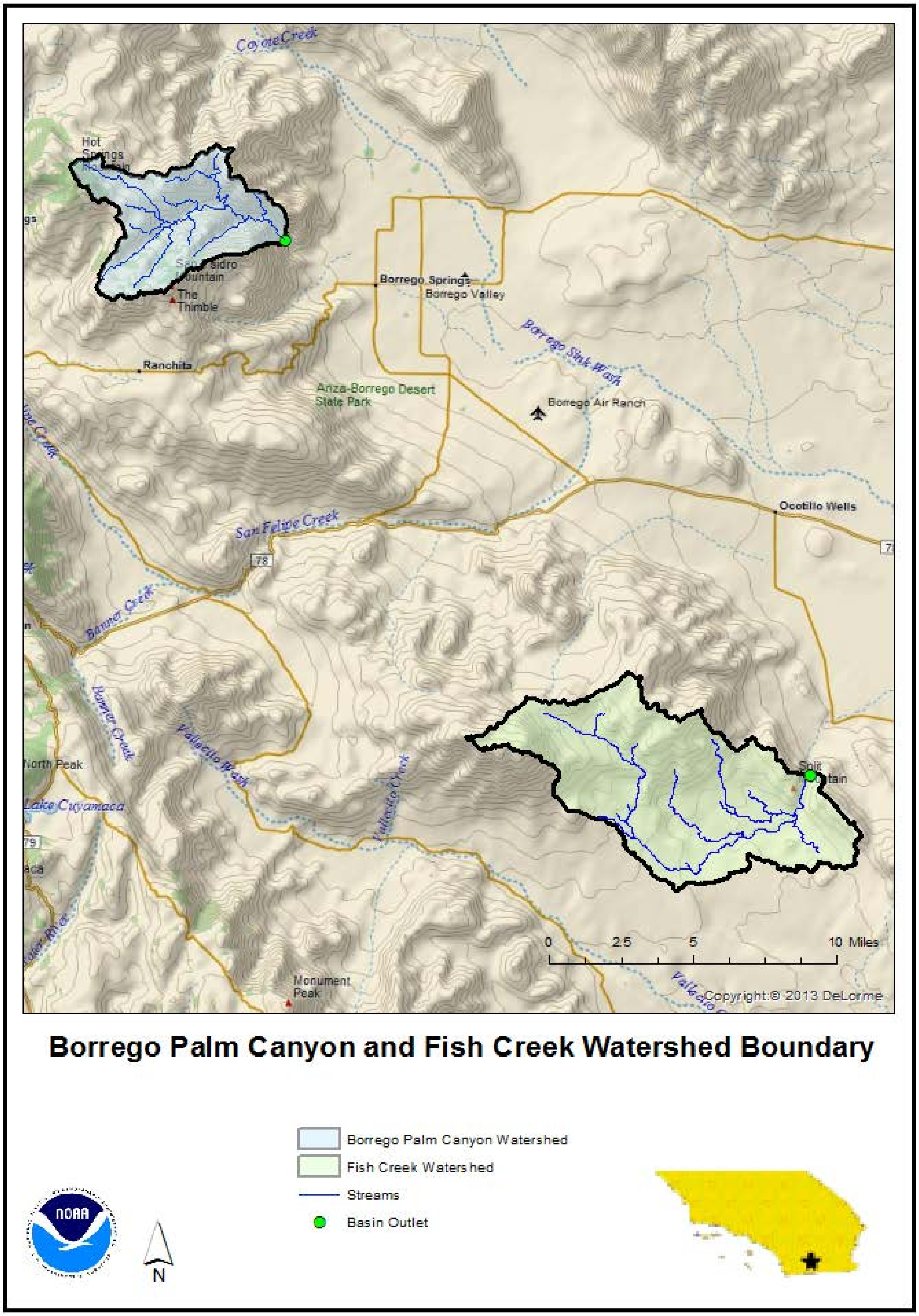

Figure 1. Location map showing Borrego Palm Canyon (in blue) and Fish Creek (in light green; bottom shaded area) watersheds.

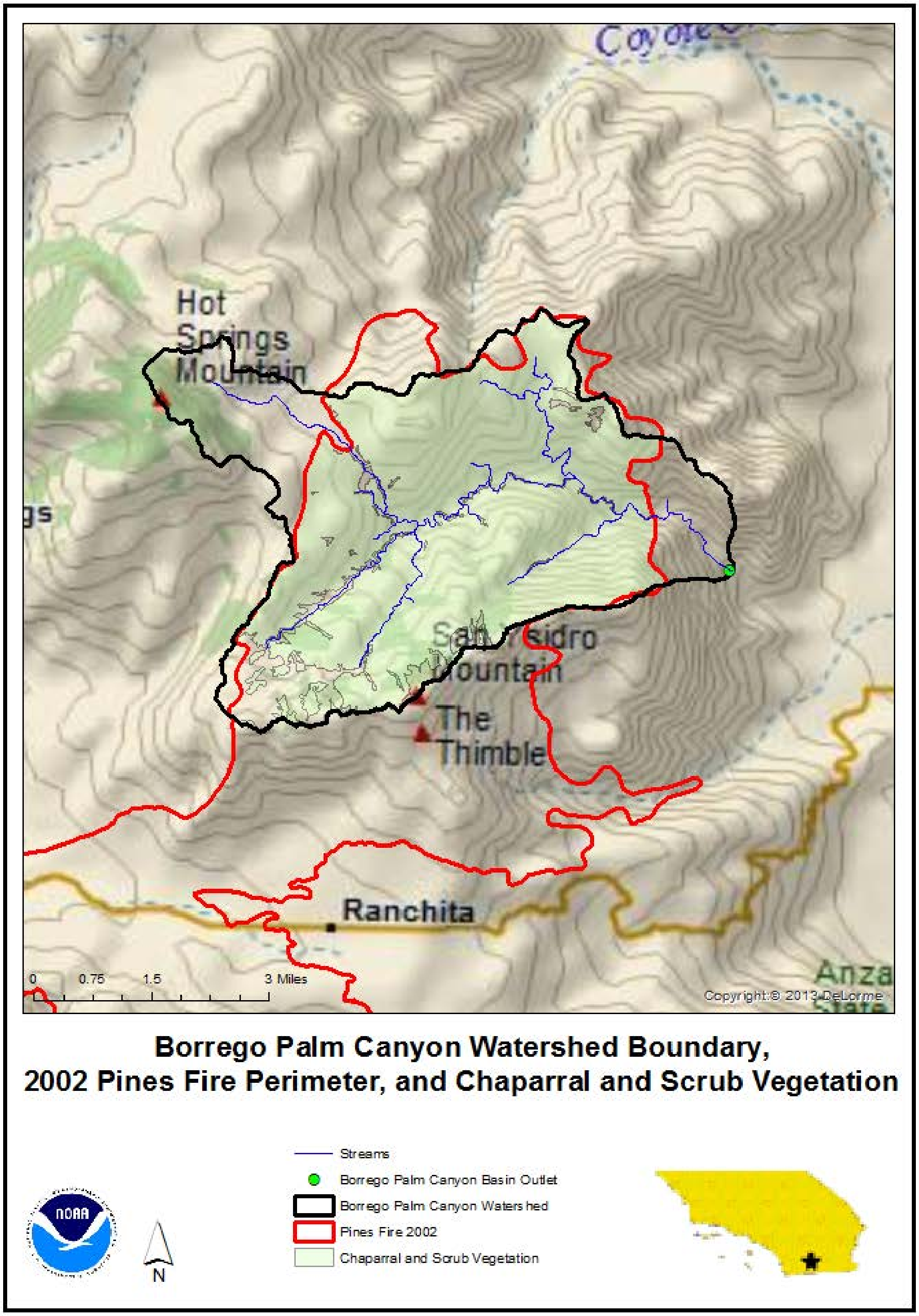

Figure 2. Watershed boundary overlaid with fire perimeter and vegetation types.

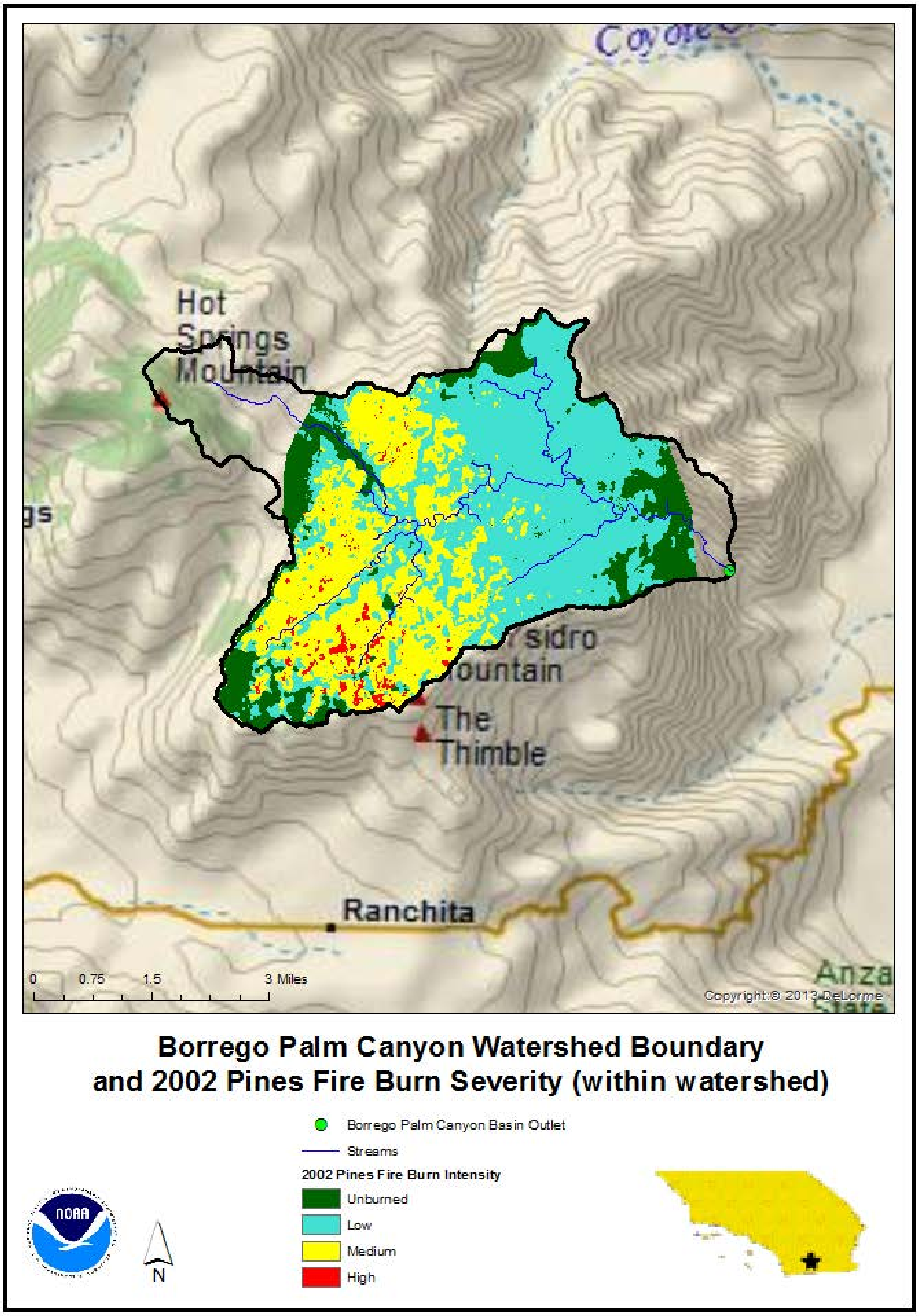

Figure 3. Burn severity map derived from BARC image.

Stage (feet)	Discharge (cfs)	USGS Peak Flow Record used in Rating Curve Development	USGS Peak Flow Streamflow Statistics	Critical Stages
0.00	0			
1.00	1			
2.00	2			
2.41	3	APR-05-1999		
2.67	10	FEB-01-1996		
2.79	14	FEB-27-2001		
2.87	21	SEP-07-1975		
2.95	75		PK2 (2-year peak flow)	
3.00	96			
3.67	154	FEB-14-1998		
4.00	355			Action Stage
4.50	522		PK5 (5-year peak flow)	
4.78	591	MAR-05-1995		
5.00	676			
5.50	882			Minor Flood
6.00	1100			
6.50	1330		PK10 (10-year peak flow)	Moderate Flood
7.00	1650			
7.50	2160	AUG-15-1977		
8.00	2250			
8.50	2330			
9.00	2400			Major Flood
9.80	2640	AUG-16-1979		
10.00	2800			
10.12	2920		PK25 (25-year peak flow)	
10.17	2990	AUG-20-2003		
11.00	3500			
11.50	4000			
12.00	4300			
12.30	4580		PK50 (50-year peak flow)	
12.50	4700			
13.00	5100			

Figure 4. Rating Curve, peak flows used to develop it, USGS peak streamflow statistics, and critical stages. Not shown is the 100-year flow of 6990 cfs and the 500-year peak flow of 14000 cfs which is outside of rating.

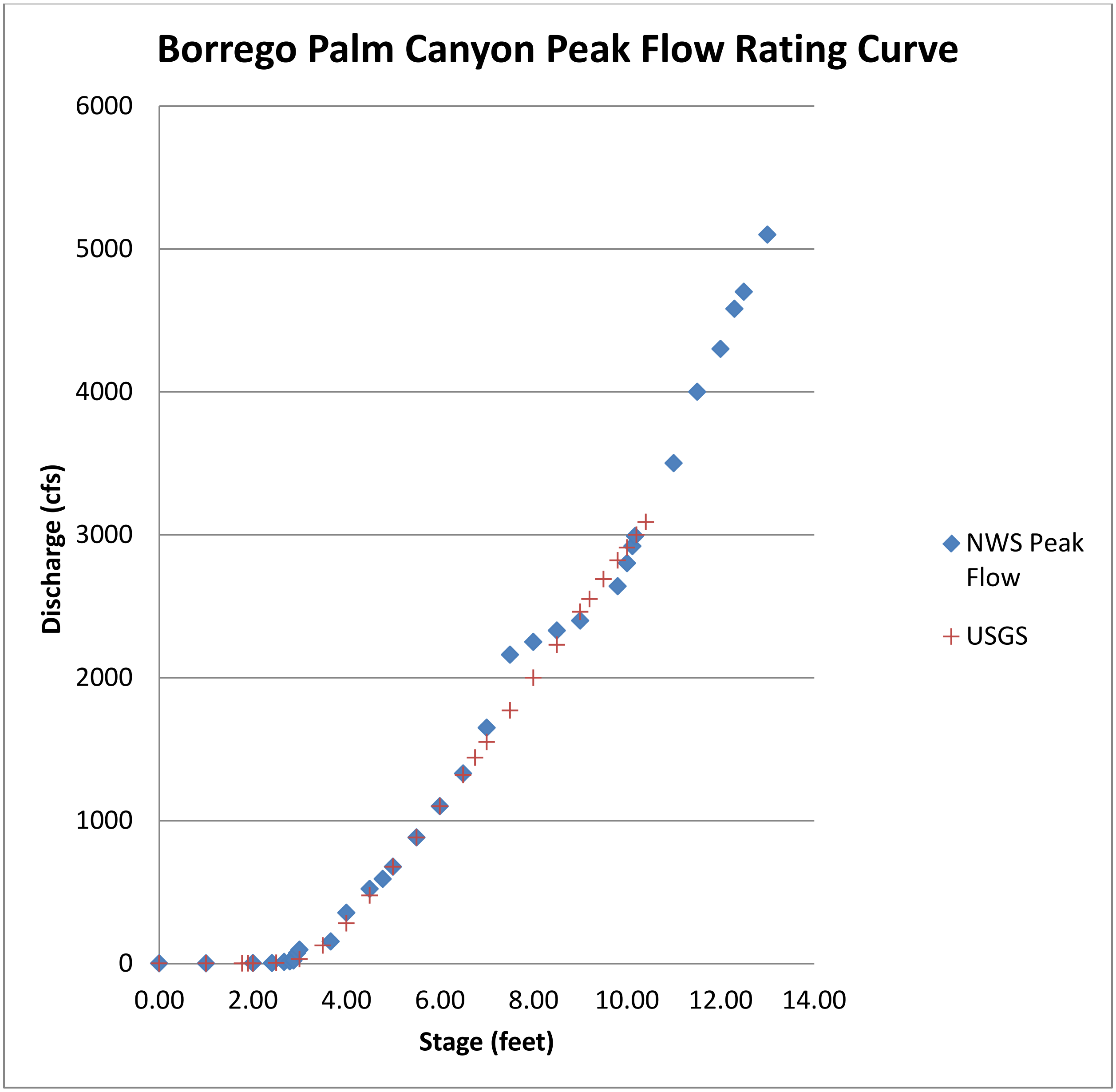

Figure 5. NWS developed peak flow rating curve compared with USGS rating curve.

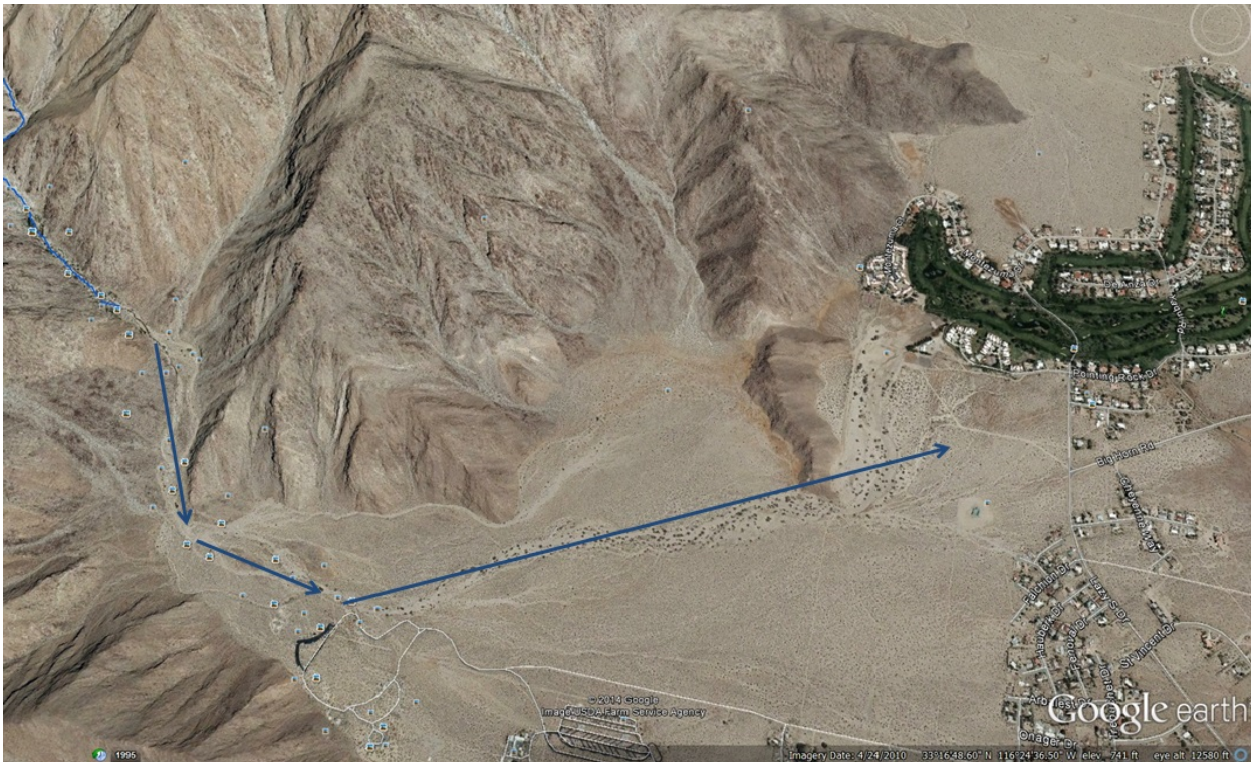

Figure 6. Google Earth image. The outlet point for the model is shown by the downstream terminus of the light blue line located in the northwest portion of the image. The dark blue arrows show the direction of flow of the majority of runoff as it flows downstream from the model outlet point, out of the mouth of the canyon, onto the alluvial fan, and ultimately impacts portions of the De Anza Country Club.

Figure 7. Image of section of Borrego Palm Canyon Trail with channel nearby. Image source: http://mudlips.files.wordpress.com/2013/02/anza-borrego-2013-035.jpg

Figure 8. Google Earth Image. The outlet point for the model is shown by the downstream terminus of the light blue line located in the upper left portion of the image. The red circle identifies the location of San Diego County Flood Control rain gage.

Figure 9. Google Earth image. The outlet point for the model is shown by the downstream terminus of the light blue line located in the top left portion of the image. The black star identifies the location of Palm Canyon Drive.

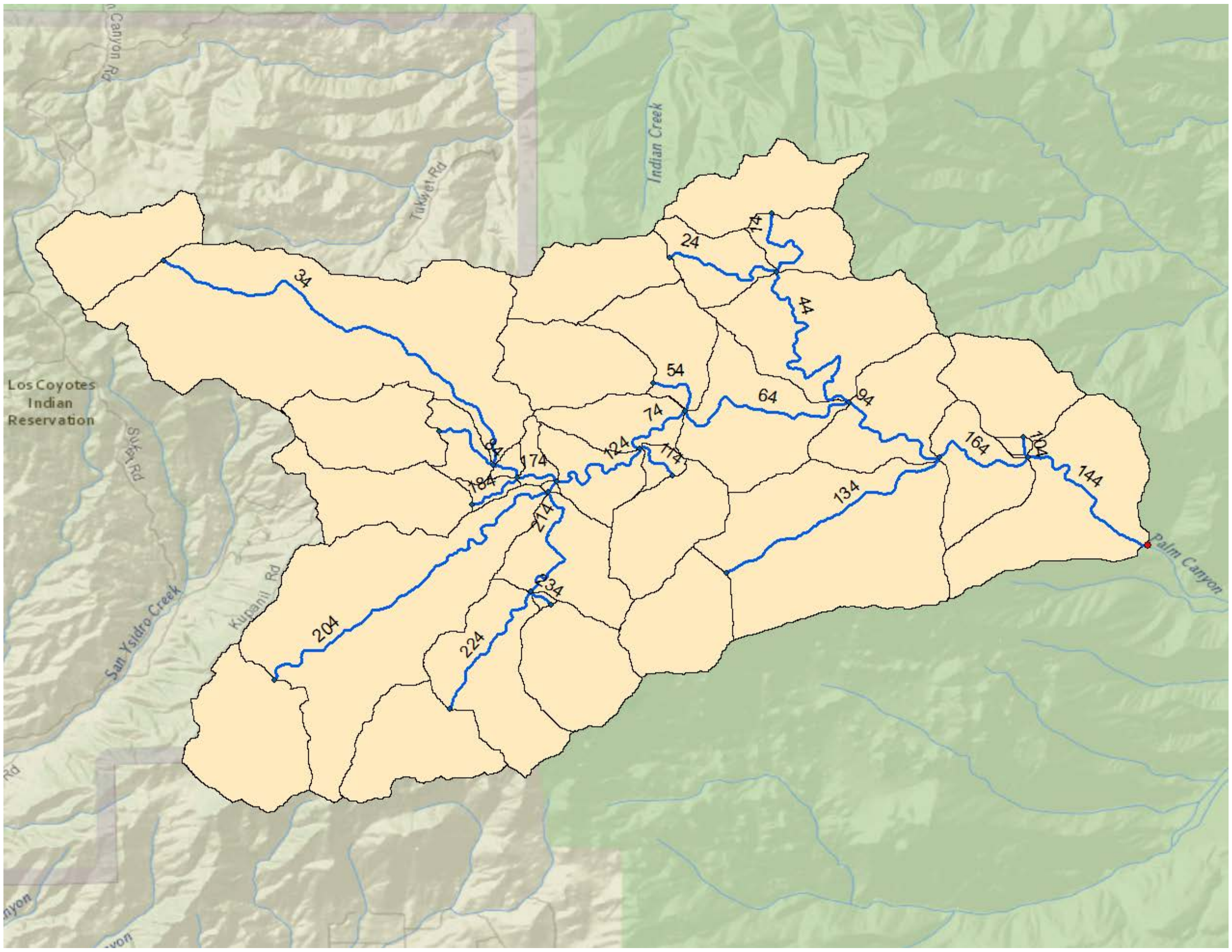

Figure 10. Plan view of KINEROS2 model elements. Open channel elements are labeled and represented by blue line segments. Model outlet point represented by red circle at east end of watershed.

Figure 11. Panorama of five pictures taken on January 31, 2010 from just above the first palm grove looking downstream toward the mouth of Borrego Palm Canyon. Image source:
http://tchester.org/sd/plants/guides/anza_borrego/pix/pano_5_down_to_first_grove.jpg
Used with permission to freely reproduce giving credit to the following overarching source page:
http://tchester.org/sd/plants/guides/anza_borrego/borrego_palm_canyon.html

Open Channel Element ID	Downstream Width (m)	Upstream Width (m)	Manning's Roughness	Channel Name
144	48	40	0.044	Mainstem Borrego Palm Canyon
104	35	23	0.045	Unnamed Tributary to Mainstem Borrego Palm Canyon
164	40	44	0.043	Mainstem Borrego Palm Canyon
134	45	30	0.045	South Fork
94	38	11	0.045	Mainstem Borrego Palm Canyon
44	20	18	0.039	North Fork
24	25	15	0.041	North Fork
14	16	16	0.040	North Fork
64	20	25	0.044	Middle Fork
54	12	8	0.046	Unnamed Tributary to Middle Fork
74	23	23	0.044	Middle Fork
114	15	15	0.045	Unnamed Tributary to Middle Fork
124	24	18	0.043	Middle Fork
194	24	24	0.043	Middle Fork
214	22	18	0.043	Middle Fork
234	15	15	0.042	Unnamed Tributary to Middle Fork
224	19	18	0.045	Middle Fork
204	26	30	0.044	Middle Fork
174	24	23	0.042	Middle Fork
184	19	15	0.044	Unnamed Tributary to Middle Fork
154	33	34	0.044	Middle Fork
84	17	18	0.046	Unnamed Tributary to Middle Fork
34	35	75	0.038	Middle Fork

Figure 12. Widths and Manning's roughness assigned to each open channel element for Borrego Palm Canyon. Location of each open channel element can be viewed in Figure 10.

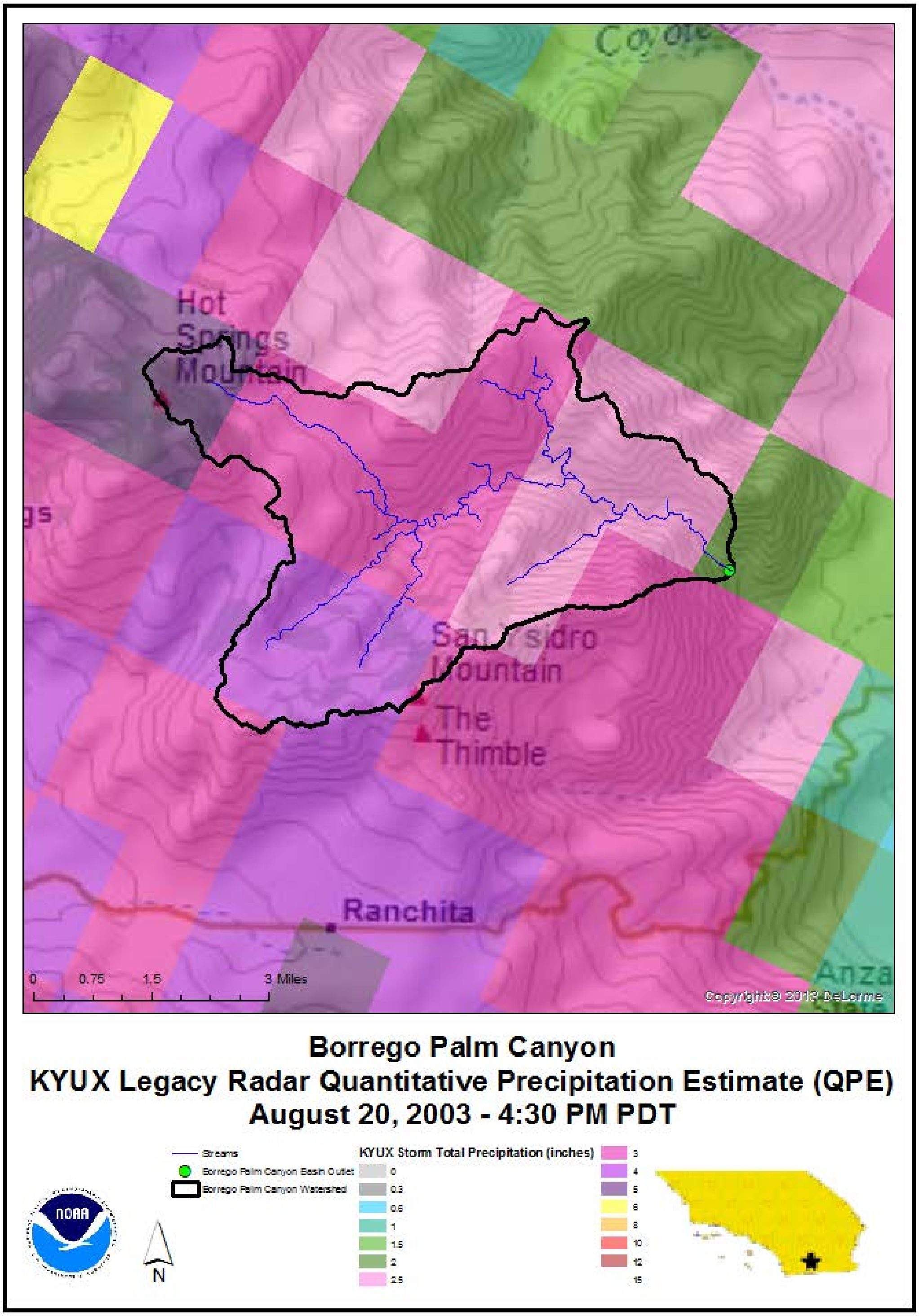

Figure 13. Radar storm total precipitation image for August 20, 2003.

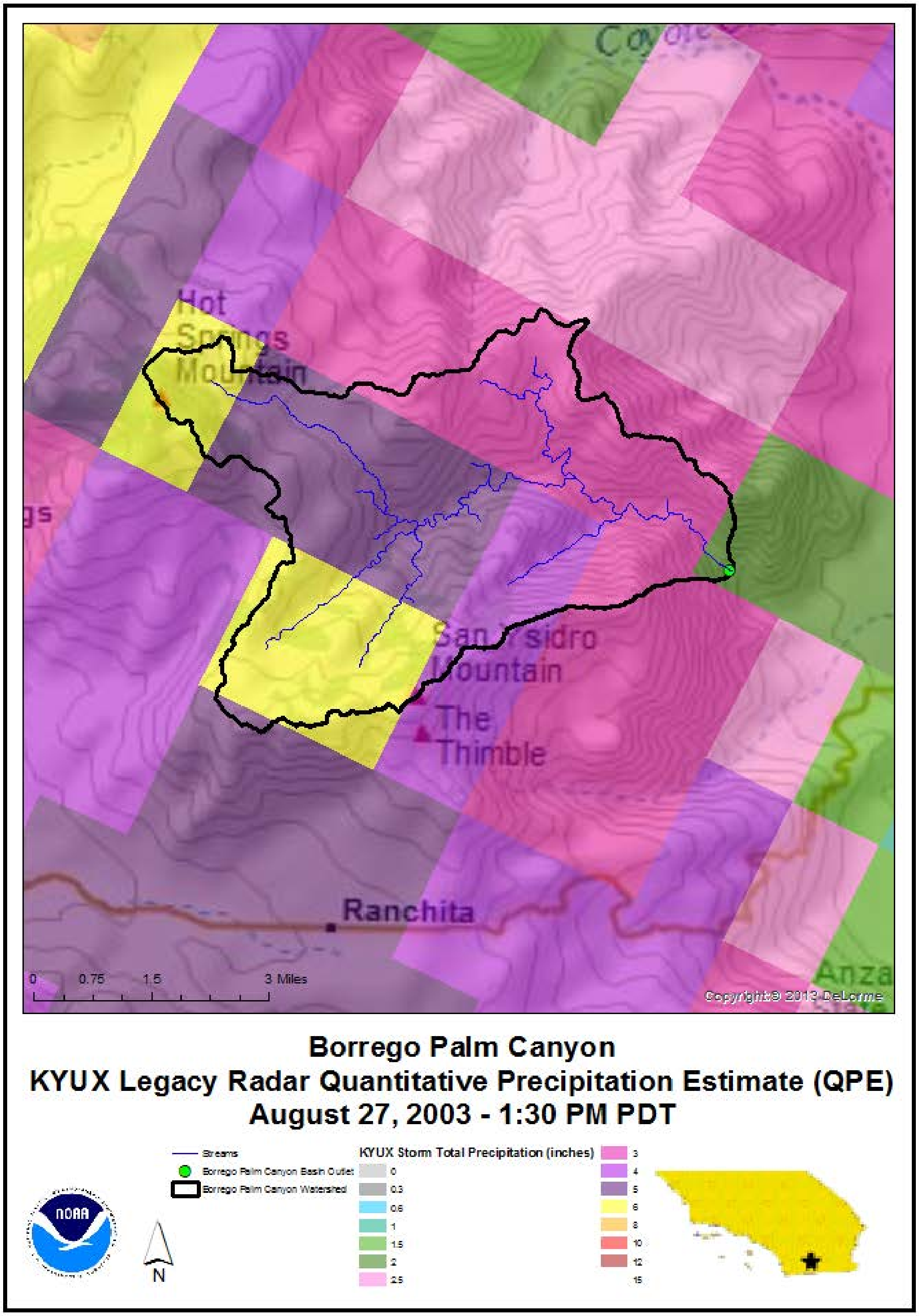

Figure 14. Radar storm total precipitation image for August 27, 2003.

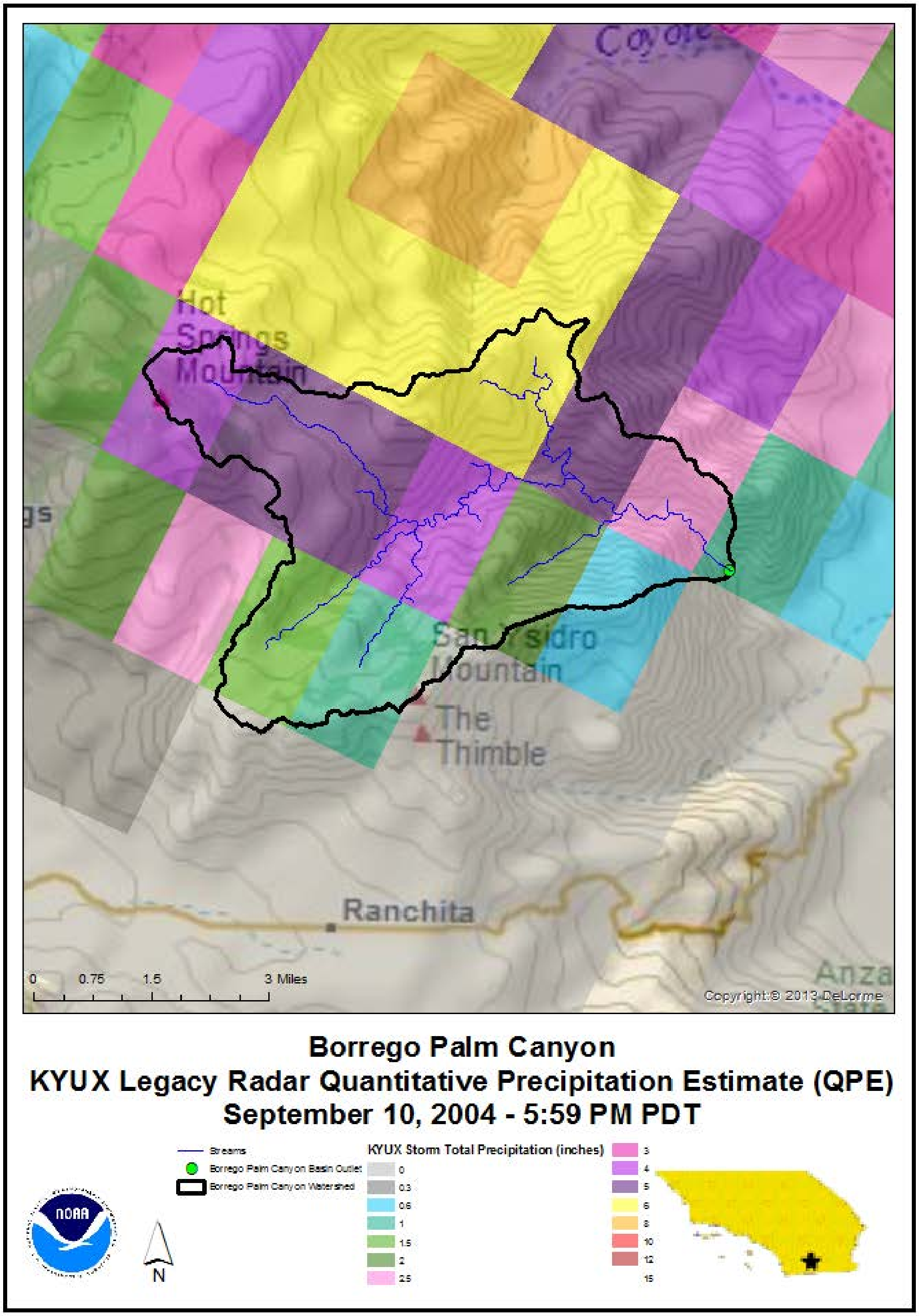

Figure 15. Radar storm total image for September 10, 2004.

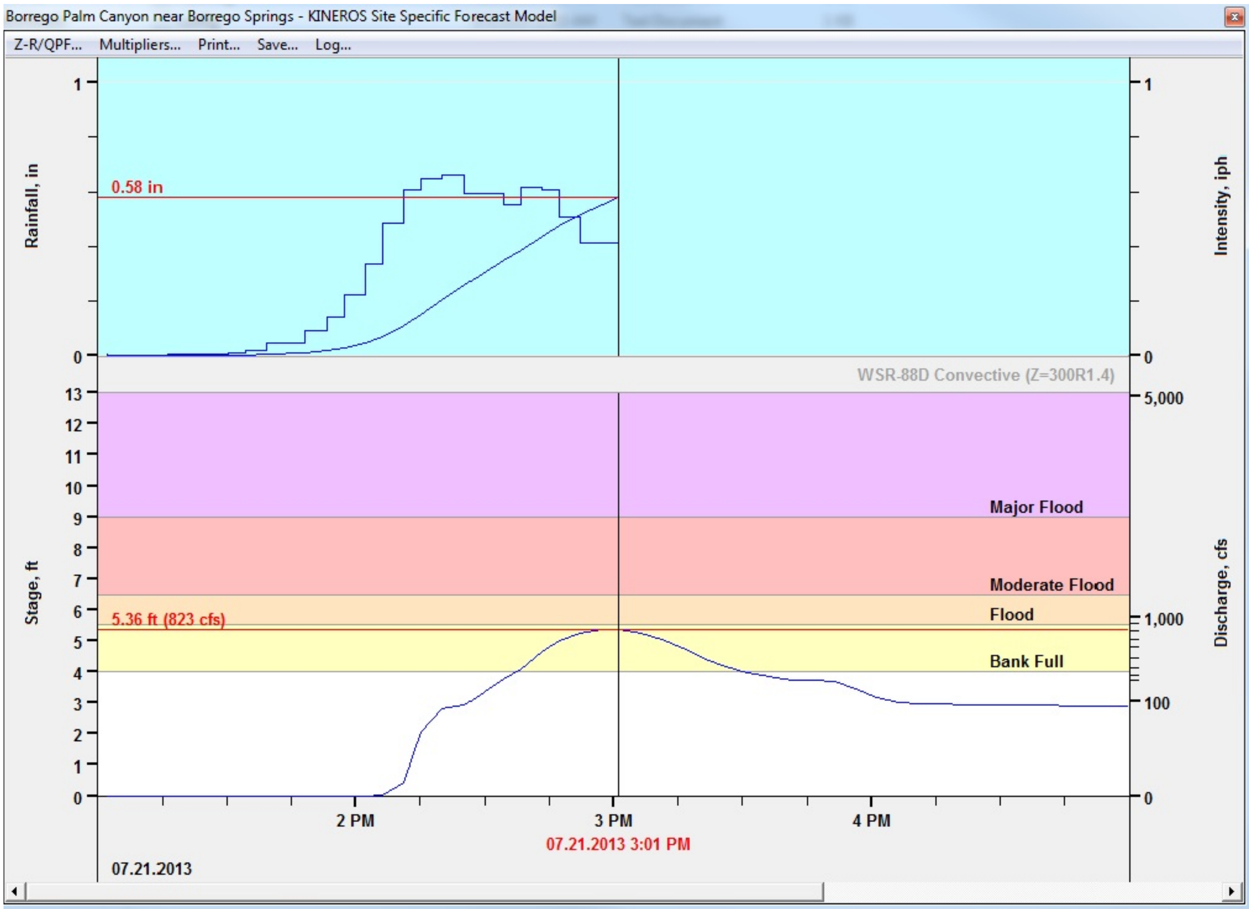

Figure 16. KINEROS2 hydrograph for the July 21, 2013 event using Fish Creek model calibration parameters.

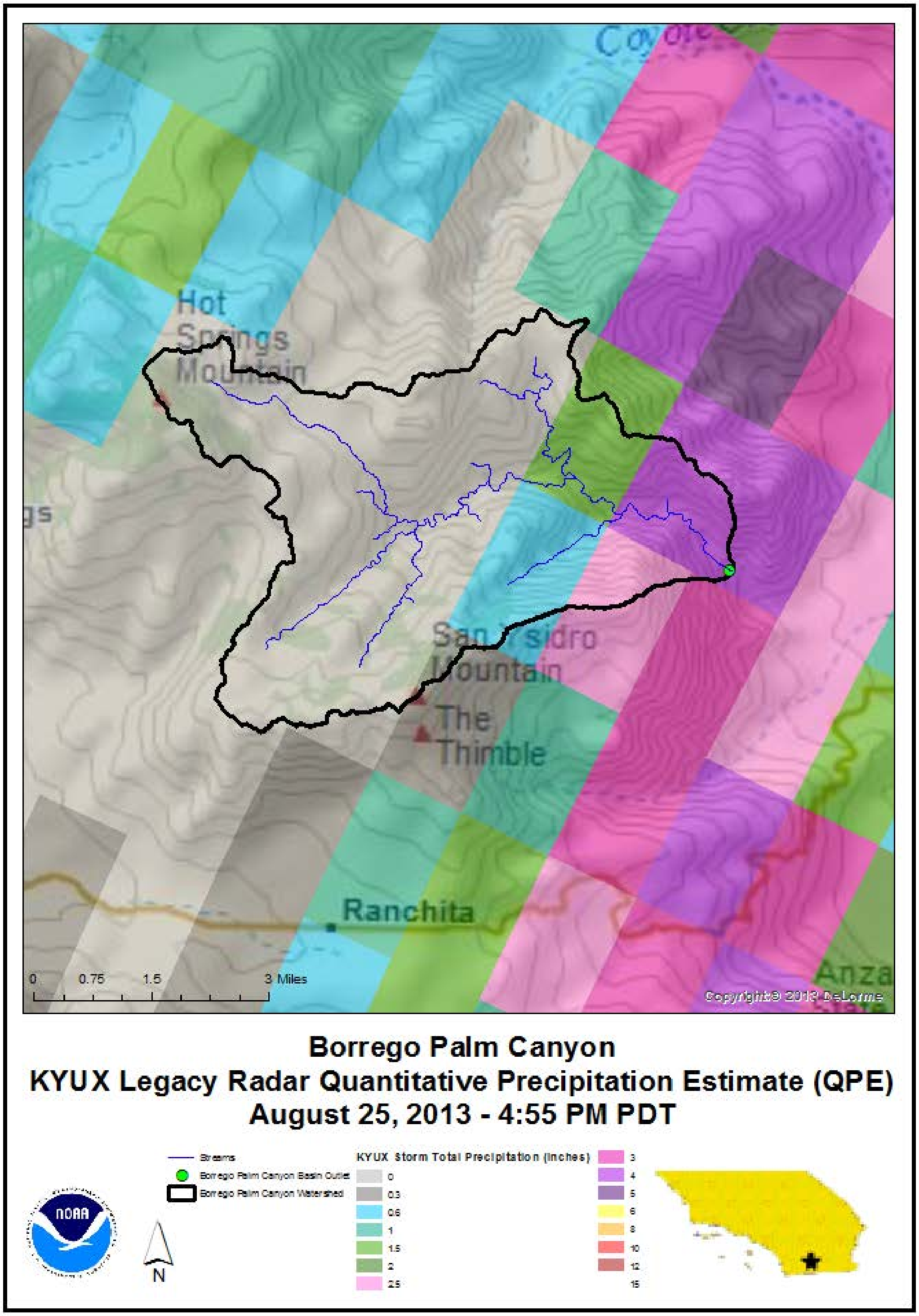

Figure 17. Radar storm total image for August 25, 2013.

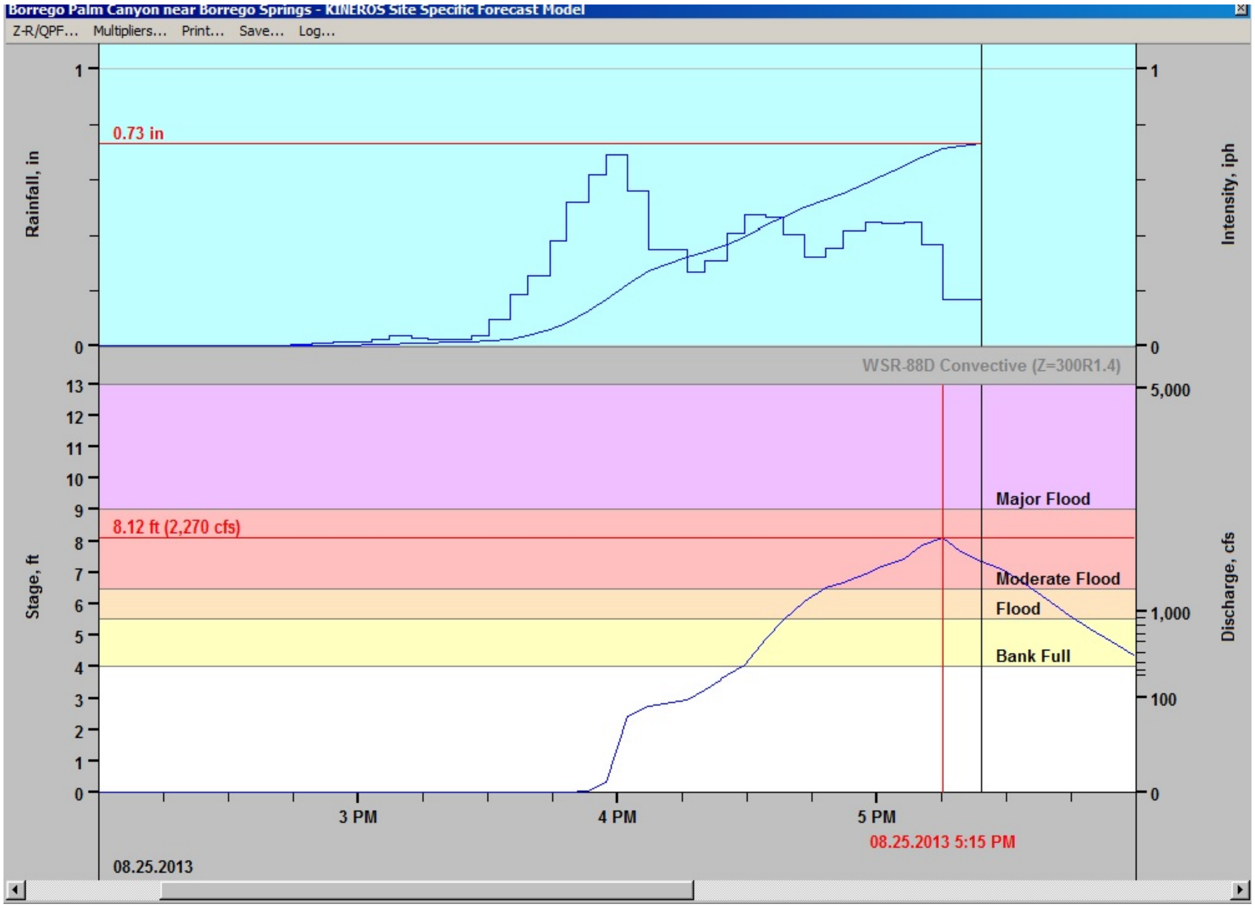

Figure 18. KINEROS2 hydrograph for the August 25, 2013 event using Fish Creek model calibration parameters.

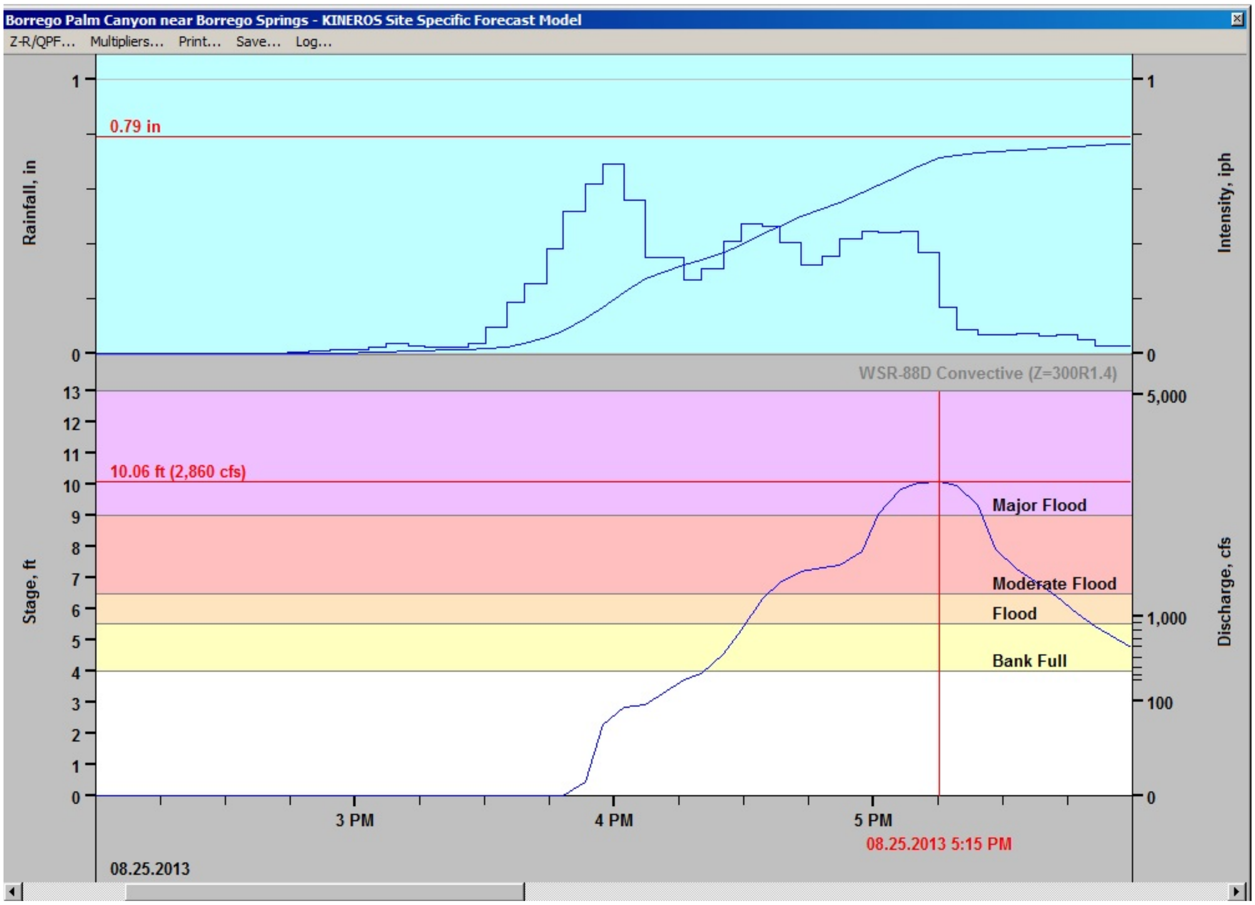

Figure 19. KINEROS2 hydrograph for the August 25, 2013 event using model calibration parameters required to match the 25-year peak flow.

Event	Lead Time to Action Stage (minutes)	Lead Time to Minor Flood Stage (minutes)	Lead Time to Moderate Flood Stage (minutes)	Lead Time to Major Flood Stage (minutes)
08-20-2003	Not simulated	25	Not simulated	20
08-27-2003	60	45		
07-21-2013	29			
08-25-2013	48	43	28	
Average Lead Time	46	38	28	20

Figure 20. Lead time for all events that exceeded Action Stage.