Modeling Flash Flood Events in an Ungaged Semi-Arid Basin using a Real-Time Distributed Model: Fish Creek near Anza Borrego, California

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ABSTRACT

Fast-responding headwater basins and canyons that quickly respond to heavy rainfall runoff pose a significant threat to life and property throughout the semi-arid western United States. This paper presents the results from application of the real-time distributed KINematic runoff and EROsion model (KINEROS2) to the complex terrain of the Fish Creek basin located at the southern end of the Vallecito Mountains and the Carrizo Badlands in the Anza Borrego State Park near Borrego Springs, California. In operations, KINEROS2 uses real-time radar data to produce a forecast hydrograph, but due to inherent uncertainties with forecasting for ungaged locations, the forecast will be categorical in nature (no flooding, minor flooding, moderate flooding, major flooding, or record flooding). The model was calibrated using a series of rainfall events representing a full range of flow outcomes from below flood stage up to record flood.

Calibration was successful in reproducing categories of flows regardless of magnitude. A simple calibration scheme was employed, using one set of parameters for low flows through low-end major flooding and another set for higher end major floods through record flooding. The timing and magnitude of the peak flow is useful information currently not available using NOAA/NWS flash flood forecasting methodologies at the Weather Forecast Office.

Introduction

On July 30, 2012, a flash flood struck Fish Creek located in the Anza Borrego State Park. Fish Creek basin is frequently visited for hiking, camping, and recreational vehicle traffic on an unmaintained state dirt road. Persons are routinely hiking or driving (and sometimes camping) on the normally dry wash (Figure 1).

Two popular destinations are Wind Caves and Sandstone Canyon. The Wind Caves are wind-sculpted rock formations on the side of a mountain above the wash and visitors park their vehicles in the wash then hike to the caves. Near the headwaters is a location called Sandstone Canyon which are narrow rock slots (Figure 2).

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 may have never visited the basin and may not have the tools or conceptual model to translate accumulated rainfall totals into a level of flood. 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.

In order to integrate the rainfall and basin response to produce a useful prediction of flow, a tool is needed to assist the forecaster. A distributed model tool that runs using real-time radar data at every volume scan to compute a forecast hydrograph is one such solution. If calibrated, it can accurately translate the rainfall into guidance for the forecaster on the magnitude and timing of the peak flow. The forecast 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). Forecasting and calibration of a distributed model for one basin can be applied to similar basins in efforts to effectively provide warning with greater specificity and longer lead time.

Background on the July 30, 2012 Flood

The KYUX radar depicted widespread and intense rainfall over the basin. Eyewitness reports and debris fields indicated water up to 15 feet high near the trailhead for Wind Caves and the confluence of the north and south forks of Fish Creek. These reports were later verified by high water marks along the North Fork of Fish Creek (Figure 3). Park rangers characterized this as a very significant event that had not been seen in years. In addition, Sergeant Jon Shellhammer, a pilot for San Diego County Sheriff's Aerial Support Detail, said that during his 24-years of flying in the area he has never seen anything like it. The remains of a small truck were found totaled about 1.5 miles downstream of the confluence of the main forks of Fish Creek. Attenuation of the peak flow height as it progressed downstream seems to have been minimal. Bier reported that the height of the flood was at least a 10 foot high swell beyond the mouth of Fish Creek canyon near Split Mountain Road. At this location the channel spreads out extensively and becomes distributary.

The flash flood occurred on a Monday but if it had taken place on a weekend, the number of persons in the basin could have been considerably higher. Images taken at the parking area for Wind Caves show that about a dozen vehicles can be parked at this location at any given time (http://www.panoramio.com/photo/46761615).

In this study, the peak discharge will be estimated for the July 30, 2012 event and will be used as part of a calibration dataset for a distributed model of the watershed in efforts to predict the timing and magnitude of peak flows in this basin. This information will also be utilized to develop a synthetic rating curve needed by the model.

Fish Creek Watershed Information

Fish Creek basin is 49.5 square miles above the outlet point selected for this study. This location is about 1-mile downstream of the North Fork confluence with the mainstem channel of Fish Creek Wash where the HUC12 boundary for Upper Fish Creek Wash (181002030601) is located. The watershed is composed of 38.1 square miles contributing to the mainstem channel portion and 11.4 square miles to the North Fork (Figure 4).

Discharge Estimation for July 30, 2012 Flood

The discharge estimates were made from debris marked on photographs, discussions with NWS personnel who had visited the location shortly after the flash flood, and from viewing aerial imagery. It was compared to a discharge estimate determined by a second hydrologist using the same information. Finally, the results were compared to output from USGS regional regression equations. The primary imagery used was taken a short distance downstream from the confluence of the North Fork and mainstem of Fish Creek (see Figures 5 and 6).

The channel cross section was divided into two sub-sections (a main channel section and an overbank section). Using aerial and ground-based photograph imagery, the main channel section was estimated to be 200 feet wide and the overbank section 70 feet wide. The main channel section was estimated to be 5 feet high on the overbank side and has steep rock cliffs on the other side. The peak flow was estimated to be 8 feet deep at the thalweg. The thalweg is the lowest elevation within a watercourse/channel. An idealized sketch of this cross section can be seen in Figure 7. The cross sectional area for the main channel was estimated at 1,280 square feet. This represents 80% of the cross sectional area of the main channel as a perfect rectangle and is meant to serve as a reasonable approximation of a trapezoidal channel. The cross sectional area for the overbank area was estimated at 100 square feet. Flow velocity, in the main channel, was estimated at 10ft/sec given the significant size of the event in terms of the depth of the flood, the rapid onset of the event, the lack of any significant in-channel vegetation remaining after the event, and evidence of some large rocks moved a considerable distance along the bottom of the channel bed. Overbank flow velocities, due to increased manning roughness and vegetation, were estimated slightly lower at 8 ft/sec. This equals 12,800 cfs for the main channel and 800 cfs for the overbank area or a total peak discharge of 13,600 cfs.

The results were compared to an independent estimate by hydrologist Bill Reed (NWS retired), determined using the same information. Reed estimated a single trapezoid channel with a depth of 8 feet at the thalweg, a total top width of 300 feet, a bottom width of 60 feet, a total cross sectional area of 1,440 square feet, and a velocity of 10 ft/sec applied to the entire cross section. Reed estimated the peak discharge at 14,400 cfs.

The results were further compared to the output from the USGS regional regression equations (South Great Basin Region 10) using StreamStats to calculate the flows of various recurrence intervals. Normally StreamStats could have been routinely run for a single point along the main channel of Fish Creek below the confluence of the North Fork to generate results for the entire watershed including both the mainstem and the North Fork of Fish Creek. However, an error exists in the GIS-generated streamflow network in StreamStats where the North Fork is not correctly connected with the main channel of Fish Creek, (Figure 8). Therefore, StreamStats was run individually for the main channel and for the North Fork of Fish Creek and the results were combined, based on the recommendation of the USGS, to achieve a result equivalent to having the correct stream network in StreamStats (Figure 9).

The estimated discharge of 13,600 cfs is approaching the 100-year peak flow value. Given the extreme nature of the event, it is reasonable to say that the peak discharge could have been as high as a 100-year peak flow. Therefore, the peak discharge for Fish Creek was estimated to be a minimum of 13,600 cfs, with Reed's estimate of 14,400 cfs being considered a median value, and a maximum value of 14,970 cfs equaling the 100-year peak flow.

Timing of the July 30, 2012 Flood

Sergeant Shellhammer noted a time of 5:40 PM when the call came in requesting assistance from the persons in the pickup truck that was washed downstream. Portions of the watershed further upstream, such as Sandstone Canyon Narrows, would have experienced flooding considerably earlier during the rainfall event. The location being modeled is slightly downstream of the location where the call is thought to have come in from, thus for the model calibration a time of 5:50 PM was used.

Development of Rating Curve

The graphical user interface (GUI) requires a rating curve to convert modeled discharge to stage. A rating curve was developed using the idealized channel geometry, the peak discharge estimate for the July 30, 2012 event, and assumptions about the average streamflow velocity across the entire cross sectional area at various depths (Figure 10). Since the July 30, 2012 event is not necessarily the upper limit, the rating curve was extended by one foot to a stage of 9 feet. The average streamflow velocity was increased by 15% from 8 to 9 feet and the cross sectional area by 270 square feet to compute the extension of the rating curve. The rating curve is depicted in Figure 11. The data is grouped into main channel and overbank flow regimes, and a power curve is fitted through each group, as a power curve fit the data better than other functions including a logarithmic curve.

The channel is composed of sand and subordinate gravel, therefore it will likely change significantly over time due to fill and scour. Furthermore, the rating curve is static and was based on idealized channel geometry and assumptions on flow velocity during the July 30, 2012 event. Therefore, the rating curve should not be used to determine the precise discharge that will take place at a given stage. The rating curve was designed to represent a generalized or typical depth to discharge relationship for the one and a half mile stretch of Fish Creek Wash downstream from the confluence of the mainstem Fish Creek Wash channel with the North Fork.

The modeling approach is semi-quantitative where the simulated hydrograph will be used for categorical forecasting. 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). Therefore, the limitations of the rating curve were taken into account in the modeling approach. 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.

<u>Determination of Flood Thresholds for Fish Creek</u>

Modeling Fish Creek requires the determination of action, minor, moderate, and major flood stages. For most of the country, flood stages begin above bankfull. Since Fish Creek is in a dry wash canyon setting, 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 one-mile long reach of the Fish Creek Wash downstream of the confluence of the mainstem Fish Creek Wash with the North Fork. Flood impacts with respect to vehicles are referenced in the NWS Turn Around Don't Drown (TADD) campaign where two feet of rushing water can carry most vehicles downstream including sport utility vehicles (SUV's) and pick-up trucks. Setting flood stages for a location like Fish Creek is challenging since conditions vary spatially along the creek 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 2 feet which corresponds to an estimated peak discharge of 745 cfs and an average flow velocity of 2.80 ft/sec. This corresponds to 5.5% of the flood of record peak discharge. Action Stage equates to greater than a 2-year peak flow and less than a 5-year peak flow. At Action Stage, water is bank-to-bank within the main flow channel and water depth is approximately 2 feet at the deepest part of the main channel but rather shallow near the margins. At Action Stage, water velocity and depth should be low enough for persons and vehicles to safely escape harm's way unless they were situated in the deepest part of the channel. The likelihood of a vehicle being swept downstream at flows corresponding to Action Stage is relatively low. A vehicle would have to be situated in the deepest portion of the channel to be impacted by a 2-foot deep peak flow. Vehicles situated at the margins of the main channel would experience considerably lower flood depths and velocities while those outside of the main channel would be on totally dry ground assuming a compound channel with main channel and overbank sections.

Minor Flood Stage was set at 3 feet which corresponds to an estimated peak flow of 1,638 cfs and an average flow velocity of 3.90 ft/sec. This corresponds to 12.0% of the flood of record peak discharge. Minor Flood Stage equates to greater than a 5-year peak flow and less than a 10-year peak flow. At Minor Flood Stage, water is 3 feet deepest part of the main channel. At Minor Flood Stage, water depths and velocities are sufficient enough that there is a good probability that a vehicle will be swept downstream if located in the main channel. At Minor Flood Stage, the likelihood is high that persons on foot would have to climb to higher ground.

Moderate Flood Stage was set at 4 feet which corresponds to an estimate peak flow of 3,210 cfs and an average flow velocity of 5.35 ft/sec. This corresponds to 23.6% of the flood of record peak discharge. Moderate Flood Stage equates to greater than a 10-year peak flow and less than a 25-year peak flow. At Moderate Flood Stage, water depths and velocities are sufficient enough that there is a high probability that a vehicle will be swept downstream if located in the main channel.

Major Flood Stage was set at 5 feet which corresponds to an estimated peak flow of 5,504 cfs and an average flow velocity of 6.88 ft/sec. This corresponds to 40.5% of the flood of record peak discharge. Major Flood Stage equates to just under a 25-year peak flow. Major Flood Stage equates to bankfull conditions where there is both an overbank and main channel section of Fish Creek Wash. In areas of Fish Creek Wash without well-developed overbank areas, the wash would be flowing wall-to-wall and there would be no high ground for vehicles to be parked or persons to escape to. At Major Flood Stage, water depths and velocities are sufficient enough that there is a very high probability that a vehicle will be swept downstream if located in the main channel.

In addition, at major flood stage, impacts several miles downstream from the modeled point occur as shown in Figures 12 and 13, both taken during the flood of record at Split Mountain Road. Split Mountain Road crosses Fish Creek Wash 2.5-miles downstream of the modeled location and 1-mile downstream of the mouth of Fish Creek Canyon. It should be noted that impacts are still significant despite of the fact that the channel becomes more distributary and much wider after it exits Fish Creek Canyon and eventually drains into the Salton Sea.

Events used in Model Calibration

In addition to the “record” flow event of July 30, 2012, several additional flow events were required to calibrate the model. These included the events on July 21, 2013 and July 22, 2013. The Anza Borrego State Park confirmed that July 21st was the larger of the two flow events as a jeep was destroyed during the event and two occupants had to be helicoptered out. According to the San Diego County Sherriff’s department, the 911 call for rescue came in at 7:00 PM. The Anza Borrego State Park characterized the 22nd as a flow event that did not rise to levels that would be considered a flood. During the model calibration, the event on the 21st was modeled as a moderate flood and the 22nd as a flow event below action stage.

On August 22, 2012, the NWS issued a flash flood warning, but no record of flooding could be found. This event was used as one of several null events during the calibration to ensure that the model does not produce a flood when one did not occur. The test for all null cases was to ensure that the simulated peak flow did not exceed action stage. News reports mention flooding of roads in the Fish Creek area on July 14, 2012 (CBS News, 2012). This event was run through the model during the calibration process to assess any impact to the watershed. A blog posting by David Clapp, an eco-tourism and natural history tour leader, makes reference to flooding in the town of Borrego Springs on October 20, 2010 (Clapp, 2010). While it is not known if the rainfall impacted the Fish Creek watershed, this event was examined during the model calibration.

Finally, August 24 – 26, 2013 characterized a multi-day rain event that impacted the greater Borrego Springs area causing significant damage to route S22 out of Borrego Springs and the Agua Caliente County Park. The Anza Borrego State Park described the flow event as significant enough to "pretty much wipe away all evidence of the July (2013) events." At the time, Split Mountain Road at the mouth of the canyon was severely damaged and closed. Rock and debris impacted the canyon which was only accessible to high clearance 4-wheel drive vehicles. This event was modeled as a flow event of larger magnitude than the July 21, 2013 moderate flow event and served as an example of a major flow event, but well below the record flood.

The strategy behind the events included in calibration was to evaluate the performance of the model over a full range of flows from those below action stage and up to the flood of record. The calibration parameters selected allow the user to run the model successfully over a full range of potential flow scenarios.

<u>Model Calibration Assumptions</u>

The model was run for all events using a constant default convective Z-R ($Z = aR^b$ 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. Fish Creek is remote and lacks any rain gages within its watershed boundaries so the convective Z-R 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.

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 Fish Creek area are near 700 mb, or 10,000 feet, the radar captures the important layers needed for proper processing of radar QPE. The hydrology model requires the user to provide an initial soil moisture state. These are selected from a drop-down menu on the start-up GUI. Five selections are available with these being “super dry,” “very dry,” “dry,” “wet,” and “very wet.” Each selection represents a percentage of soil pore spaced filled with water. For the selections these are 0, 20, 40, 60, and 80 percent.

The user provides the initial flow rate in cfs at the start of each event to be modeled. The assumption was that the Fish Creek channel was dry at the start of each event as this is the typical condition. For events modeled where there has been a flow event the day 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 the flood flows and as such would be relatively insignificant from a modeling standpoint.

KINEROS2 Model

The KINEROS2 model is an event-oriented, distributed, physically-based model developed to simulate watersheds with moderate to steep slopes without backwater effects (Woolhiser et al. 1990; Smith et al., 1990; Goodrich et al., 2012).

Runoff from infiltration excess occurs when the rainfall rate exceeds the rate at which the soil can absorb water. Runoff due to saturation excess occurs when the upper soil layer becomes saturated due to a restriction, such as shallow bedrock, regardless of rainfall rate. KINEROS2 does not account for downslope movement of subsurface soil water (lateral subsurface flow). Infiltration and saturation excess are not mutually exclusive, but geography, initial conditions and rainfall rate will determine which mechanism is dominant at any given location and time. Short, high intensity storms typical in semi-arid regions during the monsoon season favor infiltration excess runoff, whereas saturation excess runoff is more common in humid areas, due to lower intensities and longer precipitation durations.

The KINEROS2 model at a Weather Forecast Office runs on a PC (outside of AWIPS) and requires a source of real-time radar precipitation. The Digital Hybrid Reflectivity Scan (DHR) product from the WSR-88D radar is utilized by the model. The DHR product provides reflectivity values for each volume scan (approximately every 4 minutes) on a polarimetric grid of 1 degree by 1 km. Historically the DHR product has been the default precipitation input for the Flash Flood Monitoring and Prediction (FFMP) program. The FFMP program is widely used throughout the NWS during the flash flood warning process and utilizes the DHR product for similar temporal and spatial resolution advantages.

The DHR product is extracted for each radar bin using a modified version of the NWS FFMP DHR decoder. KINEROS2 checks for new DHR products at regular intervals. This is configurable and currently a 30 second interval is used. When a new DHR product appears, KINEROS2 applies a user selected Z-R relationship and runs the new rainfall data through the model. The model then continues to simulate into the future for a prescribed forecast interval (typically 1-4 hours). The model does not include any future rainfall (i.e., QPF). When new DHR arrives, the model goes back to the end of the previous DHR interval, processes the new rainfall data, and simulates a new forecast interval. By doing this, KINEROS2 produces a new forecast hydrograph about every 4 to 5-minutes as new DHR products are received. In computing a new hydrograph after each new volume scan, the timeliness of KINEROS2 is equivalent to that provided by the FFMP program. The time-step used during the forecast interval is user configurable and, for a fast responding basin like Fish Creek, 5-minutes would be appropriate.

The model is initialized with a soil moisture condition category (super dry, very dry, dry, wet, very wet) and the known or assumed base flow discharge at the forecast point. The base flow component remains constant during the event, and is distributed along the channel network such that there is a linear increase from zero at the heads of the first order channels to the value at the forecast point. If base flow is zero, the channels will infiltrate and there will be transmission losses. For the simulations detailed in this paper, a base flow of zero was used for all events therefore channel transmission losses occurred.

The forecast hydrograph provided by KINEROS2 provides guidance on the timing and the magnitude of the peak flow. In this case, due to the added uncertainties in forecasting for a non-gaged location, the model will be used to perform categorical forecasting. It will allow the user to determine if the flow will be below action stage, above action stage but below minor flood stage, over minor flood stage but below moderate flood stage, over moderate flood stage but below major flood stage, over major flood stage but below record flood, or near record flood stage. Theoretically, the model may have some skill in simulating a flow exceeding the flow of record since the rating curve was extended by 1 foot in stage above the flood of record. The model provides the magnitude and timing of the flash flood event which are incredibly useful pieces of information currently not available from existing flash flood tools such as the FFMP program.

An additional advantage of KINEROS2 over existing lumped modeling approaches is the ability to accurately distribute rainfall in space and time over the model domain.

This is of particular value for convective rainfall events that routinely impact the complex terrain that comprises the Fish Creek basin.

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, 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 elements within the watershed (contributing hillslope elements and open channel elements). Refer to Figure 14 for an image of the model elements AGWA created for the KINEROS2 model for Fish Creek. AGWA assigns a uniform manning 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 elements and manning roughness.

Google Earth was used to measure channel widths for each channel element, and was used to evaluate the Manning roughness coefficient by viewing pictures that were geocoded based on their latitude and longitude. Manning roughness values of 0.036 to 0.039 were assigned to the main channel sections of Fish Creek. Smaller headwater tributary streams and narrows such as Sandstone Canyon were given Manning roughness values of 0.040 to 0.045. Figure 15 displays a summary of the channel widths and Manning 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 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).

A. July 30, 2012

The flood of record had full rainfall coverage over the basin with the heaviest being over the upper half of the mainstem (Figure 16), an areal average rainfall of 1.60 inches from the start of the rainfall event to the time of the peak flow, and a maximum areal average rainfall intensity of 2.00 inches/hour. The model was run without modifying either the saturated hydrologic conductivity or channel length (multipliers equal to 1.00). The simulated flow was 13,808 (8.06 feet) cfs at 5:53 PM (Figure 17). This compares well to the estimated peak flow value of 13,600 cfs (8.00 feet) and the time from the 911 call. The length of time between the peak rainfall and the peak flow was 40-minutes.

If the model were run in real-time, it would have detected the first steady rainfall at 4:00 PM and a peak in rainfall intensity at 5:10 PM. The model would have begun generating flow at the outlet at 4:58 PM. It would have predicted minor flooding at 5:04 PM, moderate flooding at 5:08 PM, major flooding at 5:12 PM, and indicated that flow would exceed 10,000 cfs at 5:32 PM. The model would have provided a lead time of 49 minutes for minor flooding, 45 minutes for moderate flooding, 41 minutes for major flooding, and 21 minutes for 10,000 cfs.

As you will see later in the paper, the ideal calibration for this event (saturated hydrologic conductivity and channel length multipliers of 1.00) could not be applied to all events calibrated. As a result, the operational calibration yielded slightly less lead time.

B. July 21, 2013

The July 21st event had full rainfall coverage over the basin with the heaviest being over the central portion of the mainstem and the headwaters of the North Fork (Figure 18), an areal average rainfall of 1.23 inches from the start of the rainfall event to the time of the peak flow, and a maximum areal average rainfall intensity of 1.40 inches/hour. This amounted to the second largest rainfall event and the 3rd most intense rainfall rate used in the calibration. The model simulated a flow of 4,133 cfs (4.45 feet) at 6:33 PM. Moderate flooding began at 3,210 cfs (4.00 feet) and extended up to 5,504 cfs (5.00

feet) where major flooding began. The simulated flow was in the middle of the range for moderate flooding. The timing of the peak flow was earlier than the reported time of 7:00 PM. The model was run using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00. The length of time between the peak rainfall and the peak flow was 1-hour and 13-minutes.

C. July 22, 2013

Due to the moderate flow event just the day before, the July 22nd event was modeled with an initial soil moisture condition of wet. This was one of two events modeled with an initial soil moisture condition of wet. The rainfall from the event was characterized by a basin average rainfall of 0.11 inches from the start of the rainfall event to the time of the peak flow, and a maximum basin average rainfall intensity of 0.22 inches/hour. The model was run using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00. The model simulated a flow of 461 cfs (1.62 feet). This flow was below action stage.

D. August 22, 2012

The August 22nd rainfall event was characterized by an areal average rainfall of 0.30 inches from the start of the rainfall event to the time of the peak flow, and a maximum areal average rainfall intensity of 0.42 inches/hour. The storm total radar precipitation shows that rainfall was light over the basin and did have complete areal coverage (Figure 19). The model was run using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00. The model did not simulate any flow using these parameters. A peak flow of 51 cfs (0.66 foot) was simulated when the parameters multipliers were kept at 1.00.

E. July 14, 2012

No significant rain fell in the Fish Creek basin this day. Media reports of flooding on roads in the Fish Creek area was from rain that fell outside of the modeled area (Figure 20). Running the model in hindsight could potentially help more precisely identify the area impacted by flooding for Storm Data.

F. October 20, 2010

The October 20th event was characterized by low intensity and sporadic rainfall over the morning hours, not exceeding 0.05 inches within any 1-hour period. The storm total radar precipitation image can be viewed in Figure 21. The event ended in a brief burst of heavier rainfall around 3:00 PM leading to a simulated rise of 223 cfs (1.27 feet). This flow was below the action stage. An areal average rainfall of 0.25 inches from the start of the rainfall event to the time of the peak flow was simulated, and a maximum areal average rainfall intensity of 0.36 inches/hour. The model was run using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00.

G. August 24, 2013

The August 24th event only had rainfall coverage over the lower half of the basin (Figure 22), an areal average rainfall of 1.01 inches from the start of the rainfall event to the time of the peak flow, and a maximum areal average rainfall intensity of 1.60 inches/hour. This amounted to the third largest rainfall event and the 2nd most intense rainfall rate used in the calibration. The model simulated a flow of 8,280 cfs (6.08 feet) at 5:16 PM. Major flooding began at 5,504 cfs (5.00 feet) making the simulated peak flow about 1-foot above major flood stage. The timing of the peak flow was not known for this event. The model was run using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00. The length of time between the peak rainfall and the peak flow was 1-hour and 16-minutes (assuming the model simulated an appropriate peak flow time).

H. August 25, 2013

Due to the major flow event the day before, the August 25th event was modeled with an initial soil moisture condition of “wet”. The August 25th event was characterized by an areal average rainfall of 0.50 inches from the start of the event to the time of the peak flow, and a maximum areal average rainfall intensity of 0.54 inches/hour. The model simulated a flow of 780 cfs (2.07 feet) at 11:04 PM. Action stage begins at 745 cfs (2.00 feet) making this the only simulated event to exceed action stage, but fall short of exceeding flood stage. The model was run using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00.

It should be noted that there was some uncertainty as to which day the higher flow event occurred over the August 24th through 26th time period. The Anza Borrego State Park headquarters mentioned flooding to the north in Borrego Springs and to the south along Vallecito Creek to the south on August 25th. The first day the Anza Borrego State Park employees was able to enter Fish Creek Canyon was on August 27th when the road was passable following the recent high flows. Due to the considerably larger rainfall event on August 24th, the authors regard that day as likely the more significant, damaging flood event for that weekend. The rain that fell over the watershed on the 25th would have been incapable of producing a flow exceeding Major Flood Stage (Figure 23). For this event, the rain fell only over the upper third of the watershed.

I. Parameter Multiplier Selection for Real-Time Modeling

The calibration model runs were incredibly consistent in terms of the needed parameter multipliers. All modeled events with the exception of the record flood event simulated peak flows in the appropriate flood category using a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00. The record flood event required a saturated hydrologic conductivity multiplier of 1.00 and a channel length multiplier of 1.00 to reproduce the estimated record flood discharge. What sets the record flood event apart is that it has the greatest maximum areal average rainfall intensity of 2.00 inches/hour. The next most intense rainfall events modeled were 1.60 and 1.40 inches/hour. Therefore the operational calibration will apply a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00 to all rainfall events with a maximum areal average rainfall intensity of less than 1.80 inches/hour. Rainfall events with a maximum areal average rainfall intensity of 1.80 inches/hour or greater apply multipliers of 1.00 and 1.00 respectively. The maximum areal average rainfall intensity of 1.80 was selected since it is the mid-point between the two calibrated events where the parameter multiplier change takes place.

Consideration was also given to running the model with just a single parameter multiplier set. One option would be to use a saturated hydrologic conductivity multiplier of 0.50 and a channel length multiplier of 2.00. This would however under-simulate the magnitude of the peak flow and delay the timing of the flood of record - a peak flow of 5,634 cfs (5.07) at 6:50 PM which is just barely over the major flood stage of 5.00 feet and one full hour after the observed peak flow time. Another option would be to use multipliers of 1.00, 1.00 but this would overestimate the peak flow and underestimate the time to peak for most events. The worst case would be the August 24, 2013 event where these parameter multipliers yielded a peak flow of 15,657 cfs (8.53 feet) which is 114% of the flood of record. A listing of all calibration results for all rainfall events can be found in Figure 24.

J. Model Sensitivity to Initial Soil Moisture Condition

In order to assess the sensitivity of the model to initial soil moisture state, the moderate flood event of July 21, 2013 was selected. This was the first rainfall of the 2013 monsoon season with the 4 prior months being essentially dry. An initial soil moisture state of “super dry” was used in the calibration and simulated a peak flow of 4,133 cfs (4.45 feet). Modifying the initial soil moisture state to “very dry”, “dry”, “wet”, and “very wet” respectively simulated peak flows of 5,024 cfs (4.90 feet), 6,391 cfs (5.46 feet), 7,764 cfs (5.98 feet), and 10,306 cfs (6.93).

Deviating by one soil moisture category resulted in no change in flood category. Deviating by two categories (e.g. “dry” instead of “super dry”) resulted in a categorical change in peak flow. In this case, the peak flow would change from moderate flood to major flood. User guidance can assist in selecting the most appropriate initial soil moisture state. Figure 25 depicts guidance for selecting the most appropriate initial soil moisture state.

Lead Time Provided by KINEROS2

KINEROS2 provided substantial simulated lead time for action, minor flood, moderate, and major flood stage (Figure 26). The average lead time provided for minor flood stage, based on the three events, was 63 minutes. This is in excess of the national 2013 flash flood lead time goal of 58 minutes. The lead times for moderate and major flooding were 50 and 48 minutes respectively. Action stage, having the lowest flow threshold, had an average lead time of 98 minutes. All lead times exceeded the time from peak rainfall to peak flow both as an average value and for individual flow events. Even the 10,000 cfs threshold had a lead time, based on the record flood event, of 20 minutes.

Discussion and Conclusions

The current study was undertaken to evaluate the feasibility of using a real-time distributed model to forecast flash flood events in an ungaged semi-arid basin. The KINEROS2 model was selected to forecast peak flows at an outlet point along the lower reach of Fish Creek below the confluence with the last significant tributary in the watershed. The recreational use of the watershed including its mainstem channel and tributary channels is regular during the monsoon season. The ability to accurately forecast the timing, magnitude, and impacts of flash flooding has the strong potential to save lives and property. The WFO will attempt to use decision support services and the model output for the Anza Borrego State Park public safety planning and response.

Calibration was accomplished by adjusting the saturated hydrologic conductivity and channel length multipliers to match the magnitude and timing of the peak flow. One set of calibration parameters successfully simulated a full range of flows from low flows below Action Stage upward through Major Flooding. The only exception was the flood of record which required a different calibration parameter set. It is encouraging that there were no events that were outliers and could not be calibrated. Additional rainfall events in particular on the upper end in terms of areal average rainfall intensity would be helpful to ensure the model is capable of simulating all extreme events near and above record flood.

Looking at the findings in this paper, it is clear that the KINEROS2 model, when well calibrated, can provide valuable information across the full spectrum of the flash flood warning process. It is capable of simulating the peak flow both in terms of magnitude and timing and can provide lead times generally exceeding the national flash flood lead time goal. In particular, considering the fast responding nature of the basin, enough lead time can be provided to warn affected parties in the basin. The modeling approach employed here allows locations without a stream gage to be modeled. Collecting data in the field and from other sources allowed the reconstruction of not only the flood of record, but also of several other significant flood events.

For WFOs looking to set up and calibrate the model for an ungaged location, this takes a significant amount of effort. The WFO will need to create a synthetic rating curve and establish flood stages. Flow events need to be cataloged. Each flow event at a minimum needs to categorized by flood category. The timing of at least some of the events is needed. A minimum of 6 flow events for model calibration are recommended. The events should span a full range of flows from those below flood stage through major flooding. Null events are critical as well to ensure that the model does not simulate flooding when none was reported. The basin selected requires good radar coverage as well.

WFO Collection of Basin Specific Data

Flash flood events are documented in Storm Data, which is an archive of official NWS storm reports. The storm report includes the start and end time of an event, location, cause, any direct or indirect fatalities or injuries, and a descriptive narrative of the event. The narrative can vary widely based on available data, experience of the Storm Data preparer and other factors. The narrative may contain information on the height of the flash flood, rainfall amounts, and impacts. Storm Data is however not designed to serve as an archive of basin specific data that one might need to calibrate an ungaged basin. Collecting this level of detail involves going above and beyond collecting what is typically collected in Storm Data. After a WFO has identified a customer need in forecasting for an ungaged location, the WFO may want to consider collecting impacts from flash flood events. Events across a full range of flows (both below and above flood stage/flow) would be ideal to evaluate the model. If peak discharge cannot be collected, information should be collected that allows events to be differentiated by degree of impact. This allows for flow events to be categorized as low flow, action, minor flood, moderate flood, or major flood. In addition to collecting data on the magnitude of each event, it is essential to document the timing of the peak flow.

Future Plans

The portability of KINEROS2 across the semi-arid west has increased with the positive results from this work. The authors will seek opportunities to field the model in other gaged and ungaged basins across the region.

Concurrent with research outlined above, the USDA in collaborative efforts with the National Weather Service will work to modify the model's radar interface to accept not just the "legacy" DHR rainfall product, but also the new dual pol radar precipitation input. This work is expected to be completed by the end of calendar year 2014.

Acknowledgements

Shea Burns (USDA) set up the model and radar interface using AGWA. Bill Reed (retired NWS hydrologist) assisted in the comparing results of flood of record discharge estimate, rating curve development, and channel manning roughness. The Anza Borrego State Park headquarters and California park rangers (in particular Steve Bier) for providing a wealth of useful information about the flow and flood events in the watershed. The San Diego Sheriff's Department shared the times in the 911 logs for calls that came in from Fish Creek.

References

CBS News Channel 8, 2012: Flash Flood Watch issued for San Diego Mountains, Deserts. Retrived from http://www.cbs8.com/story/19026161/flash-flood-watch-issued-for-san-diego-mountains-deserts

Clapp, D., 2010: Flash Flood in Anza Borrego. On the Road with DEC [web blog]. Retrived from http://ontheroadwithdec.blogspot.com/2010/10/flash-flood-in-anza-borrego.html

Goodrich, D.C., 1990: Geometric simplification of a distributed rainfall-runoff model over a range of basin scales. Ph.D. Dissertation, Univ. of Arizona, Tucson. (Order from: ProQuest Microfilm, Ann Arbor, MI 48106).

Goodrich, D.C., Burns, I.S., Unkrich, C.L., Semmens, D., Guertin, D.P., Hernandez, M., Yatheendradas, S., Kennedy, J.R., Levick, L. 2012. KINEROS2/AGWA: Model Use, Calibration, and Validation. Transactions of the ASABE. 55(4): 1561-1574.

Miller, S. N., D. J. Semmens, D. C. Goodrich, M. Hernandez, R. C. Miller, W. G. Kepner, and D. P. Guertin. 2007. The automated geospatial watershed assessment tool. J. Environ. Modeling and Software 22(3): 365-377.

Smith, R.E., Goodrich, D.C., Woolhiser, D.A., Unkrich, C.L. 1995. KINEROS - A kinematic runoff and erosion model. Chpt. 20 In: Computer Models of Watershed Hydrology, V.P. Singh (ed.), Water Resources Publs., pp. 697-732.

Woolhiser, D.A., Smith, R.E., Goodrich, D.C. 1990. KINEROS, a kinematic runoff and erosion model: Documentation and user manual. U. S. Depart. of Agric., Agric. Res. Service, ARS-77, 130 p. (13835 KB PDF) (Downloadable at: http://www.tucson.ars.ag.gov/unit/Publications/Search.html)

Figures

Figure 1. Entrance to Fish Creek. Photo Credit: NWS San Diego.

Figure 2. Sandstone Canyon Narrows. Photo credit: NWS San Diego.

Figure 3. Looking at high water marks along North Fork of Fish Creek. Wood debris found wedged 15-feet above channel floor. This debris was noted not to have been there prior to the flood. California State Parks ranger Steve Bier is in the picture. Photo Credit: NWS San Diego.

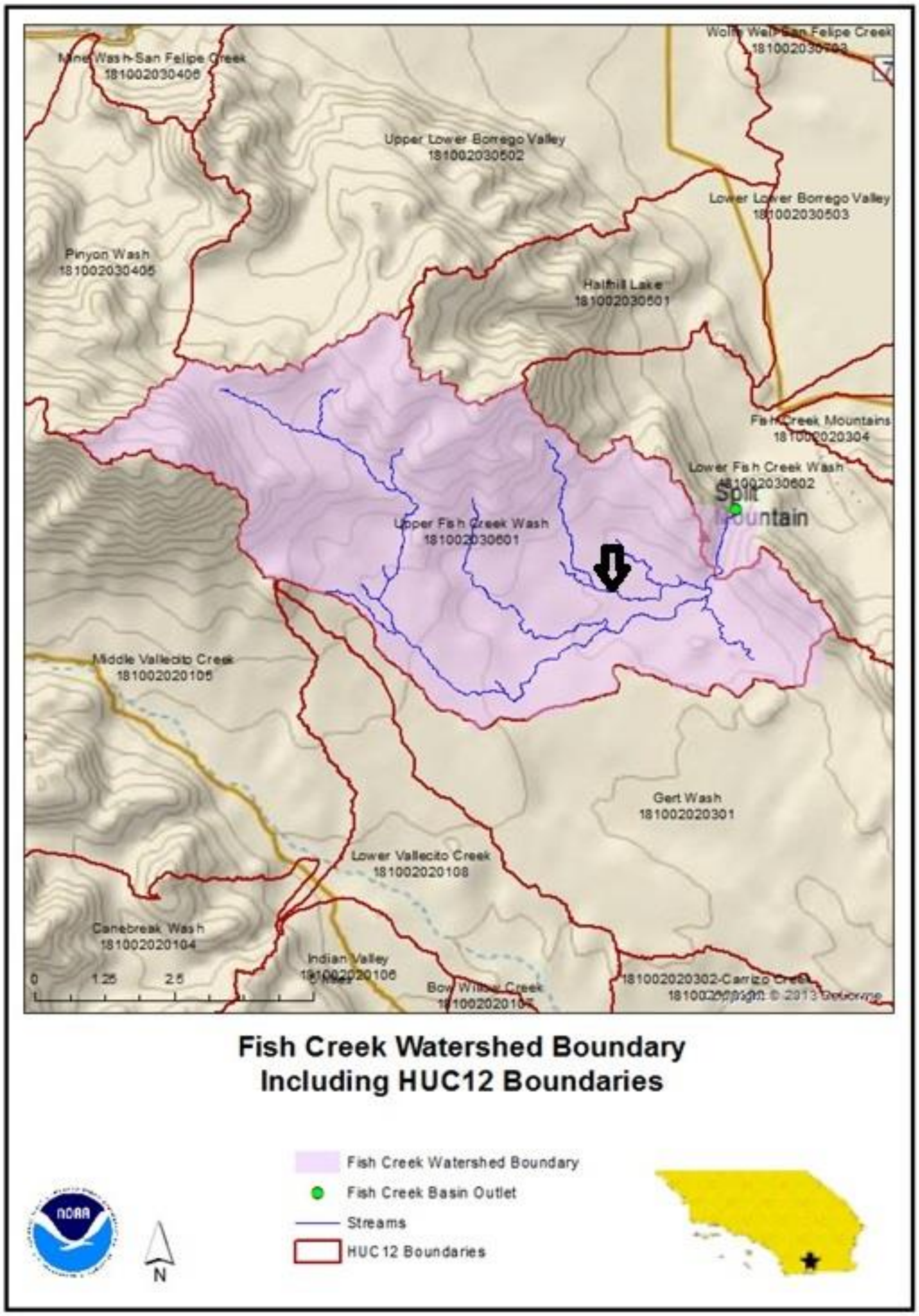

Figure 4. Watershed boundary of Fish Creek compared with the HUC12 boundaries. North Fork labeled with arrow.

Figure 5. Image of main flow channel of Fish Creek on right hand side with overbank on left side. High water line appears to be in the far left side of image against the line of bushes (see arrow). Photo Credit: NWS San Diego.

Figure 6. Another image of the main channel of Fish Creek with the debris field covering the overbank area. Approximate extent of debris shown by yellow curved line. Photo Credit: NWS San Diego.

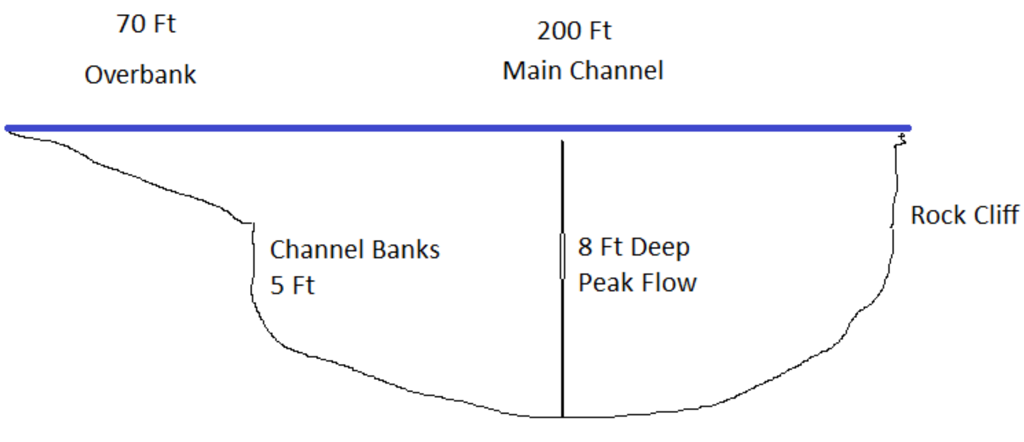

Figure 7. Idealized sketch of channel cross section taken from figures 5 and 6. Not drawn to scale.

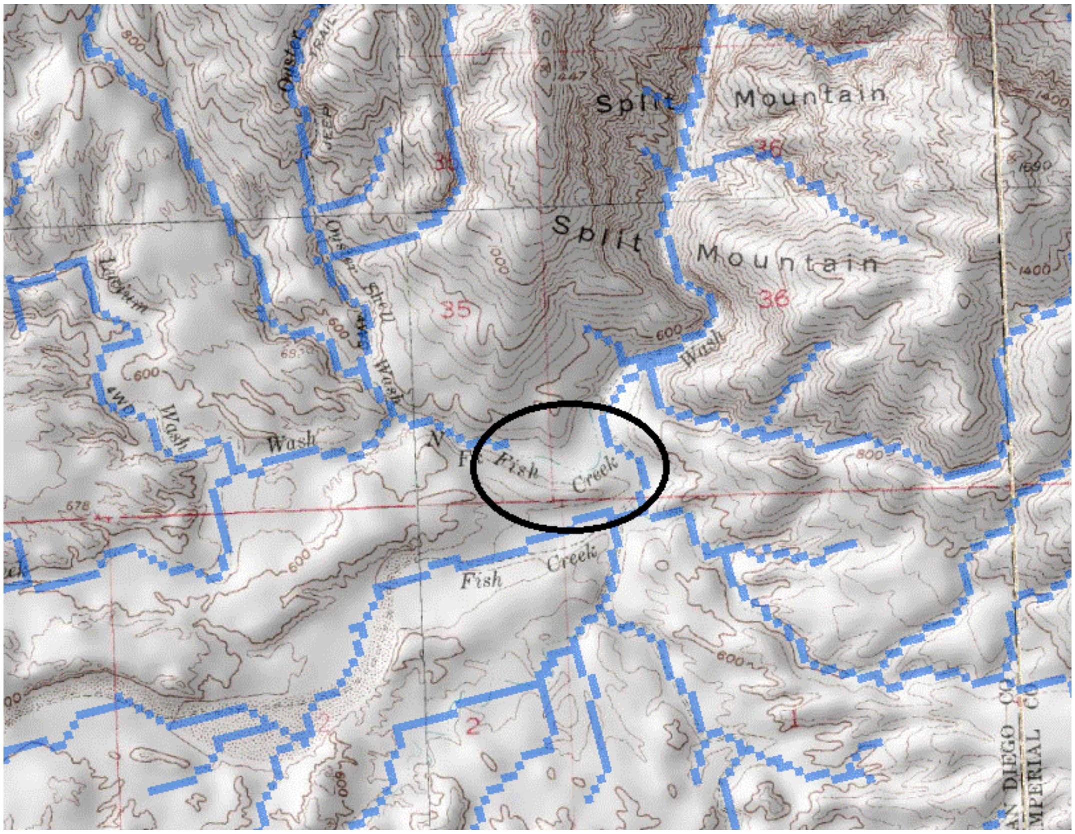

Figure 8. StreamStats zoomed into the portion of Fish Creek watershed where there is a break in the streamflow network (see black circle). Photo credit: USGS StreamStats.

	Mainstem Fish Creek	North Fork Fish Creek	Combined
PK2 (2-year peak flow)	99 cfs	49 cfs	148 cfs
PK5 (5-year peak flow)	728 cfs	352 cfs	1,080 cfs
PK10 (10-year peak flow)	1,910 cfs	889 cfs	2,799 cfs
PK25 (25-year peak flow)	4,260 cfs	1,910 cfs	6,170 cfs
PK50 (50-year peak flow)	6,760 cfs	2,960 cfs	9,720 cfs
PK100 (100-year peak flow)	10,500 cfs	4,470 cfs	14,970 cfs
PK500 (500-year peak flow)	21,400 cfs	8,580 cfs	29,980 cfs

Figure 9. Peak flow statistics calculated from StreamStats.

Stage (ft)	**Cross Sectional Area (sq ft)**	**Average Velocity (ft/sec)**	**Discharge (cfs)**
0.5	40	0.70	28
1	100	1.00	100
1.25	153	1.40	214
2	266	2.80	745
2.5	360	3.20	1,152
3	420	3.90	1,638
3.5	510	4.60	2,346
4	600	5.35	3,210
4.5	710	6.10	4,331
5	800	6.88	5,504
5.5	905	7.55	6,833
6	1010	8.00	8,080
6.5	1130	8.42	9,515
7	1230	8.70	10,701
7.5	1300	9.10	11,830
8	1380	9.57	13,600
8.5	1520	10.20	15,504
9	1650	11.00	18,150

Figure 10. Table showing data used to compute rating curve.

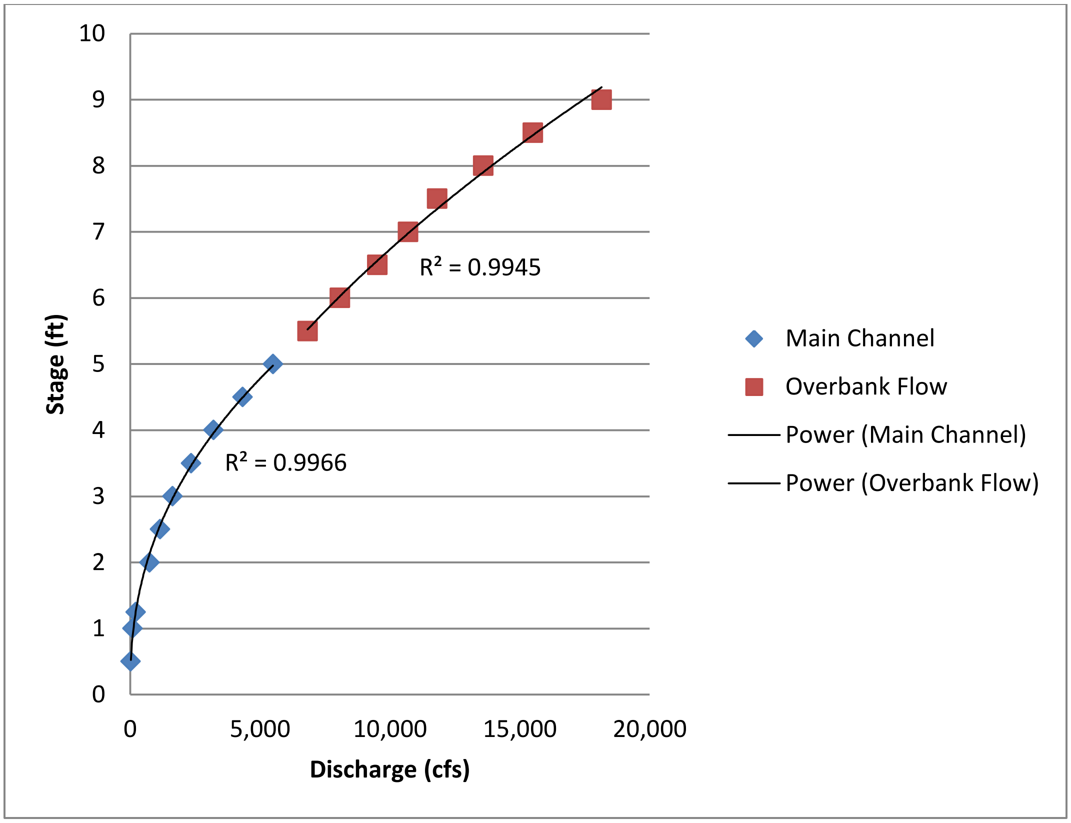

Figure 11. Rating curve.

Figure 12. Picture of the July 30, 2012 flood of record. Image was taken from Split Mountain Road looking upstream toward the mouth of Fish Creek Canyon.

Figure 13. Picture of the July 30, 2012 flood of record. Image was taken from Split Mountain Road looking upstream toward the mouth of Fish Creek Canyon. This image was taken zoomed in to show perspective (see roadway signs).

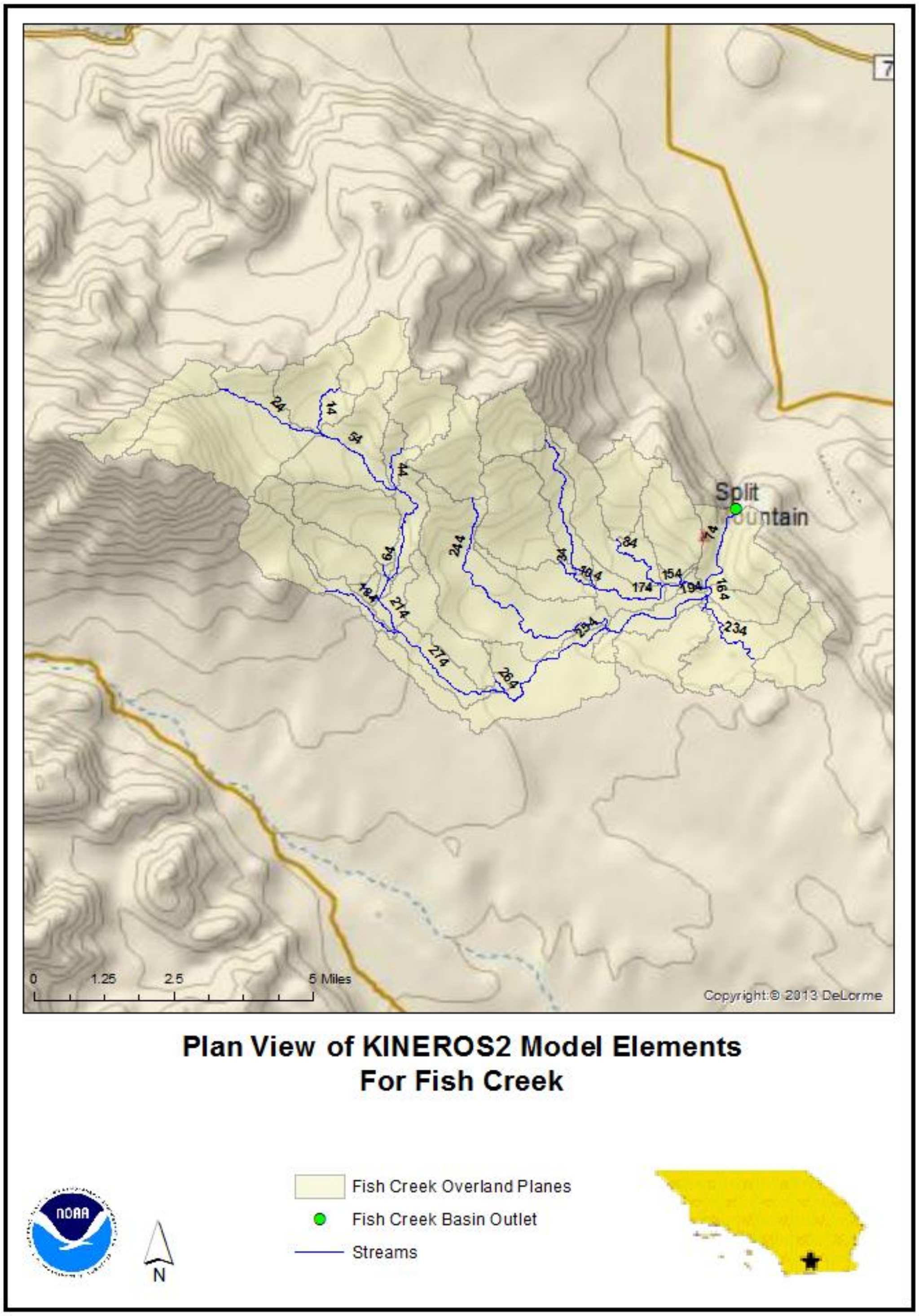

Figure 14. Plan view of KINEROS2 model elements for Fish Creek. Open channel elements are labeled and represented by blue line segments.

Open Channel Element ID	Downstream Width (m)	Upstream Width (m)	Manning Roughness	Channel Name
74	78	174	0.036	Fish Creek Wash
134	108	67	0.036	North Fork Fish Creek Wash
114	35	35	0.036	Oyster Shell Wash
154	56	65	0.036	North Fork Fish Creek Wash
84	28	32	0.036	Lycium Wash
174	102	37	0.036	North Fork Fish Creek Wash
104	13	19	0.038	Unnamed Tributary to North Fork Fish Creek Wash
34	50	19	0.039	North Fork Fish Creek Wash
164	125	107	0.036	Fish Creek Wash
194	98	100	0.037	Fish Creek Wash
204	17	15	0.036	Unnamed Tributary to Fish Creek Wash
224	5	5	0.039	Unnamed Tributary
234	13	16	0.037	Unnamed Tributary to Fish Creek Wash
244	54	17	0.039	Unnamed Tributary to Fish Creek Wash
254	92	52	0.037	Fish Creek Wash
264	17	13	0.041	Unnamed Tributary to Fish Creek Wash
274	46	60	0.037	Fish Creek Wash
214	71	80	0.038	Fish Creek Wash
194	98	100	0.036	Fish Creek Wash
184	20	17	0.045	Sandstone Canyon
144	40	80	0.038	Unnamed Tributary
124	138	138	0.040	Fish Creek Wash
94	39	40	0.040	Unnamed Tributary to Fish Creek Wash
64	57	37	0.039	Fish Creek Wash
44	19	19	0.042	Unnamed Tributary
54	47	89	0.040	Unnamed Tributary to Fish Creek Wash
14	77	19	0.040	Unnamed Tributary
24	40	24	0.041	Unnamed Tributary

Figure 15. Widths and manning roughness assigned to each open channel element for Fish Creek.

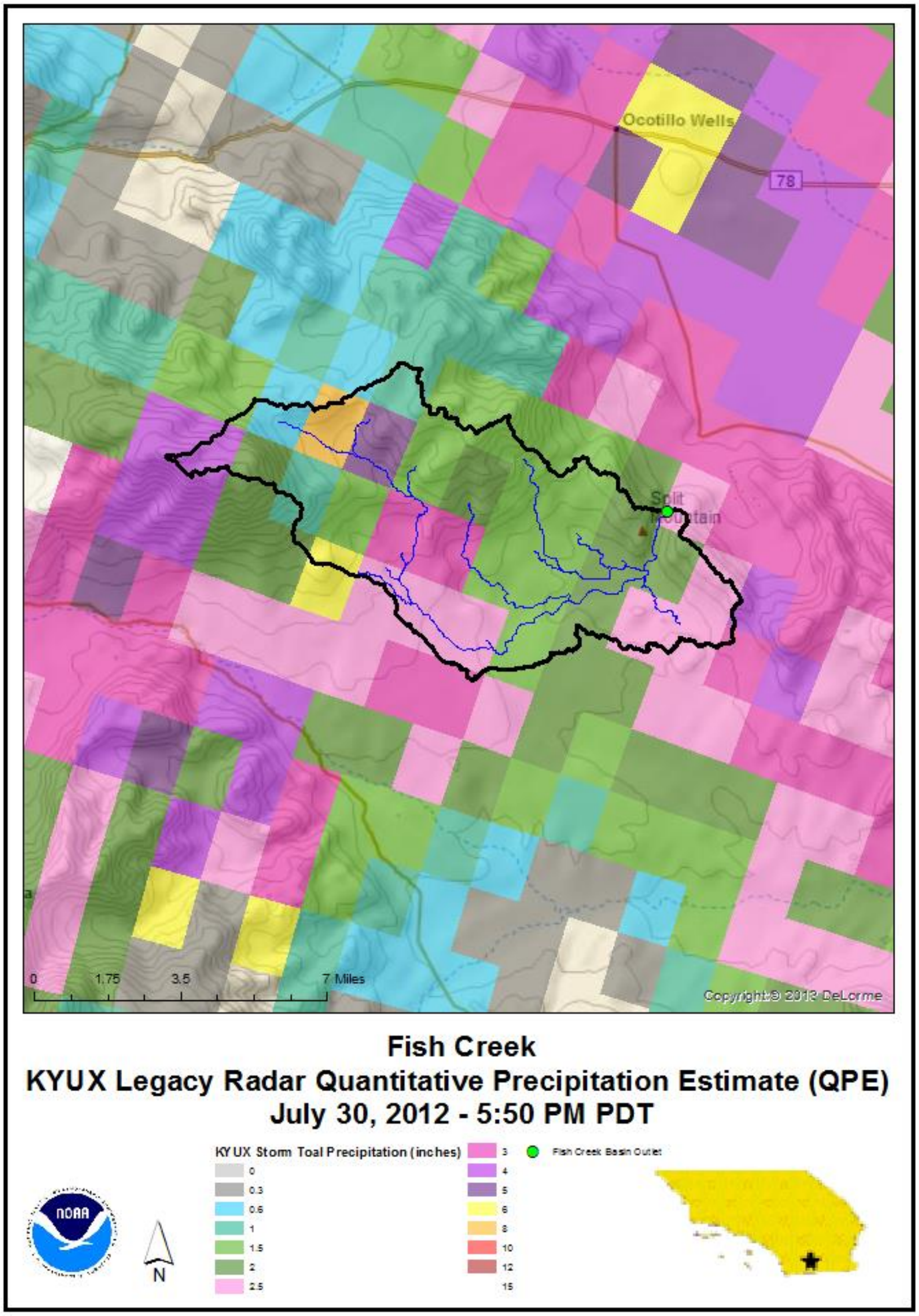

Figure 16. Radar storm total precipitation image for Fish Creek at the time of peak flow on July 30, 2012.

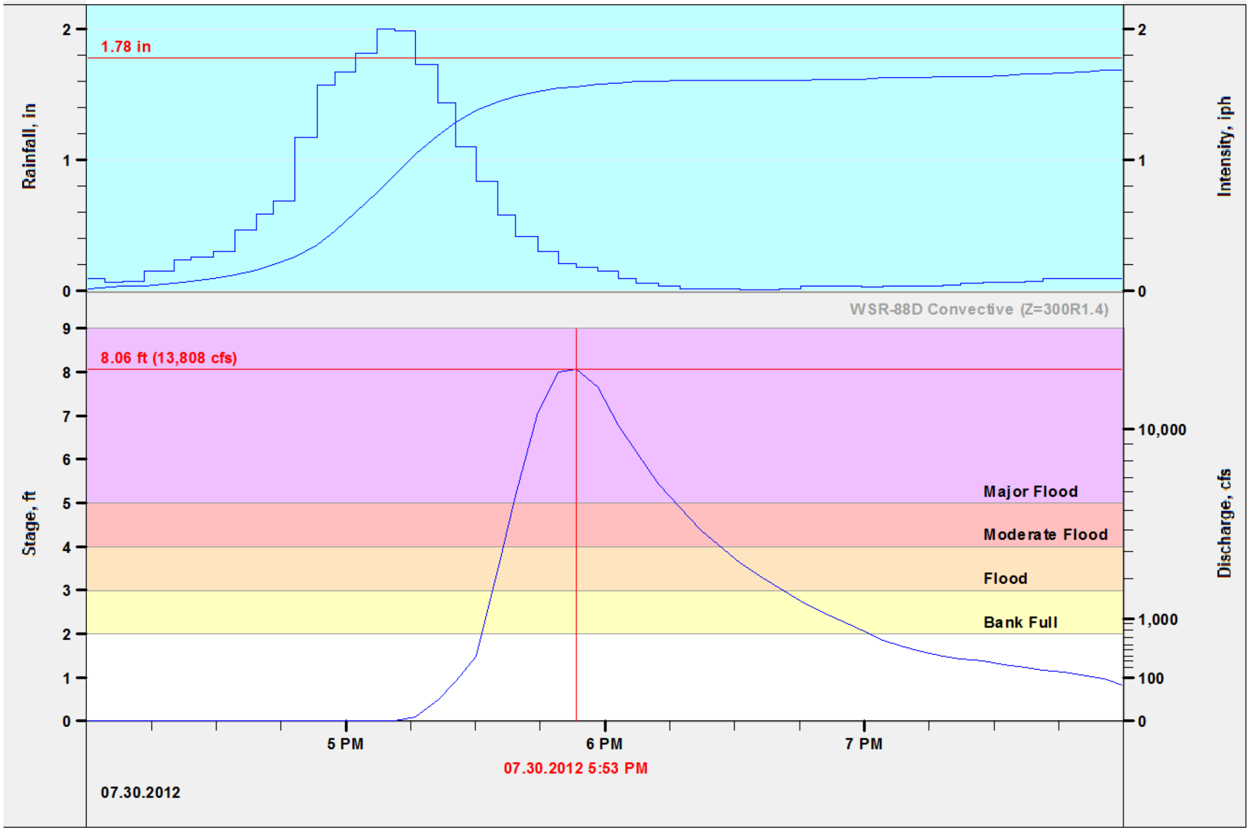

Figure 17. KINEROS2 model calibration results for the July 30, 2012 flood of record. On the hydrograph, the red vertical line indicated the time of the simulated peak flow and the horizontal line indicates the magnitude of the peak flow.

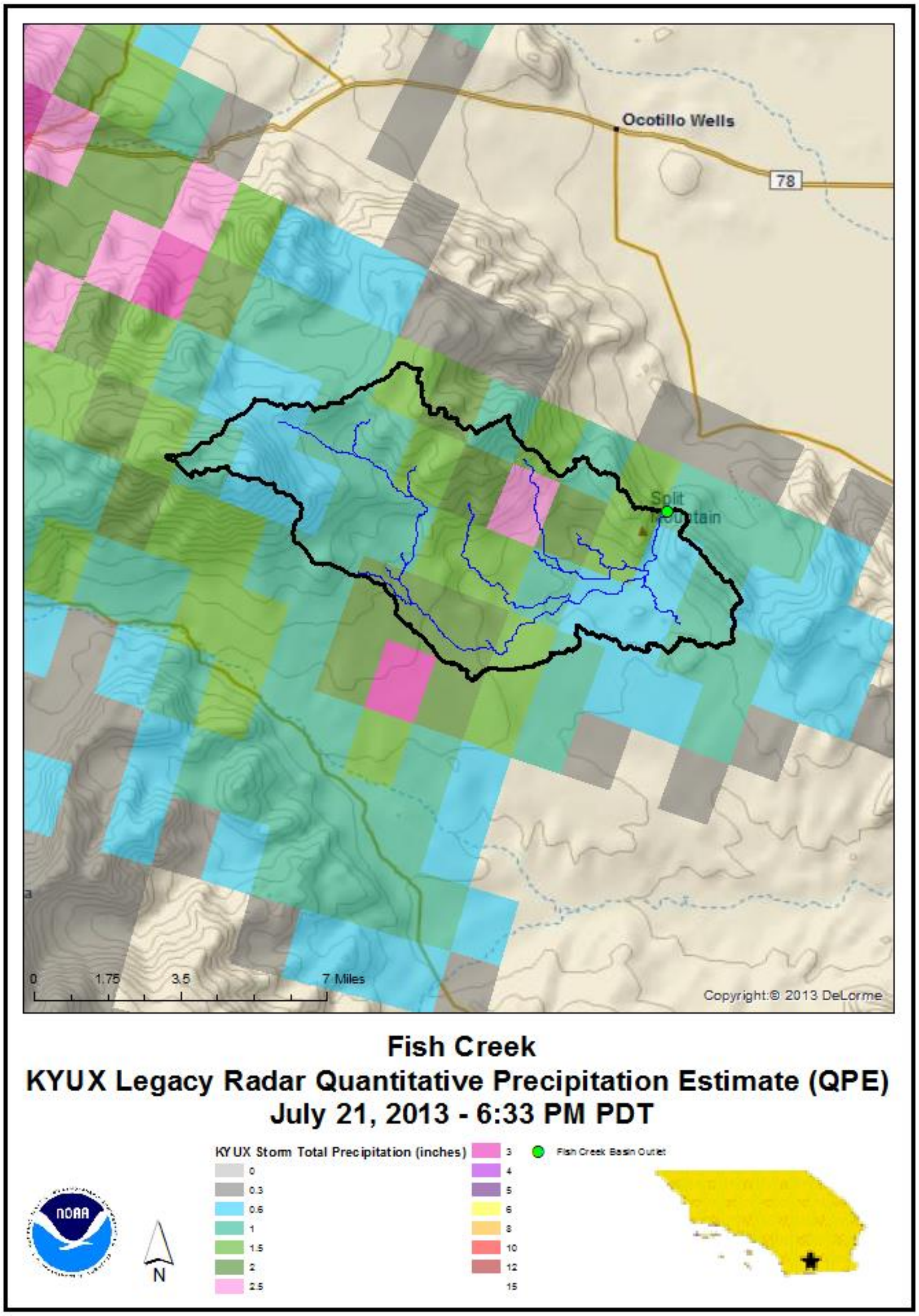

Figure 18. Radar storm total precipitation image for Fish Creek at the time of peak flow on July 21, 2013.

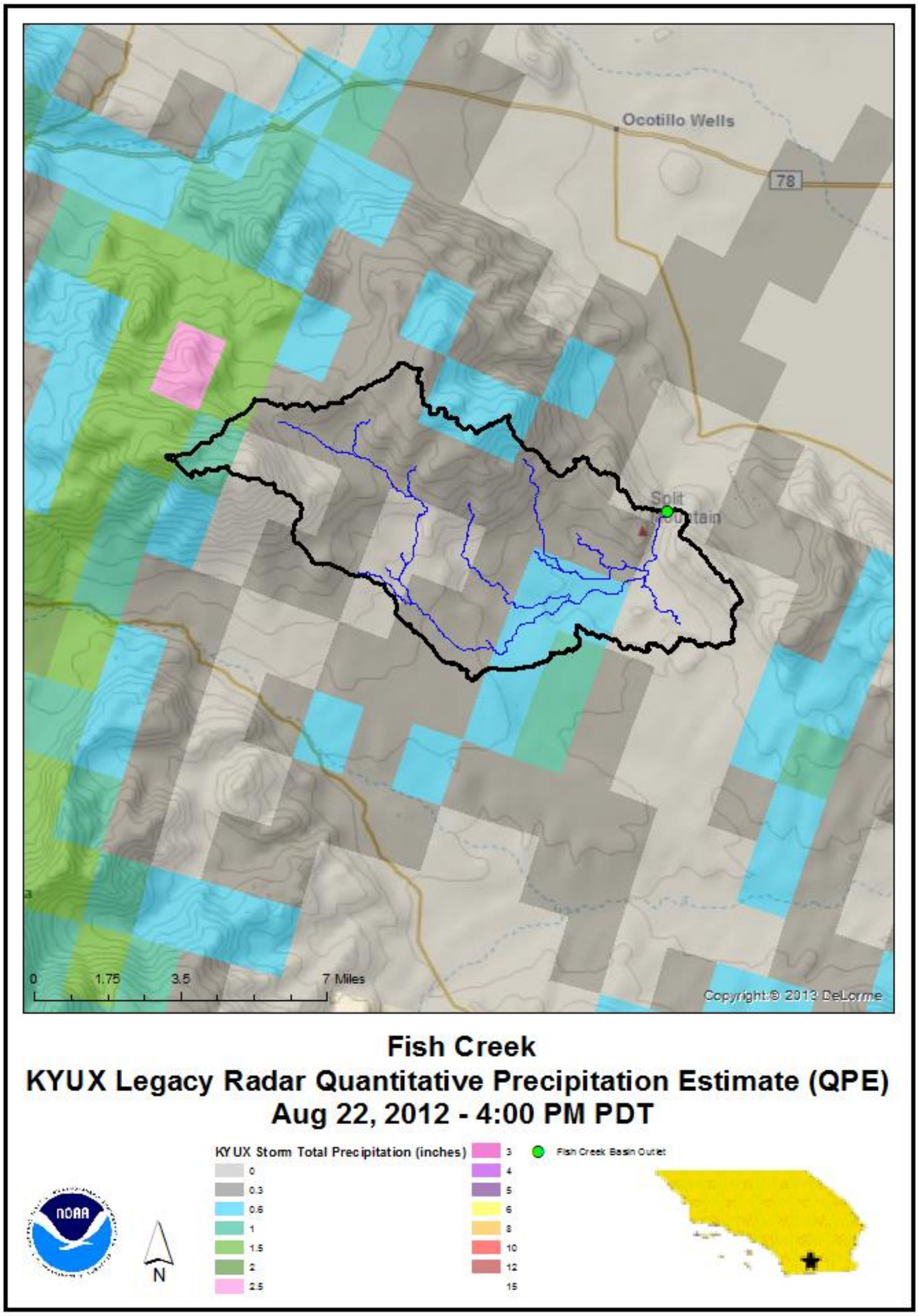

Figure 19. Radar storm total precipitation image for Fish Creek on August 22, 2012.

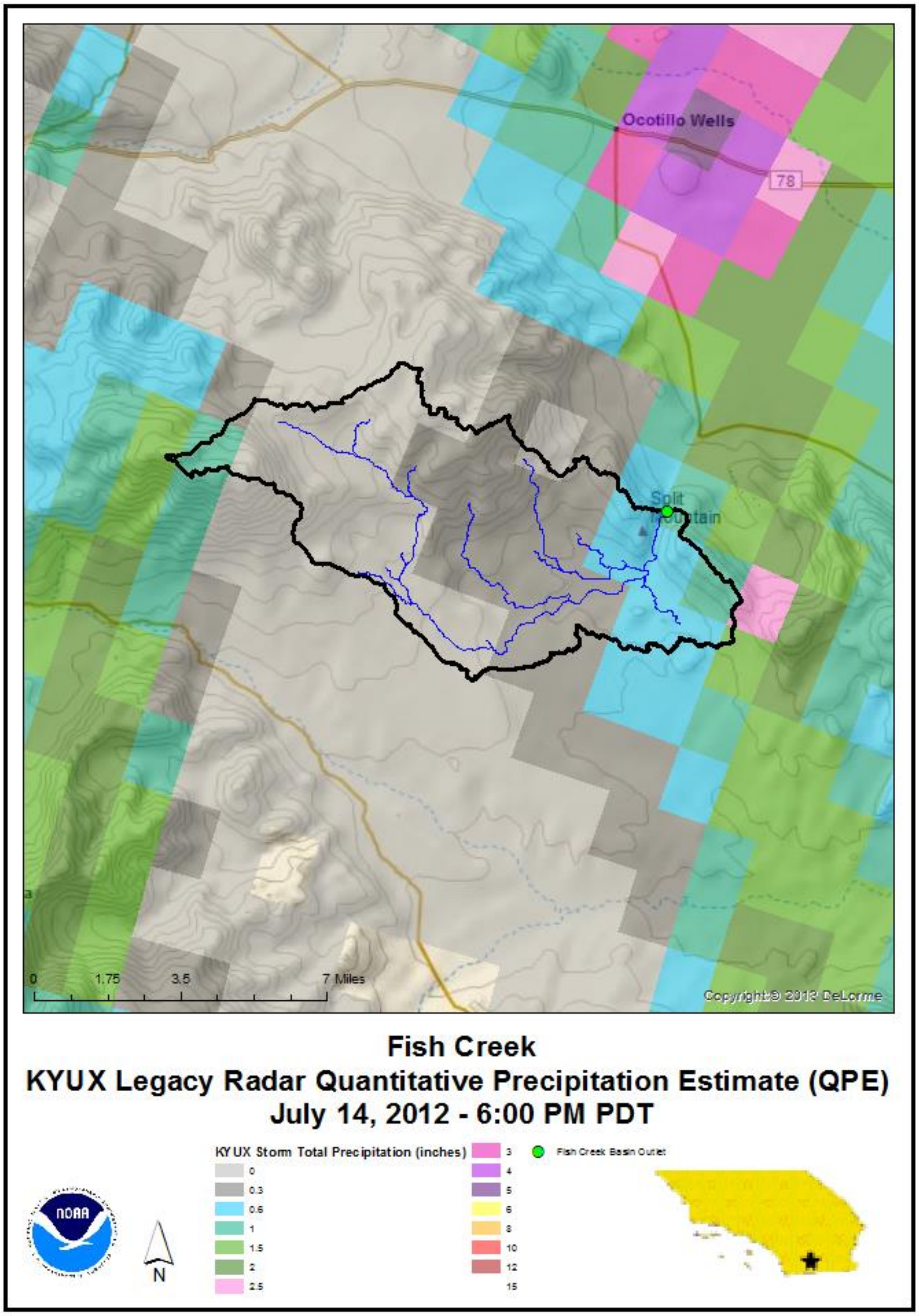

Figure 20. Radar storm total precipitation image for Fish Creek on July 14, 2012.

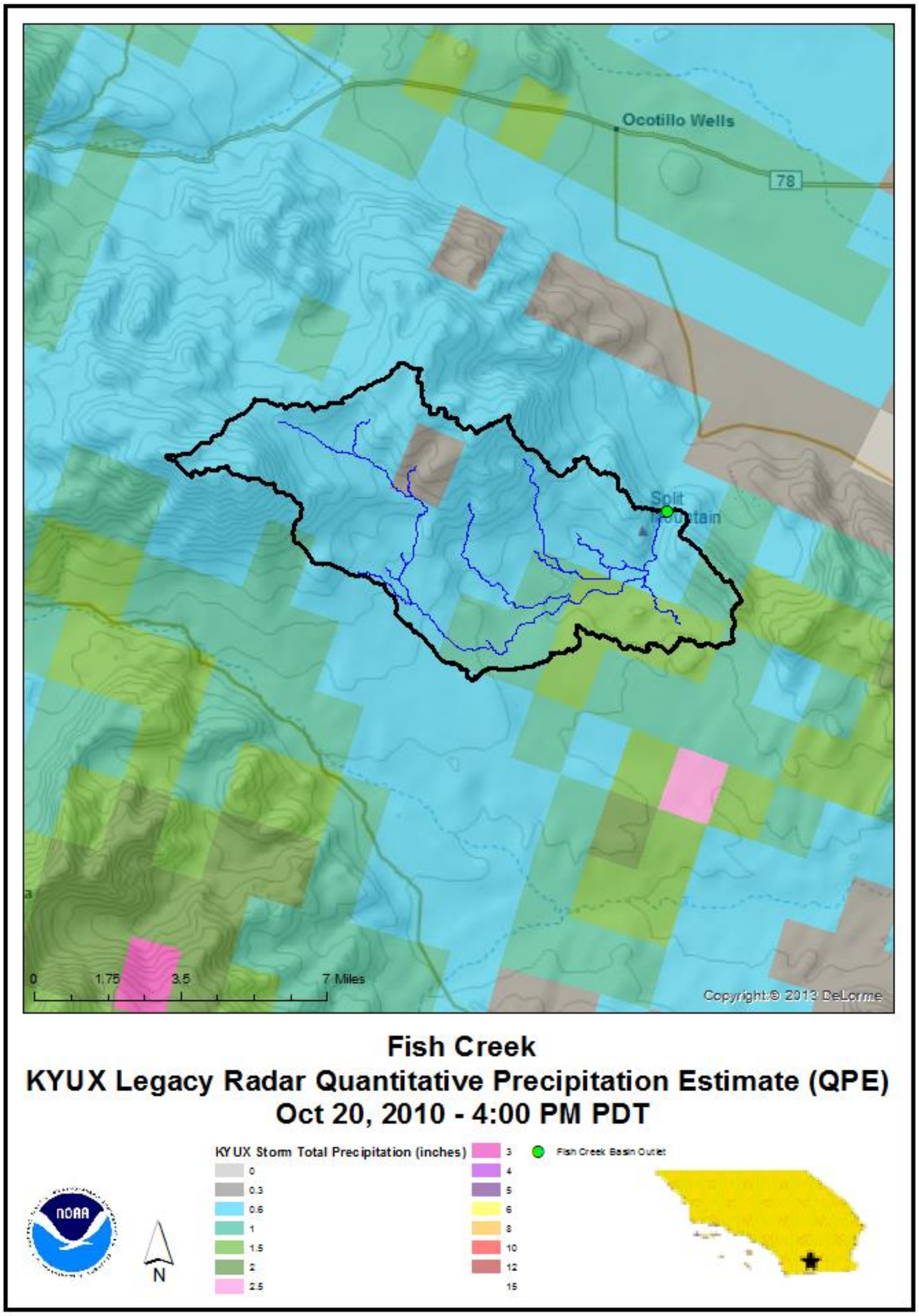

Figure 21. Radar storm total precipitation image for Fish Creek at the time of peak flow on October 20, 2010.

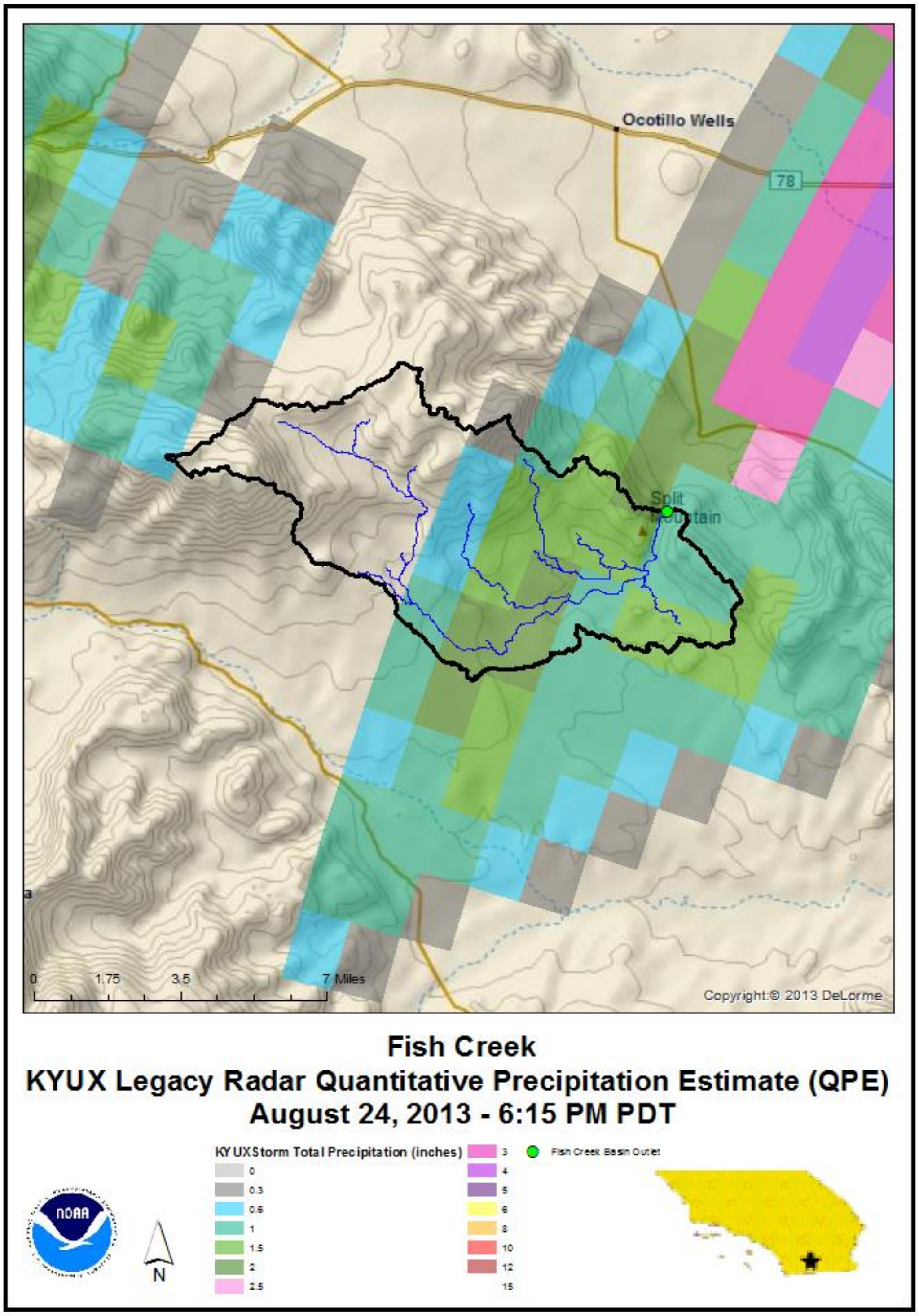

Figure 22. Radar storm total precipitation image for Fish Creek at the time of peak flow on August 24, 2013.

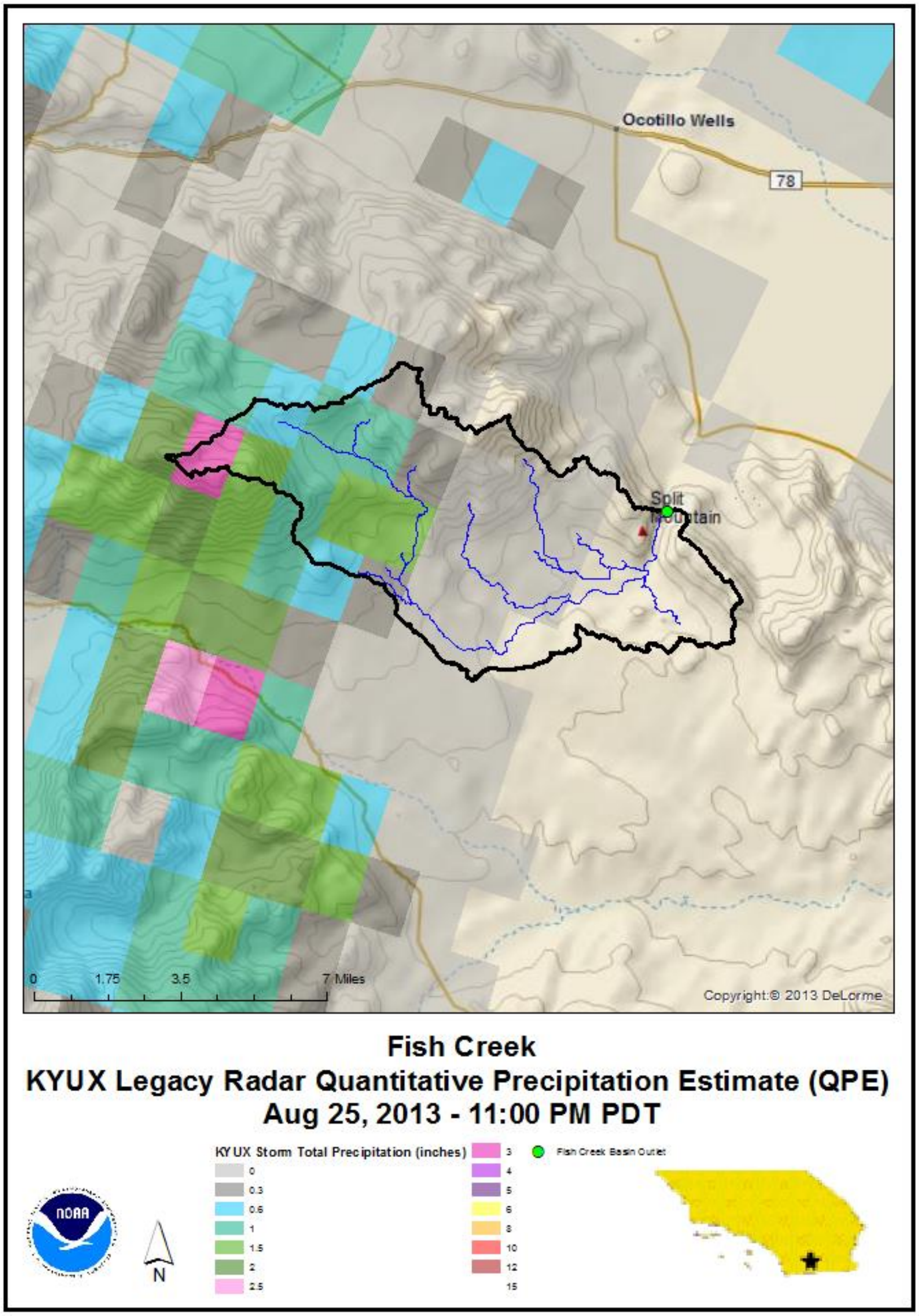

Figure 23. Radar storm total precipitation image for Fish Creek at the time of the peak flow on August 25, 2013.

Event	Initial Flow Rate (cfs)	Initial Soil State	Rain (in)	Max Intensity (in/hr)	Simulated Flow (cfs)	Saturated Hydrologic Conductivity Multiplier	Channel Length Multiplier
10-20-2010	0	Very Dry	0.25	0.36	223	0.50	2.00
07-30-2012	0	Super Dry	1.60	2.00	13,761	1.00	1.00
08-22-2012	0	Very Dry	0.30	0.42	0	0.50	2.00
07-21-2013	0	Super Dry	1.23	1.40	4,133	0.50	2.00
07-22-2013	0	Wet	0.11	0.22	461	0.50	2.00
08-24-2013	0	Super Dry	1.01	1.60	8,280	0.50	2.00
08-25-2013	0	Wet	0.50	0.54	780	0.50	2.00

Figure 24. Calibration results.

Initial Soil Moisture State	Percent Soil Moisture Capacity	User Guidance	Number of occurrences in calibration of the model
Super dry	0	Should be used when there has not been a significant rain event over the watershed in the past several week.	3
Very dry	20	Can be used when there have been small and periodic rainfall events over the basin in the past several weeks.	2
Dry	40	Can be used when there have been small to moderate rainfall events in the past weeks.	0
Wet	60	Should be used when there was a significant flow event exceeding flood stage/flow within 24-hours (e.g. the afternoon/day before).	2
Very wet	80	This would be rare to seldom used in a semi-arid setting such as Fish Creek. If the user is in doubt, do not select the very wet initial soil moisture state. Consecutive days of significant rainfall within the basin would qualify. A high-end major flood event or record flood event the day before might also qualify.	0

Figure 25. User guidance on selecting initial soil moisture state.

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)	Lead Time to 10,000 cfs (minutes)
07-30-2012	Not Simulated	44	40	35	20
07-21-2013	81	70	45		
08-24-2013	97	75	64	60	
08-25-2013	117				
Average Lead Time	98	63	50	48	

Figure 26. Lead time for all events that exceeded Action Stage. Average lead times were rounded up.