Operational Success with Distributed Modeling to Inform Flash Flood Warning Operations at Weather Forecast Office San Diego

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Abstract

National Weather Service (NWS) San Diego identified Fish Creek as a basin of high flash flood hazard after a flood of record on July 30, 2012. This event required a helicopter rescue and the loss of vehicles in the flood waters. Interaction with Anza-Borrego Desert State Park rangers and NWS visits to the Fish Creek canyon identified this as a basin needing additional flash flood guidance. At the time, the Weather Forecast Office (WFO) had little skill in determining when flash flooding would occur in this basin. The WFO required guidance to be real-time, rapid-updating, and on the small spatial scale that generates flash flooding in this basin. Guidance not only needed to inform the forecaster if flash flooding was going to occur, but also the magnitude of flooding and the timing of the flood wave. To this end, NWS Western Region and the USDA-ARS Southwest Watershed Research Center selected this basin for a distributed modeling proof of concept. The concept was to see if it was possible to quantify and provide timely forecasts for a rapid response basin that was ungaged for WFO flash flood warning operations. In addition to two high flow events, the WFO evaluated one low flow event to determine if the model might produce false alarms.

When forced with Dual Pol radar precipitation, the model simulated the correct magnitude of peak flow. For all events, the model was run in NWS operations and verified with reports on the ground during the event as well as two NWS flood surveys. Categorical forecasting of flash floods allowed for value added information to be inserted in flash flood warning and statements. The severity of the event and anticipated impacts could be provided to end users including Anza-Borrego Desert State Park. The duration of the event provided information of how long to warn for Fish Creek and for downstream road crossings.

<u>Model Calibration</u>

The real-time distributed KINematic runoff and EROsion model (KINEROS2) was selected. In order to setup and calibrate the model for this location, which is ungaged, a fair amount of research was required. This involved locating historic rainfall, runoff, and flood events. A rating curve was created and flood stages and flows established. Flash flood events had to be assigned a category of flooding (e.g. below Action Stage, Action Stage, minor flooding, moderate flooding, or major flooding).

The model was calibrated with a total of 8 rainfall events including the flood of record of July 30, 2012. This included a full range of events from low flow to the flood of record.

In addition to calibrating the model, the model was evaluated for sensitivity to initial soil moisture condition.

Additional details on hydrology of Fish Creek and the model calibration can be found in the following NWS Western Region Technical Attachment:
https://www.tucson.ars.ag.gov/agwa/download/docs/publications/TA1402.pdf

The legacy radar Digital Hybrid Reflectivity Scan (DHR) product was used to calibrate the model. Later the model was recalibrated using the Dual Pol Digital Precipitation Rate (DPR) product. Both the Legacy and Dual Pol editions of the model are available for use in WFO operations.

Application of the Model to WFO Flash Flood Operations

The model had been delivered to the WFO by Western Region Headquarters (WRH) prior to the start of the 2014 monsoon season. During the WFOs annual pre-monsoon workshop, a demo of the model was provided. A Frequently Asked Questions (FAQ) document had been provided to the WFO to be referenced by operations staff. A forecaster created templates to streamline the process of issuing a flash flood warning for Fish Creek and include information on the category of flooding.

Over the past 4 monsoon seasons, the WFO had several opportunities to run the model and evaluate the results. Two of these events were high end events and the WFO visited Anza-Borrego Desert State Park and Fish Creek to validate and verify on the ground how the model performed. Other events were low flow events that allowed the model in operations to be evaluated for situations that did not meet warning criteria. The later is important to ensure that the model does not produce false alarms.

August 3, 2014

August 3rd was a major flash flooding outbreak for the WFO. Widespread rainfall of several inches across the Borrego Valley resulted in multiple reports of flooding. Further north, a debris flow stranded thousands of persons in the Forest Falls and Oak Glen areas and caught national news attention. That same day, there was heavy rainfall over the Fish Creek watershed. This was the first significant rainfall over the basin when the modeling framework was run real-time in WFO operations.

The model indicated areal average rainfall of 0.75 inch from the start of the event to the time of the simulated peak flow, maximum areal average rainfall intensity of 0.80

inch/hour, and a simulated peak flow of 3,473 cfs which equates to a low-end moderate flood event (Figure 1). Radar showed that rainfall was intense, but confined to the lowermost reaches of the basin (Figure 2). KINEROS2 was run using the legacy DHR product and a dry initial soil moisture state. Radar precipitation estimates seemed reasonable when rainfall reports from the greater Borrego Springs area were compared.

Shortly after the event, the only verification the WFO received was that the road up through Fish Creek had been closed due to storm damage. The state park had not been up into the watershed to evaluate things in further detail. A field visit was conducted by Alex Tardy, Jayme Laber, and Michael Schaffner. State park ranger Steve Bier accompanied the group. The field visit to Anza-Borrego Desert State Park allowed for ground truth to be gathered to evaluate how the model performed. The first stop was Split Mountain Road which is the main road encountered that crosses downstream from the mouth of the Fish Creek canyon. The flow at the road was several feet deep and had caused road damage. Heavy equipment had to be brought in to clean the roadway of debris. This location is downstream from the model's outlet point and does have some local runoff contribution that is not included in the simulation. Further upstream, the group stopped at several locations upstream of the mouth of Fish Creek canyon including the reach of the stream modeled by KINEROS2 (Figure 3). A high water mark was observed 6 to 7 feet above the channels current streambed elevation (Figure 4). Further upstream near the confluence of the mainstem Fish Creek and the North Fork, a state park road sign was discovered. It had been removed from its original location by the flash flood and transported 1-mile downstream (Figure 5).

When state park ranger Steve Bier was asked if this event would have been a minor, moderate, or major flash flood, he commented that based on what he had seen in the field with us, it would have been a moderate flood event. Based on the field visit, KINEROS2 simulated a peak flow that fell into the appropriate flood category of moderate flooding. This is important since it not only verified the model during an actual event, but demonstrated that categorical forecasting is possible in semi-arid ungaged canyon locations using a distributed model forced with real-time radar data being run at a WFO. This is important in that it is aligned with other efforts within the agency to potentially provide categorical information in our flash flood warning products indicating the severity of the flash flood event (NWS 2015). The performance of the model is noteworthy since the rainfall was only over a small fraction of the basin and it correctly simulated the flood category.

In terms of lead time, the model provided approximately 1 hour and 36 minutes of lead time for Action Stage, 1 hour and 30 minutes of lead time for minor flooding, and 30 minutes of lead time for moderate flooding. Lead time for minor flooding was well in excess of both national and regional flash flood lead time metrics. The simulated hydrograph once exceeding minor flood stage spent a considerable amount of time flattening out as opposed to progressing higher in terms of simulated stage. According to the simulation, this resulted in Fish Creek being over minor flood stage for a full 2-hours. Moderate flood stage was exceeded for about 15-minutes.

August 12, 2017

On August 12th, Fish Creek had areal average rainfall of 1.93 inches using the legacy DHR product. The heaviest rainfall was over the upper one third of the watershed. The model was run at the WFO with legacy DHR product as forcing as seen in figure 6. The model was run with the “dry” initial soil moisture state. Areal average rainfall was two and half times what was seen during the August 3, 2014 event. Maximum areal average rainfall intensity was more than three times greater at 2.39 inch/hour. Model output, as viewed in WFO operations, showed Fish Creek cresting above the top of the rating curve. The rating curve tops out at 9.00 feet or 18,150 cfs. See figure 7. This is above the flood of record event of July 30, 2012 included in the calibration of the model. The flood of record was estimated at a minimum of 13,600 cfs and maximum of 14,970 cfs (Schaffner et al. 2014). The upper end discharge estimate is the 100-year peak flow value obtained from USGS regional regression equations. The flood of record included a helicopter rescue, vehicle transported downstream, media coverage, and high water marks throughout the watershed of a minimum of 10 foot depths. While it is not impossible for Fish Creek to generate peak flows exceeding the flood of record or the 100-year flood, multiple lines of evidence would need to validate this. To this end, a NWS flood survey was conducted, search of media, and a radar rainfall analysis.

A NWS flood survey, conducted by Alex Tardy, observed that the entrance into the creek was not drivable and the flood waters appeared to have been as wide as 250 feet with up to 3 feet deep near Split Mountain Road.   The depth of flood waters was observed in the field and the width estimated using Google Earth. Split Mountain Road was recently graded and plowed, after the flood, to reopen a lane for traffic. The creek was carrying a sediment load that was deposited once flow left the mouth of Fish Creek canyon closer to Split Mountain Road. See figure 8. Additional images from the flood survey can be viewed in figures 9 and 10.

The following was posted on Facebook by the Anza-Borrego Foundation on August 15, 2017.

“Our District's new ESI, Michael Ortiz, had quite the adventure last weekend out at Fish Creek! Here's what he had to say: "It started storming in the Fish Creek Watershed around 4 pm. We could see the storm and hear the thunder from Shell Reef. We got ourselves to high ground, the Fish Creek Campground, about 5:30pm. The temp dropped from 113F to 60F in a matter of minutes! The wind-driven, large rain drops hurt, but we were only on the edge of the storm and the main center was over the Upper Fish Creek Watershed. The storm sat there for an hour and then dissipated. The sun came out and things calmed down, and then we got flash flood warnings on our phone. We knew we should NOT be going in the wash, so we stayed safe at the campground above. At 6:30 pm, we heard a loud roaring coming down the canyon and we instantly recognized that a flood was coming. The flow lasted until about 3 am!" See the video posted on Facebook at:

https://www.facebook.com/AnzaBorregoFoundation/videos/1332961693469217/?hc_ref=ARSVPLDhuxd6eZzr9fBMiLcuoRa2U_6t2JVY5rrNNMOXPUDg82td8Z6Lq3-NT6ea8kM

The campground is a located a short distance downstream from the model outlet. Images courtesy of California State Parks taken by Michael Ortiz can be seen in figures 11-13. Channel width at the campground is estimated at 200 feet based on Google Earth imagery (Figure 14). Using an average estimated depth of flow of 2 feet and flow velocity of 8 feet per second yields a discharge of 3,200 cfs.

One rain gage (located at 32.913 -116.242) was in the path of the storm south of Fish Creek. The observer measured 1.05 inch for the storm total rainfall. At this point, radar Storm Total Precipitation (STP) estimates were 1.2 inches for Dual Pol, and 2.0 inch for Legacy Quantitative Precipitation Estimates. Based on reflectivity and radar algorithms there was likely hail in the storm which may have produced a high bias for legacy radar estimates.

Running the model with Dual Pol Digital Precipitation Rate (DPR) resulted in a peak flow of 3.95 feet or 3,118 cfs. The model was run with the “dry” initial soil moisture state. Areal average rainfall was 1.01 inch with maximum areal average rainfall intensity of 1.34 inch/hour. See figure 15. Rainfall over the basin can be viewed in figure 16. KINEROS2 being forced with Dual Pol precipitation produces reasonable results in terms of discharge. The location being modeled is further upstream from the location of the NWS flood survey. The channel is more constricted and hence the peak stage of 3.95 feet seems representative. In addition the peak flow simulated by the model of 3,118 cfs is nearly identical to the estimated peak flow of 3,200 cfs at the campground.

Recommendation going forward is for the WFO to run the model with Dual Pol forcing. If Legacy and Dual Pol editions of the model are running, more weight should be given to Dual Pol. This event demonstrates how precipitation forcing can produce over-simulation of peak flow. Precipitation forcing is the largest source of uncertainty in rainfall-runoff modeling. In addition, the maximum areal average rainfall intensity was greater than those included in the calibration dataset. The calibration dataset had a maximum areal average rainfall intensity of 2.00 inches per hour for the flood of record of July 30, 2012. This event had a 20% higher maximum areal average rainfall intensity at 2.39 inch/hour. While it is always physically possible to have a flood higher than the flood of record, radar rainfall estimates should be viewed with increased scrutiny when the model produces a simulation above the top of the rating curve.

The model first simulated Action Stage would be exceeded at 5:07 PM. This provided 1 hour and 22 minutes of lead time based on the time reported by Michael Ortiz. Lead time provided for Minor Flood Stage was 1 hour and 18 minutes. The model simulated peak flow, just below Moderate Flood Stage, with about an hour of lead time. Lead time for Action Stage, Minor Flood Stage, and maximum peak flow were well in excess of both national and regional flash flood lead time metrics. The amount of lead time for the maximum peak flow (~ Moderate Flood Stage) was 30-minutes longer than the prediction for August 3, 2014. This was due to the placement of heavy rainfall. In the August 2014 event, it was close to the outlet and in the August 2017 event upstream in the headwaters of mainstem Fish Creek.

NWS San Diego issued a Flash Flood Warning at 4:49 PM. This was 8 minutes before the model forecast Action Stage to be exceeded. The warning forecaster issued the warning based on storm reflectivity and radar trends over the basin. The radar data was critical before the model could assimilate the precipitation and predict the flow. The forecasters thought the KINEROS2 model was helpful with quantitative and temporal prediction. As a tool, It gave some context to the decision making process. Even though it likely overstated the severity of the flood at the Forecast Point (due to using Legacy Precip estimates), it was still helpful in visualizing the timing and trend of the flash flood. Flash Flood Warnings normally cover areas inclusive of varied terrain, which may augment or lessen severity of flow. Because of this, severity wording across the Warning is often nonspecific. In this case, it provided a specific geographic reference point of Fish Creek instead of a generic warning referencing "the warned area."

September 20, 2016

On September 20th, state park ranger Steve Bier reported some flow in the creek over 3 miles of travel and only a couple inches in depth. Flow during this event was minimal likely not more than 1 or 2 cfs. See figures 17 and 18. The model run with both Legacy and Dual Pol did not produce any flow. Light rain fell over the basin starting around 9:00 AM through 5:00 PM. Maximum areal average rainfall intensity was less than 0.20 inch/hour. Moderate rain fell from 5:00 PM through 11:00 PM with maximum areal average rainfall intensity of 0.51 inch/hour. Areal average rainfall for the event was 1.12 inches on Dual Pol and 1.02 with Legacy radar. This event demonstrated a very low or no flow successful simulation.

Conclusions

Prior to running KINEROS2 which began during the 2014 monsoon season, the WFO operations staff found it challenging to determine when flash flooding was to occur in Fish Creek. Even more difficult, was predicting the magnitude of flash flood events. Being able to predict the magnitude is essential to knowing if the basin should be mentioned by name or not in a Flash Flood Warning. Higher severity events likely require a longer flash flood warning.

The warning can now be clear and indicate not only “flash flood,” but level of impact. Location and degree of severity can be predicted in advance. The WFO can provide a location specific warning with adequate lead time exceeding national and regional flash flood metrics. Flash flood warning can be issued on a severity scale. The model can predict the severity of flash flooding due to its skill at categorical forecasting. The WFO has templates configured to streamline the issuance of a flash flood warning which contain predefined wording based on flood category. In the case of major flooding, the following wording would be used:

“Major Flooding of Fish Creek will likely occur due to the heavy rains. Persons near, within and well downstream of the canyon should seek higher ground immediately. This is a serious situation with significant flooding possible several miles downstream.”

As a result of this project, the WFO has defined impacts, a better understanding of flood risks, and a usable distributed model for Fish Creek. It allows forecasters the ability to predict the severity of flooding in the Fish Creek basin and provide enhanced DSS. These practices can be applied to other basins in Anza-Borrego Desert State Park.

Communicating flash flood risk in real time is challenging and considering Fish Creek is a remote canyon location with some portions having limited cellular coverage. The state park has limited ranger staff and may not be in the vicinity of Fish Creek when a flash flood warning is issued. One idea may be the installation of signage with flashers that are activated upon issuance of a flash flood warning. Such an installation could be potentially placed at the mouth of Fish Creek. Currently, the roadways only have signage which states year round “road may be flooded” or they place temporary barricades during events with the word “flooded”.

Forcing the model with Dual Pol as opposed to Legacy rainfall should result in more accurate forecasts of peak flow. Precipitation forcing is the largest source of error for the magnitude of peak flow. The August 12, 2017 event showed the potential for Legacy radar to overestimate and hence oversimulate the magnitude peak flow. Dual Pol provided a more representative simulation of peak flow magnitude.

An opportunity presents itself to inform national distributed modeling efforts. Fish Creek model parameters may be transferrable to other distributed models. In particular the ability of the model to handle channel transmissions losses and account for soil infiltration during localized convective rainfall events. The authors are interested in collaboration with other researchers to improve distributed modeling efforts in semi-arid regions.

Acknowledgements

In memory of the late Steve Bier and his shared years of knowledge of past flood events and their effects on the Fish Creek basin.

References

Anza-Borrego Foundation, 2017, August: Our District's new ESI, Michael Ortiz, had quite the adventure last weekend out at Fish Creek! [Facebook status update and video]. Retrieved from https://www.facebook.com/AnzaBorregoFoundation/videos/1332961693469217/?hc_ref=ARSVPLDhuxd6eZzr9fBMiLcuoRa2U_6t2JVY5rrNNMOXPUDg82td8Z6Lq3-NT6ea8kM

Schaffner, M., Unkrich, C., Goodrich, D., Tardy, A., Laber, J., 2014: Modeling Flash Flood Events in an Ungaged Semi-Arid Basin using a Real-Time Distributed Model: Fish Creek near Anza Borrego, California. NWS Western Region Technical Attachment 14-02. Retrieved from http://www.weather.gov/media/wrh/online_publications/TAs/TA1402.pdf

National Weather Service, 2015: Flash Flood Services of the Future: Flash Flood Summit and Focus Group Findings. Retrieved from http://www.nws.noaa.gov/os/water/resources/NOAA_Flash_Flood_Summit_Report5_29_15.pdf

<u>Figures</u>

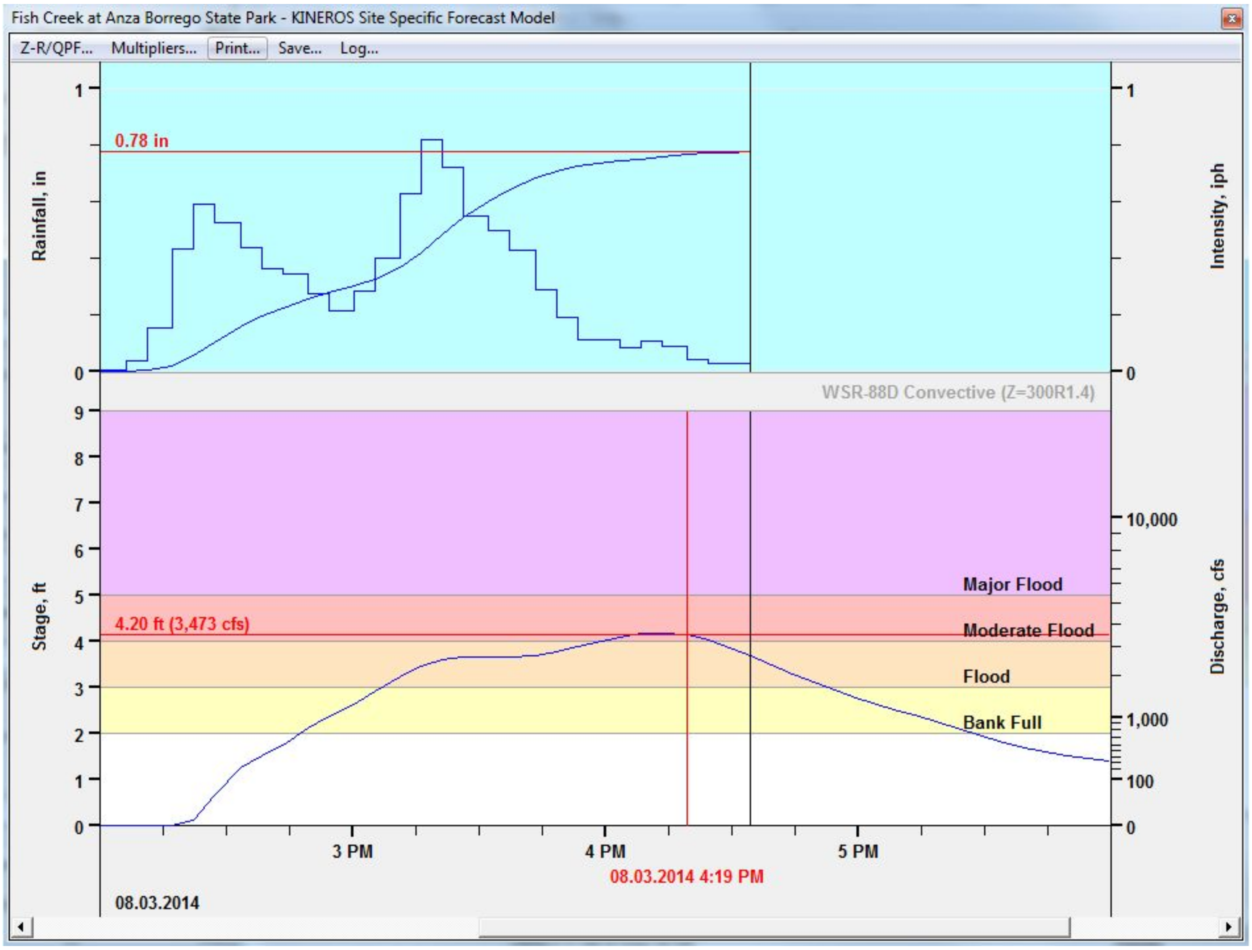

Figure 1: Screen capture from KINEROS2 model, for Fish Creek, run in WFO San Diego operations during the afternoon of August 3, 2014.

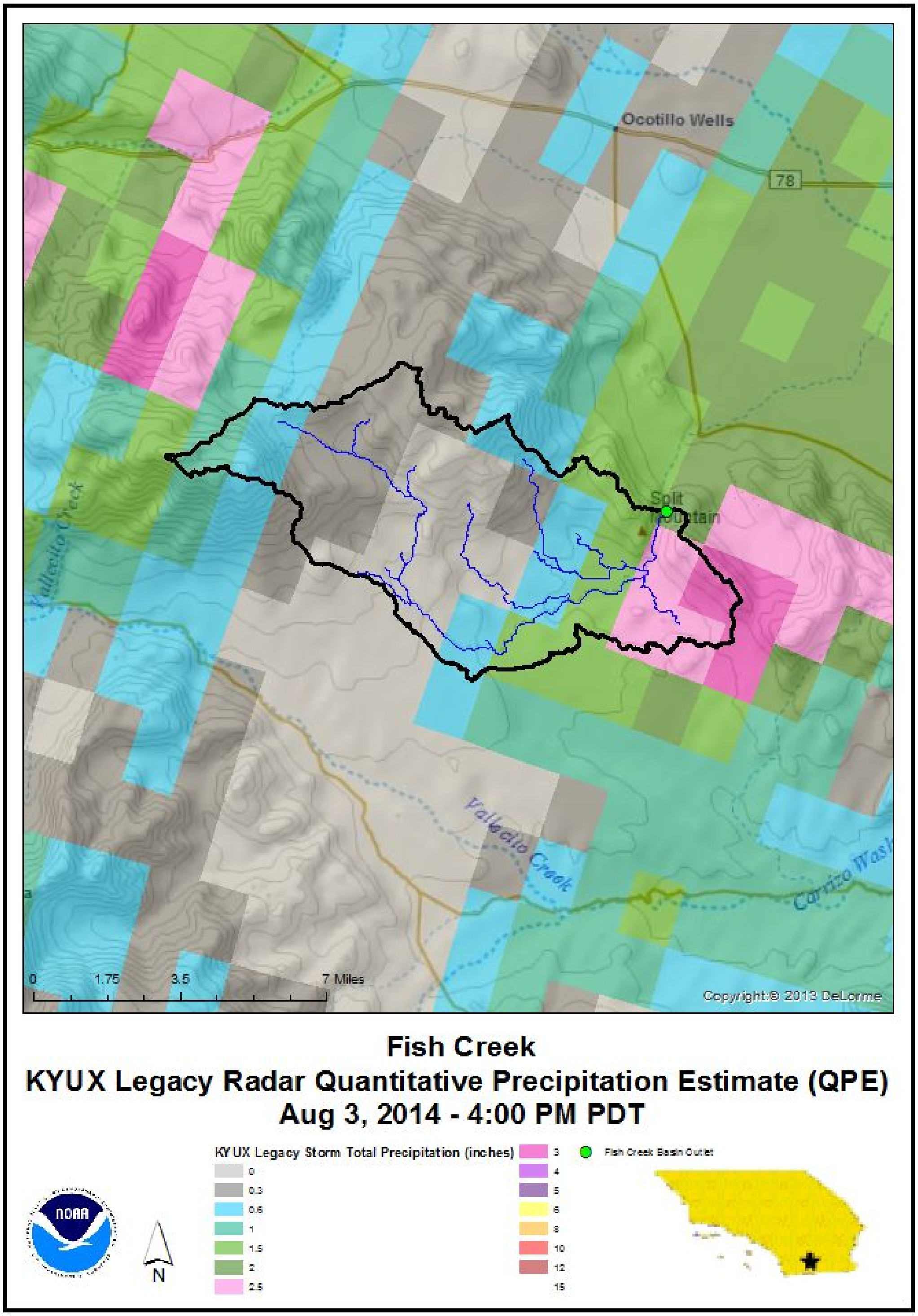

Figure 2: Radar Estimated Precipitation over the Fish Creek basin on August 3, 2014.

Figure 3: Portion of the modeled reach near Split Mountain. Alex Tardy in the foreground and state park ranger Steve Bier in the background. Photo by Jayme Laber.

Figure 4: High water mark 6 to 7 feet above Fish Creek channel bottom in the vicinity of where the creek cuts through Split Mountain. This is in the reach of the stream modeled by KINEROS2. Michael Schaffner pictured. Photo by Alex Tardy.

Figure 5: State park road sign uprooted and transported 1-mile downstream. State park ranger Steve Bier holding sign. Photo by Alex Tardy.

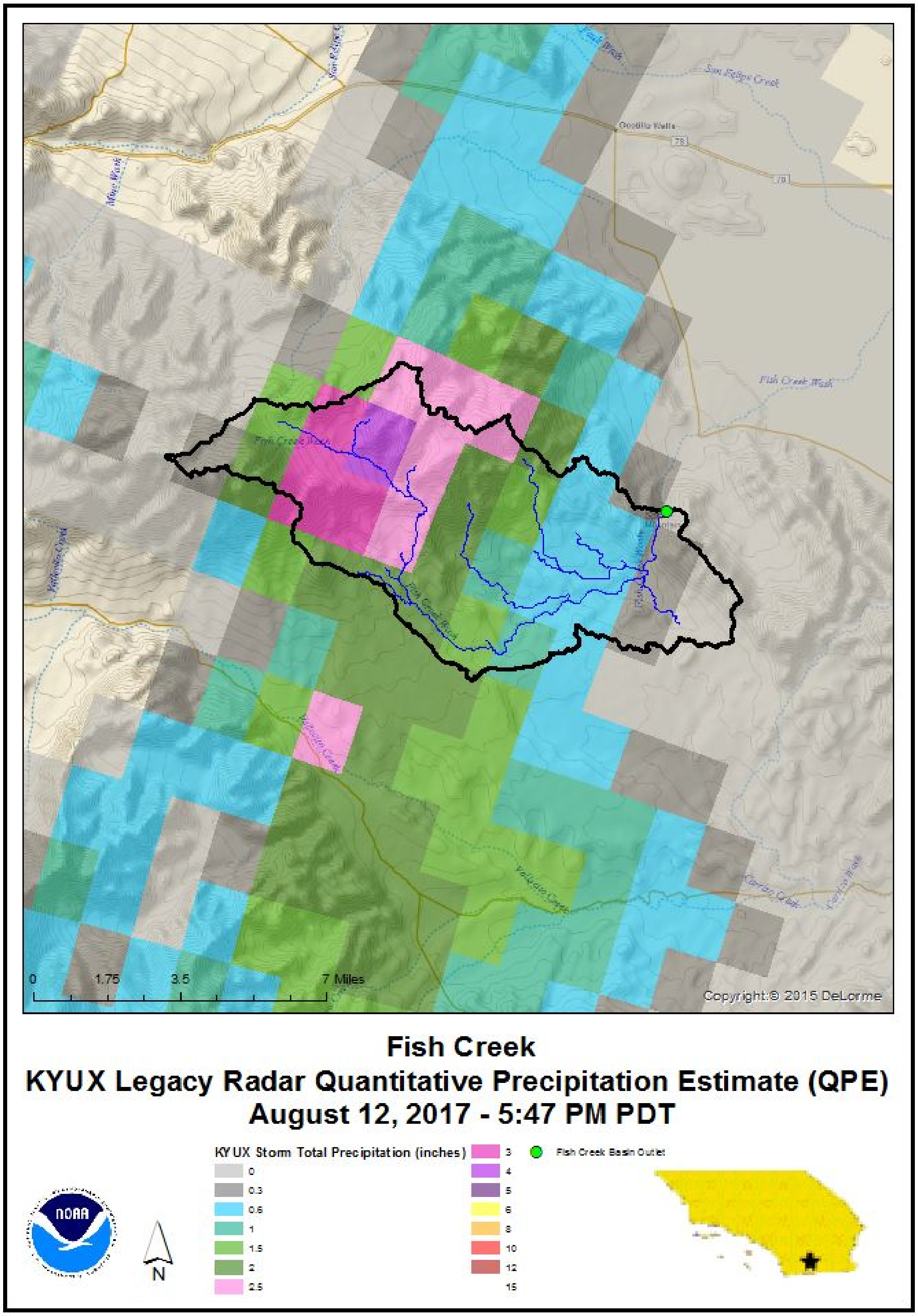

Figure 6: Legacy Radar Precipitation Estimate over the Fish Creek basin on August 12, 2017.

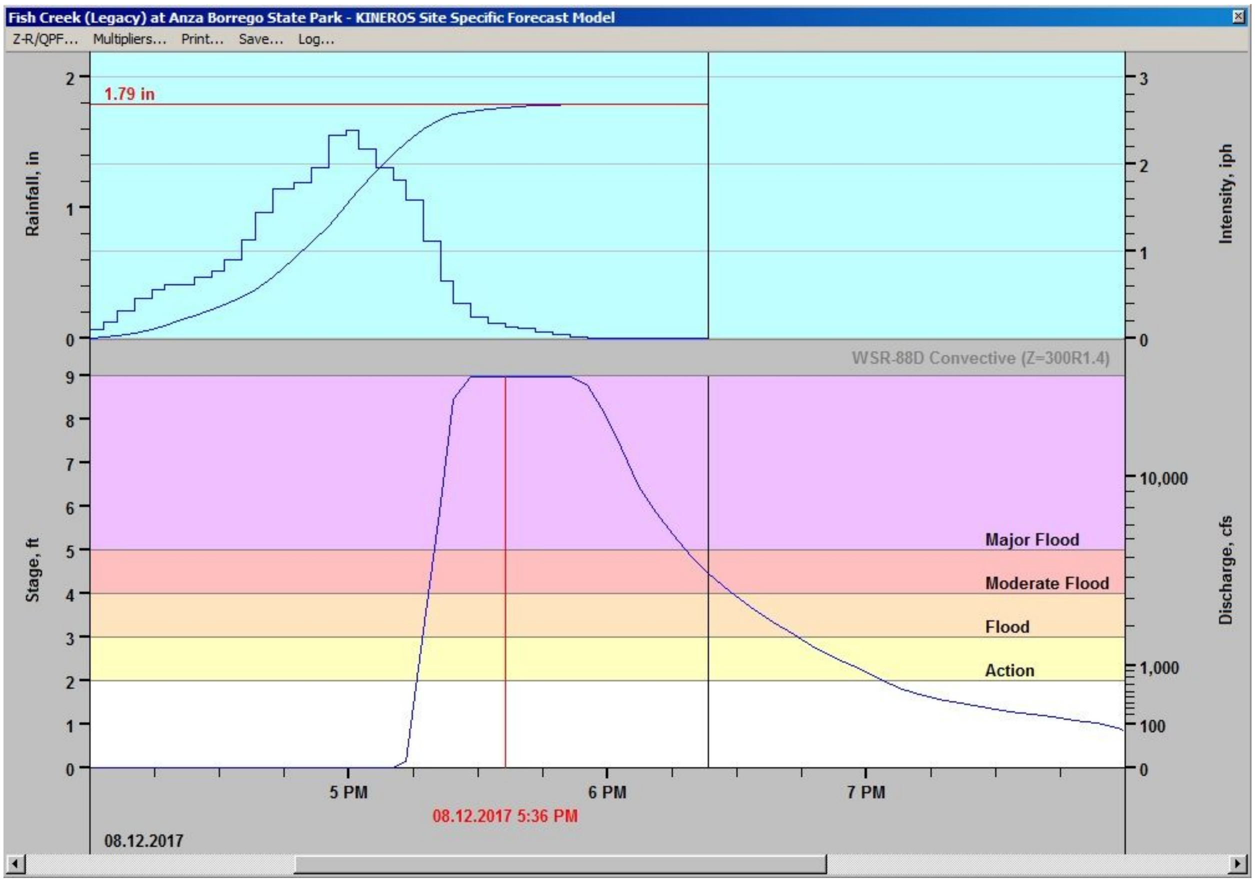

Figure 7: KINEROS2 model output, using legacy DHR radar, for August 12, 2017.

Figure 8: Sediment deposition near Split Mountain Road downstream from the mouth of Fish Creek canyon. Looking upstream toward Fish Creek canyon on the left. Photo by Alex Tardy.

Figure 9: Water overtopped bank near Split Mountain Road downstream from the mouth of Fish Creek canyon. Photo by Alex Tardy.

Figure 10: NWS flood survey images showing high water marks and conditions near Split Mountain Road. Image credit WFO San Diego.

Figure 11: Fish Creek channel looking from right bank to left bank from Fish Creek Primitive Campground taken on August 12, 2017. Photo courtesy of California State Parks (Michael Ortiz).

Figure 12: Fish Creek channel looking upstream from Fish Creek Primitive Campground taken on August 12, 2017. Photo courtesy of California State Parks (Michael Ortiz).

Figure 13: Fish Creek channel looking downstream toward Split Mountain Road from Fish Creek Primitive Campground taken on August 12, 2017. Photo courtesy of California State Parks (Michael Ortiz).

Figure 14: Channel width just upstream of Fish Creek Primitive Campground. Width estimated at 200 feet. Imagery and channel width estimate from Google Earth.

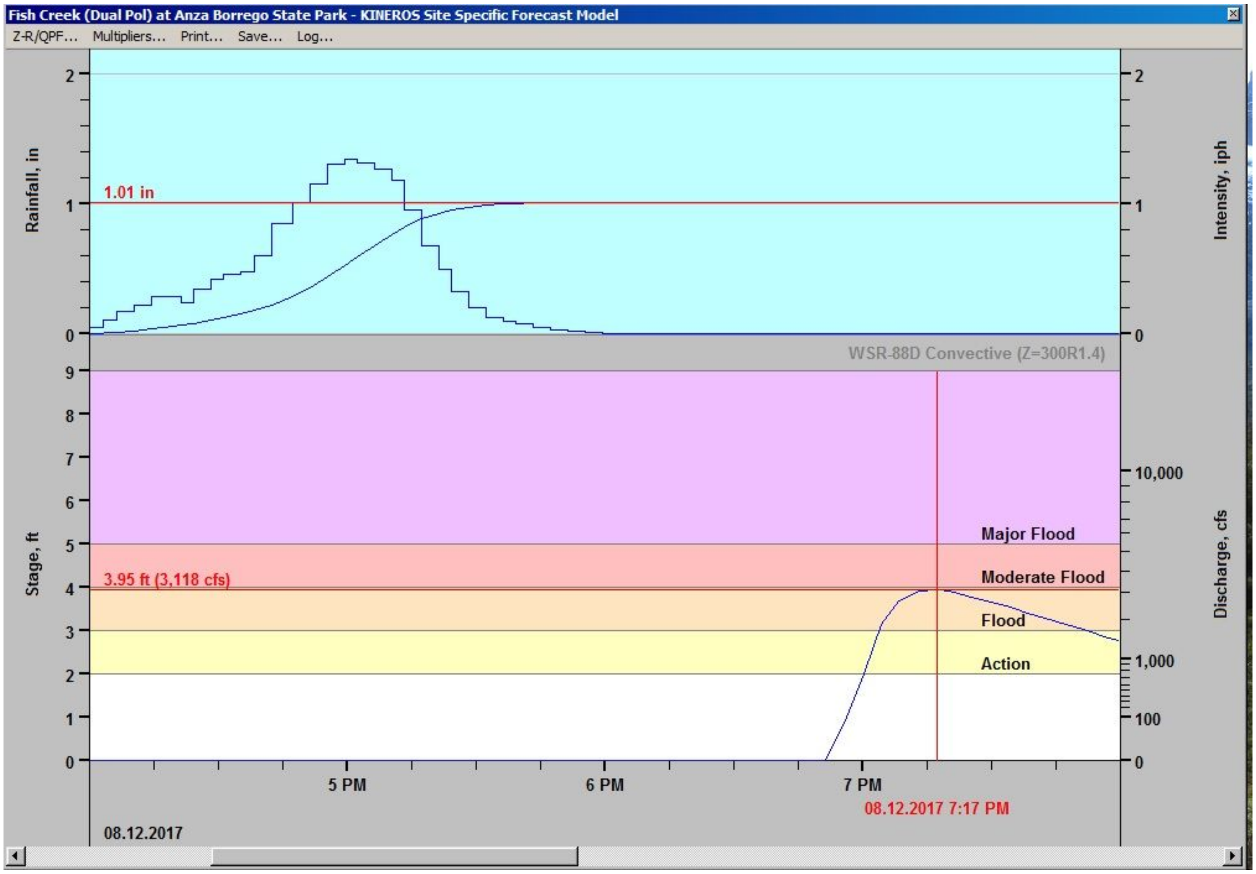

Figure 15: KINEROS2 model output, using Dual Pol DPR, for August 12, 2017.

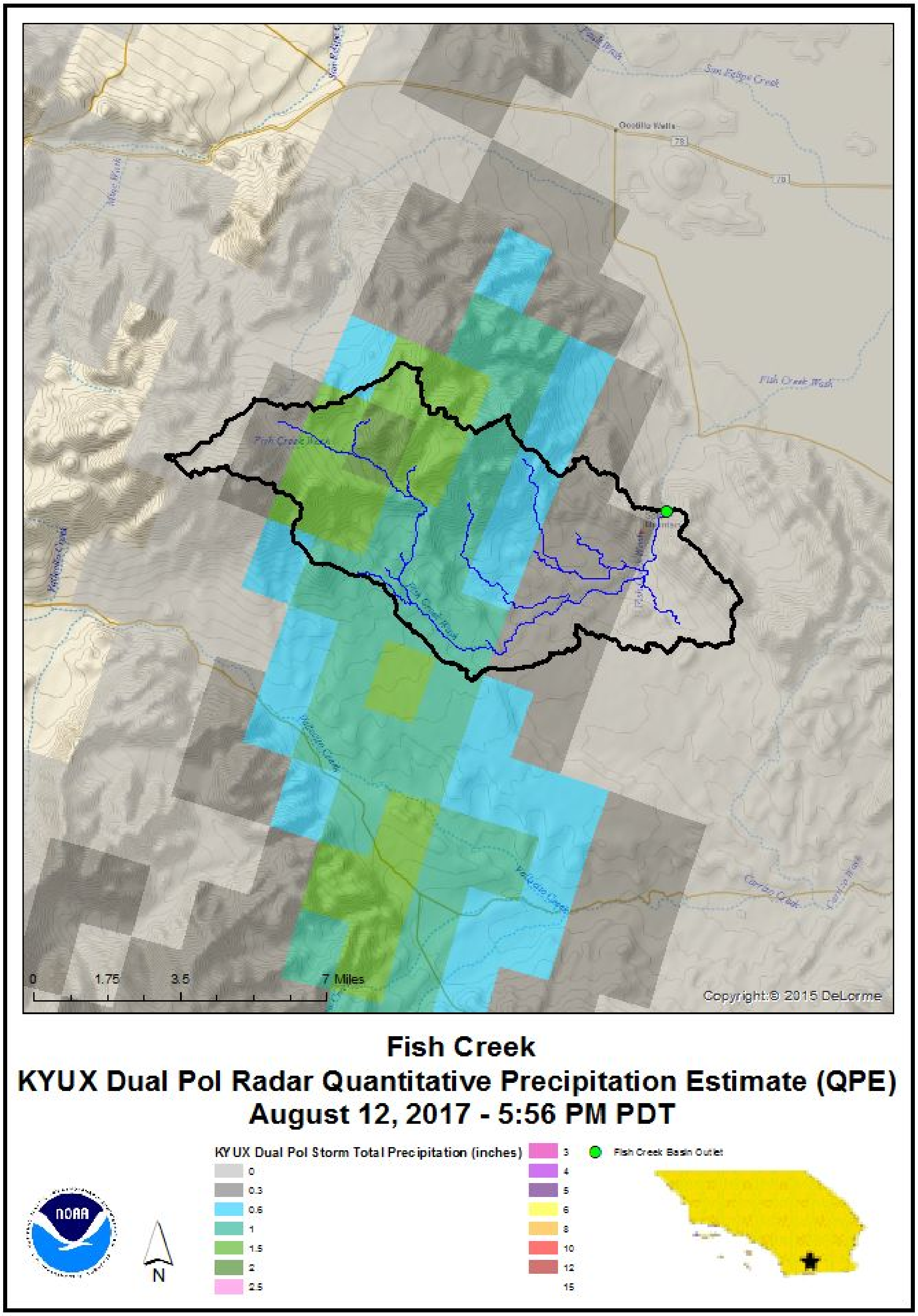

Figure 16: Dual Pol Radar Precipitation Estimate over the Fish Creek basin on August 12, 2017.

Figure 17: Low flow event in Fish Creek from September 20, 2016. Image taken looking toward the opening of Fish Creek canyon a short distance downstream from the modeled location. Image credit Steve Bier.

Figure 18: Low flow event in Fish Creek from September 20, 2016. Image taken inside Fish Creek canyon a short distance upstream from the modeled location. Image credit Steve Bier.