Modeling Hydrologic Events in a Semi-Arid Basin of Complex Terrain using a Real Time Distributed Model: Short Creek at Colorado City, Arizona

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ABSTRACT

Headwater basins and canyons that quickly respond to heavy rainfall 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 Short Creek basin located upstream of Colorado City, Arizona. In operations, KINEROS2 uses real-time radar data to produce a forecast hydrograph, but due to inherent uncertainties in calibrating for gauged locations without a maintained rating curve, the forecast will be categorical in nature (no flooding, minor flooding, moderate flooding, or major flooding). The model was calibrated using a series of rainfall events representing a range of flow outcomes from low flow events below action stage up to events exceeding action stage. Calibration was successful in reproducing the correct flood category for four out of five simulated events. Timing of simulated and observed peak flows, for events that exceeded Action Stage, had a mean difference of four minutes. A calibration scheme was employed which varied with increasing areal average maximum rainfall intensity. The timing and magnitude of the peak flow, in small fast responding basins, is useful information currently not available using NOAA/NWS flash flood forecasting methodologies at the Weather Forecast Office.

Introduction

Short Creek covers 24 square miles above the outlet point selected for this study. Short Creek basin is frequently visited for hiking and recreational vehicle traffic further upstream. Persons are routinely canyoneering the 11-mile loop through Water Canyon and Squirrel Canyon. Contained within are narrows, slot canyons, and rock arch formations. The watershed is essentially a dissected plateau with steep cliff-like formations. Short Creek is a fast responding basin with time from peak rainfall to peak flow at Colorado City ranging from 30-minutes to 90-minutes. The outlet point corresponds to the location of a Mohave County Flood Control stream gage at the Central Street bridge in Colorado City. The gage was installed in March of 2006. Station sensors include a pressure transducer and precipitation gage. The gage is stage only and a rating curve is not maintained.

Despite reasonable radar coverage from the Cedar City (KICX) WSR-88D (Weather Surveillance Radar 88 Doppler), 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 that runs using real-time radar data at every volume scan to compute a forecast hydrograph is one such solution. When calibrated, it can translate the rainfall into guidance for the forecaster on the magnitude and timing of the peak flow. The guidance could be incorporated into a flash flood warning and other DSS could be provided. Forecasting and calibration of a distributed model for one basin can be applied to similar nearby basins in efforts to effectively provide warning with greater specificity and longer lead time.

Discharge Estimation for September 14, 2015 Flood

The flood of September 14, 2015 was the highest recorded peak since installation of the stream gage. After being damaged by debris and sedimentation, the gage continued to function until 17-minutes after the time of the peak flow. The peak discharge was an indirect discharge estimate. Channel cross section was estimated based on observations in the field, stream gage stage readings, and Google Earth imagery. The channel just upstream of the stream gage was estimated as a trapezoid. Dimensions were 6.67 feet high corresponding to the stream gage peak stage. It is assumed the gage captured the height of the peak flow before being damaged. Other dimensions were 40 feet wide at the bottom of the channel and 120 feet wide at the top of the cross section. This equals 533 square feet. Using 3 feet per second average flow velocity results in a peak flow of 1600 cfs. The peak flow corresponds to the USGS 50-year return flow. USGS return flows were generated using StreamStats (Kenney et al., 2008). Regression equations for Utah were used since 90% of the watershed is in Utah as opposed to Arizona. The average flow velocity was conservative and hence the magnitude of the peak flow should be considered the minimum discharge for the event.

Development of Peak Flow Rating Curve

The graphical user interface (GUI) requires a rating curve to convert modeled discharge to stage. A rating curve was developed using channel geometry near the stream gage, the peak discharge estimate for the September 14, 2015 event, and assumptions about the average streamflow velocity across the entire cross sectional area at various depths. Since the September 14, 2015 event is not necessarily the upper limit, the rating curve was extended to a stage of 8 feet.

The channel is composed of sand and subordinate gravel, therefore it will likely change significantly over time due to fill and scour. The rating curve is static and was based on idealized channel geometry and assumptions on flow velocity during the September 14, 2015 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 stretch of Short Creek within Colorado City in the vicinity of the Central Street bridge.

The modeling approach is semi-quantitative where the simulated hydrograph will be used for categorical forecasting. Categorical forecasting provides the 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.

Determination of Flood Thresholds

Modeling Short Creek required the determination of action, minor, moderate and major flood stages. For most of the country, flood stages begin above bankfull. Since Short Creek is in a dry wash canyon landscape, flood impacts begin at stages below bankfull so the Minor Flood Stage selected is designed to represent within-bank flooding, rather than traditional out of bank flows.

Flood stages generally apply to the reach of Short Creek 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.

Setting flood stages for a location like Short Creek 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 an actively updated rating curve for the stream gage. Therefore flood stages should be considered preliminary.

Action Stage was set at 3.0 feet which corresponds to an estimated peak discharge of 262 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 channel and does not impact any of the overbank area. Low water crossings likely have water flowing over them. Action stage is set low to account for bank erosion and proactive monitoring and closing of bridges and low water crossings by emergency services in Colorado City and upstream in Hildale along Short Creek. An automated alarm is generated when the stream gage records a streamflow event that exceeds 1.5 feet in depth or when event rainfall exceeds 1.00 inches within a 1-hour period.

Until the September 14, 2015 flood event, Mohave County Flood Control conveyed that to their knowledge all of the previous higher flows were contained within the channel. Therefore it is assumed that no out of bank flooding occurred below 4.10 feet / 550 cfs. It is not known at what stage / flow water begins to break out of the channel and inundate fields and at what point bridges would be overtopped.

Minor Flood Stage was set at 5.0 feet which corresponds to an estimated peak discharge of 882 cfs. This equates to greater than a 10-year peak flow and less than a 25-year peak flow.

Moderate Flood Stage was set at 6.0 feet which corresponds to an estimated peak discharge of 1295 cfs. This equates to greater than a 25-year peak flow and less than a 50-year peak flow. Moderate Flood Stage is 0.67 feet below the September 14, 2015 flood. The flood of September 14, 2015 was considered to be a high end moderate flood. The Central Street bridge was overtopped due to the deposition of sediment. Other bridges had damage and concrete erosion. Channel breakouts occurred in several locations flooding agricultural fields and out buildings. Primary residences received some flood damage from flooding along tributary streams to Short Creek, but not from Short Creek itself.

Major Flood Stage was set at 7.0 feet which corresponds to an estimated peak discharge of 1715 cfs. This just exceeds a 50-year peak flow. Major Flood Stage is 0.33 feet above the September 14, 2015 flood. At major flooding, primary residences and other bridges should begin to be impacted

Flood stages in context to historical peak flows and USGS peak flow statistics can be viewed in Figure 1.

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 KINEROS2 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 watershed into hillslope elements contributing to open channel elements. The hillslopes are represented by sloping rectangular planes. AGWA, along with some manual edits to the plane polygons was used to create what the authors refer to as a "cascading planes" discretization of the watershed. Manual edits were made by overlaying the plane polygons with elevation contours and a hillshade map. This allowed for planes to be divided at major slope breaks. The cascading planes discretization provides a more accurate representation of the watershed which is characterized by deep canyons cut into a relatively flat plateau. The watershed response could be much different depending on whether rain falls on the flat areas versus the steeper canyon areas. AGWA, when run in default mode, would blur this effect by averaging the slopes.

Refer to Figure 2 for an image of the model elements AGWA created for the KINEROS2 model for Short Creek. 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 using regional regression relationships.

Mainstem channels in Short Creek are sandy and likely have transmission losses. Most of the year, there is no base flow at the stream gage. AGWA assigns a uniform saturated hydrologic conductivity in the channels of 210 mm/hr assuming a sandy bottom channel without restricting bedrock underneath.

<u>Model Calibration Events</u>

A total of seven events were evaluated to create an initial calibration. All events were convective in nature. Except for one event from mid-October, all events occurred during the monsoon season months of July, August, and September. Rainfall events varied widely in terms of areal average rainfall and maximum areal average rainfall intensity (Figure 3). Events of both single and multiple rainfall pulses were evaluated. Six events had peak flow times in the afternoon, evening, or early overnight hours. Only one event peaked in the mid-morning hours.

<u>Model Calibration Assumptions</u>

The model was run for all events using the Dual Pol Digital Instantaneous Precipitation Rate (DPR) product. The 1-degree, 250m DPR was down-sampled to 1-degree, 1km by computing the area-weighted average of the precipitation rates in the four 250m range gates within each 1-km range gate.

The user provides the initial flow rate in cfs at the start of each event to be modeled. The assumption was that the Short Creek channel was dry at the start of each event. The ALERT stream gage record shows zero flow most of the year.

The model requires the user to provide an initial soil moisture state. These are selected from a drop-down menu on the KINEROS2 start-up Graphical User Interface. Five selections are available with these being super "dry," "very dry," "dry," "wet," and "very wet." Each selection represents a percentage of soil pore space filled with water. For the selections these are 0, 20, 40, 60, and 80 percent. An initial soil moisture state of dry was used for all simulations.

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 for overland flow planes would increase the original parameter value for each overland flow model element by 50%. 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. The saturated hydrologic conductivity of channel segments was varied to evaluate the influence of transmission losses.

Parameter multipliers for each event can be seen in Figure 4. Model calibration resulted in a set of parameters that varied with maximum basin average rainfall intensity. The saturated hydrologic conductivity multiplier of channel segments was kept constant for all events at 0.50. Channel length multiplier and channel manning roughness multiplier showed some trend from 0.50 to 0.75 for lower intensity events upward to 1.00 for higher intensity events. Saturated hydrologic conductivity multiplier of overland planes trended upward with increasing maximum basin average rainfall intensity, but contained two outlier events (Figure 5). An increase in steady state infiltration rates with increasing rainfall intensity has been observed by Hawkins (1982), Dunne et al. (1991), Morin and Kosovsky (1995), Janeau et al. (1999), Gomez et al.

(2001), Holden and Burt (2002), Merz et al. (2002), Paige et al. (2002) and Stone et al. (2008) when estimating steady-state infiltration using the difference in rainfall volume and outflow volume (Hawkins 1982). This increase to the apparent infiltration rate with increasing rainfall intensity is explained by the spatial variability of the soils and vegetation in the area of interest (Stone et al., 2008). With an increase in rainfall intensity, more area will begin to contribute to runoff, and this newly contributing area will typically have a greater infiltration rate (Stone et al., 2008). According to Dunne et al. (1991) the higher parts of the microtopography of a hillslope will have higher infiltration rates due to a greater density of macropores caused by vegetation and the higher concentration of organic matter from vegetation litter that accumulates under vegetation (Abrahams 1995; Bhark and Small 2003).

The July 26, 2013 event required an abnormally high saturated hydrologic conductivity multiplier to match the magnitude of the peak flow. The ALERT stream gage recorded a peak stage of 1.29 feet. This is below Action Stage and Minor Flood Stage. The observed hydrograph for the event does not appear to have any erroneous data (Figure 6). NWS Storm Database recorded two flash flood reports. One storm report 1 mile northwest of Colorado City reported several basements in Colorado City were flooded with an estimate of $50,000 in property damages. Another storm report located in Colorado City reported four to six inches of water and small rocks across streets in Colorado City with an estimate of $1,000 in property damage. These reports nor the gage height point to flooding originating from Short Creek. The most likely reason for the model over-simulation and high saturated hydrologic conductivity multiplier was a significant overestimation of rainfall by the radar. This event is an outlier and should not be included in the development of the operational calibration.

Conversely, the September 14, 2015 event required an abnormally low saturated hydrologic conductivity multiplier to come close to matching the magnitude of the peak flow. The ALERT stream gage recorded a peak stage of 6.67 feet. A saturated hydrologic conductivity multiplier of 0.01 produced a simulated peak stage of 6.18 feet. One reason why such a low saturated hydrologic conductivity multiplier might be required would be significant underestimation of rainfall by the radar. But this was not the case when available rain gages were compared to radar rainfall estimates. NWS Salt Lake City conducted a comparison of radar rainfall vs rain gage totals for the second of two rainfall pulses from the event. The comparison showed close agreement between the radar rainfall and rain gage reports (Figure 7). A NWS flood survey confirmed the magnitude of the peak stage recorded by the ALERT stream gage. NWS conducted an indirect discharge estimate near the mouth of Maxwell Canyon at a low water road crossing (Figure 8). Maxwell Canyon intersects Short Creek 1.50 river miles upstream of the ALERT stream gage. The estimate for peak discharge was 2,000 cfs (Schaffner 2015). The indirect discharge estimate at the Maxwell Canyon low water crossing approximated a 500-year recurrence interval flow. It equaled about 60% of the Crippen and Bue probable maximum flow generated from a 2 square mile watershed. Persons interviewed during the NWS flood survey mentioned elevated flow in the mainstem of Short Creek, but most of the flow originated from Maxwell Canyon. It is entirely possible that natural debris dam(s) formed in Maxwell Canyon or its small tributary streams contributed to the magnitude of the peak flow. KINEROS2 does not have the ability to model such physical processes. As such, this event was an outlier and should not be included in the development of the operational calibration.

Excluding the two outlier events, a total of five events were available to develop the operational calibration. The operational calibration consists of the parameter multipliers that KINEROS2 will run to generate a forecast hydrograph for the outlet point of the watershed in real-time. The operational calibration can be viewed in Figure 9.

Model Simulations in Forecast Mode

The model was run in forecast mode using the operational calibration. For all events, the model was run on 5-minute time steps. Model forecasts were compared to ALERT stream gage unit values with the exception of the October 17, 2015 flow event. Model simulation results were evaluated based on the difference in magnitude of peak flow, predicted flood category, and timing of peak flow. The model correctly predicted the flood category for four out of five events (Figure 10). The difference between observed and simulated peak stage was within one foot for all except one event.

The stream gage was not working for the October 17, 2015 event in the aftermath of the September 14, 2015 flash flood. For this event, model simulation results were compared to flood impacts derived from video of the event (St. George News 2015) and from reports NWS Las Vegas received from Colorado City emergency services. Video footage shows Short Creek well contained within the channel just upstream of the State Highway 389 Bridge (Figures 11 and 12). Further upstream, near the model outlet point, video shows water going over and around a bridge crossing (Figures 13 and 14). The September 14, 2015 event laid down a significant amount of sediment and debris near the model outlet point. This contributed to the impacts at the bridge pictured in Figures 13 and 14. Without the added sedimentation and debris, the flow would have likely been able to pass under the bridge. The model simulated a peak flow of 1.40 feet which is a modest rise within the channel, but below Action Stage (Figure 15). Based on video footage, this is a reasonable simulation.

Peak flow times were within less than 20-minutes of the observed for all events (Figure 16). If we exclude the July 28, 2013 event and only evaluate those events that exceeded Action Stage, peak flow times were within less than 8-minutes with an average difference of 4-minutes.

Lead Time Provided by KINEROS2

Two events where Action Stage was exceeded and reports were received from impacts in Colorado City due to Short Creek were evaluated for lead time provided by KINEROS2. Information provided by the model simulation was compared to warnings and products issued by the NWS Las Vegas.

The August 26, 2013 event was simulated well by KINEROS2 both in terms of the magnitude and timing of the peak flow. The model first predicted Action Stage would be exceeded at 5:39 PM. This provided 1-hour and 5-minutes of lead time based on an observed time of 6:44 PM when Action Stage was exceeded.

NWS issued a Flash Flood Warning for northeast Mohave County at 4:56 PM which was valid till 7:00 PM. Colorado City was included in the warning. It mentioned a near-stationary line of thunderstorms with very heavy rain located 6-miles west of Colorado City. At 5:37 PM a Flash Flood Statement was issued. The statement updated the position of the line of thunderstorms with heavy rainfall which was now located over Colorado City. The statement mentions a report of one foot of water running down Johnson Avenue from a trained weather spotter with a timestamp of 5:30 PM. Johnson Avenue is several blocks south of Short Creek and the referenced flooding was likely due to local runoff and not from Short Creek. A second Flash Flood Warning was issued at 6:55 PM and valid till 8:00 PM. Mention was made of continued flash flooding in Colorado City as water drained out of the mountains from earlier rainfall.

Forecast output from KINEROS2 could have been used from this event to support NWS operations by providing key details on the flash flooding from water that drained out of the mountains which was likely a reference to rainfall that fell in the headwaters of Short Creek and drained down through the Short Creek drainage.

The September 27, 2014 event was under-simulated in terms of magnitude, but did well on timing of peak flow. The model first predicted Action Stage would be exceeded at 8:55 AM. This provided 1-hour and 3-minutes of lead time based on an observed time of 9:58 AM when Action Stage was exceeded.

NWS issued a Flash Flood Warning for northeast Mohave County at 8:40 AM which was valid till 11:45 AM. The warning mentioned a thunderstorm near Colorado City that was nearly stationary. At 9:53 AM a Flash Flood Statement was issued. The statement indicated thunderstorms producing flash flooding continued over the Colorado City area.

The Flash Flood Warning was extended in time at 11:39 AM. The warning mentioned that trained weather spotters reported flash flooding from thunderstorms that moved through Colorado City. The warning made mention that Mohave County gauges reported 2 to 3 feet of water flowing in Short Creek. A Flash Flood Statement was issued at 12:27 PM canceling the warning. Reports indicated that flood waters had receded in Colorado City. NWS Storm Database recorded one flash flood report. The storm report 2 miles west-northwest of Colorado City reported numerous roads were flooded in Colorado City including every Short Creek crossing in town with an estimate of $10,000 in property damages.

Forecast output from KINEROS2 could have been used from this event to provide information on the length of time Short Creek would have remained elevated above/near Action Stage.

Model Sensitivity to near term Antecedent Rainfall

The September 27, 2014 event contained several pulses of rainfall. An initial smaller pulse of rain fell from 1:30 to 3:30 AM and totaled 0.39 inches (Figure 17). This resulted in an observed peak flow of 0.75 feet at 3:25 AM. KINEROS2 simulated a peak flow of 0.87 feet (Figure 18). Both the observations and the simulation receded back to zero flow by 7:00 AM. Magnitude of simulated peak flow differs if the start time of the model includes or excludes the antecedent rainfall. A simulation start time of 1:15 AM results in a peak flow of 3.27 feet (320 cfs) (Figure 19). A simulation start time of 7:00 AM results in a peak flow of 2.31 feet (158 cfs) (Figure 20). The infiltration model in KINEROS2 includes a soil moisture redistribution component which estimates the reduction in soil moisture due to continued drainage of soil water. It is intended for relatively brief interruptions in rainfall or periods of low rainfall, as it does not account for evaporation or transpiration. It is a judgment call for the user as to whether evapotranspiration is significant enough to stop the model during the hiatus and start a new event with a user-estimated soil moisture state. From a NWS operational standpoint, the selection of start time and including/excluding the initial 0.39 inch basin average rainfall results in the peak flow exceeding or falling short of Action Stage. **A best practice would be to include measurable antecedent rainfall over the basin within the past 8- to 12-hours**.

Summary and Conclusions

Providing guidance for Short Creek at Colorado City is important for characterizing the magnitude of a flash flood. The magnitude of flash flooding is related to impacts both within the channel and more importantly out of the channel. This includes inundation of fields, and flooding of low water crossings and bridges. This information can add value to legacy Flash Flood Warning products and help to communicate the severity and urgency of an event. Timing information is important for conveying the onset of flash flooding and receding of flood waters. Combining model output with radar precipitation estimates, future radar trends, observations from the Short Creek ALERT stream gage, and real-time reports on the ground provided by Colorado City Communications Center can help to form a more comprehensive flash flood warning system.

The KINEROS2 model simulated the magnitude of the peak flow within the correct flood stage category for the majority of events and did well on the timing of the peak flow. Considering the semi-arid nature of the basin, the complex terrain, areas of slick rock, vertical cliff breaks, sand channels subject to scour and fill and transmission losses, the model results are reasonable. The model will be run in operations at NWS Las Vegas in an experimental mode during the 2016 monsoon season to evaluate its performance in real-time along with existing tools and methods of flash flood detection. Model output can also be compared to that generated by the National Water Center National Water Model (NWM).

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	Stage (feet)	Discharge (cfs)
July 26, 2013	1.29	40
July 20, 2008	1.36	50
July 28, 2013	2.06	125
2-Year Flow	2.15	134
Action	3.00	262
July 18, 2015	3.02	270
5-Year Flow	3.40	370
August 26, 2013	3.47	380
September 27, 2014	4.10	550
Minor Flooding	5.00	882
25-Year Flow	5.55	1100
Moderate Flooding	6.00	1295
50-Year Peak Flow	6.67	1600
September 14, 2015	6.67	1600
Major Flooding	7.00	1715
100-Year Flow		2090
200-Year Flow		2780
500-Year Flow		3920

Figure 1. Flood stages with historical peak flows and peak flow statistics. Stages for flow events provided by Mohave County Flood Control District. Discharge for flow events estimated from NWS rating curve. Peak flow statistics calculated by USGS StreamStats.

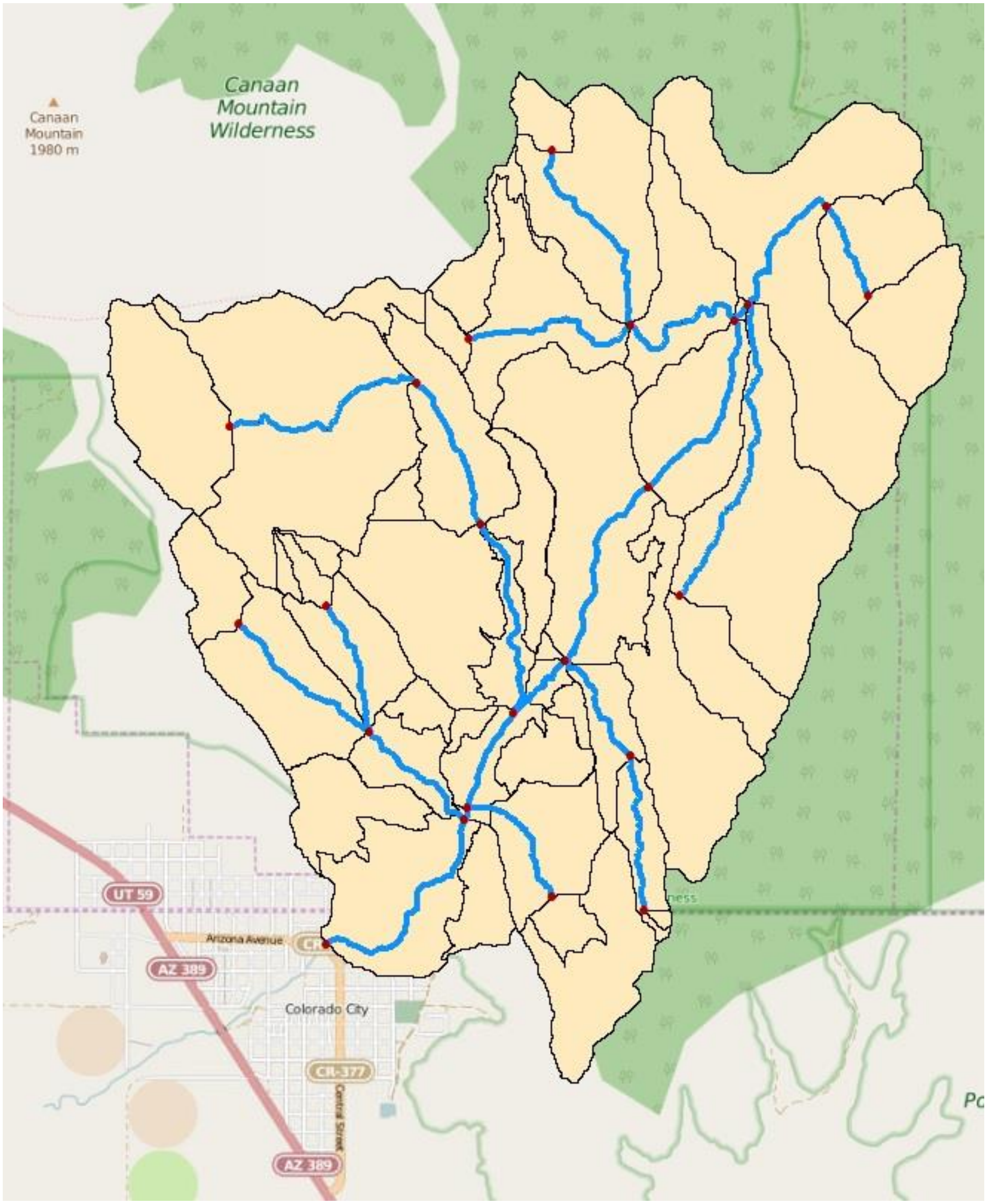

Figure 2. Plan view of KINEROS2 model elements. Open channel elements are represented by blue line segments. Model nodes are represented by red circles. The red circle located at the extreme southwest corner of watershed is the outlet point.

Event	Observed Peak Stage (ft)	Basin Average Rainfall (inches)	Basin Average Maximum Rainfall Intensity (inches/hour)
July 26. 2013	1.29	1.00	0.97
July 28, 2013	2.06	1.25	1.11
August 26, 2013	3.47	0.75	1.70
September 27, 2014	4.10	0.80	0.87
July 18, 2015	3.02	1.00	2.16
September 14, 2015	6.67	0.59	1.09
October 17, 2015*	NA	0.37	0.54

Figure 3. Model calibration rainfall events. Rainfall is totaled from the start time of the event to the time of peak river stage as recorded by the stream gage. *For the October 17, 2015 event where the stream gage was not functioning, the total rainfall was reported.

Event	Basin Average Maximum Rainfall Intensity (inches/hour)	Saturated Hydrologic Conductivity Multiplier of Overland Planes	Saturated Hydrologic Conductivity Multiplier of Channel Segments	Channel Manning Roughness Multiplier	Channel Length Multiplier
July 26. 2013	0.97	4.94	0.50	1.00	1.00
July 28, 2013	1.11	0.90	0.50	0.75	0.75
August 26, 2013	1.70	0.63	0.50	1.00	1.00
September 27, 2014	0.87	0.24	0.50	0.60	0.60
July 18, 2015	2.16	1.06	0.50	1.00	1.00
September 14, 2015	1.09	0.01	0.50	0.50	0.50
October 17, 2015	0.54	0.10	0.50	0.60	0.60

Figure 4. Model calibration results.

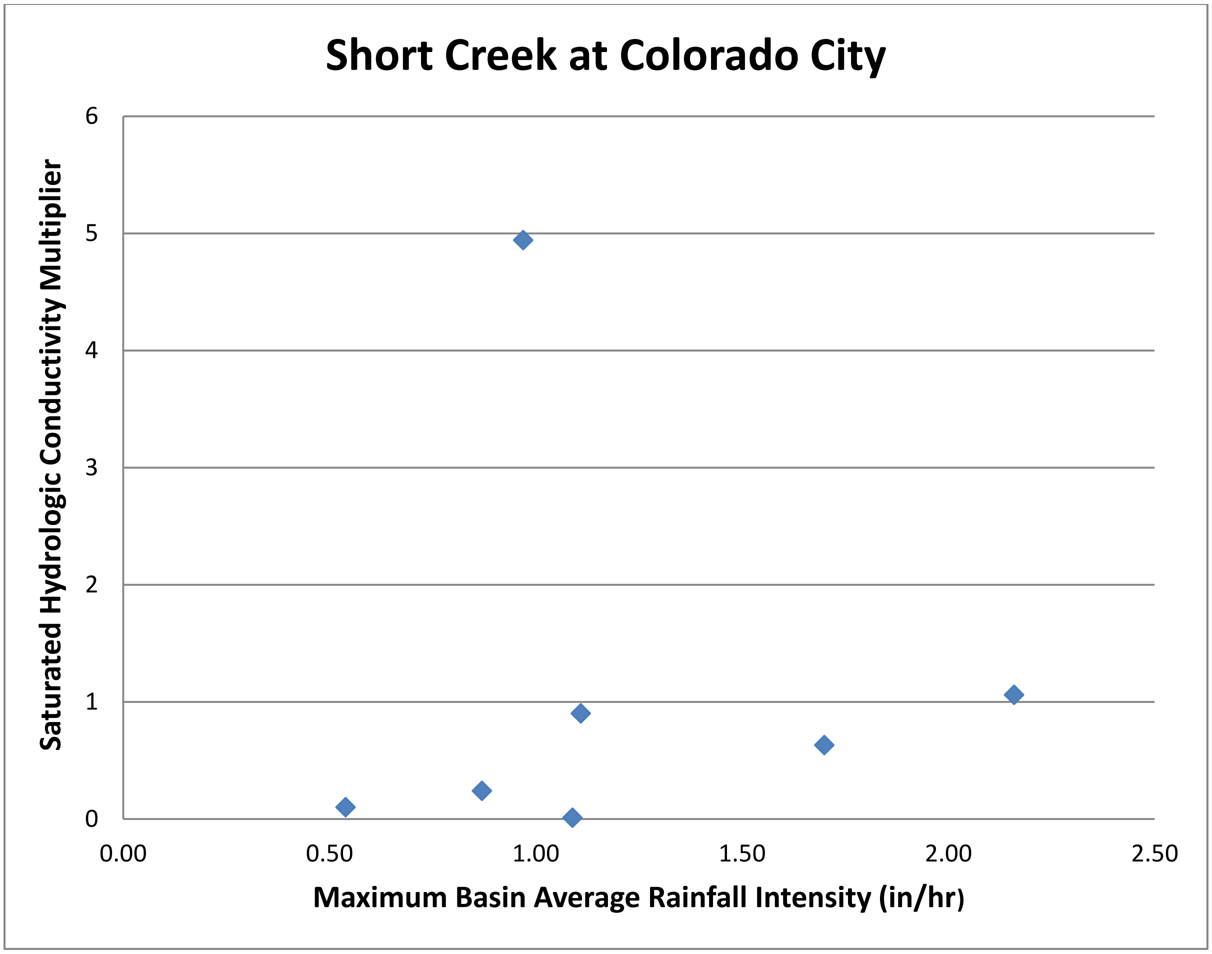

Figure 5. Plot of Saturated Hydrologic Conductivity Multiplier of overland planes vs maximum basin average rainfall intensity.

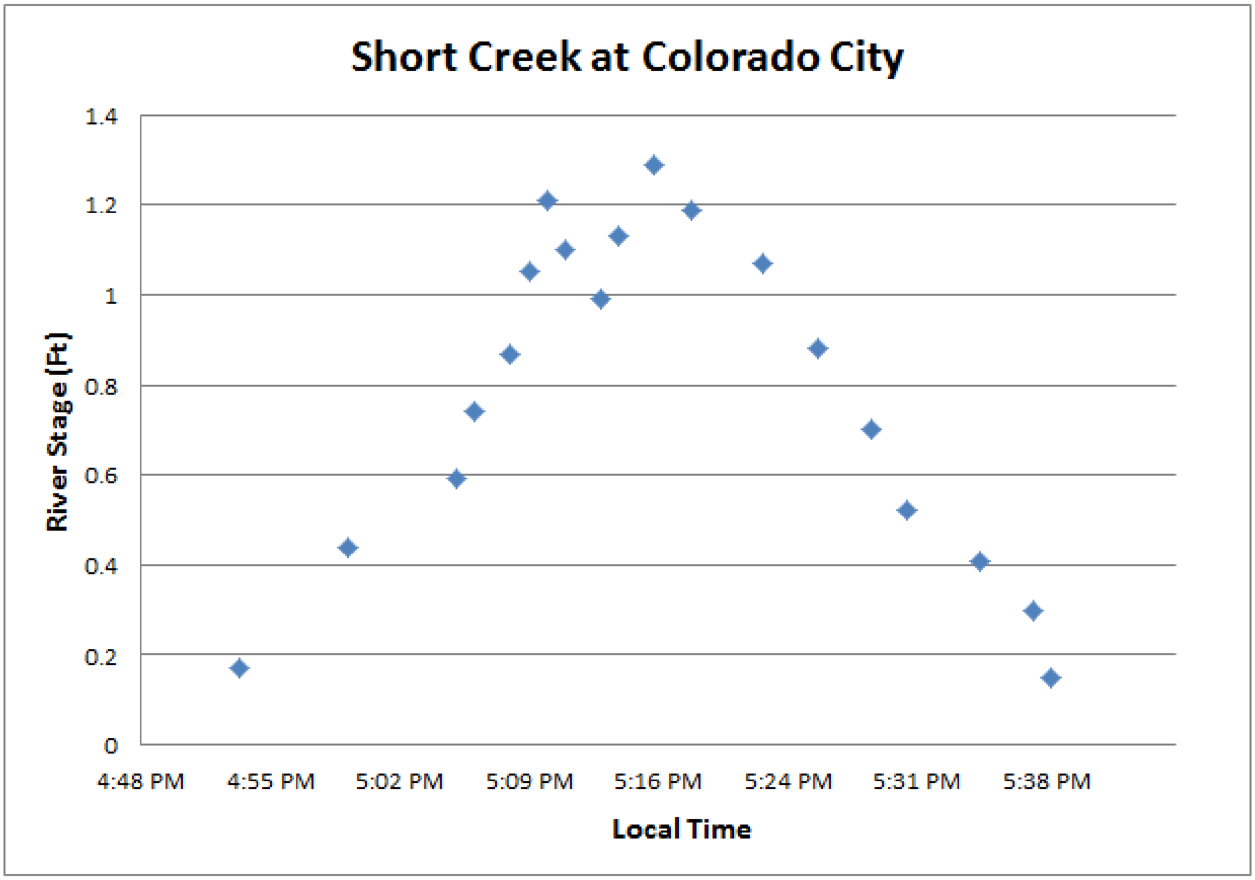

Figure 6. Hydrograph for July 26, 2013. Data from Mohave County Flood Control District.

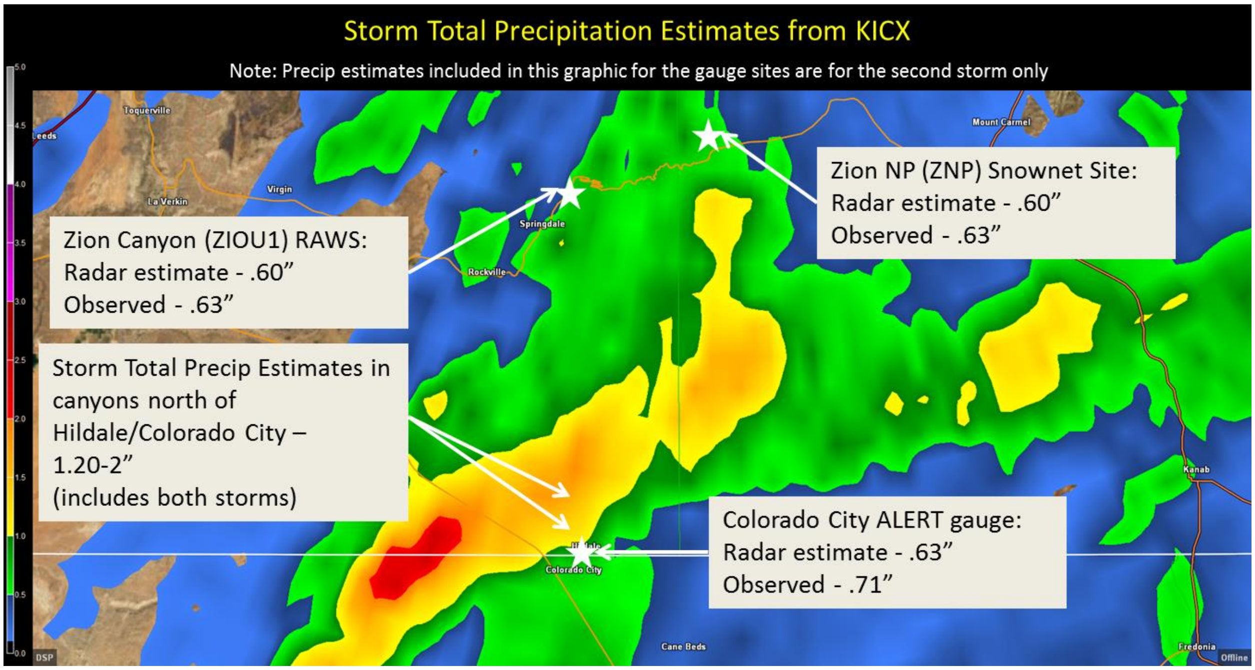

Figure 7. Rainfall totals vs. radar rainfall estimates, from the Cedar City radar, for second of two precipitation pulses from the September 14, 2015 storm.

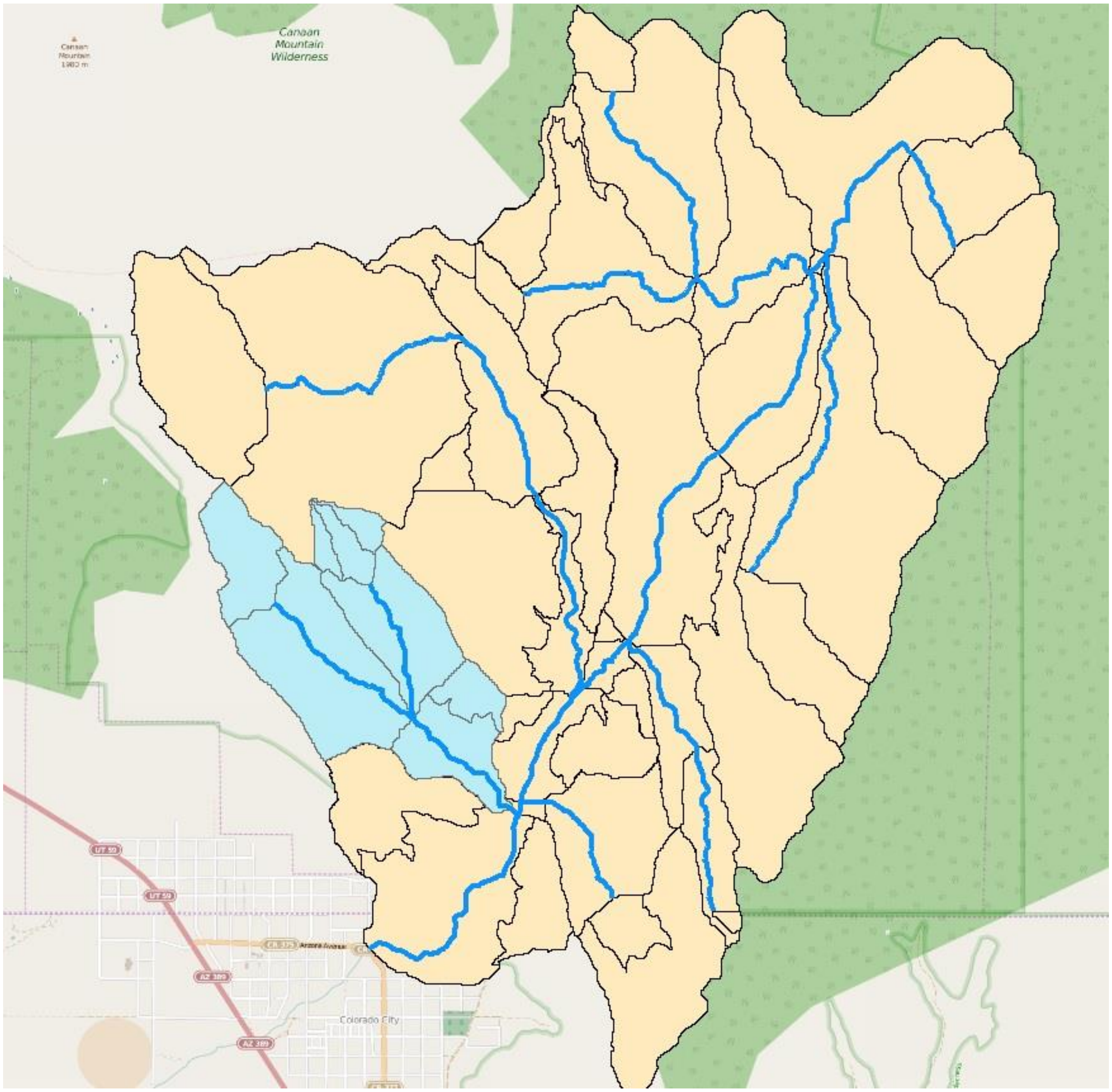

Figure 8. Plan view of KINEROS2 Short Creek watershed with the upstream contributing area for the Maxwell Canyon indirect discharge estimate highlighted in light blue.

Maximum Rainfall Intensity (in/hr)	Saturated Hydrologic Conductivity Multiplier (overland flow planes)	Saturated Hydrologic Conductivity Multiplier (channel segments)	Channel Manning Roughness Multiplier	Channel Length Multiplier
0.01	0.08	0.50	0.70	0.70
0.60	0.16	0.50	0.75	0.75
0.65	0.18	0.50	0.75	0.80
0.70	0.20	0.50	0.75	0.80
0.80	0.24	0.50	0.75	0.90
0.90	0.33	0.50	1.00	1.00
1.00	0.39	0.50	1.00	1.00
1.05	0.44	0.50	1.00	1.01
1.10	0.48	0.50	1.00	1.01
1.20	0.50	0.50	1.00	1.01
1.30	0.52	0.50	1.00	1.01
1.40	0.54	0.50	1.00	1.01
1.50	0.58	0.50	1.00	1.01
1.60	0.62	0.50	1.00	1.02
1.70	0.65	0.50	1.00	1.02
1.80	0.80	0.50	1.00	1.02
1.90	0.90	0.50	1.00	1.02
2.00	1.05	0.50	1.00	1.02
2.10	1.07	0.50	1.00	1.02
2.20	1.10	0.50	1.00	1.02

Figure 9. Operational calibration for KINEROS2.

Event	Observed Peak Stage (ft)	Observed Flood Category	Simulated Peak Stage (ft)	Simulated Flood Category	Difference between observed peak stage and simulated peak stage (ft)
July 28, 2013	2.06	Below Action Stage	4.33	Above Action Stage	+2.27
August 26, 2013	3.47	Above Action Stage	3.41	Above Action Stage	-0.06
September 27, 2014	4.10	Above Action Stage	3.27	Above Action Stage	-0.83
July 18, 2015	3.02	Above Action Stage	3.01	Above Action Stage	-0.01
October 17, 2015*	NA	Below Action Stage**	1.40	Below Action Stage	NA

Figure 10. Model simulation results. *Stream gage was not operating for the October 17, 2015 event. **Observed flood category estimated from news video footage.

Figure 11. View of Short Creek looking upstream of State Highway 389 Bridge. Screencapture from St. George News, 2015.

Figure 12. View of Short Creek looking upstream of State Highway 389 Bridge showing flow below channel banks. Screencapture from St. George News, 2015.

Figure 13. View of Short Creek at bridge crossing near model outlet point. Screencapture from St. George News, 2015.

Figure 14. View of Short Creek at bridge crossing near model outlet point. Screencapture from St. George News, 2015.

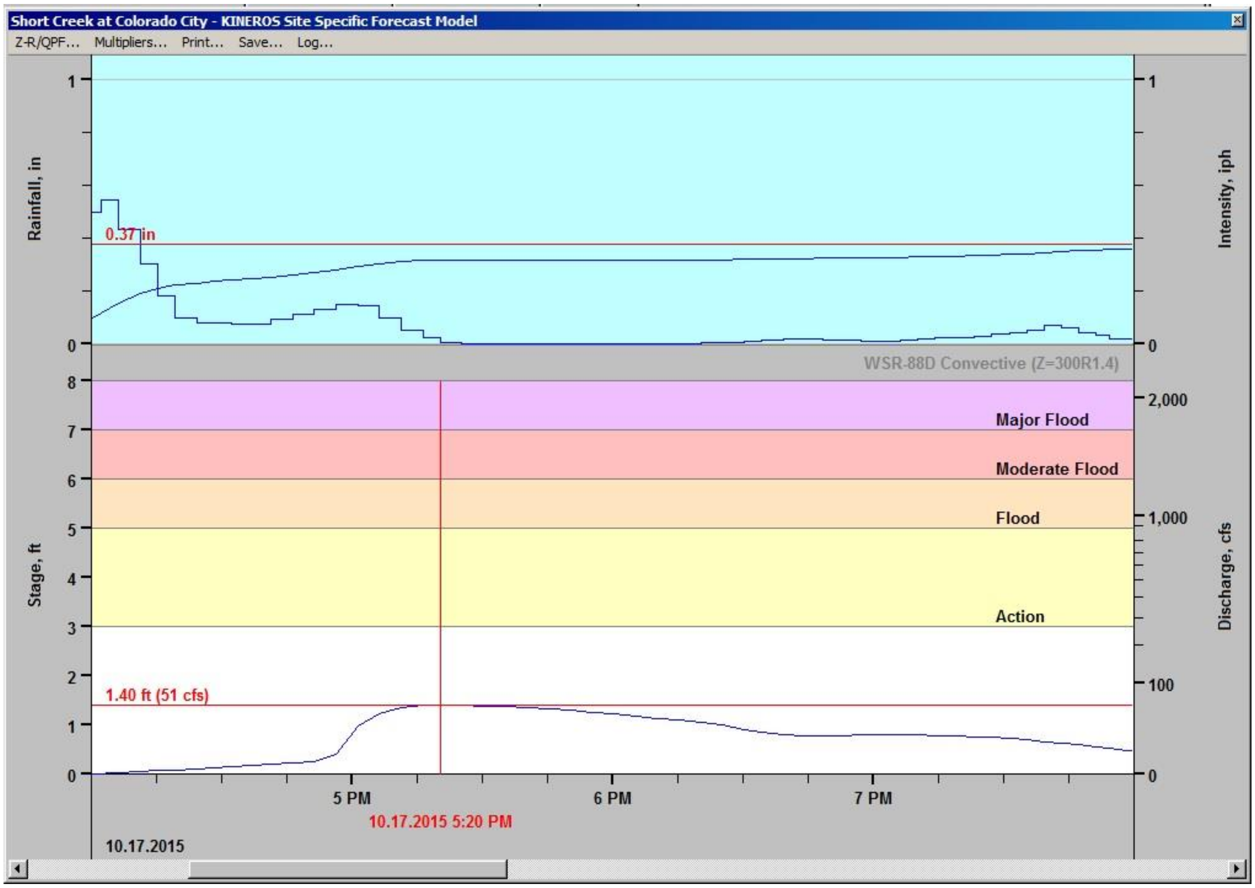

Figure 15. Forecast hydrograph for October 17, 2015.

Event	Observed Peak Flow Timing (MST)	Simulated Peak Flow Timing (MST)	Difference between observed and simulated peak flow timing (min)
July 28, 2013	7:09 PM	7:28 PM	19
August 26, 2013	6:48 PM	6:47 PM	1
September 27, 2014	10:07 AM	10:00 AM	7
July 18, 2015	2:54 PM	2:59 PM	5
October 17, 2015*	NA	5:20 PM	NA

Figure 16. Observed and simulated peak flow times. *Stream gage was not operating for the October 17, 2015 event.

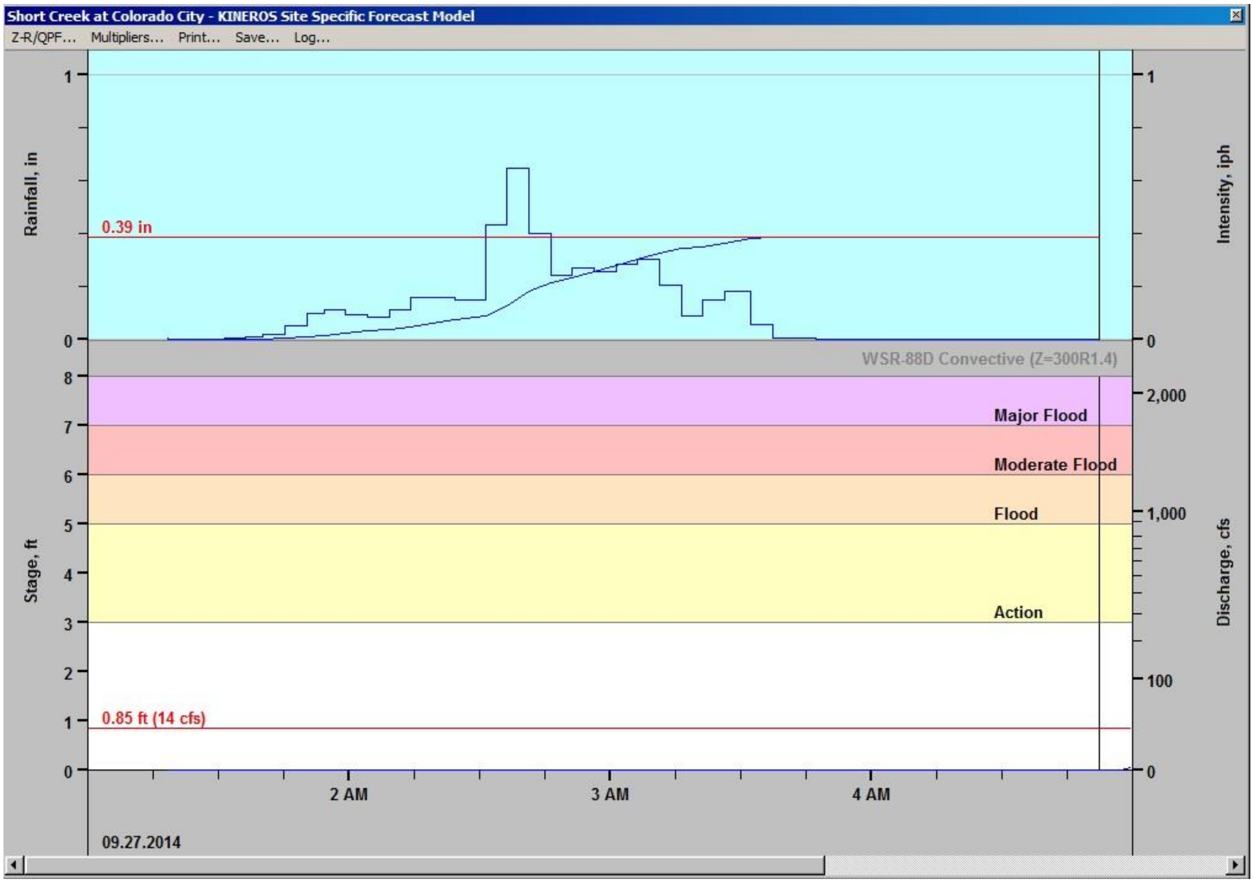

Figure 17. Initial rainfall pulse from September 27, 2014.

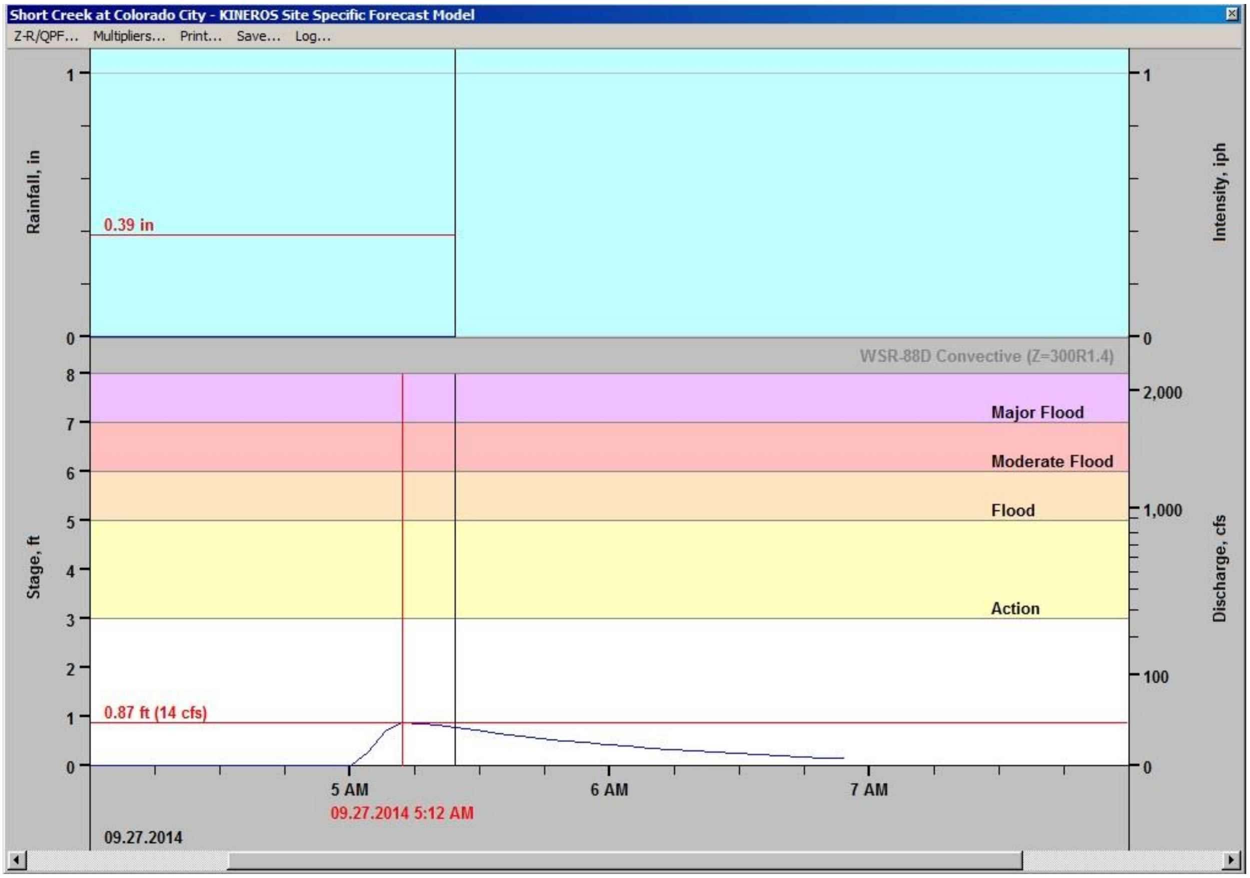

Figure 18. Initial small rise from from September 27, 2014.

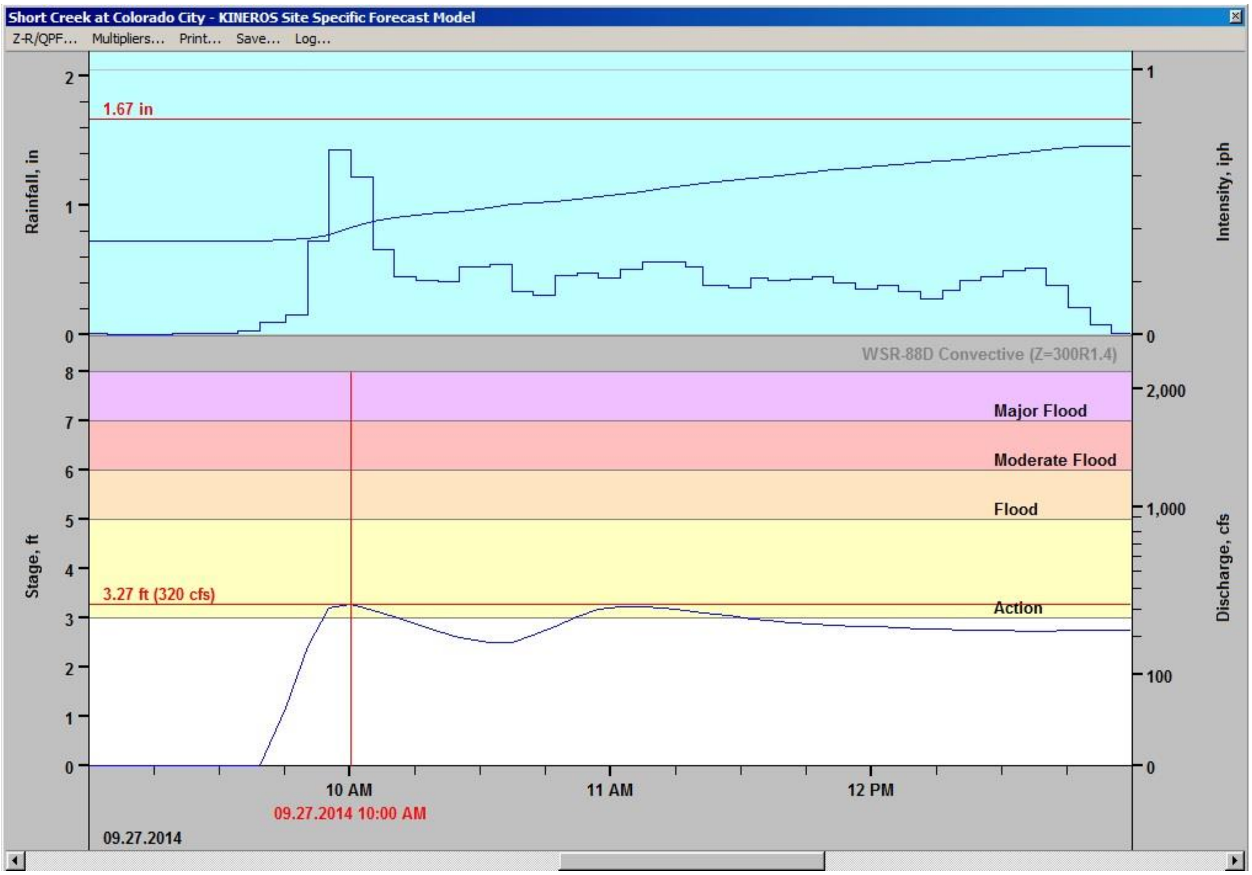

Figure 19. Peak flow for September 27, 2014 with a start time of 1:15 AM.

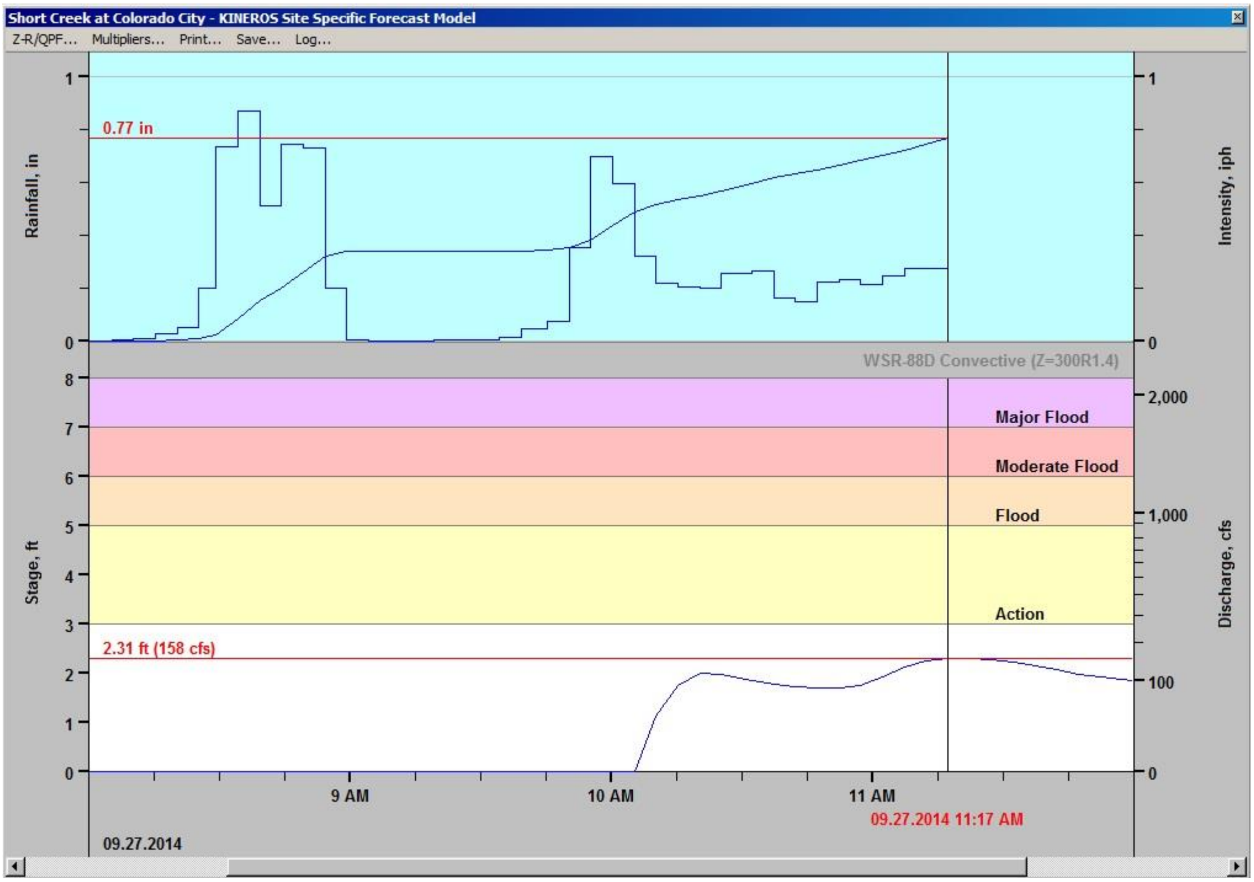

Figure 20. Peak flow for September 27, 2014 with a start time of 7:00 AM.