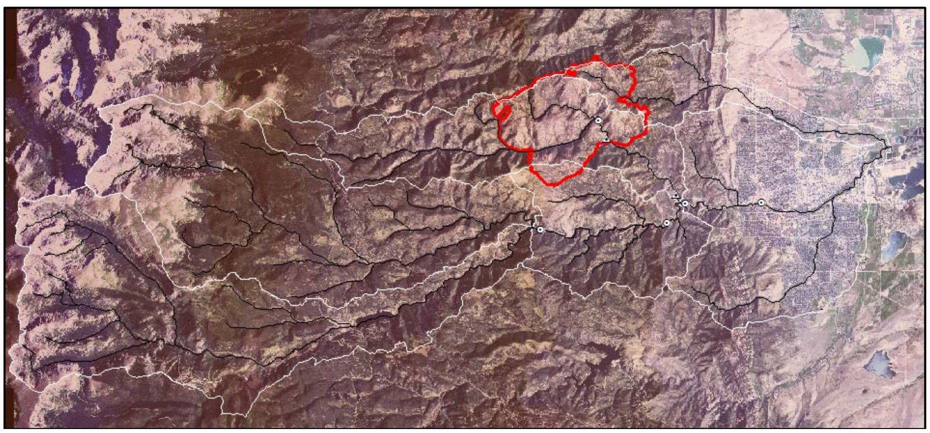
DEVELOPMENT OF A REAL-TIME HYDROLOGIC MODEL

FOR THE BOULDER CREEK WATERSHED

Agreement No. 11-03.11

Phase II Model Preparation for Real-time Report

February 13, 2012



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Background

The Fourmile Creek and Fourmile Canyon Creek basins experienced a significant fire beginning on Labor Day, September 6, 2010, which continued to burn until it was brought under control on September 16, 2010. The Fourmile burn area, also known as the Fourmile Canyon Fire, burned an area of 6,179 acres composed primarily of open ponderosa pine. Due to the population density within the basin, there is a potential for loss of life due to flash flooding, and from increased probability of landslides (Ruddy et al., 2010). Many properties are located near the creek and in low-lying areas affected by floodwater. Investigation of the altered hydrologic conditions caused by the fire focused on the effect on soil infiltration and vulnerability to erosion, transport, and debris flow. Limited soil samples identified a strong water infiltration barrier at approximately 2-6 inches. Preliminary soil erosion estimates projected the sediment yield to increase from 0.7 tons/ac to 6 tons/ac in some areas, thus increasing potential for landslide/debris flow. The resulting loss of vegetative cover and decrease in soil permeability due to the fire poses an increased flood threat to people and property within the basin (FEST, 2010). In the 2011 flood season, many of the projected impacts from the Fourmile burn area came true with flooding and landslides/debris flow occurring within the Fourmile Creek basin.

Urban Drainage and Flood Control District (UDFCD) desired the capability for flood threat prediction over the burn area. The distributed hydrologic modeling approach using V*flo*™ was selected. This approach integrates diverse information on the land surface with radar-based rainfall input to simulate the hydrologic effects of the wildfire, develop specific flood-threat rainfall categories, and create a predictive hydrologic information system for real-time flood threat alerts. The model approach used by V*flo*™ supports the evaluation of the effects of the wildfire and resulting flood threat within the watershed and in downstream areas of the watershed including the City of Boulder and Boulder County.

This project is composed of three phases. In Phase I, an initial model of Fourmile Creek was developed and evaluated to simulate the effects of the wildfire burn area. In Phase II, the model domain was expanded to include the watersheds of Fourmile Creek, Fourmile Canyon Creek, North Boulder Creek and Boulder Creek between Barker Dam and Boulder's city limit, that drain to 6th Street. Phase III consists of hosting the operational system and supporting real-time flash flood forecasting services. The following sections describe the project objectives, results from simulations, and model enhancements made in preparation for real-time operations.

Project Objectives

The project objective in Phase II is to enhance the V*flo*™ model of the watershed affecting the City of Boulder from Boulder Creek, including Fourmile Creek, and associated drainage from Fourmile Canyon Creek to its canyon mouth. To accomplish this objective, these tasks were performed:

1. Calibrate and evaluate the model with radar data sets for selected events to test the model sensitivity to heavy rainfall, and prepare the model for real-time operation.
2. Describe the model enhancements and sensitivity testing for up to six events selected from periods of severe storms with flooding. Two archival and four events from the 2011 flood season were selected.

3. Quality control and assurance procedures will document metadata, model setup, methodology, and results.

The analysis presented below describes model development and its improvement using data from archived historical events, and the 2011 flood season events that occurred in the Fourmile Creek, Fourmile Canyon Creek, and Boulder Creek to the canyon mouth in the City of Boulder. The following sections describe the approach used to model the burn area, the data quality control, modifications made to the V*flo*™ model, and results of model evaluation for selected events.

Methodology

Model Setup and Evaluation

For the selected events, model calibration uses a physics-based parameter adjustment approach where runoff volume is first adjusted, followed by hydraulic parameters (Vieux, 2004). The hydrologic conditions for the Fourmile burn area are incorporated into the V*flo*™ model through parameter adjustments. The model of the Fourmile Creek drainage basin was set up and used to evaluate the burn area. The modeling approach involves modifying maps of soil properties to represent infiltration rates characteristic of surface sealing in the burn area due to vegetation removal. The initial estimates of hydraulic conductivity were modified using observed streamflow from review of observed watershed response during historical periods prior to 2011, and then subsequently adjusted for the burn area condition based on more recent events in 2011. In these areas, the soil depth and selected infiltration parameters were adjusted in the Fourmile burn area to improve runoff volume simulation.

Model testing and evaluation were performed with gage-adjusted radar rainfall (GARR) for the six selected events. Archival flood events were selected that had available radar/gage data and reports of flooding in the Boulder vicinity. Testing of the model sensitivity consisted of model runs using calibrated radar data extracted for these dates. Besides adjustments to model parameters, other model improvements considered were the application of calibration techniques to improve and optimize for channel hydraulics, e.g. roughness and geometry. These improvements included addition of hydraulic cross-sections in Fourmile Creek, Fourmile Canyon Creek, North Boulder Creek and Boulder Creek between Barker Dam and Boulder's city limit and rating curves at two stream gauging locations. The geospatial data and ancillary data used to setup and parameterize the model are described as follows.

Geospatial Data

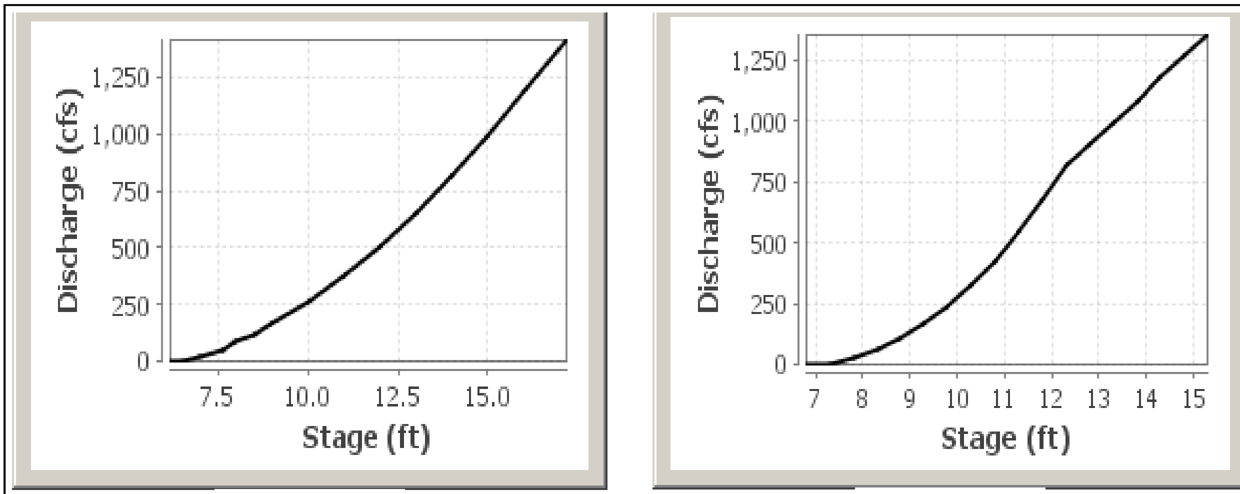
V*flo*™ model parameters and drainage network are derived from geospatial data. Slope and drainage network connectivity are derived from a digital elevation model (DEM); soil infiltration parameters from reclassification of soil maps, hydraulic roughness from reclassification of land use/cover from satellite (see Landuse (NLCD) metadata in the Appendix); and supplemental geomorphic relationship from aerial photography and the DEM. The aerial photography used to measure approximate stream width has a resolution of 1-m (see the National Agricultural Inventory Program (NAIP) Metadata in the Appendix). Other supporting data used in model setup and configuration is documented in the Appendix.

Hydraulics

Model refinement included adding hydraulic cross-sections and a geomorphic relationship between channel width and drainage area. Where stream gages are established, rating curves are added for making specific stage forecasts. At the other locations in the channel network, a combination of trapezoidal cross-sections based on the drainage area, surveyed cross-sections and extracted cross-sections from the DEM are employed to route runoff downstream within V*flo*™. First, we consider the rating curves, and then the geomorphic relationship, followed by channel cross-sections obtained from field surveys or the 10-m DEM.

Rating Curves

Rating curves relating discharge to stage are used for hydraulic routing calculations in V*flo*™. In each rated channel cell, a rating curve is used to determine the stage for discharge computed from conservation of mass. Figure 1 shows the stage-discharge relationships for the USGS gages at Fourmile Creek at Orodell, CO (06727500) and Fourmile Creek at Logan Mill Road near Crisman, CO (06727410). The rating curve for USGS gage 06727410 was updated following field measurements from the July 13, 2011 event. Because the area-stage relationship must represent the active flow through the cross section, stage-area relationships were modified in the model to preserve the kinematic wave celerity in each of the rating curve cells.



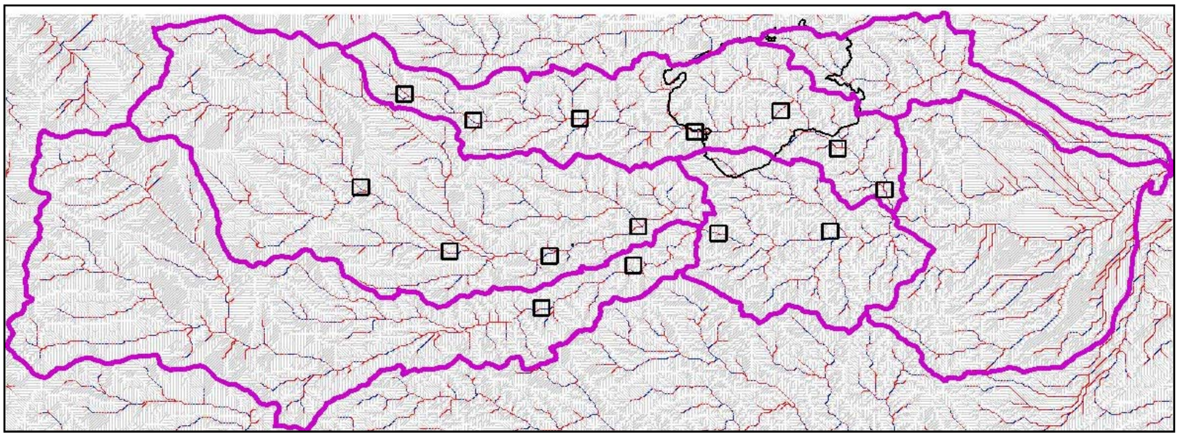
(a) (b)

Figure 1 Stage-discharge rating curves for (a) Fourmile Creek at Orodell (06727500), and (b) Fourmile Creek at Logan Mill Road near Crisman (06727410)

Geomorphic Relationship

The distributed model requires channel geometry for routing runoff through the drainage network. A relationship between the approximate channel width and drainage area was derived for Fourmile Creek, Fourmile Canyon Creek, and the rest of Boulder Creek. The geomorphic relationship was derived for Fourmile Creek, Fourmile Canyon Creek, and North and Middle Boulder Creek. While not as detailed as surveyed cross-sections, the geomorphic relationship helps define more realistic channel hydraulics than could be obtained from the digital terrain data alone, particularly when the channel width is less than the resolution of the digital terrain data

(DEM). Drainage area was determined from the flow direction estimated from the DEM. Measurement locations in the Boulder Creek watershed are indicated by the symbols (open squares) in Figure 2 (upper), and the measurements are listed together with a plot of width versus drainage area (Figure 2, lower). The relationship identified between channel width, W (ft), and drainage area, A (mi^2), is identified as, $W=8.7A^{0.22}$. The hydraulic modification of the model achieved using this relationship is applied to improve routing times of flood waves even though there are likely some departures from actual stream channel widths and those predicted from by the power law geomorphic relationship. The trapezoidal cross-sections defined by this relationship are used at intermediate locations between cross-sections derived from the DEM.



Area (mi^2)	Width (ft)
3	11
13	10
16	16
21	16
24	17
23	24
12	18
34	17
36	21
89	24

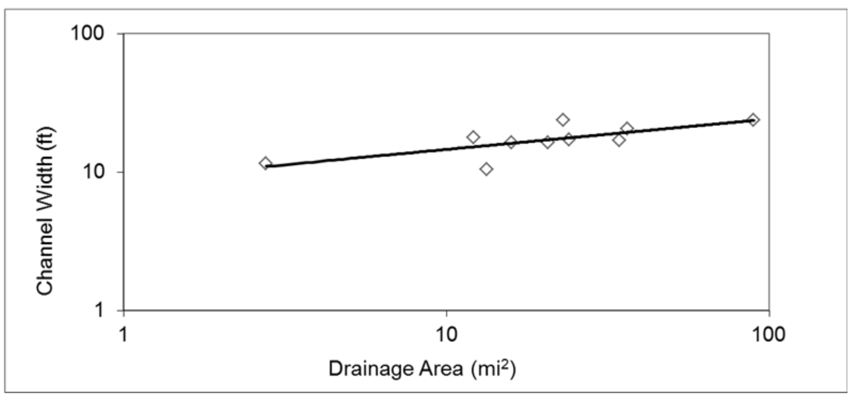


Figure 2 Geomorphic relationship for channels in Fourmile Creek, Fourmile Canyon Creek, and North and Middle Boulder Creek

Channel Cross-sections

Where available, surveyed channel cross-sections from the USGS 10-m resolution DEM (Gesch, 2007) were added to the hydrologic model based on field surveys and the DEM. An advantage of adding trapezoidal or surveyed cross-sections is that it reduces the influence of the relatively coarse DEM resolution. Cross-sections from survey data at stream gage sites were obtained from the UDFCD at four gage locations: Boulder Falls, Fourmile, Boulder Creek at Highway 119, and Orodell. Cross-sections are added to key areas within the basins to support flood routing and timing of the hydrographs produced. Figure 3 shows a sample cross-section surveyed on Boulder Creek at Highway 119 for the E-19 survey (HDR Engineering, 1999). The model drainage network is superimposed on the topography, showing both overland (gray elements) and channel (red and blue) elements. Red elements are trapezoidal cross-sections while blue elements are cross-sections extracted from the DEM or taken from field surveys. Initially, channel hydraulic roughness values were assigned based on land use/cover from the NLCD in overland areas, and in channels, based on the UDFCD Storm Drainage Criteria Manual for streams and assumed size distribution (D_{50}). After model evaluation with historical events, roughness parameters were adjusted to improve peak discharge timing.

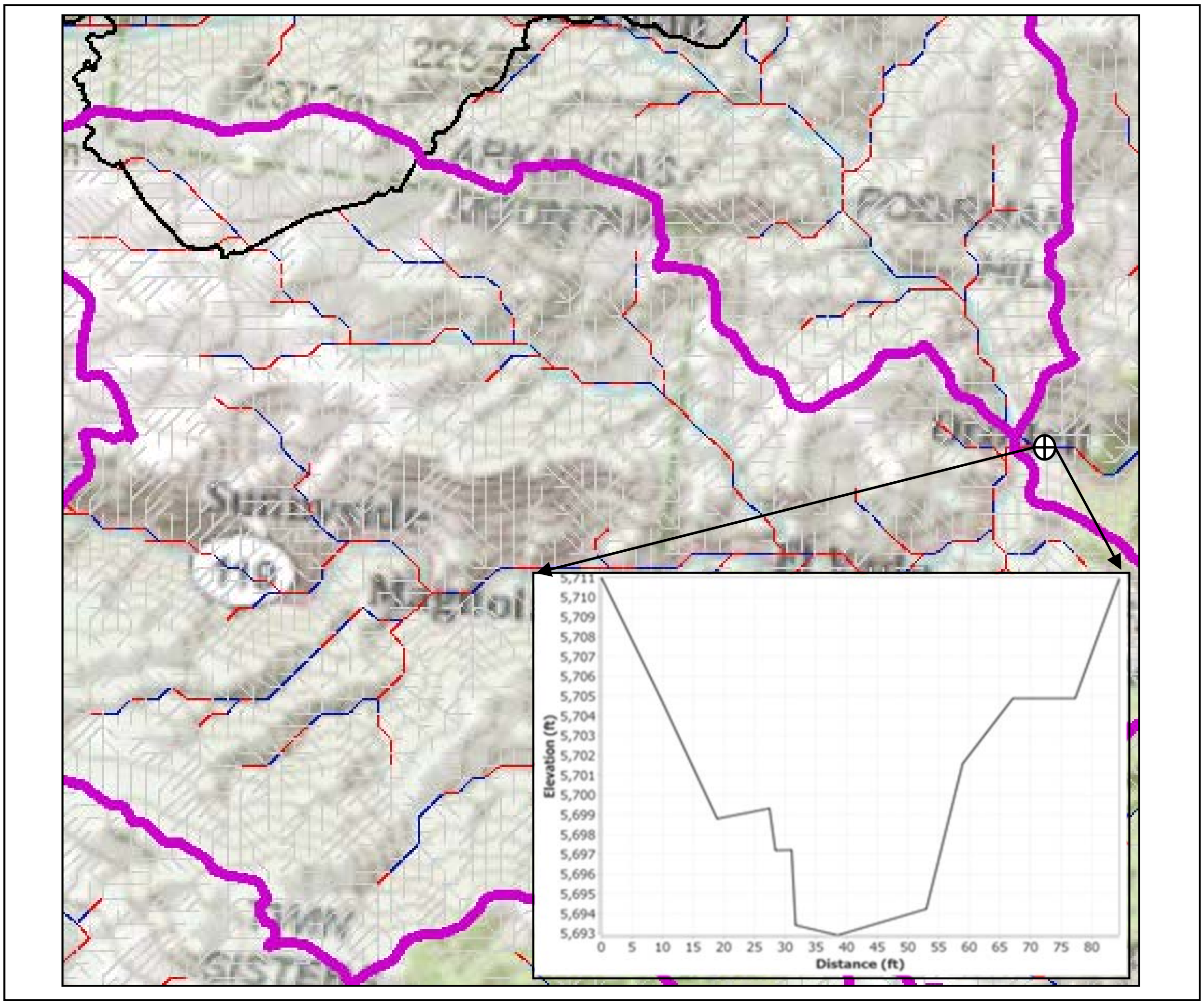


Figure 3 Topography with channel network (background) and surveyed cross-section on Boulder Creek downstream of Highway 119 (lower right inset)

Soil Moisture

The rate at which soil moisture is depleted during inter-event periods of no rainfall is determined by the potential evapotranspiration (PET). Because the soil moisture affects the rate at which rainfall can infiltrate, it is important for real-time operations to update continuously soil moisture in the soil infiltration model for proper initiation of runoff simulations. PET rates can be input from seasonal climatological values, although actual evapotranspiration depends on the available moisture in the soil profile and can be considerably less than potential rates of evapotranspiration. From the climatology of Boulder Creek, annual potential evaporation is approximately 37 inches (Farnsworth, et al. 1982). The monthly distribution of PET is presented in Figure 4 with rates expressed as an hourly rate (in/hr). The seasonal variation reaches a maximum in May at 5.9 inches (0.0082 in/hr), then diminishes slightly during June and July to 5.2 inches (0.0072 in/hr) and 4.4 inches (0.0061 in/hr), respectively. This trend continues through the fall with 3.9, 2.6, and 1.4 inches in August, September, and October, respectively.

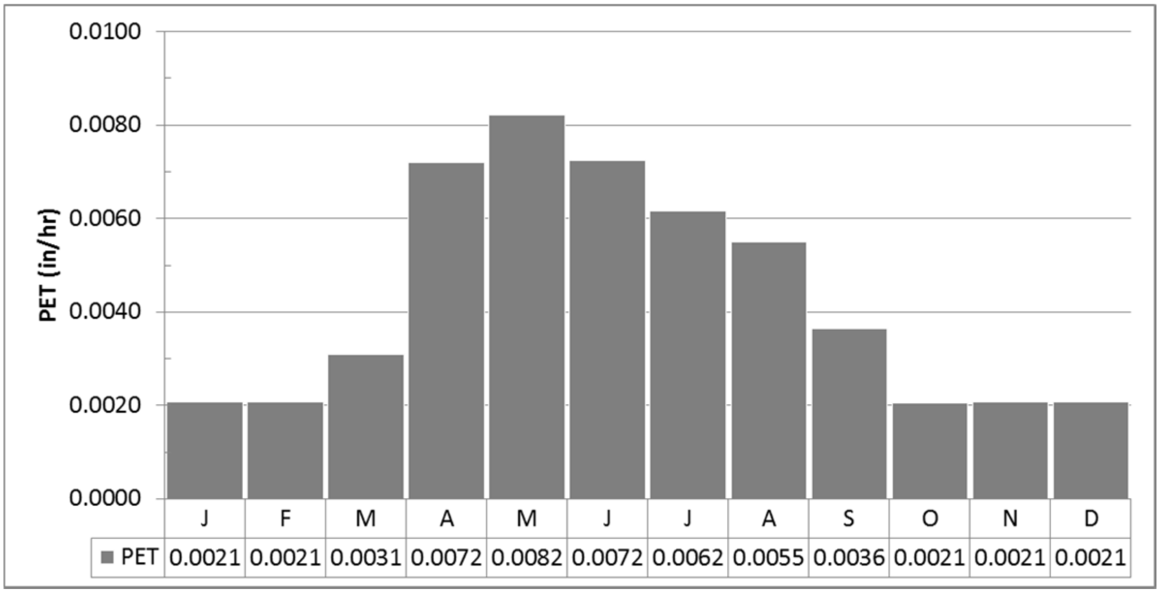


Figure 4 Monthly distribution of PET rates expressed in units of hourly rates (in/hr)

Green and Ampt Infiltration Model

Enhancing the model physics in support of real-time operations requires adjustment of parameters initially assumed from soils data and vegetative cover that discriminate between non-burn and burn areas. In the original setup of the model, abstraction of 1.0 inch was applied in non-burn (natural) areas, and was used in developing the hydrologic response to hypothetical rainfall depths. However, because initial abstraction cannot be used in real-time, i.e. there is no "beginning of the event," soil depth and hydraulic conductivity are adjusted to represent the initial abstraction of rainfall associated with duff in forested (non-burn) areas.

The updated model parameters for the burn area are a result of the model calibration and evaluation with archival storm events, especially those from the 2011 flood season. After reviewing actual events for which stream stage/discharge was available, the simulated volume of runoff was in excess of observed. From the observed runoff volume, it was evident that assuming zero infiltration in the burn area was excessive. Phase II modifications to the G&A parameters are:

1. Non-burn Area – Hydraulic conductivity previously set to 0.5 in/hr.
2. Burn Area – Hydraulic conductivity increased from 0.0 in/hr to 0.05 in/hr.

Figure 5 shows the differentiation of saturated hydraulic conductivity mapped for the Fourmile Creek burn area. The rate is set in the non-burn area to limit runoff in areas where the duff layer was not removed by wildfire. Adjustments were made to produce soil depth, saturated hydraulic conductivity, and porosity that results in runoff equivalent to the initial abstraction previously used for non-burn areas and to improve the volume of runoff modeled from the burn area for events modeled during the 2011-flood season.

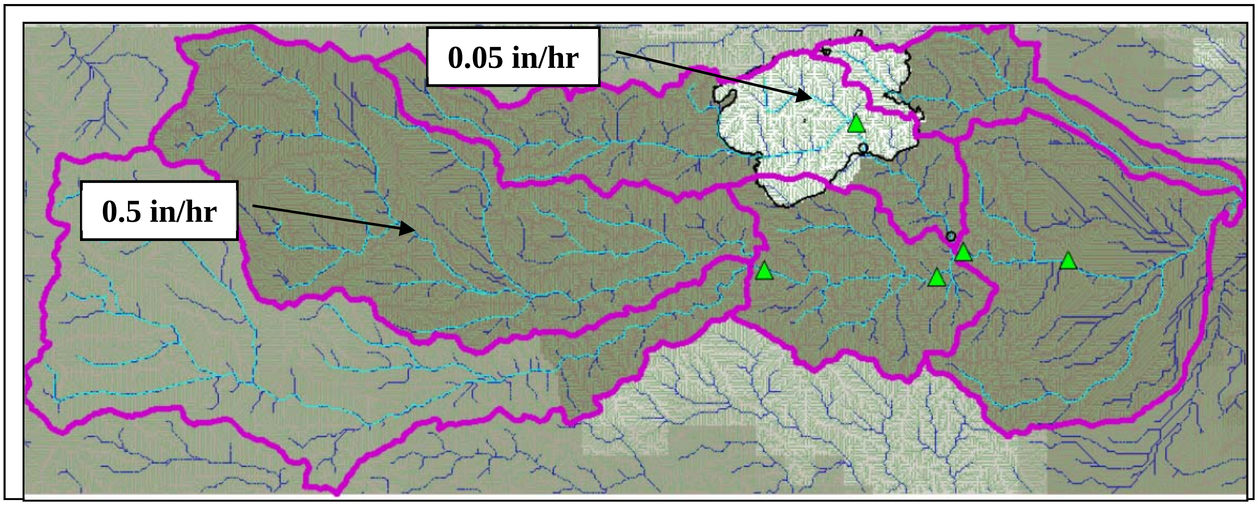


Figure 5 Map showing differentiation of areas modeled with pre-burn and post-burn values of saturated hydraulic conductivity

Results

Model Events

The following events with observed flow were used to evaluate the model performance and to adjust parameters. The two archival events were identified from the NCDC (2012) storm events database that contain reported flood impacts of significant storms. RainVieux is the GARR system developed by Vieux & Associates, Inc. It uses a statistical control approach and database to generate, display, query, and analyze GARR. Radar data was obtained from the RainVieux website for the events in 2011, and from the National Climatic Data Center along with storm reports describing impacts for the two events, August 4, 1999 and May 15, 2003. Along with radar, snowmelt data as obtained for the July 7, 2011 event from archived data. In addition, UDFCD provided rain gage data which was supplemented with available NWS rain gage data.

1. August 4, 1999
2. May 15, 2003
3. May 18, 2011
4. June 19, 2011
5. July 7, 2011
6. July 13, 2011

Each of these events is used to evaluate the model, and is described as follows.

Event – August 4, 1999

Flooding and flash flooding problems developed over portions of the Urban Corridor as thunderstorms produced 2 to 3.5 inches of rainfall in approximately 3 hours (NCDC, 2012). Widespread street flooding was reported by the City of Boulder, and several buildings were flood damaged in Fort Collins as well as at the CU Memorial Center in Boulder. Radar shows that most of the rainfall from this event fell below the confluence of North and Middle Boulder Creek in urban areas of the City of Boulder where street flooding was reported (NCDC, 2012). Precipitation is much greater (+4 in) in the City of Boulder than the remaining watersheds (see crosshair symbol in Figure 6). Simulation of this event produced only minor runoff within the mountainous portions of the subject watersheds, which is consistent with expected runoff from *non-burn areas* with a duff layer present. Because of the model performed as expected for this event, it was not adjusted.

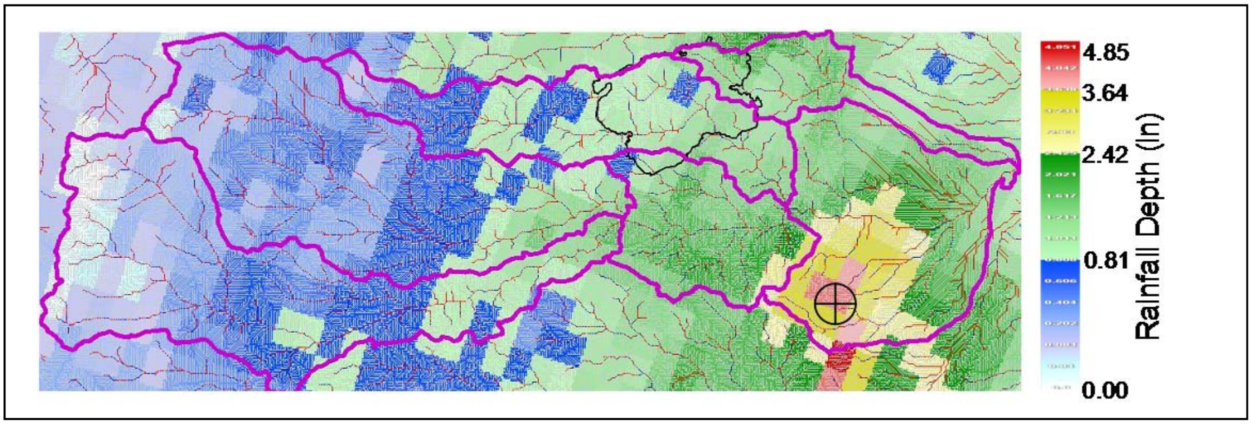


Figure 6 Rainfall depth showing more than 4 inches (open crosshairs) August 4, 1999

Event – May 15, 2003

Thunderstorms produced very heavy rain and localized flash flooding in the foothills of central Boulder County, with 1.5 to 2.5 inches of rainfall in less than 2 hours (NCDC, 2012). Water depths covering State Highway 119 in Boulder Canyon ranged from 6-9 inches. Other impacts reported were that dirt and rocks washed over the road (presumably, State Highway 119), and in the Sugarloaf area some basements were flooded. Rockslides were reported at Boulder Falls, Lefthand Canyon and Fourmile Canyon. UDFCD estimates that, while the event was approximately a 100-year event based on rainfall recorded at Betasso, there was only 400 cfs estimated in Fourmile Creek.

The majority of the rainfall occurred between 19:00 - 22:00 hrs (MDT) in May 15, 2003 event. Maximum rainfall intensities of approximately 5 in/hr occurred, with storm totals exceeding 3.6 inches over localized areas of the watershed as seen in Figure 7 (upper panel). The lower panel in Figure 7 shows a scatter plot of radar and rain gage accumulations for the storm total after bias correction, hence the 1:1 slope of the trendline. While the majority of gages show a close correlation with radar, several fall outside the upper and lower 80% confidence control limits. Both gages inside and outside of the basin are used to calibrate the radar, which accounts for the large number of gages shown in the scatter plot. The mean of the spatially variable bias correction factors applied to the radar was 0.92, and the resulting calibrated average difference between gage and radar was 16.7%. The average difference before calibration was 26% based on a convective Z-R relationship of $Z=300R^{1.4}$. Of the 55 gages possible, 35 were used because the storm motion that produced large rainfall gradients oriented along a north-south axis across the watershed.

Because this event occurred before the Fourmile Canyon wildfire, infiltration parameters in the post-burn model were rolled back to represent conditions prior to the wildfire. Hydrograph agreement is shown in Figure 8 in terms of peak and timing, which is obtained from the calibrated model for this event. During the May 15, 2003 event, there was only one streamflow gage, Boulder Creek @ Bridge (4423) with archival data. This streamflow gage is located on

Boulder Creek downstream of the confluence with Fourmile Creek on Highway 119. The streamflow gage recorded a rise in flow from 150 cfs to 966 cfs a 48-min period. The modeled streamflow had a rise in flow of 100 cfs to 1083 cfs over a 40 min period. The travel time is for this event is estimated from Boulder Creek @ Hwy 119 Bridge (4423) to Boulder Creek @ Broadway known as BOCOBOCO (4583). The travel time between these gages, from 4423 to 4583, was 18 minutes, which is consistent with the travel times noted in the Boulder Creek Flood Warning Plan (BCFWP, 2008, p. III-10) for the 10-yr storm event, i.e. 15 min for the 10-yr discharge of 2,050 cfs.

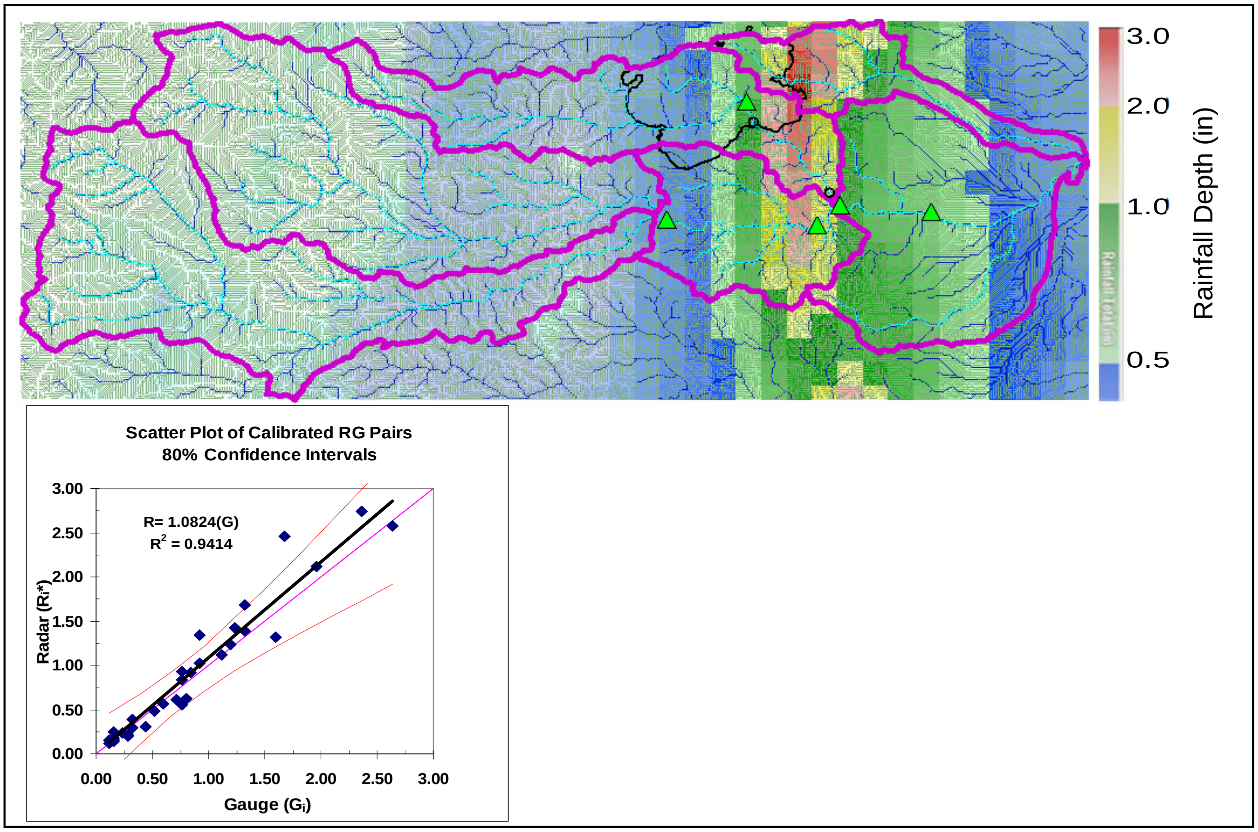


Figure 7 Calibrated radar rainfall storm total and scatterplot for May 15, 2003

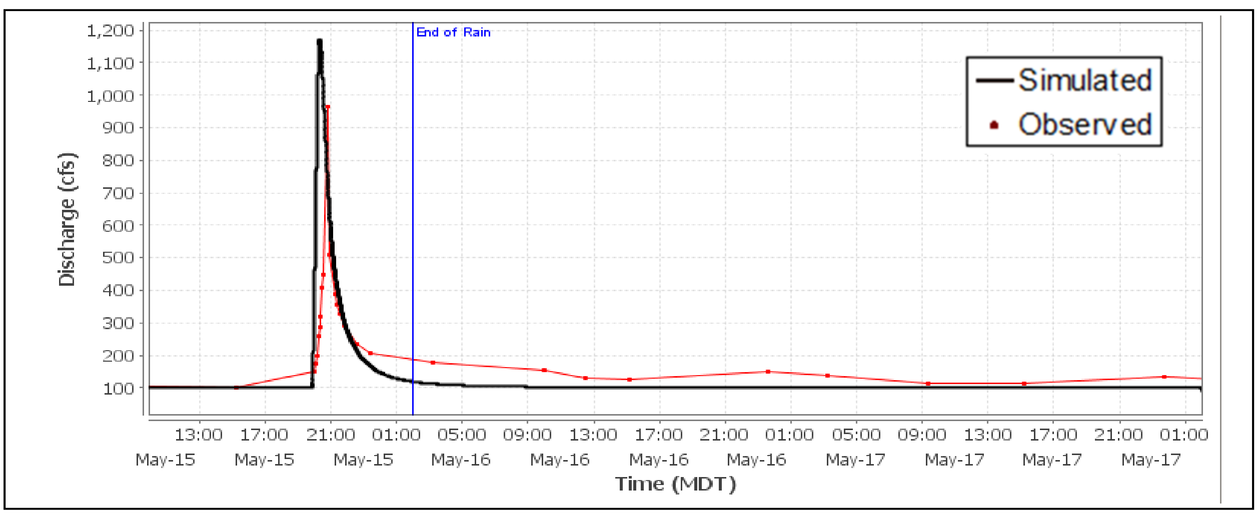


Figure 8 Simulated (black line) and observed (red line) response for UDFCD Gage 4423 for May 15, 2003

Event – May 18, 2011

The prototype RainVieux system started operating at the end of April 2011. The GARR produced by this system was used to simulate this event in post-analysis. This event produced very low runoff primarily due to the low precipitation rates within the Fourmile Creek watershed. The rainfall and its hyetograph averaged over the burn area are seen in Figure 9. The hydrologic response for the May 18, 2011 event appears to be dominated by snowmelt upstream of the Fourmile burn area. The NOAA National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) developed SNOw Data Assimilation System (SNODAS), beginning 1 October 2003. SNODAS is a modeling and data assimilation system developed by the NOHRSC to provide estimates of snow cover and associated variables for hydrologic modeling and analysis (NOHRSC, 2012). For this event, SNODAS was used to simulate baseflow as seen in Figure 10, and the hydrograph response at Crisman (06727410) shown in Figure 11. Because the rainfall rates only exceeded 0.25 in/hr, totaling 1.02 inches over the burn area, the runoff response was relatively low at only 37 cfs. Under pre-burn conditions with 1.0 inch of initial abstraction, the runoff from this part of the watershed is zero as witnessed by re-running the model with initial abstraction re-applied to the burn area to simulate natural conditions with a duff layer.

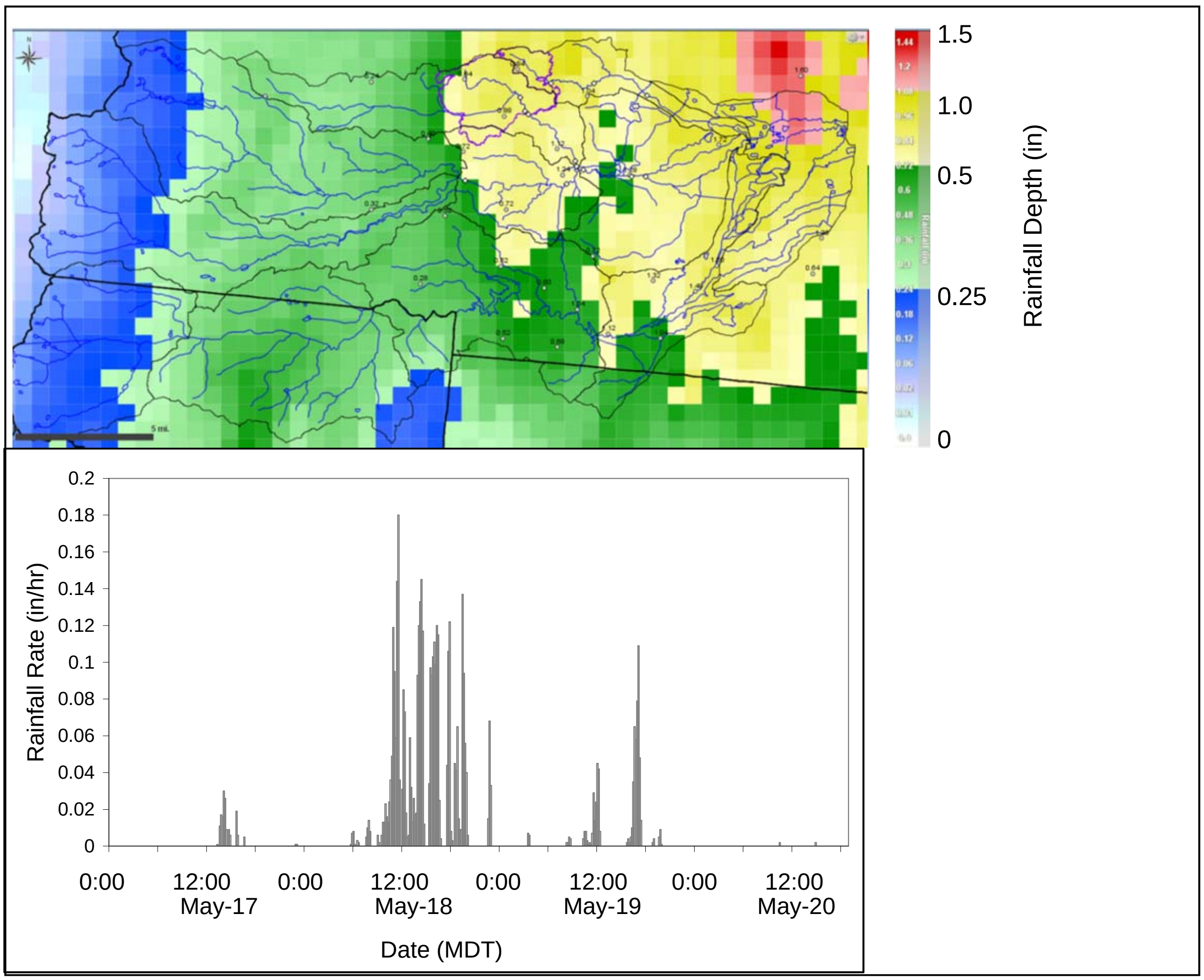


Figure 9 Storm total (upper) and burn area hyetograph (lower) for May 18-19, 2011

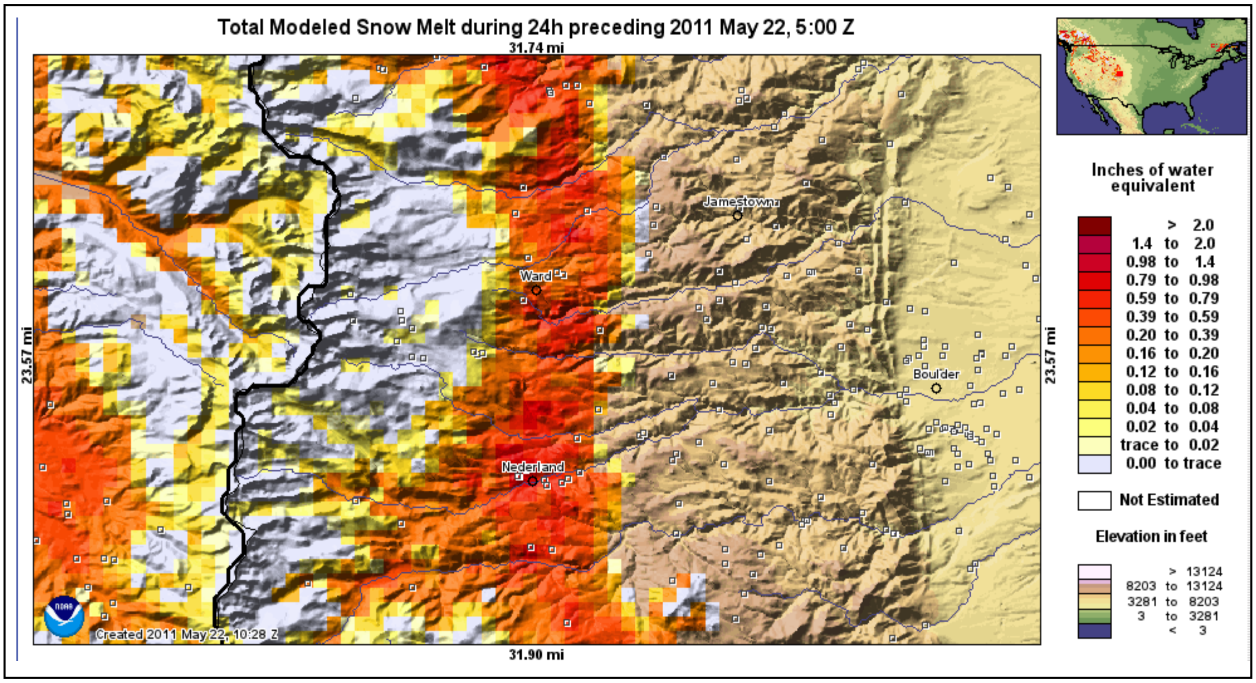


Figure 10 Snowmelt rates from NOHRSC for May 22, 2011

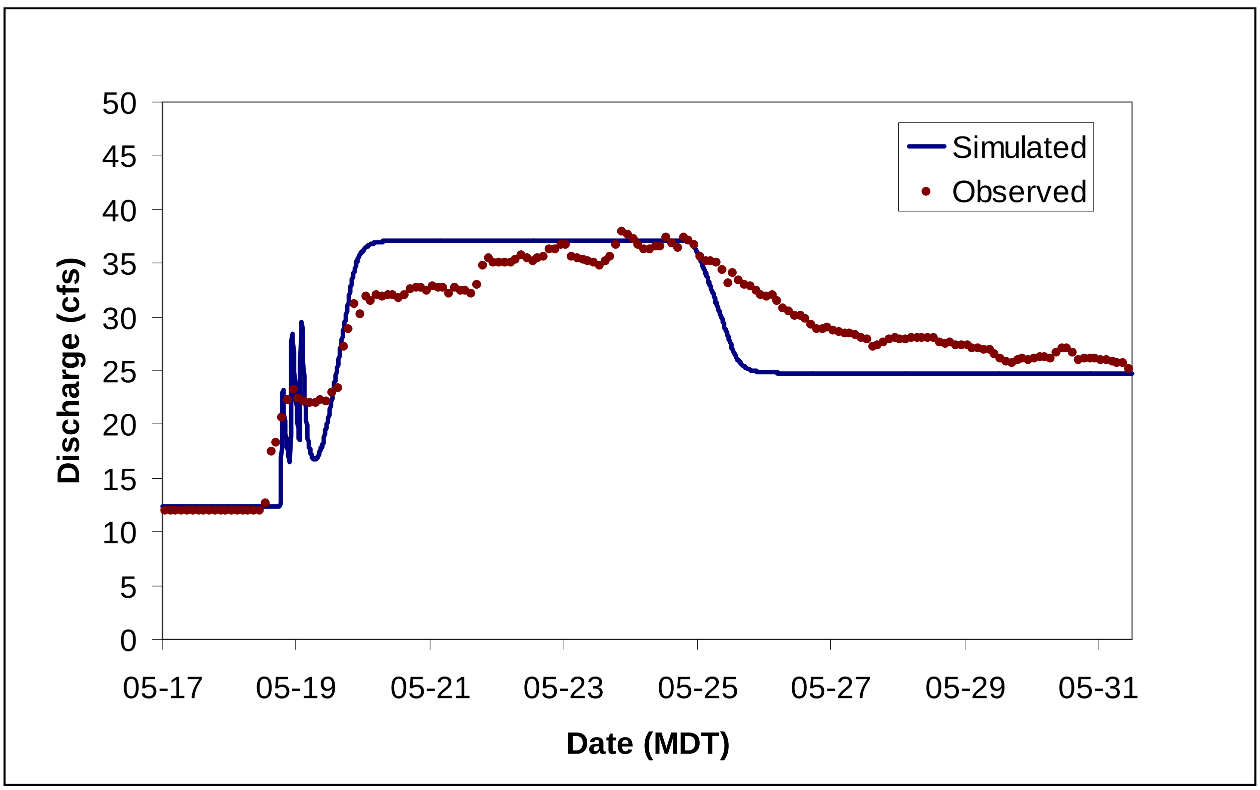


Figure 11 Hydrograph response at Fourmile Creek at Logan Mill Road near Crisman, CO (06727410) for May 18-19, 2011

The response from rainfall over the Fourmile burn area is witnessed by the increase from 12 cfs to approximately 30 cfs. Both the rainfall and snowmelt contributes to the observed and simulated runoff response. The model performed as expected for this event, so no adjustments were made.

Event – June 20, 2011

During this event, precipitation was heavier in the City of Boulder than in the Fourmile burn area as seen in Figure 12 (upper panel). Light precipitation rates are evident in the hyetograph for the burn area shown in Figure 12 (lower panel). Even when assuming 90% saturation, the hydrograph response (not shown) is zero for both pre- and post-burn conditions at the burn outlet in Fourmile Creek. Because the model performed as expected with no response to the light rainfall, no adjustments were made.

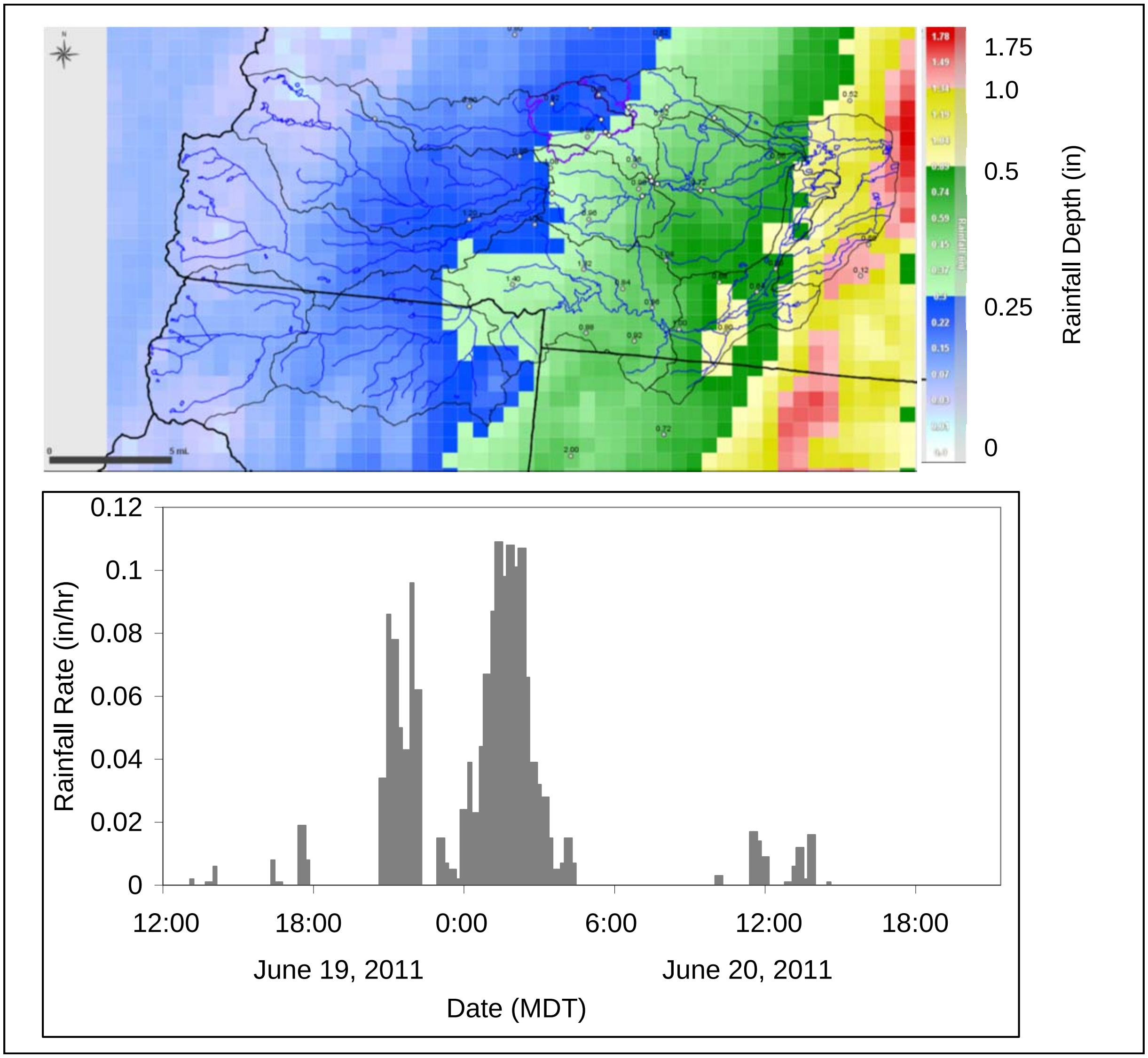


Figure 12 Storm total (upper) and burn area hyetograph for June 20, 2011

Event – July 7, 2011

Heavy rain produced a large debris flow along Fourmile Canyon Drive. Heavy rain produced flash flooding in the Four Mile Canyon burn scar. Four debris slides occurred along Four Mile Canyon Drive, including one that was 100 yards wide and 4 feet deep (NCDC). Over the burn area, the majority of the rainfall fell between 17:50 and 18:30 the evening of the 7th. Maximum rainfall intensities exceeded 3 in/hr, with more than 1.79 inches over localized areas of the watershed as seen in Figure Figure 713 (upper panel). The lower panel shows the hyetograph averaged over the burn area and the resulting stage hydrograph response. The rainfall hyetograph over this area was approximately 60 minutes and included a 5-minute interval of 1 in/hr, but remaining intervals with less than 0.2 in/hr. Observed discharge peaked around 30 cfs at Crisman (06727410) as did the operational forecast during the event. Simulated stage increased about 0.4 ft at Crisman (06727410), and similarly, observed stage increased by 0.3 ft. Even though maximum intensities were high, it fell over non-burn areas producing similar though small stage increase of 0.35 ft at the BOCOBOCO Gage (4583).

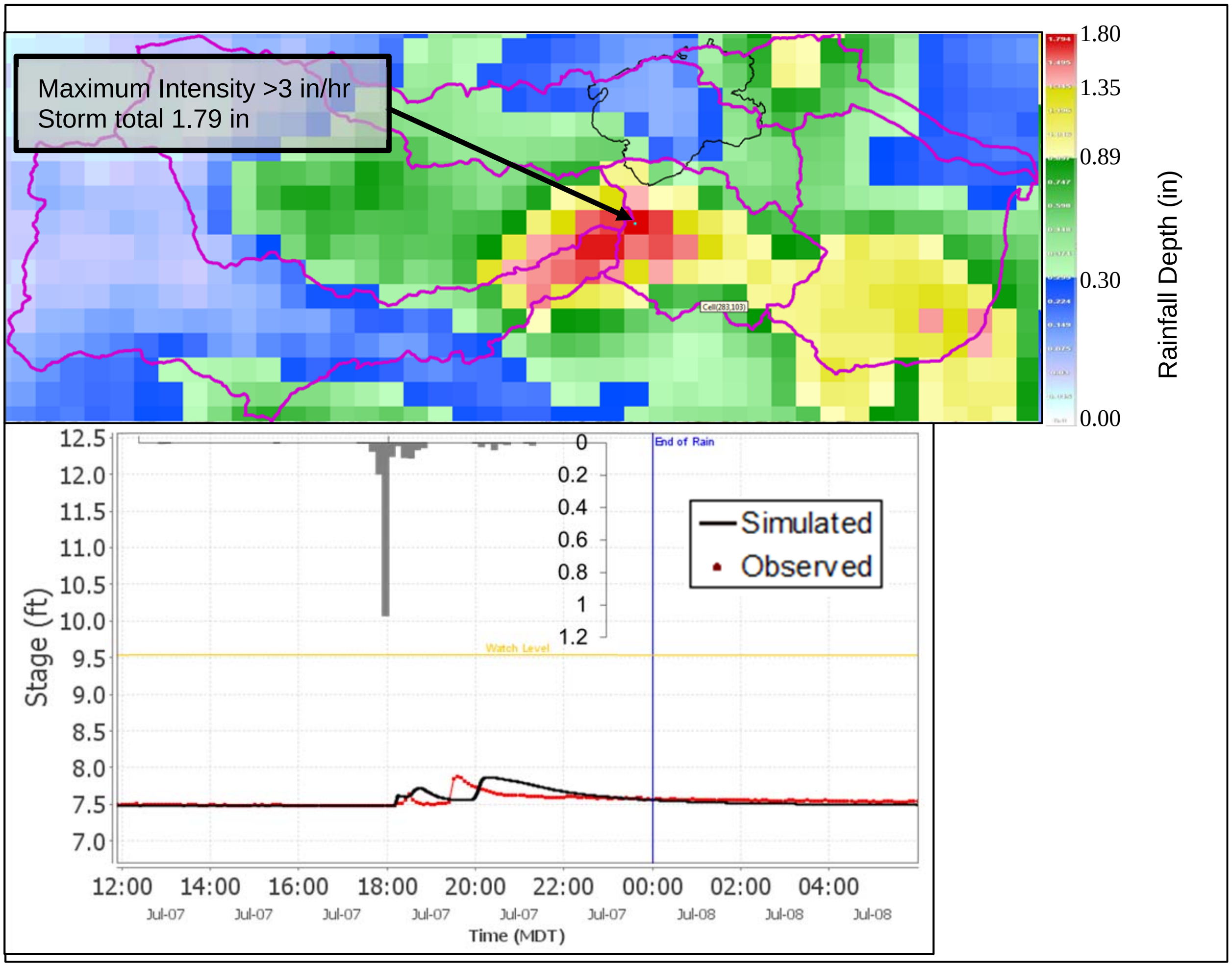


Figure 13 Storm total (upper) and stage hydrograph at Crisman (06727410) (lower), July 7, 2011

Hypothetical Model Response – July 7, 2011

The hypothetical response of the burn area resulting from superposition of the most intense part of this storm over the Fourmile burn area was tested with the calibrated model (described below for the July 13 event). The maximum pixel hyetograph consists of total rainfall of 1.79 inches with peak intensity of 3 in/hr. Figure 14 shows the hyetograph and resulting hydrograph from uniform input over the Fourmile burn area. The response is considerably more pronounced with peaks at Crisman (06727410) greater than 4800 cfs. Had the more intense storm cells, generating rainfall rates in excess of 3 in/hr, tracked over the burn area, the result could have been much more severe, 4,800 cfs compared to 30 cfs. Runoff simulation for the Fourmile burn area was relatively minor because the rainfall over that area was only 0.29 inches. The model was not adjusted for this event, because it did produce the expected low runoff response, only 30 cfs at Crisman (06727410), due to low rainfall depths, of 0.29 inches over the burn area

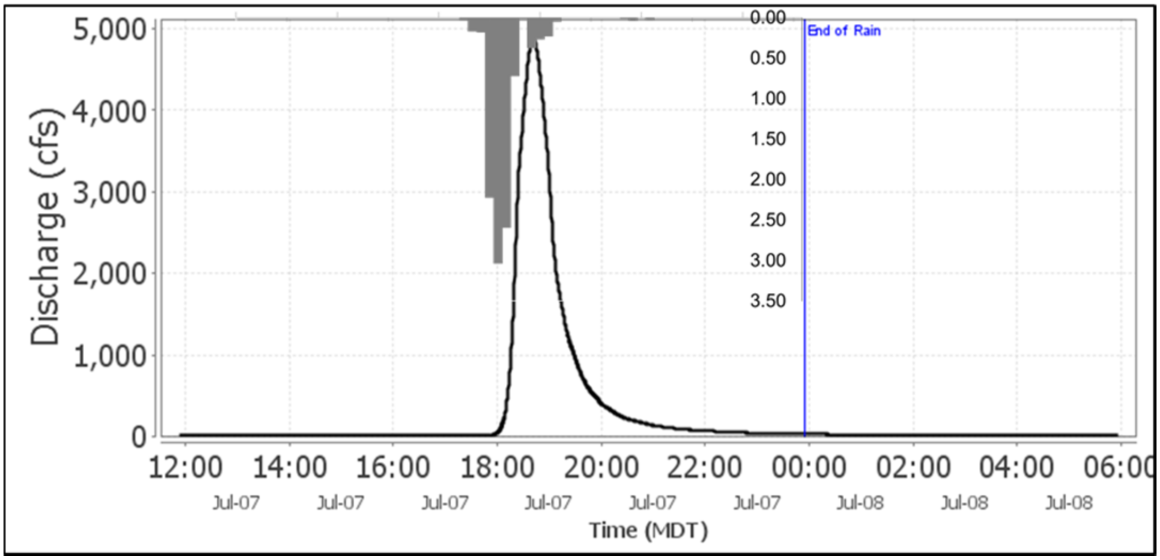


Figure 14 Hypothetical response of the Fourmile burn area in response to the maximum intensity recoreded by GARR on July 7, 2011

Event – July 13, 2011

Thunderstorms produced very heavy rainfall causing flash flooding in the Fourmile burn area west of the City of Boulder, and within Fourmile Canyon. Three homes reportedly had water up to the windows with water flowing into structures at the intersection of Fourmile Canyon Road and Gold Run Road. Heavy rain caused a 4-ft surge along Fourmile Creek at both USGS gaging stations at Crisman (06727410) and Orodell (06727500). Several roads were affected which restricted access to the area. Roads were closed due to water and debris. Private bridges and drives were washed out and several residents were stranded but later rescued. One home became uninhabitable because of the floodwaters. Though not destroyed, several structures suffered flood damage, and numerous cars were damaged by debris flows (NCDC, 2012).

After multiple model runs, the calibrated model was predominantly based on the July 13, 2011 event. The most intense rainfall is over the burn area as shown in Figure 15, and the resulting area-averaged hyetographs (Figure 16). Intensities over 1.0 in/hr are produced with the most intense rainfall in the burn area, but negligible precipitation in the remainder of the watershed.

During the July 13, 2011 event, streamflow observations were available for USGS gaging stations at Crisman (06727410) and Orodell (06727500). Field measurements stage and discharge were taken by USGS beginning April 1, 2011. Since that time, fourteen field measurements have been made for establishing a rating curve. Most notably, the largest direct flow field measurement was on July 1, 2011 with a stage of 7.58 ft and discharge of only 17.2 cfs. USGS conducted field observations and indirect flow calculations from high watermarks for this event.

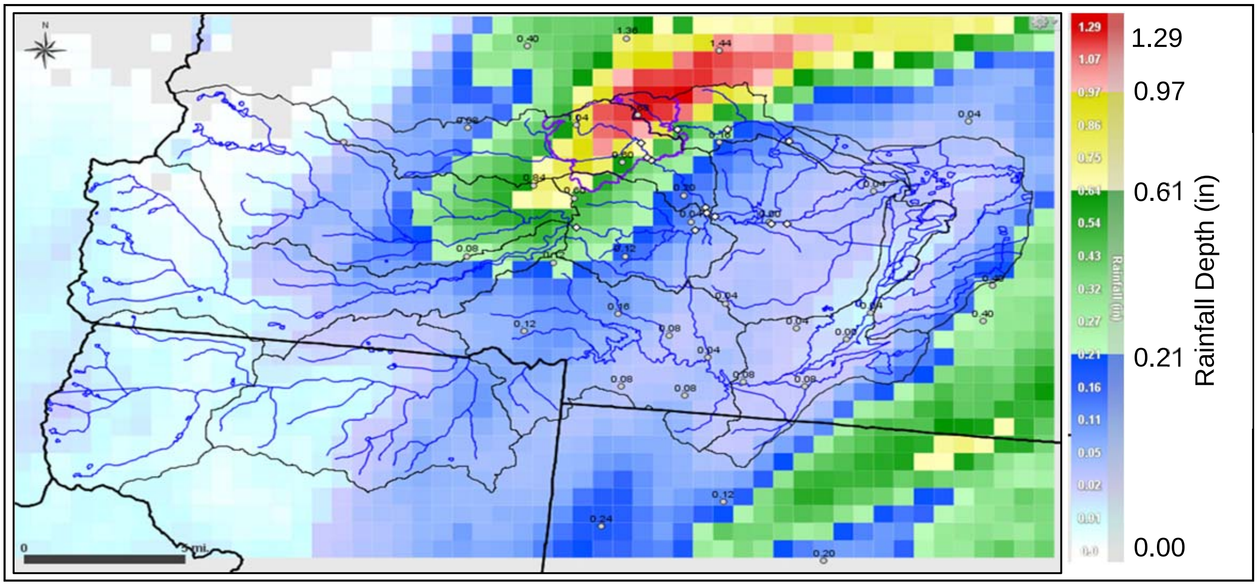


Figure 15 Distribution of rainfall over the burn area during July 13, 2011

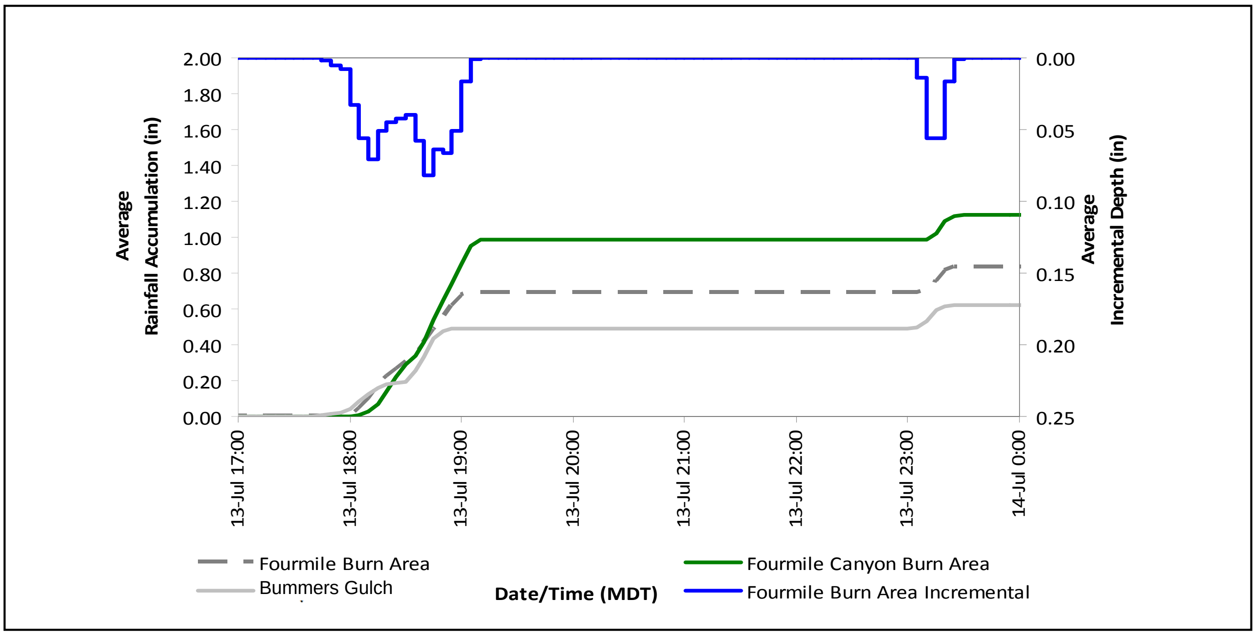


Figure 16 Basin averaged rainfall hyetographs for various areas on July 13, 2011

Flood Wave Travel Times

An important characteristic of the flood alert system and its use in emergency management is the routing times from the burn area to the mouth of Boulder Creek within the City of Boulder. Figure 17 shows the location of three stream gages in the upper panel: Fourmile Creek at Orodell (06727500), Boulder Creek @ Hwy 119 Bridge (4423), and BOCOBOCO (4583). A live video camera is located at the Orodell (06727500) gage, with near-peak flooding at 20:06 (MDT) on July 13, 2011. Downstream, the BOCOBOCO gage peaks later at ~20:42, with an observed stage of 4.31 ft.

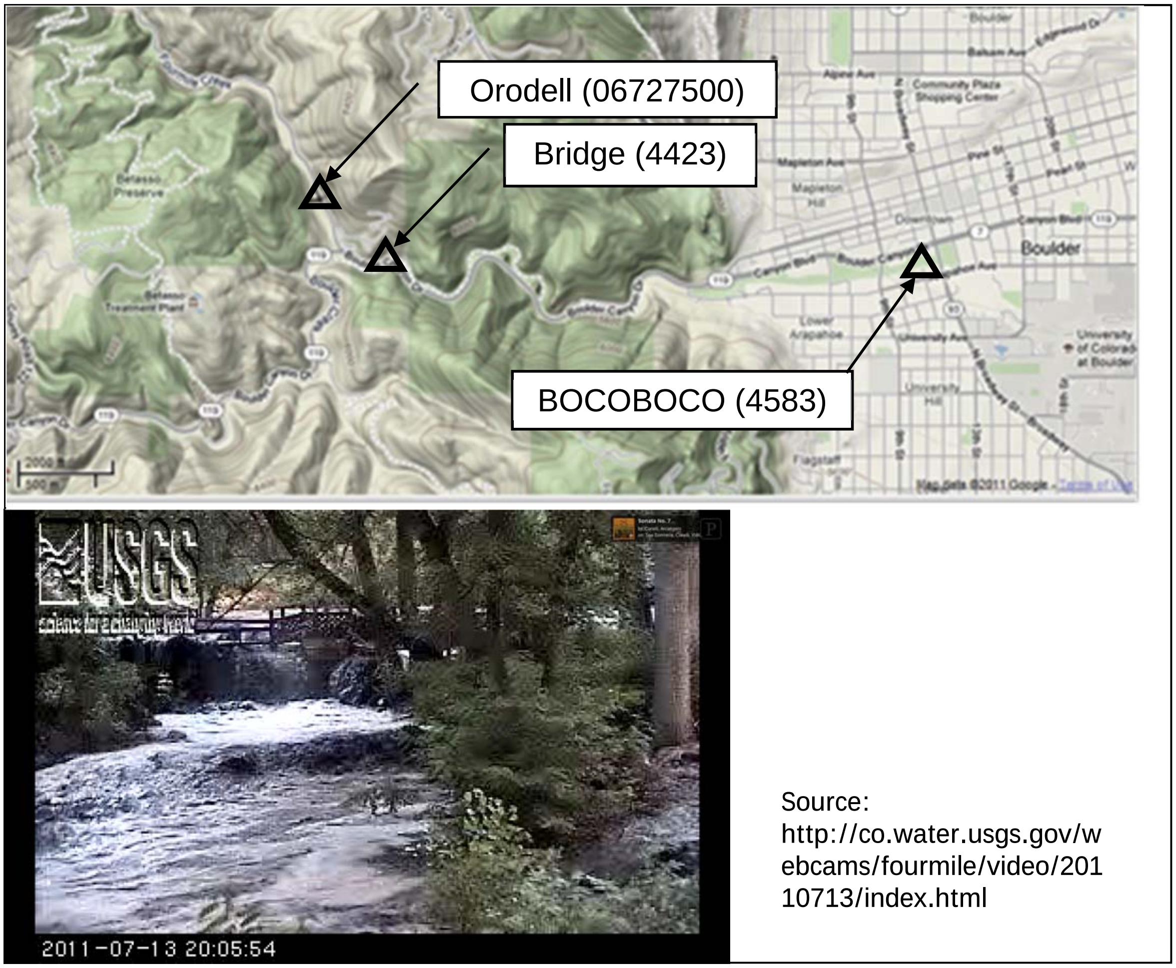


Figure 17 Location of Fourmile Creek at Orodell (06727500), Boulder Creek @ Hwy 119 Bridge (4423), and BOCOBOCO (4583) (upper panel), and live video taken at 20:06 pm (MDT) on July 13, 2011

Retrospective analysis is shown in Figure 18 where the model with modifications was run with the operational GARR input obtained from the RainVieux website. Hydrographs are shown for the Crisman (06727410) gage where observed and simulated peak discharge occurred at 19:17 and 19:15 (MDT) respectively on July 13th. These stage and discharge results are presented using the revised stage-discharge relationship subsequently developed by the USGS since this event occurred. The stage-discharge relationship is used by V*flo*™ to predict stage from discharge; while for the stream gage, discharge is estimated from stage. Any change made to a rating curve that increases (decreases) estimated discharge for a given stage measurement, will by contrast, decrease (increase) the stage estimated for a given simulated model discharge.

A critical consideration for the flood threat notification system is the time of travel of a flood wave from the burn area to the urban core of the City of Boulder. Figure 19 shows the simulated flood wave advancing from the burn area outlet at Crisman (06727410), to just upstream of Orodell (06727500), and the stream gaging station BOCOBOCO (4583) located at the Boulder County Library. Lateral inflow below the burn area outlet was not included in this simulation for testing travel times from the burn area outlet to the City of Boulder. Table 1 shows the time of peak discharge for simulated flood waves without lateral inflow.

Table 1 Simulated time of peak discharge for selected locations, July 13, 2011

Location	Time of Peak (MDT)
Crisman (06727410)	7/13/2011 19:15
Orodell (06727500)	7/13/2011 19:35
BOCOBOCO (4583)	7/13/2011 20:05

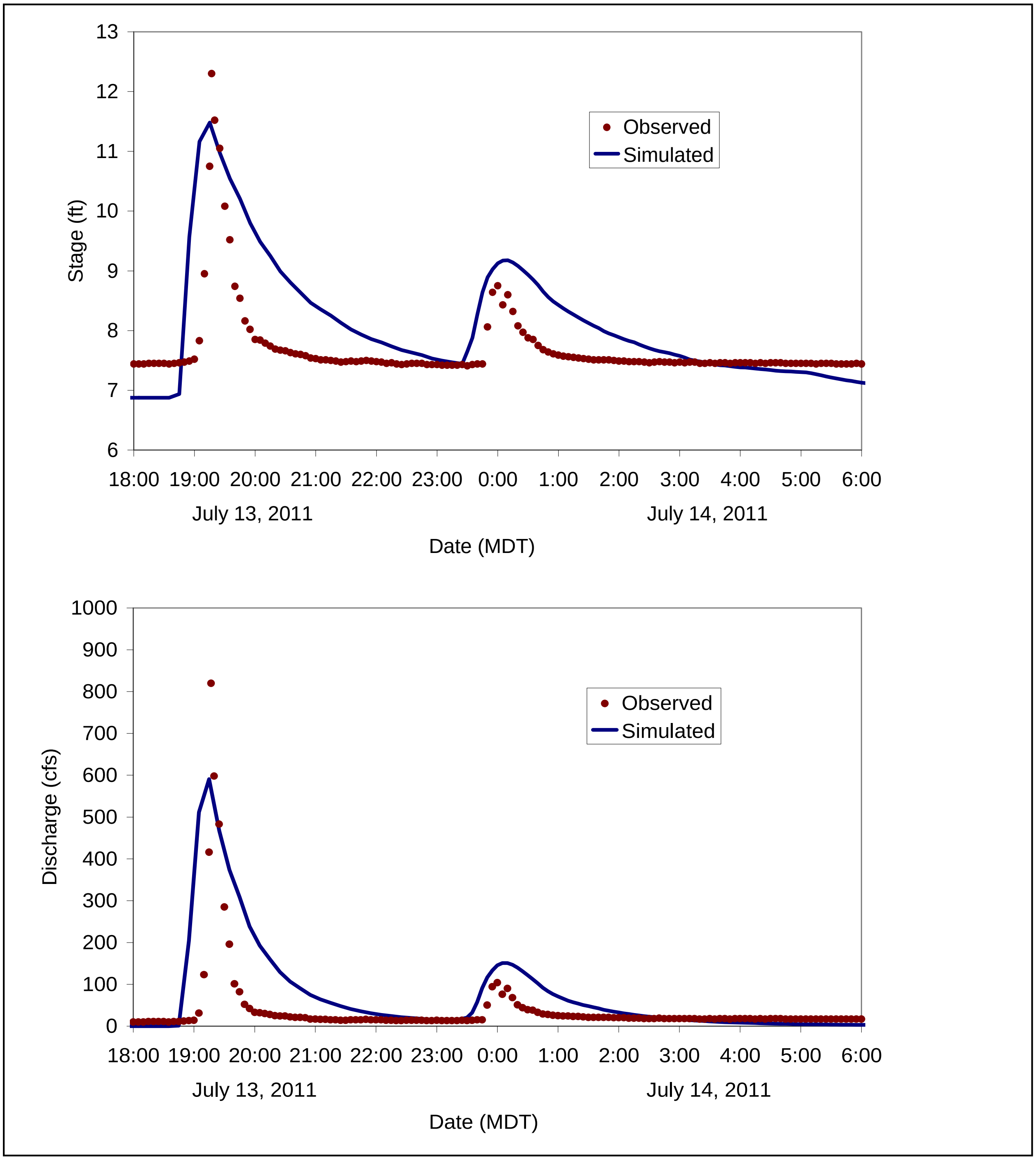


Figure 18 Simulated and observed stage (upper) and discharge (lower) on July 13, 2011 for the Fourmile Creek at Crisman (06727410)

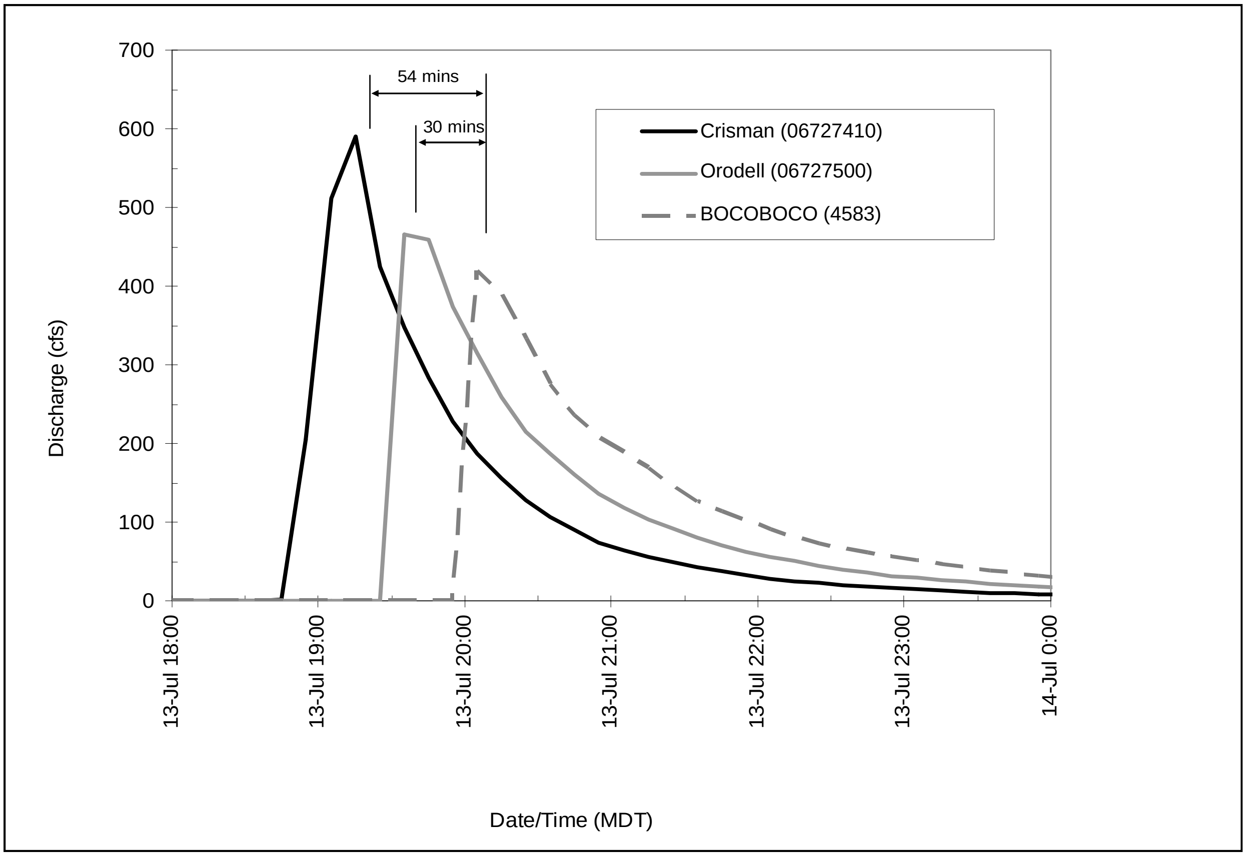


Figure 19 Progression of flood wave from the burn area outlet to the satellite-linked gage at BOCOBOCO (4583) for July 13, 2011.

Summary

In Phase II, the model was expanded to include Fourmile Canyon Creek and the unburned portion of the Boulder Creek watershed draining to the City of Boulder. Real-time simulation of the basin required model enhancements and calibration with archived events. The model enhancements included addition of cross-sections and rating curves to improve hydraulic routing, development of a geomorphic relationship between drainage area and channel width, improved infiltration and roughness parameter estimation, and incorporation of potential evapotranspiration rates. The six events selected for analysis include two archival events, August 4, 1999 and May 15, 2003, along with the four events: May 18, June 20, July 7, and July 13 from the 2011 flood season.

The hydraulic routing enhancements included adding surveyed cross-sections from the E-19 surveys extracted from 10m DEM dataset, including rating curves at USGS gages with modified area-stage relationships. At intermediate locations, cross-sections derived from the DEM supplemented assumed trapezoidal channel geometry developed from the geomorphic relationship. Streamflow observations from the calibration events revealed that hydraulic roughness was adequately represented within the model based on peak discharge and its arrival time measured between stream gages.

During Phase II, improved infiltration parameters were estimated based on the model performance for the calibration events. In the original model configuration, initial rainfall abstraction of 1.0 inch was applied in non-burn (natural) areas and zero hydraulic conductivity in the burn area, and used to develop flash flood guidance. The hydraulic conductivity in the Fourmile burn area and upstream of the burn area was increased to 0.05 in/hr in the burn area. Whereas, upstream of the burn area, saturated hydraulic conductivity was set to 0.5 in/hr to account for the estimated 1.0 inch of abstraction by the duff layer associated with natural conditions. For continuous modeling of soil moisture during real-time operation, potential evapotranspiration rates were estimated and modeled from climatology. As the hydrologic condition of the basin recovers with reestablished vegetation, further adjustment to model parameters will likely be necessary.

The simulations conducted for the six events provided useful information for model evaluation. The flood events on July 7 and July 13, 2011, provided insight into the hydrologic response from the Fourmile burn area. The May 15, 2003 event produced the largest hydrologic response from natural (unburned areas). Simulation of superimposed the 3 in/hr hyetograph from the maximum pixel during the July 7th event showed that 4,800 cfs response could have occurred instead of the 30 cfs response observed from the burn outlet. Analysis of the July 13th event revealed that the simulated stage at Crisman (06727410) was within 1 ft of the observed stage during the event, and agreed to within a few minutes of observed peak. Agreement between the model and observed flood wave travel time is demonstrated by the travel time from the Orodell (06727500) to the BOCOBOCO (4583) gage of 30 and 36 min for simulated and observed peak discharge, respectively. With these model enhancements during Phase II, the V*flo*™ model was made ready for operations in the coming 2012 flood season.

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Appendix – Metadata

1. *Digital Elevation Model (DEM)*

Source: National Elevation Dataset
Source data: Maps/Aerial Photos/Lidar
Resolution: 10m
Vertical accuracy: 2.44 RMSE
(http://ned.usgs.gov/downloads/documents/NED_Accuracy.pdf)

Description: Digital elevation model is derived from cartographic contours and mapped hydrography and generated at 10-m resolution. Most often, such data are produced by or for the USGS as a standard elevation product, and they currently account for the bulk of the NED.

2. *Soil Datasets (STATSGO)*

Source: State Soil Geographic (STATSGO) Database
Resolution: 1 km
Description: The U.S. General Soil Map consists of general soil association units. It was developed by the National Cooperative Soil Survey and supersedes the State Soil Geographic (STATSGO) dataset published in 1994. It consists of a broad-based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped.
Green and Ampt source: Rawls, W. J., Brakensiek, D. L., and Miller, N., 1983a. “Predicting Green and Ampt infiltration parameters from soils data.” ASCE, J. of Hydraul. Engineer., 109(1), pp.62-70.

3. *National Agricultural Inventory Program (NAIP)*

Source: Geospatial Data Gateway
Resolution: 1m
Description: The NAIP mosaics are county mosaics of aerial photos in quarter quads produced for the National Agricultural Imagery Program (NAIP) and are comprised of scanned photographs that were acquired with a precision aerial mapping camera at a nominal scale of 1:40,000 on color positive film. Acquisition was leaf on with mature crops prior to harvest.

4. *Landuse (NLCD)*

Source: National Land Cover Database (NLCD), 2001
Resolution: 30 m
Reference: Homer, C., C. Huang, L. Yang, B. Wylie and M. Coan, 2004. Development of a 2001 national land cover database for the United States. Photogrammetric Engineering and Remote Sensing Vol.70,No.7,pp 829-840 or online at www.mrlc.gov/publications.
Overland roughness source: Engman, E. T., 1986, Roughness coefficients for routing surface runoff. *J. of Irrig. and Drain. Eng.*, 112(1):39-53.

Description: Anderson LU/LC classification scheme is reclassified to hydraulic roughness values according to Vieux (2004) and Engman (1986).

5. Impervious cover

Source: NLCD 2001 impervious surface
Reference: Yang, L., C. Huang, C. Homer, B. Wylie and M. Coan. 2003. *An approach for mapping large-area impervious surfaces: Synergistic use of Landsat 7 ETM+ and high spatial resolution imagery.* Canadian Journal of Remote Sensing, Vol. 29, No. 2, pp.230-240. Available on the Internet at:
http://landcover.usgs.gov/pdf/imppaperfinalwithall.pdf
Description: The impervious surface data classifies each pixel into 101 possible values (0% - 100%). The data show the detailed urban fabric in which many of us reside. Low percentage impervious is in light gray with increasing values depicted in darker gray and the highest value in pink and red. White areas have no impervious surface.

6. Stream network

Source: National Hydrography Dataset (NHD) Medium Resolution
Description: The National Hydrography Dataset (NHD) is the surface-water component of The National Map. The NHD is a comprehensive set of digital spatial data that represents the surface water of the United States using common features such as lakes, ponds, streams, rivers, canals, streamgages, and dams. Polygons are used to represent area features such as lakes, ponds, and rivers; lines are used to represent linear features such as streams and smaller rivers; and points are used to represent point features such as stream gages and dams. Lines also are used to show the water flow through area features such as the flow of water through a lake. The combination of lines is used to create a network of water and transported material flow to allow users of the data to trace movement in downstream and upstream directions.

7. Watershed boundaries

Source: Watershed Boundary Dataset (WBD) Hydrologic Unit Code (HUC) 12
Agency: National Resources Conservation Service (NRCS)
Description: The hydrologic unit (HU) data that you have download from the USDA Geospatial Data Gateway is called the Watershed Boundary Dataset (WBD). This new dataset at 1:24,000 scale is a greatly expanded version of the hydrologic units created in the mid-1970's by the U.S. Geological Survey under the sponsorship of the Water Resources Council. The WBD is a complete set of hydrologic units from new watershed and subwatesheds less than 10,000 acres to entire river systems draining large hydrologic unit regions, all attributed by a standard nomenclature.