# Evaluation of Fourmile Hydrologic Model and Updates for 2015 Flood Season

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**Urban Drainage and Flood Control District**
**2480 W. 26th Avenue, Suite 156-B**
**Denver, CO 80211**


VIEUX, INC.

350 David L. Boren, Blvd. Suite 2500
Norman, Oklahoma 73072
www.vieuxinc.com
405 325-1818

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# 1 Introduction

This report reviews the V*flo*® model hydrologic simulation and forecast performance during the 2013-2014 flood seasons including the September Flood of 2013. In terms of infiltration capacity, the Fourmile Burn Area (FBA) recovery is investigated for 2011-2014. Based on a model performance review, recommendations are made in preparation for the 2015 operational flood season. The model updates are based on observations from the 2011-2014 flood seasons, and any observed improvement in the FBA saturated hydraulic conductivity (KSAT).

## *1.1 Background*

Vieux, Inc. provides real-time hydrologic prediction services to the UDFCD for monitoring the hydrologic conditions along Boulder Creek, Fourmile Creek (FMC), and Fourmile Canyon Creek (FMCC). The setup of the hydrologic forecast model was accomplished in a three-phase project that resulted in the setup, calibration/validation, and finally an operational model for the Boulder Creek, FMC, and FMCC Basins, beginning with the 2011 flood season and continuing through 2014.

## *1.2 Objectives*

The following are the specific objectives that are the focused of this report.

1. Review V*flo*® model performance during the 2013-2014 flood seasons, including the September Flood of 2013
2. Determine whether the FBA has recovered based on calibrated model results from 2011-2014, and data contained in RainVieux.
3. Develop recommendations for model updates in preparation for the 2015 flood season.

Locations chosen for evaluation of model performance are presented in Table 1, and shown in Figure 1.

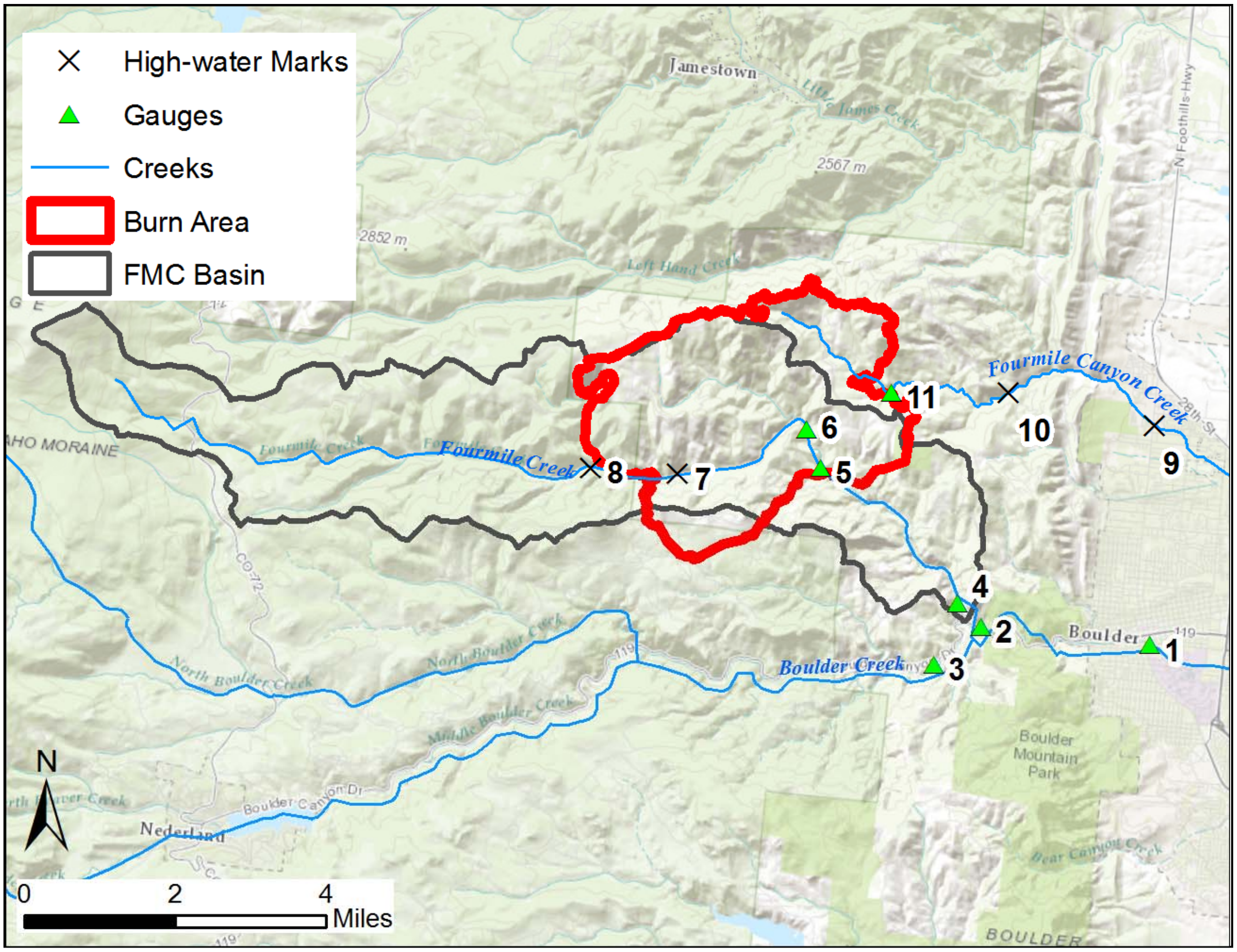



**Figure 1 Locations for model performance analysis within the FBA**

**Table 1 Locations for model performance analysis**

| ID | Name | Gauge ID | Drainage Area ($mi^2$) | Description |
|---|---|---|---|---|
| 1 | Boulder Creek at Broadway | 4583 | 134.5 | Boulder Creek at Broadway, City of Boulder, CO (BOCOBOCO) |
| 2 | Boulder Creek at Bridge | 4423 | 128.8 | Boulder Creek downstream of confluence with Fourmile Creek |
| 3 | Boulder Creek at Orodell | 4403 | 102.1 | Boulder Creek upstream of confluence with Fourmile Creek |
| 4 | FMC at Orodell | 06727500 | 24.2 | Fourmile Creek at Orodell, CO |

| ID | Name | Gauge ID | Drainage Area ($mi^2$) | Description |
|---|---|---|---|---|
| 5 | FMC at Crisman | 06727410 | 19.2 | Fourmile Creek at Logan Mill Road near Crisman, CO |
| 6 | FMC at Salina | 4413 | 18.9 | Fourmile Creek at Salina, CO |
| 7 | FMC d/s of Emerson Gulch | High-water Mark[1] | 14.7 | Fourmile Creek Downstream of Emerson Gulch |
| 8 | FMC u/s of burn area | High-water Mark[1] | 9.0 | Fourmile Creek Upstream of Burned Area |
| 9 | FMCC at Broadway | High-water Mark[1] | 7.6 | Fourmile Canyon Creek at Broadway, City of Boulder, CO |
| 10 | FMCC at Pinto Dr. | High-water Mark[1] | 4.0 | FMCC at Pinto Dr. |
| 11 | FMCC at Burn Outlet | 06730160 | 1.8 | Fourmile Canyon Creek near Sunshine, CO |

*Notes: [1]High-water marks measured by Jarrett (2013)*

# 2 Events

This section describes evaluation of the operational system performance for the 2013 and 2014 seasons. The September Flood of 2013 occurred in this period, and is examined to identify if the model over-predicted during this very large event.

## *2.1 Flood Season 2013*

The events considered in 2013 consist of two events of differing magnitude. With model input derived from the operational system, re-construction of the following events is considered.

1. Minor event on August 26, 2013
2. Major flood of September 11-12, 2013

The minor event that occurred on August 26, 2013 was important because it improved the operational system before the September 2013 event occurred. The August event provided an opportunity to adjust the KSAT parameter for the FBA. During this event, there was a large over prediction of peak streamflow at the downstream location, FMC at Orodell.

### 2.1.1 Event on August 26, 2013

On August 26, 2013, the rainfall totaled between 0.5 - 1.0 inches between 16:00 - 23:00 MDT over the FBA (Figure 2). Rainfall rates for shorter periods (less than 10 minutes) exceeded 2.5 in/hr within the middle of the FBA. However, runoff from this area was over-predicted by the real-time hydrologic model. The KSAT parameter for the FBA used prior to this event was 0.07 in/hr. This was based on the assumption that the FBA infiltration rate was low due to the 2010 fire effects. Through event calibration, the KSAT parameter exhibited recovery from the initial 2013 estimate of 0.07 in/hr. Model simulations were performed showing the impact of increasing the KSAT parameter for the FBA using 0.07, 0.25, and 0.3 in/hr (Figure 3). The KSAT parameter changes are discussed in more detail in Section 3 below.

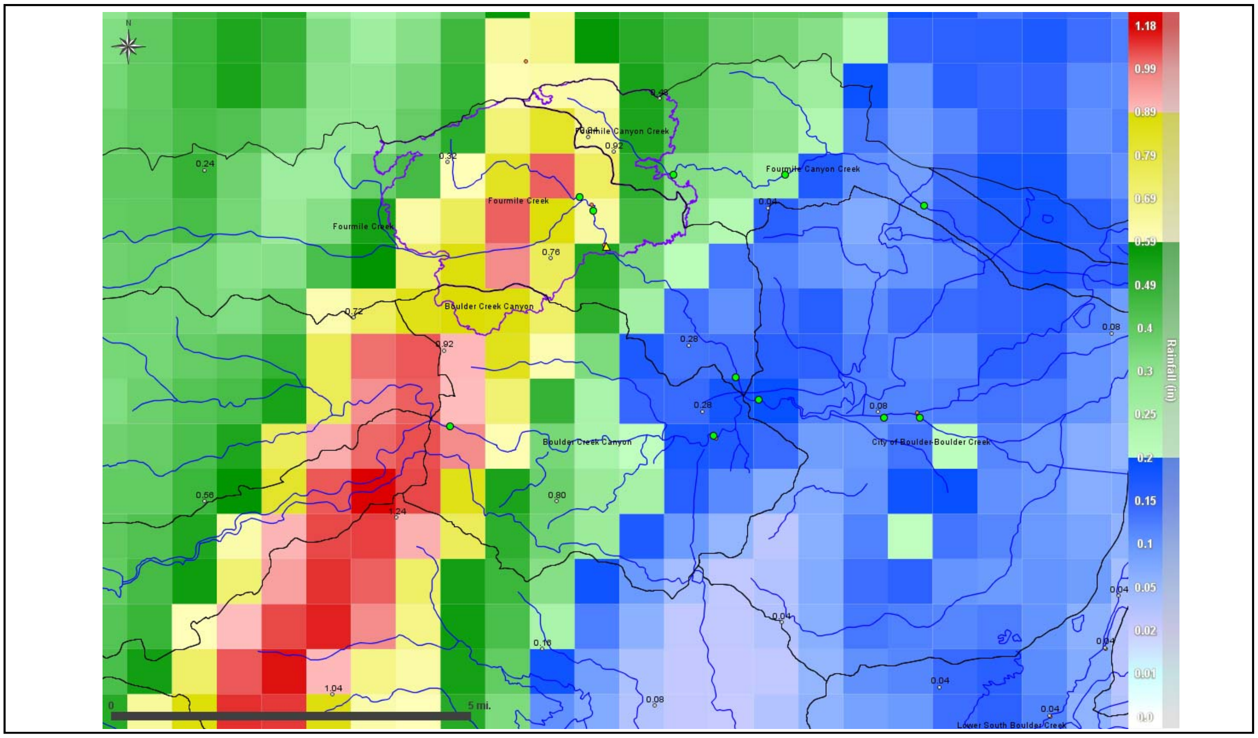
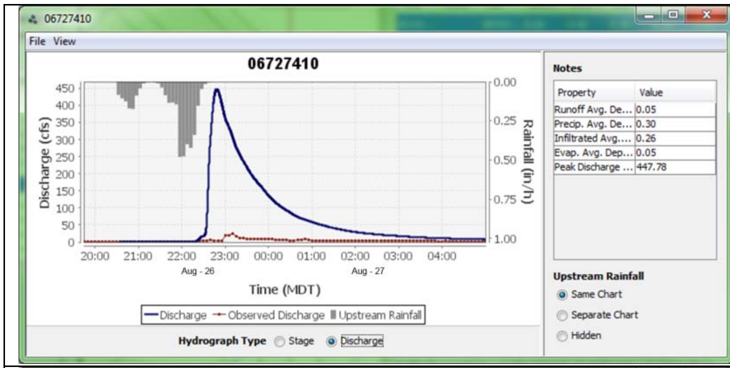
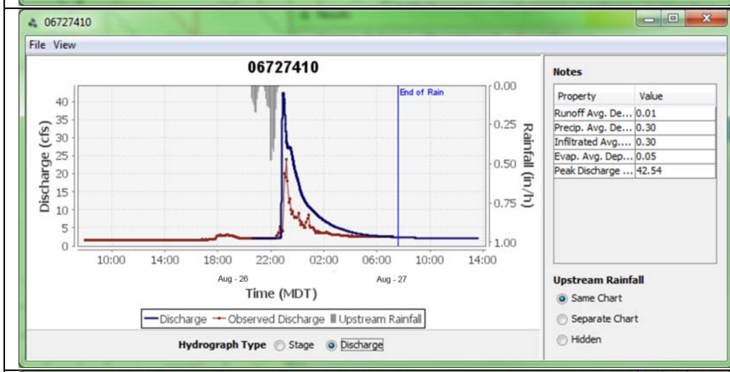



**Figure 2** ***Storm total rainfall for Fourmile Creek from August 26, 2013 16:00 – 23:00 MDT***

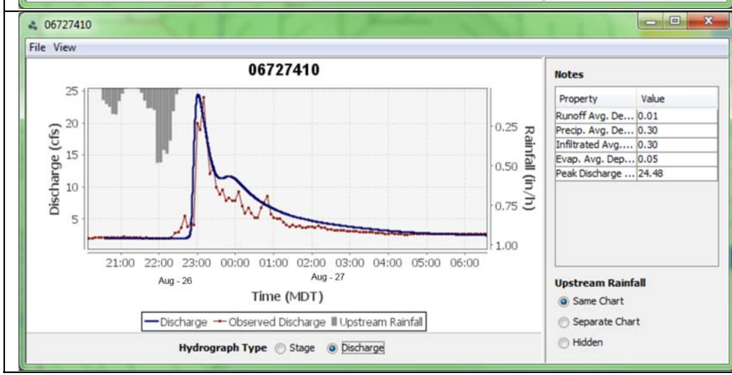
When KSAT was changed from 0.07 in/hr to 0.3 in/hr, the simulated runoff volume matched with the observed runoff volume for the August 26, 2013 event. The third panel in Figure 3 shows the improved simulation with a peak discharge of 25 cfs. In retrospect, it was fortunate that the model was adjusted after this event. If the model had not been adjusted, then there could have been a larger over-prediction during the September Flood of 2013.




KSAT 0.07 in/hr




KSAT 0.25 in/hr




KSAT 0.30 in/hr

**Figure 3 Hydrograph sensitivity to infiltration rate for the August 26, 2013**

### 2.1.2 September Flood of 2013

The September Flood of 2013 occurred on September 11-13, 2013. Due to stream gauge failures and sedimentation or bypassing, field-measured high water marks, determined after the event, are used to validate model performance at several locations (Houck, 2014; Jarrett, 2013; USGS, 2014). The peak stage and discharge measured for each of the USGS gauges is shown in Table 2. The “ID” next to each location corresponds with the data shown in Figure 1 and Table 2. The last col. of Table 2 presents the operational values from USGS or UDFCD ALERT gauges, some of which were subsequently revised.

**Table 2 Comparison of simulated and observed peak discharge estimates for the September Flood of 2013**

| ID | Name | Gauge ID | Simulated (cfs) | Observed Houck (2014) (cfs) | Observed Jarrett (2013) (cfs) | Observed USGS - Revised (cfs) | Operational USGS or ALERT (cfs) |
|---|---|---|---|---|---|---|---|
| 1 | Boulder Creek at Broadway | 4583 | 4,352 | | | | 4,948 (ALERT) |
| 2 | Boulder Creek at Bridge | 4423 | 4,053 | | | | 3,783 (ALERT) |
| 3 | Boulder Creek at Orodell | 4403 | 2,552 | | 2,020 | | 1,761 (ALERT) |
| 4 | FMC at Orodell | 06727500 | 3,290 | 2,733 | 2,300 | 2,510 | 1,210 (USGS) |
| 5 | FMC at Crisman | 06727410 | 1,793 | | | 2,040 | 1,270 (USGS) |
| 6 | FMC at Salina | 4413 | 1,694 | | 3,300 | | 595 (ALERT) |
| 7 | FMC d/s of Emerson Gulch | | 594 | | 1,070 | | |
| 8 | FMC u/s of burn area | | 256 | | 490 | | |
| 9 | FMCC at Broadway | | 3,807 | | 1,460 | | |
| 10 | FMCC at Pinto Dr. | | 1,836 | | 1,080 | | |
| 11 | FMCC at Burn Outlet | 06730160 | 1,112 | | | 1,090 | 203 (USGS) |

The simulated and observed peak discharge estimates are compared in Figure 4. The dashed line indicates the one-to-one line between simulated and observed peak discharge, and the solid black line indicates the linear regression line fit through the origin. Observed peak discharge estimates, in Figure 4, are obtained from three sources:

1. UDFCD ALERT gauge network (indicated by filled circles)
2. USGS revised stream gauge estimates (indicated as filled squares)
3. Peak discharge estimates by Jarrett (2013) (indicated by x's)

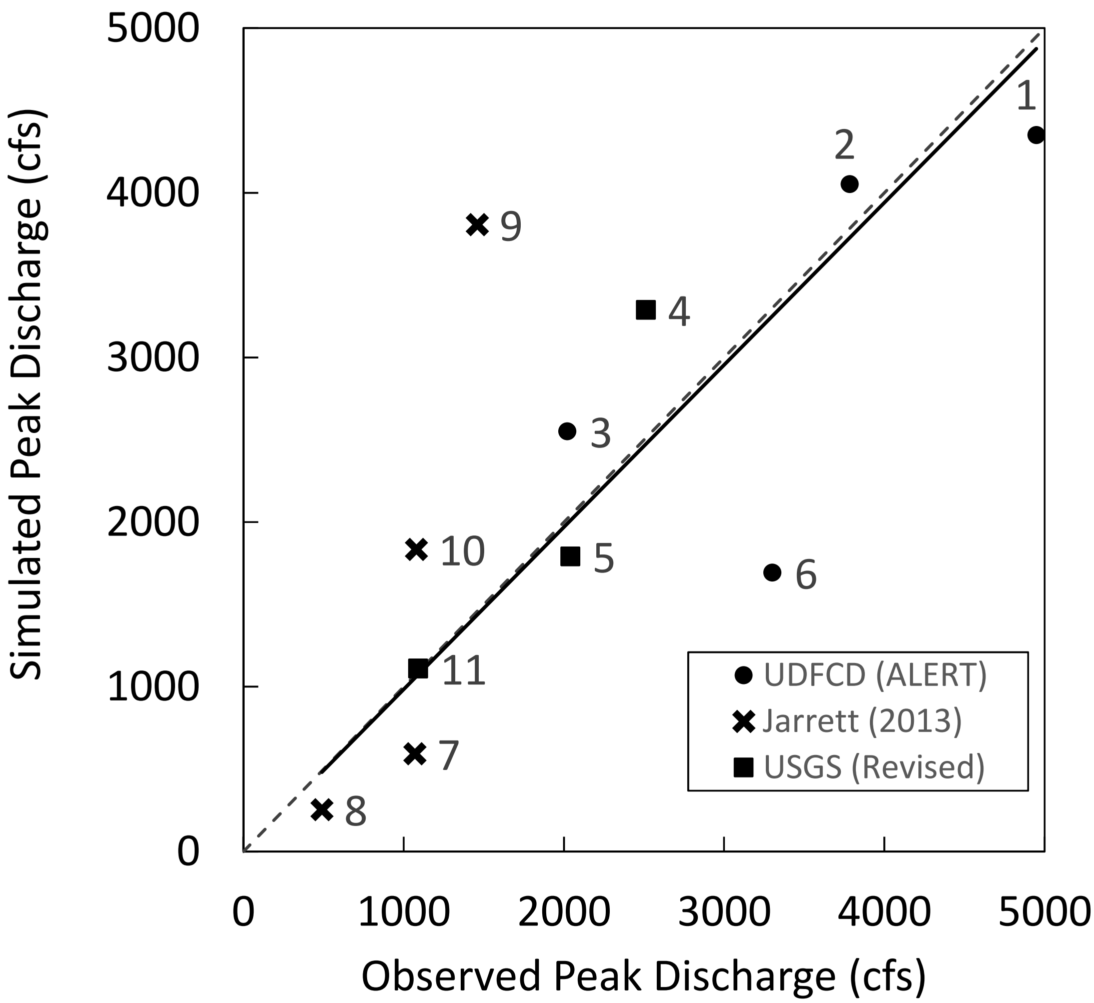



**Figure 4 Peak discharge comparison for locations within the Boulder/Fourmile Creek and Fourmile Canyon Creek watersheds during the September Flood of 2013**

Comparisons are made for the three main creeks within the hydrologic model: Boulder Creek, FMC, and FMCC. For Boulder Creek, the simulated peak discharge percentage error ranged between -12% to +26%. The model predicted 2,552 cfs, while Jarrett (2013) estimated 2,020 at the Boulder Creek at Orodell (ID 3) location. For the FMC sites, the simulated peak discharge for the Orodell gauge (ID 4) was overestimated by 31% (780 cfs) when compared with the revised USGS estimate. While, the simulated peak discharge for the Crisman site (ID 5) was underestimated by 12% (247 cfs). For FMC at Salina, the observed peak discharge estimate was 3,300 cfs. This estimate appears to be uncertain since it is 1,000 cfs greater than the downstream estimate for FMC at Orodell. Based on high-water marks measured in the field by Jarrett (2013), simulated peak discharge was under-predicted at two locations, ID 7 located in the FBA, and at ID 8, which is upstream. For the FMCC, the largest overestimate was 3,807 cfs versus the estimate of 1,460 cfs (Jarrett, 2013) for the FMCC at Broadway (ID 9). However, when the KSAT parameter for non-burn areas is adjusted from 0.5 to 1.4 in/hr, the simulated peak would be 1,610 cfs or within +10 %. At the location of FMCC at Pinto Drive (ID 10), the model also over-predicted due to the assumed KSAT=0.5 in/hr, which is apparently too low for non-burn areas. For the USGS gauge located at FMCC at Burn Outlet site (ID 11), simulated peak discharge was nearly equal to the observed peak discharge (within 22 cfs), or only 2%. The simulated hydrographs for locations representative of Boulder Creek, FMC, and FMCC are shown in Figure 5. Appendix A includes hydrographs for all 11 sites.

The greatest difference between simulated and observed peak discharge was for the drainage area downstream of the FBA, in both FMC and FMCC. In the areas of FMC and FMCC, where the September 2010 fire did not affect infiltration significantly (i.e. non-burn areas), the infiltration rates should have been greater than originally assumed. The KSAT parameter for the FBA during the September Flood of 2013 was 0.30 in/hr, and the KSAT parameter for the drainage area downstream of the FBA was 0.50 in/hr. The initial estimate of 0.5 in/hr was conservative to ensure that the model *did not* generate runoff for the drainage area downstream of the FBA. For the September Flood of 2013, there was approximately 1.3 inches of runoff generated for this area. This amount of runoff was large for non-burn areas, and is most likely due to the assumed value of KSAT = 0.5 in/hr that caused the greater than expected runoff depth. In post analysis, KSAT was varied between 0.5 – 1.5 in/hr to see the runoff sensitivity for this area during the event as shown in Table 3. The KSAT parameter of 1.1 in/hr results in a peak discharge that is more consistent with the revised USGS peak discharge of 2,595 cfs for FMC at Orodell, than the operational value of 3,290 cfs. In areas of the FMC and FMCC not affected by the FBA, the model computed the volume of infiltration during this event to be 9.3 out of 10.2 inches of rainfall. Some of this infiltrated volume returned as streamflow as evidenced by prolonged recession limbs of observed hydrographs. This quick return flow process was not accounted for in the model due to its configuration as a flood alert application.

A similar overestimate of peak discharge occurred for the FMCC at Broadway (ID 11). The simulated peak discharge during the event was 3,807 cfs while the observed was 1,460 cfs. The majority of the drainage area for the site (76%) is downstream of the FBA. The KSAT parameter for the non-burn area had been estimated at 0.5 in/hr. Revising KSAT to 1.4 in/hr brings the simulated peak discharge into agreement with the estimated value by Jarrett (2013).

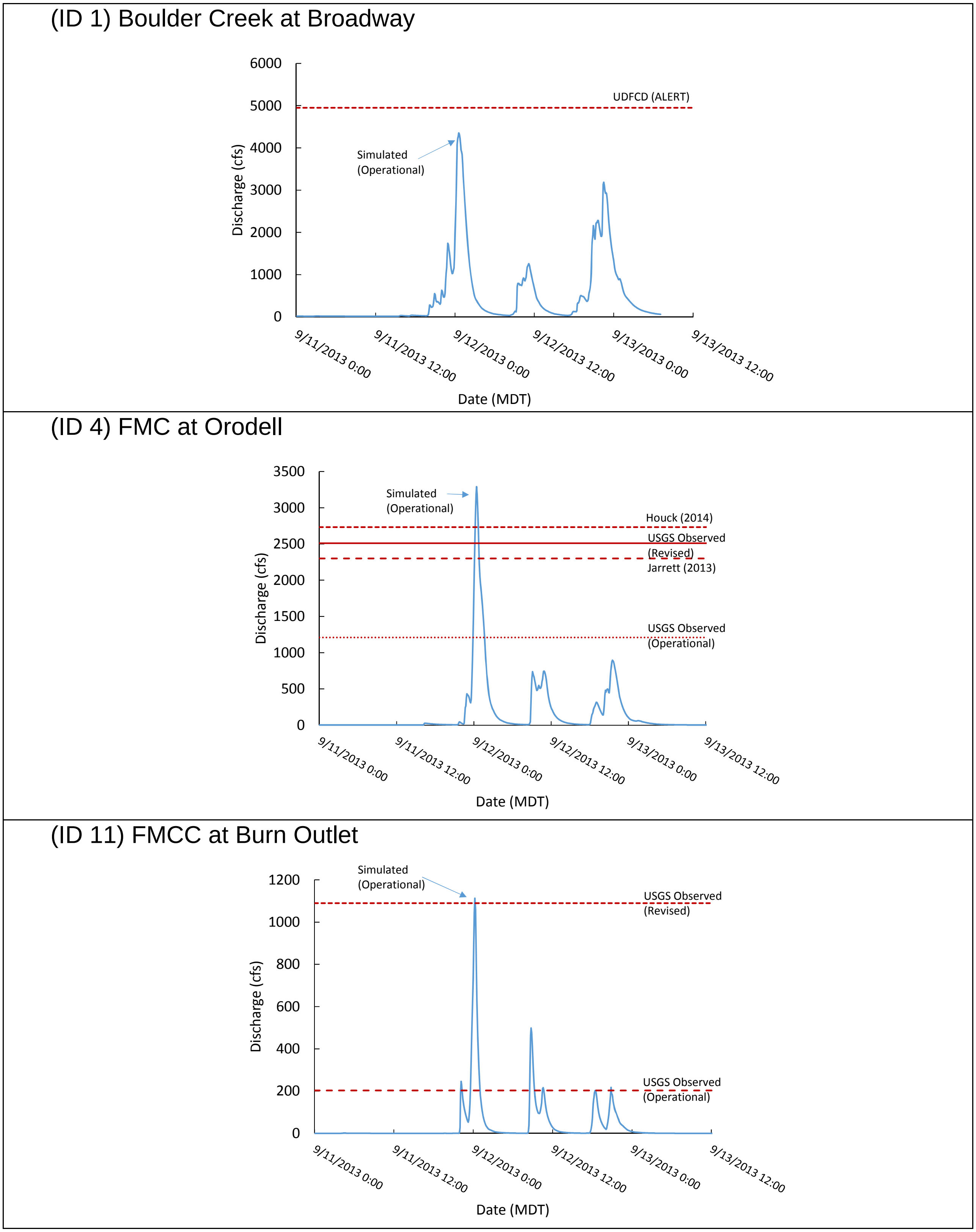



**Figure 5 Comparison of simulated hydrographs and observed peak streamflow estimates for representative locations during the September Flood of 2013**

The hydrologic model does not account for flow bypass of stream gauges, or degradation/aggradation of stream beds; nor can it model the effects of debris dams or the sudden release or surge of streamflow when debris dams fail during an event of this magnitude. Since the September Flood of 2013, USGS has revised the rating curve for FMC at Orodell (06727500), seen in Figure 6. The shift accounts in part for the alteration in channel geometry and hydraulics resulting from this event.

**Table 3 Peak discharge sensitivity with respect to KSAT for FMC at Orodell gauge**

| KSAT (in/hr) | Orodell Peak Discharge (cfs) | Simulated Runoff Depth (in) | Rainfall Depth (in) | Simulated Runoff Coefficient |
|---|---|---|---|---|
| 0.5 | 3,290 | 1.31 | 10.2 | 0.110 |
| 1.0 | 2,595 | 0.92 | 10.2 | 0.093 |
| 1.1 | 2,490 | 0.85 | 10.2 | 0.083 |
| 1.5 | 2,259 | 0.63 | 10.2 | 0.061 |

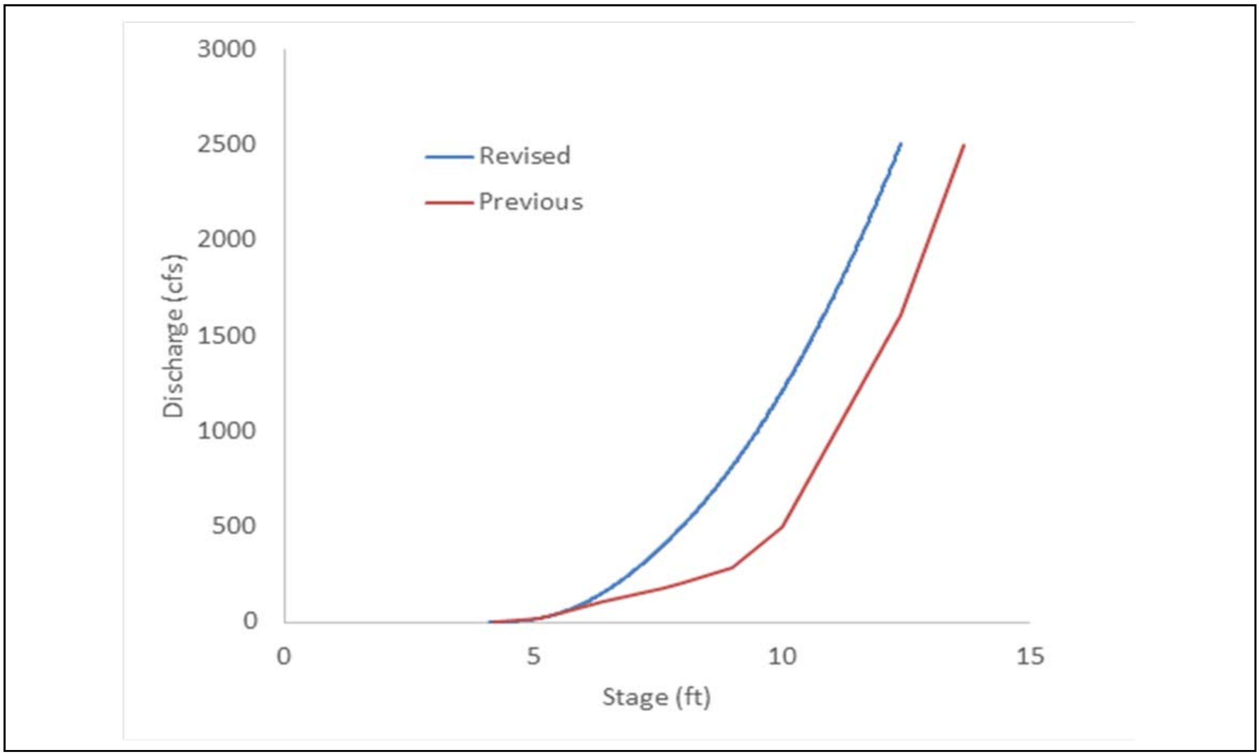



**Figure 6 Previous and revised USGS rating curves for FMC at Orodell (06727500)**

Table 4 provides the range of runoff depths that were estimated from the model during the event. The runoff coefficients ranged from 0.07 – 0.19. The greatest runoff coefficient occurred for the Fourmile Canyon Creek area. The majority of the runoff for this area was generated from the FBA that had a reduced infiltration rate of 0.3 in/hr. The observed runoff depth was difficult to estimate for this event due to sediment and streamflow gauge malfunctions during the event. Rating curves have been modified by the USGS to account for changes to the cross sections due to this event.

**Table 4 Runoff depth and runoff coefficients for USGS gauges for the September Flood of 2013**

| Name | USGS Gauge | Simulated Runoff Depth (in) | Rainfall Depth (in) | Simulated Runoff Coefficient |
|---|---|---|---|---|
| FMC at Orodell | 06727500 | 0.71 | 8.35 | 0.085 |
| FMC at Crisman | 06727410 | 0.55 | 7.84 | 0.070 |
| FMCC at Burn Outlet | 06730160 | 2.11 | 11.06 | 0.19 |

# 3 FBA Recovery Evaluation

An objective of this study is to evaluate whether the FBA exhibits recovery in its infiltration properties. Within the model, one of the key parameters for controlling the infiltration rate is the KSAT parameter. Mean KSAT estimates have been estimated for the 2011 - 2014 seasons using events that occurred during each season.

The 2014 season provided some information about the infiltration capacity of FBA, even though there were only small events (Figure 7). Two direct runoff events occurred during this period on May 23rd and May 30th. During the May 23rd event, snowmelt accounted for 40 cfs of the total runoff. The observed peak discharge from direct runoff was 44 cfs and the simulated peak discharge from direct runoff was only 3 cfs. Using a KSAT value of 0.3 in/hr, the simulated results agreed closely, 23 cfs (observed) compared with 18 cfs (simulated). Note that the snowmelt-generated runoff is shown with an adjustment to baseflow on May 23rd.

Another small event occurred on July 30th, as seen in Figure 8. The observed peak discharge from this event was 15 cfs, and the simulated peak discharge was 48 cfs, with both less than the flood threshold of 200 cfs. On August 7, 2014, there was another small event, with zero observed flow response, and only 3.3 cfs simulated flow (not shown due to its small magnitude). Neither of these events produced observed direct runoff from the FBA as evidenced by UDFCD ALERT gauges or USGS stream gauges.

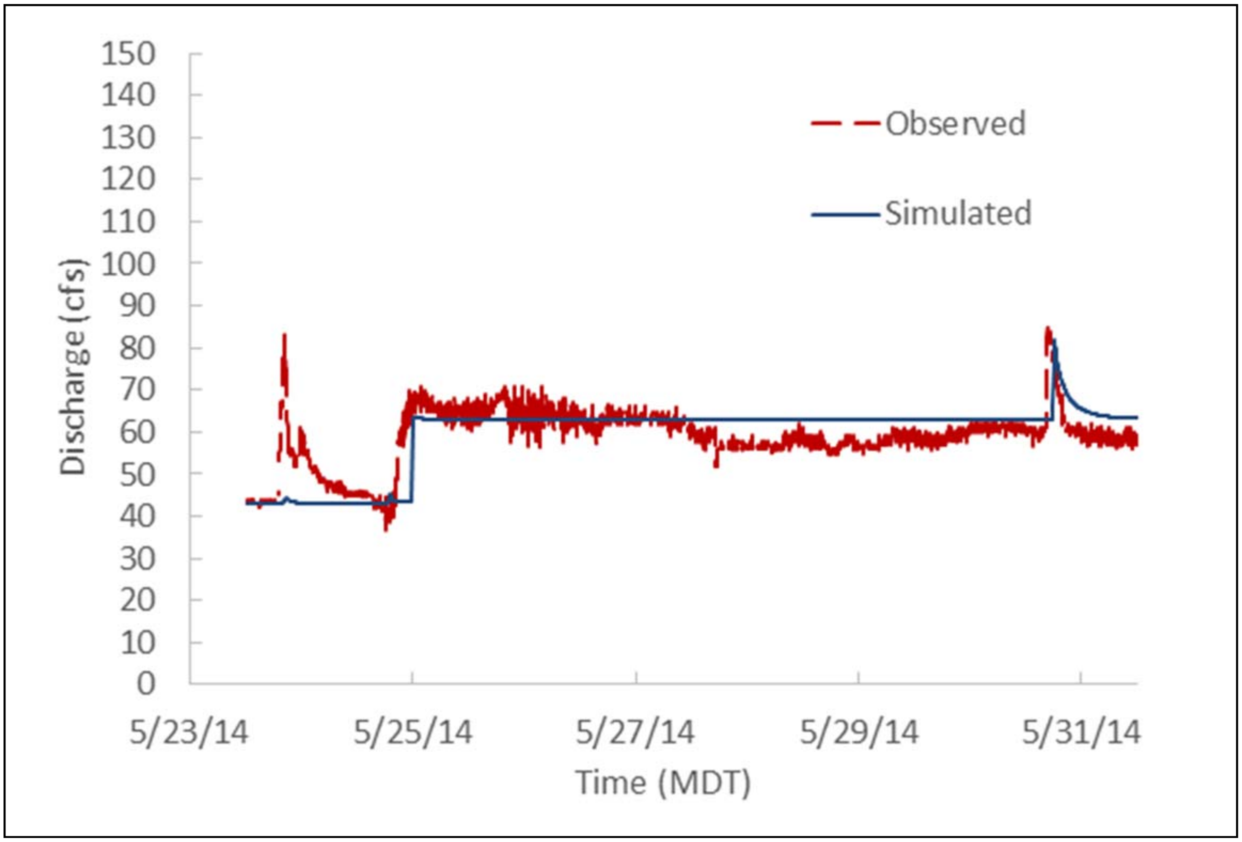



**Figure 7 Comparison of simulated and observed hydrographs at Orodell for May 2014 events**

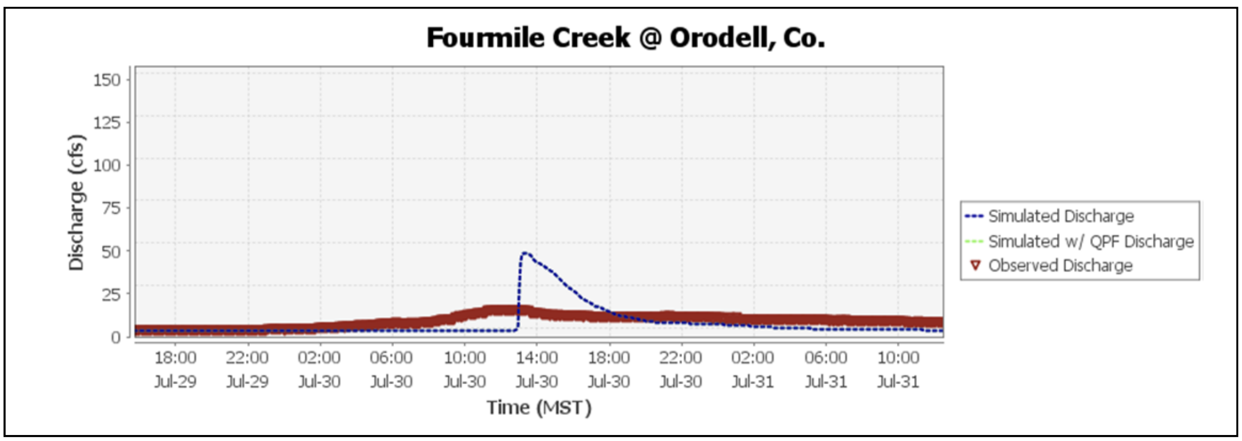



**Figure 8 Comparison of simulated and observed hydrographs at FMC at Orodell for July 30, 2014 event**

Even though the 2014 events are small in magnitude, the simulated and observed runoff results indicate that the model tends to over-predict in the July and August events with KSAT=0.3 in/hr. During the May 30th event, this value of KSAT did produce a hydrograph response consistent with the observed flow FMC at Orodell. This performance in 2014 suggests that recovery in the FBA may justify using a value of KSAT that is higher than 0.3.

Projections of model recovery for the coming season, 2015, is examined and based on infiltration changes for flood seasons, 2011-2014. Figure 9 shows the operational mean KSAT progression during each season from 2011 to 2014 for FBA. In 2011, the initial estimate of KSAT was assumed 0.0 in/hr, and then increased in subsequent years through calibration to observed hydrographs. In the first part of 2012, KSAT was 0.0 in/hr, and then adjusted to 0.07 in/hr after calibration to six storm events during that season. Thus, on average for 2012, the value was 0.04 in/hr. In late 2013, and continuing into 2014, it was increased from 0.07 in/hr to 0.3 in/hr as a result of the August 26th 2013 event. Projection of recovery in the FBA for the coming season, 2015, is KSAT =0.4 in/hr. This estimate is based on the increase in KSAT of about 0.10 in/hr from 2013 to 2014.

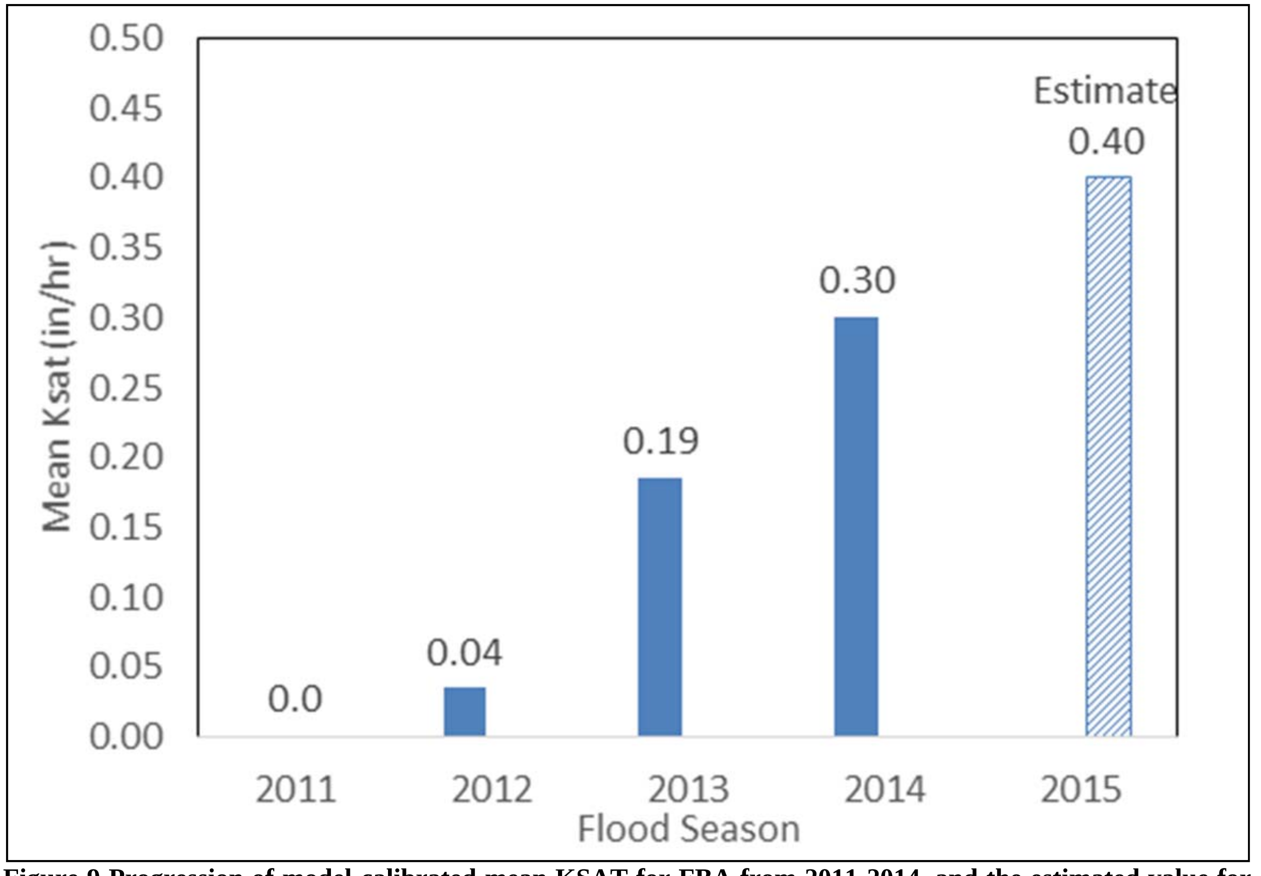



**Figure 9 Progression of model-calibrated mean KSAT for FBA from 2011-2014, and the estimated value for 2015**

# 4 Summary and Recommendations

This report reviews the V*flo*® model performance during the 2013-2014 flood seasons including the September Flood of 2013. Evaluation of the FBA recovery is also made, and is based on calibrated model results for each flood season since 2011. Based on the review of the model performance, recommendations are presented below in preparation for the 2015, operational flood season.

From model calibration, the KSAT parameter has increased from an assumed initial value of 0.0 in/hr in 2011, to 0.3 in/hr in 2014. During the September Flood of 2013, downstream and outside of the FBA, the model over-predicted peak discharge by 31% at FMC at Orodell, most likely due to excess runoff generated by the model in non-burn areas. On Boulder Creek at Orodell, the model forecast was relatively close at 2,552 cfs, compared with 2,020 estimated from a high-water mark. For the FMCC at Pinto and Broadway locations, the model over-predicted due to assumed KSAT values assigned to non-burn areas that were too low. After adjusting for non-burn area infiltration upstream of FMCC at Broadway, the agreement was 1,610 cfs simulated versus 1,460 cfs estimated. Similarly, the model agreed closely with field-measured high-water marks, to within 12% and 2% at FMC at Crisman and FMCC at Burn Outlet, respectively. Evidence suggests that KSAT should be increased in three areas: 1) within the FBA, 2) in the *non-burn* area above the FMC at Orodell gauge, and 3) in the *non-burn* area in FMCC to reduce direct runoff.

When considering the most reliable streamflow measurements for the September 2013 Flood, the model did not appear to over-predict, with a mean absolute percentage error of 12% at four locations in Fourmile Creek, Fourmile Canyon Creek and in Boulder Creek. In cases where over-prediction did occur, these appear to be related to assumed model parameters, which have been revised to represent better the conditions in non-burn areas.

## Recommendations

Model preparation for the 2015, operational season includes the following recommendations.

1. Continue with KSAT of 0.3 in/hr until storm events demonstrate that adjusting the KSAT model parameter to 0.4 in/hr for the FBA is merited.
2. Adjust non-burn areas of the model outside of the FBA to have higher infiltration, namely, increase KSAT to 1.1-1.4 in/hr from 0.5 in/hr.
3. Adjust rating curves in the model to reflect current conditions, as determined by USGS
4. Perform a model stress test to identify potential numerical instabilities due to rating curve modifications.
5. Compare initial soil moisture estimates with the Critical Zone Observatory (CZO) soil moisture probes for the Boulder Creek Basin, and initialize the model accordingly for 2015.

# 5 References

Gochis, D., Schumacher, R., Friedrich, K., Doesken, N., Kelsch, M., Sun, J., Ikeda, K., Lindsey, D., Wood, A., Dolan, B., Matrosov, S., Newman, A., Mahoney, K., Rutledge, S., Johnson, R., Kucera, P., Kennedy, P., Sempere-Torres, D., Steiner, M., Roberts, R., Wilson, J., Wei, Y., Chandrasekar, V., Rasmussen, R., Anderson, A., and Brown, B. 2014. The Great Colorado Flood of September 2013. *Bulletin of the American Meteorological Society*. Prepublication e-View dx.doi.org/10.1175/BAMS-D-13-00241.1.

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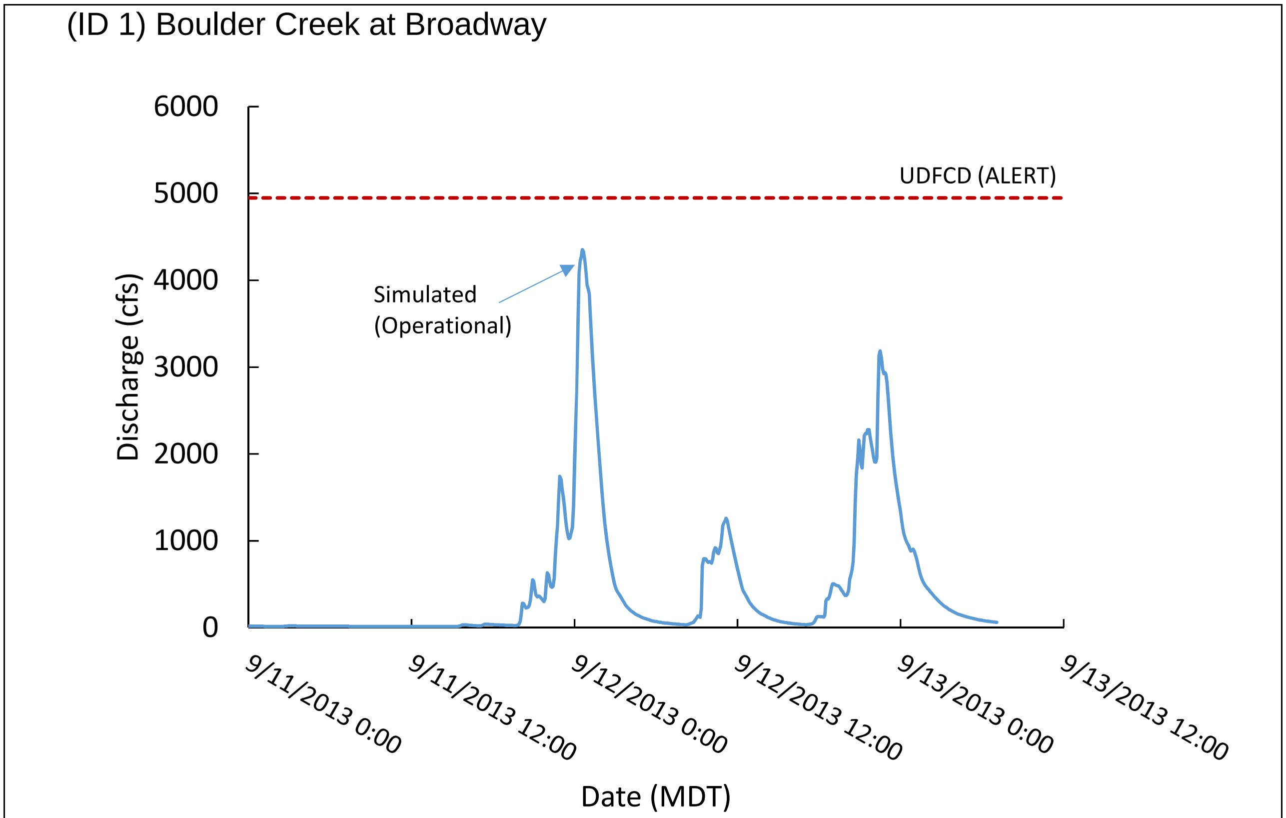
# 6 Appendix

The appendix contains simulated hydrographs compared with peak discharge estimates from September Flood of 2013 for locations within Boulder Creek, Fourmile Creek, and Fourmile Canyon Creek. Site IDs correspond with Figure 1 locations.



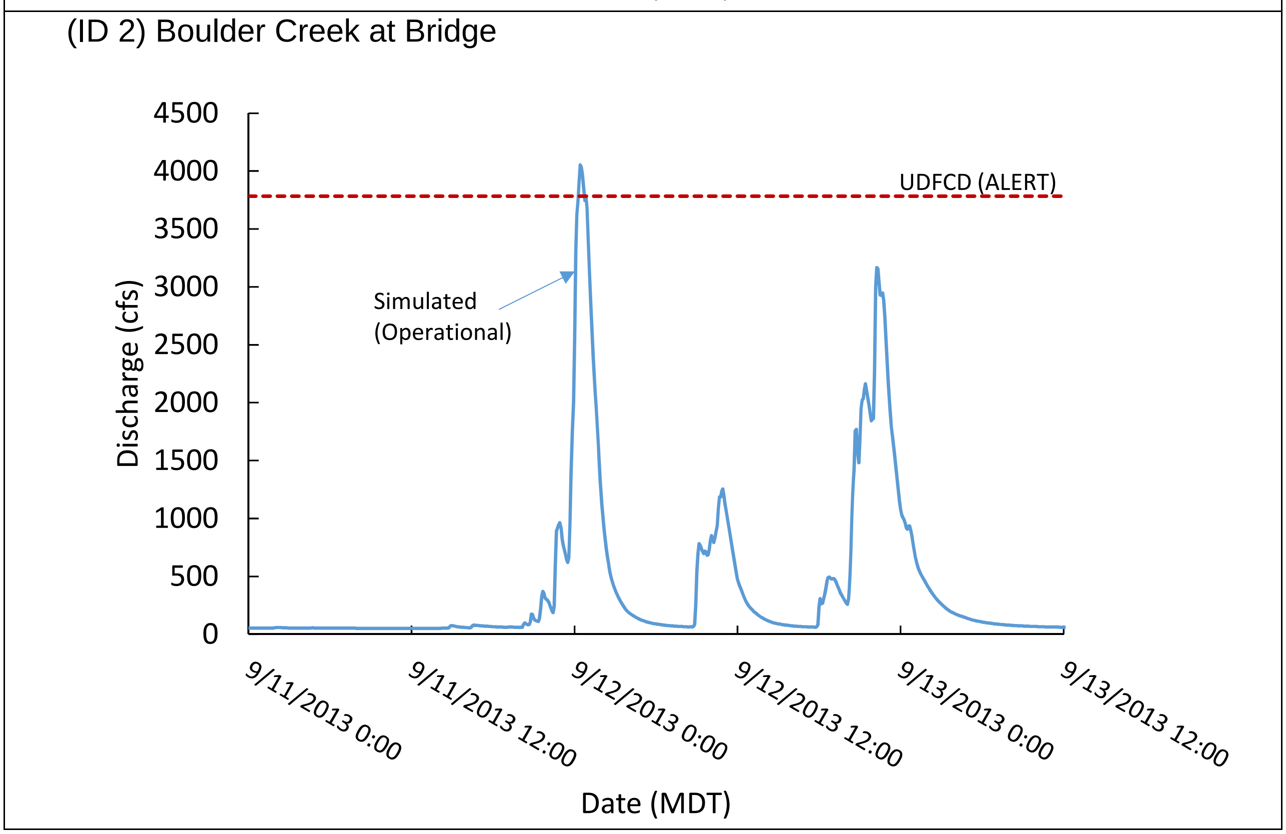




**Figure A-1 Comparison of simulated hydrographs and observed peak streamflow estimates for site IDs 1 and 2 during the September Flood of 2013**

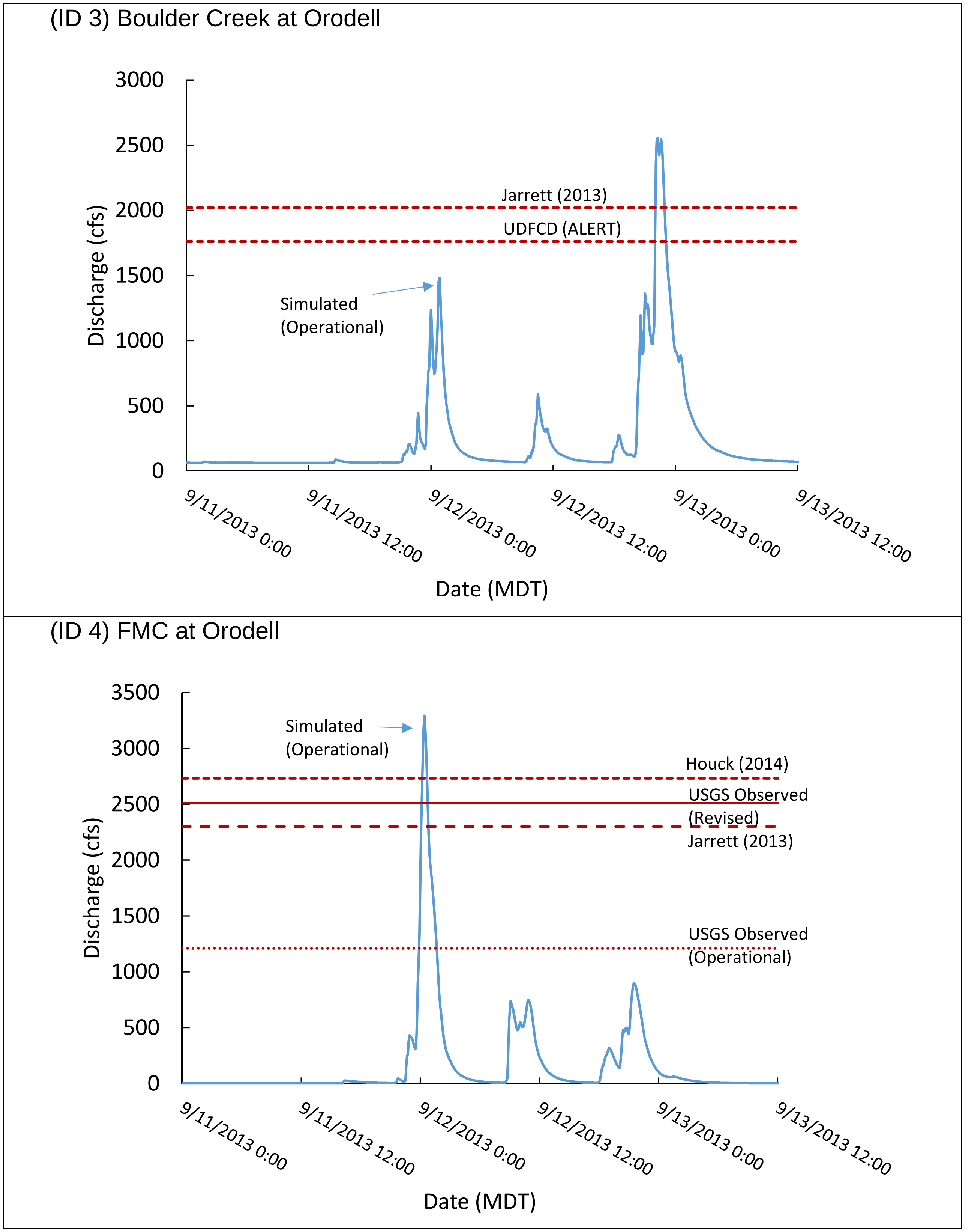
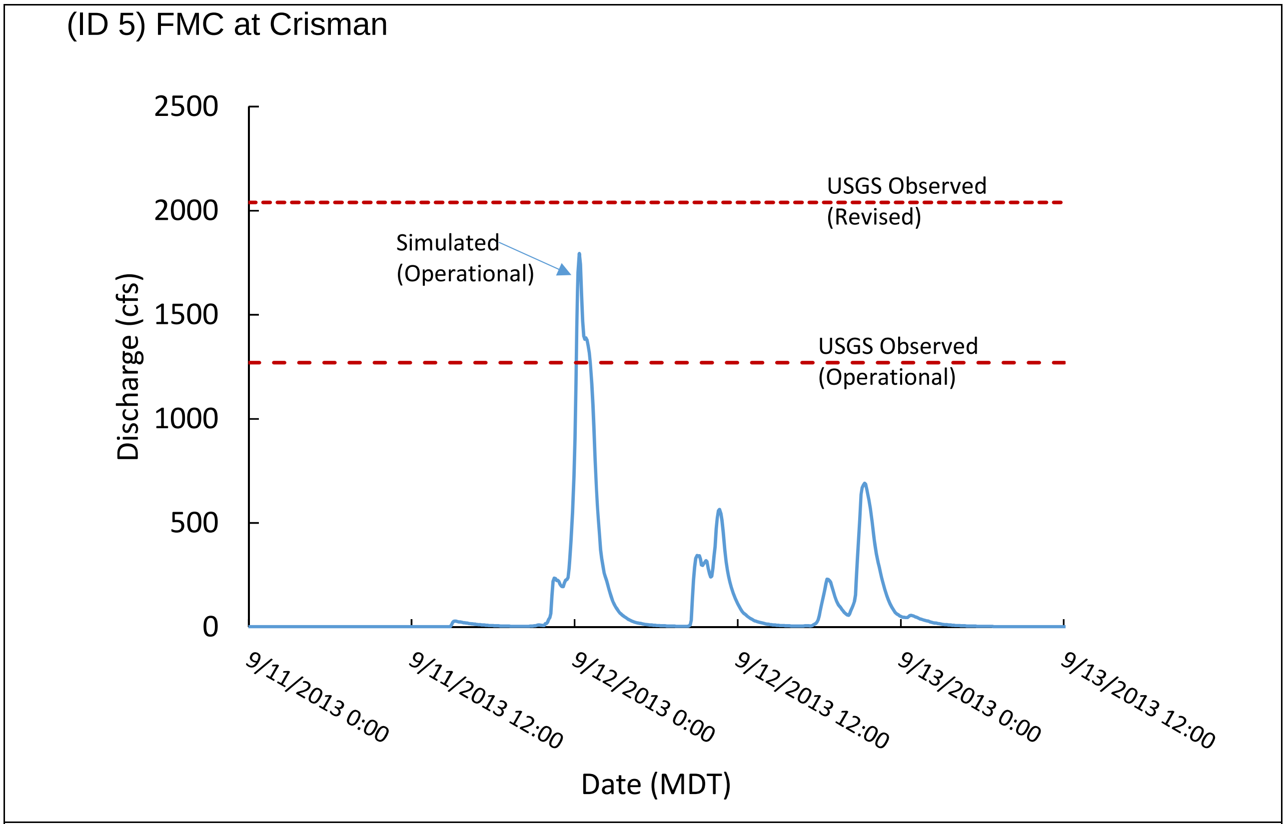



**Figure A-2 Comparison of simulated hydrographs and observed peak streamflow estimates for site IDs 3 and 4 during the September Flood of 2013**



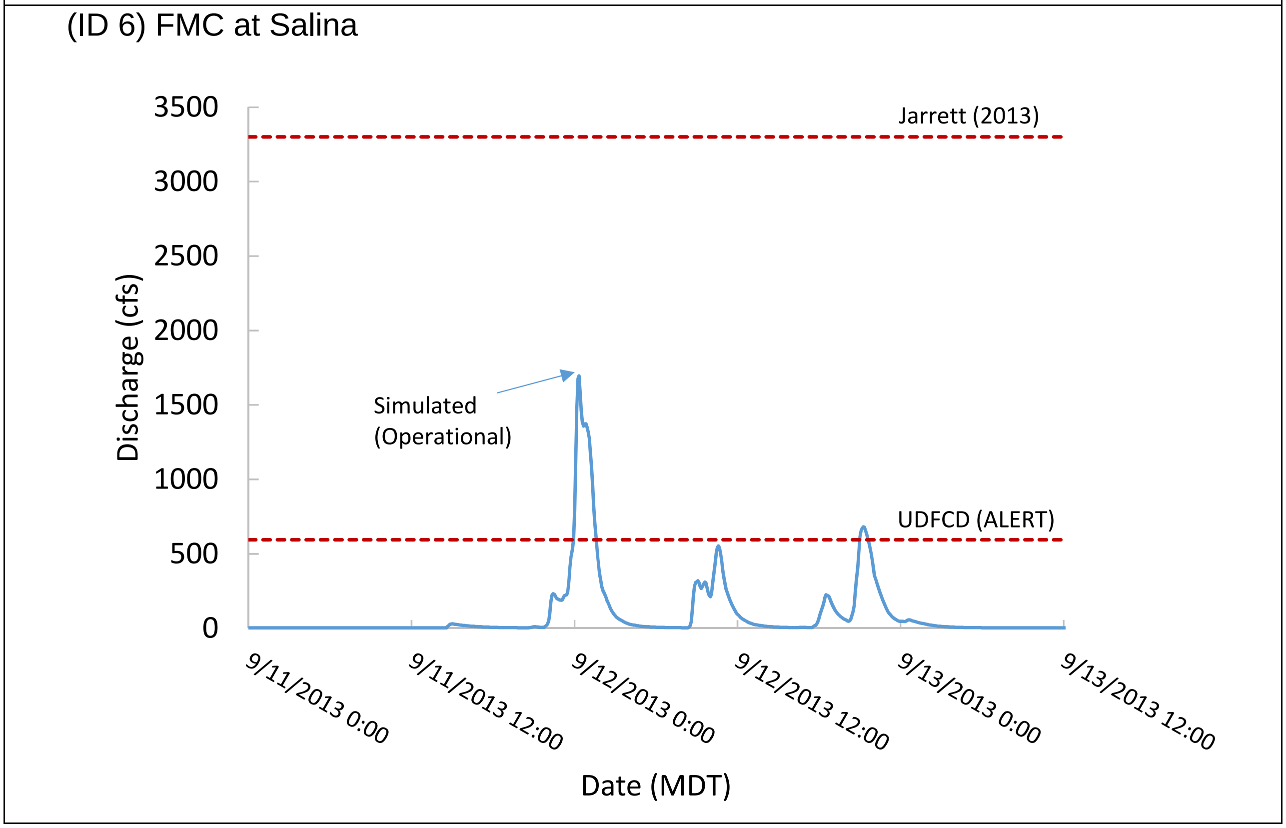
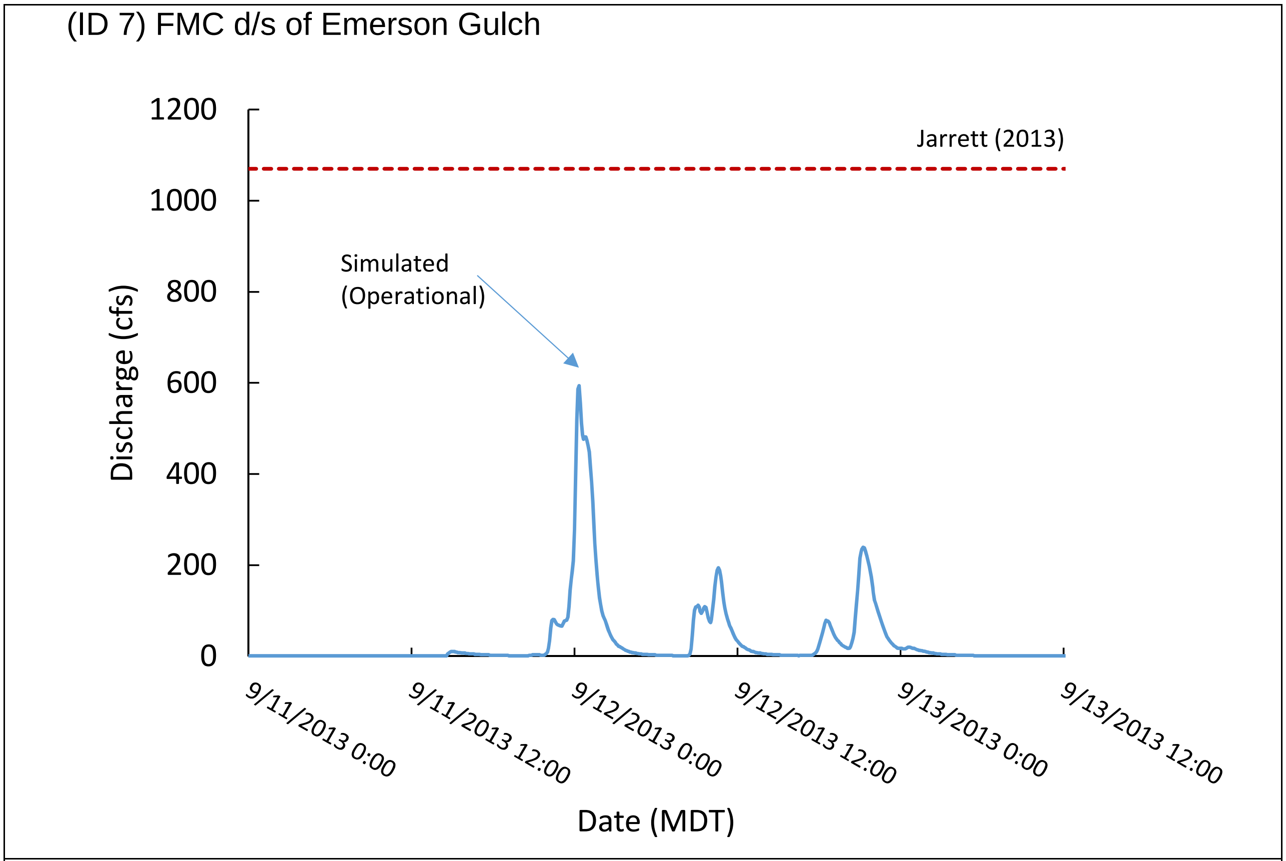




**Figure A-3 Comparison of simulated hydrographs and observed peak streamflow estimates for site IDs 5 and 6 during the September Flood of 2013**



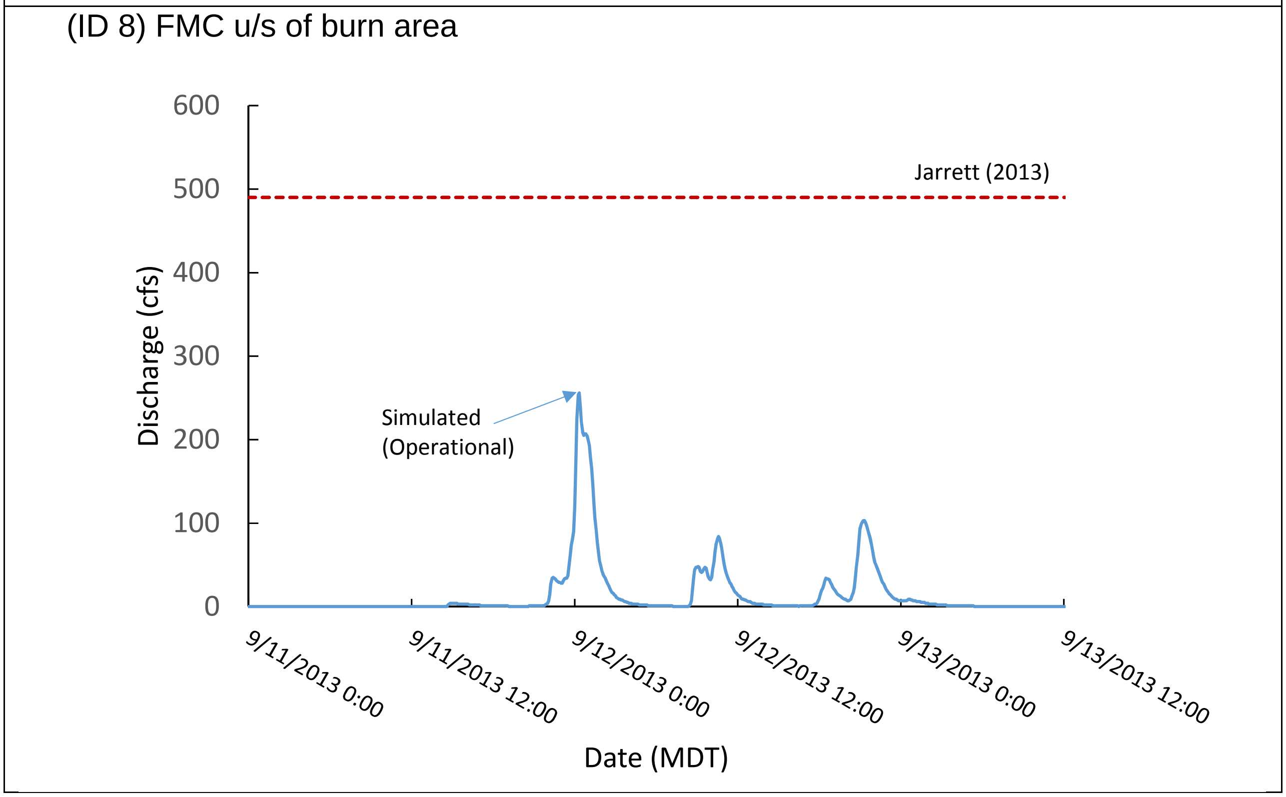




**Figure A-4 Comparison of simulated hydrographs and observed peak streamflow estimates for site IDs 7 and 8 during the September Flood of 2013**

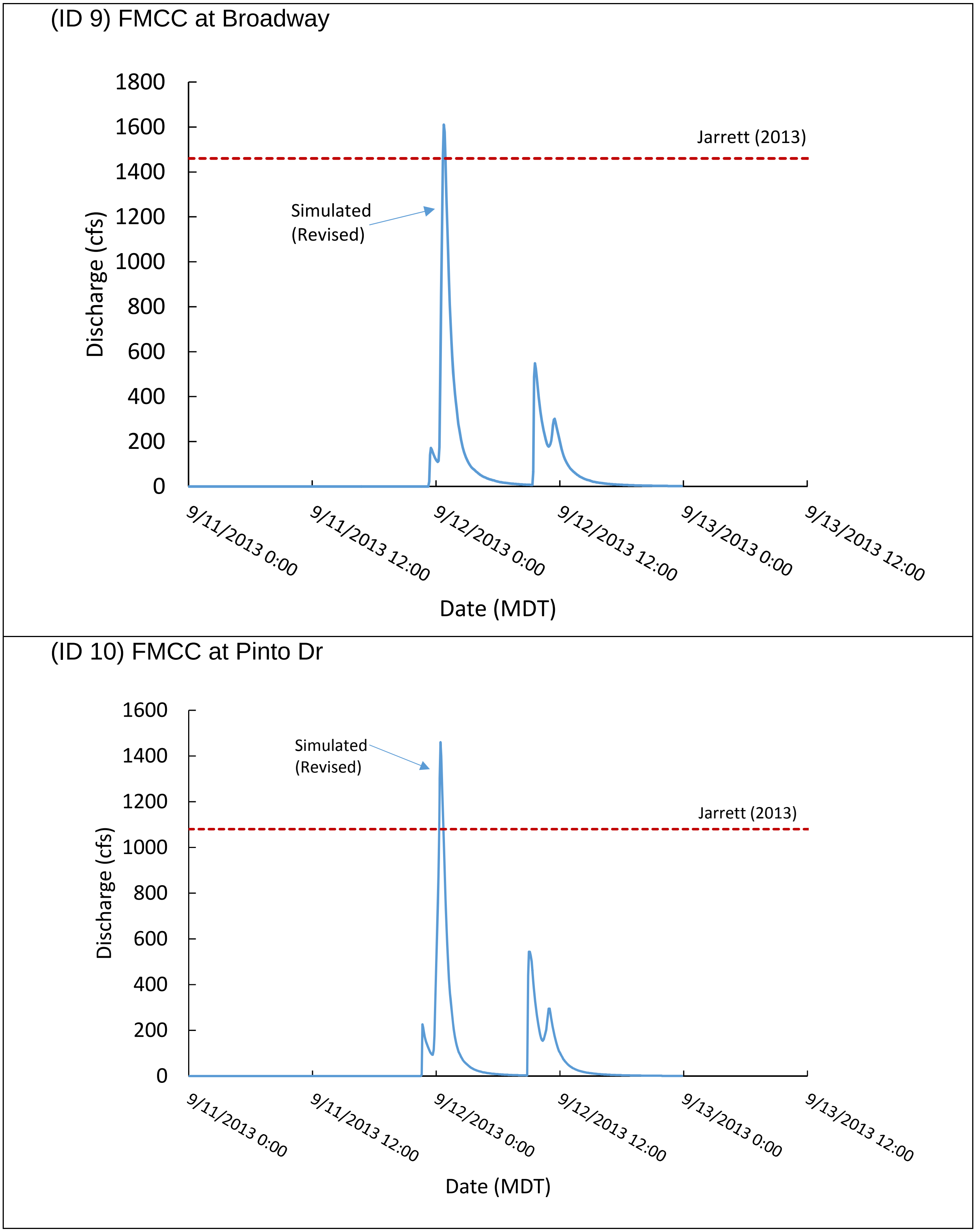



**Figure A-5 Comparison of simulated hydrographs and observed peak streamflow estimates for site IDs 9 and 10 during the September Flood of 2013**

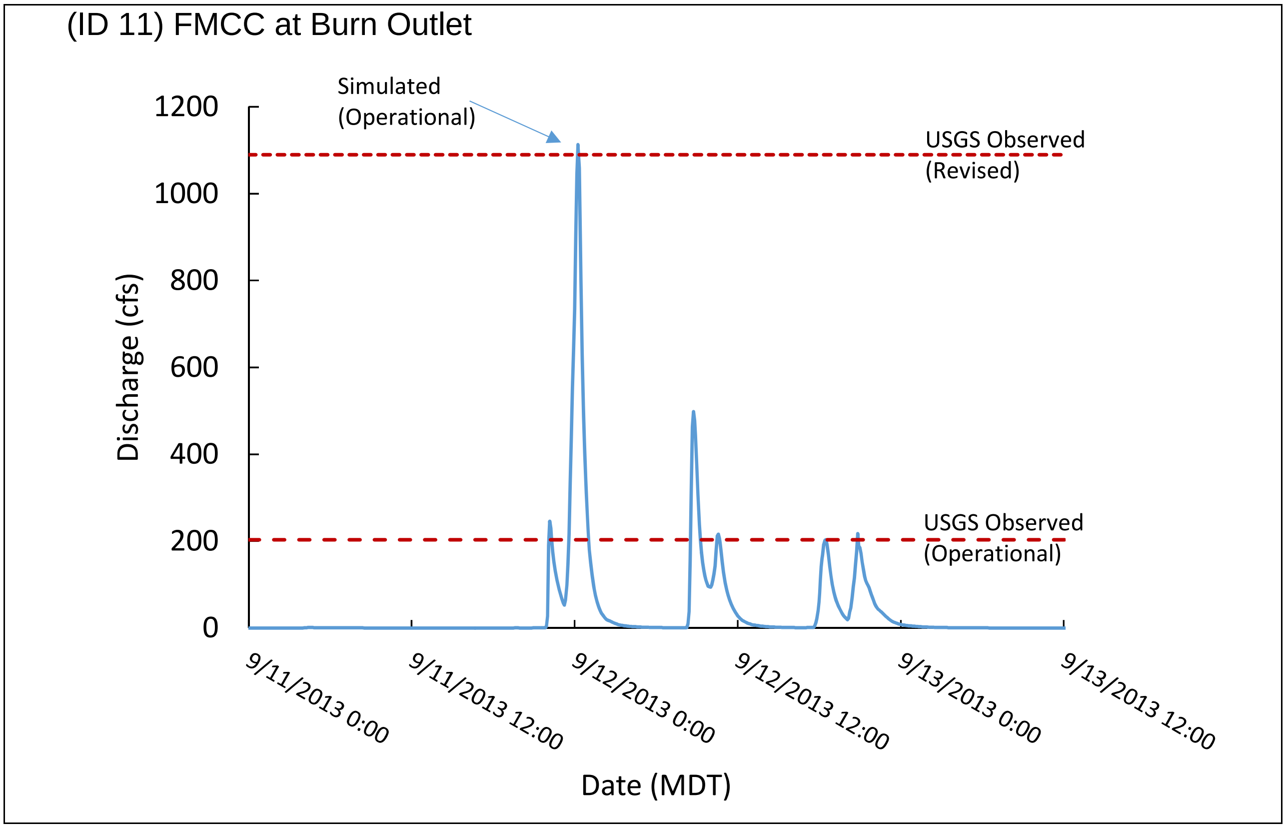



**Figure A-6 Comparison of simulated hydrographs and observed peak streamflow estimates for site ID 11 during the September Flood of 2013**