Hayden Pass Fire – Big Cottonwood Drainage Recovery Plan | 2018

HYDROLOGY AND HYDRAULICS REPORT

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EXECUTIVE SUMMARY

Previous efforts by the U.S. Forest Service (USFS) and the U.S. Army Corps of Engineers (Corps) identified peak stream flows associated with rainfall events with various intensities and return intervals for drainages throughout the Hayden Pass Fire burn area. These estimates were the only hydrological and hydraulic information available to a recently funded Emergency Watershed Protection (EWP) project meant to provide engineering for infrastructure reinforcements and other protection measures. No historical hydrological data is available for the Hayden Pass burn area and neither the assessment provided by USFS or by the Corps were based on observed flood characteristics. Instead, each was developed using best practices for post-wildfire peak flow modeling in data-poor drainages. The USFS employed the Wildcat model while the Corps utilized the Hydraulic Engineering Center (HEC) Hydrologic Modeling System (HMS) model to estimate peak flow magnitudes. Ten-year peak flow predictions from the Corps were significantly lower than those from the USFS, indicating the relatively high-degree of uncertainty associated with these types of predictions. The Corps report suggested that the reliability of peak flow predictions could be improved by calibrating model outputs to observed flood events.

Extremely high flows on Big Cottonwood Creek following a rainfall event on July 24th, 2018 provided an opportunity to refine and improve estimates of peak flow hydrology and the inundation surfaces associated with different flood sizes. This large flood event is the best evidence available to-date for understanding and quantifying post-fire hydrological responses to late season monsoon rainfall events.

Uviation World Water (d.b.a. River Science) and Lotic Hydrological used the July 24th rainfall event to refine hydrological and hydraulic assessments for the Big Cottonwood Creek drainage. Flood wave modeling and streamflow data collected on the Arkansas River at Parkdale (USGS 07094500) was used to estimate a peak flow magnitude of ~3,500 cubic feet per second (cfs) on Big Cottonwood Creek. This estimate of flood size was combined with storm characteristics provided by National Weather Service (NWS) to calibrate a HEC-HMS model similar to the one developed by the Corps. The calibrated model was used with National Oceanographic and Atmospheric Administration (NOAA) Atlas 14 precipitation characteristics for the burn area. The calibrated model produced a 2,031 cfs flood associated with a 10-year, 2-hour rainfall event of and a 10,209 cfs flood associated with the 100-year, 2-hour rainfall event. These estimates compare rather favorably to estimates generated from an analytical methodology developed by the U.S. Geological Survey (USGS).

Debris line elevations and bathymetric profiles collected from the banks of Big Cottonwood Creek, Bitter Creek (a.k.a. Butter Creek), and Little Cottonwood Creek following the July 24th event were used to calibrate a 2-dimensional hydraulic model. Modeling results suggested that the July 24th rainfall event produced flows of 4,000 cfs in upper Big Cottonwood Creek, 2,200 cfs in Bitter Creek, and 4,000 cfs in Little Cottonwood Creek and 10,200 cfs at the Arkansas River confluence. The total flow estimated for lower Big Cottonwood Creek using this method was significantly higher than the peak flow estimated by flow wave modeling. This discrepancy is not unexpected in burned watersheds and suggests that entrained sediment and debris bulking in flood flows create a multiplying effect of approximately 2.8 on flood inundation surfaces.

1 Overview

1.1 PURPOSE AND BACKGROUND

The Hayden Pass fire burned approximately 16,520 acres in the Hayden Creek and Big Cottonwood Creek drainages near Coaldale, Colorado in the Summer of 2016. The majority of Big Cottonwood Creek and its tributaries (i.e. Wolf Creek, Little Cottonwood Creek, and Bitter/Butter Creek) experienced moderate to high burn severity (Figure 1). Wildfires in mountainous watersheds are generally expected to increase the hydrophobicity of soils and reduce understory vegetation densities. Rainfall events in these watersheds are expected to produce high runoff volumes and increase the likelihood of debris flows for several years following the wildfire. Anecdotal evidence provided by residents of Coaldale suggest that these effects are present in the Big Cottonwood Creek drainage as well.

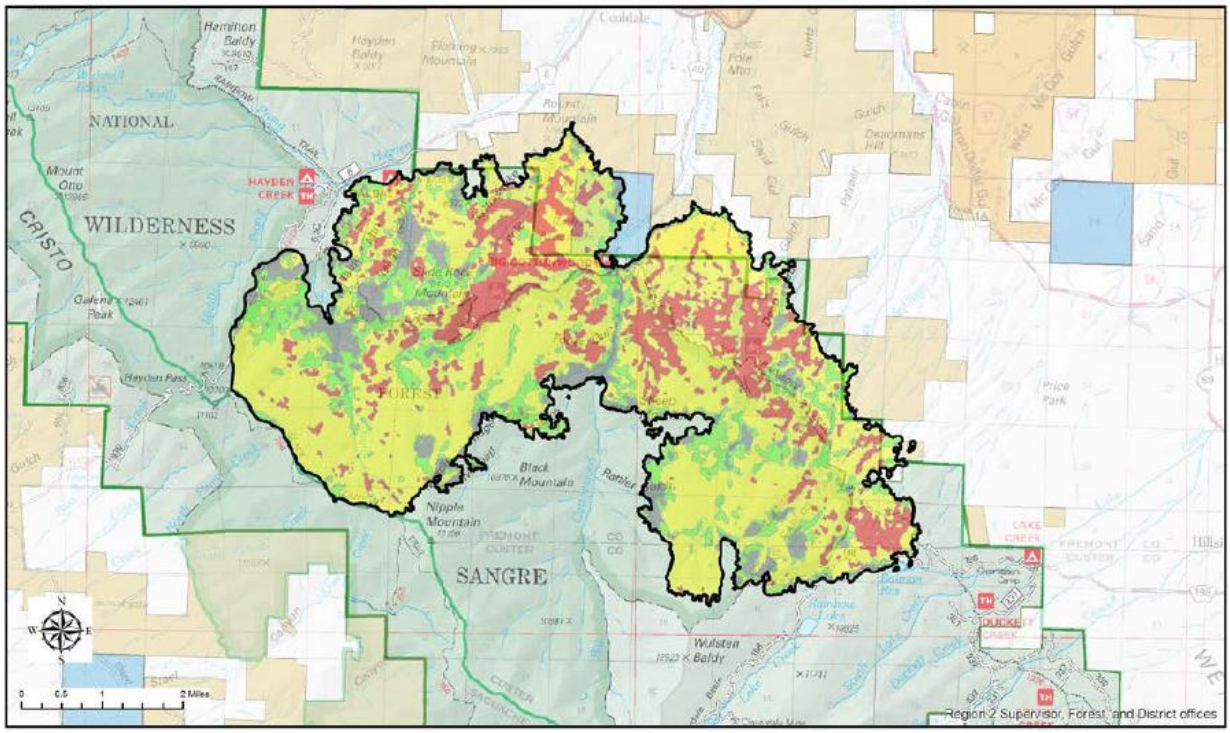

Figure 1: Hayden Pass fire extent and burn severity map (USFS, 2016).

Rainfall events in the fall of 2016 and the summer of 2017 were estimated by locals to produce flows in Big Cottonwood Creek of several hundred cubic feet per second. Residents recall that Bitter Creek rarely produced any discharge prior to the fire and required only a 12" culvert to pass its flow under Dinkle Ditch Road. Rainfall events now regularly produce large flows from Bitter Creek following rainstorms. An afternoon rainstorm on July 24th, 2018 generated extremely large flood flows out of the upper portions of Big Cottonwood Creek, Bitter Creek, and Little Cottonwood Creek. The damage produced by this storm event led Freemont County to pursue grant funding for infrastructure protection.

An Emergency Watershed Protection project, funded in 2018 by the Natural Resources Conservation Services (NRCS), focused on post-wildfire risk reduction to infrastructure, human life, and property along several reaches of the Big Cottonwood Creek. Engineering projects completed under the EWP needed to be designed to withstand a 10-year flood event. Anecdotal evidence from local residents and field observations of the flood impacts associated with the July 24th rainfall event suggest that the post-fire the 10-year hydrological behaviors predicted by the USFS (Table 1) and the Corp's hydrologic assessment (Table 2) may not be a reliable basis for engineering designs produced under the EWP Project.

Table 1: Pre- and post-fire peak discharges estimated by USFS (2016) using the Wildcat model.

Modeled Drainage	Percent USFS land	2-year, 30 minute event		10-year, 1-hour event	
		Pre-fire estimated discharge (cfs)	Post-fire estimated discharge (cfs)	Pre-fire estimated discharge (cfs)	Post-fire estimated discharge (cfs)
South Prong Hayden Creek	100%	0	120	35	465
Italian Gulch	100%	0	71	35	225
Pole Gulch	49%	0	93	45	282
Wolf Creek	98%	0	137	32	468
Big Cottonwood Creek	100%	0	55	89	220
Butter Creek	74%	0	97	53	288
Little Cottonwood Creek	85%	0	86	114	365
Deep Gulch	41%	0	27	6	77
Mosher Creek	62%	0	57	33	202
Oak Creek	59%	0	26	29	109
Sullivan Creek	58%	0	74	23	238

Table 2: Pre- and post-fire peak discharges estimated by U.S. Army Corps of Engineers (2017) using a HEC-HMS model.

		Big Cottonwood Creek	Falls Gulch	Fox Canyon	Hayden Creek	Oak Creek	Pole Gulch
0.5 AEP (2 year)	Pre-Wildfire (cfs)	95	32	17	90	82	36
	Post-Wildfire (cfs)	104	32	18	94	83	47
	Change (cfs)	9	0	1	4	0	12
	Change (%)	9	0	8	4	0	33
0.2 AEP (5 year)	Pre-Wildfire (cfs)	126	41	23	119	103	46
	Post-Wildfire (cfs)	135	41	24	123	104	57
	Change (cfs)	9	0	1	4	0	11
	Change (%)	7	0	6	3	0	24
0.1 AEP (10 year)	Pre-Wildfire (cfs)	161	52	38	153	128	59
	Post-Wildfire (cfs)	170	52	40	157	128	148
	Change (cfs)	10	0	2	4	0	90
	Change (%)	6	0	5	3	0	153
0.04 AEP (25 year)	Pre-Wildfire (cfs)	228	71	129	710	525	82
	Post-Wildfire (cfs)	464	71	131	717	526	479
	Change (cfs)	236	0	2	7	0	397
	Change (%)	104	0	2	1	0	486
0.02 AEP (50 year)	Pre-Wildfire (cfs)	624	89	305	1820	1172	103
	Post-Wildfire (cfs)	1610	89	327	1829	1453	806
	Change (cfs)	985	0	22	9	282	703
	Change (%)	158	0	7	1	24	682
0.01 AEP (100 year)	Pre-Wildfire (cfs)	1868	148	622	3747	2374	380
	Post-Wildfire (cfs)	4443	261	766	3795	3301	1276

This assessment endeavors to provide more reliable estimates of 10-year flood hydrology than the other available information. Results can be used as the basis for engineering designs or simply characterize the uncertainty associated with the predictions provided by the Corps and/or the USFS.

1.2 SITE DESCRIPTION

The geological, geographical, and physical characteristics of the Hayden Pass burn area and the Big Cottonwood Creek drainage area described in detail by the USFS (2016) and the Corps (2017). Readers interested in this information are referred to their respective reports. Both sources were heavily drawn on to inform this assessment.

This assessment employed dynamic wave routing, luped hydrological modeling, empirical modeling, and 2-dimensional (2D) hydraulic modelign to characterize the July 24th, 2018 flood and and estimate post-fire peak flow hydrology and hydraulics in the Big Cottonwood Creek drainage.

2.1 DYNAMIC WAVE ROUTING

No record of historical observed discharges exists for Big Cottonwood Creek. The nearest downstream streamflow gauging station is on the Arkansas River near Parkdale Colorado (USGS 07094500). This location is approximately 25 miles downstream of the confluence of Big Cottonwood Creek and the Arkansas River and is the best source of data for directly estimating the size of the Big Cottonwood Creek flood event on July 24th, 2018. Dynamic wave routing provided a means for estimating the characteristics of the flood hydrograph at the confluence of Big Cottonwood Creek and the Arkansas River, based on the observed hydrgraph at Parkdale and some approximated hydraulic characteristics of the river channel between the two locations.

The streamflow gauge at Parkdale registered a sharp spike in discharge, peaking near 2050 cfs, at 21:15 on the evening of July 24th. Measured flows earlier in the day were closer to 650 cfs. Annecdotal information collected from local residents indicated that Big Cottonwood Creek was the only creek between Coaldale and Parkdale flooding significantly during the rainfall event. It was, therefore, assumed that the observed spike in discharge at Parkdale was attributable to Big Cottonwood Creek flows and not flows at some other location.

A dynamic wave model was developed in the *R* statistical computing environment using the '*rivr*' library. The timing of flood flows from Big Cottonwood Creek were estimated from NWS NextRad Doppler radar returns and annecdotal information collected from local residents. One-dimensional hydraulic characteristics of the Arkansas River channel between Coaldale and Parkdale were approximated using characteristics reported in Freemont County's HEC River Analysis System (RAS) model for the Arkansas River at Howard and from review of aerial photographs and elevation data.

The dynamic wave model implemented the MacCormack scheme and computed solutions on a 10 second timestep and 1640 foot distance interval to ensure the Courant number did not exceed 1.0. The initial condition was set to 650 cfs, the flow rate measured at Parkdale immediately prior

to the flood pulse. The downstream boundary was set to a zero gradient condition. Channel slope in the Arkansas River was estimated to be 0.004 ft/ft. The bed width was estimated at 130 ft, channel side-slope at 0.5 ft/ft, and the Manning's roughness coefficient (n) was set to 0.035. The flood hydrograph was assumed to include a near-instantaneous spike in flows, followed by an exponential decay. The characteristics of the flood pulse that described its timing, magnitude, and rate of decay were approximated by manually adjusting these parameters and comparing simulation results to the measured streamflows at Parkdale. This manual fitting procedure was repeated until and accpetable fit between model results and observed conditions was achieved.

2.2 LUMPED HYDROLOGICAL MODELING

The dynamic wave routing simulation results were used to calibrate a HEC-HMS model of the Big Cottonwood Creek drainage. The HMS model was constructued to closely resemble the model described by the Corps (2017) in order to maintain a high degree of fidelity to their approach (Figure 2). Initially, basin and reach characterisitics were set equal to those reported by the Corps (2017). Their approach accounted for the space-varying effects of wildfire by adjusting canopy interception, soil storage, initial loss, infiltration rates, storage coefficient, and time of concentration parameters away from 'look-up' values provided in engineering manuals. Their general approach for making these modifiations was to apply adjustment ratios that reflected the mean burn severity experienced by a sub-basin.

Calibration of the HEC-HMS model requried simulating the July 24th rainfall event and manually adjusting several parameters until simulated peak flows at the mouth of Big Cottonwood Creek matched approximations from the dynamic wave routing procedure. The characteristics of the July 24th rainfall event were approximated using NextRad Doppler radar returns and aggregated NWS data products for that date. Model parameters selected for modification included maximum canopy storage, maximum surface storage, initial loss, constant loss rate, time of concentration, and storage coefficient. The calibrated HEC-HMS model was then used to simulate runoff responses to 2-hour rainfall events with various return intervals. This assessment used the same NOAA Atlas 14 precipitation depth probability estimates used by the Corps (2017) (Table 3). However, rather than modeling 6-hour storm events, this assessment modeled 2-hour events with a 50% intensity position and a 5 minute intensity duration to reflect the short-duration and high-intensity characteristics of late summer monsoon events in the burn area.

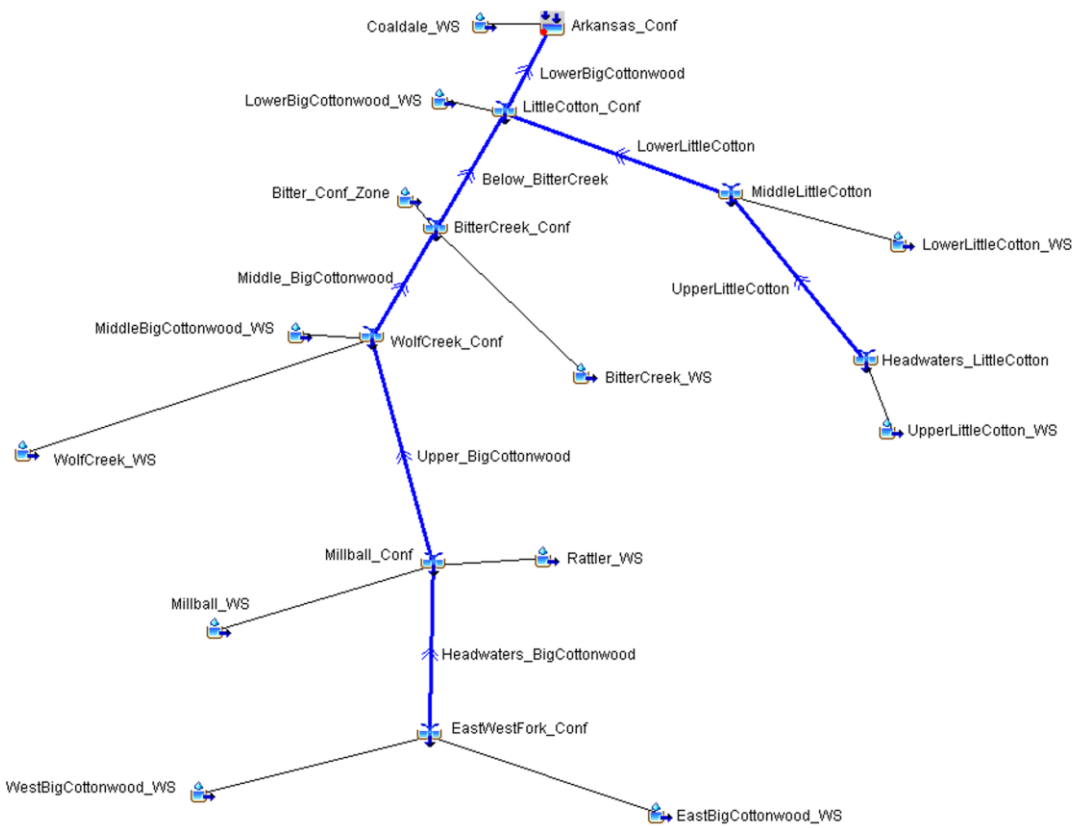

Figure 2. The HEC-HMS model network approximated the structure of the model developed by the Corps (2017) but used different naming conventions and added several reach and junction elements.

Table 3: NOAA Atlas 14 precipitation depths with varying return intervals for a point centered on the Big Cottonwood Creek drainage.

Duration	Precipitation Frequency Estimates (in)						
	50%	20%	10%	4%	2%	1%	0.2%
5-min:	0.25	0.29	0.35	0.45	0.55	0.67	1.02
15-min:	0.44	0.52	0.62	0.80	0.98	1.19	1.82
60-min:	0.79	0.92	1.07	1.38	1.67	2.02	3.05
2-hr:	0.94	1.09	1.28	1.62	1.96	2.36	3.55
3-hr:	1.01	1.18	1.37	1.73	2.07	2.48	3.66
6-hr:	1.18	1.39	1.61	1.99	2.34	2.74	3.88
12-hr:	1.45	1.73	1.99	2.40	2.77	3.17	4.26
24-hr:	1.78	2.12	2.43	2.90	3.30	3.72	4.84

2.3 EMPIRICAL FLOOD MODELING

Even though the HEC-HMS model calibrated to the July 24th rainfall event likely provides more realistic representations of peak flow hydrology in the Big Cottonwood Creek drainage, the lack of additional data to calibrate across a range of rainfall event types means it is still provides relatively crude approximations. A USGS analytical method for predicting peak flow magnitudes

in burn areas in the western United States (Moody, 2012) provides a simpler, empirically-based appraoch for estimating 'natural pairs' of rainfall intensities and the resulting flood flows. The 'level 1' application of this method is relatively simple, requiring only total burned area and rainfall intensity generated by storms with various return intervals as an input. Rainfall intensity data for the Big Cottonwood Creek drainage was retreived from NOAA Atlas 14, Volume 8, Version 2. Conveniently, the USFS (2016) and the Corps (2017) provided calculations for total drainage area and burned area fraction for upper Big Cottonwood Creek, Bitter Creek, Little Cottonwood Creek, and lower Big Cottonwood Creek drainages. An assumption was made that only burned areas contribute to peak flows in Big Cottonwood Creek. Only the 'first year' equation was utilized for computing flood flows. HEC-HMS modeling results were subsequently compared to predictions from the Moody (2012) approach, the Corps (2017), and the USFS (2016).

2.4 HYDRAULIC MODELING

A two-dimensional hydarulic model was developed to illustrate hydraulic responses to rainfall events in the Big Cottonwood Creek drainage. Development of the model required a topographical survey, mapping debris lines associated with the July 24th flood, and simulation of flood flows to match innundation surfaces and debris lines.

2.4.1 Survey and Mapping

Topographic data was acquired from Big Cottonwood Creek in the vicinity of its confluences with Bitter Creek and Little Cottonwood Creek. A digital elevation model (DEM) was generated using a Structure-from-Motion (SfM) photogrammetric technique. Development of the DEM followed published protocols (Javernick, Brasington, & Caruso, 2014). Generation of the DEM required i) acquisition of surveyed ground control points (GCPs), ii) collection of high-resolution aerial imagery, and iii) SfM software for processing the data. GCPs were surveyed using a Trimble RTK-GPS (accuracy of ~1-2 cm). Debris lines produced by the July 24th precipitation event were surveyed at several dozen locations between the USFS gate on County Road 40 and Highway 50. Additional elevation points were collected at various locations across the area of interest. These points were held in reserve and used to determine the accuracy of the fully-processed DEM (i.e. ground truthing). Aerial imagery was collected from a commercial unmanned aircraft system (UAS, or drone). The UAS captured photos at 375 feet above ground level to produce a ground sample distance (GSD) of 1.3 inches per pixel.

Agisoft PhotoScan was used to process the imagery and GCPs into a DEM. The initial elevation surface had a resolution of approximately 5 inches and included the vegetation canopy. Vegetation removal was accomplished using the Whitebox Geospatial Analysis Tools and the remove off-terrain-objects tool (OTO). Several large (~200 square feet) floodplain areas required further adjustment to remove effects from vegetation. Bare earth elevations in these areas were approximated by linearly interpolating adjacent bare earth elevation values through vegetated areas. Channel elevations were also occasionally obstructed due to overhanging tree cover. Automated vegetation removal often resulted in unreasonably narrow channels in these areas.

Final channel elevations were 'cut' through the DEM using the cross-sectional linear interpolation method in HEC-RAS. Cross-sections in areas with reliable elevation data were used to interpolate cross-sectional elevations along the channel centerline at intermediate locations affected by tree cover. Interpolated cross sections were oriented perpendicular to the channel center line and spaced at 10-foot intervals through the entire affected area. While some detail in streambed topography was lost using this method, it is frequently used in hydraulic modeling to produce reasonable approximations of channel depth, width, and grade.

The quality of the final DEM was assessed using the elevation ground truthing data points held in reserve. The elevations of these points were compared to the modeled surface. Differences between the observed and modeled elevations were characterized statistically. The residuals of the mean errors approximated the overall accuracy of the model and standard deviations of the errors approximated the overall precision. DEM accuracy and precision are critical controls on hydraulic model performance (Legleiter, Kyriakidis, McDonald, & Nelson, 2011).

2.4.2 Hydraulic Simulations

The completed DEM was used to build a 2-dimensional (2D) HEC-RAS (version 5.0.5) model of Big Cottonwood Creek and its confluences with Bitter Creek and Little Cottonwood Creek. The model used a processed DEM with a 7-foot grid resolution in floodplain areas and a 3-foot grid resolution in channel areas. Manning's roughness coefficient (n) was mapped across the simulation area according to dominant landcover (e.g. channel, dense brush, sparse trees, roads, floodplains, etc.) identifiable in post-flood orthoimages. Typical values for n associated with each land cover followed recommendations from Chow (1959). The minimal acceptable roughness value was selected for each landcover class since roughness generally decreases with increasing discharge (e.g. Kim, et al., 2010) (Table 4).

Table 4: Hydraulic roughness (Manning's N values) for the various landcover types.

Landcover	Manning's N
Channel	0.030
Dense Brush	0.110
Dirt Roads	0.018
Floodplain	0.040
Shurbs and Tall Grass	0.050
Sparse Trees	0.045
Dense Trees	0.060

Simulations were carried out using unsteady flow solutions at the upstream boundaries (i.e. middle Big Cottonwood Creek, Bitter Creek, and Little Cottonwood Creek) and normal depth at the downstream boundary (i.e. the Harry Walker Dam). Inflow hydrographs at each upstream boundary started at 25 cfs and climbed to 4,000 cfs over a 24-hour simulation period. An initial simulation determined the approximate discharge in each drainage that produced an inundation

surface that aligned with surveyed debris lines from the July 24th flood. A second simulation began with inflows in each drainage set to 25 cfs and then increased flows to the discharges identified in the first simulation. The model was allowed to run for an extended period at these peak flows to ensure that inundation surfaces reached an equilibrium condition. The sensitivity of the final model to variability in *n* was assessed by altering roughness values +/- 10% and characterizing the relative differences in simulation results.

Results produced by the employed methodologies provided a characterization of the hydrological and hydraulic characteristics of the Big Cottonwood Creek drainage. These results are expected to be more reliable than previous assessments in the area.

3.1 DYNAMIC WAVE ROUTING

Manual adjustment of the timing and magnitude of the flood hydrograph produced by the July 24th rainfall event yielded a peak flow of approximately 3,500 cfs at the mouth of Big Cottonwood Creek (Figure 3). The dynamically routed flow produced a reasonable match to the observed peak flows at Parkdale (Figure 4).

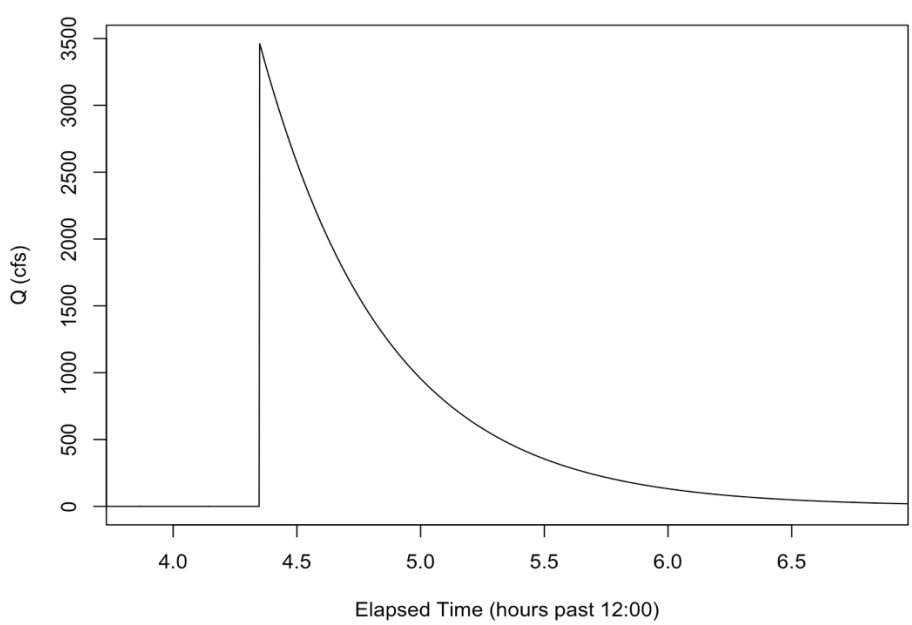

Figure 3. Manually fitted peak flow hydrograph for the mouth of Big Cottonwood Creek following the July 24th rainfall event.

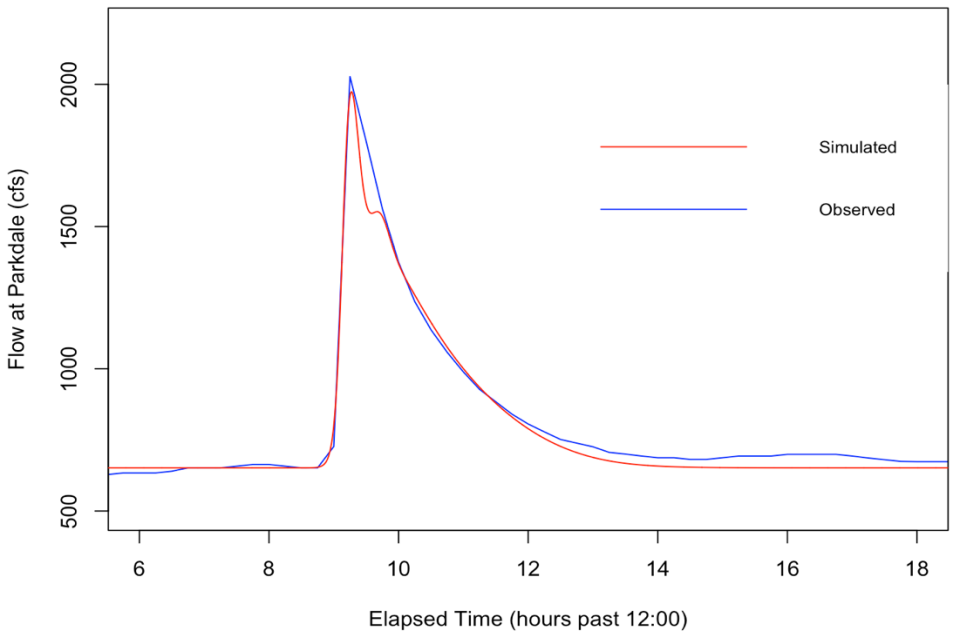

Figure 4. Observed flows on the Arkansas River at Parkdale (blue) compared to dynamic wave routing simulation results (red).

Dynamic wave routing showed itself sensitive to characterization of upstream boundary conditions and selected hydraulic characteristics of the stream channel. Altering channel characteristics shifted the timing of simulated peak flows at Parkdale. The shape of the hydrograph was less influenced by hydraulic parameters but some flood pulse attenuation could be achieved by increasing Manning's *n* and channel width. The accuracy of the model appeared most sensitive to the characteristics of the flood pulse described at the upstream boundary. Alteration of the timing of peak flows, magnitude of peak flows, and exponential decay rate of the inflow hydrograph significantly affected results.

3.2 LUMPED HYDROLOGICAL MODELING

The HMS model was initially calibrated using the characteristics of the July 24th rainfall event and the flood pulse magnitude and timing approximated by the dynamic wave routing exercise. A review of 15-minute NextRad Doppler radar returns provided a means to determine the approximate timing (21:15) and duration (1.75 hours) of the rainfall event. It also provided qualitative information about the intensities of rainfall experienced in different locations (Appendix A). Most of the rainfall appeared to fall in the first hour, a notion supported by observations made by local residents. A 24-hour gridded precipitation depth data file provided by NWS was used to estimate total storm depth (1.38 inches) in the Big Cottonwood Creek drainage. The storm was simulated as a 2-hour event with a 15-minute intensity duration and a 75% intensity position (Appendix B).

Several model parameters were adjusted until the model simulated a peak flow at the mouth of Big Cottonwood Creek of approximately 3,500 cfs (Figure 5). Parameters selected for modification included maximum canopy storage, maximum surface storage, initial loss, constant loss rate, time of concentration, and storage coefficient. Initially, these values were set to 50% of the values reported by the Corps (2017). Further modifications were made to reflect the qualitative impressions expressed by local residents regarding the relative 'flashiness' of Bitter Creek, Little Cottonwood Creek and upper Big Cottonwood Creek during rainfall events (Appendix C).

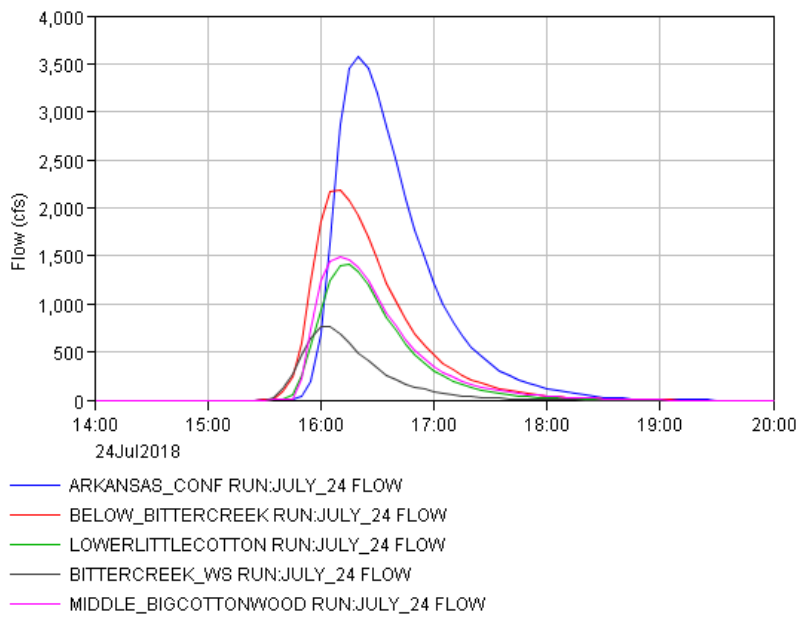

Figure 5. Model simulations of July 24th flood pulses in Big Cottonwood Creek, Bitter Creek, and Little Cottonwood Creek.

The calibrated model was then used to predict flood pulses associated with the 2-, 5-, 10-, 25-, 50- and 100-year rainfall events expected in the Big Cottonwood Creek drainage (Table 5) (Appendix D). Results were significantly different from predictions made by the Corps (2017) across the entire range. These differences prompted consideration of additional assessment approaches for predicting peak flows.

Table 5. Peak streamflows for several locations in the Big Cottonwood Creek drainage associated with various rainfall events. All values reported as cubic feet per second.

AEP	Return Interval	Middle Big Cottonwood Creek	Bitter Creek	Little Cottonwod Creek	Lower Big Cottonwood Creek
0.5	2	0	198	246	436
0.2	5	461	364	579	1313
0.1	10	1054	583	1048	2590
0.04	25	1764	824	1590	4043
0.02	50	3333	1425	2906	7556
0.01	100	4903	1919	3984	10964

3.3 EMPIRICAL FLOOD MODELING

Application of the analytical methodology developed by Moody (2012) for characterizing 'natural pairs' of rainfall and peak streamflow events generated flood pulse estimates for middle Big Cottonwood Creek, Bitter Creek, Little Cottonwood Creek, and lower Big Cottonwood Creek. The model was parameterized with rainfall intensities for 30-minute storms predicted to occur during 2-, 5-, 10-, 25-, 50- and 100-year events (Appendix E). Flood predictions for the entire drainage aligned well with those from the calibrated HEC-HMS model for events with recurrence intervals less than 50 years (Figure 6). Predictions produced by both the calibrated HEC-HMS model and empirical modeling approach were significantly larger than those provided by the Corps (2017) and somewhat higher than the 10-year event flows estimated by the USFS (2016) in most locations (Table 6).

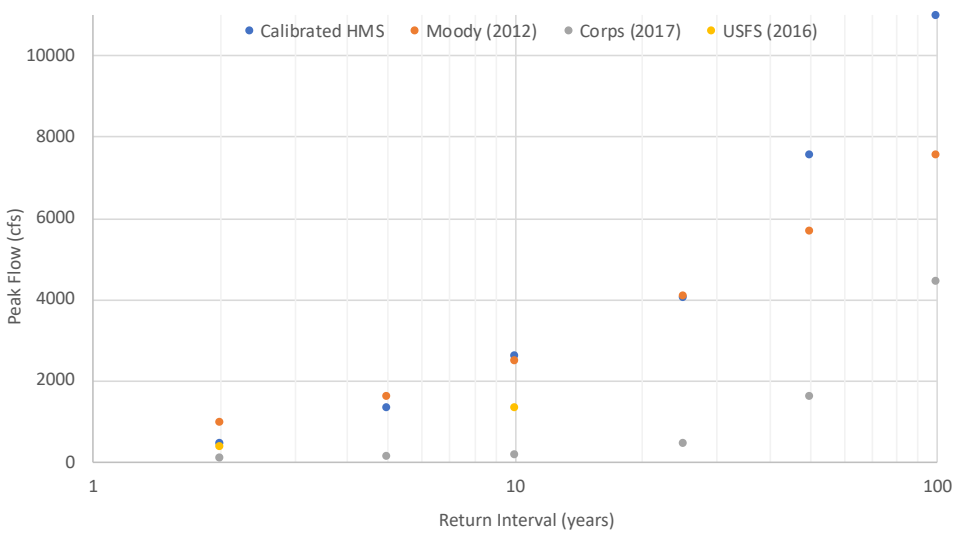

Figure 6. Flood magnitudes at the mouth of Big Cottonwood Creek predicted by the calibrated HMS model, the analytical approach following Moody (2012), reported by the Corps (2017), and reported by the USFS (2016).

Table 6. Flood magnitudes for several drainages in the assessment area predicted by the calibrated HMS model, the analytical approach following Moody (2012), reported by the Corps (2017), and reported by the USFS (2016).

Return Interval (yr)	Middle Big Cottonwood Creek			Bitter Creek			Little Cottonwod Creek			Lower Big Cottonwood Creek			
	Calibrated HMS	USFS (2016)	Moody (2012)	Calibrated HMS	USFS (2016)	Moody (2012)	Calibrated HMS	USFS (2016)	Moody (2012)	Calibrated HMS	USFS (2016)	Corps (2017)	Moody (2012)
2	0	192	456	198	97	128	246	86	233	436	375	104	962
5	461		771	364		216	579		394	1313		135	1624
10	1054	688	1175	583	288	330	1048	365	600	2590	1341	170	2476
25	1764		1937	824		544	1590		990	4043		464	4084
50	3333		2685	1425		753	2906		1372	7556		1610	5661
100	4903		3568	1919		1001	3984		1823	10964		4443	7521

3.4 HYDRAULIC MODELING

The land survey collected 58 flood debris line points over the three drainages of Big Cottonwood Creek (downstream of Wolf Creek), Little Cottonwood Creek, and Bitter Creek. The DEM generation included 83 GCPs and 1,786 aerial images. The generated point cloud produced over 442 million points across the surveyed 2.5 miles. The arbitrarily-located point cloud was shifted, rotated, and scaled into the State Plane Colorado Central projection system using 51 GCPs (some GCPs were not used because of proximity to vegetation or visibility). Three-dimensional point clouds were interpolated to produce a 1-foot resolution digital surface model (DSM) (Figure 7). Data thinning and interpolation procedures effectively removed vegetation, houses, and other structures while preserving natural topographic features.

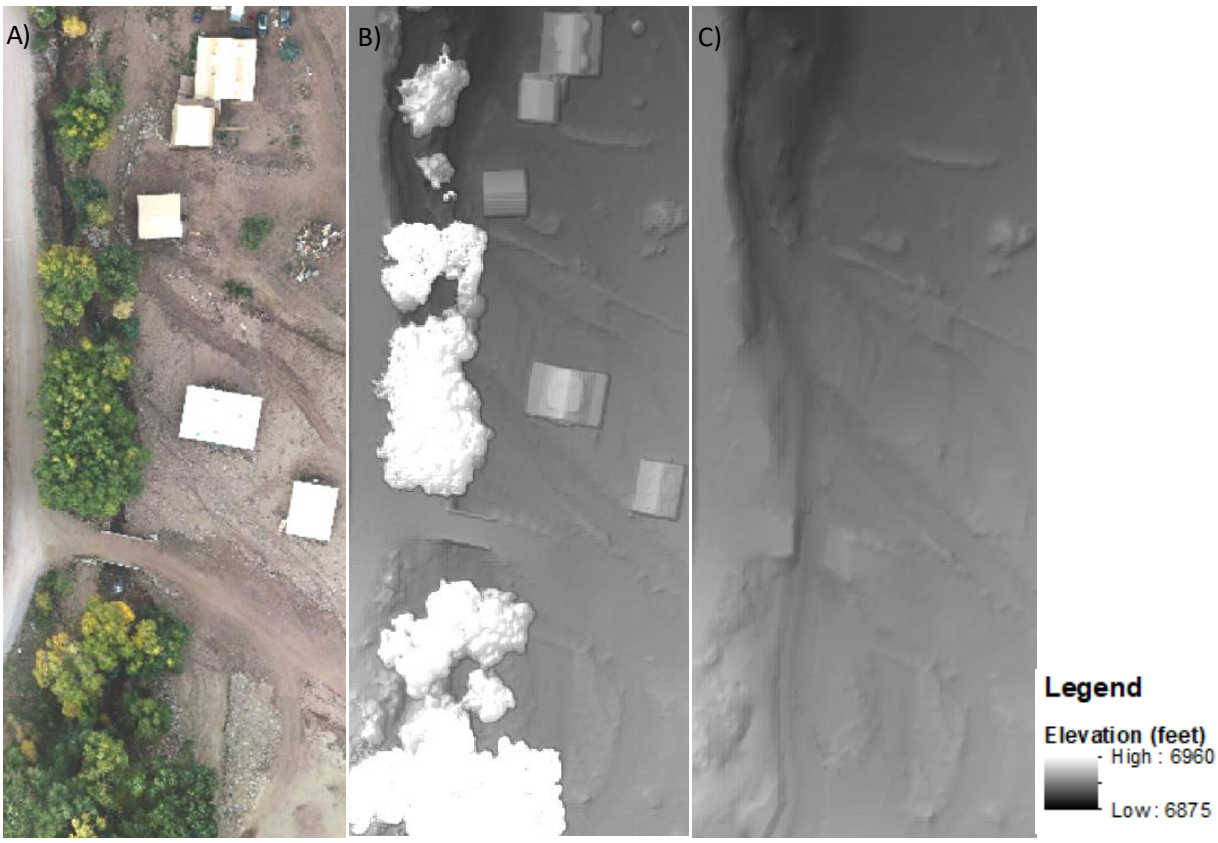

Figure 7: Modeled surfaces for the A) the area shown, B) DSM with vegetation, and C) post-processed DEM with vegetation removed and cut stream channel.

Accuracy of the final bare-earth DEM was assessed using 188 ground truthing points located away from vegetation, steep banks, or the river channel (i.e. areas expected to be representative to the modeled accuracy). Assessed this way, the DEM had an average error (accuracy) of 0.04 feet and a standard deviation (precision) of 0.27 feet.

Matching surveyed debris lines to inundation surfaces produced by the 2D HEC-RAS model estimated discharges during the July 24th flood event to be 4,000 cfs on middle Big Cottonwood Creek, 2,200 cfs on Bitter Creek, and 4,000 cfs on Little Cottonwood Creek (Figures 8 – 15).

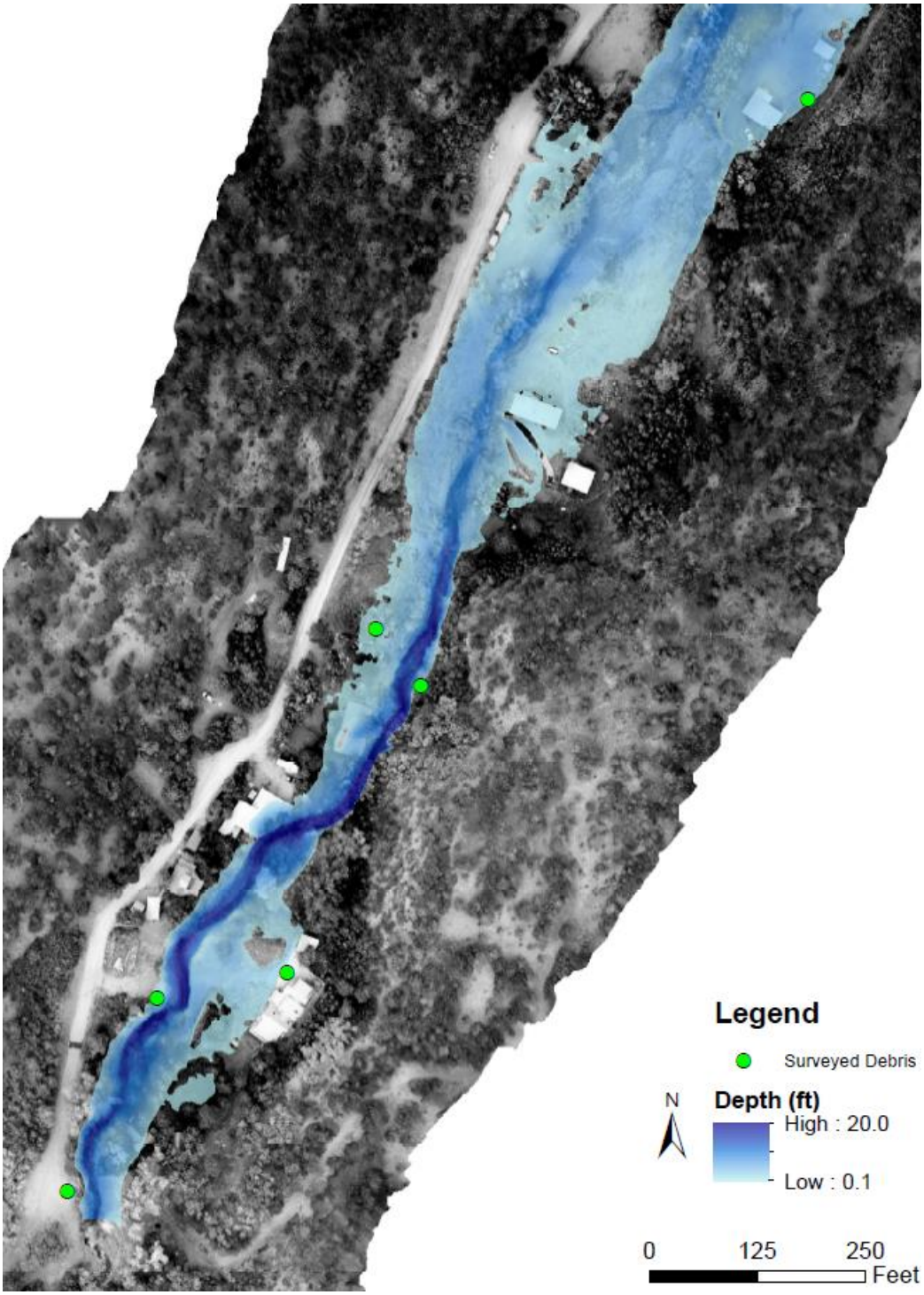

Figure 8: HEC-RAS hydraulic simulation's depth and inundation extent results for upstream Big Cottonwood Creek at River Mile 2.2.

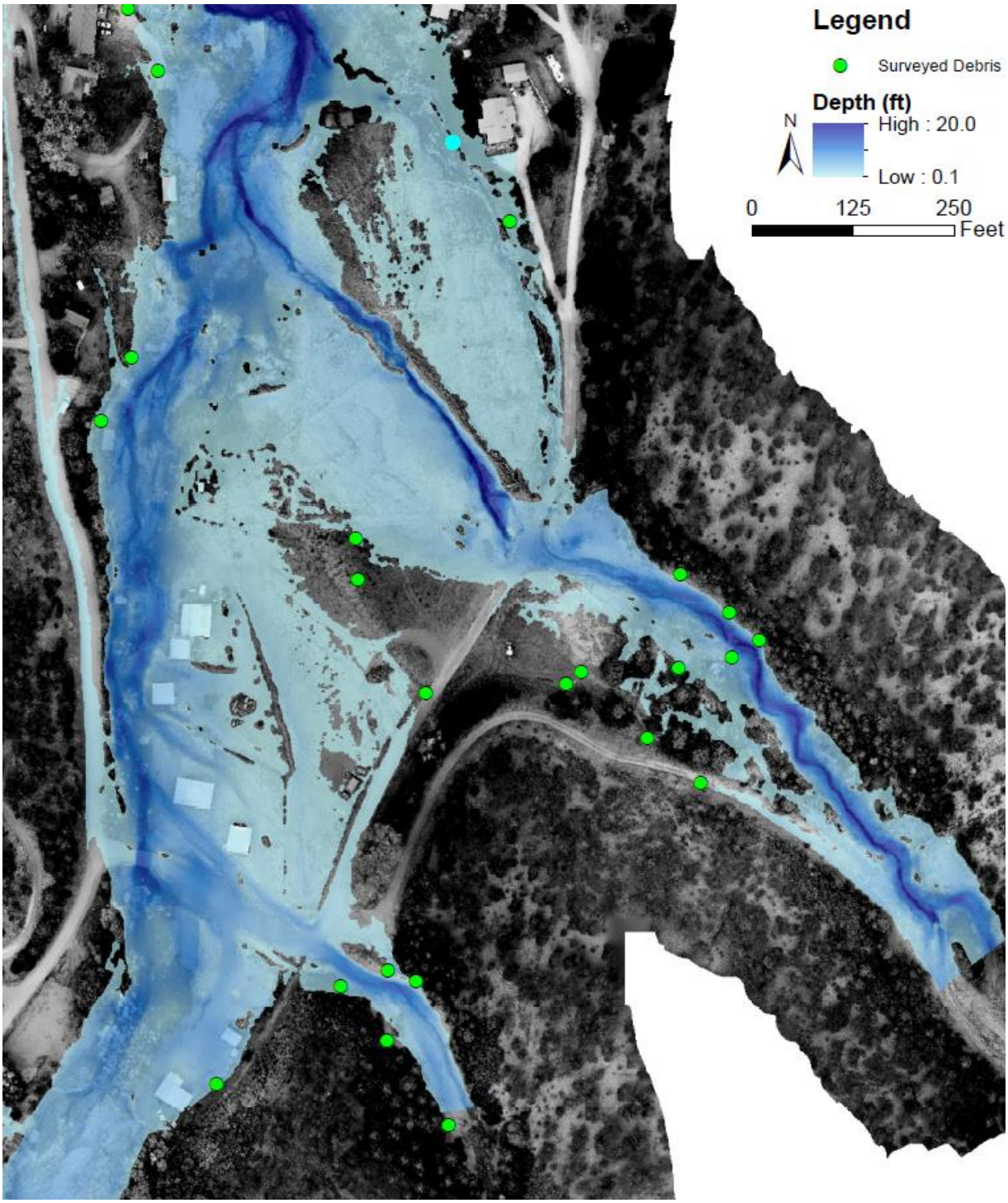

Figure 9: HEC-RAS hydraulic simulation's depth and inundation extent results for the confluence of Big Cottonwood Creek, Bitter Creek, and Little Cottonwood Creek at river mile 1.9.

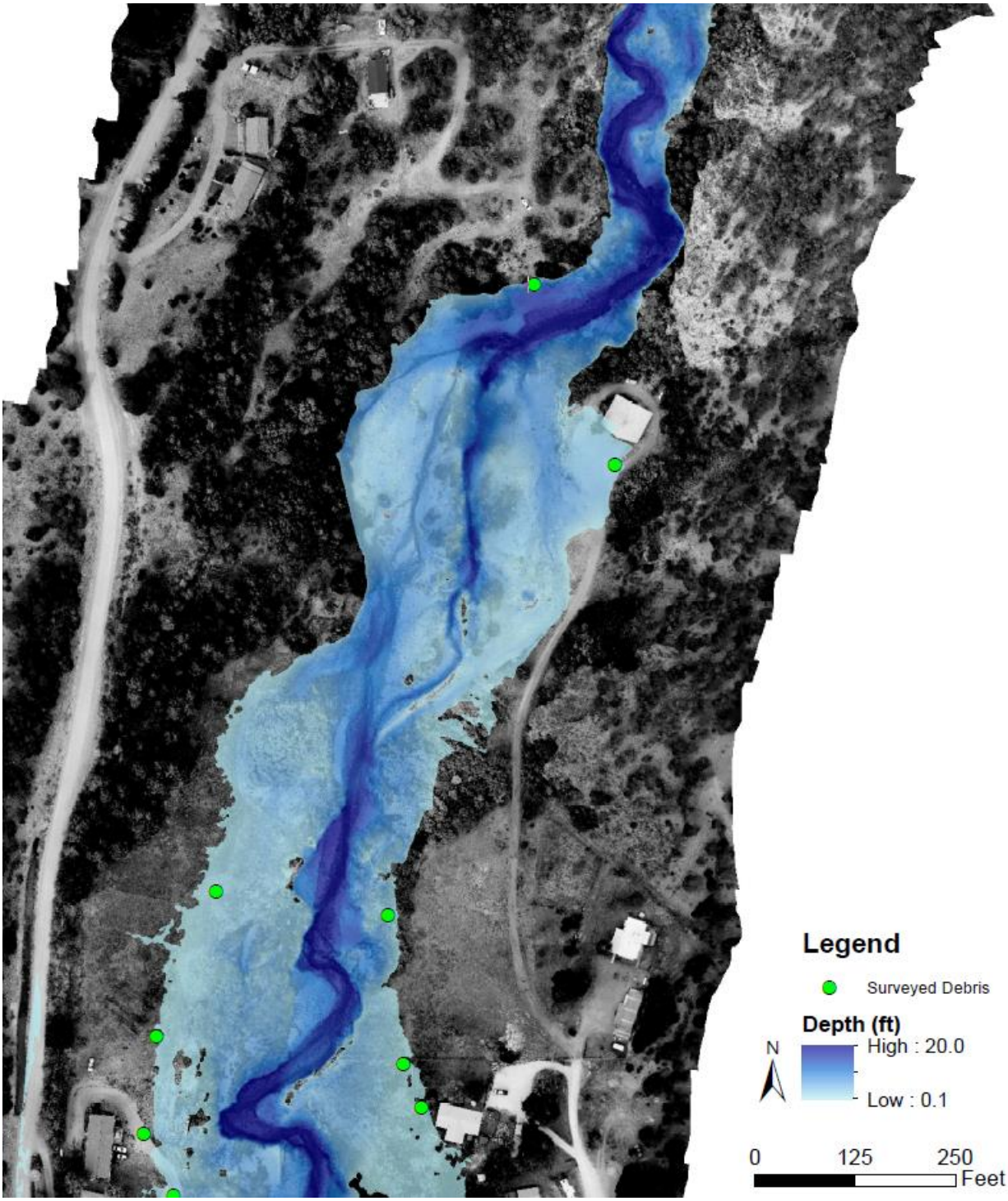

Figure 10: HEC-RAS hydraulic simulation's depth and inundation extent results for the Big Cottonwood Creek at river mile 1.7.

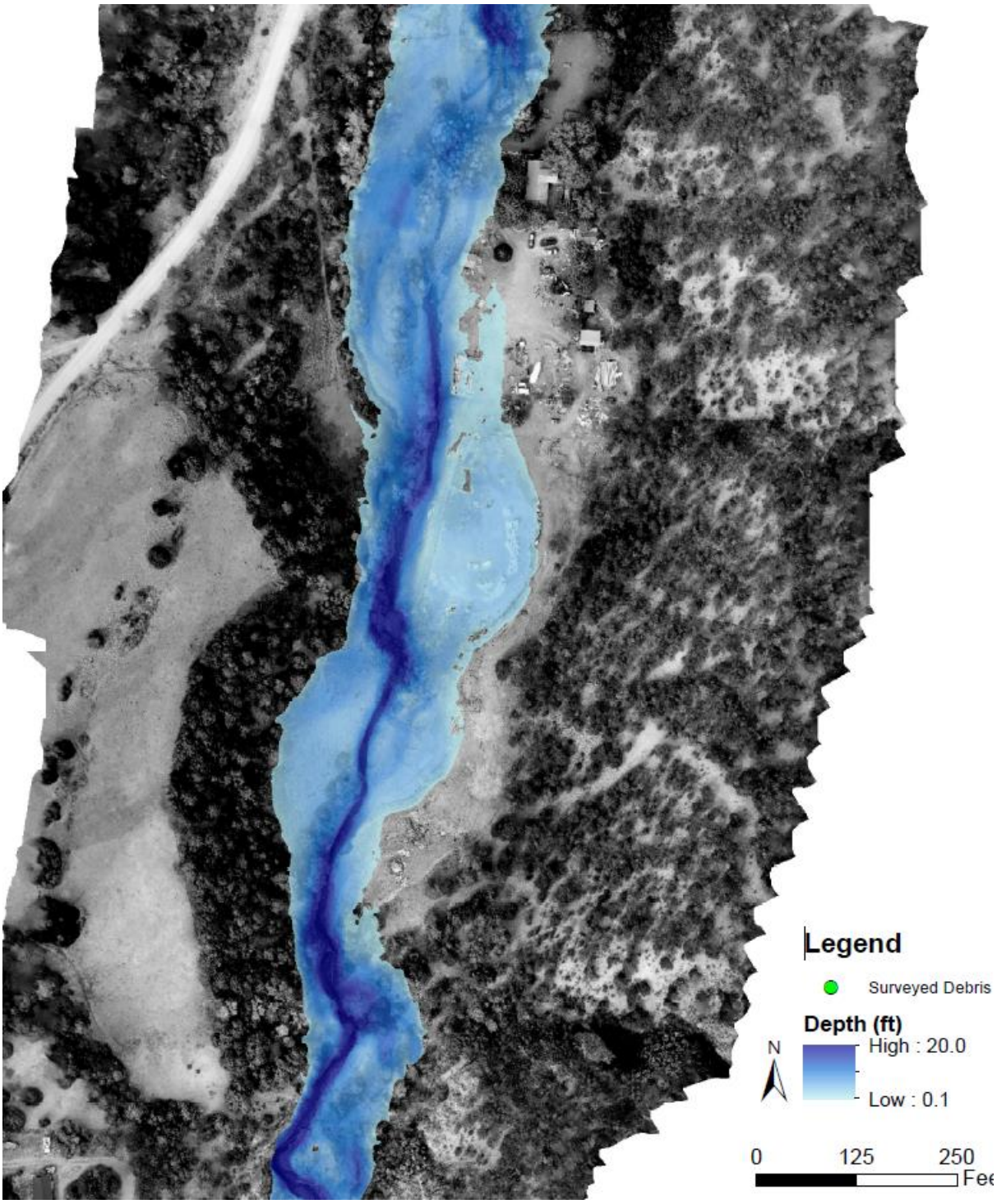

Figure 11: HEC-RAS hydraulic simulation's depth and inundation extent results for the Big Cottonwood Creek at river mile 1.4.

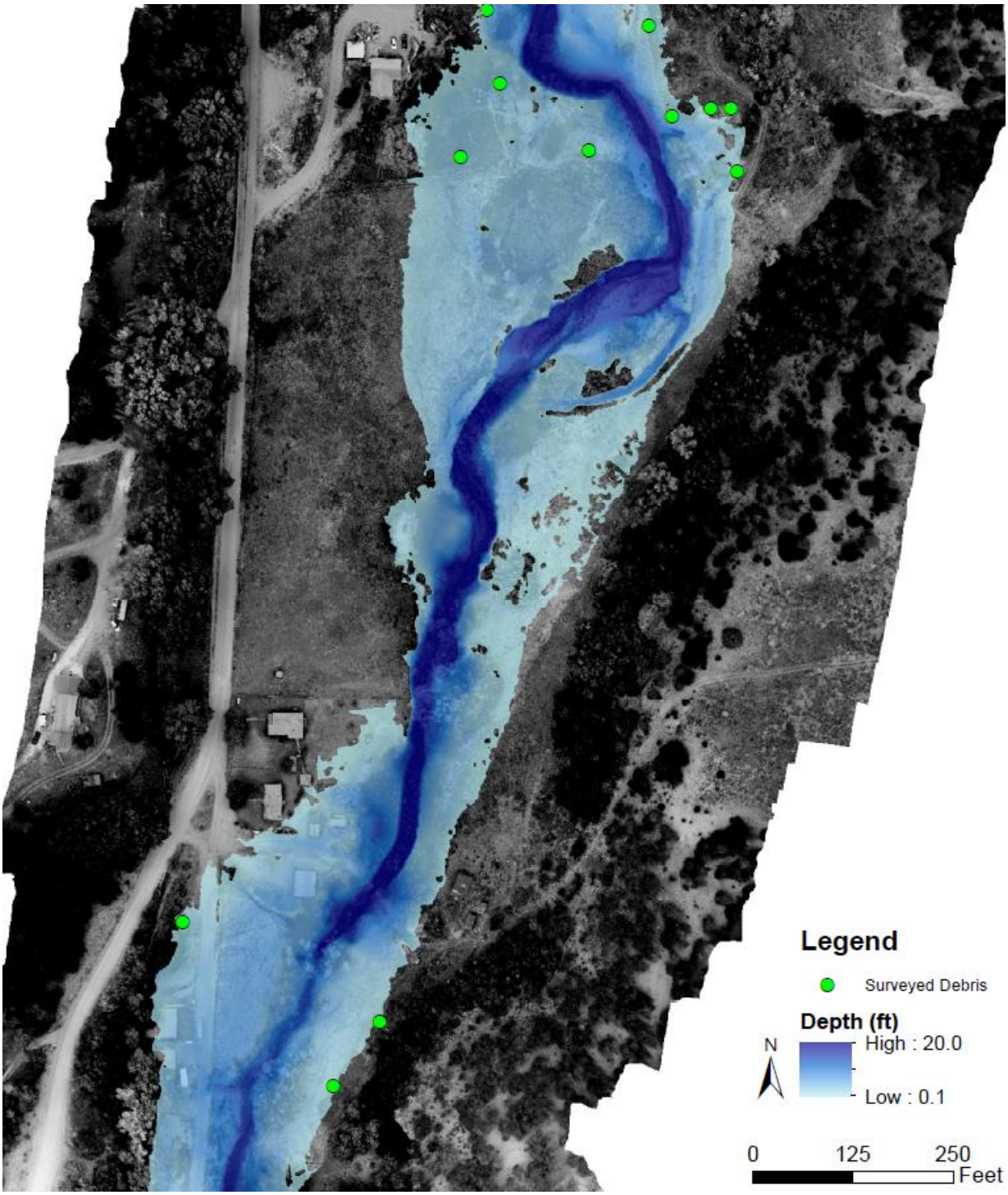

Figure 12: HEC-RAS hydraulic simulation's depth and inundation extent results for the Big Cottonwood Creek at river mile 1.

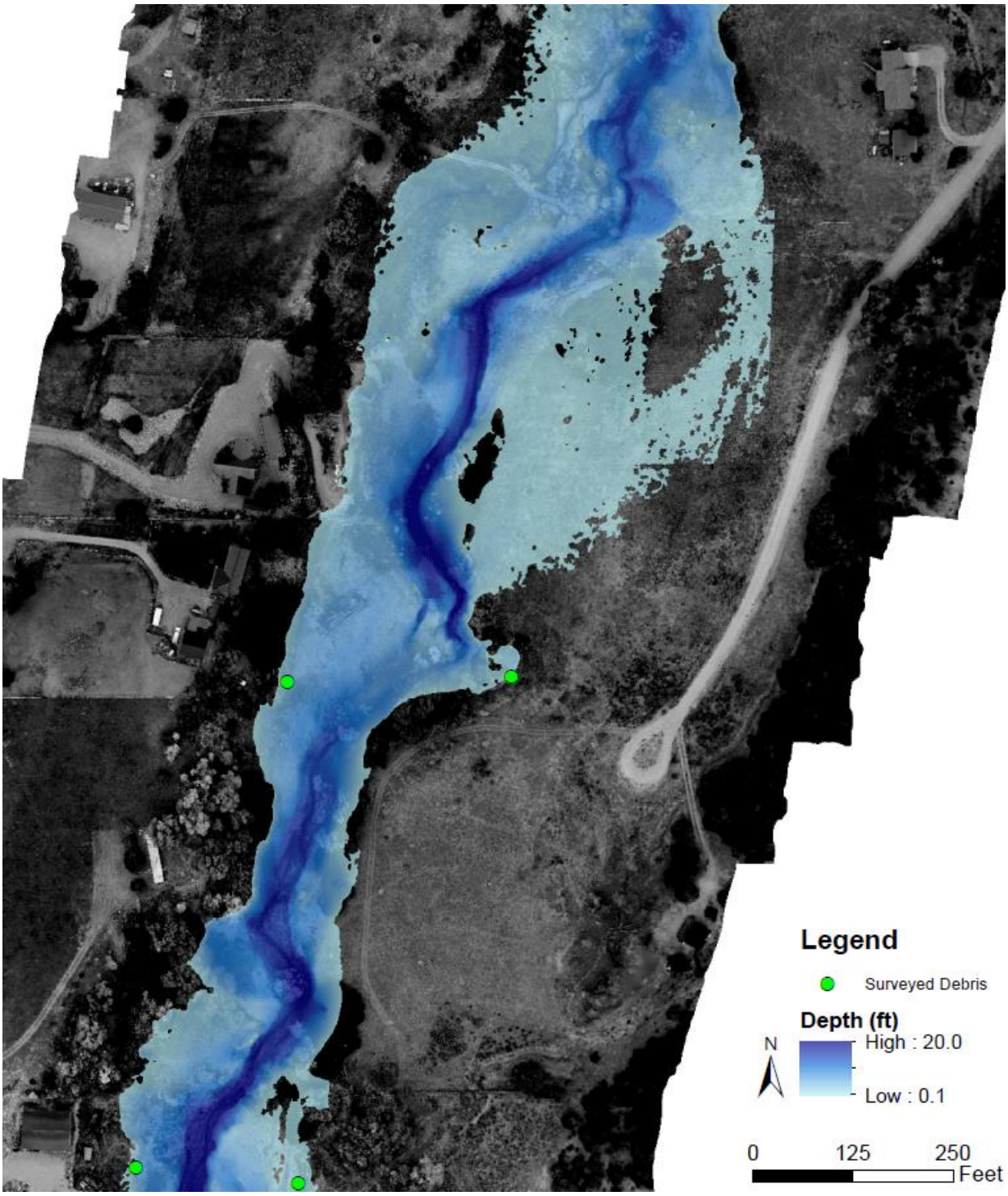

Figure 13: HEC-RAS hydraulic simulation's depth and inundation extent results for the Big Cottonwood Creek at river mile 0.7.

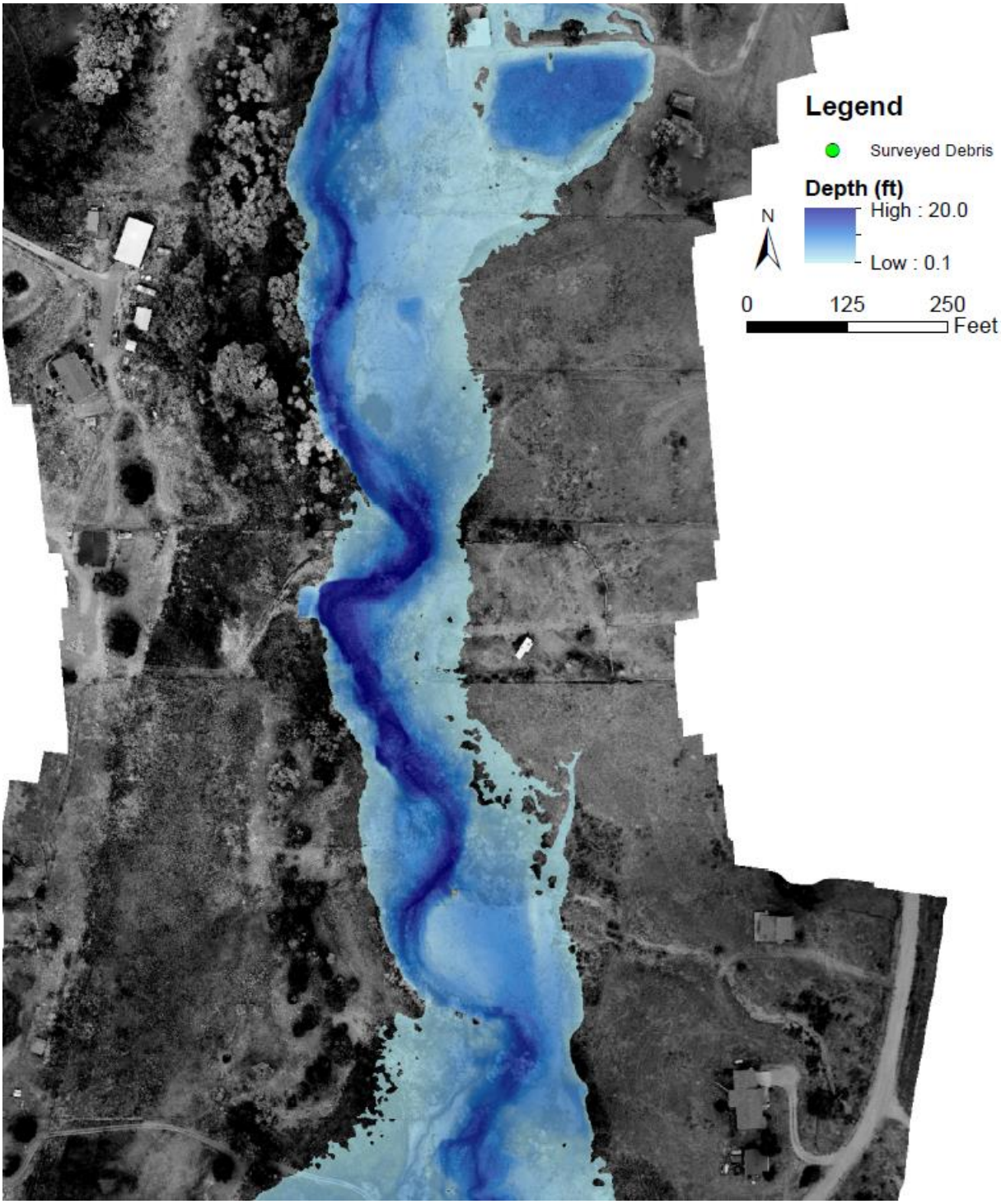

Figure 14: HEC-RAS hydraulic simulation's depth and inundation extent results for the Big Cottonwood Creek at river mile 0.4.

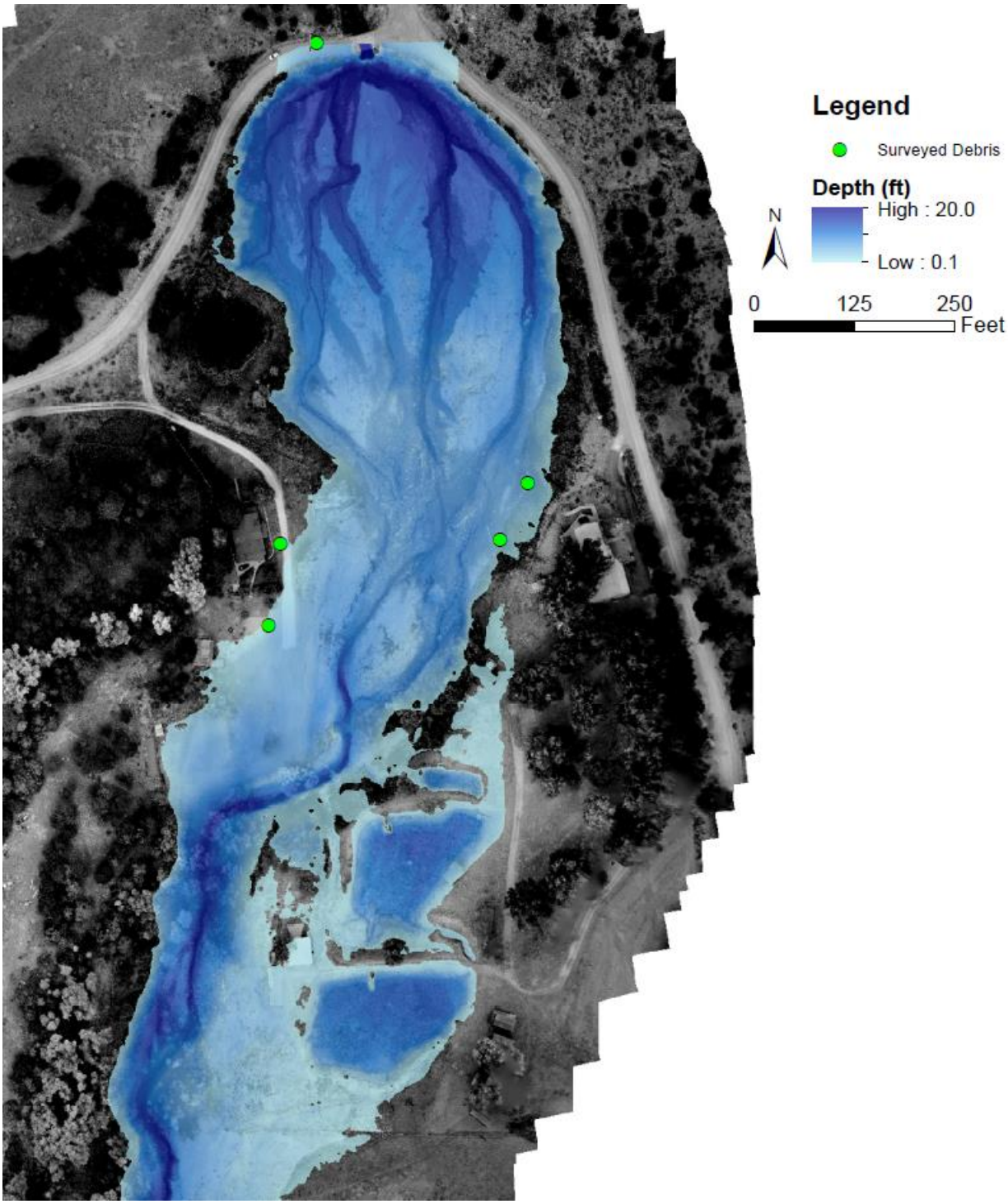

Figure 15. HEC-RAS hydraulic simulation's depth and inundation extent results for the Big Cottonwood Creek at river mile 0.2.

A sensitivity analysis was performed by adjusting Manning's roughness coefficients +/- 10% and reviewing simulation results (Figure 16). The adjustments to roughness values caused relatively-minor inundation and depth changes in simulation results. The model did not appear particularly sensitive to selection of roughness values for various landcover types.

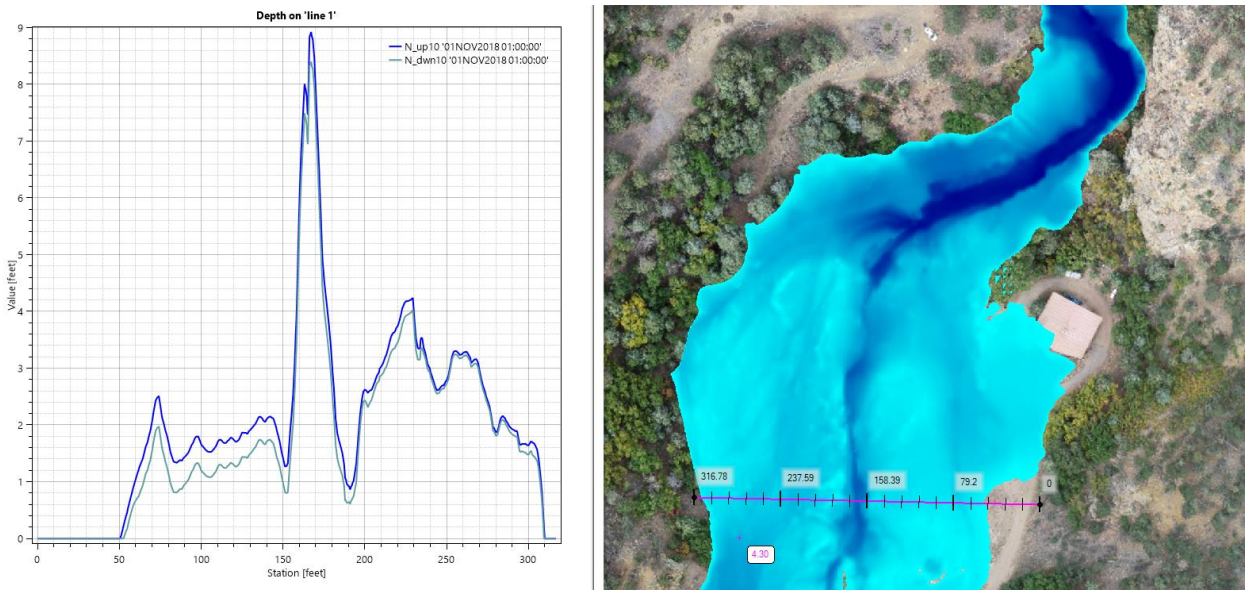

Figure 16: Sensitivity testing results for +10% and -10% roughness values and the associated changes in depth (left) across the transect shown (right).

4 Discussion and Conclusion

The methodologies employed by this assessment provide predictions of flood hydrology and hydraulics in the Big Cottonwood Creek Drainage. Dynamic wave routing was used to estimate the size of a rainfall-driven flood event on July 24th, 2018. The estimated peak flow was then used to calibrate a lumped parameter hydrological simulation model, which predicted peak flows associated with rainfall events of varying likelihoods of occurrence. Those results were compared to predictions from an empirically-based approach for approximating post-wildfire flood response and to the predictions made by the USFS (2016) and the Corps (2017).

Results reported here are, likely, more reliable than peak flow predictions made elsewhere due to the incorporation of new data and information. The hydrological analyses conducted by USFS (2016) and the Corps (2017) were greatly disadvantaged by the lack of observed rainfall or streamflow data in the areas affected by the Hayden Pass fire. Their respective predictions relied on 'typical' runoff characteristics of undeveloped watersheds, modified to reflect the relative impact of burn severity in different sub-basins. There was no way for either organization to 'ground-truth' simulation outputs against observed conditions as we have done here.

While we feel the results presented here are an improvement on other available information, caution should be exercised when utilizing our results for engineering design or characterization of flood risk. The HMS model we used to produce estimates of flood size associated with different rainfall events was calibrated on data collected following a single storm. It is reasonable to expect that as the characteristics of future storms diverge further and further away from the characteristics of the event used for calibration, the quality and accuracy of model predictions will decrease. It follows, then, that the hydrological simulation tools discussed here may be greatly improved in the future as more data comes available. Critically, peak flow predictions are expected to become less relevant as time passes and soils and vegetation in the Big Cottonwood Creek drainage recover from the effects of wildfire.

In lieu of additional data for characterizing existing or time-varying conditions, we can look for unusual behaviors among the different approaches we applied to illustrate where we have more or less certainty in our predictions. The largest discrepancies exist between the magnitude of the July 24th flood flows predicted by dynamic wave routing and the 2D hydraulic model. Hydraulic simulations' accuracies are largely dependent upon the model's input elevation accuracy (e.g. Legleiter, et al., 2011). As demonstrated, the DEM used for hydraulic modeling had high accuracy and precision, and thus should provide a basis for an accurate hydraulic simulation. The modeled inundation extents matched the surveyed debris lines relatively well over the entire simulated area. There were several locations where inundated extents were over- or under-predicted. For

example, discrepancies in Little Cottonwood Creek show surveyed debris lines over an access road and over the river-left floodplain. Model simulations with flow rates up to 10,000 cfs failed to produce inundation extents that matched the river-left surveyed debris lines. Matching debris lines to simulated inundation extents elsewhere suggests that Little Cottonwood Creek's discharge did not significantly exceed 4,000 cfs and that peak flows in Big Cottonwood Creek reached 10,200 cfs. The widespread flooding that appears to have affected Little Cottonwood Creek drainage may have been a local hydraulic response to debris jams. Video and photographic evidence from the July 24th event confirm that debris flow was widespread. The presence of this debris is related to differences in peak flow predictions using dynamic wave routing and 2D hydraulic modeling.

Dynamic wave routing used observed streamflow data from Parkdale and approximated 1D Arkansas River channel characteristics to estimate a July 24th peak streamflow near 3,500 cfs on Big Cottonwood Creek. This peak flow estimate is significantly lower than the peak flow estimate produced by the HEC-RAS model. The discrepancy may be explained by non-Newtonian flow characteristics of the debris and sediment laden water flowing down Big Cottonwood Creek and its tributaries on July 24th. Flood events in burned watersheds often collect, transport, and deposit large amounts of debris and sediment. As sediment loads increase, the flow transitions from a conventional sediment transport that includes suspended load and bedload to hyper-concentrated flow (i.e. mud flow) and then to debris flow. The fluid properties of these flows change from a Newtonian fluid with constant viscosity to a non-Newtonian fluid with variable viscosities that are typically significantly higher than 'clear' flood waters. Such properties are challenging to accommodate in hydraulic models since most models rely on assumptions of Newtonian fluid flow.

Recent publications (e.g. Travis, Gusman, and Teal, 2012) discuss using clear-water models like HEC-RAS to study and predict post-fire flood events. Their approach involves 'bulking' flows predicted by clear-water models to simulate the increased flood impact (i.e. larger inundation surface) associated with mud and debris flows. A bulking factor is applied to predicted flood flows as a multiplier. If predicted flood flows for an event are 1,000 cfs, a bulking factor or 2.0 would predict an inundation surface associated with that event would resemble the clear-water inundation surface produced by a 2,000 cfs flow. While a bulking factor of 2.0 is common, higher factors are possible in watershed that experience a high burn severity, high debris storage. Currently, the Ventura County Watershed Protection District uses bulking factors around 2.0 to predict flood responses in burned watersheds. There are no guidelines on estimating bulking factors, but factors up to 3.0 or 4.0 may be possible in certain circumstances (personal communication with Brent Travis, November 2018).

Our assessment may provide a unique opportunity to estimate the bulking factor for the Big Cottonwood Creek drainage. Peak flows predicted by matching inundation surfaces to debris lines are approximately 2.9 times greater than the flows estimated by dynamic wave routing, suggesting a bulking factor of 2.9. The flood event on Big Cottonwood Creek associated with the 10-year rainfall event was predicted by the calibrated HMS model to be 2,590 cfs. If the bulking factor identified here is applied to this flow, then the clear-water simulation required to assess

flood risks and inundation surfaces would need to simulate peak flows of 7,511 cfs.

4.1 RECOMMENDATIONS

- The rainfall characteristics associated with the July 24th storm fall between a 10- and 25-year event. The likelihood of one of these events occurring before the drainage is recovered from the Hayden Pass Fire is relatively high, underscoring the need for infrastructure protection projects.
- Collection of real-time streamflow at the mouth of Big Cottonwood Creek and rainfall data in the middle of the Big Cottonwood Creek drainage will facilitate ongoing improvements in hydrological prediction models.
- The peak streamflows associated with a 10-year rainfall event are estimated to be 2,590 cfs by a lumped parameter model and 2,476 cfs by an empirically-derived model. However, bulking of flood flows due to entrainment of sediment and debris. A bulking factor of 2.9 might be appropriate on Big Cottonwood Creek.
- Due to the likelihood of high sediment loads and non-Newtonian flow characteristics, a higher shear stress factor of safety should be considered in the design of bed and bank protections under the EWP.
- Due to large flood inundation extents and the likelihood of significant woody debris transport during future flood events, EWP projects should emphasize providing adequate space for the river to store and activate material in floodplain areas.
- The July 24th Big Cottonwood flood event demonstrated the hazards of post-fire flood events. While the BAER report and EWP are critical and valuable to the recovery of the Hayden Pass fire, stakeholders involved in the project have requested a more thorough assessment of risks and needs across the entire area impacted by the fire. This work is recommended and will include additional community outreach, coalition building, and monitoring that are essential to improve the public safety and future recovery of these heavily impacted areas.

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6. APPENDICES (A-E) SEE SEPARATE FILES