# Calibrating 2D Hydraulic Models Using End-Members of Watershed Response to Wildfire: A Tiered Hydraulic Modeling Framework

Master's Plan B: Engineering Report

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# Abstract

Regions affected by wildfires may experience dramatic flooding in subsequent years. Following large floods, it is often important to characterize the channel response and predict future flow conditions using hydraulic models, but data collection for streams in remote areas that have experienced recent wildfires and floods can be challenging for access constraints and safety concerns. This study provides guidance for using remotely sensed data to develop and calibrate two-dimensional hydraulic models in recently burned areas. Remotely sensed data allow for minimal time spent on site in dangerous areas affected by wildfire and flooding. Specifically, this study evaluates the applicability of remotely sensed data to develop hydraulic models of stream reaches within two small catchments of the Cache la Poudre River watershed, Black Hollow and Little Beaver Creek. These watersheds represent endmembers to wildfire response. Black Hollow experienced a debris flow in July of 2021 following the Cameron Peak fire of 2020 that resulted in four fatalities, whereas Little Beaver Creek stabilized more quickly due to less severe burn intensity and rapid riparian vegetation recovery. I present a Tiered Hydraulic Modeling Framework that can be applied to calibrating two-dimensional hydraulic models in watersheds affected by wildfire. The framework uses tiers of data collection methods that correlate to accuracy of model results and level of effort for model creation. Tier 1 encompasses strictly remotely sensed data, specifically structure-from-motion (SfM) photogrammetry. Tier 2 allows for minimizing time on site to conduct salt tracer tests and collect discharge, and Tier 3 involves in-depth data collection of bathymetric survey. This framework aims to assist post-wildfire flood prediction efforts in a streamlined manner for researchers, consultants, and other interested parties.

Results from this study show variation in hydraulic roughness values depending on which tier was applied. For Tier 1 modeling, I observed lower roughness coefficients at Little Beaver Creek due to the overestimation of discharge for Tier 1 and the higher complexity of the Little Beaver Creek reaches. Following the fire and debris flow, Black Hollow tended towards a denuded channel particularly in the reaches of study, with little to no vegetation or channel spanning large wood, which is more typical of reaches at Little Beaver Creek. The results supported that these watersheds did represent end members to wildfire response with Tier 2 and Tier 3 showing higher roughness values at Little Beaver Creek. Little Beaver Creek has more complex geomorphology than the steep confined reaches at Black Hollow, where the additional impact of riparian vegetation at the lower reach and large wood jams at the upper reach resulted in the inflated calibrated roughness values even when large wood was manually filtered from the upper Little Beaver Creek topography. These results were demonstrated with Little Beaver Creek having calibrated roughness values at the upper and lower reaches of 0.08 and 0.09, respectively, and Black Hollow having calibrated roughness values at the upper and lower reaches of 0.05 and 0.03, respectively.

Many major takeaways of the Tiered Hydraulic Modeling Framework are with respect to the model creation process rather than the actual results. The list below outlines a few major takeaways of using remotely sensed information and the supplemental datasets in the framework.

- Preserving SfM accuracy is challenging in reaches with in-channel large wood and with higher quantities of riparian vegetation.
- SfM is remarkably effective at capturing bathymetry in streams with low sediment transport at low flow conditions, capturing highly detailed topographic data.

- Tier 2 and 3 model calibration typically requires less iterations to converge on a composite roughness value than the water surface elevation approach in Tier 1.
- Even highly detailed bathymetric surveying using GPS does not capture the detail of channel topography captured with SfM. Bathymetric survey is recommended only for streams that are larger and have more sediment transport, limiting what the SfM can capture.
- Tier 1 is highly sensitive to the assumed depth and estimated discharge, introducing high uncertainty in model results and in the calibrated roughness values.

When applying the Tiered Hydraulic Modeling Framework, project context and outcome are key for determining which tier to apply. For example, Tier 1 with estimated discharge is best applied for conceptual design and management practices when prioritizing reaches at risk following extreme events like wildfires, debris flows, or flooding. Tier 2 is best applied to research, restoration design, and improvement projects to understand the specific hydraulics accurately in small mountain streams or streams that have low baseflow with low sediment transport. Finally, Tier 3 is best applied to similar projects as Tier 2, but in cases where baseflows are high in large streams with high sediment transport, SfM will struggle to accurately characterize channel bathymetry. These recommended approaches are intended to provide streamlined guidance and procedures for managing challenges associated with post-fire hydraulic and sediment dynamics, for researchers, consultants, and management agencies.

# Introduction

Climate change in the western United States is having a dramatic impact on hydrologic regimes (Brogan et al., 2019; Elliott et al., 2005; Van Eeckhout, 2010). In Colorado, one of the most threatening natural disasters on the rise is wildfires (CO Division of Fire Prevention and Control, 2022). Wildfires have increased tremendously in the last several years, with four fires in 2020 breaking the previous record for the state's largest fire (CO Division of Fire Prevention and Control, 2022). The most notable of these fires was the 2020 Cameron Peak Fire, the largest fire in Colorado history at 208,000 acres (CO Division of Fire Prevention and Control, 2022). This fire primarily affected the Cache la Poudre River watershed, with several tributaries experiencing extreme response in the form of flooding and debris flows (Kostelnik et al., 2022). One of the most notable was Black Hollow, a tributary to the Cache la Poudre River just west of Rustic, Colorado. The debris flow that occurred on July 20, 2021, destroyed several structures and resulted in four fatalities (Kostelnik et al., 2022). Events of this magnitude are prime examples of the destruction and loss that can occur following wildfires in high mountain watersheds. Debris flows also pose questions for understanding the risk associated with communities in these highrisk regions.

A long-standing method of predicting flood risk is hydraulic modeling (Brogan et al., 2019; Elliott et al., 2005; Legleiter et al., 2011; Martin, 2022; Van Eeckhout, 2010). Hydraulic modeling is used to predict hydraulic response at varied spatiotemporal scales, from FEMAregulated floodplains to local drainage problems. The most widely used and accepted hydraulic modeling software is the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System (HEC-RAS), freely downloadable from the USACE website (U.S. Army Corps of Engineers, 2022). FEMA typically requires HEC-RAS models for federally regulated floodplain maps and map revision documentation. Historically, one-dimensional hydraulic models were used to predict flood hazard zones (Van Eeckhout, 2010). However, as computers progress and computational power increases, multi-dimensional models are increasing in popularity (Brogan et al., 2019; Legleiter et al., 2011; Martin, 2022; Ongdas et al., 2020).

The Colorado Water Conservation Board (CWCB) is interested in using the capabilities of twodimensional HEC-RAS modeling for regions affected by wildfire for risk assessment and flood prediction. Hydraulic models play an important role in determining flood inundation areas, distribution of hydraulic parameters, and sediment transport capacity in channels. This is particularly relevant following wildfire, when both base and peak flows commonly increase. A key piece of hydraulic modeling is calibration, in which the CWCB is interested in developing a streamlined procedure for collecting information to calibrate models for sites affected by wildfire (Elliott et al., 2005; Martin, 2022). Additionally, calibration of hydraulic models is particularly critical to accurately predicting flood inundation, yet calibration can be challenging after fire when large inputs of sediment and abrupt channel change increase hydraulic roughness. Debris flows and flash floods are common following wildfires (Brogan et al., 2019; Elliott et al., 2005; Rengers et al., 2020; Van Eeckhout, 2010), so limiting time spent in the field with dangerous conditions is of concern for researchers and managers. With this in mind, I propose the Tiered Hydraulic Modeling Framework, where hydraulic models are calibrated with remotely sensed data supplemented by additional field data.

A prevalent technological advance in engineering data science is the use of remotely sensed data, which are easily accessible through regional GIS databases (Domeneghetti et al., 2014; Grimaldi et al., 2016; James et al., 2019; Liu et al., 2019). Common modeling remote sensing techniques include LiDAR and structure-from-motion photogrammetry for collecting geometric and

topographic information (Abu-Aly et al., 2014; Bandini et al., 2020; Grimaldi et al., 2016). However, freely available remotely sensed data commonly lack detail to create an accurate hydraulic model and additional survey is required. Remotely sensed data do have the potential to create extremely accurate digital elevation models with SfM photogrammetry collected from drone data (James et al., 2019; Woodget et al., 2015). An important consideration for remotely sensed data is spatial resolution. Work on this topic has been conducted using cross sectional spacing to represent digital elevation model (DEM) precision (Legleiter et al., 2011). However, refining the results of this study conducted using global positioning systems to instead incorporate remotely sensed data will limit time spent in dangerous post-fire regions. In general, this framework intends to provide recommendations that will reduce field work under hazardous conditions and reduce the labor costs of collecting data needed to parameterize 2D hydraulic models.

I chose four field sites in sub-watersheds of the Poudre River that burned during the 2020 Cameron Peak fire. These sites represent common biogeomorphic configurations in the Colorado Front Range: steep, narrow forested river corridors; wider, lower gradient forested corridors; and wet meadows (White et al., 2022; Wohl et al., 2022). I focused work in two watersheds that represent endmembers of wildfire response: Little Beaver Creek with widespread sheetwash, rilling, and gullying on uplands, and Black Hollow with a massive debris flow. This report contrasts these watersheds throughout the modeling process, and I have made site-specific recommendations and suggested general modeling practices when dealing with a variety of datasets for watersheds affected by wildfire. These watersheds are shown in the vicinity map in Figure 1 below, along with the extents of the Cameron Peak burn area and nearby Fort Collins, Colorado.



Figure 1: Vicinity map of Cameron Peak Fire burned area with Black Hollow and Little Beaver Creek watershed area.

# Black Hollow: Site Description and Event Background

Black Hollow is a 28 km<sup>2</sup> watershed that is tributary to the Cache la Poudre River. The

watershed is primarily a steep, confined system where the average valley slope is approximately 10%, with elevations ranging from approximately 2280 m to 3470 m in the upper portions of the watershed. The reaches analyzed at Black Hollow were at 2300 m and 2360 m in elevation, both approximately 100 m in stream length. Black Hollow was severely burned during the Cameron Peak Fire and was shown as having high likelihood of experiencing debris flows by the US Geological Survey (USGS) (Kostelnik et al., 2022). Figure 2 below from the USGS shows the location of Black Hollow (blue star) relative to Fort Collins and within the Cameron Peak burn area. The other locations depicted were discussed in Kostelnik et al. (2022), but these events were not considered in this report.



*Figure 2: Black Hollow vicinity map with Cameron Peak burn area and debris flow event likelihoods estimates for stream segments and drainage basins from USGS overview of the event (Kostelnik et al., 2022)* 

On July 20, 2021, a convective storm during Colorado monsoon season formed, with precipitation around 25-50 mm/hr (Kostelnik et al., 2022). The aftermath of the debris flow that was triggered by the storm is depicted below in Figure 3. At the stream's confluence with the Poudre River, several residential structures were destroyed, seen at left. According to firsthand accounts of the residents, mobilized debris and equipment broke open doors, resulting in several fatalities. Two years later, the watershed is still recovering from the blaze, but vegetation is returning. Field data for this study were collected during conditions depicted at right (Figure 3) following some stabilization after the debris flow. The site is still experiencing a high degree of geomorphic change as observed through several site visits during the 2022 runoff season.



Figure 3: Drone photo (left) of debris flow aftermath in July 2021, courtesy of Ayres Associates. Revegetation of Black Hollow during July 2022 field work (right).

# Little Beaver Creek: Site Description

Little Beaver Creek is a 41 km<sup>2</sup> watershed in the Cache la Poudre watershed. Little Beaver Creek is tributary to the South Fork of the Poudre River and is less steep than Black Hollow with an average valley slope of 3%. The Little Beaver Creek catchment ranges from approximately 2400 m to nearly 3500 m in elevation. Little Beaver Creek (LBC) was also burned severely during the Cameron Peak Fire (Figure 4), but the presence of unconfined, vegetated corridors with connected floodplains resulted in greater resiliency and more rapid recovery from the burn.



*Figure 4: Drone photo (left) of LBC lower reach. Revegetation of LBC upper reach during July 2022 field work (right).* 

# Methods

### Tiered Wildfire Modeling Framework

As previously introduced, I used HEC-RAS 2D to perform the analyses due to the widespread use of HEC-RAS by researchers and consultants (Martin, 2022; Ongdas et al., 2020; Van Eeckhout, 2010). Hydraulic models aim to characterize the site as realistically as possible, while also attempting to optimize the balance with computational demand and time investment with data collection and model creation (Bilgili et al., 2023; Teng et al., 2017). The primary objective of this project was to develop a Tiered Hydraulic Modeling Framework for burned areas. The framework I developed presents a range of modeling techniques where the tiers correspond to the level of effort required to create the model and the resulting variation in roughness parameters when calibrating models. For example, a Tier 1 model could be applicable for general management decisions or conceptual designs regarding prioritization of reaches for improvements and restoration efforts following wildfires. In contrast, a Tier 2 or 3 model would be better applied for detailed design or research applications with calibrating to a known discharge. The differences in tiers are presented below, in conjunction with descriptions of the components of model creation when using SfM photogrammetry to create 2D HEC-RAS models. The Tiered Hydraulic Modeling Framework with approaches and necessary data is introduced below in Figure 5. Note that components of the framework denoted with an asterisk (\*) were not considered for the purposes of this report but could be collected and applied effectively for use in the Tiered Hydraulic Modeling Framework.



Figure 5: Tiered Hydraulic Modeling Framework graphical representation

# Tier 1

The Tier 1 modeling approach corresponds to minimal data collection, time in field, and lowest level of effort. Tier 1 modeling approach uses remotely sensed data such as SfM or LiDAR in addition to estimated parameters to create an initial model. I recommend using only the Tier 1 approach if working in a gauged watershed, or if discharge measurements can be collected, as calibrating an estimated discharge can introduce sources of error. However, collecting discharge is sometimes not feasible for certain projects, so I also outline estimating a discharge, using the USGS method for estimation of roughness and estimating a discharge using an approximated cross section (Acrement Jr. & Schneider, 1989). Figure 6 below explains the general process for the Tier 1 model approach graphically.



Figure 6: Graphical representation of Tier 1 modeling approach

The following sections, *Digital Elevation Model Creation, Cloth Simulation Filter*, and *Hydraulic Model Creation*, detail procedures used for model creation techniques used for all tiers in the Tiered Hydraulic Modeling Framework. Additional information can also be found in the *Appendix* regarding a walkthrough of the Tiered Hydraulic Modeling Framework at upper Black Hollow.

## **Digital Elevation Model Creation**

A critical task for creating any hydraulic model is the creation and use of a digital elevation model (DEM) for topographical information (James et al., 2019; Over et al., 2021; Purinton & Bookhagen, 2017). Although 1-m cell size LiDAR datasets are freely available for download through the USGS or CWCB online, many modeling applications require more precise topographic information, particularly for design and restoration. This project primarily discusses the use and application of SfM photogrammetry, a common remote sensing technique for creation of DEMs (Bandini et al., 2020; Grimaldi et al., 2016; James et al., 2019; Teng et al., 2017).

Agisoft Metashape and Cloud Compare were the two programs used to post process drone flight information (Agisoft, 2023). The USGS workflow for processing raw drone photos was used to create a SfM model in Agisoft Metashape (Over et al., 2021). This procedure was used to create the dense cloud and DEM, primarily filtering and deleting points based on certain parameters in Over et al., 2021. In general, this workflow details processes for calibrating cameras, setting accuracy and the use of tie points, point error optimization, reconstruction uncertainty, project accuracy and error, and optimizing the point cloud overall (Over et al., 2021). The resulting DEMs had varying centimeter level precision per pixel both in the collected coordinate system (GCS WGS84), and in the projected coordinate system (NAD83 UTM zone 13N). An important note is that the SfM model was accurate enough to be able to capture roughness elements such as in-channel large wood and boulders, considered further in the *Discussion* section. DEM creation is also specifically outlined in the *Appendix* example for upper Black Hollow.

#### **Cloth Simulation Filter**

Drone flights were completed at both Black Hollow reaches on July 20<sup>th</sup>, 2022 and at the upper Little Beaver Creek reach on July 26<sup>th</sup>, 2022. A previous drone flight at the lower Little Beaver Creek reach from October 17<sup>th</sup>, 2021 was used due to the lack of riparian vegetation for simpler post processing. A major drawback of using SfM as a terrain generation approach is that vegetation needs to be filtered out manually (James et al., 2019; Over et al., 2021; Zhang et al.,

2016). LiDAR, in contrast, can be set to only create a DEM using the last returned points, which automatically filters out first and second returned points to exclude points associated with vegetation (Abu-Aly et al., 2014). For this study, I used the Cloth Simulation Filter, a plug in tool in Cloud Compare to filter vegetation (Zhang et al., 2016). The filter allows you to set a classification threshold, grid size, and number of iterations to remove points that exceed the elevation threshold within the gird size, subsequently categorizing points as either ground or offground (Zhang et al., 2016). Due to the steep relief inside the Black Hollow and Little Beaver Creek watersheds, I found that the grid size typically needed to be reduced from the default value presented in Zhang et al., 2016, and iteration was required depending on the site-specific conditions. For example, the upper Little Beaver Creek reach has several cliffs on the northwest portion of the DEM and required a grid size of 0.1 m to preserve the hillslope topography in addition to filtering the vegetation. As expected, decreasing the grid size, or increasing the number of iterations, increases computational expense and poses a cost-benefit dilemma. I found that keeping the number of iterations consistent with Zhang et al., 2016 and adjusting the grid size was found to keep computation times low while still preserving DEM accuracy to effectively filter vegetation. See the Appendix for a specific example of Cloth Simulation Filter use for upper Black Hollow.

### **Hydraulic Model Creation**

Hydraulic models were created for each tier using the same approach. Typical two-dimensional hydraulic models in HEC-RAS require a few basic features to run properly. These features consist of a terrain (developed from the DEM), computational mesh, boundary condition lines, and flow information (U.S. Army Corps of Engineers, 2022). The terrain, computational mesh, and boundary conditions combine in HEC-RAS to create a geometry file (U.S. Army Corps of

Engineers, 2022). Boundary conditions and flow information (typically a hydrograph for running unsteady 2D flow analysis) combine to create a flow file (U.S. Army Corps of Engineers, 2022). Geometry files and flow files in HEC-RAS combine to create a plan file, which runs the unsteady flow simulation (U.S. Army Corps of Engineers, 2022). For this report, the geometry files were changed between iterations to adjust the roughness values to converge on a calibrated model.

Creating an effective computational mesh is key for accurately representing channel geometry. In the case of a SfM digital elevation model, the accuracy of the DEM is on the order of a few centimeters, so being able to reflect this accuracy in the hydraulic model mesh is important (U.S. Army Corps of Engineers, 2022). The USACE developed HEC-RAS such that each cell face has a detailed cross section to accurately represent the DEM (U.S. Army Corps of Engineers, 2022). The more cells in the computational mesh, the more closely the DEM is discretized. However, increasing the number of computational cells dramatically increases computation time, and optimizing the cell size for both a relatively fast model run time and an accurate representation of hydraulic conditions is critical. For this case, an in-channel mesh grid size of 0.25 m was selected, which had approximately 10 cells across the width in each reach. The floodplain grid size was selected to be 1 m, as is typical with many hydraulic models to increase the grid size outside the active channel. There is little specific guidance from the USACE on the specifics of grid size selection, and these sizes were selected to balance the accuracy of the DEM and having a computation run time under two hours.

Another important parameter to consider when creating a two-dimensional model is the Courant number. USACE notes that for the diffusion wave equations utilized for these models (and typically for many consulting purposes due to the faster computation time), the Courant number should not exceed 5 (U.S. Army Corps of Engineers, 2022). Because the grid size had already been selected based on preserving DEM accuracy, the time step was used to control the model stability, with a similar target of model run time around or under two hours. For the 0.25 m grid size, a 0.2 second time step was found to produce stable model results, while also keeping the Courant number under 5 for all cells.

The grid creation methods for the model utilized the standard 2D flow area generation technique in addition to refinement regions and break lines when necessary (Bilgili et al., 2023; Liu et al., 2019; U.S. Army Corps of Engineers, 2022). The grid creation methodology is specifically outlined in the appendix of the report for the upper Black Hollow example.

The primary purpose of this study is to provide streamlined guidance for roughness calibration in burned watersheds. As previously stated, much previous guidance exists on calibration of hydraulic models (Liu et al., 2019; Martin, 2022; Teng et al., 2017; U.S. Army Corps of Engineers, 2022; Van Eeckhout, 2010), but little specific guidance exists on calibration in burned watersheds for in-stream hydraulics. In many cases, identifying a composite roughness can streamline hydraulic modeling and provide comparably accurate results (Liu et al., 2019). Composite roughness values were calibrated in this case due to the extreme variation in geomorphology that burned watersheds can experience, particularly after a debris flow. For most flood inundation prediction applications, a composite roughness can be utilized (Liu et al., 2019), but I recommend using spatial varied roughness for design modeling applications to understand local morphodynamics.

### **Calibration Using Water Surface Data**

A common approach for calibrating hydraulic models is using measured water surface elevations to converge on a roughness value (Bandini et al., 2020; Brogan et al., 2019; Domeneghetti et al.,

2014; Grimaldi et al., 2016; Legleiter et al., 2011). Because the Tier 1 modeling approach only relies on remotely sensed data, gathering water surface elevation information is one of the only ways to calibrate one of these models. Tier 1 calibration uses the SfM point cloud to obtain the water surface data, with the water surface determined visually by the modeler. Commonly, the point cloud creates a stark contrast where the three-dimensional coordinate of the water surface can be determined with little uncertainty due to the difference in point colors. I also recommend collecting the drone data at low flows to allow for easy identification of water surface points along geomorphic features that are not inundated, like point bars. For the models presented in this report, I calibrated approximately 12 water-surface elevations along each reach. However, adding more points for calibration will increase accuracy but increases the level of effort.

An important note when using an estimated discharge in Tier 1 modeling is that the discharge must approximate the flow on the day that the drone images were collected. The variation of the water-surface elevation does not vary much more than on the order of tens of centimeters when varying roughness values. If the flood inundation area is much smaller or larger than the orthomosaic image or point cloud exhibits, I recommend that the discharge estimation calculation be checked to represent the flow conditions more accurately on that day.

Discharge was estimated using an approximate cross section, estimated depth, and Manning's n estimate from the USGS method (Acrement Jr. & Schneider, 1989). The orthomosaic developed from the SfM data provides accurate visual data required for the USGS Manning's n method. In each of the reaches outlined in this report, an initial Manning's n value of 0.09 was determined from the method, detailed in Figure 7 below, using Tables 1 and 2 from Arcement & Schneider, 1989. For all reaches,  $n_b$  was taken to be equal to 0.035 for coarse gravel,  $n_1 = 0.015$  for severe channel irregularities,  $n_3 = 0.015$  for frequent alternations,  $n_3 = 0.025$  for appreciable

between 1.0 and 1.2, exhibited in Equation 1 below.

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m = (0.035 + 0.015 + 0.015 + 0.025 + 0)1.0 = 0.09$$
 (1)

				[Modified from Al	fridge and Garrett, 19	73, table 2]		
				Channel	conditions	n value adjustment <sup>1</sup>	Example	
				3	Smooth Minor	0.000 0.001-0.005	Compares to the smoothest channel attainable in a given bed material. Compares to carefully dredged channels in good condition but having slightly eroded are scoured cite slopes.	
Table 1. Base values o	f Manning's n			Degree of irregularity	Moderate	0.006-0.010	Compares to dredged channels having moderate to considerable bed roughness	
[Modified from Aldridge an	nd Garrett, 1973, ta	able 1; -, no da	ata]	(n <sub>1</sub> )	(n <sub>1</sub> ) Severe		and moderately sloughed or erooted side slopes. Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channels in rock.	
Bed	Median size of bed material	Base n Straight	Smooth	Variation in channel	Gradual Alternating occasionally	0.000 0.001-0.005	Size and shape of channel cross sections change gradually. Large and small cross sections alternate occasionally, or the main flow occasionally shifts from side to side owing to changes in cross-sectional three.	
material	(in millimeters)	uniform channel <sup>1</sup>	channel <sup>2</sup>	$(n_2)$	Alternating frequently	0.010-0.015	shape. Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape.	
	Sand channels				Negligible	0.000-0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the cruss-sectional area.	
Sand <sup>3</sup>	. 0.2	0.012	_		Minor	0.005-0.015	Obstructions occupy less than 15 percent of the cross-sectional area, and the spacing between obstructions is such that the sphere of influence around on obstruction does not extend to the sphere of influence around anothe	
	.4	.020		Effect of			obstruction. Smaller adjustments are used for curved smooth-surfaced object than are used for sharp-adjact angular objects.	
	.5	.022	-	(n <sub>3</sub> )	Appreciable	0.020-0.030	Obstructions occupy from 15 to 50 percent of the cross-sectional area, or th	
	.6	.023	-				space between obstructions is small enough to cause the effects of sev obstructions to be additive, thereby blocking an equivalent part of a c	
	.8	.025	-				section.	
	1.0	.026	-		Severe	0.040-0.050	Obstructions occupy more than 50 percent of the cross-sectional area, or the space between obstructions is small enough to cause turbulence across most	
Stable	channels and flo	od plains			Small	0.002.0.010	of the cross section. Dense growths of flavible turf grass, such as Barmuda, or words growing when	
Concrete	. –	0.012-0.018	0.011		Sman	0.002-0.010	the average depth of flow is at least two times the height of the vegetation	
Rock cut	. –	-	.025				supple tree seedlings such as willow, cottonwood, arrowweed, or saltceda growing where the average depth of flow is at least three times the height of	
Firm soil	. –	0.025-0.032	.020				the vegetation.	
Coarse sand	. 1–2	0.026-0.035	-		Medium	0.010-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree	
Fine gravel	. –	-	.024				seedlings growing where the average depth of flow is from two to three time	
Gravel	. 2-64	0.028-0.035						the height of the vegetation; brushy, moderately dense vegetation, similar t 1- to 2-year-old willow trees in the dormant season, growing along the banks
Coarse gravel	. –	-	.026	Amount of			and no significant vegetation is evident along the channel bottoms where th	
Cobble	. 64-256	0.030-0.050	-	vegetation	Large	0.025-0.050	hydraulic radius exceeds 2 ft. Turf grass growing where the average depth of flow is about equal to the heigh	
Boulder	. >256	0.040-0.070	-	(n <sub>4</sub> )			of the vegetation; 8- to 10-year-old willow or cottonwood trees intergrow with some weeds and brush (none of the vegetation in foliage) where th	
<sup>1</sup> Benson and Dalrym <sup>2</sup> For indicated mater	ple (1967). ial; Chow (1959).						hydraulic radius exceeds 2 ft; bushy willows about 1 year old intergrown wit some weeds along side slopes (all vegetation in full foliage), and n significant vegetation exists along channel bottoms where the hydrauli radius is greater than 2 ft.	
<sup>3</sup> Only for upper regin	ne flow where grain	n roughness is pr	edominant.		Very large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the heigh of the vegetation; bushy willow trees about 1 year old intergrown with weed along side loops (all vegetation in full folging), or dense catalis growin along channel bottom; trees intergrown with weeds and brush (all vegetatio in full folge).	
				Degree of meandering <sup>2</sup>	Minor Appreciable Severe	1.00 1.15 1.30	Ratio of the channel length to valley length is 1.0 to 1.2. Ratio of the channel length to valley length is 1.2 to 1.5. Ratio of the channel length to valley length is greater than 1.5.	

(m) Severe 1.30 Ratio of the channel length to valley length is 1.2 to 1.5. Figure 7: Table's 1 and 2 for USGS Selection of Manning's n (Acrement Jr. & Schneider, 1989)

Once a Manning's n value has been selected, the next step is approximating a cross section. For most mountain streams at baseflow, a rectangular or wedge cross section can be assumed. For confined channels in steeper reaches of mountain watersheds, baseflow conditions are best approximated using a wedge-shaped cross section. For this report, a wedge cross section was found to more accurately predict flows for both reaches at Black Hollow as well as upper Little Beaver Creek, whereas a rectangular cross section better fit wide unconfined valleys such as those at the lower Little Beaver Creek reach. When solving a flow rate using the Manning equation, presented below, an iterative solving procedure is required. For Equation 2 below, Q is volumetric flowrate, R is the hydraulic radius, S is the reach average slope (obtained from the DEM), h is the flow depth, w is the channel width, and z is the side slope for the wedge. For all confined reaches, a 4:1 side slope was assumed. Both the representative flow depth and width can be estimated from the SfM DEM.

$$Q = \frac{1}{n} R^{2/3} S^{1/2}; \text{ where } R = \frac{h(w)}{w+2h} \text{ for rectangluar, } R = \frac{zh^2}{2h\sqrt{1+z^2}} \text{ for wedge}$$
(2)

This study utilized the solver feature of Microsoft Excel to iteratively solve for the flowrate, but other online solvers or software such as Bently FlowMaster could be used to solve for the unknown flowrate. Once a flowrate has been estimated, a test hydraulic model should be run at this flowrate. Because discharge estimates are highly dependent on the assumed flow depth, be sure to verify whether the area inundated by the estimated flow matches closely to the area observed to be inundated in the orthomosaic image. If the inundated area appears to vary by more than a factor of two, recalculate the flowrate with a new flow depth until the inundated area begins to align with observed inundated area more closely in the orthomosaic imagery. Additional information on calibration procedures is described in the *Appendix* example for upper Black Hollow.

Tier 2

Tier 2 modeling approach supplements the hydraulic model and SfM DEM information with additional field data. Specifically, Tier 2 provides the addition of a measured discharge as well as salt tracer data for measuring reach average velocity. The discharge measurements and salt tracer techniques were described in detail in the *Field Data Collection* section of the *Appendix* example. This modeling approach requires that the discharge data and reach averaged velocity measurements be collected on the same day. According to Calkins & Dunne, 1970, reach averaged velocities are best predicted when comparing the centroids of attenuation curves. HOBO conductivity loggers record the variation in salt concentration with time, so comparing the time dimension centroids of the upstream and downstream loggers and dividing the average reach length by the time between centroids provides an accurate measurement of reach averaged velocity.

#### **Discharge Data Collection**

Discharge measurements are important for modeling applications because they reduce a substantial amount of uncertainty associated with estimating a discharge. Discharge can be collected using any means available, including gauge data (if applicable) or any acoustic Doppler velocimeter (ADV - such as the SonTek FlowTracker 2 used for this report). Discharge measurement here is developed by combining approximately 20 depth and velocity measurements from the ADV across a cross section. Figure 8 below shows use of the Sontek FlowTracker 2 at lower Black Hollow.



Figure 8: Sontek FlowTracker2 at lower Black Hollow

### Salt Tracers for Reach Averaged Velocities

The main process of model calibration was the use of field data to determine the reach average velocities for model calibration. This concept builds on ideas from Calkins & Dunne, 1970, which shows that salt tracer tests are a good measure of determining average channel velocities. Mixing the salt upstream allows salt to flow into eddies and gives an accurate representation of average stream velocity. The technique also involves finding the centroid of the area under the concentration-time curve (Calkins & Dunne, 1970), as shown in Figure 9 below. Calculation of the time-axis centroid is detailed in the *Appendix* example, which applied trapezoidal approximation of the integral of the time-concentration curve.

In general, basic models with single roughness coefficients were created as a basis using roughness values assumed by the modeler or beginning from the USGS roughness assumption detailed in Tier 1 above (Acrement Jr. & Schneider, 1989). Velocity results in RAS Mapper were

exported to raster files where statistics were analyzed in ArcGIS Pro. In general, I used a trialand-error method combined with applied linear interpolation to approach a calibrated roughness value. Calibration was achieved for the case where the average modeled velocity approached the calculated velocity from the salt tracer measurement. Specifics on the methodology I used are described in detail in the *Appendix* example for upper Black Hollow. Figure 9 below shows the attenuation curves for each of the sites considered for this report. Note that the concentration coordinate of the centroid was visually estimated because only the time coordinate is required for calculating the reach-averaged velocity.



Figure 9: Salt tracer attenuation curves using trapezoidal integration to determine the time-axis centroid

The Tier 2 model can be run once the measured reach-averaged velocity has been determined. For this model, use the flow file that corresponds to the measured discharge using the same model geometry files with varied Manning's n values as the Tier 1 model. Output the model results for velocity at time = 4 hours and export the velocity raster. I recommend analyzing the statistics in ArcGIS Pro and clipping the results to the limits of the concentration sensors for best results. The model has been calibrated when the mean velocity of the model output raster approaches the measured reach average velocity from the tracer test. Model outputs for each of the sites using Tier 2 modeling approach are presented in the Results section of the report.

# Tier 3

The final and most data intensive calibration method of the Tiered Hydraulic Modeling Framework is Tier 3. Tier 3 calibration uses the same method of salt tracer attenuation for reachaveraged velocity, but with the addition of GPS RTK bathymetry to the DEM. Survey data collection methodology was detailed in the *Field Data Collection* section of the *Appendix* example. Survey cross section data were collected at a 5-m spacing, surveying major grade breaks to accurately represent the features of the cross section while minimizing the points collected. Survey data were then processed using AutoCAD Civil3D, as is common among professional land surveyors. The TIN surface was generated using break lines of the channel water surface elevations on the right and left banks as well as along the channel thalweg. This method helps the TIN generation to more accurately create contour lines that would be observed in natural channels and drainageways.

#### **Bathymetry Using GNSS RTK Data**

Merging the SfM DEM and developed bathymetry surface is a critical step for creating a Tier 3 model. I merged the surfaces using functions in ArcGIS Pro to snap to one another applying

raster calculations, adjusting the mean elevation difference to equal zero, and the Mosaic to New Raster to ultimately combine the surfaces into a single DEM. I applied the raster calculator by subtracting the unadjusted bathymetric survey from the SfM DEM. If the result is positive, the unadjusted bathymetric survey should be lowered by the mean difference from the raster calculation result, and raised if the result is negative.

# Results

The overall results of model calibration for all sites are presented below in Table 1. The table displays the estimated flows using the methodology presented in Tier 1, as well as the preliminary estimated Manning's n value from the USGS method (Arcement Jr. & Schneider, 1989). In addition, variation of Manning's n between modeling approaches can be seen in Table 1 below. Note that roughness values were calibrated to the nearest 0.01. A more accurate calibration could be performed but was limited for this report to limit computational expense.

Table 1: Overall results of Tiered Hydraulic Modeling	Framework for Black Hollow and Little Beaver Creek.
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Reach	Estimated USGS Roughness (T1)	Calibrated Roughness (T1)	Calibrated Roughness (T2)	Calibrated Roughness (T3)
Black Hollow (Upper)	0.09	0.07	0.06	0.05
Black Hollow (Lower)	0.09	0.08	0.03	0.03
Little Beaver Creek (Upper)	0.09	0.04	0.08	0.08
Little Beaver Creek (Lower)	0.09	0.03	0.08	0.09

### *Tier 1 – Calibration Results*

Model results for Tier 1 are presented below in several figures. Figure 10 shows the plots of modeled and measured water surface elevations for the calibrated models at each site. The slope of the linear regression line is also presented, with a perfect model having a target slope of 1.

Table 2 below presents the estimated flowrate for each site (detailed in the appendix example),

measured flow corresponding to the drone flight date, percent error in flow estimation from

measured, and the calibrated roughness presented in Table 1. Percent error is calculated in

Equation 2 below, where *Modeled* also represents *Estimated*.

$$\% Error = \left| \frac{Modeled - Measured}{Measured} \right|$$
(2)

Table 2: Tier 1 flow estimation results, error, and calibrated Manning's n

Reach	Estimated T1 Flow [cms]	Measured T1 Flow [cms]	% Error in Flow Estimation	Calibrated Roughness
Black Hollow (Upper)	0.15	0.121	24%	0.07
Black Hollow (Lower)	0.15	0.121	24%	0.08
Little Beaver Creek (Upper)	0.16	0.137	17%	0.04
Little Beaver Creek (Lower)	0.18	0.134	35%	0.03

Figure 11 shows the calibrated depth result from RAS Mapper, along with the calibration points for each model, described in detail in the report appendix. The calibration points are plotted for each site below in pink.



Figure 10: Calibrated modeled vs. measured water surface elevation plots for each reach using Tier 1 modeling approach.



Figure 11: Tier 1 calibration points for each site. A: upper Black Hollow, B: lower Black Hollow, C: upper Little Beaver Creek, D: lower Little Beaver Creek. Figures 11A and B have depth color scales from 0-0.25m, and Figures 11C and D have color scales from 0-0.5m

# *Tier 2 – Calibration Results*

Model results for Tier 2 are presented below in several figures. Table 3 reports the flowrates used for Tier 2 models at each site, along with the measured velocity using the centroidal approach to salt tracer measurements from Figure 9 of the Methods section. The averaged model velocity is reported along with percent error and the corresponding roughness from Table 1. Recall that all values are calibrated to the nearest 0.01 to save computational expense.

Table 3: Tier 2 velocity calibration results, error, and calibrated Manning's n

Reach	Measured T2 Flow [cms]	Measured T2 Velocity (m/s)	Modeled T2 Velocity (m/s)	% Velocity Error	Calibrated Roughness
Black Hollow (Upper)	0.244	0.749	0.722	4%	0.06
Black Hollow (Lower)	0.244	1.358	1.210	11%	0.03
Little Beaver Creek (Upper)	0.243	0.334	0.326	2%	0.08
Little Beaver Creek (Lower)	1.267	0.550	0.571	4%	0.08

Figure 12 shows the calibrated velocity raster results from RAS Mapper in HEC-RAS for Tier 2 models at each site. The velocity distributions that correspond to these outputs within the limits of the salt tracer test are shown in Figure 13.



Figure 12: Tier 2 velocity results for calibrated model results. A: upper Black Hollow, B: lower Black Hollow, C: upper Little Beaver Creek, D: lower Little Beaver Creek. Color scales for each are 12A = 0-2.0m/s, 12B = 0-3.0m/s, 12C = 0-1.5m/s, 12D = 0-2.0m/s



Figure 13: Tier 2 velocity raster distributions from calibrated model results with mean velocity reported in Table 3. Top left – upper Black Hollow, top right – lower Black Hollow, bottom left – upper Little Beaver Creek, bottom right – lower Little Beaver Creek

# Tier 3 – Calibration Results

Model results for Tier 3 are presented below in several figures. Table 4 reports the flowrates used for Tier 2 models at each site, along with the measured velocity using the centroidal approach to salt tracer measurements from Figure 9 of the Methods section. The averaged model velocity is reported along with percent error and the corresponding roughness from Table 1. Recall that all values are calibrated to the nearest 0.01 to save computational expense.

Table 4: Tier 3 velocity calibration results, error, and calibrated Manning's n

Reach	Measured T3 Flow [cms]	Measured T3 Velocity (m/s)	Modeled T3 Velocity (m/s)	% Velocity Error	Calibrated Roughness
Black Hollow (Upper)	0.244	0.749	0.710	5%	0.05
Black Hollow (Lower)	0.244	1.358	1.226	10%	0.03
Little Beaver Creek (Upper)	0.243	0.334	0.379	13%	0.08
Little Beaver Creek (Lower)	1.267	0.550	0.585	6%	0.09

Figure 14 shows the calibrated velocity raster results from RAS Mapper in HEC-RAS for Tier 3 models at each site. The velocity distributions that correspond to these outputs within the limits of the salt tracer test are shown in Figure 15. Additional split flow is observed due to the presence of break-lines for the Tier 3 DEM from the GPS RTK survey, particularly at upper Black Hollow and upper Little Beaver Creek.



Figure 14: Tier 3 velocity results for calibrated model results. A: upper Black Hollow, B: lower Black Hollow, C: upper Little Beaver Creek, D: lower Little Beaver Creek. Color scales for each are 14A = 0-2.0m/s, 14B = 0-3.0m/s, 14C = 0-1.5m/s, 14D = 0-1.5m/s



Figure 15: Tier 3 velocity raster distributions from calibrated model results with mean velocity reported in Table 3. Top left – upper Black Hollow, top right – lower Black Hollow, bottom left – upper Little Beaver Creek, bottom right – lower Little Beaver Creek

# Discussion

The primary purpose of this work is to present a modeling approach and results regarding remotely sensed data and two-dimensional hydraulic model calibration in post-fire stream reaches. Comparing modeling approaches was valuable to show how roughness values vary depending on the data collected and level of effort for the modeler, as well as how the approaches yielded differing results. Tier 1 generally resulted in opposite roughness magnitudes for each reach relative to those observed in Tier 2 and Tier 3 for the same reaches. This was primarily because Tier 1 utilizes an estimated discharge, and the calibrated roughness had to compensate for this estimation to match measured parameters. Another major result of Tier 3 modeling at baseflow was the presence of split flow that was not observed during field work or on the orthomosaic, depicted when comparing Figures 12 and 14. This is because accuracy using a GPS RTK survey does not match accuracy using an SfM DEM. The bathymetric survey had a dense resolution of 5-m spacing but the interpolation of bathymetric surveys between cross sections creates small ridgelines where the bathymetric survey meets the SfM DEM, which does not exist physically. However, these discrepancies were noted to disappear as flows increased. Figure 16 below shows how the water-surface profiles vary in some specific regions where SfM shows more detailed bathymetry or channel constrictions creating more backwater affect. Figure 16 also shows that the bathymetry of the SfM and GPS survey are similar, with SfM capturing more detail and specific features than the interpolation between cross sections of the GPS survey. Figure 17 shows how the inundated areas for Tiers 2 and 3 begin to converge as discharge increases. Additionally, Table 5 below also details the Tiered Hydraulic Modeling Framework with data needs, calibration approach, and advantages and disadvantages for each tier.



Figure 16: Lower Little Beaver Creek calibrated model outputs of water surface profiles along channel thalweg for Tier 2 and Tier 3 at 1.27 cms



Figure 17: Upper Black Hollow inundated flow areas for Tier 2 (A and C) and Tier 3 (B and D). Flow for A and B = 0.24 cms, flow for C and D = 0.99 cms (6 hour two year storm from USGS StreamStats)

Tiered Hydraulic Modeling Framework Tier	Data Needs	Advantages Limitations	
Tier 1 – Remotely Sensed Data, Water Surface Elevation Calibration Approach	SfM drone photogrammetry or other remotely sensed topographic data like LiDAR	<ul> <li>Requires the minimal amount of data required to create a hydraulic model</li> <li>SfM is accurate compared to freely available LiDAR</li> <li>SfM orthomosaic imagery is useful for determining sensibility of results</li> <li>Limited uncertainty if working in a gauged watershed/stream or if hydrologic analysis is performed</li> <li>SfM performs well with capturing bathymetry during low flow conditions with little sediment transport</li> </ul>	<ul> <li>Requires discharge estimation using an assumed Manning's n and depth resulting in high uncertainty</li> <li>SfM is challenging to filter out low lying riparian vegetation like willows and other shrubs</li> <li>Requires many iterations to converge on a roughness value</li> <li>Channel bathymetry accuracy from SfM is still uncertain in the literature</li> <li>Channel bathymetry becomes inaccurate with more sediment transport</li> </ul>
Tier 2 – Additional Discharge & Velocity Data, Velocity Calibration Approach	<ul> <li>Tier 1 data</li> <li>Discharge data (gauge data or measurement with ADV or equivalent)</li> <li>Salt tracer tests using concentration meters to measure reach velocity attenuation</li> </ul>	<ul> <li>Streamlined calibration approach using velocity</li> <li>Uses a known discharge reducing uncertainty</li> <li>Requires minimal field work to collect data</li> <li>SfM is accurate compared to freely available LiDAR</li> <li>Strong balance between level of effort and model accuracy</li> <li>SfM orthomosaic imagery is useful for determining sensibility of results</li> <li>SfM performs well with capturing bathymetry during low flow conditions with little sediment transport</li> </ul>	<ul> <li>Assumes fully mixed condition for salt tracers to represent reach average velocity</li> <li>Channel bathymetry accuracy from SfM is still uncertain in the literature</li> <li>Channel bathymetry becomes inaccurate with more sediment transport</li> <li>SfM is challenging to filter out low lying riparian vegetation like willows and other shrubs</li> </ul>
Tier 3 –GPS RTK Bathymetry Data, Velocity Calibration Approach	<ul> <li>Tier 1 and 2 data</li> <li>GPS RTK cross section bathymetric survey data</li> </ul>	• Bathymetry is more accurate, particularly in streams with high sediment transport with high turbidity	<ul> <li>At low flow with clear water, SfM can better capture bathymetry and near channel geometry</li> <li>Hauling GPS equipment to remote sites is difficult</li> <li>GPS equipment struggles in heavily vegetated sites</li> <li>Collecting data is difficult during peak flow, especially for large systems</li> <li>Requires more equipment and knowledge of survey practices</li> </ul>

## Table 5: Advantages and Limitations of each tier within the Tiered Hydraulic Modeling Framework

When applying the Tiered Hydraulic Modeling Framework, project context and outcome are key for determining which tier to apply. For example, Tier 1 with estimated discharge is best applied for conceptual design and management practices when prioritizing reaches at risk following extreme events like wildfires, debris flows, or flooding. Tier 2 is best applied to research, restoration design, and improvement projects to understand the specific hydraulics accurately in small mountain streams or streams that experience low baseflow with low sediment transport. Finally, Tier 3 is best applied to similar projects as Tier 2, but in cases where baseflows are high in large streams with high sediment transport and SfM will not accurately characterize channel bathymetry.

Black Hollow and Little Beaver Creek were selected for this study because they were inferred to represent endmembers on the spectrum of watershed response to wildfires. The results indicate that these watersheds do represent end members to wildfire response, with Tier 2 and Tier 3 showing higher roughness values at Little Beaver Creek. Little Beaver Creek has more complex geomorphology than the steep confined reaches at Black Hollow, and the additional impact of riparian vegetation at the lower reach and large wood jams at the upper reach of Little Beaver Creek resulted in the inflated calibrated roughness values, even when large wood was manually filtered from the upper Little Beaver Creek DEM. These results were exhibited in Table 1, where Little Beaver Creek had calibrated roughness values at the upper and lower reaches of 0.05 and 0.03, respectively. Slope was observed to vary proportionally to roughness as well, with lower Black Hollow having the steepest overall reach gradient and lowest roughness value, where lower Little Beaver Creek has the lowest reach gradient and highest roughness

value. Slope is an important parameter when analyzing velocity and was reflected in these results.

A meaningful impact of these processes for using SfM on restoration projects is the application to the use of large wood in design. One benefit of SfM is the detail at which it can capture large roughness elements like large boulders and wood in the channel and in the floodplain. Removal of large wood from the model has advantages and disadvantages from a geomorphic context since large wood is critical in mountain streams for many biogeomorphic processes (Wohl et al., 2017, 2022). However, due to the three-dimensional nature of the in-channel large wood, logs often needed to be filtered out manually because they create regions of hydraulic dysconnectivity, even within reaches of the main channel.

In-channel large wood presented significant difficulties when creating the 2D hydraulic model. As mentioned above, the SfM DEM precision ranged between 2-6 cm/pixel, which was accurate enough to show large roughness elements like boulders and large wood. Although this is an excellent benefit for understanding the complexity of the system, the three-dimensional nature of flow around large wood jams and features presented a challenge. In some cases where a single log was present or overhanging, manual point omission was successful to get better flow dynamics behavior. An example of this was a large, channel-spanning log in the lower Black Hollow reach. In this case, the log was positioned nearly 3 m above the channel bed, causing the HEC-RAS mesh and terrain to create a dam, sending flow around the log with nearly 3 m of backwater, a poor physical representation of the system at baseflow. Once the log was removed, the system behaved as observed in the field. However, when large wood jams are present, simple removal of the logs did not produce an accurate DEM. Metashape builds the DEM from the point

cloud using the nearest points, and when removing channel-spanning jams, the DEM would interpolate laterally rather than longitudinally (Agisoft, 2023).

Vegetation filtration of SfM is challenging at lower Little Beaver Creek and other unconfined systems with lots of riparian vegetation. Trees are filtered nicely using the cloth simulation filter, but willows that gradually blend into the terrain are challenging to handle. SfM works well for wide, open gravel-bed streams with little riparian vegetation or in severely burned scenarios, such as Black Hollow, where the burned tree trunks were filtered with relative ease. Even upper Little Beaver Creek, which was more severely burned than the lower reach, was slightly more challenging to obtain a vegetation filtered DEM from due to the lower reach gradient and more complex geomorphic system. Additionally, the steepness of some of the surrounding hillslopes made filtering using strictly the cloth simulation filter tool challenging, as the parameters that worked well in the channel would delete much of the hillslope in the steeper sections of the floodplain. In this case, shrinking the grid size of the cloth simulation filter was able to preserve the hillslope terrain features while also filtering most of the vegetation out of the main channel.

This work also highlighted some of the flaws in the procedures and DEMs used. Although Calkins & Dunne, 1970 show that this salt tracer method adequately mixes with the flow to account for turbulent eddies, the distribution shows a high number of low velocity areas that could skew the roughness values to inaccurately represent the bulk flow velocity. This analysis could also be used to validate the velocity measurements used in this study. Additionally, the SfM model was accurate enough to capture large roughness elements like large boulders and inchannel large wood. This is critical for accurately representing baseflow conditions because these roughness elements are important for bed morphology and geometry. However, if these elements are still incorporated as being part of the bed during larger flows in a morphodynamic

model, uncertainty in estimation of erosion and deposition may be introduced unless grain size distributions are accurately incorporated into the model. Depending on the goals of the model analysis, the variation due to topographic precision could be neglected, particularly when dealing with larger flows where the relative influence of bed roughness decreases.

Furthermore, a primary use of modeling is prediction of flood hazard zones, which were observed to have little difference between tiers for higher flow events. The SfM model with higher precision was observed to activate more secondary channels at low flows. Secondary channels are critical for predicting habitat and geomorphic change during channel-forming discharges. For this application in restoration, a more detailed DEM can be advantageous. Additionally, in highly dynamic systems like Black Hollow, continued monitoring and quantification of geomorphic change would be more easily captured using a detailed DEM like the SfM model, particularly on an annual basis during low flows and when flows recede following large convective storms. When modeling large flows, tools like R2Cross (Oikonomou et al., 2021) can be used to adjust the calibrated baseflow roughness values for larger flows where roughness has relatively less impact as depth increases.

Calibration is a commonly used practice in academia for numerical modeling, and refining procedures for quick, accurate calibration is useful for scientists and engineers. However, further analysis to support or expand on existing work is needed to draw additional conclusions that will be beneficial to the field. The models created were simple 2D hydraulic models and no work was done to further refine the computational mesh. Comparison of both calibration results and velocity model results could be conducted to determine the influence of mesh creation and spatial discretization on results for baseflow and large floods. These results would be valuable for optimizing the computational time of the hydraulic model and the accuracy of results. Further

research could also be done to consider additional calibration methods, such as comparing inundated areas to the orthomosaic imagery, using the RTK GNSS survey information to perform kriging analysis (Legleiter & Kyriakidis, 2008).

Additional work in a geomorphic context is also of interest to researchers on this project. Some work on reconstructing major floods in numerical models has been done in both a classical morphodynamic model using Nays2DH (Brogan et al., 2017) and with non-Newtonian fluid models (Floyd, 2021). The Black Hollow debris flow was a significant event in which a case study could be interesting in attempts to validate current modeling procedures with recreation of this event. This work could be done with a focus on large events like the 20 July 2021 flood or using channel-forming discharges observed throughout the course of the runoff season during field visits.

# References

Abu-Aly, T. R., Pasternack, G. B., Wyrick, J. R., Barker, R., Massa, D., & Johnson, T. (2014). Effects of LiDAR-derived, spatially distributed vegetation roughness on two-dimensional hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull. *Geomorphology*, 206, 468–482. https://doi.org/10.1016/j.geomorph.2013.10.017

Acrement Jr., G., & Schneider, V. (1989). Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains. USGS Water-Supply, 2339, 44.

Agisoft. (2023). Agisoft Metashape: User Manuals. Retrieved July 3, 2023, from https://www.agisoft.com/downloads/user-manuals/

Bandini, F., Sunding, T. P., Linde, J., Smith, O., Jensen, I. K., Köppl, C. J., et al. (2020). Unmanned Aerial System (UAS) observations of water surface elevation in a small stream: Comparison of radar altimetry, LIDAR and photogrammetry techniques. *Remote Sensing of Environment*, 237, 111487. https://doi.org/10.1016/j.rse.2019.111487

Bilgili, E., Bomers, A., van Lente, G. J.-W., Huthoff, F., & Hulscher, S. J. M. H. (2023). The effect of a local mesh refinement on hydraulic modelling of river meanders. *River Research and Applications*, *39*(5), 832–846. https://doi.org/10.1002/rra.4110

Brogan, D. J., Nelson, P. A., & MacDonald, L. H. (2017). Reconstructing extreme post-wildfire floods: a comparison of convective and mesoscale events. *Earth Surface Processes and Landforms*, 42(15), 2505–2522. https://doi.org/10.1002/esp.4194

Brogan, D. J., MacDonald, L. H., Nelson, P. A., & Morgan, J. A. (2019). Geomorphic complexity and sensitivity in channels to fire and floods in mountain catchments. *Geomorphology*, *337*, 53–68. https://doi.org/10.1016/j.geomorph.2019.03.031

Calkins, D., & Dunne, T. (1970). A salt tracing method for measuring channel velocities in small mountain streams. *Journal of Hydrology*, *11*(4), 379–392. https://doi.org/10.1016/0022-1694(70)90003-X

Division of Fire Prevention and Control. (n.d.). Historical Wildfire Information | Fire Prevention and Control. Retrieved December 11, 2022, from https://dfpc.colorado.gov/wildfire-information-center/historical-wildfire-information

Domeneghetti, A., Tarpanelli, A., Brocca, L., Barbetta, S., Moramarco, T., Castellarin, A., & Brath, A. (2014). The use of remote sensing-derived water surface data for hydraulic model calibration. *Remote Sensing of Environment*, *149*, 130–141. https://doi.org/10.1016/j.rse.2014.04.007

Elliott, J. G., Smith, M. E., Friedel, M. J., Stevens, M. R., Bossong, C. R., Litke, D. W., et al. (2005). Analysis and mapping of post-fire hydrologic hazards for the 2002 Hayman, Coal Seam, and Missionary Ridge wildfires, Colorado. *Scientific Investigations Report*. https://doi.org/10.3133/sir20045300

Floyd, I. (2021). *Non-Newtonian Model Development for Post-Wildfire Flood Risk Management* (Ph.D.). Louisiana State University and Agricultural & Mechanical College, United States -- Louisiana. Retrieved from

https://www.proquest.com/docview/2665130718/abstract/BCD5C00CB1144599PQ/1

Grimaldi, S., Li, Y., Pauwels, V. R. N., & Walker, J. P. (2016). Remote Sensing-Derived Water Extent and Level to Constrain Hydraulic Flood Forecasting Models: Opportunities and Challenges. *Surveys in Geophysics*, *37*(5), 977–1034. https://doi.org/10.1007/s10712-016-9378-y

James, M. R., Chandler, J. H., Eltner, A., Fraser, C., Miller, P. E., Mills, J. P., et al. (2019). Guidelines on the use of structure-from-motion photogrammetry in geomorphic research. *Earth Surface Processes and Landforms*, 44(10), 2081–2084. https://doi.org/10.1002/esp.4637

Kostelnik, J., Schmitt, R. G., Rengers, F. K., & Kean, J. W. (2022, February 24). Cameron Peak Fire: Flooding and Debris Flows. Retrieved November 17, 2022, from https://storymaps.arcgis.com/stories/af3cd28cad6040e9a3a3d608f58292a7

Legleiter, C. J., & Kyriakidis, P. C. (2008). Spatial prediction of river channel topography by kriging. *Earth Surface Processes and Landforms*, *33*(6), 841–867. https://doi.org/10.1002/esp.1579

Legleiter, C. J., Kyriakidis, P. C., McDonald, R. R., & Nelson, J. M. (2011). Effects of uncertain topographic input data on two-dimensional flow modeling in a gravel-bed river. *Water Resources Research*, 47(3). https://doi.org/10.1029/2010WR009618

Liu, Z., Merwade, V., & Jafarzadegan, K. (2019). Investigating the role of model structure and surface roughness in generating flood inundation extents using one- and two-dimensional hydraulic models. *Journal of Flood Risk Management*, *12*(1), e12347. https://doi.org/10.1111/jfr3.12347

Martin, M. T. (2022). *Development, Calibration, and Validation of a High-Resolution 2D HEC-RAS Model at St. Arbor Wetland to Extract Rating Curves at Levee Breach Locations* (M.S.). Tennessee Technological University, United States -- Tennessee. Retrieved from https://www.proquest.com/docview/2671701237/abstract/CE5F034083324999PQ/1

Oikonomou, P. D., Sidhu, R., Wible, T., & Morrison, R. R. (2021). R2Cross: A Web-Based Decision Support Tool for Instream Flows. *JAWRA Journal of the American Water Resources Association*, *57*(4), 652–660. https://doi.org/10.1111/1752-1688.12939

Ongdas, N., Akiyanova, F., Karakulov, Y., Muratbayeva, A., & Zinabdin, N. (2020). Application of HEC-RAS (2D) for Flood Hazard Maps Generation for Yesil (Ishim) River in Kazakhstan. *Water*, *12*(10), 2672. https://doi.org/10.3390/w12102672

Over, J.-S. R., Ritchie, A. C., Kranenburg, C. J., Brown, J. A., Buscombe, D. D., Noble, T., et al. (2021). *Processing coastal imagery with Agisoft Metashape Professional Edition, version 1.6— Structure from motion workflow documentation* (No. 2021–1039). *Open-File Report*. U.S. Geological Survey. https://doi.org/10.3133/ofr20211039 Purinton, B., & Bookhagen, B. (2017). Validation of digital elevation models (DEMs) and comparison of geomorphic metrics on the southern Central Andean Plateau. *Earth Surface Dynamics*, *5*(2), 211–237. https://doi.org/10.5194/esurf-5-211-2017

Rengers, F. K., McGuire, L. A., Oakley, N. S., Kean, J. W., Staley, D. M., & Tang, H. (2020). Landslides after wildfire: initiation, magnitude, and mobility. *Landslides*, *17*(11), 2631–2641. https://doi.org/10.1007/s10346-020-01506-3

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F. W., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, *90*, 201–216. https://doi.org/10.1016/j.envsoft.2017.01.006

U.S. Army Corps of Engineers. (2022, August 25). HEC-RAS 2D User's Manual. Retrieved December 11, 2022, from https://www.hec.usace.army.mil/confluence/rasdocs/r2dum/latest

Van Eeckhout, M. (2010). Integrating HEC-RAS and ArcView in predicting post wildfire 100year floodplains on the Pajarito Plateau, Los Alamos, New Mexico. *Water Resources Professional Project Reports*. Retrieved from https://digitalrepository.unm.edu/wr\_sp/57

White, D. C., Morrison, R. R., & Wohl, E. (2022). Fire and ice: Winter flooding in a Southern Rocky Mountain stream after a wildfire. *Geomorphology*, *413*, 108370. https://doi.org/10.1016/j.geomorph.2022.108370

Wohl, E., Lininger, K. B., Fox, M., Baillie, B. R., & Erskine, W. D. (2017). Instream large wood loads across bioclimatic regions. *Forest Ecology and Management*, 404, 370–380. https://doi.org/10.1016/j.foreco.2017.09.013

Wohl, E., Marshall, A. E., Scamardo, J., White, D., & Morrison, R. R. (2022). Biogeomorphic influences on river corridor resilience to wildfire disturbances in a mountain stream of the Southern Rockies, USA. *Science of The Total Environment*, 820, 153321. https://doi.org/10.1016/j.scitotenv.2022.153321

Woodget, A. S., Carbonneau, P. E., Visser, F., & Maddock, I. P. (2015). Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. *Earth Surface Processes and Landforms*, 40(1), 47–64. https://doi.org/10.1002/esp.3613

Zhang, W., Qi, J., Peng, W., Wang, H., Xie, D., Wang, X., & Yan, G. (2016). An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation. *Remote Sensing*, *8*, 501. https://doi.org/10.3390/rs8060501

# Appendix

#### **Software Download Links**

HEC-RAS 6.3 (free): https://www.hec.usace.army.mil/software/hec-ras/download.aspx Cloud Compare 2.12.4 (free): https://www.danielgm.net/cc/ ArcGIS Pro 3.0.0: https://pro.arcgis.com/en/pro-app/latest/get-started/download-arcgis-pro.htm AutoCAD C3D 2023: https://www.autodesk.com/products/civil-3d Agisoft Metashape 1.8.1: https://www.agisoft.com/downloads/installer/ Emlid ReachView3 (now Emlid Flow): https://apps.apple.com/us/app/emlid-flow/id1463967138

### Example Tiered Modeling Framework - Upper Black Hollow

## Field Data Collection

To effectively calibrate a hydraulic model, several field data measurements are needed, including drone survey, discharge, salt tracer, and bathymetric survey data. Understanding the site and modeling objectives is important so that the data collected accurately reflects the reach of interest. Modeling objectives could include but are not limited to flood inundation prediction, channel design, erosive potential, or prediction of channel change. Once a site is selected, field data collection can begin.

A likely first step is to fly the reach of interest and surrounding area with a drone to create a digital elevation model (DEM). This report does not intend to provide a comprehensive overview of drone flight procedures. A licensed drone pilot will need to conduct the survey to ultimately provide the processed photos that can be used to develop a SfM DEM using Agisoft Metashape and the procedure outlined in this report. For this project, both a DJI Phantom 4 RTK and Mavic 2 Pro drone were used to collect photogrammetry information. Special thanks to Peter Nelson,

Danny White, Cameron Turnbow, and Aidan Cruz for their help with drone flights for this project.

While the drones are in the field, I collected other relevant data regarding flow characteristics like discharge and salt tracer data, relevant for calibration in Tiers 2 and 3 of the Tiered Hydraulic Modeling Framework. Discharge can be collected using any means available, including gage data (if applicable) or any acoustic doppler velocimeter (ADV - such as the SonTek FlowTracker 2 used for this report). Discharge measurement in this case is developed by combining depth and velocity measurements from the ADV across a cross section. More information on the use of ADV's generally can be found in the literature. Figure A1 below shows use of the Sontek FlowTracker 2 at lower Black Hollow.



### Figure A 1: Sontek FlowTracker2 at lower Black Hollow

Additionally, salt tracer tests require the use of a concentration meter (in this case the HOBO U20L-0x Water Level Logger), which can measure the variation in salt concentration with time.

At least two loggers are required to measure the attenuation in salt concentration through time across a known longitudinal distance. The technique is more closely outlined in Calkins & Dunne, 1970, and involves mixing salt thoroughly in buckets and dumping instream at a location upstream of all sensors. Figure A2 below shows an image of our team placing rebar to hold a concentration meter in stream at Lower Black Hollow. More detail on processing is included later in this report.



Figure A 2: Tracer test at Lower Black Hollow.

An final important piece of data to be collected for Tier 3 of the Tiered Hydraulic Modeling Framework is bathymetry. Bathymetry can be collected in a variety of ways, but this report utilized typical a global navigation satellite system with real time kinematic global positioning system (GNSS RTK GPS). The specific unit was the Emlid RS2 RTK, utilizing the Emlid ReachView3 app on iPad (now Emlid Flow). The author has substantial experience working with a professional land surveyor, and surveyed the sites at a similar level of detail to what a typical PLS might complete for this type of project. For these sites, cross sections were surveyed every 5 meters, surveying major grade breaks along the cross section. Figure A3 shows an image of the team collecting survey using the Emlid RS2 equipment. A detailed description of processing the survey data is included later when discussing merging SfM with GPS bathymetry.



Figure A 3: Emlid RS2 GPS RTK equipment at Black Hollow.

## Data Processing (SfM DEM, Tracers, Bathymetry)

Once field work is complete, data processing is needed to create a hydraulic model. As mentioned above, a key piece of any hydraulic model is a digital elevation model (DEM), which is created using the drone data collected. Photogrammetry drones will collect images that have a latitude, longitude, and elevation (or another cartesian coordinate depending on the coordinate system) associated with the location of the drone at the time of the photo. To process these photos, Agisoft Metashape was used to process the drone data. The USGS developed a workflow for processing drone data in Metashape (Over et al., 2021). Specifically, "Table 1: Quick start guide for the structure from motion workflow…" on pages 3-5 of Over et al., 2021 were used for calibrating cameras, setting accuracy and the use of tie points, point error optimization,

reconstruction uncertainty, project accuracy and error, and optimizing the point cloud overall (Over et al., 2021). Once the point cloud has been filtered and optimized, the cloth simulation procedure described in the body of the report was used in Cloud Compare to filter trees and other vegetation (Zhang et al., 2016). When importing a project to Cloud Compare, be sure to select "yes for all" when asked to perform a coordinate transformation from the project coordinate system to local coordinates. This ensures that point cloud accuracy is preserved, and the point cloud can be reprojected when building the DEM in Metashape. For Upper Black Hollow, the standard values of Zhang et al., 2016 were modified slightly to more effectively filter the vegetation and still preserve the steep slopes that exist in this high mountain watershed. The standard values of Zhang et al., 2016 are a cloth resolution of 2.0 meters, which was reduced to 1.0 meters for this case, 500 max iterations, and a classification threshold of 0.5 meters. Each of these parameters can be adjusted to filter vegetation more accurately at different sites. For example, at Upper Little Beaver Creek, the cloth resolution was reduced to 0.5 meters, max iterations increased to 750, and classification threshold reduced to 0.2 meters. This was required to remove the lower lying riparian vegetation present at Little Beaver Creek that is not present at Black Hollow, and to preserve the steep hillslopes near the Upper Little Beaver Creek reach. In general, reducing the clot resolution and the classification threshold will remove a higher number of points. Reducing the cloth resolution is more likely to keep steep hillslopes since the elevation variation in a smaller gird size is typically less than large grid resolution. Increasing iterations also is more effective in removing low lying riparian vegetation since the cloth simulation filter makes more passes after already removing points. However, these changes typically increase computational power, and depending on DEM size can take several hours or more to filter point clouds. Figure A4 below shows the default cloth simulation filter parameters.

Cloth Simulation Filter		>							
CSF Plugin Instruction									
Cloth Simulation Filter (CSF) is a tool to extract of ground points in discrete return LiDAR pointclouds. The detailed theory and algorithms could be found in the following paper:									
Zhang W, Qi J, Wan P, Wang H, Xie D, Wang X, Yan G. An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation. <i>Remote Sensing</i> . 2016; 8(6):501.									
And please cite the paper, If you use Cloth Simulation Filter (CSF) in your work.									
You can download the paper from <a href="https://www.researchgate.net/profile/Wuming_Zhang2">https://www.researchgate.net/profile/Wuming_Zhang2</a> .									
You can also visit the homepage : <a href="http://ramm.bnu.edu.cn/researchers/wumingzhang/english/default_contributions.htm">http://ramm.bnu.edu.cn/researchers/wumingzhang/english/default_contributions.htm</a> for more information.									
General parameter setting Advanced parameter setting									
Cloth resolution	Advanced Parameter Instruction								
2.000	1. Cloth resolution refers to the grid size (the unit is same as the unit of								
Max iterations	pointclouds) of cloth which is used to cover the terrain. The bigger cloth resolution you have set, the coarser DTM you will get.								
500	2. Max iterations refers to the maximum iteration times of terrain simulation. 500 is enough for most of scenes.								
Classification threshold 0.500	<ol> <li>Classification threshold refers to a threshold (the unit is same as the unit of pointclouds) to classify the pointclouds into ground and non-ground parts based on the distances between points and the simulated terrain.</li> <li>0.5 is adapted to most of scenes.</li> </ol>								
Export cloth mesh									
	OK Cancel								

*Figure A 4: Cloth Simulation Filter dialog box, Cloud Compare, descriptions for advanced parameter setting (Zhang et al., 2016).* 

Once point clouds are filtered using the cloth simulation filter, there are typically still features that the cloth simulation filter did not remove that must be filtered manually. These features might include low lying riparian vegetation or in channel large wood jams. These points were removed in Cloud Compare using the segmentation tool, which allows the user to draw a polygon and filter the points inside the polygon easily. In some instances, the impact of large wood jams was not observed until after the hydraulic model was run, in which case this process would be completed at that point. Figure A5 shows the section of large wood at upper Little Beaver Creek that was manually filtered using the segmentation tool. In most cases, preserving as much of the point cloud outside the large wood is crucial for preserving DEM accuracy through the impacted section of the reach. The polygonal black sections in Figure A5 represent where large wood jams were manually filtered, and the other sections without points either were

filtered with the cloth simulation filter or were not collected in the drone flight. Metashape interpolates between the nearest remaining points to build the resulting DEM. Little Beaver Creek was highlighted here due to the lack of channel spanning log jams at the selected Black Hollow reaches.



*Figure A 5: Manually filtered large wood jam at upper Little Beaver Creek using Cloud Compare segmentation tool.* Once the filtered is deemed acceptable by the user based on comparison to field characteristics, the point cloud is saved in Cloud Compare and re-imported into Metashape. This procedure allows for us to continue the Over et al., 2021 workflow for building the DEM in the specified coordinate system. The workflow would then typically progress to creating the orthomosaic image, a composite bidrs-eye georeferenced image of the site, which is typically far more detailed than any freely available imagery. Our team found better success with building the orthomosaic from the non-filtered point cloud to preserve location of vegetation that can be useful for analyzing model results. Figure A6 below shows a progression of the point cloud to DEM results for upper Black Hollow. The point cloud after being filtered has 20,675,597 points, the DEM has a precision of 5.89cm/pixel, and the orthomosaic has a precision of 2.94cm/pixel.



Figure A 6: Upper Black Hollow filtered point cloud (left) and resulting digital elevation model (right) HEC-RAS Model Overview

The Army Corps of Engineers Hydrologic Engineering Center developed the River Analysis System (HEC-RAS) as a freely available hydraulic modeling software (U.S. Army Corps of Engineers, 2022). Recently, two dimensional hydraulic models are becoming increasingly popular because the more accurately represent open channel flow mechanics of natural systems than the more traditional one dimensional model (Abu-Aly et al., 2014; Legleiter et al., 2011; Martin, 2022; Ongdas et al., 2020). In a two dimensional hydraulic model, the model uses a DEM and computational mesh to allow water to move longitudinally and laterally in a channel but ignores vertical flow paths to improve computational expense. The first step for creating a HEC-RAS hydraulic model for all approaches of the Tiered Hydraulic Modeling Framework is to open the RASMapper GIS application inside HEC-RAS and set the projection. In this case, the coordinate system used was NAD83 UTM Zone 13N, in meters. Importing the DEM to create a HEC-RAS terrain file is the next major step. Select the terrain DEM created from Metashape, and specify a rounding value. The default is 1/128, but since each of the DEMs developed for this project had DEM precision of a few centimeters, 1/100 rounding is sufficient. Specify the path for terrain file will be stored on your computer, and create the terrain.

Another important component of a good 2D hydraulic model is a good computational mesh. This is created in RASMapper using the geometry creation tools. The first step of creating a model geometry is to specify the perimeter or modeling extents. In most cases, this should cover any area that you expect to be inundated during an extreme event, including the main channel and its floodplain. Once the perimeter has been determined, a grid size and roughness can specified. If creating a Tier 1 model, specify the roughness from the USGS method estimation detailed below in Tier 1, or assume a common roughness for your stream (if working with mountain streams, assume a typical value for gravel bed streams). For grid size, determine a size that is appropriate for floodplain or overbank hydraulics, typically a much courser resolution than for the main channel. For each of these models, a 1m by 1m cell size resolution was selected for the base grid resolution. After creating the base computational mesh, a refinement region can be applied to the model geometry to model the instream hydraulics more accurately. This tool is also under the geometry tools in RAS Mapper and is created by drawing the refinement polygon and specifying a new mesh cell size. The active channel refinement region should represent the bankfull channel. I estimated the bankfull channel using the orthomosaic image, aligning the polygon along locations with prominent vegetation and other geomorphic features indicating the bankfull channel location. The refinement regions for each model were taken to have a cell size resolution of 0.25m by 0.25m. The overall channel mesh as well as the refinement region used for modeling the upper Black Hollow reach is depicted in Figure A7 below.



*Figure A 7: Model perimeter and active channel refinement region for upper Black Hollow. Floodplain/hillslope grid resolution = 1m, channel grid resolution (refinement region) = 0.25m.* 

Once the channel mesh is deemed acceptable by the modeler, the model requires boundary conditions. Common HEC-RAS model boundary conditions include inflow hydrographs, outflow hydrographs, rating curves, and normal depth. For each of the models presented in this report, an inflow hydrograph was used as the upstream boundary condition, and a normal depth was used for the downstream boundary condition. For normal depth, the user must provide the slope along the thalweg at the boundary condition and specify whether to compute a normal depth for each cell across the boundary condition or compute a single water surface. For the models used in this report, a single water surface was selected in order to have flexibility for modeling a wide range of flows. The inflow hydrograph is specified in the unsteady flow data dialog box, where a 4 hour hydrograph was input. Since these models focused on baseflow for calibration, a ramp up technique was used to smoothly approach the desired steady flow. At upper Black Hollow, for example, the estimated flow was 0.15cms, which was ramped from 0.05cms at time = 0 hours, to 0.1cms at time = 1 hour, to a constant 0.15cms from time = 2 hours to time = 4 hours.

HEC-RAS models are run using plan files, which are a combination of flow and geometry files. The unsteady flow file used for 2D hydraulic models applies the specified hydrograph to the boundary conditions to run for the duration of the hydrograph (or shorter). The geometry file is the computational mesh created. For this report, geometry files changed between iterations by varying the roughness coefficient to match the data utilized in one of the three tiers, and flow files for each tier remained constant at each site. All models were run for the entire duration of the 4 hour hydrograph, and all results were analyze at t = 4hr assuming a developed and wet hydraulic model. The following sections provide an example of calibration using each tiered approach for the Tiered Hydraulic Modeling Framework.

### *Tier 1 Calibration – Upper Black Hollow*

As introduced in the body of the report, a Tier 1 model relies primarily on the data collected from the drone and the DEM for calibration. A common method of calibration of hydraulic models is the use of measured water surface elevations (Bandini et al., 2020; Domeneghetti et al., 2014; Legleiter & Kyriakidis, 2008). For Tier 1 models, I used the drone surveyed point cloud to visually estimate where the water surface extents met the terrain to extract the three dimensional coordinates of the water surface elevation. Tier 1 also relies on strictly remotely sensed data, and requires an estimation of discharge. Discharge was estimated using an approximate cross section, estimated depth, and manning's n estimate from the USGS method (Acrement Jr. & Schneider, 1989). The orthomosaic developed from the SfM data provides accurate visual data required for the USGS Manning's n method. In each of the reaches outlined in this report, an initial Manning's n value of 0.09 was determined from the method, detailed in Figure A8 below, using Tables 1 and 2 from George Acrement Jr. & Verne Schneider, 1989. For all reaches, n<sub>b</sub> was take to be equal to 0.035 for coarse gravel,  $n_1 = 0.015$  for severe channel irregularities,  $n_3 = 0.015$  for frequent alternations,  $n_3 = 0.025$  for appreciable obstructions,  $n_4 = 0$ 

for no vegetation, and m = 1.0 for minor meandering and a sinuosity between 1.0 and 1.2.

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m = (0.035 + 0.015 + 0.015 + 0.025 + 0)1.0 = 0.09$$

				[Modified from Aldridge and Garrett, 1973, table 2]				
				Channel conditions		n value adjustment <sup>1</sup>	Example	
Table 1 Dava unliver a	(Manainata a			Degree of	Smooth Minor	0.000	Compares to the smoothest channel attainable in a given bed material. Compares to carefully dredged channels in good condition but having slightly eroded or scoured side slopes.	
Table T. Base values of Manning's n			irregularity	Moderate	0.000-0.010	and moderately sloughed or eroded side slopes.		
[Modified from Aldridge an	d Garrett, 1973, ta	able 1; -, no da	ita]		Severe	0.011-0.020	Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channels in rock.	
Bed material	Median size of bed material (in millimeters)	Base n value		Variation	Gradual Alternating	0.000 0.001-0.005	Size and shape of channel cross sections change gradually. Large and small cross sections alternate occasionally, or the main flow	
		uniform channel <sup>†</sup>	Smooth channel <sup>2</sup>	in channel cross section $(n_2)$	occasionally Alternating frequently	0.010-0.015	occasionally shifts from side to side owing to changes in cross-sectional shape. Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape.	
Sand channels					Negligible	0.000-0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the	
Sand <sup>3</sup>	. 0.2	0.012	-	Effect of obstruction (n <sub>3</sub> )	Minor 0.	0.005-0.015	Obstructions occupy less than 15 percent of the cross-sectional area, and the	
	.3	.017	-				spacing between obstructions is such that the sphere of influence around on obstruction does not extend to the sphere of influence around anoth obstruction. Smaller adjustments are used for curved smooth-surfaced objec	
	.4	.020						
	.5	.022	-		Appreciable	0.020-0.030	than are used for sharp-edged angular objects. Obstructions occupy from 15 to 50 percent of the cross-sectional area, or the	
	.6	.023	-				space between obstructions is small enough to cause the effects of sever	
	.8	.025	-				obstructions to be additive, thereby blocking an equivalent part of a cross section.	
	1.0	.026	-		Severe	0.040-0.050	Obstructions occupy more than 50 percent of the cross-sectional area, or the snace between obstructions is small enough to cause turbulence across most	
Stable of	channels and flo	od plains					of the cross section.	
Concrete	. –	0.012-0.018	0.011		Smali 0.	0.002-0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vogetation supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedan growing where the average denth of flow is at least three times the height of	
Rock cut		-	.025					
Firm soil	. –	0.025-0.032	.020		222722		the vegetation.	
Coarse sand	. 1–2	0.026-0.035	-	Amount of	Medium	0.010-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tre seedlings growing where the average depth of flow is from two to three time times are also be average to the stemmer and the set of	
Fine gravel	. –	-	.024					
Gravel	. 2-64	0.028-0.035					the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season, growing along the banks,	
Coarse gravel	. –	-	.026				and no significant vegetation is evident along the channel bottoms where the	
Cobble	. 64-256	0.030-0.050	-	vegetation	Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height	
Boulder	. >256	0.040-0.070	-	$(n_4)$			of the vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the	
<sup>1</sup> Benson and Dalrym <sup>2</sup> For indicated materi	ple (1967). ial; Chow (1959).						hydraulic radius exceeds 2 ft; bushy willows about 1 year old intergrown with some weeds along side slopes (all vegetation in full foliage), and no significant vegetation exists along channel bottoms where the hydraulic radius is greater than 2 ft.	
<sup>3</sup> Only for upper regin	ne flow where grain	n roughness is pro	edominant.		Very large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; bushy willow trees about 1 year old intergrown with weeds along side slopes (all vegetation in full foliage), or dense cattails growing along channel bottom; trees intergrown with weeds and brush (all vegetation in full foliage).	
				Degree of meandering <sup>2</sup> (m)	Minor Appreciable Severe	1.00 1.15 1.30	Ratio of the channel length to valley length is 1.0 to 1.2. Ratio of the channel length to valley length is 1.2 to 1.5. Ratio of the channel length to valley length is greater than 1.5.	

#### *Figure A 8: Table's 1 and 2 for USGS Selection of Manning's n (Acrement Jr. & Schneider, 1989)*

Once a Manning's n has been selected, approximating a cross section is the next step. For most mountain streams at baseflow, a rectangular or wedge cross section can be assumed. For confined channels in steeper reaches of mountain watersheds, baseflow conditions are best approximated using a wedge shaped cross section. For this report, a wedge cross sections was found to more accurately predict flows for both reaches at Black Hollow as well as upper Little Beaver Creek, whereas a rectangular cross section better fit wide unconfined valleys like at the lower Little Beaver Creek reach. When solving a flow rate using the Manning equation, presented below, an iterative solving procedure is required. For the equation below, Q is volumetric flowrate, R is the hydraulic radius, S is the reach average slope (obtained from the DEM), h is the flow depth, w is the channel width, and z is the side slope for the wedge. For all confined reaches, a 4:1 side slope was assumed. Both the flow depth and width can be determined from the SfM DEM.

$$Q = \frac{1}{n}R^{2/3}S^{1/2}; where R = \frac{h(w)}{w+2h} for rectangluar, R = \frac{zh^2}{2h\sqrt{1+z^2}} for wedge$$

This report utilized the solver feature of Microsoft Excel to iteratively solve for the flowrate, but other online solvers or software such as Bently FlowMaster could be used to solve for the unknown flowrate. Once a flowrate has been estimated, a test hydraulic model should be run at this flowrate. Since discharge estimates are highly dependent on the assumed flow depth, be sure to verify if the area inundated by the estimated flow matches closely to the area observed to be inundated in the orthomosaic image. If the inundated area varies by more than a factor of two, recalculate the flowrate with a new flow depth until the inundated area begins to align with observed inundated area more closely in the orthomosaic imagery.

To calibrate a Tier 1 hydraulic model, Manning's n is varied to approach the measured water surface elevations. Since Tier 1 relies on the SfM DEM, the point cloud can be used to visually determine the location of the water surface and the corresponding three dimensional cartesian coordinate. Figure A9 below exhibits visual estimation of the water surface using the point cloud. For the reaches described in this report, approximately 12 water surface points were used to calibrate each reach. Figure A8 also shows multiple sets of coordinates that are displayed in

Cloud Compare, where the second set of coordinates (projected coordinate system NAD83 UTM13N) were recorded an input into HEC-RAS as a point layer in RAS Mapper.



Figure A 9: Tier 1 water surface cartesian coordinates from Cloud Compare in local and projected coordinates.

The first iteration for calibrating a Tier 1 model is run at the estimated flow rate and assumed Manning's n estimated from the USGS method shown in Figure A8 above. From here, the points obtained from Cloud Compare are compared with the water surface produced by the model at time = 4 hours. If the modeled water surface elevations tend to be higher than the measured water surface elevations, I reduced the Manning's n roughness coefficient and ran the model again. The model with the lowest root mean square error (RMSE) was selected as the calibrated roughness for the Tier 1 model approach at that site. Figure A10 below shows a plot of modeled and measured water surface elevations, where a perfect roughness coefficient and model will produce a trendline equation of y = 1.0x + 0. It is important to note that all HEC-RAS models were calibrated to the nearest 0.01 for Manning's n, and a more accurate Manning's n could be obtained with more iterations but were not included in this report to save computational expense.



Figure A 10: Modeled vs. Measured water surface elevation plot for calibrated Tier 1 model at upper Black Hollow, Q = 0.15 cms, n = 0.07.

## *Tier 2 Calibration – Upper Black Hollow*

Tier 2 modeling approach supplements the hydraulic model and SfM DEM information with additional field data. Specifically, Tier 2 provides the addition of a measured discharge as well as salt tracer data for measuring reach average velocity. The discharge measurements and salt tracer techniques were described in detailed in the Field Data Collection section of the appendix example. This modeling approach requires that the discharge data and reach averaged velocity measurements be collected on the same day in order to create an accurately calibrated Tier 2 hydraulic model. According to Calkins & Dunne, 1970, reach averaged velocities are best predicted when comparing the centroids of attenuation curves. HOBO water level loggers record the variation in salt concentration with time, so comparing the time dimension centroids of the upstream and downstream loggers and dividing the average reach length by the time between centroids provides an accurate measurement of reach averaged velocity.

To determine the centroid under a curve of irregular shape, the general form of the equation to calculate the first moment of area can be applied. Due to the shape of the curve, a trapezoidal approximation of the integral can be used to calculate the area under the curve as follows, where  $\bar{t}$  is the centroid for the time axis,  $\int_A \tilde{t} dA$  is the first moment of area for time, and  $\int_A dA$  is the area under the attenuation curve. The attenuation curve is a function of both concentration and time (f(t,C)), where  $t_i$  represents the i-th index of the time variable and  $C_i$  the i-th index of concentration. The centroid will have the coordinate pair ( $\bar{t}, \bar{C}$ )

$$\bar{t} = \frac{\int_A \tilde{t} dA}{\int_A dA} \approx \frac{\sum dA_i(\tilde{t}_i + t_i)}{\sum dA_i}$$

where 
$$\tilde{t}_i = \frac{(t_{i+1} - t_i)}{3} \left( \frac{C_{i+1} + 2C_i}{C_{i+1} + C_i} \right)$$
 and  $dA_i = \frac{1}{2} (C_i + C_{i+1})(t_{i+1} - t_i)$ 

Processed tracer calculations are shown below in Figure A11 for the upper Black Hollow reach. Note that the y-axis coordinate of the centroid for concentration ( $\overline{C}$ ) was visually estimated since only the time coordinate of the curve was needed to calculate the reach averaged velocity. The time difference between centroids was found to be 96 seconds, which when the reach length of 72 meters is divided by 96 seconds yields a reach averaged velocity of 0.75 m/s for upper Black Hollow. Note that the user must determine the time-axis integration limits based on the curves. I found that best results were determined when a background concentration was determined from an additional concentration meter positioned upstream. This additional sensor provides insight for the specific time that the attenuation curve begins and when it returns to base level.



#### *Figure A 11: Salt tracer attenuation curve for upper Black Hollow Reach*, $\Delta t = 96s$ *between centroids*

Once the reach averaged velocity has been determined, the Tier 2 model can be run. For this model, use the flow file that corresponds to the measured discharge using the same model geometry files with varied Manning's n values as the Tier 1 model. Output the model results for velocity at time = 4 hours and export the velocity raster. I recommend analyzing the statistics in ArcGIS Pro and clipping the results to the limits of the concentration sensors for best results. When the mean velocity of the model output raster approaches the measured reach average velocity from the tracer test, the model has been calibrated. Again, the results presented in this report go to the nearest 0.01 value for Manning's n, and a more accurate roughness could be calibrated with more iterations. For upper Black Hollow, the average measured velocity from the salt tracers of 0.75 m/s was closely approximated with a Manning's n value of 0.06 where the

model velocity resulted in a mean of 0.72 m/s. The model velocity distribution from ArcGIS Pro is presented below in Figure A12.



Figure A 12: ArcGIS Pro modeled velocity raster distribution for Tier 2: Upper Black Hollow, n = 0.06Tier 3 Calibration – Upper Black Hollow

The final and most data intensive calibration method of the Tiered Hydraulic Modeling Framework is Tier 3. Tier 3 calibration uses the same method of salt tracer attenuation for reach averaged velocity, but with the addition of GPS RTK bathymetry. Survey data collection methodology was detailed in the Field Data Collection section of this appendix example. Survey cross section data was collected at a 5 meter spacing, surveying major grade breaks to accurately represent the features of the cross section. Survey data was then processed using AutoCAD Civil3D, as is common among professional land surveyors. The TIN surface was generated using break lines of the channel water surface elevations on the right and left banks as well as along the channel thalweg. This method helps the TIN generation to more accurately create contour lines that would be observed in natural channels and drainageways. Merging the SfM DEM and developed bathymetry surface is a critical step for creating a Tier 3 model. I merged the surfaces using functions in ArcGIS Pro to snap to one another with raster calculations, adjusting the mean elevation difference to equal zero, and the Mosaic to New Raster to ultimately combine the surfaces into a single DEM. I applied the raster calculator by subtracting the unadjusted bathymetric survey from the SfM DEM. If the result is positive, the unadjusted bathymetric survey should be lowered by the mean difference from the raster calculation result, and raised if the result is negative. Figure A13 below shows the unadjusted raster calculation result on top of the SfM DEM for upper Black Hollow. The bright white represents fill of around 1.5 meters, and the black represents the fill of 1.2 meters near the steep channel banks following the debris flow. The bathymetric surface was adjusted in the vertical direction such that the cut-fill distribution mean approached 0.



*Figure A 13: ArcGIS* Pro raster calculator result from subtracting bathymetric surface from SfM DEM superimposed on SfM DEM.

Once the surfaces are merged, the same process that was described above for Tier 2 of the Tiered Hydraulic Modeling Framework is used to calibrate the model using tracer tests and reach averaged velocity. In general, the reach averaged velocity approach is faster than Tier 1 modeling since models typically converge on a roughness more quickly. An important note is that the Tier 3 output will likely look very different than the Tier 2 model in terms of inundated flow area affected. This is due to the interpolation effects of the TIN surface generated from the bathymetric survey. Even when using an extremely fine cross section spacing of 5 meters, the bathymetric survey struggles to capture the minor details that a SfM DEM can capture with 2-6 cm accuracy with far less effort. This topic is discussed in the *Discussion* section of the report above further.