Modeling Non-Newtonian Debris Flows in HEC-RAS: Two Diverse Applications

Kellie Jemes, Hydraulic Engineer, U.S. Army Corps of Engineers (USACE) – Sacramento District, Sacramento, CA, Kellie.A.Jemes@usace.army.mil
Stanford Gibson, Sr. Research Civil Engineer, USACE – Hydrologic Engineering Center, Davis, CA, Stanford.Gibson@usace.army.mil
Jay Pak, Sr. Research Civil Engineer, USACE – Hydrologic Engineering Center, Davis, CA, Jay.H.Pak@usace.army.mil

Introduction

Debris flows are a dangerous and destructive geologic process that can transport large volumes of sediment, boulders, trees, and other debris. Debris flow hazards have long been recognized as an issue in mountainous regions and areas with developments on alluvial fans. Awareness for post-wildfire impacts to watersheds and resulting debris flows has been increasing. The Hydrologic Engineering Center River Analysis System (HEC-RAS) software version 6.0 included the ability to model non-Newtonian debris flows, which is more appropriate for high-concentration events. This paper highlights two diverse applications of modeling non-Newtonian debris flow in HEC-RAS: 1) a community planning study in Ouray, Colorado and 2) an emergency post-wildfire inundation mapping effort in Mapleton, Utah.

Background

As the concentration of debris within water increases, the fluid begins to behave under the assumptions of non-Newtonian physics. Consequently, the approach of bulking clear water flows to simulate debris flows has limitations in its ability to properly capture the inundation depths and runout. Therefore, different rheological and geotechnical models have been incorporated into HEC-RAS to represent the internal loss processes associated with debris flows more appropriately (USACE 2020).

The concentration of debris in water can be used to classify flow types and determine which debris flow methods to use in HEC-RAS. The general ranges of debris concentrations for each flow classification are listed in Table 1. For some methods, volumetric concentration is an input parameter. Volumetric concentration can be estimated through differencing pre- and post-event terrain data (i.e., LiDAR, surveyed cross sections), maintenance records of debris removal, regression equations, and debris yield methods in the HEC Hydrologic Modeling System (HEC-HMS) software (USACE 2020).

Table 1. Flow classifications and associated debris concentrations (WEST Consultants, Inc. 2011)

Flow Classification	Debris Concentration (% by Volume)
Normal streamflow	0 - 20
Hyperconcentrated flow	20 - 40
Debris flow/mud flow	40 - 55
Landslide	55 +

Non-Newtonian fluids require stress to deform (i.e., have a non-zero intercept on the stress-strain relationship), unlike water that deforms under zero stress. The amount of stress that can be applied before the fluid deforms defines the yield stress parameter in the non-Newtonian HEC-RAS model. Further, non-Newtonian fluids can have either a linear or non-linear stress-strain relationship, while Newtonian fluids are defined by having a linear stress-strain relationship. The fluid viscosity dictates the slope of the stress-strain line. At very high concentrations, fluids can be dominated by internal friction, and the yield stress is best represented by a geotechnical model (USACE 2020).

Through practice, it has been found that higher Manning's n values than would typically be used in a hydraulic model can be applied to achieve reasonable (and stable) results in a debris flow model. The high Manning's n values account for the steepness of the watershed, where debris flows typically occur (Yochum 2010). Increasing the Manning's n values can also be used to account for additional processes or losses (i.e., large floating debris, log jams, structures, blockages) that are not captured in the rheological or geotechnical model. Ranges of values found in literature for debris flow modeling input parameters are summarized in Table 2.

Table 2. Ranges of values for debris flow modeling parameters

Parameter	Range of Values	References
Yield stress (Pa)	5 - 4,600	Floyd et al. 2020; Phillips 1988; Tiranti and Deangeli 2015
Dynamic Viscosity (Pa·s)	0.003 - 320	Floyd et al. 2020; Phillips 1988
Manning's n	0.021 - 0.96	Yochum et al. 2014

Ouray, Colorado

Ouray, Colorado is situated in the steep and highly erosive San Juan sub-range of the Rocky Mountains. Debris flows have been recorded since the 1870s when the area was developed for mining. Several of the drainages around Ouray, including Corbett Creek, experience frequent debris flows which pose a threat to residential areas and infrastructure (roads, utilities, etc.). A road crossing (County Road 17) that passes over Corbett Creek and serves as the secondary evacuation route for the City of Ouray has been damaged or destroyed by debris flows twelve times in the last fifteen years. The County of Ouray required a more sustainable solution, and requested assistance from the USACE Sacramento District.

A two-dimensional (2D) non-Newtonian debris flow model was developed in HEC-RAS to evaluate the existing conditions of the Corbett Creek road crossing, propose and test alternatives, and ultimately recommend a conceptual design to be engineered and constructed. The alternatives that were evaluated included a single box culvert, multiple box culverts, lateral embankments to contain flow to the channel, and two bridge configurations. During the development of the existing conditions model, debris flow parameters were applied and calibrated (summarized in Table 3) to match the model results to field observations of tree scour marks (Figure 1) and sediment deposition within and outside the channel. The calibration results for Corbett Creek are shown in Figure 2.

Figure 1. Observed scour marks on trees from past debris flows

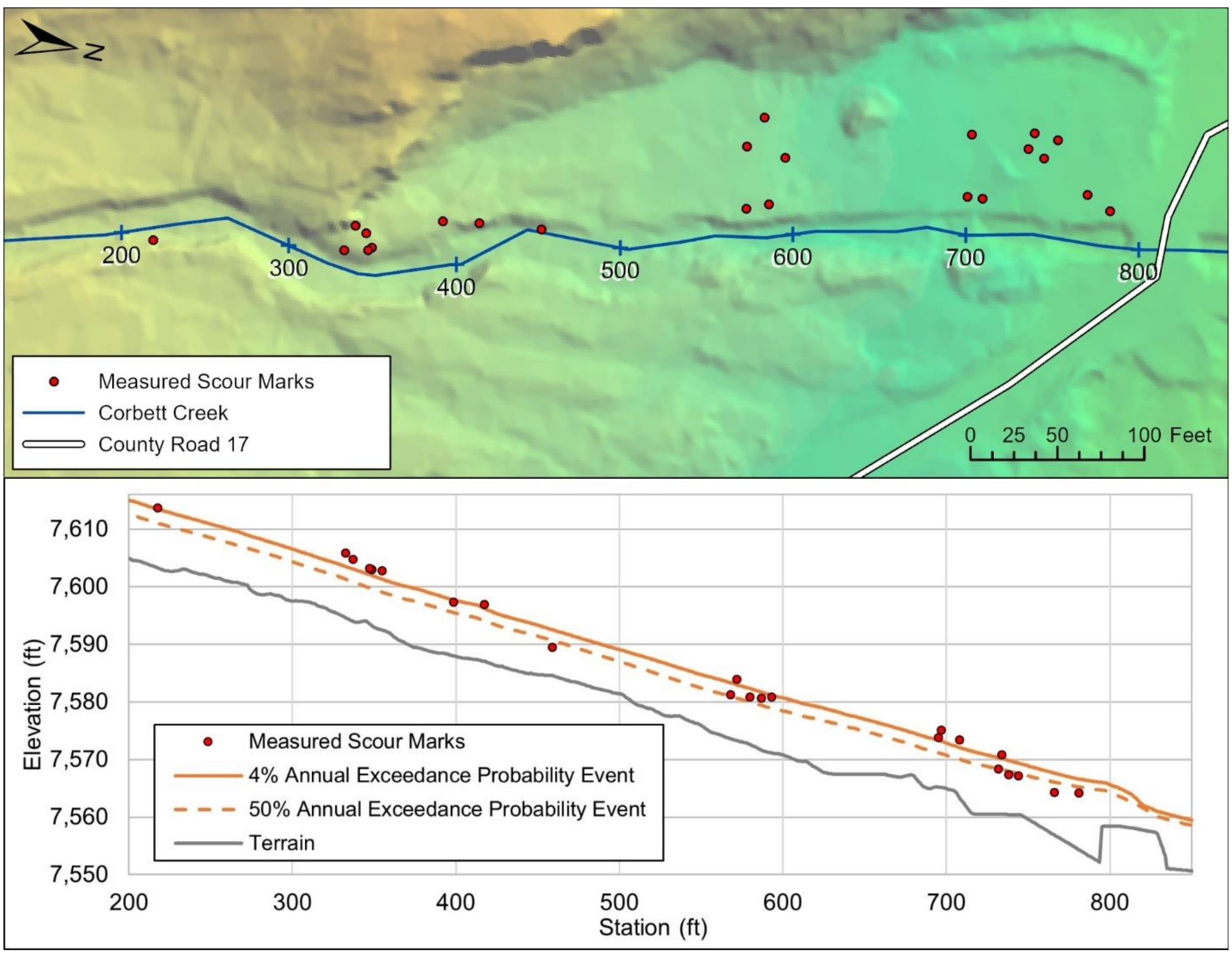

Figure 2. Debris flow calibration results for Corbett Creek

Modeling with non-Newtonian parameters resulted in floodplains that matched the depths and extents of previous debris flow events better than the clear water modeling results (Figure 3). This gave confidence that the model could be used to simulate debris flow events to compare alternatives. The proposed alternatives were modeled in HEC-RAS using the culvert and lateral structure features, and the results were evaluated to determine if the structures could pass different magnitudes of debris flow events. The simulation results were used to optimize the features and appropriately size a dual box culvert for the recommended conceptual design that would be able to pass debris flows, unlike several of the previously installed culverts (Figure 4). This approach provided benefit over modeling with Newtonian parameters, as it produced results that were representative of the conditions and processes that exist within the watershed, which was necessary to propose an effective solution for the community.

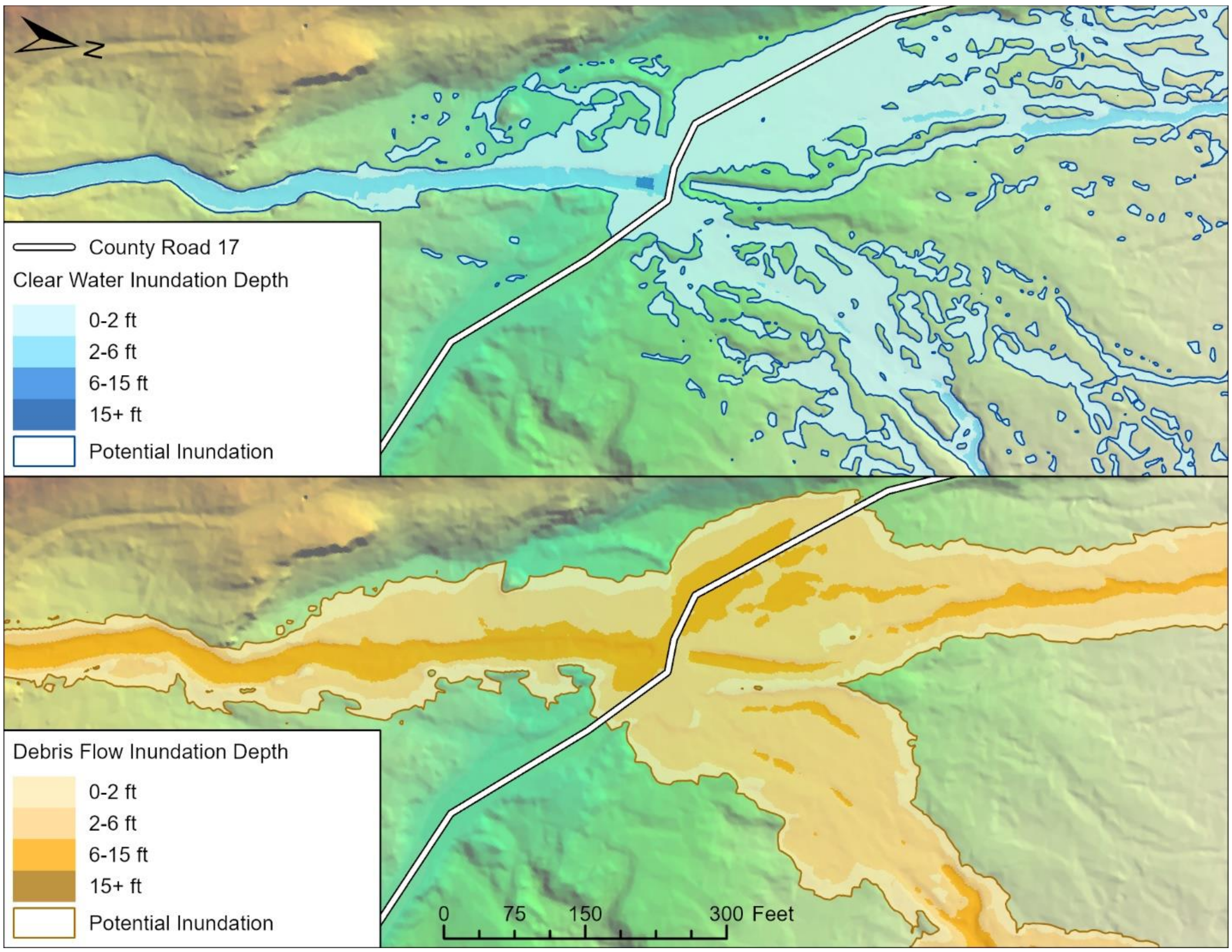

Figure 3. Comparison of clear water and debris flow inundation maps for the 4% annual exceedance probability event

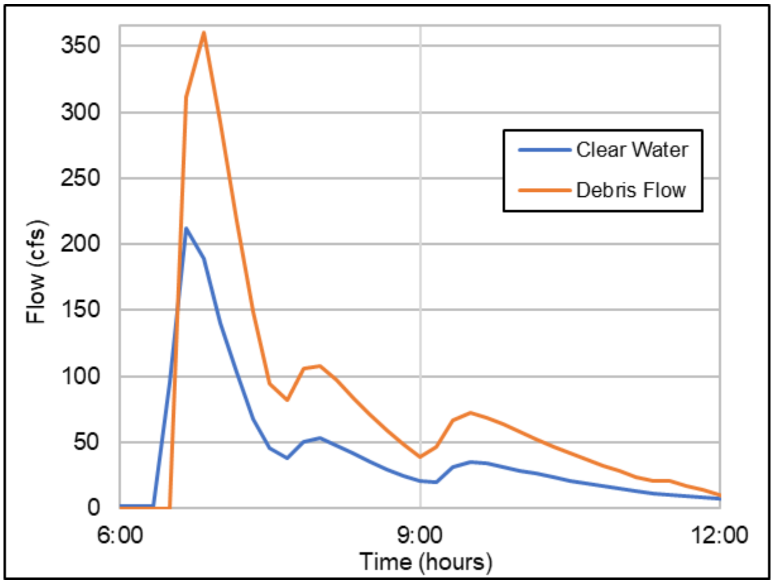

Figure 4. Comparison of clear water and debris flow at County Road 17 for the 4% annual exceedance probability event

Mapleton, Utah

Non-Newtonian modeling in HEC-RAS was also used in an emergency application to rapidly develop inundation maps for the City of Mapleton, Utah following a wildfire. In October 2020, the Ether Hollow fire burned 849 acres in a steep drainage upstream of a residential area which resulted in a high likelihood of a debris flow event occurring, as predicted by the U.S. Geologic Survey (USGS) (2020). Assistance was requested from the USACE Sacramento District for technical support, and a HEC-RAS, 2D, non-Newtonian debris flow model and inundation maps were developed in two weeks (Figure 5). The placement of flood barriers (i.e., sandbags, supersacks, jersey barriers) was also briefly evaluated in the debris flow model. Debris yield estimates from the USGS and a simplified hydrograph produced with the Wildcat5 software from the U.S. Forest Service (USFS) were used to inform model inputs. Given the limited timeframe and data available for the project, the model was not calibrated. Instead, the sensitivity of parameters was tested, and conservative assumptions were made to present a worst-case, yet realistic scenario.

The inundation maps were used by emergency personnel to determine which homes to put on evacuation notice reducing the initial evacuation area and thus reducing response and evacuation times. This evacuation plan was successfully implemented during the summer of 2021 when high intensity rainfall resulted in a minor debris flow and evacuations kept community members out of harm's way. The 2021 event generally matched the inundation path as predicted by the debris flow modeling.

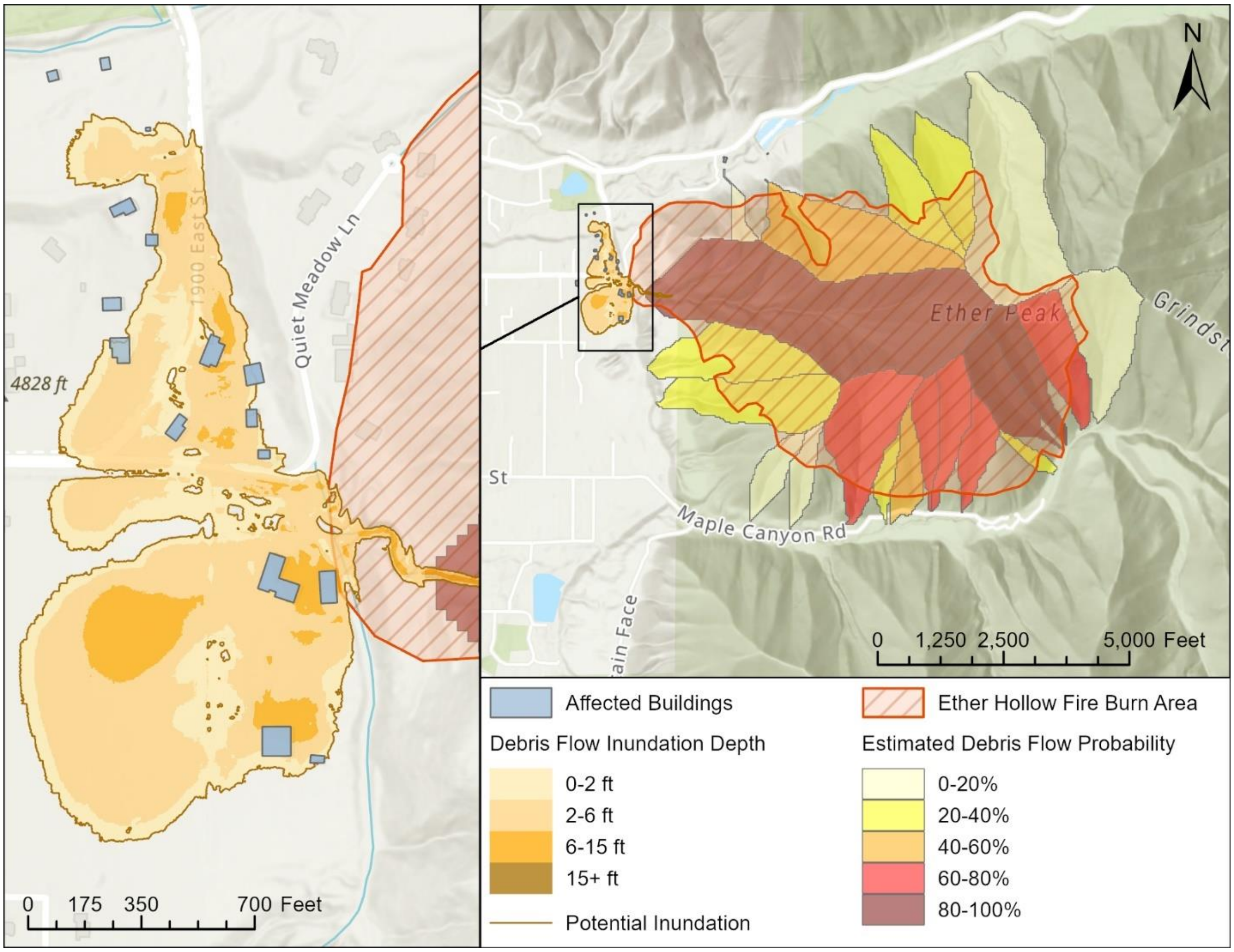

Figure 5. Ether Hollow fire emergency assessment debris flow probability (USGS 2020) and debris flow inundation maps

Summary

The different parameters used for the Ouray, Colorado and Mapleton, Utah non-Newtonian debris flow models are compared in Table 3.

Table 3. Comparison of parameters for each project

Parameter	Ouray, Colorado	Mapleton, Utah
Watershed condition	Highly erosive, frequent debris flows, unburned	Stable, recently burned
Watershed size (sq. miles)	2.9	0.4
Debris flow method	Turbulent-dispersive (quadratic)	Turbulent-dispersive (quadratic)
Yield stress (Pa)	3,000	700 - 2,500
Dynamic Viscosity (Pa·s)	4.2 – 5.9	11
Volumetric concentration (%)	48 - 59	80
Representative grain size (mm)	20	2
Manning's n	0.25	0.04 - 0.12
Calibration	Historic observations, tree scour marks, debris deposition	Sensitivity testing
Project timeframe	2 years	2 weeks
Deliverables	Inundation maps, alternatives analysis, conceptual design	Emergency inundation maps, evaluation of flood barrier placement

Conclusion

In conclusion, modeling non-Newtonian debris flows in HEC-RAS has diverse applications and is a useful tool for evaluating high concentration flows. The application of this tool can be scaled based on project timeframe, desired level of detail, and amount of tolerable error in the results. Both the Ouray, Colorado and Mapleton, Utah projects prove the benefit of this modeling software for providing appropriate results for studies ranging from conceptual planning to emergency response efforts.

References

Floyd, I.E., Sanchez, A., Gibson, S., Savant, G. 2020. "A Modular, Non-Newtonian, Model, Library Framework (DebrisLib) for Post-Wildfire Flood Risk Management," Hydrology and Earth System Sciences, Preprint.

Phillips, C.J. 1988. Rheological Investigations of Debris Flow Materials. University of Canterbury Doctor of Philosophy Thesis.

Tiranti, D. and Deangeli, D. 2015. "Modeling of debris flow depositional patterns according to the catchment and sediment source area characteristics," Frontiers in Earth Science, 3(8):1-14.

USACE. 2020. HEC-RAS Mud and Debris Flow Manual. U.S. Army Corps of Engineers, Hydrologic Engineering Center. Davis, CA.

USGS. 2020. Ether Hollow Preliminary Hazard Assessment. Landslide Hazards Program, U.S. Geologic Survey.

WEST Consultants, Inc. 2011. Sediment / Debris Bulking Factors and Post-Fire Hydrology for Ventura County, Draft Report. Prepared for Ventura County Watershed Protection District, prepared by WEST Consultants, Inc., San Diego, California.

Yochum, S. and Bledsoe, B. 2010. "Flow Resistance Estimation in High-Gradient Streams," Proc. 4th Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV.
Yochum, S., Comiti, F., Wohl, E., David, G.C.L, Mao, L. 2014. "Photographic Guidance for Selecting Flow Resistance Coefficients in High-Gradient Channels," Gen. Tech. Rep. RMRS-GTR-323, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 91 p., Fort Collins, CO.