ANALYSIS OF EXTREME FLOOD SIGNATURE: CAN 2-D HYDRAULIC MODELING MATCH OBSERVATIONS?

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INTRODUCTION

Paleoflood hydrology is critical to the understanding of flood magnitude-frequency responses because it extends the timescale of the gaged record to include extreme floods that occurred prior to human observation. Paleoflood studies usually produce flood chronologies that can be used to improve flood-frequency analysis and flood hazard evaluations. Paleoflood studies rely on assumptions of shear stress values necessary to erode stream terraces with stable soils and the predictive capability of the hydraulic model to generate accurate peak discharge estimates to produce a paleoflood signature, deposition on or erosion of a stream terrace surface. While a range of values is reported that includes uncertainty in the peak discharge estimates, only limited comparisons between physical observations of large historical floods and the model simulations of the same events have been performed. These comparisons typically have involved historical floods that are decades old and therefore many of the flood indicators have been removed or obscured from field observation. A post-flood investigation of a recent extreme flood can provide a more robust estimate of the uncertainty in model predictions of surface erosion and deposition and can also provide greater overall understanding of flow dynamics during extreme floods and the shear stress values necessary to leave a signature, erosion or deposition of surface sediment.

This study poses the following questions: (1) how well does the hydraulic model simulate a recent, extreme flood; (2) do field observations and model predictions indicate surface erosion in the same areas during an extreme event; (3) do field observations and model predictions infer sediment deposition in the same areas during an extreme event; and (3) what are the limitations of the model and paleoflood studies in general to predict the modification of stream terraces or areas of sediment deposition during extreme floods?

To answer these questions this study will: (1) survey high water marks and make field observations and interpretations of erosion and deposition during a recent large flood; (2) construct 2D hydraulic models to simulate the extreme flood; and (3) compare model predictions with the surveyed flood stage and real world observations of erosion, deposition and other modifications to the stream channel.

PALEOFLOOD HYDROLOGY

Paleoflood hydrology has been used for the past century in a wide variety of settings throughout the world (Costa, 1986; Patton, 1987; Baker et al., 1988). Early studies by Mansfield (1938) on the Ohio River and Jahns (1947) on the Connecticut River recognized that historical floods on those rivers overtopped stream terraces that had not been inundated for thousands of years. The stratigraphic record present along streams in the form of terrace and flood plain deposits can be direct indicators of the magnitude of large floods on a river and may be 10 to 100 times longer than conventional stream gaging records of large floods (e.g., Patton, 1987; Baker, 1989; Jarrett, 1991).

One widely-used technique in paleoflood studies uses the fine-grained sedimentological record that accumulates in backwater areas (slackwater) to construct a detailed history of past floods (e.g., Patton et al., 1979; Kochel and Baker, 1988). This technique can be extremely useful in characterizing the frequency of large floods, but can fall victim to the inherent assumption that a sequence of slackwater sediments represents a complete and continuous record of floods at a particular site. In addition, the physical setting of a backwater site may not be ideally suited for reconstructing or accurately estimating the peak discharge for the flood associated with a particular sequence of slackwater deposits in one-dimensional hydraulic models. Two-dimensional hydraulic modeling (e.g., Denlinger et al., 2002) can aid in estimating peak discharges in these complex geometries.

Another methodology uses the age of a terrace surface that lacks clear evidence of recent inundation, erosion and deposition, or alternatively displays evidence for long-term stability, to establish an upper limit to flooding. This non-inundation approach can be very useful in flood hazard assessment because geomorphic and stratigraphic information derived from the terrace surface can provide an upper limit or bound on the age and magnitude of extreme floods (Levish, 2002). Rather than constructing a detailed record of past floods, the non-inundation approach focuses on identifying a non-exceedance bound. Establishing a non-exceedance bound is accomplished by identifying terrace surfaces that serve as limits for the paleostage of large floods and estimating ages for those terraces (Figure 4). These bounds do not represent actual floods, but instead limits the peak flood stage over some measured time interval. Simply stated, a non-exceedance bound is a maximum stage that has not been exceeded in the time period since the terrace surface stabilized. The maximum stage can be used to estimate peak discharge given some knowledge of the channel characteristics.

SETTING

The study reach is located along Cottonwood Creek in El Paso County near Colorado Springs, Colorado approximately 60 miles south of Denver (Figure 1). The Cottonwood creek watershed is about 18.9 mi^2, heading in the southern portion of the Black Forest region and draining to the southwest into Fountain Creek. A flood of record during June 2012 on Cottonwood Creek provided an ideal dataset to study recent flood signatures and physical/hydraulic properties associated with a large-magnitude flood in a small watershed. The study reach is located within the city of Colorado Springs open space and begins 150 feet downstream of the East Woodman Bridge, extending downstream 5,800 feet to just upstream of Rangewood Drive Bridge. Cottonwood Creek is incised into Cretaceous bedrock and about 10-20 ft. below housing developments. Limited grade control features and other human structures within the reach provide a mostly natural setting in which to study the geomorphic characteristics of the flood. Drainage area associated with the study reach is approximately 10.2 mi^2 as documented at the USGS stream gage no. 07103980.

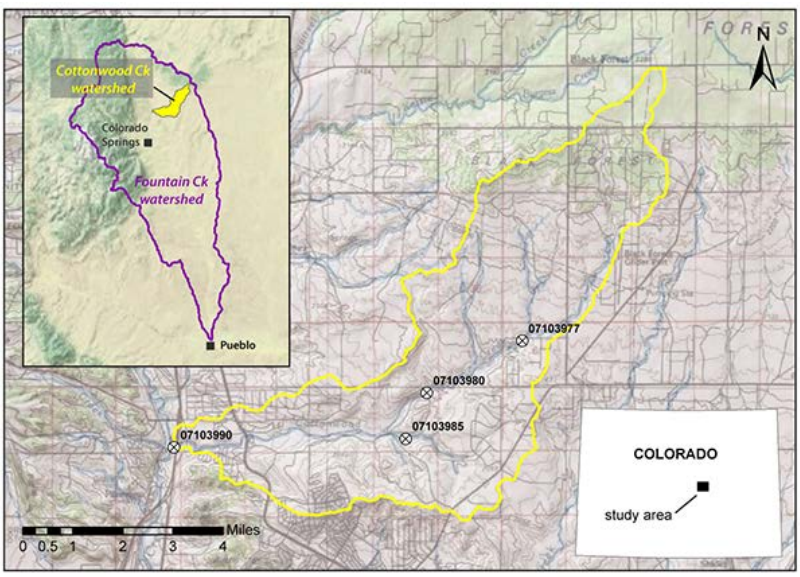


Figure 1 Cottonwood Creek study reach located downstream of East Woodman Road near Colorado Springs, CO. USGS stream flow gage stations are denoted on the map with cross hatched circles.

THE JUNE 6, 2012 FLOOD, COTTONWOOD CREEK, COLORADO SPRINGS, CO

Peak flows on Cottonwood Creek typically occur during the summer months of June through September and are commonly caused by convective storm systems which deliver moisture in the form of intense thunderstorms in the late afternoon and early evening hours. The flood of June 6, 2012 peaked between 8:15 and 8:30 pm and had a peak discharge of 1,610 ft^3/s at USGS stream gage no. 07103980 (Cottonwood Creek at Woodmen Road near Colorado Springs, CO), which was the peak of record for the 20-year history of the stream gage (Figure 2). The flood lasted approximately 2 hours with a slightly more gradual rising limb and a steep falling limb. Within about 81/2 hours, flows had returned to less than 10 ft^3/s at the stream gage. During August 2013 a larger-magnitude peak discharge of 3,500 ft^3/s was recorded after the field survey of high water marks.

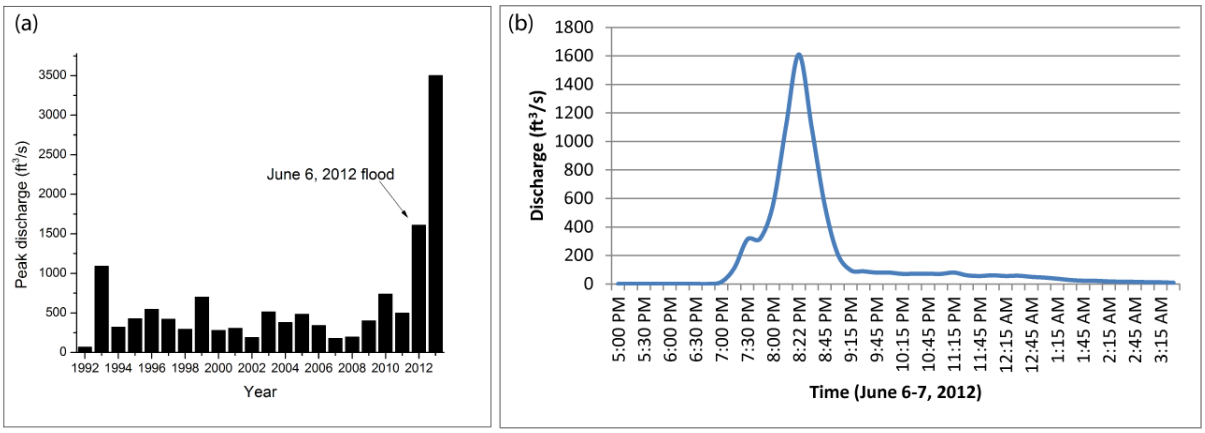


Figure 2 Hydrologic data, Cottonwood Creek at Woodmen Road near Colorado Springs, CO (USGS gage no. 07103980). (a) Peak discharge data; (b) runoff hydrograph, 15-minute discharge data, June 6-7, 2012.

MODEL SELECTION

Reclamation Technical Service Center (TSC) utilizes hydraulic modeling as part of paleoflood studies to estimate peak discharge magnitude associated with the stage of slackwater deposits and stream terraces. The majority of detailed paleoflood studies have used Sedimentation and River Hydraulics 2D (SRH-2D) (Lai, 2008) for 2D hydraulic modeling. This study used SRH-2D to test the current methodology that is incorporated into the paleoflood studies. SRH-2D can analyze flow complexities of the interaction between the main channel, banks, and floodplain that are best represented with an unstructured arbitrarily-shaped mesh.

SRH-2D was used to model flow under steady and unsteady-state conditions. Steady state analysis was used to determine whether modeled depth averaged maximum water surface elevations matched field observations and to compare the modeled depth average maximum shear stress values with erosional and depositional areas. Unsteady-state flow modeling was performed to examine the variation in shear stress values at different points in the flood hydrograph for selected observation areas. To define the SRH2D downstream boundary condition, an Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) (U.S. Army Corps of Engineers Hydrologic Engineering Center, 2010) model was constructed for the study reach. The HEC-RAS model was extended 650 feet downstream of the study reach to ensure the boundary condition would not impact SRH2D model results.

DATA COLLECTION

This section describes the field survey, topographic, and geomorphic data that were collected for this study. The collection methods, locations, and data uncertainty are described.

Survey Data and Terrain Development

The terrain developed for the study reach used a combination of in-channel surveyed points and contour data. Site specific survey points were collected by the authors on June 5, 2013 to identify the stage and lateral extent of the June 6, 2006 flood and to further define the channel topography. The June 6, 2012 flood was the event of record and it was assumed that the highest high water marks were a result of this event. To define the flood stage and lateral extent, we surveyed trim lines, flotsam and tops of sandy flood deposits. An effort was made to find the highest flood indicators to identify the peak stage of the flood. In order to define channel topography, survey points were collected to capture the channel thalweg, sand bars and banks. All survey points were collected using Real Time Kinematic (RTK) Global Positioning System (GPS) equipment. An NGS Online Positioning User Service (OPUS) solution was obtained for control at the base station. Positional accuracies for RTK and this survey are +/- 0.05 feet horizontally and +/- 0.10 feet vertically. The survey used NAD 1983 (2011) Epoch 2010.00, State plane coordinates,

Colorado Central zone in U.S. Survey Feet (USFT), based on station Marshall Field Cors Arp with coordinates 1298154.39 N and 3448788.1 W.

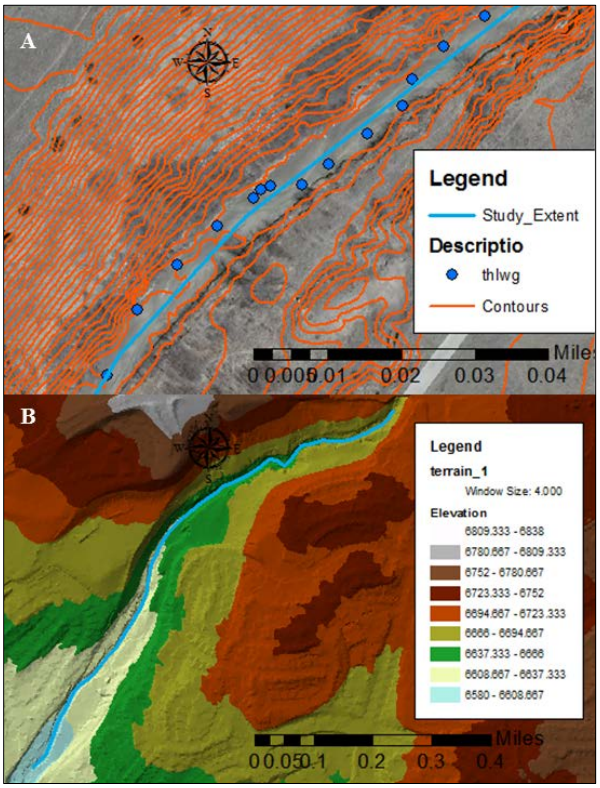


Figure 3 A) Example of survey data and contour lines along Cottonwood Creek, B) Terrain developed for the study reach.

The City of Colorado Springs contracted with Sanborn to provide a digital orthoimagery dataset. The imagery was acquired over approximately 240 square miles of the City of Colorado Springs, Colorado. Sanborn acquired new 0.5-foot pixel imagery of the Colorado Springs area in the spring of 2010 during leaf-off conditions. The acquisition was performed using Sanborn's UltraCam-D digital camera system and aircraft equipped with AGPS/IMU. Digital orthoimagery was produced using existing DEM, updated as needed to support production of the orthoimagery. The City of Colorado Springs used the imagery to develop 2-foot contour lines for the Cottonwood Creek basin.

The digital imagery of the study reach was collected while water was in the stream; therefore, the channel survey points collected in 2013 were used to define the channel bed and then combined with the 2-foot contours to develop a t errain for the study reach (Figure 3). GPS surveyed points were taken along the stream bank and compared to Sanborn contour data. The points were within the ±1 foot tolerance and provide confidence in the topographic data.

Geomorphology

Surficial geologic mapping involves the delineation of surficial geologic features on the landscape. When mapping along river corridors, these features typically include stream terraces, bedrock outcrops, axial and tributary stream channels, eolian landforms, and other deposits along valley margins, such as landslide deposits and glacial deposits. Surficial map units are landforms that can be grouped together based on similar physical or geomorphic characteristics such as position in the landscape, surface morphology, sedimentology, soil development and process of formation. Deposits in this study are mapped along the Cottonwood Creek stream corridor and therefore are typically composed of fluvially-derived sediments and are landforms that were created and modified by fluvial processes. The extent and character of these features provide information concerning controls on lateral and vertical channel movement over longer time frames than the historical period and many times are important factors in explaining variation in channel morphology along the length of the study reach. Surficial geologic units defined in this study are described on the basis of surface morphology, character of deposits, vertical and lateral relation to other mapped units, relative or absolute age, and geographic location. Stratigraphic descriptions were performed on a limited number of exposures along the channel banks using sedimentological terminology from Boggs (1995) and soil nomenclature from Birkeland (1999) in order to understand the depositional processes associated with the stream deposits. Five Sediment samples were collected from the surface of alluvial deposits near model observation points along Cottonwood Creek and submitted for particle size analysis and bulk density determinations at Colorado State University Soil, Water and Plant Testing Laboratory. Bulk density samples were collected using a soil core sampler.

Flood observations were made during field work in July and August 2013. Types of features that were noted included depositional features such as sand bars, flotsam and debris lines. Scour features included trim lines, scoured bedrock and vertical bank exposures. When combined the observations reveal the stage of flood waters and areas where the channel was scoured both vertically and laterally during the flood.

GEOMORPHIC OBSERVATIONS AND MAPPING

In order to compare the geomorphic effects of the June 6, 2012 flood with model predictions, high water marks and other features created during the flood were documented during field observations. T he main goal of the geomorphic mapping of flood features was to determine areas of deposition and erosion along the channel during the 2012 flood. Areas that were above the level of low bars were mapped based on whether they appeared to be primarily depositional or erosional areas. Depositional areas consisted of abundant flotsam and sand deposits which were deposited on younger terraces or in areas of recirculation, such as upstream of sharp meander bends, or in small tributary or sideslope gullies along the margins of the channel (Figure 4). Erosional areas consisted of scoured bedrock benches, and areas with distinct trim lines or vertical bank exposures of fluvial sediment or bedrock. Low bars were not mapped as areas of deposition because these areas are also modified by lower stage flows than the 2012 flood.

A surficial geologic map was also produced to show the extent of the channel, channel bars, terraces (labeled younger and older on a relative scale), bedrock benches and bedrock outcrops in the channel. Mapped flood features generally correspond to specific landforms that were mapped in the reach; for example, many depositional areas were located on younger stream terraces and erosional areas were located on bedrock benches. Mixed depositional and erosional areas occur within the channel itself but cannot be related to the 2012 flood because they have been modified by more recent, lower flows.

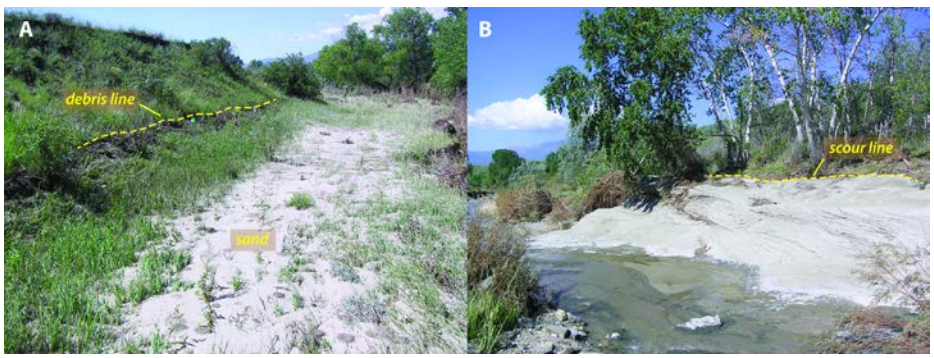


Figure 4 Example of erosional and depositional areas; A. depositional area showing sand and debris line from recent flood; B. erosional area showing scour line on bedrock outcrop.

HYDRAULIC MODELING

Boundary Condition

Hydraulic models require an exit boundary condition to converge on solutions for various hydraulic parameters. SRH-2D requires either a r ating curve or a known downstream water surface elevation to satisfy a b oundary condition. There was no flow or stage data at the downstream end of the model. As such, a HEC-RAS model was developed for the Cottonwood Creek Study using HEC-geoRAS (U.S. Army Corps of Engineers, 2010) to develop the geometry. The HEC-RAS model was extended far enough beyond the downstream boundary of the 2D model that the computed water surface elevation in the HEC-RAS model at the station of the outlet of the 2D model was not influenced by the boundary.

The flow data was obtained from USGS gaging station located at cottonwood creek for the June 6, 2012 flooding event. A manning's n of 0.03 and 0.06 was selected for the main channel and the left and right bank, respectively for the channel roughness (Chow, 1959). The HEC-RAS boundary condition used for both steady-state and unsteady-state was the normal depth. The normal depth can be determined by the slope of the channel and Cottonwood Creek has a slope of 0.025 ft/ft that was derived from the contour data. This HEC-RAS boundary condition will be referred to the regular boundary condition. We performed a boundary conditions sensitivity analysis and altered the slope to 0.03 ft/ft and 0.02 ft/ft.

Mesh Generation

Table 1 Manning's n values selected for study reach areas.

Material Type	High n	Mid n	Low n
Channel	0.035	0.03	0.025
Overbank grass	0.055	0.05	0.045
Overbank shrub	0.08	0.07	0.075
Overbank tree	0.1	0.095	0.09

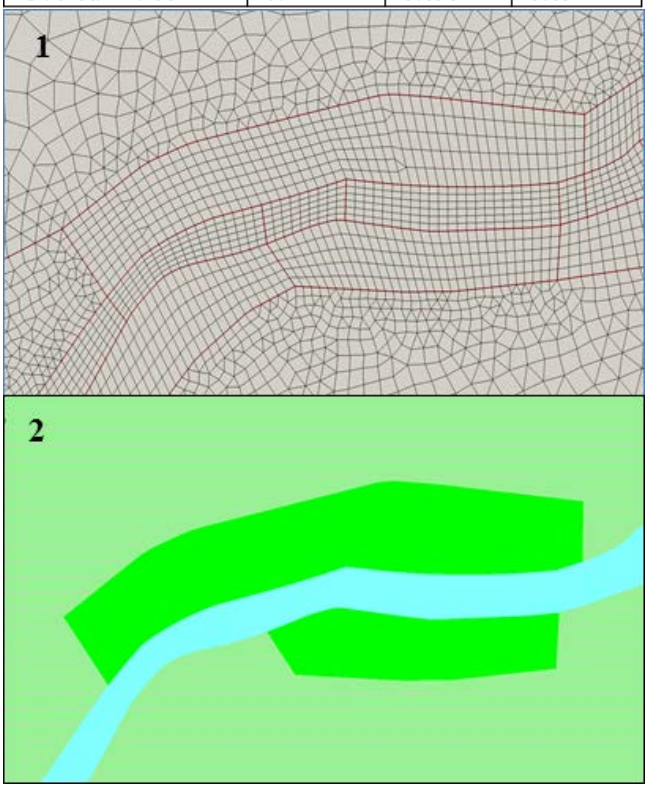


Figure 5 (1) Quadrilateral elements in the main channel and triangular elements on the over bank areas. (2) Material properties for the main channel, the dense vegetated area, and grassed and small shrub vegetated area.

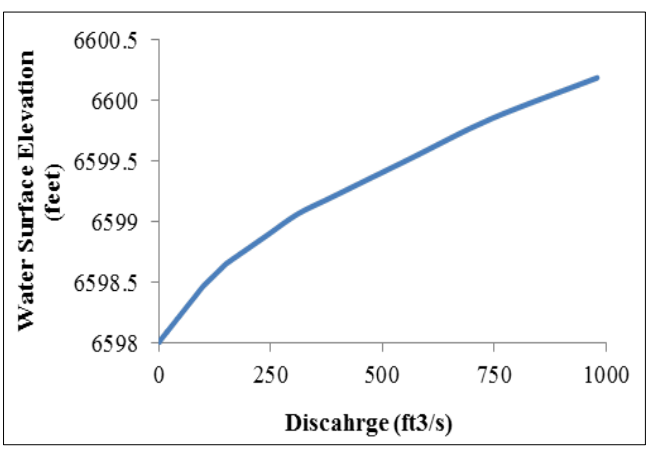


Figure 6 The rating curve developed at River station 812.67 feet for SRH-2D unsteady-state model downstream boundary condition.

Two main components of the 2D model are the mesh and the topography. The mesh was constructed in Surface water Modeling System (SMS) version 10.1 and contains all spatial data such as ground/bed elevations, channel roughness, and overbank roughness. Elevation values are stored at each node while roughness values are stored in each element (Figure 5). The average cell size within the main channel was 10 feet longitudinally and 8 feet laterally. Mesh cell sizes increased with increasing distance from the main channel. The entire mesh contained 17,320 cells. The mesh elevation is imported from ArcGIS and is interpolated to each mesh node. Roughness is assigned to polygons created to construct the mesh. Based on site visit observations and aerial photography the study reach was broken up into four roughness areas: the main channel, overbank grass, overbank shrub and overbank tree (Table 1) and were estimated from (Chow, 1959).

Model parameters

The 2D model was run under both steady state and unsteady state conditions with slightly different input parameters. For steady-state flow the inlet discharge was 1610 ft^3/s. The model had a simulation time of 74 hours with a time step of 2 seconds. Three boundary conditions of 6599.71 feet, 6600.21 feet, and 6600.71 feet developed from the HEC-RAS model were modeled to observe where water surface elevations converged to a common elevation. Convergence indicates the boundary condition no longer impacts the water surface elevation. Model results downstream of this location would be considered void since they are driven by the boundary conditions and not flow dynamics of the river system.

For the unsteady flow model the total time simulated was 80 hours and a time step (model time integration) of 1 second. A rating curve was used for the downstream boundary condition. The rating curve was taken from the HEC-RAS model at river station 812.67 feet (Figure 6).

Soil Samples and Shear Stress

Julien (1998) defined the critical shear stress as the beginning of motion when the ratio of hydrodynamic focus exceeds the submerged weight of a particle.

Julien developed a graphical relationship between critical shear stress and median grain size d_{50} on a flat horizontal surface (Table 2). This method also assumes that fractions of sediment enter motion at the same values of applied shear stress.

Table 2 Threshold shear stress conditions for granular material at 20˚ C (Julien, 1988).

Size Class	Shear Stress Range (Pa)
Medium Silt	0.010-0.083
Coarse Silt	0.084-0.110
Very Fine Sand	0.111-0.145
Fine Sand	0.146-0.194
Medium Sand	0.195-0.270
Coarse Sand	0.271-0.470
Very Coarse Sand	0.471-1.260

In previous paleoflood studies, these values have been used to infer surface erosion of stream terraces when the critical shear stress is exceeded during a modeled flood. Discharges necessary to produce the critical shear stress and inundate a particular stream terrace are given a range based on uncertainty in the model, topography, and flood stage associated with the range of critical shear stress values.

Field evidence of surface erosion or stability is used as an indicator of whether floods have recently overtopped terrace surfaces, providing lasting visible evidence of surface modification. These modifications take the form of secondary or overflow channels, bar and swale topography, channel splay deposits, or reentrant channels near the downstream ends of terrace surfaces. Soil/stratigraphic evidence in the form of truncated or buried soils would also indicate overtopping of the terrace surface. On the contrary, soils that show long term stability indicate the lack of flooding on the terrace over the timeframe of the developing soil. Discharge estimates for overtopping terraces with stable soils rely on these critical shear stress values in order to define a range of discharges that would erode the soil if the discharge had occurred over the timeframe of the developing soil (Levish, 2002).

The hypothesis for this study was that critical shear stress values should exceed the threshold critical shear stress on erosional surfaces and be below the threshold critical shear stress on depositional surfaces, thus reflecting higher stream power in the areas that were eroded. To test whether critical shear stress can be used to differentiate erosional versus depositional areas, we collected sediment samples from the upper 10cm of surface sediments on stream terraces at three different sites, COTT2, COTT3, and COTT4.The locations of the sediment samples correspond to the locations of stratigraphic descriptions of terrace deposits. Particle size analysis was completed for all three sites, whereas bulk density was completed only for COTT2 and COTT3 (Table 3). Bulk density was not completed for COTT4 because the sample lacked cohesion and crumbled apart during sampling. Soils were analyzed and characterized at the Soil, Water and Plant testing Laboratory at Colorado State University in Fort Collins, CO. Based on the soil samples data we concluded that the critical shear stress for our study reach was a very coarse sand corresponding to a threshold shear stress of 0.55 Pa.

Table 3 Soil sample results for Cottonwood creek.

Sample ID	Bulk Density (g/cm^3)	% Retained By Sieve Size (mm)						% Composition			Texture
		2	1	0.5	0.25	0.106	0.053	Sand	Silt	Clay	
COTT2	1.50	2.92	4.37	8.89	15.38	18.54	8.82	56	18	26	Sandy Clay Loam
COTT3	1.59	1.61	1.89	8.23	51.95	9.08	3.85	75	8	17	Sandy Loam
COTT4	N/A	1.91	3.75	6.49	28.45	32.28	2.83	74	6	20	Sandy Clay Loam

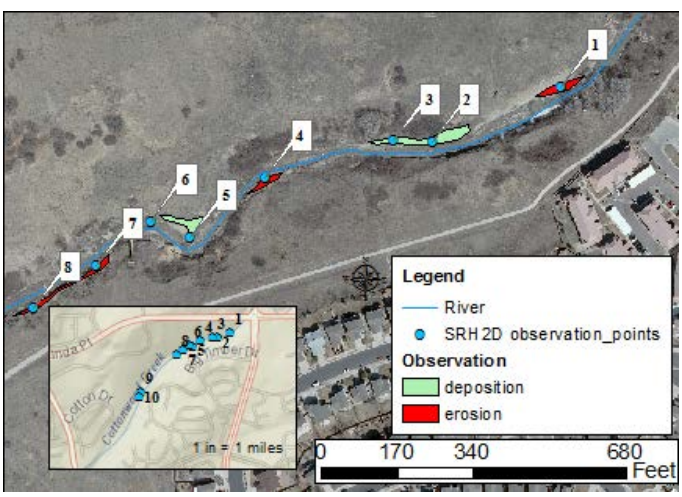


Figure 7 Location of observed erosion and deposition and the monitoring shear stress points in the SRH-2D model.

We wanted to determine if the threshold critical shear stress identified in the soil samples was exceed in the study reach, how much it was exceeded by, and for what duration. SRH-2D allows users to identify monitoring points, locations where simulated results are recorded at each time step. Ten monitoring points were placed within field observation polygons identified as areas of deposition and scour that were associated with the 2012 flood (Figure 7) Monitoring points 1, 4, 7, and 8 were located in polygons with observed erosion and monitoring points 2, 3, 5, 6, 9, and 10 were located within polygons where deposition was observed.

RESULTS

Model Extent

The results of the HEC-RAS model for the three boundary conditions provided three water surface elevations for SRH-2D steady-state downstream boundary conditions of 6600.71 feet, 6600.21 feet, and 6599.71 feet. The SRH-2D steady-state model water surface elevations for the high, regular, and low modeling scenarios were plotted (Figure 8) and show that the boundary condition had no impact for model results upstream of 4933.69 (HEC-RAS station 812.67 feet). The model extent in this study refers to all results upstream of station 812.67 feet.

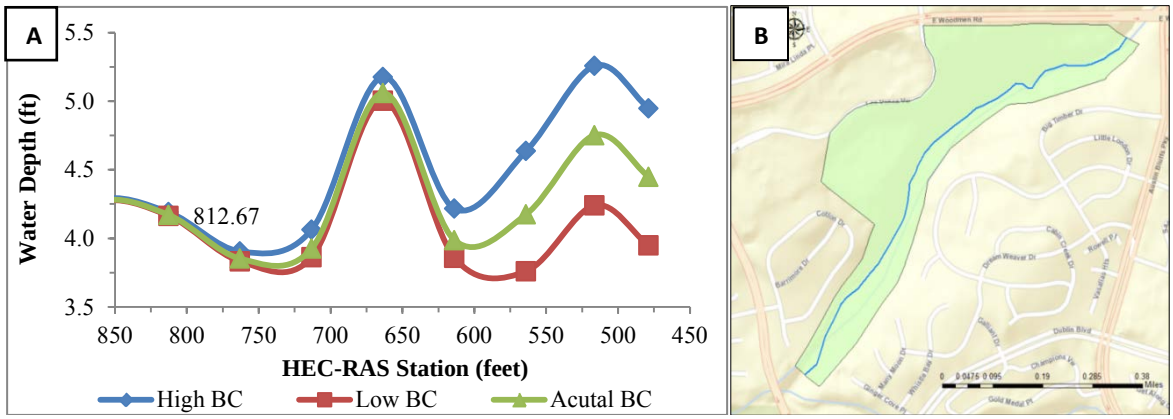


Figure 8 A) The 2D water surface profiles results for high downstream boundary condition, "Reg" or Regular downstream boundary condition and Low boundary conditions. B) The SRH-2D modeling extends to project station 4933.69 feet.

Model Uncertainty – Water Surface Elevation

Model uncertainty for water surface elevation was estimated to be ±1.02 ft. for the modeled reach. The modeled water surface elevation uncertainty was computed using the sum in quadrature equation (Taylor, 1997):

$$\sigma_\tau = \sqrt{\sigma_s^2 + \sigma_r^2 + \sigma_d^2}$$

Where σ_τ = absolute error, σ_s = topography error, σ_r = the roughness error, and σ_d = the error in the discharge measurement.

The terrain data for the study reach was developed from contours and surveyed points. Because there are two sources of data to develop the terrain the sum in quadrature equation was used to define the topographic uncertainty. The contour data is at 2 feet intervals which has an uncertainty of ± 1 foot. The vertical error associated with the surveyed point is ±0.1 feet. The total error for topography (σ_s) is 1.01 feet.

Roughness uncertainty (σ_r) was set at 0.03 ft. by comparing the difference in water surface elevation between selected roughness values and a 25% increase in roughness at a flow of 1610 ft^3/s. Differences in modeled water surface elevations ranged from 0.43 to 0 feet. An average value of 0.03 feet was used as a general indicator.

For a flow measurement to qualify as "good" under USGS standards it should be within ± 5 percent of the true value and a "poor" measurement is considered to have greater than 8 percent error (Sauer & Meyer, 1992). The daily discharge measurements at Cottonwood Creek generally receive a fair or poor rating. The 2012 water year report indicates that records are fair to poor because flow is affected by erosion-control and livestock-watering reservoirs and groundwater withdraws. For purposes of uncertainty estimation, the error in a given flow value was assumed to be ± 8 percent (e.g. 128.8 ft^3/s for 1610 ft^3/s). This translates to an estimated water surface elevation uncertainty (σ_d) of ± 0.17 feet at 1610 ft^3/s.

Water surface elevation fit

A comparison between the measured water surface elevations and the modeled steady state water surface elevations determine how well the model replicated flow depth. The survey points identified as flotsam were used as the

measured water surface elevation and were compared to the water surface elevations for the SRH-2D unsteady model (Figure 9). A comparison of 49 locations along the study reach found that the modeled water surface elevation was on average 0.81 feet above the measured water surface elevations. This indicates an over prediction of water surface elevation, on average, by 1.2 feet in the upper reach (River Stations 5746.36-4160.24), slightly over predicted water surface elevation by 0.3 feet in the middle reach (River Stations 4532.63-2736.01), and over predicted water surface elevations on average 1.1 feet in the lower reach (<2736.01 River Station) of the model.

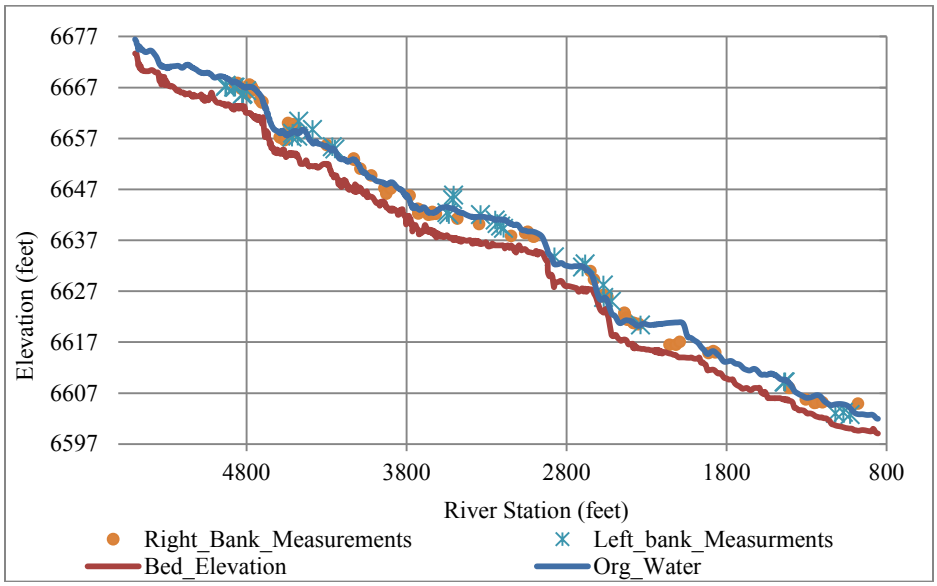
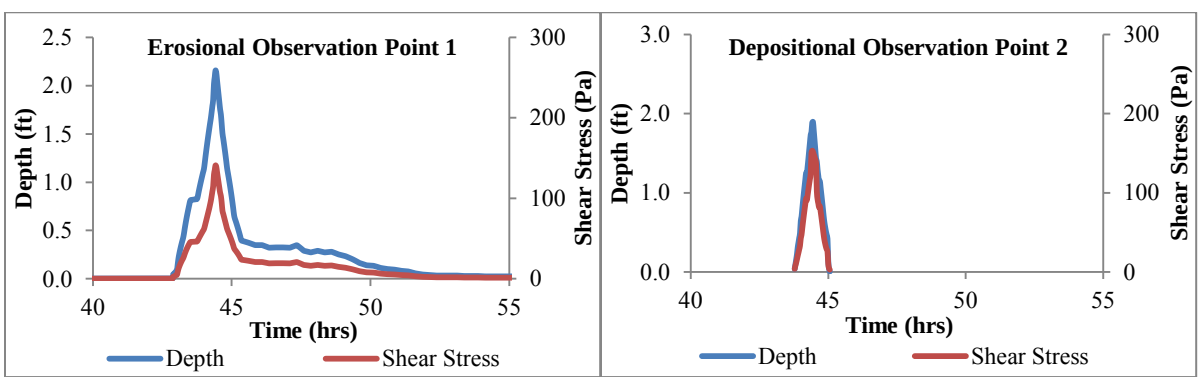


Figure 9 A comparison between the field measured and computer modeled water surface elevations for Cottonwood Creek study reach.

Critical Shear Stress Analysis

The ten SRH-2D monitoring points provided time series data for flow depth and critical shear stress. These values were plotted together against time (Figure 10). There was no flow at monitoring points 5, 6, 7, 8 and 10. For the monitoring points that did receive flow, they all exceed the critical shear stress values of 0.55 Pa. Although all surfaces showed modification in the form of either deposition or erosion, the methodology used in the paleoflood studies would have only assumed surface erosion above the critical shear stress value. Observation points 1 and 4 showed signs of erosion; however, observations sites 2, 3, and 9 were all mapped as locations where deposition had occurred. Observation points 1 and 4 had modeled peak critical shear stress values that were between 300 and 700 times larger than the threshold critical shear stress. They also experienced shear stresses that exceeded the threshold critical shear stress for over ten hours. Observations points 2, 3, and 9 had modeled peak critical shear stresses that were between 80-300 times larger than the threshold critical shear stress for durations around one hour.



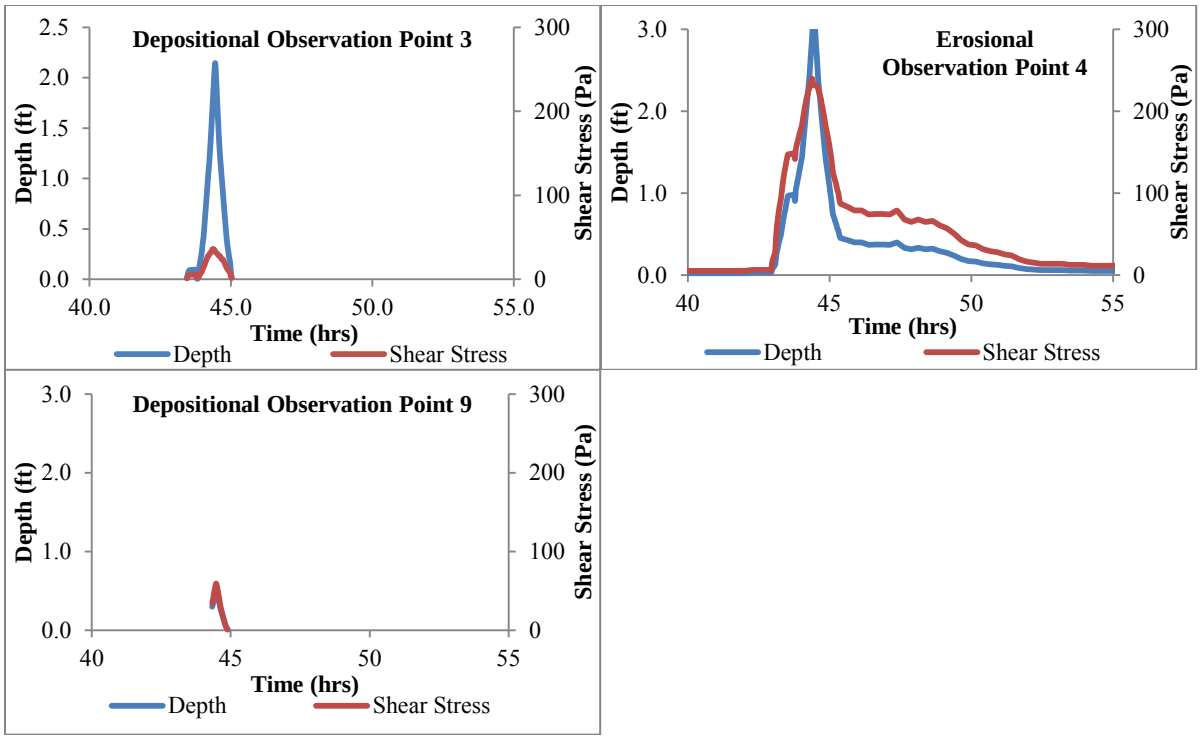


Figure 10 The charts plot the change in shear stress and depth over time for the describe monitoring points. Note the proposed threshold critical shear stress of (0.55 Pa).

DISCUSSION

Comparison of modeled water surface elevations and stage of high water marks

Modeled water surface elevations were within approximately 1ft of the field surveyed high water marks. Because the hydraulic model had a water surface elevation uncertainty of 1.02 feet this fit is within the range of uncertainty and is considered satisfactory. Higher resolution topographic data inside the channel would have the greatest impact on reducing the hydraulic model uncertainty. Finally, the uncertainty in collecting water marks is very difficult to quantify. Flow around objects in the channel is dynamic and complex where debris can be deposited throughout the hydrograph, making it difficult to discern the correct flood stage from the high water marks. Debris can be super elevated from in channel vegetation or obstructions, can be entrained during the hydrograph rising limb, or be suspended during the peak and then deposited during the falling limb at a lower channel elevation. To ensure high quality measurements of high water marks, a large number of measurements should be taken to rule out the mentioned outliers. This study measured over 233 high water marks over a one mile study reach and was considered satisfactory.

Comparison of steady state model output and field observations

For depth-averaged values in the steady state model, the SRH-2D model shows good correspondence with field observations. In other words, higher shear stress is computed in areas that were mapped as erosional and lower shear stress values are computed for areas that were mapped as depositional. Deviations from this pattern occur along the margins of the surfaces at their boundary and in transitional areas between erosional and depositional areas, where high shear stress values are computed at the upstream portions of the depositional areas.

Comparison of unsteady state model output and field observations

Results from the unsteady flow modeling at observations points along the study reach show that threshold critical shear stress is exceeded at every observation point regardless of whether the observation point was within an erosional or depositional area. We concluded that the Julien defined critical shear stress for our study site was not a

good predictor of erosion or deposition. The three assumptions of the Julien method (flow occurs over a plane bed, the particles shape are uniform, and the particles are non –cohesive) may have contributed to the low correlation. Our study site had steep bed slopes, segments of bedrock, and bank vegetation all of which affect the flow of sediment. Our soil samples had as high as 26% clay content indicating particle cohesion. Finally, natural stream systems have imbrication or armoring of the bed. It is likely that our site could have had imbrication or interlocking sediment particles of varying shape impacting sediment transport. These three conditions may have contributed to the poor correlation between the Julien comparison of grain size and critical shear stress and our site.

Maximum shear stress values also varied and appeared to have no distinct difference in values between erosional and depositional surfaces. The results also show that the duration and depth of inundation on erosional surfaces was much greater than on depositional surfaces, which may be the reason why these areas experienced greater removal of sediment.

CONCLUSIONS

Geomorphic observations of an extreme event can provide insight into flood dynamics. One dimensional and two dimensional modeling provided quantitative data on flow velocities, depths and shear stress for the June 6, 2012 flood. There was a strong agreement between field observations and modeled results of flood stage. Anomalies occurred in locations where three dimensional flow effects were likely during the flood. Critical shear stress as an indicator of surficial erosion is currently used to develop non-exceedance bound discharges for paleoflood studies; this research shows that the critical shear stress value can only be used to develop a minimum stage and discharge required to modify a f luvial surface; other parameters should be explored to better define the range of peak discharges for paleoflood studies.

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