UTILIZING A TWO-DIMENSIONAL HYDRAULIC MODEL FOR MAKING DISCHARGE ESTIMATES OF PREHISTORICAL PALEOFLOODS ON THE SOUTH FORK BOISE RIVER, SOUTH-CENTRAL IDAHO

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Abstract

An important aspect of understanding prehistorical paleofloods is developing estimates of their peak discharge. This is most commonly achieved by using numerical hydraulic models. Two-dimensional hydraulic models can provide valuable information for paleoflood studies not attainable with one-dimensional models and provide greater confidence in the resulting peak discharge estimates. The SRH-2D model was used in the current study of the South Fork of the Boise River as part of a Bureau of Reclamation Dam Safety hydrologic hazard assessment for Anderson Ranch Dam to evaluate shear stress exerted on preserved stream terraces and make an estimate of the peak discharge for a single pre-historical paleoflood.

Eight soil pits were excavated along the South Fork Boise River to determine the sediment characteristics and evaluate the effects of shear stress on the flood plain and stream terraces. Soil properties and detrital charcoal samples recovered from discrete stratigraphic units exposed in the excavations provided age information on the timing of paleofloods and as a measure of stream terrace stability. The landscape was assumed to be stable over the timeframe provided by the chronology, but the roughness due to vegetative cover and sediment characteristics may be more uncertain. To account for this uncertainty, the Manning's roughness throughout the model was varied by ±0.005. Using this roughness range, one hundred fifty model runs were made in increments of 30 m^3/s to determine peak discharges needed to just inundate each site and to cover each site to the depth of at least one meter. Additional model runs were also made to evaluate the shear stress at specific excavation sites for higher flows. Shear stress was evaluated at each site to assess the potential for landscape disturbance over the entire range of flows. Results indicate that shear stress was generally high enough at each site to mobilize bare sediment, but the shear stress was only high enough at three of the eight sites to move grass covered soil. Model results also show that the development of eddies with increasing discharge at two of the sites greatly limited the shear stress. Cross referencing model results with stratigraphic data among all eight sites allowed estimates of peak discharge to be refined given the changes in velocity, shear stress, and flow patterns over the range of modeled discharges. A minimum discharge of 420±45 m^3/s (14,800±1,590 ft^3/s) is required to cause recognizable disturbance of the terrace surface at site AR3. The age of the terrace deposits at this site of 4175±20 14C years B.P. provides the basis for a non-exceedance bound on the South Fork of the Boise River downstream of Anderson Ranch Dam. Evidence for a single paleoflood is preserved at site AR6 where a flood deposit buries a 1310±20 14C year B.P. old soil. Six radiocarbon ages on deposits correlative to the flood deposit indicate the paleoflood occurred sometime between 150 and 430 years ago and had a minimum peak discharge of 240 +/- 15 m^3/s (8,500±530 ft^3/s), similar in magnitude to the largest historical flood.

INTRODUCTION

Paleoflood data are a critical component used in assessing the flood hazard at Reclamation dams. The addition of paleoflood data to a more traditional flood frequency analysis based solely on the systematic record allows for an extension of that record and can lead to a more accurate estimate of the flood hazard. The two basic elements of paleoflood data that are developed for a flood hazard analysis are 1) an age of either a specific paleoflood or a non-exceedance bound and 2) an estimate of the associated peak discharge. An important distinction that needs to be pointed out here is the difference between a paleoflood and a non-exceedance bound. Simply stated, a paleoflood is an actual flood for which there is some preserved evidence; a non-exceedance bound is not an actual flood, but an estimate of a peak discharge that has not been exceeded over a given time frame.

Typically, paleoflood peak discharge estimates are developed using one of several different one-dimensional methods (Benson and Dalrymple, 1967; O'Connor and Webb, 1988; Webb and Jarrett, 2002) with the most widely applied being the step-backwater model. At Reclamation, three different methods have been used to estimate the peak discharges of paleofloods used in hydrologic hazard studies, 1) a simple single cross-section slope-conveyance calculation based on Manning's equation, 2) a one-dimensional step-backwater model through multiple cross-sections and of varying reach lengths (primarily using HEC-RAS), and 3) a two-dimensional depth-averaged hydraulic model (SRH-2D, Lai, 2009). The use of a particular methodology has varied largely based on the scope of the study and the perception of the risk. The more simplistic methodologies are utilized as a tool in an initial evaluation of flood hazard or in cases where hydrologic risk is viewed as being very low based on other information. Due to greater input data requirements, one- and two-dimensional models are employed in broader-scoped studies to make estimates of discharge to either verify initial findings, develop more defensible results, or reduce uncertainty where the flood hazard is determined to be high.

The two-dimensional hydraulic model SHR-2D was used to estimate peak discharge for paleofloods on the South Fork Boise River located in south-central Idaho. This analysis was undertaken as part of an evaluation of the flood hazard at Anderson Ranch Dam, a Reclamation structure located on the South Fork of the Boise River about 60 miles upstream of Boise, Idaho. Peak discharge estimates were generated for eight sites in a ten mile reach downstream of the Dam.

PHYSICAL SETTING

The South Fork of the Boise River is one of two large tributary drainages that come together to form the Boise River. The watershed of the South Fork of the Boise River ranges in elevation from about 4000 feet to more than 10,000 feet and principally drains the southern flank of the Boise Mountains. The basin area for the Boise River where it joins the Snake River plain is about 2,680 square miles; the basin area impounded by Anderson Ranch Dam is about 960 square miles. Runoff from the upper part of the basin is predominately associated with late spring snowmelt, which is reflected in the historical flood record. The largest flood in the historical record however is associated with a large mid-latitude storm that pushed moisture inland from the Pacific Ocean in December of 1964. This particular storm produced widespread flooding across northern California, Oregon, and into Idaho and represents the flood of record at many gaging stations across the region. Studies indicate a flood of this magnitude in northern California had not been exceeded in more 300 years (Helley and LaMarche, 1973); data on the Payette River in southwestern Idaho indicate that the 1964 flood may have been the largest flood in almost 700 years (Weghorst and Klinger, 2000).

The South Fork of the Boise River between its confluence with the mainstem Boise River and Anderson Ranch Dam flows through a deep canyon incised into Quaternary basaltic rocks and a sequence of poorly-consolidated lacustrine and fluvial deposits that overlie late Cretaceous granitic and metamorphic rocks associated with the Idaho batholith. The canyon through the study area downstream of the dam is marked by numerous large landslides that have on at least one occasion completely blocked the river canyon. In addition to large landslides, there are several large tributary drainages that have shed large alluvial fans into the canyon. The remnants of both the landslides and the alluvial fans affect the channel morphology of the river within the canyon and influence the channel gradient locally. A debris flow shed out of Rough Creek sometime within the last decade appears to have temporarily blocked the channel, currently forms a rapid, and effectively changed the channel slope upstream to the extent that it has drowned the riparian vegetation along the channel.

Stratigraphic Data

Utilizing the stratigraphic record of fluvial deposits preserved along rivers is a widely used technique for evaluating the flood history (Mansfield, 1938; Patton and others, 1979; Baker, 1989; Jarrett, 1991). Paleoflood data and specifically non-exceedance information has been used to evaluate flood hazard at Reclamation since the early 1990s due to the need to better understand the magnitude of extreme and low probability floods (Levish, 2002). Along the South Fork of the Boise River downstream of Anderson Ranch Dam, in addition to the usual floodplain deposits, a sequence of three stream terraces is preserved. Eight soil pits were excavated on each of these terraces to 1) document the deposition record and evaluate the flood history that might be preserved, 2) develop ages for the deposits and evaluate the relative stability of the terrace surface, and 3) quantify the character of the sediment on the terrace surface to more accurately model estimates of discharge required to produce erosion utilizing shear stress calculations.

Along the South Fork of the Boise River, the terrace and floodplain deposits are most commonly composed of coarse gravelly alluvium that is representative of the sediment carried by the river as bedload. The surface of the topographically higher stream terraces and parts of the floodplain are also often overlain by finer-grained sediment interpreted as overbank or slackwater flood deposits. Evidence for a single paleoflood is preserved where a flood deposit buries a 1310±20 14C year old soil. Six radiocarbon ages on deposits correlative to the flood deposit indicate the paleoflood occurred sometime between 150 and 430 years ago. Additionally, an age on older terrace deposits of 4175±20 14C years provides the basis for a non-exceedance bound.

HYDRAULIC MODEL

Topographic Data

LiDAR data were collected in October 2007 using the NASA Experimental Advanced Airborne Research Lidar (EAARL) pulsed laser system (USGS 2009a, USGS 2009b). This system is capable of measuring xyz coordinates above and below the water surface. The stated vertical accuracy of the data is +/- 15cm on flat open terrain and +/- 25cm in submerged areas. The point density varied throughout the study reach, but down-valley spacing was generally between 1 and 3 meters and cross-valley spacing was often less than 1 meter.

The LiDAR data covered most of the study reach, but there were several places where the data did not go far enough up the canyon walls or where data were just not available. In these areas USGS 10 meter DEM data were added. Upon first inspection, the LiDAR data seemed very good. Closer inspection, however, showed a large number of spikes especially in the floodplain and on islands. These elevation spikes appear to be related to vegetation.

The bare earth data were smoothed by interpolating the data into raster format. This interpolation was also needed to reduce the number of points used to generate the 2D model mesh. The software package used to generate the mesh can only import approximately 1 million points. Channel and floodplain points were interpolated to a 2 meter grid and upland points were interpolated to a 5 meter grid using an inverse distance weighted routine in ArcMap.

The resulting grids eliminated most of the spikes on the floodplain, but additional adjustments were needed in areas with dense vegetation such as islands. In many of these locations the vegetation was so dense very few true ground points were available. These areas stood out because they were as much as 5m higher than the ground. Elevation adjustments were made directly to the model mesh rather than adjusting the raw data.

Model Setup

A HEC-RAS model was created for the study reach and was used to estimate the water surface elevations for the downstream boundary in the 2-dimensional model, and determine the maximum extent of flooding. Inundation mapping with the HEC-RAS model also helped highlight many of the elevation spikes in the raw topographic data.

The SRH-2D (Lai, 2009) hydraulic model was used to model flows. This model solves the 2D depth-averaged form of the standard St. Venant depth-averaged shallow water equations. The model utilizes an implicit scheme to achieve solution robustness and efficiency. This model uses a flexible mesh and can incorporate multiple roughness zones. In all, nine roughness zones with similar roughness characteristics were identified and delineated within the study reach. Roughness values used in the hydraulic model (Table 1) are based on observations made in the field and comparisons made to published values (Barnes, 1967).

One particular challenge with modeling large paleofloods is the lack of data with which to calibrate the model. Data are typically collected during low flows, and there is no gaged record of paleofloods to estimate water surface elevation. Channel roughness and channel characteristics can only be inferred based on the current channel configuration. Uncertainty in topography, roughness, and vegetation were addressed in this analysis by varying roughness and evaluating terrace surface stability using shear stress. Site stability was further evaluated by considering the velocity magnitude and direction over a range of discharges. To compensate for some of this uncertainty, roughness values used in the model are varied globally by+/- 0.005. In this way, peak discharges at each site are bracketed by a range of flows.

Table 1 Roughness classification and Manning n values used in the hydraulic model.

Classification	Manning n
Channel Low	0.035
Channel Medium	0.037
Channel High	0.04
Floodplain Open	0.037
Floodplain Medium Vegetation	0.05
Floodplain Dense Vegetation	0.06
Upland Scrub	0.045
Upland Tree/Rock	0.055
Side Channel	0.038

The final mesh had approximately 60,000 cells. Mesh cells in the channel had an approximate size of 5 by 10 meters. Mesh cells in the floodplain were larger and have cross-valley spacing between 6 and 15 meters while down-valley spacing ranged from 10 to 15 meters. Areas of interest, especially those near the soils pits, had smaller mesh cells to provide more detail.

The water surface elevation used at the downstream boundary for each flow was estimated from a HEC-RAS model developed from the same terrain. The location of the downstream boundary was established far enough downstream so that any uncertainty in this value would not affect model results in areas of interest. The model was started from a dry condition and was run with a 5 second time step for a simulation time of approximately 55 hours. During this time, the incoming and outgoing flows, and water surface elevation at monitoring points were able to stabilize.

Model Results

A total of 150 model runs were made. The large number of runs was needed to establish the discharge needed to just inundate (wetting flow) each of the 8 pit locations for each of the three roughness levels used. Figure 1 shows the extent of inundation for the wetting flow at sites AR1, AR2, and AR3. In addition to estimating the discharge required to inundate a particular surface, additional flows were modeled to estimate a disturbance flow. Shear stress values were evaluated over the range of flows and compared to critical shear stress values needed to erode the terrace surface and leave a recognizable record of flooding (Table 2). The discharge range for each flow was similarly determined by running the model using a high, medium, and low set of roughness values. With lower roughness values a higher discharge is needed for the water surface elevation to reach a given elevation. Conversely, higher roughness values decrease the discharge needed to reach a given elevation.

Table 2 Minimum flow needed to inundate or disturb each site.

Site	Wetting Flow, m^3/s	Disturbance Flow, m^3/s
AR1	210 +/- 30	600 +/- 186
AR2	300 +/- 60	675 +/- 317
AR3	420 +/- 90	NA
AR4	1,530 +/- 210	NA
AR5	570 +/- 120	NA
AR6	240 +/- 30	690 +/- 382
AR7	240 +/- 30	NA
AR8	570 +/- 150	NA

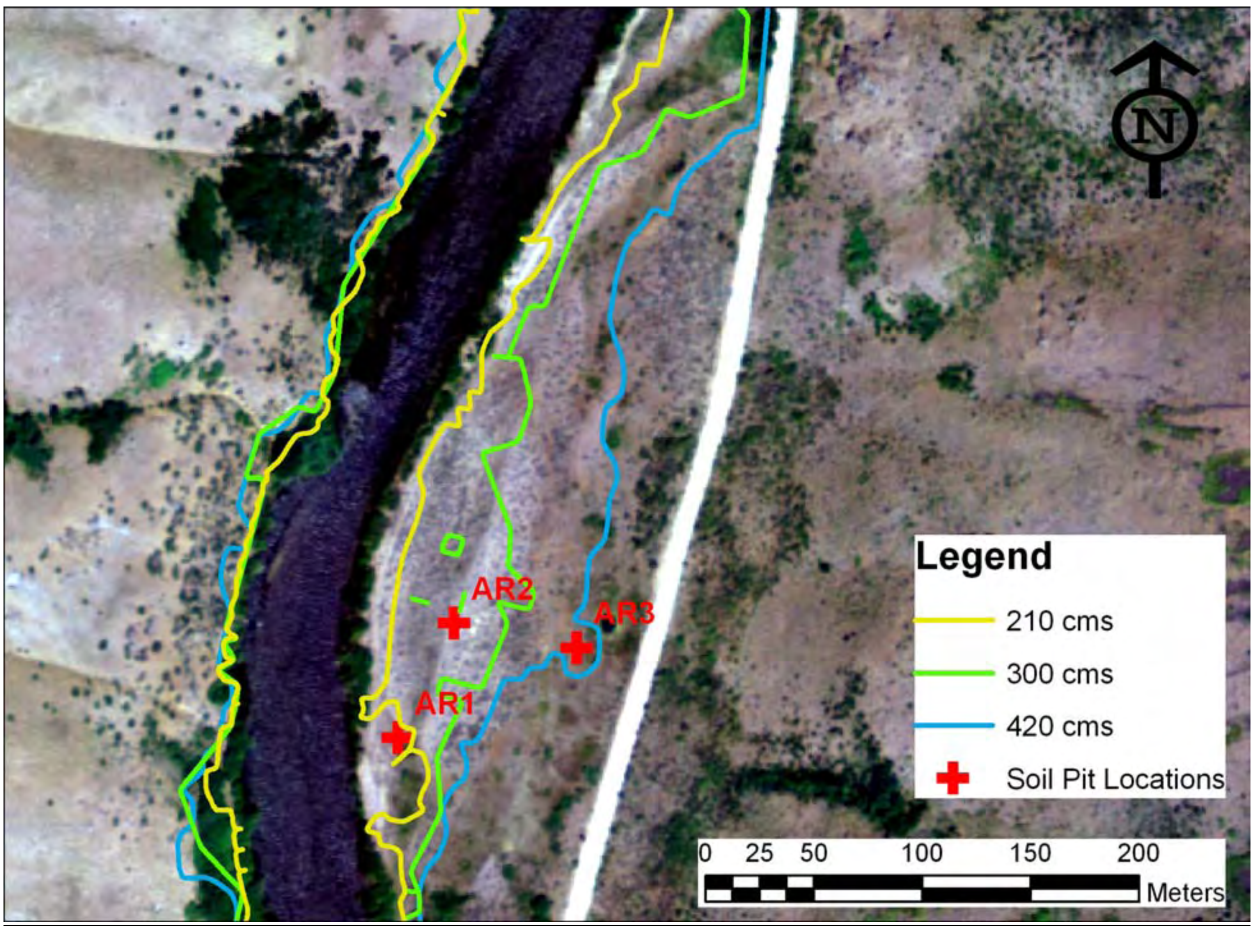

Figure 1 Soil pits AR1, AR2, and AR3 and model results showing the extent of inundation for the wetting flow for each site.

Soil Stability

Soil stability was evaluated at each site to determine the likelihood of surface disturbance once a site is covered with water. This was accomplished by noting the type and state of vegetative cover and describing soil properties such as texture, structure, and wet and dry consistence in the field. This disturbance flow is determined by comparing the total shear stress computed in the model to a total critical shear stress based on vegetative cover (US DOT, 2005). This method for determining the critical shear stress in vegetation lined channels uses vegetation height, the type of vegetation, the amount of cover, boundary shear stress, and grain size information to estimate a critical shear stress for the soil. The equation is somewhat sensitive to the amount of cover and more sensitive to the vegetation height. The study sites along the South Fork Boise River at the time of the study were generally covered with low grasses and sage. For application purposes, the vegetation was assumed to consist of bunch grass with good coverage and a height of 16 inches. The coverage and vegetation height were varied to give a range of discharges needed to produce shear stresses that would disturb the sites.

The permissible shear stress is calculated using the following formula:

$$\tau_p = \frac{\tau_{p,soil}}{(1-C_f)}\left(\frac{n}{n_s}\right)^2 \tag{1}$$

where,

- τ_p = permissible shear stress on the vegetative lining, N/m^2
- $\tau_{p,soil}$ = permissible soil shear stress, N/m^2
- C_f = grass cover factor
- n_s = soil grain roughness
- n = overall lining roughness

$$n = \alpha C_n \tau_o^{-0.4} \tag{2}$$

where,

- τ_o = mean boundary shear stress, N/m^2
- C_n = grass roughness coefficient
- α = unit conversion constant, 1.0 (SI), 0.213 (CU)

All parameters in the permissible shear stress equation are constant except for the overall lining roughness. Unlike a critical shear stress calculated for bare mineral soil, the permissible shear stress on a vegetative lining changes with discharge because it is based on the mean boundary shear stress.

Vegetative cover can significantly increase the strength of soil over that of bare sediment. A rough approximation for the critical shear stress needed to move bare sediment is that it takes approximately 1 Pascal per millimeter of grain size (Julien, 1995). Many of the sites had sediment in the fine (0.125 to 0.25mm) to medium (0.25 to 0.5mm) sand range, but soil properties such as structure and consistence that develop over time may also effectively increase the soil strength. Based on the model results, the shear stress at nearly all the sites would be large enough to move this sediment at a discharge close to the wetting flow. Only three of the eight sites had conditions favorable for soil disturbance with vegetation present. At the other sites the shear stress was never large enough to overcome the critical shear stress of the vegetated soil. At the three sites where enough shear stress was developed to mobilize vegetated soil, the discharge was two to three times greater than the discharge needed to wet the site. Figure 2 shows the model generated shear stress and the computed critical shears stress with vegetation at sites AR1 and AR2.

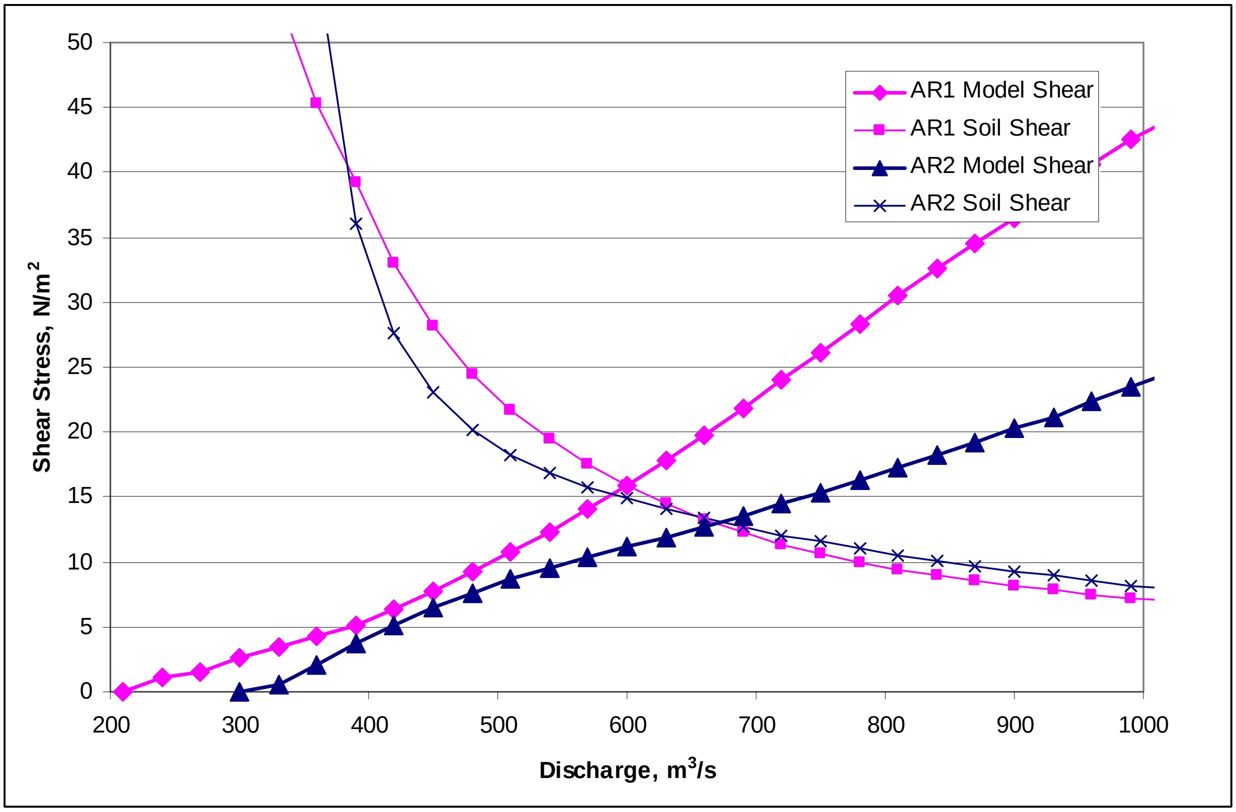

Figure 2 Model generated shear stress and computed critical shear stress with vegetation at sites AR1 and AR2.

The values associated with the disturbance flow in Table 2 were determined by first calculating the critical shear stress with the assumed cover and vegetation height and model shear stress values using the mean roughness. The disturbance flow for each site is the discharge at which the model generated shear stress is equal to the computed critical shear stress. The disturbance range was determined by varying either the vegetation cover or height while holding the other parameter constant. After this was done for both vegetation cover and height, the range of disturbance discharge for each parameter was determined. The differences were squared and then added before the square root of the sum was computed. If the low end of the range is considered, the disturbance discharge is only slightly larger than the wetting discharge; however, there is a considerable amount of uncertainty in the type of vegetation at these sites and its effect on soil stability.

Secondary Flow

Subtle changes in topography can significantly affect the shear stress and flow pattern at a given site. Sites AR1, AR2, and AR3 are on a sequence of terraces on the inside of a bend with site

AR3 on the highest surface farthest away from the channel. Flood flows are confined to the channel at the upstream end of the point bar by landslide deposits but spread out over the downstream surface with increasing discharge. The landslide deposits block direct flow on the point bar to site AR3 and cause a recirculation to occur until the site is overtopped by more than 3 or 4 meters of water. Figure 3 shows model output of shear stress at site AR3. There is a rise in shear stress as the discharge increases to approximately 700 m^3/s. The shear stress falls until the discharge approaches 1,800 m^3/s when the shear stress begins to rise rapidly. Critical shear stress values for vegetative cover at this site are approximately 50 times higher than those estimated by the model.

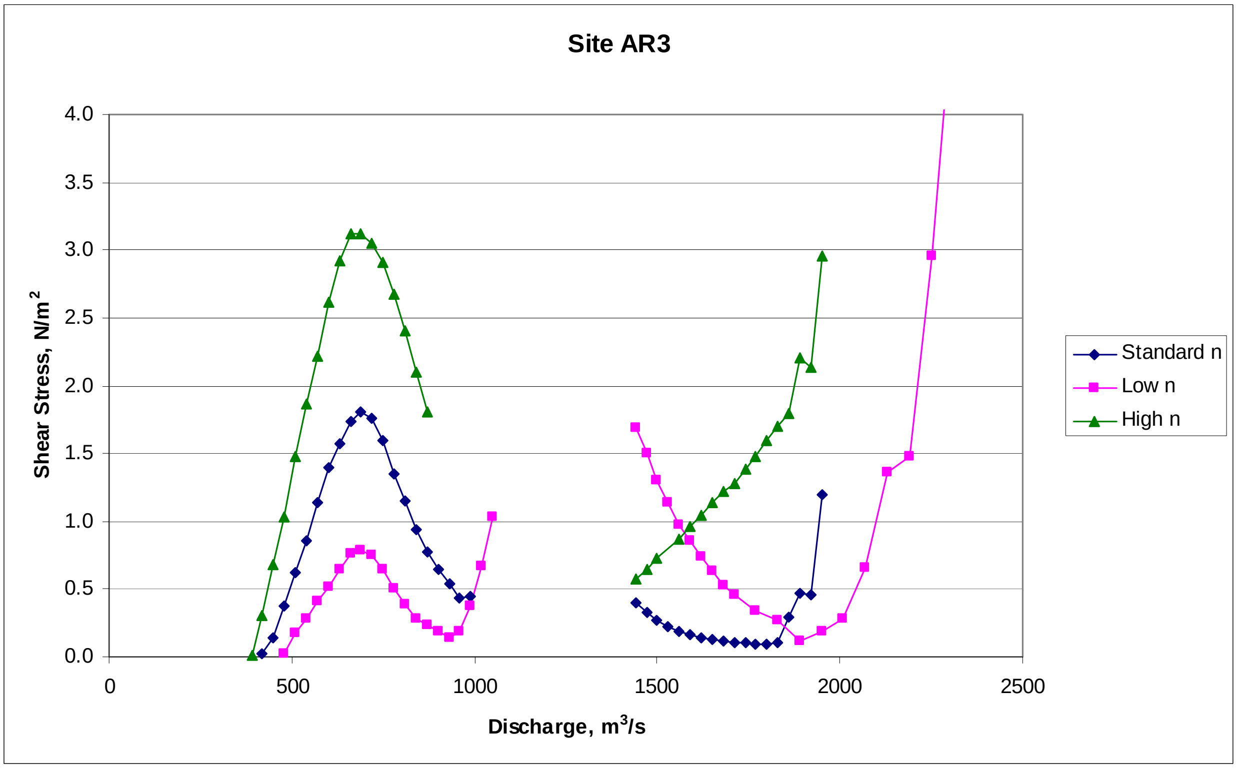

Figure 3 Model output of shear stress at Site AR3 for high, medium, and low values of roughness.

CONCLUSIONS

Discharge estimates were developed for prehistorical paleofloods on the South Fork Boise River in south-central Idaho using the SRH-2D hydraulic model. Radiocarbon ages and stratigraphic data from terraces in the study reach indicate that a paleoflood with a discharge between 240 and 300 m^3/s occurred between 150 and 300 years ago based on evidence preserved at four different sites. This flood appears to be the largest flood in at least the last 1,300 years based on evidence of flood deposits that have buried a soil preserved at site AR6. A non-exceedance bound was developed at site AR3 from terrace deposits that are approximately 4175 years old. The wetting discharge required to inundate these deposits is estimated by the model to be about 420 m^3/s.

Model results were used to assess the effect of vegetation on soil stability and the shear stress required to leave clear and recognizable evidence of flooding in the stratigraphic record. At sites where flow conditions were favorable for soil disturbance the discharge required was two to three times greater than the wetting flow. Model output can also used to identify areas with secondary currents and possibly depositional areas.

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