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Report DSO-11-03

Evaluation of Paleoflood Peak Discharge Estimates in Hydrologic Hazard Studies

Dam Safety Technology Development Program



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Dam Safety Technology Development Program

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Bureau of Reclamation
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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Dam Safety Technology Development Program
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DSO-11-03

**Evaluation of Paleoflood Peak Discharge
Estimates in Hydrologic Hazard Studies**

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Introduction

Paleoflood data are a critical component used in assessing the flood hazard at Bureau of Reclamation (Reclamation) dams. The addition of paleoflood data to a more traditional flood frequency analysis based solely on the stream gaging record allows for an extension of that record and can lead to a more accurate estimate of the flood hazard (see Blainey and others, 2002). 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 discharge and 2) an estimate of the associated magnitude of the peak discharge. The focus of this study is on the estimation of peak discharge. An important distinction exists between a paleoflood and a non-exceedance discharge. A paleoflood is an actual flood for which there is some preserved evidence. This evidence may exist as either a physical or historical record in the form of preserved flood-related erosional or depositional features or as a written or photographic record of the flood. A non-exceedance discharge is not an actual flood, but an estimate of a peak discharge that has not been exceeded over a given time frame. The magnitude of the discharge is constrained by evidence of landscape stability that precludes inundation by flooding that would leave a clear, recognizable record of erosion and or deposition. For the purposes of this study the two are assumed to be equivalent as the intention of modeling extreme floods is to accurately estimate the magnitude of the peak discharge associated with either.

Paleoflood peak discharge estimates are often developed using one of several different one-dimensional methods with the most widely applied being the step-backwater model (see Benson and Dalrymple, 1967; Webb and Jarrett, 2002). Reclamation has applied three different methods to estimate the peak discharges used in hydrologic hazard studies; 1) a simple single cross-section slope-conveyance calculation based on Manning's equation, 2) a 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 (TRIM2D or SRH2D). The use of a particular methodology often depends on the scope of the study and the availability of topographic data of the required resolution. The general perception of the accuracy of the paleoflood peak discharge estimates is that they are improved relative to the detail of the topographic data and the computational sophistication of the model used. However, little or no research has actually demonstrated this perception to be true as it is applied by Reclamation. In addition, the amount of variability associated with peak discharge estimates made using any of the above methodologies has not been evaluated quantitatively. These two points represent the primary objectives of this analysis.

Of the three general methodologies described above, the vast majority of paleoflood peak discharge estimates by Reclamation have been made based on slope-conveyance calculations in support of Comprehensive Facility Reviews (CFR). In the current CFR process, the hydrologic hazard is evaluated on the basis of readily available information. The paleoflood peak discharge estimates incorporated into the hydrologic hazard studies for the CFR are intentionally limited in scope and based on a slope-conveyance discharge using a simple spreadsheet calculator. Data input required to make this calculation include a single measured cross-section at the site of interest, an estimate of the channel roughness based on field observations, and a channel slope typically derived from USGS 7.5' quadrangle maps (1:24,000 scale). To improve the accuracy of the estimate, attempts are made to locate study sites near stream gaging stations so that the peak stage and discharge for an historical flood can be used as a guideline for the input parameters of slope and channel roughness. Direct comparison of the results to floods of known discharge is rarely undertaken, and the variability in the estimates derived using this methodology remains poorly understood.

It is important to note that the principle objective of this study is not to evaluate a particular methodology used for making the paleoflood peak discharge estimates, but to develop a better understanding for the accuracy and potential variability in peak discharge estimates that are widely used within Reclamation's risk assessment process. Due to potential uncertainty incorporated in estimates of peak discharge related to data quality and computation methods this study was performed to better understand the accuracy of the discharge estimates and evaluate the sources of potential error in making these estimates. Because these estimates are used in making decisions regarding the hydrologic hazard and dam safety, an improved knowledge of this variability is critical.

The findings of this study are a compilation of two different research projects. The initial project considered the differences in peak discharge estimates made using a single cross-section slope-conveyance calculation with the Manning equation (Method 1) to discharge estimates made using a more sophisticated one-dimensional hydraulic model (i.e., HEC-RAS; Method 2). Initial results were documented in a draft report with the same title as this report, but dated December 2007. The findings of that report have been updated and are included in their entirety in this report, which supersedes the findings of the draft report.

The second study included a similar evaluation as the previously mentioned study, but in this case comparing one-dimensional model results (Method 2) to two-dimensional hydraulic model (SRH2D) results (Method 3). At the time of the first study, the two-dimensional hydraulic model SRH2D was not fully developed, and the detailed topographic data needed as model input were not readily available. Over several years the development of SRH2D improved to the point that it can easily be applied to a paleoflood study as long as the topographic data are sufficiently detailed (Lai, 2009). After using SRH2D to estimate peak discharge on several projects (Los Banos IE, Klinger and Bauer, 2004;

Whiskeytown CAS, Klinger and Bauer, 2009; Anderson Ranch IE, Klinger and Bauer, 2010), enough data were available with which to compare one and two-dimensional model results.

Methodology

As previously stated, the vast majority of the paleoflood peak discharge estimates developed for Reclamation CFR-level flood hazard studies have been based on slope-conveyance calculations. For this evaluation, peak discharge estimates made using slope-conveyance calculations were compared to the results of a HEC-RAS step-backwater model to better understand variability in those peak discharge estimates. In turn, HEC-RAS results were also compared to SRH2D results. New data were not collected as part of this study. Instead existing data were utilized to make comparisons between the different computation methods.

In this analysis, slope-conveyance calculations are made by using cross-sections from existing HEC-RAS models. Cross-section station and elevation pairs from paleoflood study sites or sites that had appropriate river terraces are entered into the conveyance calculator spreadsheet along with the desired water surface elevation and slope determined from 7.5' USGS topographic maps. For each site, discharges are simulated to predict the wetting flow and a disturbance flow that would cover each site with 2 feet of water (Figure 1). A wetting flow is defined as the discharge required to just inundate or "wet" a site of interest, usually a particular terrace surface or stratigraphic site. A disturbance flow is the peak discharge used to help define a non-exceedance bound. A disturbance flow therefore is the discharge required to produce a "disturbance" of the site. The depth of 2 feet of water over the terrace was utilized in developing estimates of a disturbance flow for several reasons: 1) to ensure inundation of irregularities in the topography on the terrace surface through a specific reach, 2) to accommodate variation in peak stage along the margins of a channel based on fluctuations in flow, and 3) this depth of water over a terrace has been utilized in estimating non-exceedance discharges based on the assumption that inundation of this magnitude is the minimum depth of flow required to leave some record of flooding, either erosional or depositional. However, surface disturbance is a function of velocity and shear stresses in addition to depth. Surface disturbance may actually occur with less than 2 feet of depth. Therefore, the disturbance flow represents a conservative estimate or a maximum discharge required to cause a disruption to a particular topographic surface.

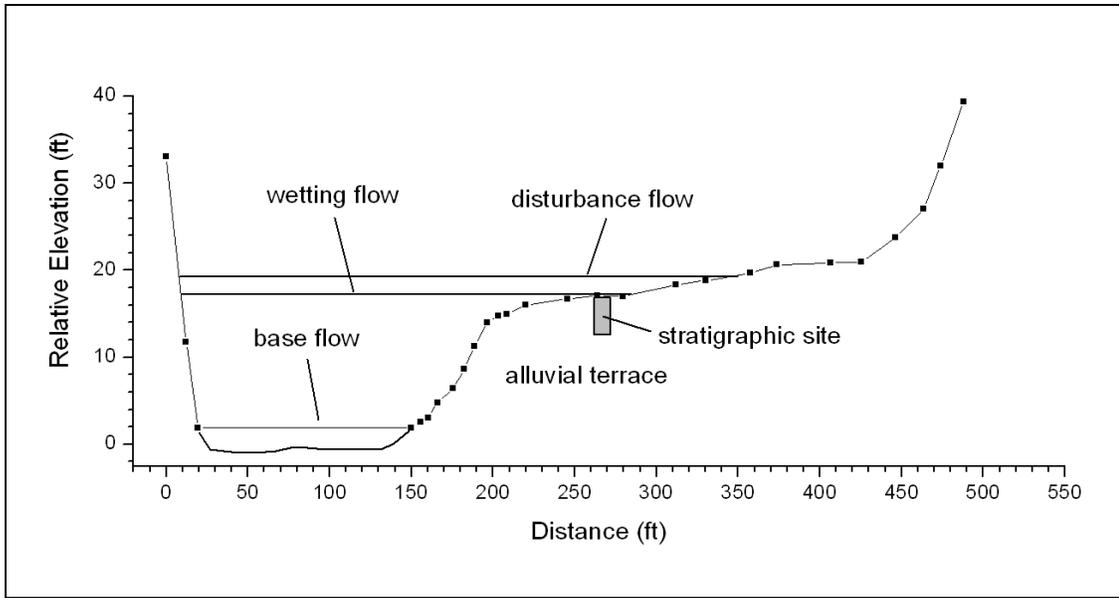


Figure 1. Schematic cross-section showing the stage difference between base flow normally measured by stream gages, a wetting flow that just inundates an alluvial terrace at a particular stratigraphic site, and a disturbance flow that inundates the terrace to an extent that it is assumed to leave clear evidence of flooding in the form of erosion and/or deposition at that same site.

For the comparison of slope-conveyance to HEC-RAS modeled peak discharges, a total sample set of 134 peak discharge estimates were calculated from surveyed channel geometries in 67 reaches from 13 different study sites (Table 1). The HEC-RAS models used in this analysis had topographic data derived from ground surveys, photogrammetry, and digital elevation models. Because the comparisons of peak discharge were made using the same topographic data, differences in the types and accuracies of the topographic information across the sites were not considered even though factors such as cross-section spacing, alignment, model length, and boundary condition can affect the accuracy of model results. While this analysis was undertaken to evaluate peak discharge estimates for paleofloods, the HEC-RAS models utilized were not necessarily from paleoflood studies. In order to increase the number of sites and comparison points, additional HEC-RAS models from other studies were also utilized in the evaluation. Sites from these models were chosen based on the channel and terrace configuration. The study reaches for this evaluation include a wide variety of rivers with large differences in basin area, hydrometeorology, channel geometries including slope, and channel roughness. Basin areas ranged from 2 mi² for the Salt Run drainage in Ohio to 15,700 mi² for the site on the Snake River in Idaho. Typical peak discharges at these sites result from spring snowmelt (S), winter-season rainfall (W), or summer thunder rainstorm (T) floods (Table 1 and Table 2).

Table 1. Data sources for slope-conveyance and HEC-RAS comparison.

Site	Location	Basin Area (mi ²)	Dominant Flood Type	Number of Discharge Estimates
1	Little Panoche Creek, CA	101	W	10
2	Los Banos Creek, CA	159	W	6
3	Panoche Creek, CA	293	W	44
4	Arkansas River, CO	611-4670	S,T	12
5	Uncompahgre River, CO	265	S	8
6	Snake River, ID	15,700	S	8
7	Salt Run, OH	2	S	8
8	Fish Creek, UT	60	S	4
9	Indian Creek, UT	10	T	6
10	Red Creek, UT	89	T	6
11	Strawberry River, UT	150	T	10
12	Yellowstone River, UT	114	S	4
13	Puyallup, WA	172	W	8
S – snowmelt; T – summer thunderstorm; W – winter rainstorm				

After the peak discharge estimates are made using HEC-RAS, the same wetting and disturbance flow values are computed using the slope-conveyance calculation. Because it is not always possible to estimate the water surface slope for extreme floods in the field without the benefit of high water marks or similar physical evidence, particularly for pre-historical paleofloods, the channel slope used in the slope-conveyance equation is measured from USGS 7.5 minute topographic maps. Channel slope is assumed to closely approximate the water surface slope. In a HEC-RAS step-backwater model, the channel slope can be determined from a line fitted to the thalweg profile of the HEC-RAS cross sections. The roughness parameters used in main channel of the HEC-RAS model are used in the slope-conveyance calculation to hold variables associated with roughness constant to minimize potential bias in the resulting peak discharge estimates. All channel roughness values are estimated based on field observations and published values (Barnes, 1967). The wetted area and hydraulic radius are calculated from the measured cross section data in the slope-conveyance equation using an Excel macro.

A similar process is used to evaluate the difference between peak discharge estimates made using HEC-RAS and SRH2D. Due to the requirement for greater resolution in the topographic data as input to the two-dimensional model, the number of comparable sites is much smaller. Three study sites with sufficient, readily available data were utilized in the analysis: Clear Creek downstream from Whiskeytown Dam, Los Banos Creek upstream of Los Banos Detention Dam, and South Fork Boise River downstream from Anderson Ranch Dam. The topographic data were developed using photogrammetry and different LiDAR methodologies. HEC-RAS and SRH2D models were created from the same

topographic data for each study reach in a similar fashion as the comparison of the slope-conveyance to HEC-RAS estimates. Discharge estimates were made at 20 different sites within the study reaches. The wetting and disturbance flows were determined from model output.

Table 2. Data sources for HEC-RAS and SRH2D comparison.

Site	Location	Basin Area (mi ²)	Dominant Flood Type	Number of Discharge Estimates
1	Clear Creek, CA	115-172	W, S	8
2	Los Banos Creek, CA	150-156	W	16
3	South Fork Boise River	982-1090	S	16

Evaluation of Peak Discharge Estimates

Slope-Conveyance to One-Dimensional Hydraulic Model Comparison

For this analysis, the peak discharge estimate derived from the slope-conveyance peak discharge calculation at each site was compared to the results of a one-dimensional step-backwater model (HEC-RAS). This comparison was made solely for the purpose of understanding the potential variability in peak discharge estimates. While the peak discharge estimates derived from the HEC-RAS step-backwater model are assumed to be more accurate than the results of the slope-conveyance calculations, and SRH2D estimates are assumed to be more accurate than HEC-RAS estimates, the principle objective was to quantify the difference between the peak discharge estimates. Figure 2 shows the comparison of peak discharge estimates made using the slope-conveyance versus HEC-RAS methods.

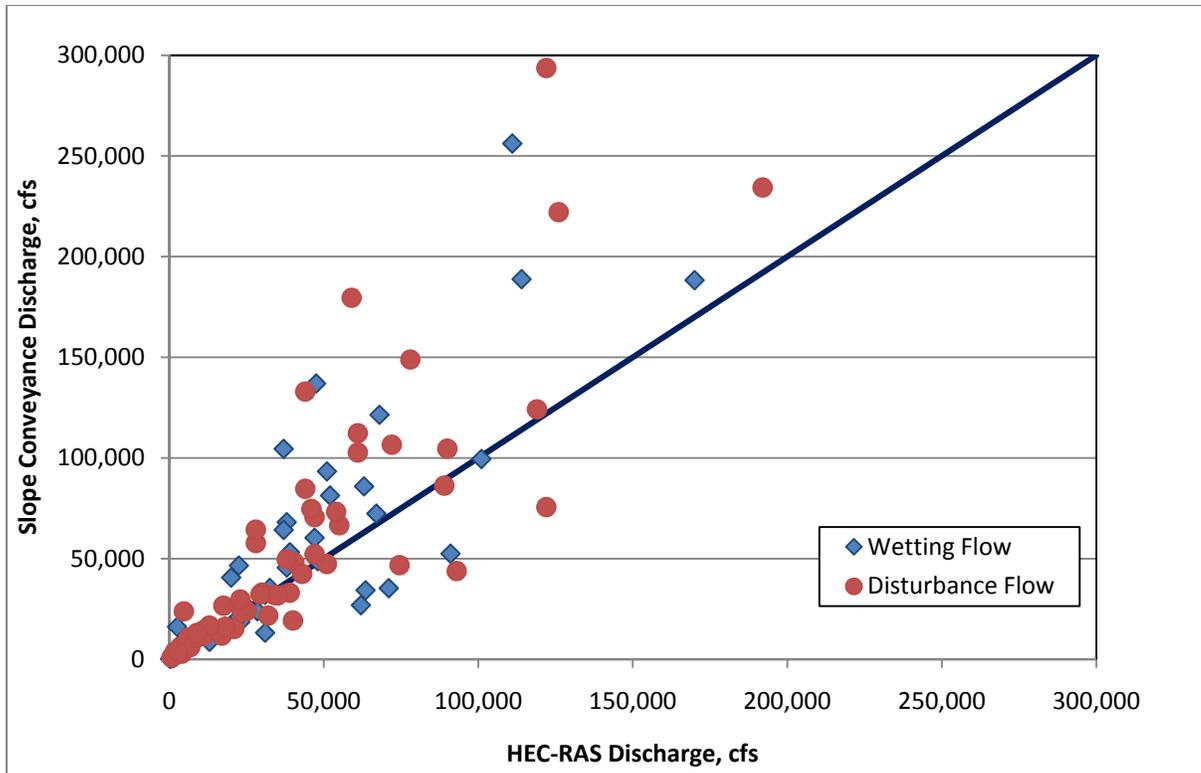


Figure 2. Comparison of slope-conveyance (Manning’s equation) and HEC-RAS peak discharge estimates.

On the basis of this comparison, it appears that the estimates made by the slope-conveyance computation are generally greater or overestimate the peak discharge estimate relative to those derived from HEC-RAS. On average, the slope-conveyance method over predicts the discharge compared to HEC-RAS by approximately 34 percent. The standard deviation between the two datasets is about 76 percent. The vast majority of the peak discharge estimates fall within the 95 percent confidence interval about the mean, but the difference reaches a maximum of 550 percent (Table 3) at Yellowstone Creek, UT. This suggests that the peak discharge estimate could be overestimated by as much as a factor of 6.

If the Yellowstone Creek site is removed from the analysis, the average percent difference between the slope-conveyance and HEC-RAS discharge estimate is reduced to 27 percent and the standard deviation is reduced to about 50 percent. Even by removing a site with a large difference in discharge estimates, there is still a significant amount of variability in these comparisons. In cases where there was a significant difference between the slope-conveyance estimate and the HEC-RAS value, the difference is believed to be related to complex channel geometry including changes in the overall width, and slope that could not be accommodated adequately in the slope-conveyance calculation.

Table 3. Statistical comparison of the percent difference between peak discharge estimates.

	% Difference between Slope-Conveyance vs. HEC-RAS	% Difference between HEC-RAS vs. SRH2D
Mean	35	15
Median	19	10
Mode	53	0
Standard Deviation	76	23
Range	606	98
Minimum	-57	-15
Maximum	549	83
Count	134	40
Confidence Level (95.0%)	13	7

Based on the discharge comparison in Figure 2, it appears that the difference in estimated discharge generally increases as the discharge increases. However, when the percent difference between the computation methods is compared to the base discharge (HEC-RAS for method 1 and SRH2D for method 2), the greatest difference actually occurs at a relatively low discharge (Figure 3) on a small stream (e.g., Yellowstone Creek, UT). For the slope-conveyance to HEC-RAS comparison, the percent difference for 16 of the 134 comparisons are greater than 100 percent, while 10 of those are for discharges greater than 20,000 ft³/s.

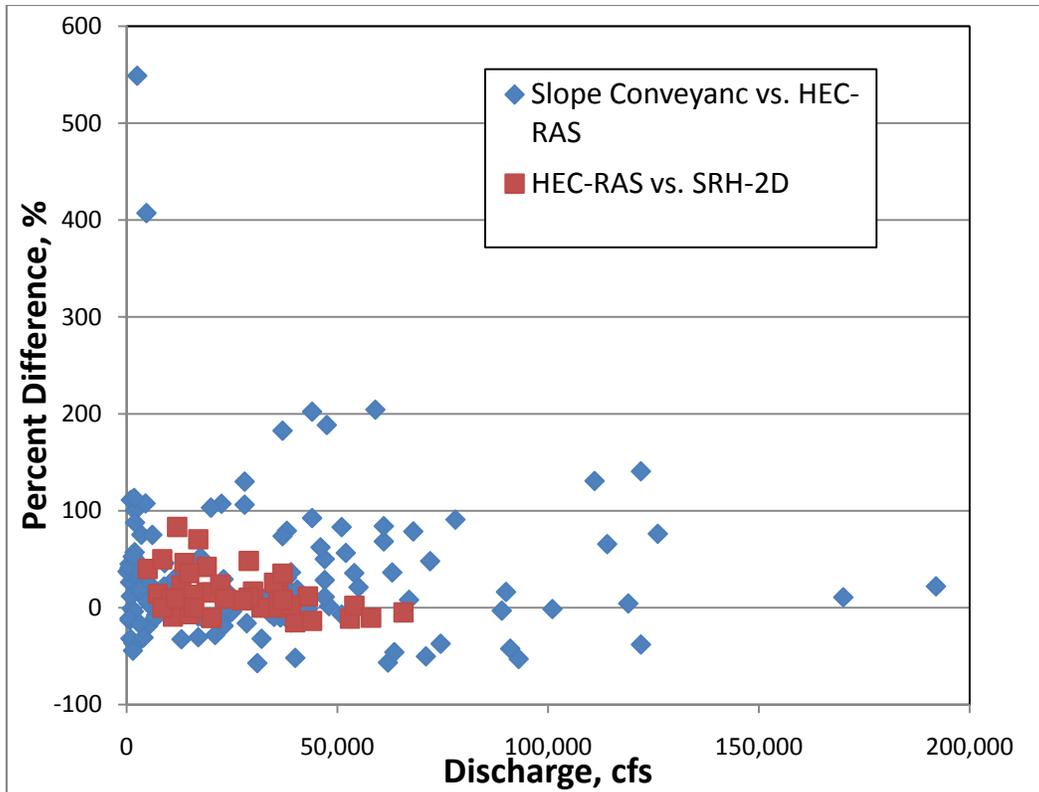


Figure 3. Plot showing the percent difference between computation method and discharge.

One-Dimensional to Two-Dimensional Hydraulic Model Comparison

Discharge estimates made using HEC-RAS were found to be generally larger than those made using SRH2D (Figure 4). On average, HEC-RAS discharge estimates are about 15 percent larger than estimates made using SRH2D. The mean and 95 percent confidence level for the HEC-RAS/SRH2D comparison are about half of those for the slope-conveyance/HEC-RAS comparison (Table 3). The most notable difference in the HEC-RAS/SRH2D comparison is that the standard deviation in the data is much less (23 percent) relative to that of the slope-conveyance/HEC-RAS comparison (76 percent). This result is supportive of the assumption that modeled results (i.e., using either a one-dimensional or two-dimensional hydraulic model) are more accurate than estimates made using a slope-conveyance computation used in all of the CFR flood hazard assessments.

Differences between HEC-RAS and SRH2D discharge estimates are believed to be largely related to velocity and conveyance. In a one-dimensional model, flow is assumed to be steady and uniform meaning that the discharge is constant (not surging) and that the flow velocity is the same at all points in a cross-section. This assumption becomes more and more invalid as water spreads across the

floodplain. Variations in channel and floodplain geometry as well as vegetation can cause significant differences in channel and floodplain velocity, which ultimately affects the water surface elevation and discharge that can pass through a given cross-section. Two-dimensional hydraulic models, such as SRH2D, can account for variation in velocity for each mesh cell, which ultimately more accurately estimates discharge at a given site.

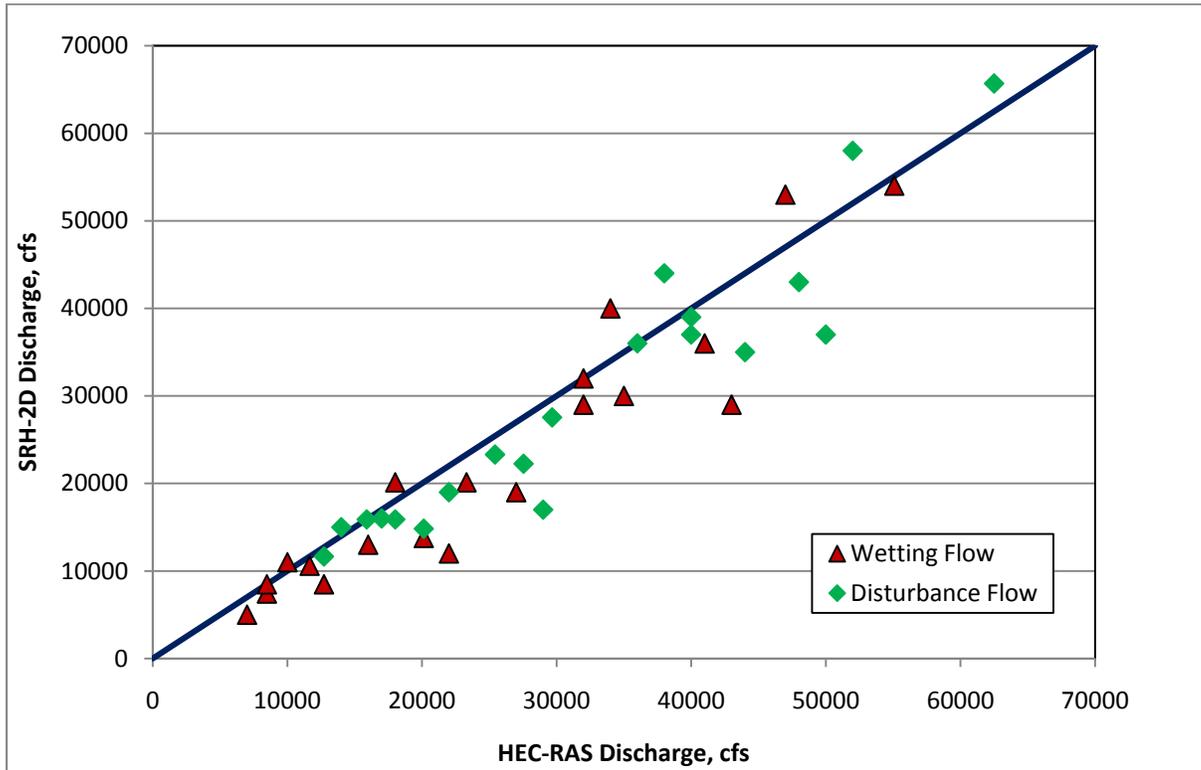


Figure 4. Comparison of HEC-RAS and SRH2D peak discharge estimates.

Discussion

The advantage of using a step-backwater model like HEC-RAS instead of the slope conveyance method to estimate discharge at a site is that physical changes in channel geometry can be better accounted for in this model over the simple single cross-section calculation. In the single cross-section slope-conveyance calculation, downstream changes in channel and floodplain width as well as slope and other topographic influences are assumed to remain constant, and any change in these characteristics from the measured cross-section are not accommodated in the Manning calculation. In turn, estimates made using the step-backwater model are understood to be most reliable in settings with simple geometry and of uniform width and slope. This can be a problem when making peak discharge estimates in reaches that have more complex channel geometries or multiple bends or meanders. Quite commonly, the best sites along rivers to evaluate the

stratigraphic evidence for flooding is in areas of complex channel geometries (bends, areas of changing channel width, at the mouth of tributaries) where flood depositions are best preserved. These model short-comings and problems associated with them illustrate the importance in site selection to making peak discharge estimates and especially when using the Manning's equation.

Sensitivity analyses on the slope and channel roughness parameters, used in the slope-conveyance calculation indicate that relatively minor changes in slope can significantly change peak discharge estimates. Slope is also the single most difficult parameter to measure in the field in regards to its relevance to a single measured cross-section. This is particularly true in channels with low slope or in channels that exhibit large changes in slope over a very short distance (e.g., in areas near rapids and riffles). Typically in the process of gathering reconnaissance-level data, channel slope is derived from USGS 7½' topographic quadrangle maps. Slope measurements for a specific site that are made from these maps are subject to significant error. In most cases the contour interval for these maps is often between 20 and 40 feet. Even in high gradient streams, there may be thousands of feet between contours on the map. These slope values may be useful for assessing site conditions, but it is very difficult to obtain a precise slope measurement from these maps and they may be too general for making accurate discharge calculations.

In regards to channel roughness, a single roughness value is used in the slope-conveyance method currently used in the CFR process, while HEC-RAS has the ability to use multiple roughness values across a single cross section as well as between cross sections. HEC-RAS also accommodates changes in channel geometry (i.e., channel width and slope) and areas of ineffective flow in developing peak discharge estimates. In general, the more accurately the channel geometry can be described in the model, the more likely it is that variability in the peak discharge estimates will be minimized.

An example of this situation is provided by two paleoflood studies that were performed to address perceived risk, one on the Uncompahgre River at Ridgway Dam (Klinger and Bauer, 2005), the second on the Cimarron River for Silver Jack Dam (Klinger and Bauer, 2007). Estimates of paleoflood non-exceedance discharges were made on each of these rivers using slope-conveyance estimates for peak discharge as part of the CFR risk analyses. In each case, the hydrologic hazard was deemed to pose a risk to the structure, so additional field studies (Issue Evaluations) were undertaken to verify the data that were utilized in the CFR.

In the case of the Uncompahgre River, it was determined that the reconnaissance-level data significantly overestimated the paleoflood peak discharge used for the non-exceedance discharge. The large discrepancy was determined to be the result of complex channel geometry that was not adequately accommodated in the slope-conveyance calculation and by local changes in channel slope. In the case

of the Cimarron River, an estimate of 5,000 to 7,000 ft³/s for the CFR using minimal field data as input significantly underestimated the discharge . A second estimate was made incorporating additional field data, but still using the slope-conveyance methodology, significantly increased the discharge estimate to 18,000 to 30,000 ft³/s. An issue evaluation utilizing a one-dimensional model to estimate the peak discharge was completed to resolve the tremendous discrepancy between the two previous studies. Estimates made at the same site using a HEC-RAS model predicted a peak discharge in the range of 12,000 to 14,250 ft³/s.

In the comparison of HEC-RAS and SRH2D discharge estimates, differences are likely due to the assumption of steady uniform flow in the HEC-RAS model. One-dimensional step-backwater models like HEC-RAS assume that the flow in the cross-section is flowing at a constant discharge (not surging) and that flow across the entire cross-section is of uniform velocity. SRH2D solves the two-dimensional depth-averaged form of the standard St. Venant depth-averaged shallow water equations for each cell in the model mesh, and as a result, is able to calculate a depth and velocity for each cell in the model grid (Lai, 2009). Due to non-uniform and often lower velocity flow across the floodplain versus the channel, discharge estimates using a two-dimensional model are usually lower than those calculated from a one-dimensional model, and rightfully so given the actual site conditions.

Numerous studies have previously been undertaken to evaluate the source of error associated with peak discharge estimates of stream flow, both gaged and from indirect measurements (see Pelletier, 1988). Evaluations of the quality of individual stream gaging records are also quite common (e.g., Meyer, 1998). In general, estimates of variability in stream flow measurements using current meters are reported to be as great as ± 10 percent, and variability in individual gage records vary depending on specific site conditions to as much as ± 40 percent. This is particularly true for larger peak discharges whose magnitudes may be many times greater than actual metered flows that define the gage rating curve.

In the published literature, peak discharge estimates of paleofloods have typically been derived using one-dimensional models, and many of the assumptions, potential errors, and quality control in these estimates have been discussed (O'Connor and Webb, 1988; Webb and Jarrett, 2002). Based on the results of numerous studies, error in peak discharge estimates for extreme historical floods using one-dimensional techniques range from 10 percent to more than 30 percent (Webb and Jarrett, 2002). Although this same range of error has been assumed to apply to peak discharge estimates for paleofloods, there is no reason to expect that this range of error is necessarily applicable. In Reclamation, hydrologic hazard studies, an error of ± 25 percent has commonly been applied, but without any quantitative reason for doing so.

Uncertainties in estimating paleoflood peak discharges are often complicated by the passage of time. Critical to the determination of peak discharge is the accurate measurement of the maximum water surface profile or peak stage. Substantial attention has been paid to methodologies involved in making these measurements and how to improve their accuracy (e.g., Williams and Costa, 1988; Jarrett and England, 2002). Webb and Jarrett (2002) contend that the greatest unknown and the most critical variable needed to ensure accurate paleoflood peak discharge estimates is the roughness value (Manning's n) used in the calculation. They discuss at length the impacts of vegetated channels found today versus the commonly unvegetated channels in the historical past and how this can have significant impacts on the results.

Results from this study suggest that the channel survey (i.e., topographic data) and specifically the determination of channel slope used in the slope-conveyance calculation have a much greater effect on peak discharge estimates than channel roughness. This point is illustrated by the recent evaluation of an indirect flow measurement done at Brushy Creek, NE for a flood in June 1947. At the time of the flood the stream gage at the site was not in operation and the indirect flow measurement is poorly documented. Based on the available information, the reported discharge for this flood is approximately 70,000 ft³/s. When cross-section values (width, depth, slope, and roughness) collected after the flood are used in the Manning equation, the estimated discharge is approximately 90,000 ft³/s. Closer inspection of the reported values revealed that the measured water surface slope was an order of magnitude higher than channel or valley slopes for the reach in question. If a more realistic slope value is used in the Manning equation, the discharge estimate is reduced to approximately 30,000 ft³/s. The source and location of the cross-section and slope measurements are poorly documented so it is difficult to reconstruct the conditions during the flood, but it is likely that high water marks from the flood were misinterpreted or errors were made in the measurement. This example shows how change in slope can greatly affect discharge estimates made using the Manning equation.

This point can be further illustrated with a simple exercise with the Manning equation. Differences in the estimated discharge can be evaluated by creating a simple cross section and varying either the roughness coefficient (n) or the slope while holding the other variable constant. For this case the cross-section was assumed to be 100 feet wide and 5 feet deep. A roughness of 0.03 and slope of 0.001 ft/ft were used as the starting point the comparison. For the first part of the comparison the roughness was increased and decreased by 0.01 while the slope was held constant at 0.001 ft/ft. For the second part of the comparison the roughness was held constant at 0.03 while the slope was varied from 0.01 to 0.001 ft/ft (plus or minus an order of magnitude). Varying the roughness results in a discharge range of approximately 1,600 ft³/s (Figure 5). Varying the slope by plus or minus an order of magnitude results in a discharge range over 6,000 ft³/s. The range of slope values used in this comparison is quite large, but as seen in the Brushy Creek example, differences of this magnitude are not entirely uncommon.

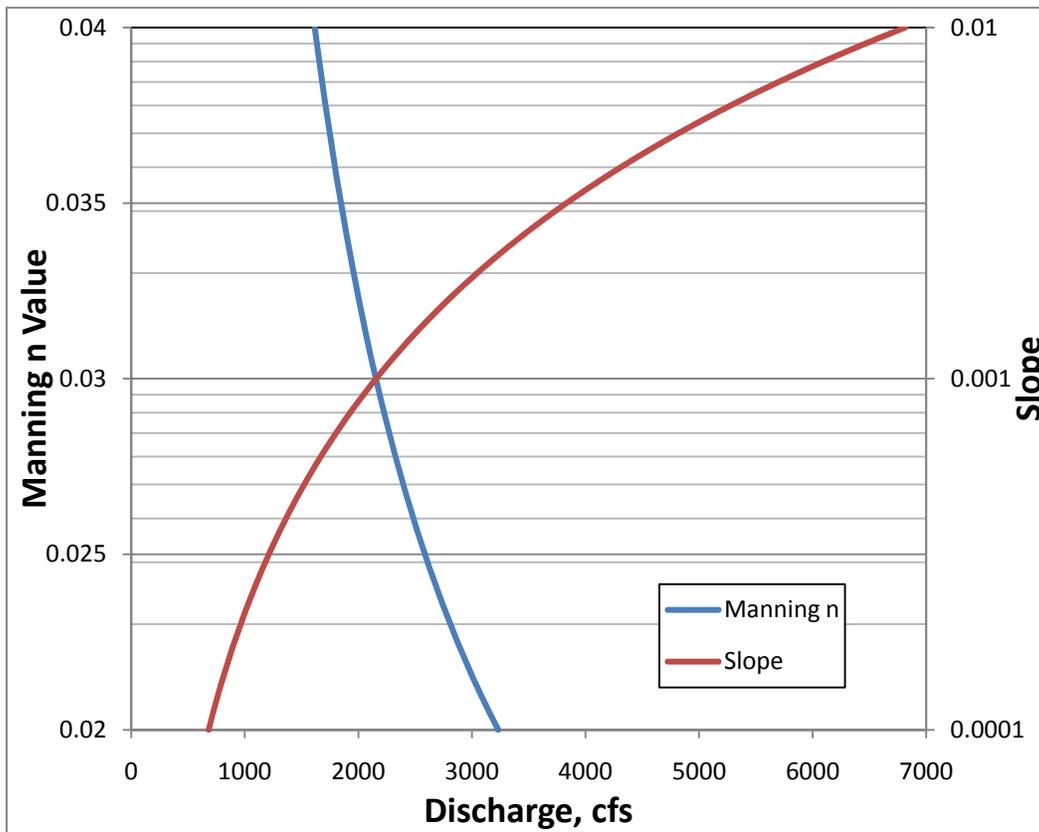


Figure 5. Comparison of discharge estimates made using the Manning equation by varying the roughness coefficient and the slope.

Attention has also focused on the amount of scour or deposition that may occur in the channel during the flood and how this affects the accuracy of a given peak discharge estimate. Much of the variability associated with these transient processes can be eliminated by selecting study reaches where bed conditions can be held constant (e.g., bedrock channels, nearby bed grade control). However, based on the results of numerous evaluations of extreme floods for Reclamation, the percentage of error in peak discharge estimates related to scour and/or deposition is considered relatively minor as there is often a large amount of water flowing over the floodplain and the channel area is often only a small portion of the overall wetted area during a flood.

Implementing the Results

The results of this research will be most useful in assessing variability associated with estimates of peak discharge made for CFR-level studies and will provide greater confidence in the methodology used in making peak discharge estimates for flood hazard studies by Reclamation. The confidence in and quality of

paleoflood peak discharge data available to risk assessment teams should help Dam Safety managers in making more informed decisions regarding flood hazards at Reclamation dams. The results of this study provide the basis for implementing an improved methodology in developing peak discharge estimates of paleofloods, thus reducing the variability in the paleoflood data and aiding in the extrapolation of frequency curves. Paleoflood peak discharge data are a major control on the position of the flood frequency curve for extreme floods with return periods beyond 100 years. Therefore, the reduction of variability in peak discharge estimates will better enable risk assessment teams to make stronger recommendations to program managers. For the greatest risks or areas with highest uncertainties regarding peak discharge estimates, a two-dimensional model offers substantially improved estimates over the slope-conveyance method. However, in circumstances where data and budget are limited and potential risks are lower, a one-dimensional model may offer sufficient certainty. The slope-conveyance method is not recommended unless sites are carefully selected and only for reconnaissance-level assessments. Sites should be selected in straight reaches with relatively constant width and slope. In addition a field measurement of channel slope should be attempted instead of using slopes estimated from USGS topographic maps. While obtaining accurate slope measurements may be difficult to obtain, given the influence this measure has on the estimate a priority should be placed on obtaining this information in the field.

For broader scoped studies conducted by Reclamation, peak discharge estimates have been made using a one-dimensional step-backwater hydraulic models (e.g., Klinger and Bauer, 2004; Klinger and Bauer, 2005; Klinger and Bauer, 2006; Klinger and Bauer, 2007) and in a few cases, the two-dimensional hydraulic model TRIM2D (e.g., Klinger and England, 2002; Levish and others, 2003). Reclamation's use of TRIM2D in the last decade has been limited because of extensive computation time and difficulty in adapting the code for accurately estimating peak discharges of paleoflood studies. SRH2D has now been successfully applied to several paleoflood studies (Anderson Ranch Dam, Klinger and Bauer, 2010; Whiskeytown Dam, Klinger and Bauer, 2009; Red Willow Dam, in preparation). Advances in computing capabilities and data processing along with the increased availability of detailed topographic data have made the use of two-dimensional hydraulic models much easier and less costly. The additional cost of using a two-dimensional model may be most suitable to situations where there is a high hazard dam with a potential for a large loss of life or high property loss and where large uncertainties in the peak discharge estimates are not acceptable.

Conclusions and Recommendations

Peak discharge estimates for either paleofloods or non-exceedance discharges comprise one part of the data used in flood hazard analyses. The objective of this

study was to directly compare peak discharge estimates made at Reclamation dams using different methodologies to quantify the variability. Comparisons were made between the results of a slope-conveyance calculation and a one-dimensional step-backwater model (HEC-RAS) and between the results of a one-dimensional model (HEC-RAS) and a two-dimensional model (SRH2D). Based on the analysis of model results, peak discharge estimates in reconnaissance-level field studies were found to be 34 percent larger on average than estimates made using HEC-RAS. However, in 4 out of the 134 cases this difference was found to be greater than 200 percent and as much as 550 percent. In the comparison between the one-dimensional model (HEC-RAS) and the two-dimensional model (SRH2D), the one-dimensional peak discharge estimates were found to be approximately 15 percent greater on average than the two-dimensional estimate, with ranges between -15 percent and 83 percent. An important result of this study is recognition of the potentially extreme variability in the peak discharge estimates made for CFR hydrologic hazard assessments. Given the potential errors in slope-conveyance estimates resulting from two important input parameters, slope and channel geometry, other indirect measurements of extreme flood peak discharges may be grossly overestimated. It is strongly recommended that all extreme peak discharge estimates be reviewed and re-evaluated if possible to improve the accuracy of the estimates, particularly for high hazard dams.

The advantage of using a two-dimensional model in paleoflood studies extends far beyond more accurately estimating peak discharge. The two-dimensional model can also be used as a reconnaissance and planning tool. If preliminary model runs can be completed prior to collecting field data, the model results can be used to identify sites that may preserve evidence of past floods. Model results can be used to identify areas that are subject to high or low shear stress. Areas of low shear stress are likely to preserve flood deposits while areas with high shear stress are likely to show signs of surface disturbance, erosion, or the truncation of soil profiles.

One of the more difficult aspects of a paleoflood study is trying to determine how much inundation is required across a floodplain or terrace surface to significantly disturb the site. The situation is complicated by vegetation growth and soil development. Soil formation can greatly change the characteristics of the ground surface by increasing particle cohesion and development of structure related to the breakdown of sediment, the formation and translocation of clay, and the accumulation of other soil materials. Root mass and the inclusion of organic matter into the soil profile can also increase the strength of a soil as well as the development of carbonate or silica cementation. Two-dimensional models can be used to help evaluate soil stability and the potential for site disturbance. The two-dimensional model SRH2D can calculate shear stress at each wetted cell in the model mesh. By using the calculated shear stress from the model output, the stability of bare granular sediment at each site can be evaluated for stability, thus providing an important tool to more precisely estimate peak discharges and evaluate related flow velocities that affect the stratigraphic record of past floods.

Some work has been done to assess site stability specifically due to vegetation. A method for designing roadside ditches (U.S. DOT, 2005) uses vegetation and soil parameters to calculate a permissible shear stress with the vegetation in place. This method was applied on the South Fork Boise River paleoflood study undertaken for Anderson Ranch Dam (Klinger and Bauer, 2010). The results showed that the discharge needed to disturb a site covered with vegetation could increase 2 or 3 times over the discharge needed to wet the site. The difficulty with this method is that there is a large amount of uncertainty in the vegetation characteristics, which results in a large range of permissible shear stress values needed to cause erosion at a particular site. In order to reduce the variability in site stability estimates, additional data are needed to verify this method for use in paleoflood studies by comparing calculated permissible shear stress values to field measurements of critical shear stress. Further exploring this aspect of the two-dimensional model capabilities is the object of proposed research in FY11.

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