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Generation of a Sediment Rating and Load Curve Demonstrated at the Mackinaw River Confluence

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) contains a description of the process to formulate sediment rating and load curves for the bed material load in the Mackinaw River. The calculated curves are intended to define the sediment yield at the mouth of the river for sediment harvesting with a sediment collector.

INTRODUCTION: The approach and data requirements described below are applicable for the generation of sediment concentration and sediment load rating curves (SRC) in a sand bed system. The SRC is a set of two complementary curves that define the sediment capacity and concentration at a given flow for a specific system. The SRC is necessary for defining sediment load for a sediment budget, a numerical model, or other sediment related field investigation.

Defining the SRC requires a series of steps. First, appropriate site-specific data are necessary. The data must include hydrodynamic, bed material gradation, basic cross-sectional data, and general site knowledge. Initially, all available data are collected and inventoried to define the missing data. Missing data may need to be estimated. Second, for each flow, normal depth computations are performed with hydrodynamic and cross-section data. Normal depth establishes the free surface at a cross-section for uniform flow conditions, and is required to pass a specific flow given the resistance coefficient (Sturm 2001). Third, using the collected, calculated, and estimated data from the previous steps, the most useful sediment transport functions are selected. Sediment transport functions are typically formulated based on regime, regression, probabilistic, and deterministic approaches. Finally, after running a series of sediment transport functions, dissemination of the calculated data is conducted to select the most appropriate function to define the SRC. The selected sediment transport functions are applied to bracket the sediment flux. Once the SRC is generated, a flow sequence can be processed through the SRC to determine the temporal supply of sediment at a given location.

BACKGROUND: The mouth of the Mackinaw River was selected as the demonstration site for this process. The confluence of the Mackinaw River and the Illinois River is four miles west of Pekin, Illinois. The Mackinaw River produces a shoal in the Illinois River that impinges on the navigation channel. The sediment deposition forms a natural delta that would encroach on the channel if not removed via dredging. However, the sediment has the potential for beneficial use. The Streamside Systems' Bedload Monitoring Collector (Lipscomb et al. 2005) is one model of a stationary sediment harvester that is capable of collecting sediment bed material before it enters the Illinois River. To estimate the removal rate for the system, the sediment load must be defined. The SRC provides a means to determine the available volume of bed material sediment available for harvesting and the peak delivery rates.

DATA REQUIRMENTS: Two forms of data are discussed here, collected and calculated, which are necessary to formulate the SRC. Collected data usually include hydrodynamic, bed gradation, and bathymetric data that are site specific. Calculated or estimated data are necessary to fill in the gaps to formulate the SRC. At this demonstration site, the calculated data include watershed adjustment computations (accounting for flow not captured by the gage), flood flow frequency analysis, and normal depth computations. These data are calculated using the collected data. Once gathered, the data are used congruently to formulate the SRC and calculate the transport potential.

Hydrodynamic data were derived from the USGS Mackinaw River near Green Valley streamflow gaging station (USGS station ID 05568000). The station has 90 years of record, including stage and discharge. It is ideal to have a long (at least 20 years) period of record. This provides the means to calculate the flood flow frequency curve. Additional collected data are the bed samples that were sieved to formulate percent finer bed gradation curves. The bed gradation curves describe the material that is available in the system for transport (Figure 1). An average bed gradation curve was calculated at the cross section of interest of all bed samples (Figure 1). If there is a large spread in the bed samples, then a sensitivity test should be performed by varying the bed gradation. The sensitivity test can be performed using the standard deviation. However, the standard deviation needs to bracket both the high and low end of the gradation spread, which it does in this case (Figure 1). The three curves can then be simulated to determine the variability in sediment flux with gradation. Here it was deemed unnecessary because the bed gradations were all within half of the magnitude of the spread. A finer sample would be more mobile, and require special attention due to their potential for flocculation. Finally, the bathymetric data were taken in the field using soundings and adjusted to pool elevation. For the Mackinaw River, the horizontal projection is State Plane North American Datum (NAD) 1983, Illinois West – 1202 U.S. Survey Feet, and the vertical datum is National Geodetic Vertical Datum (NGVD) 1929. The gage zero for the Green Valley streamflow gaging station (USGS station ID 05568000) is 477.10 feet from the soundings, and gage zero for the elevation of the bed was calculated along with the channel slope (Figure 2). These three pieces of information are imperative for the construction of an SRC.

Calculated and/or estimated data for the SRC includes the total watershed discharge, the flood flow frequency analysis, and the normal depth computation. The total watershed discharge must be estimated if there is not a streamflow gaging station at the watershed outlet. In this case, there is not a streamflow gaging station at the watershed outlet. The Green Valley streamflow gaging station (drainage area of 1,073 miles^2) encompasses 94% of the total Mackinaw River watershed (drainage area of 1,138 miles^2). Assuming the lower 6% of the watershed produces the same ratio of discharge in the river per watershed area, one can assume that the discharge can be scaled up to estimate the discharge at the watershed outlet using equation 1.

$$Q_{streamgage}/A_{streamgage} = Q_{watershed}/A_{watershed} \quad (1)$$

where $Q_{streamgage}$ is the discharge at the streamflow gaging station at each frequency interval, $A_{streamgage}$ is the watershed area at the streamflow gaging station, $Q_{watershed}$ is the discharge at the watershed outlet at each frequency interval (to be computed), and $A_{watershed}$ is the total watershed area. The total watershed discharge value was applied for the study.

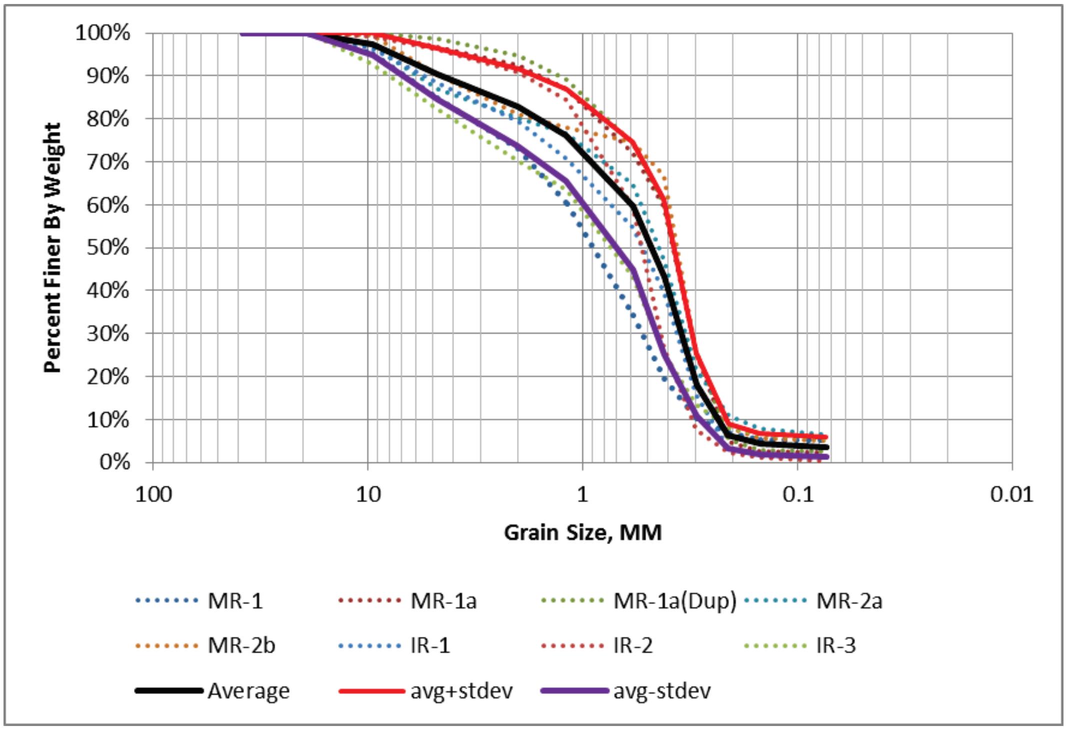

Figure 1. Bed sample gradations at the mouth of the Mackinaw River.

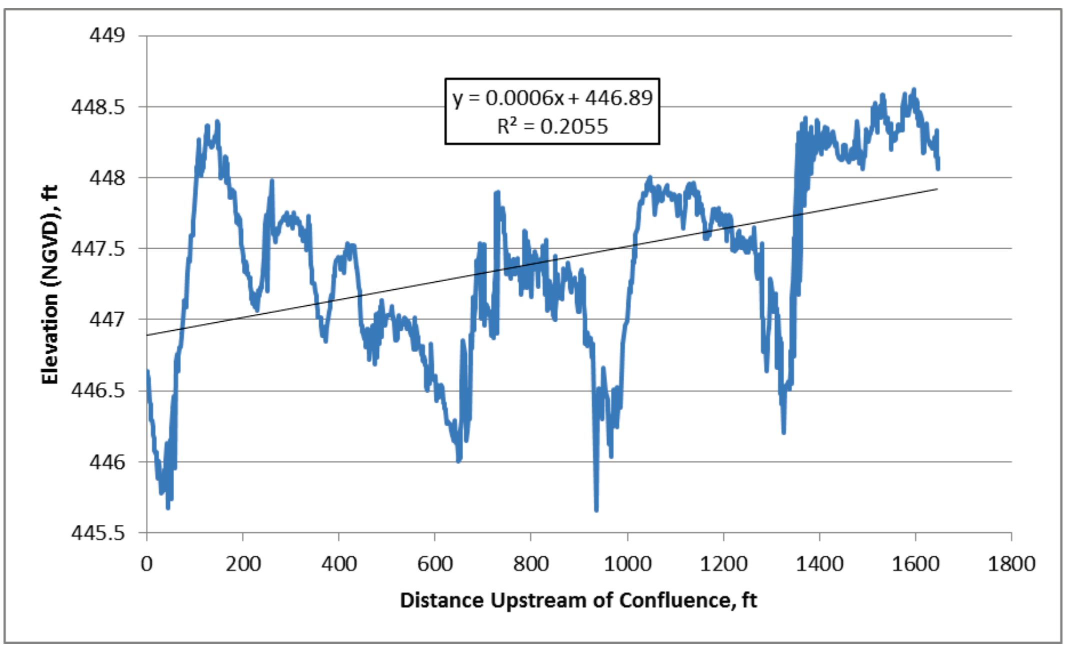

Figure 2. Estimated Mackinaw River channel slope from the confluence within the Illinois River based on bathymetry data

The flood flow frequency curve was computed using the recommended guidelines in Bulletin #17B (IACWD 1982). Here, the Log Pearson Type III method was applied. The frequency curve at the Green Valley stream gage (non-adjusted) and at the watershed confluence (adjusted) is shown in the flood flow frequency curve (Figure 3). In this system, there is a small flow difference between the two curves because the Green Valley stream gage captures 94% of the total watershed area. In other systems, the difference could be significant, thereby drastically altering the transport behavior of the system. Total flow delivered to the point of interest must be accounted for correctly in order to reduce error in the SRC computation.

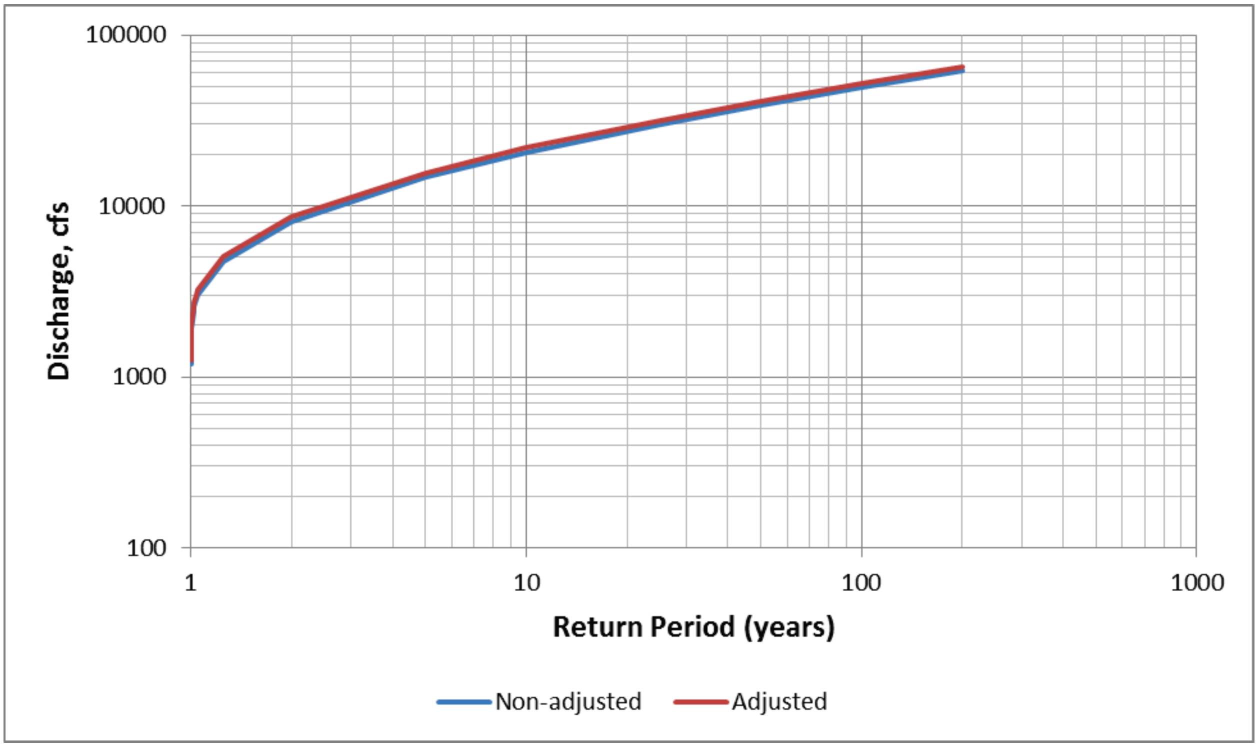

Figure 3. 1922-2011 flood flow frequency curves for the Mackinaw River near Green Valley gage (Non-adjusted) and the entire Mackinaw River watershed (Adjusted).

NORMAL DEPTH COMPUTATION: Normal depth computations were computed with the Stable Analytical Method (SAM) Hydraulic Design Package for Channels (USACE 2003). The normal depth is commonly computed with one of five uniform flow equations: Manning, Keulegan, Strickler, Limerinos, or Brownlie Bed Roughness (USACE 2003). It can also be computed using one of five Soil Conservation Service equations (USACE 2003). Careful consideration should be given to each method prior to use of any of the equations, see EM 1601 chapter 5 for additional information (USACE 1994). For this application, the Soil Conservation Service equations are not applicable (USACE 2003), but the uniform flow equations are useable for the system. The Brownlie equation is specifically formulated for transitioning from upper and lower regime flow (Brownlie 1983), a condition that is not occurring in this system. The Limerinos equation was formulated for course sand to cobble where the roughness is a function of the grain size class of the 84% passing (Limerinos 1970). While the roughness height is relatively significant for the Limerinos and Keulegan equations, it does not account for bed form losses. The remaining three equations are applicable for this location. For this effort, the Manning equation was implemented since it provided a mean range of the three functions (Figure 4).

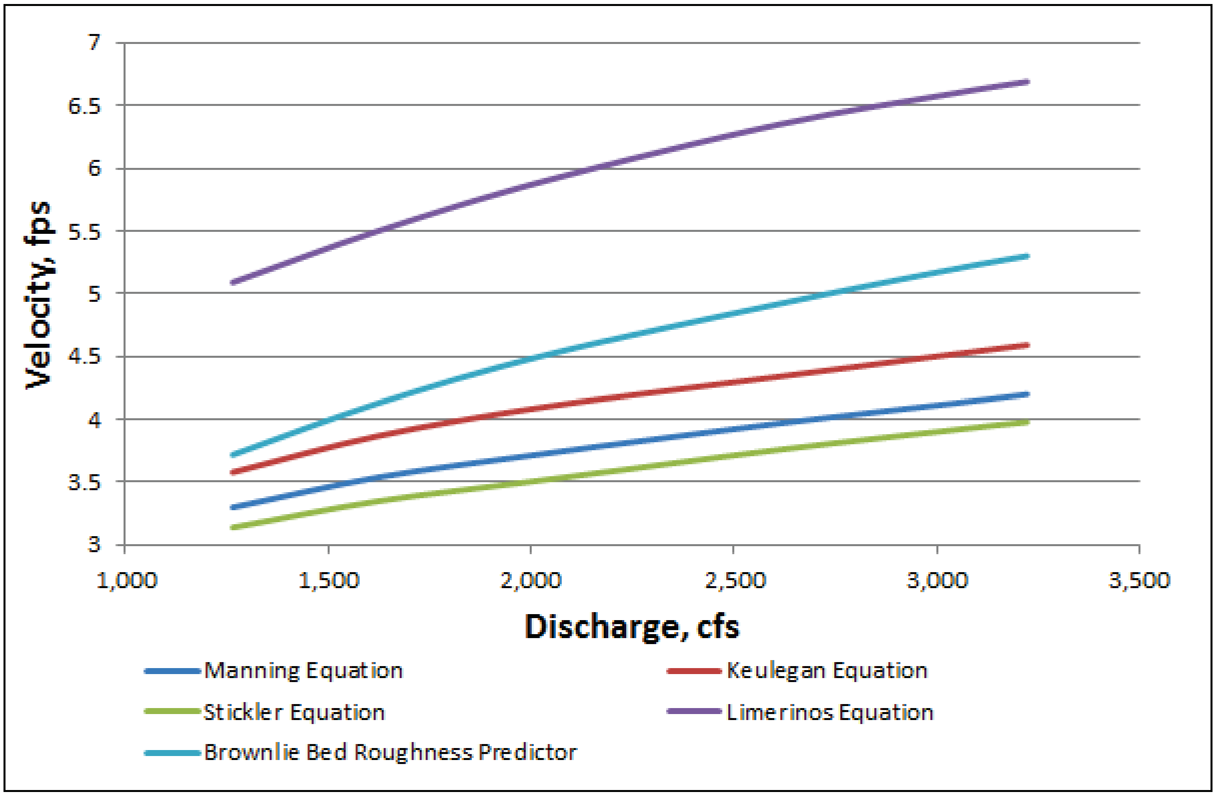

Figure 4. Results from five uniform flow equations applied to compute normal depth.

For this analysis, the normal depth computation does not consider backwater impacts. The Green Valley gage has a variation of less than 2 feet of stage height at any flow. Without stage and flow data closer to the confluence, there is not sufficient data to determine backwater impacts in the normal depth computation. Thus, there will be flows at higher stages that will not transport the calculated volumes.

TRANSPORT FUNCTION: Sediment transport functions are applicable for non-cohesive beds, which are defined as beds with frictional strength. However, the transport functions should be carefully selected as they are heavily site dependent. Furthermore, the functions at best "serve as guides to planning and usually the engineer is forced to rely strongly on experience and judgment in such work" (Vanoni 2006). SAM.aid is available within SAM to aid in the selection of the transport function. Typically, grain size class, slope, velocity, width, and depth are considered when selecting a function. Ideally, the three most appropriate functions should be selected for comparison when estimating an SRC.

The goal with applying multiple transport functions is to obtain a reasonable agreement between the selected functions. Reasonable agreement is defined as +/- 50% relative to the other calculated curves. If all three are in reasonable agreement, then any of the three can be applied. Likewise, it is recommended that if two of the three are in agreement, then one of the two can be selected. However, transport functions may not be applicable if at least two of the three selected equations are not within reasonable agreement. If there are not two functions within reasonable agreement with one another, then an alternative means should be taken to measure the SRC. This may require a long-term field data collection effort, which may be costly and time intensive.

Even with reasonable agreement between transport functions, it is possible to have an incorrect convergence. A fundamental understanding of sediment transport theory, transport functions, and how these relate to the specific site is necessary to best define the sediment load in a system. If there is insufficient agreement between the transport functions and additional data collection is planned, it is recommended to collect isokinetic depth integrated suspended samples across a cross-section at a few flows and compare the cross-section averaged observations to the computed concentration rating curve. Guidance for collecting samples can be found in Edwards and Glysson (1999). While this method accounts for the suspended load, it does not consider the bed load. However, the modified Einstein method (Colby and Hembree 1955; Einstein 1950; USBR 1955; USBR 1966) can be applied to estimate the bed load. The modified Einstein approach would give an indication to the correct magnitude of the transport capacity.

The Toffaleti-Schoklistsch was the first transport function applied for the Mackinaw River. This function is a combination of the Toffaleti (Toffaleti 1963; Toffaleti 1968; Toffaleti 1969) and Schoklistsch (Schoklitsch 1934) functions for sand and gravel bed streams. Both functions in combination are applied for the computation by grain size. The Toffaleti (Toffaleti 1963; Toffaleti 1968; Toffaleti 1969) portion of the function is applied to compute the suspended load. Bed load is computed with both functions, with the higher of the two being applied. Laursen Copeland was the second equation that was applied (Copeland and Thomas 1989), and it is a modification of the Laursen equation (Laursen 1958). This equation was modified for a broader grain size where it was extended into the larger gravel range. Finally, the third equation implemented was Yang (Yang 1973; Yang 1979). Yang initially was based on a single grain size, but was later extended for multiple grain sizes (Yang 1979). All three equations were viable options for the Mackinaw River confluence.

The concentration comparison shown in Figure 5 includes the results of the three functions along with the +/- standard deviation of the Yang equation. Two of the three, Yang and Toffaleti-Schoklistsch, show the closest agreement with an average variation of 11.6%. The Laursen Copeland average variation from that of Yang is 79.8%. Thus, the values from the Laursen Copeland equation were not considered. The Yang equation was selected as the SRC. Figure 6 shows the sediment rating curve by size class in milligrams/liter. Each color band on the curve represents the total concentration for the bed material load in its respective size class. The accumulation of all size classes represents the total bed material load at the cross section for each flow (note that the bed load is a portion of the bed material load). Likewise, Figure 7 shows the sediment load curve in tons/day. From these curves, the total daily bed material load and concentration can be estimated for a given flow. Using daily discharge and sediment rating curve, the average daily load is 4,200 tons per day and the average annual load is 1,500,000 tons per year. Therefore, based on these two curves, an appropriate streamside sediment collector can be sized and optimized for sediment harvesting.

APPLICATION AND VERIFICATION: The streamside sediment collector application was verified during 22, 23, and 24 July 2013 when two prototype bed load collectors were deployed at the Mackinaw River site. Flow rates for this period ranged from 291 to 275 cubic feet per second (cfs) and were on the falling limb of the hydrograph. Applying the average Mackinaw River discharge value for this period (283 cfs), the corresponding value in Figure 7 is 125 cubic yards per day (cy/day). The calculated sediment harvest value, based on field measurements, was 119 cy/day. Based on this trial, the SCR shows good agreement to the prototype sediment collector.

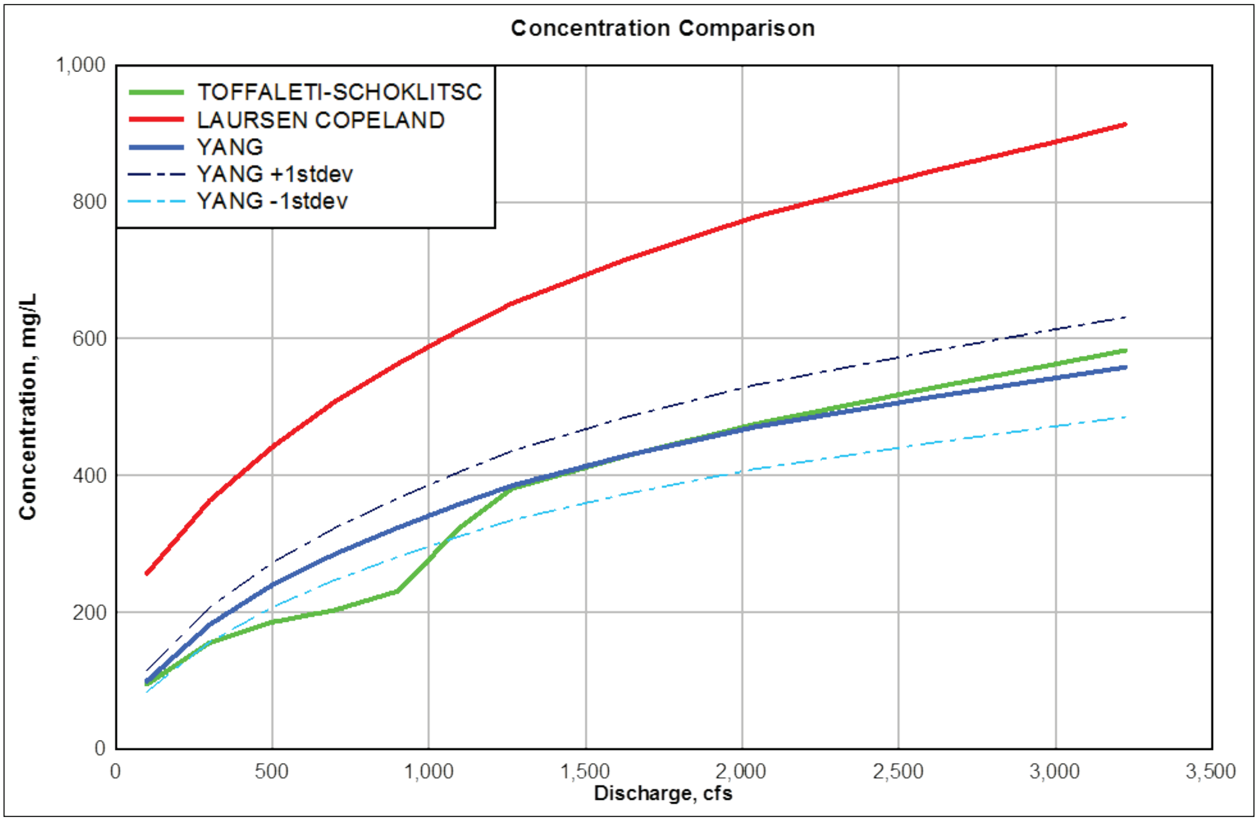

Figure 5. Concentration comparison for three selected functions.

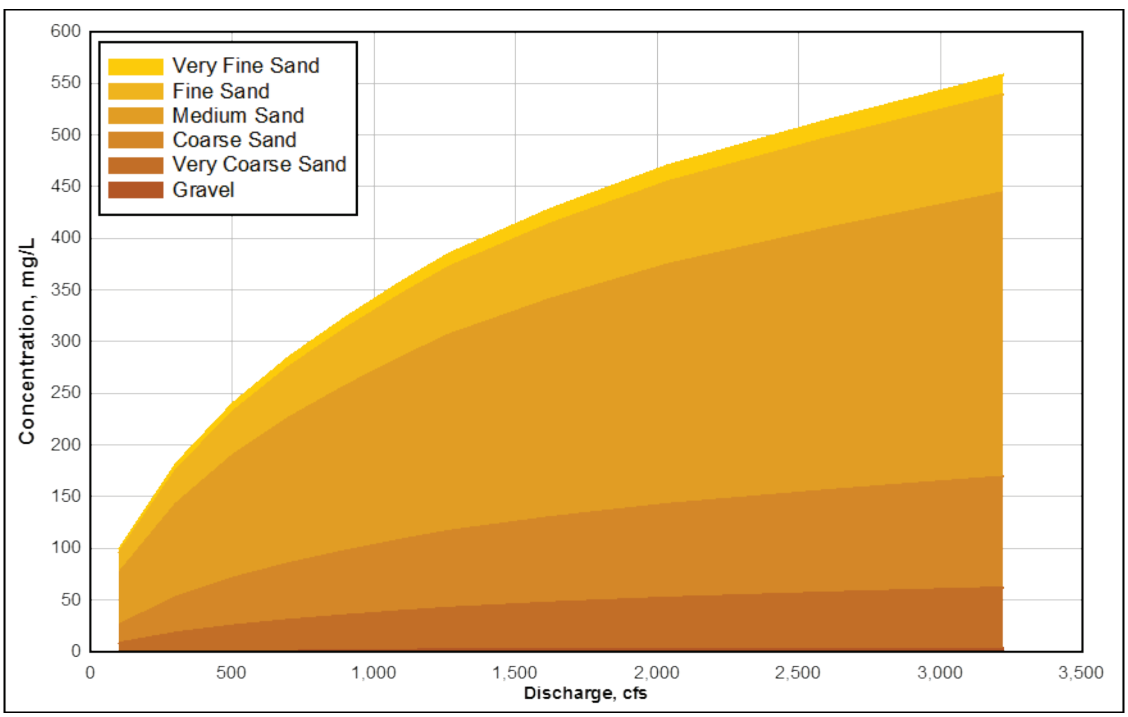

Figure 6. Sediment rating curve by size class for the Yang equation.

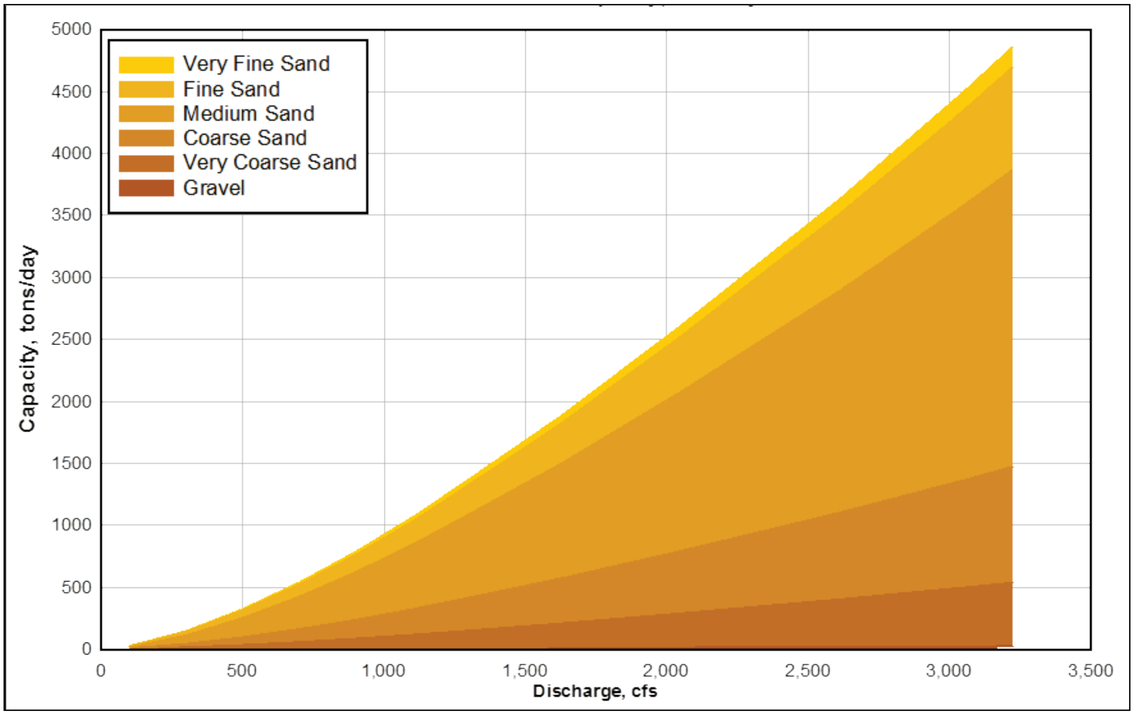

Figure 7. Sediment load curve by size class for the Yang equation.

ADDITIONAL INFORMATION: This Technical Note was prepared by Jeremy A. Sharp and Ronnie Heath, Research Hydraulic Engineers at the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center. Questions about this CHETN can be addressed to Sharp (601-634-4212; Jeremy.A.Sharp@usace.army.mil).

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