# The Sediment Rating Curve Analysis Tool: Downloading and Analyzing Suspended Sediment Rating Curves in HEC-RAS

**Stanford Gibson, PhD**, Senior Hydraulic Engineer, Hydrologic Engineering Center, USACE, Davis, CA, stanford.gibson@usace.army.mil
**Zachary Morris**, Computer Scientist, Hydrologic Engineering Center, USACE, CA
**Jim Lewis**, Senior H&H Engineer, Bard & Associates, Vicksburg, MS.
**David May,** MRG&P Lead, Mississippi Valley Division, USACE, Vicksburg, MS.

## Abstract

Sediment budgets and sediment transport models require continuous flow and sediment load data, but rarely have enough sediment data to satisfy this requirement. Scientists and modelers often use available sediment data to develop rating curves, relationships between flow and load (or concentration). They then combine the continuous flow series and the flow-load rating curve to estimate the continuous sediment load record.

This practice makes sediment budgets and models very sensitive to the rating-curve analyses. The statistical assumptions built into these rating curves can change the model or sediment budget results as much as 100%. Developing these rating curves correctly requires several statistical best-practices that are not always widely applied.

The Hydrologic Engineering Center (HEC) has developed a sediment rating curve analysis tool to help scientists and modelers analyze sediment flux data (suspended loads, concentrations, and gradations). This tool is incorporated in HEC-RAS (HEC's "River Analysis System") but can be used as a standalone tool that does not require a HEC-RAS model to use.

The Rating Curve Analysis Tool automatically downloads data from the US Geological Survey (USGS) sediment database or from local text or excel files. The tool then guides modelers and scientists through standard statistical and sediment analyses. The rating curve analysis tool helps sediment practitioners develop an unbiased rating curve, explore piecewise linear improvements, analyze data stationarity, distinguish replicates from independent observations, visualize hysteresis, and identify gradational trends.

## Introduction

Sediment budgets and sediment transport models require continuous time series of sediment flux, but temporal-census sediment flux data are rarely available. If a continuous flow time series, and opportunistic (i.e. as funding and project motivation available) suspended-sediment data are available, scientists and engineers often generate an analytical relationship between flow and load and use this flow-load or flow-concentration rating curve to convert the continuous flow time series into a continuous sediment flux time series (Figure 1).

Suspended-sediment flux data usually have a positive, non-linear relationship to flow. Fitting a power function to the data – using a log transformed linear regression – is the most common way to convert the data into a rating curve.

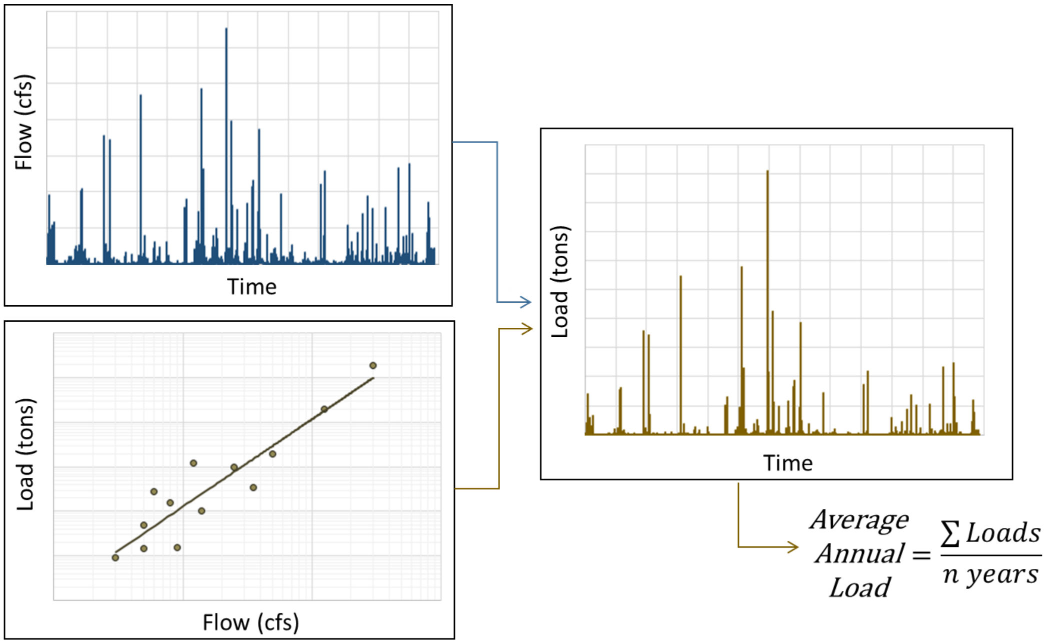


**Figure 1.** Illustration of how engineers and scientists use continuous flow data and opportunistic sediment samples to estimate continuous sediment loads. Fitting a rating curve to the flow-load samples allow analysts to "convert" continuous flow to continuous load, and, potentially to an annual average load estimate. But this process is very sensitive to the rating curve fit to the flow-load data.

The flow-load relationships usually take the form of:

$$Q_s = aQ^b$$

where $Q$ is flow, $Q_s$ is sediment load, $a$ is a small linear coefficient, and $b$ is a power, usually between 1.5 and 2.5. However, flow-load data are notoriously noisy. For a given flow, loads or concentrations often vary by an order of magnitude, and sometimes multiple orders of magnitude. Multiple scales of natural variability complicate the relationship between flow in load, driving inter-annual variability, intra-event variability (e.g. hysteresis) (Williams, 1989, Malutta et el. 2020), and even sub-hour variability between samples (Wood, 2022). This variability can mask directional trends and non-stationarity that analysts should account for when they develop sediment rating curves.

Many sediment scientists and engineers have independently developed subsets of best practices to analyze flow-load data over the years. This work set out to consolidate and standardize several of these statistical and data management best practices and develop a tool that guides sediment scientists through these standard analyses, without requiring each practitioner to develop their own independent practices.

HEC developed a Sediment Rating Curve Analysis tool in HEC-RAS that downloads sediment data directly from the USGS (or from various offline file formats) and guides users through standard statistical and sediment analyses. While this tool is included in HEC-RAS, it does not require an HEC-RAS model. Users can launch it from an empty HEC-RAS project. This paper outlines the common sediment data problems encountered while developing flow-load rating curves and how the Sediment Rating Curve Analysis Tool applies best practice analyses.

# Sediment Data Analyses

## Log-Transform Bias

Power function fits through log-distributed data and generally takes a least-mean-square, log-transform, linear regression approach. This method for fitting a power function is common, for example, Excel uses this approach. However, the de-transform calculation introduces a systemic bias into power functions fit with this approach. Log-transformed power functions are systemically biased low (e.g. they will compute too little load). Analysts must apply a bias correction to account for this data artifact. Therefore, a more appropriate equation for a fit sediment rating curve is:

$$Q_s = E\,aQ^b$$

where $E$ is a linear, bias-correction factor (>1) that compensates for the asymmetrical transformed residuals. Two common approaches to bias correction are the Duan (1983) and Ferguson (1986) approaches. Because bias correction is best practice, the Sediment Rating Curve tool applies it automatically. The tool computes both Ferguson and Duan (Figure 2). But it also computes two different corrections for each. The "All Data" correction assumes each sample is independent and "Averaged" applies the regression and bias correction to a data set that averages all samples taken within a user specified time window (e.g. same-day replicates – see section on *Averaging Replicates*).

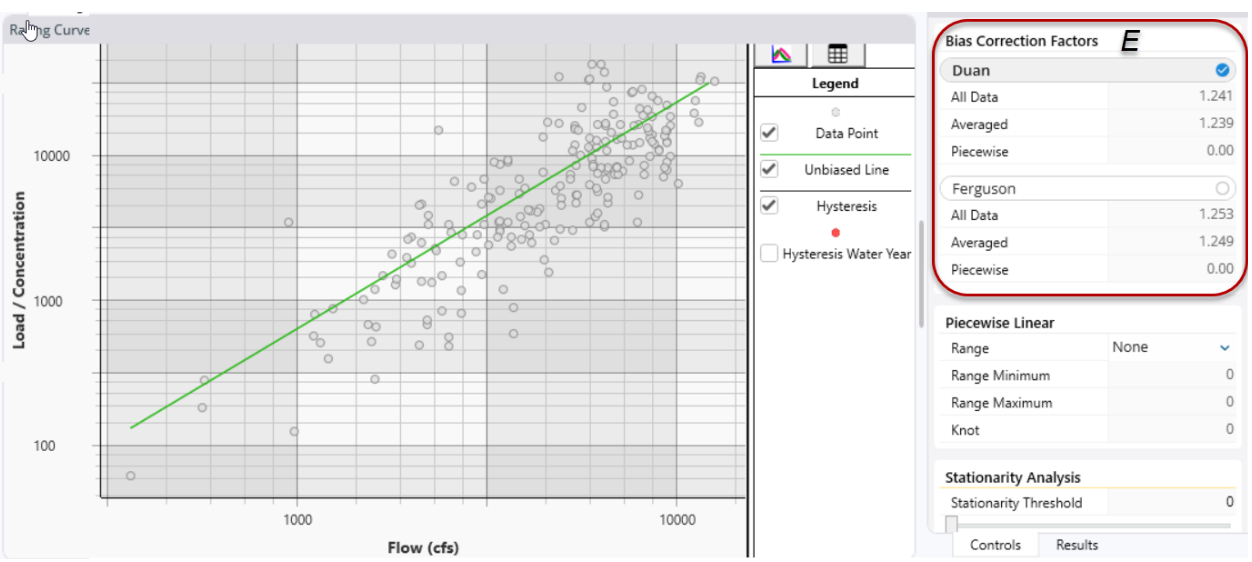


**Figure 2.** Data from the Genesee River at Avon, NY (Gage 04228500) with a fit power function using the 1.24 Duan bias correction. The tool also provides the Ferguson correction and generates separate corrections if all samples are independent ("All Data") or if same-day data are averaged.

## Piecewise Linear

A single power function represents many flow-load data sets well. However, different processes can affect low flows and high flows so that the flow-load relationships have distinctly different slopes over different flow ranges. The Rating Curve Analysis Tool includes an algorithm that fits a continuous, (transformed), piecewise-linear rating curve to the data. Figure 3 illustrates the value of this approach, as the Saline River has a distinct flow-load slope for its higher flows and a two-slope rating curve fits these data much better.

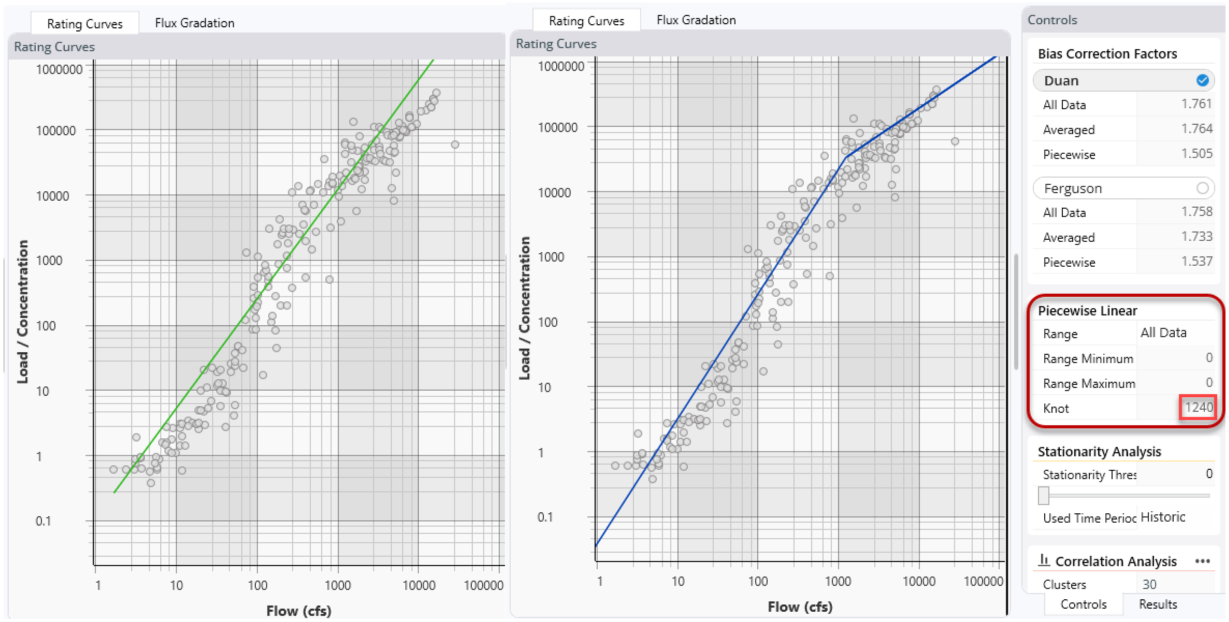


**Figure 3.** Saline River near Russel Kansas (Gage 06867000) with a single, unbiased, fit, power function fit and a continuous, piecewise linear fit (right) with an inflection point ("knot") at 1,240 cfs.

The piecewise linear, "bent" or "inflected" rating curve can fit this continuous two-slope relationship based on a user specified flow for the slope inflection point (i.e. the "knot") or it can find the inflection flow automatically, choosing the knot that gives the least mean square error. The tool also computes bias corrections for these inflected rating curves.

## Stationarity Analysis

Not all scatter in flow-load relationship can be attributed to natural variability. Sometimes loads have temporal trends. If the loads do not have a substantial trend with time (e.g. the data are stationary), it may be appropriate to include all the data in a single regression. However, if the data have a significant temporal trend, they are non-stationary, and it may be appropriate to temporally stratify the data and fit separate rating curves to separate time periods.

The stationarity analysis tool plots data before and after a user specified date with different colors and fits independent rating curves to them. Users can scroll quickly through threshold dates with the scroll bar to explore different potential non-stationarity events. For example, river engineering activities in the mid-1960s changed the sediment load regime of the river in Figure 4. The tool illustrates and quantifies this shift.


**Figure 4.** Arkansas River data at Tulsa stratified by pre-1964 (•)and pos-1964 (•) samples, illustrating the non-stationarity of these data. The Rating Curve tool develops separate unbiased regressions for each time period.

## Averaging Replicates

Sampling practices have changed over the years. At many gages, early data include single samples while more recent data include multiple replicates collected on the same day (Figure 5). Including all replicates in the regression violates the independence assumption of the regression, and over-weights the multiple, modern samples relative to the single, older, samples.

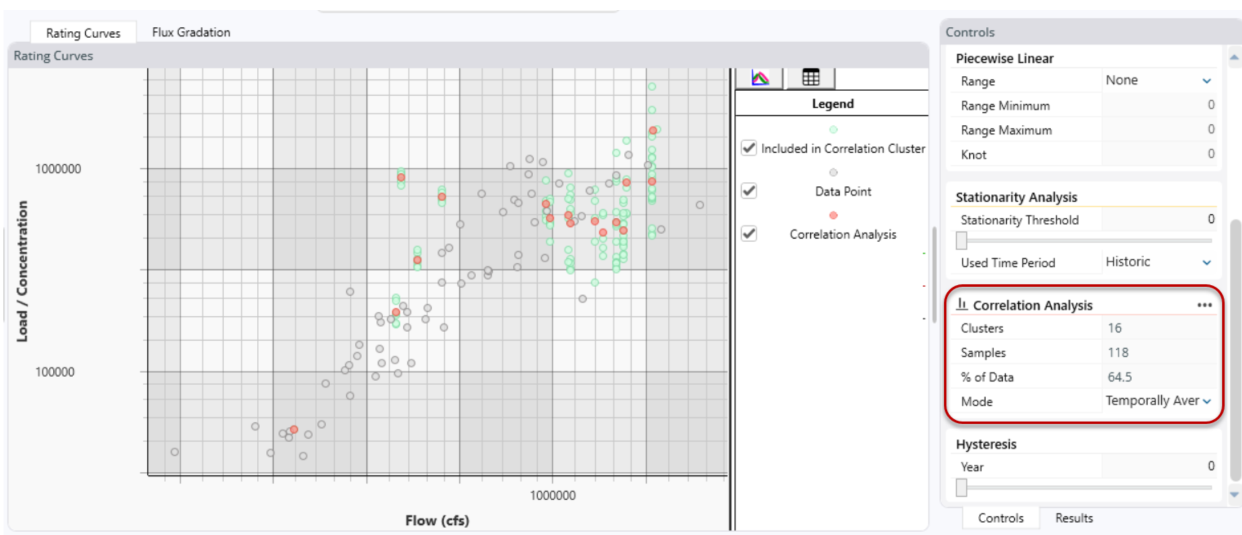


**Figure 5.** Mississippi River Sediment Data at the Memphis gage. Grey points (•) are independent (only one-per-day) samples while green points (•) are same-day replicates. Pink points (•) are the averages of each cluster of same-day replicates. The feature to "Temporally Average Clusters" is selected, which means the tool will use the grey and pink points and ignore the green points for most analyses.

The Rating Curve Analysis Tool will average all data collected within a user specified time window (usually same-day data). Figure 5 illustrates this analysis. Grey points are single, independent, samples, green points are same-day replicates, and the pink points are the averages of the same-day replicates.

The Sediment Rating Curve Analysis Tool provides some statistics on how many observations are included in the specified time windows (i.e. data clusters) and the percentage of the data in these temporal clusters. Users can choose to "Treat as Independent" or "Temporally Average Clusters." If temporal averaging is selected, the tool will use the averages for all the analyses (e.g. stationarity, hysteresis, piecewise linear). But the tool automatically computes bias correction for both averaged and non-averaged data whether this option is selected or not, because averaging data is usually appropriate.

## Hysteresis

One of the most significant sources of scatter is intra-event variability called *Hysteresis*. Sediment loads on the rising limb of the hydrograph are often different than the falling limb. Malutta *et al.* (2020) lists thirty potential causes of multiple kinds of hysteresis (e.g. clockwise, counter clockwise, figure eight) but clockwise hysteresis (more sediment on the rising limb than the falling limb) - driven by supply limitation - is the most common type.

The hysteresis tool plots the temporal path dependence of the samples in each water year so users can visualize the annual data in sequence. Figure 5 includes a data set with strong clockwise hysteresis in most years. The Hysteresis tool helps users visualize these loops and identify the intra-event variability.

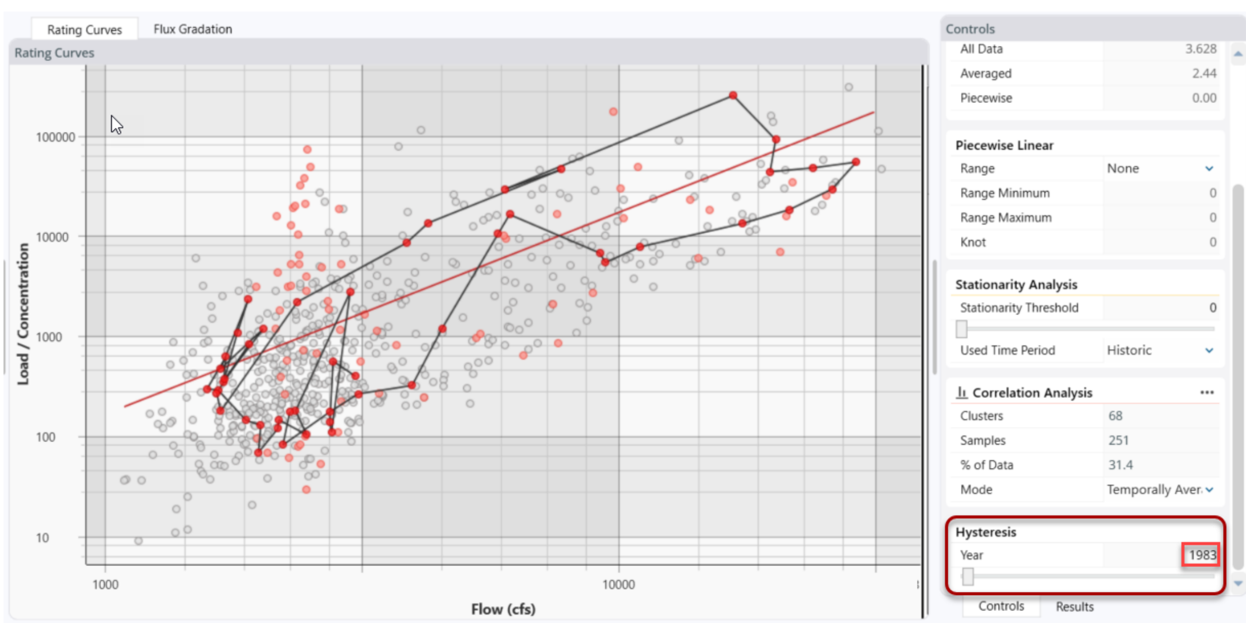


**Figure 5.** Colorado River Near Cameo (09095500) data ( independent observations and daily averaged). The sequential path of the 1983 samples (●) illustrates strong clockwise hysteresis.

## Flow-Gradation Analysis

All the previous analyses and visualizations described consider total, suspended-sediment, load data. But sediment sizes are log-distributed (Parker, 2008). The different size classes respond non-linearly to hydrodynamic forces and have very different ecological and engineering impacts. Therefore, it is usually important to understand how these suspended load data are distributed between particle-size classes. Additionally, sometimes the size-distribution of the suspended sediment also trends with flow. However, Gibson and Cai (2017) demonstrated that sediment load data can fine or coarsen with flow (i.e. as flow increases the median grain size can increase or decrease). They also demonstrated that the flow-gradation relationships can have no discernable trend or complicated non-monotonic relationships. The flux gradation tool allows users to visualize and identify these trends (Figure 6).

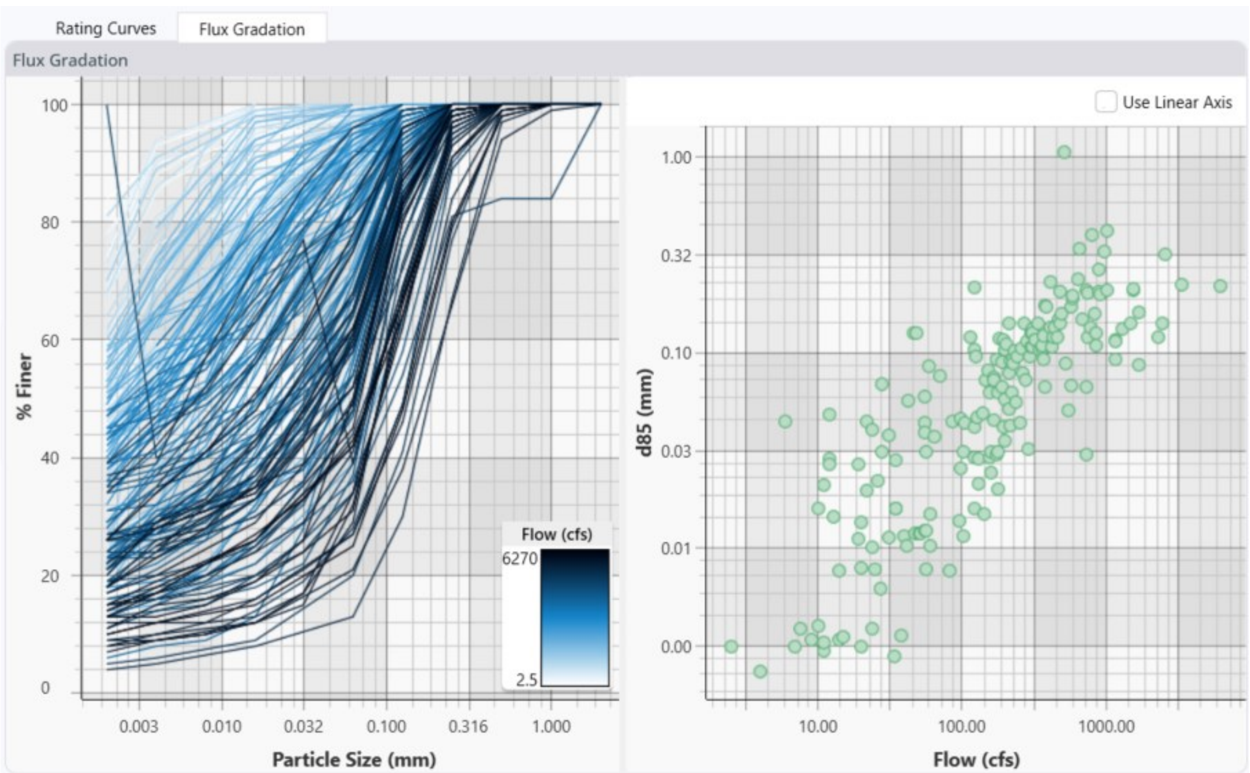


**Figure 6.** Rating Curve Analysis Tool plots of sediment gradation data from the Paria River at Lees Ferry, AZ (09382000). The higher flow curves (darker blue) are coarser than the lower flow (lighter blue) gradation curves (left). The $d_{85}$s increase with flow (right).

Figure 6 includes a data set with strong flow-coarsening trend (i.e. the loads associated with higher flows are coarser). The monochrome gradation curves on the left plot show lower flows in lighter colors and higher flows in darker colors, which illustrates the light→dark, fine→coarse trend as flow increases. The right visualization in Figure 6 plots the $85^{th}$ percentile grain size of each sample against flow. A direct relationship indicates flow-coarsening while flow-fining trends plot invers Q-$d_{85}$ relationships.

This tool pulls gradation data from the USGS database. The ability to import from other, external, file formats is not available yet.

## Availability, User Support, and Future Work

The Rating Curve Analysis Tool is available with the latest version of HEC-RAS, which is public domain software and can be freely downloaded. These features are fully documented online (HEC, 2022), and several video tutorials are available to help users get started.

The Mississippi River Geomorphology and Potamology Research and Development Program is actively investing in this tool and several additional features are under development. These included non-linear (e.g. local Loess regression), stratifying data by sampler type, bin averaging for the flow-gradation plots, more sophisticated non-stationarity analyses, and autocorrelation algorithms. We are also working on features that will compute concentration time series based on flow series and computed rating curve and will generate an annual average sediment flux.

## Conclusion

HEC has developed a Rating Curve Analysis tool to help sediment scientists and modelers to download, visualize, and analyze flow-load and flow-gradation data. The tool helps compute bias corrections, vit piecewise linear models, average replicates, analyze stationarity, visualize hysteresis, and distinguish flow-gradation trends.

## Acknowledgment

This work was funded by the USACE Mississippi River Geomorphology and Potamology R&D program (MRG&P).

## References

Duan, N. 1983. “Smearing estimate: A nonparametric retransformation method,” Journal of the American Statistical Association, 78(383):605–610.

Ferguson, R. I. 1986. “River loads underestimated by rating curves,” Water Resources Research, 22(1):74–76.

Gibson, S. A., & Cai, C. 2017. “Flow dependence of suspended sediment Gradations,” Water Resources Research, 53. https://doi.org/10.1002/2016WR020135

HEC 2022. “Sediment Rating Curve Analysis Tool,” HEC-RAS User Manual, Version 6.3, https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/hydraulic-design-hd-calculators/sediment-rating-curve-analysis-tool.

Malutta, S., Kobiyama, M., Chaffe, P.L.B., Bonuma, N.B. 2020. “Hysteresis analysis to quantify and qualify the sediment dynamics: state of the art,” Water Science and Technology,” 81.12, 2471-2487.

Parker, G. 2008. “Transport of Gravel and Sediment Mixtures,” Sedimentation Engineering Manual of Practice 110: Processes, Measurements, Modeling, and Practice – Chapter 3, edited by Marcelo Garcia, 165-251.

Williams G. P. 1989. “Sediment concentration versus water discharge during single hydrologic events in rivers,” Journal of Hydrology 111, 89–106. 10.1016/0022-1694(89)90254-0.

Wood, M. (2022) Sediment Measurement Variability, Web Video posted 15Nov2022, https://youtu.be/yGhb8EyyiBs.