# PRELIMINARY ANALYSIS OF SUSPENDED SEDIMENT RATING CURVES FOR THE KALAMAZOO RIVER AND ITS TRIBUTARIES FROM MARSHALL TO KALAMAZOO, MICHIGAN

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**ABSTRACT**: Suspended sediment concentration (SSC) rating curves for the Kalamazoo River and its tributaries from Marshall to Kalamazoo, Michigan, U.S.A., were developed based on measured data. The slopes of the at-site SSC rating curves were of two general types: either increasing or decreasing with increasing discharges. By examining the basin characteristics and flow patterns, streams with negative SSC rating curve slopes were associated with groundwater-dominated streams and those with positive slope terms were associated with surface-water dominated streams. A panel regression with fixed-effects analysis was applied to the pooled at-site data according to various grouping criteria. The results from the subgroups which considered groundwater and surface-water dominance, seasonality, and dam effects showed better fit than the at-site SSC rating curves did. It was assumed that the rating curve slopes for sites in each subgroup were the same but their intercepts varied from site to site. The groundwater and surface-water dominance division was used as the basis for estimating SSC at ungaged sites. The study was conducted as a component of hydrodynamic modeling under the Enbridge Line 6B pipeline oil-spill recovery activities.

## INTRODUCTION

**Background**: The July 25, 2010 oil spill that occurred near Kalamazoo, Michigan, was one of the largest oil spills into freshwater in North American history. The Enbridge Line 6B pipeline released approximately 843,000 US gallons of dilbit (http://www.epa.gov/enbridgespill/, accessed February, 2013), which is bitumen diluted with natural gas condensate, into a wetland draining to Talmadge Creek and then to the Kalamazoo River downstream from Marshall, Michigan. The spill impacted 38 miles of the waterway. Less than a month after the spill, the dilbit submerged, likely because of mixing and forming aggregates with fine-grained particles of mineral sediment and organic matter (Dollhopf et al., 2014). The large quantity of oil released required the development and implementation of new approaches for detection and recovery of submerged oil and oil-particle aggregates (OPAs) (Dollhopf et al., 2014). Fitzpatrick et al. (this volume) provided a detailed overview of the hydrodynamic modeling work that was done for the spill response. The modeling, which started in 2011 and continued into 2014, helped to answer questions about the fate and transport of the remaining submerged oil in the Kalamazoo River, and whether the oil would be transported out of the Morrow Lake delta and past Morrow Dam. To establish hydrodynamic model boundary conditions suspended sediment samples were collected from the oil-affected reach for analysis of suspended sediment concentrations and loads. This paper describes the challenges encountered in the development of rating curves for estimating the suspended sediment concentrations (SSC) for the hydrodynamic models used to predict the movement of sediment and OPA.

**Study Reach**: The study reach extended 38 miles from the site of the pipeline spill at Talmadge Creek downstream to the confluence with the Kalamazoo River, and downstream on the Kalamazoo River to Morrow Dam (Fig. 1). Some of the tributaries included in the study are too small to identify in figure 1 but are listed in table 1. Table 1 is a list of study reaches from the upstream to downstream direction together with their drainage areas and streamflow gage status.

**Suspended Sediment Rating Curve**: A water discharge ($Q_w$) to suspended sediment concentration (SSC) rating equation is referred to as an SSC rating curve in this paper. An SSC rating curve commonly takes the simple log-linear form as:

$$\log_{10}(SSC) = a + b \times \log_{10}(Q_w) + \varepsilon \qquad (1)$$

where:

$\log_{10}(SSC)$ = the $\log_{10}$ transformed SSC, in milligrams per liter (mg/l),
$\log_{10}(Q_w)$ = the $\log_{10}$ transformed $Q_w$ at the time of SSC measurement or estimation, in cubic feet per second (cfs),
$a$ is the intercept and $b$ is the slope of the linear regression, and
$\varepsilon$ is an error term.

The SSC rating curve has been widely used for estimating SSCs in rivers at similar flow conditions (Colby, 1956; Porterfield, 1972). However, when applying the ordinary least-squares (OLS) method to estimate the regression equation parameters based on the logarithms of measured SSC and $Q_w$, the resulting equation may underestimate SSC at high flows (Ferguson, 1986; Singh and Durgunoglu, 1989). Some authors (for example, Asselman, 2000) have proposed using nonlinear least-squares regression to mitigate this potential underestimation. Transforming $\log_{10}$(SSC) back to SSC can introduce a bias and Helsel and Hirsch (1992) recommend addressing the bias by using the Smearing estimator.

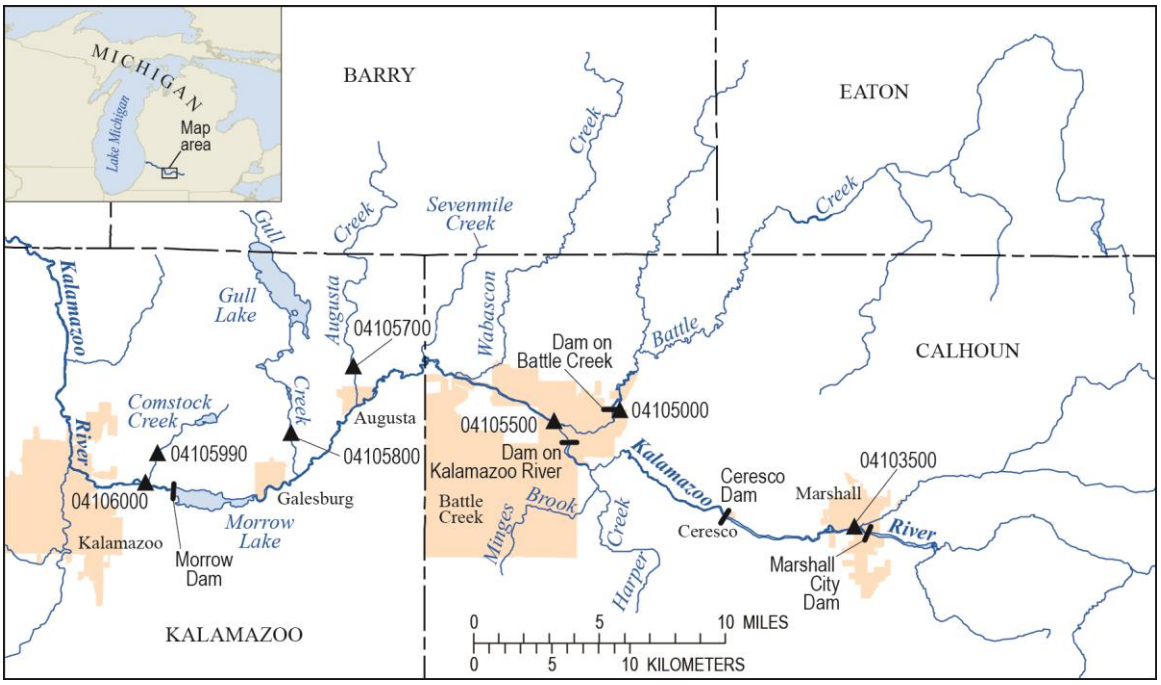


Figure 1 Diagram showing the study reach in the Kalamazoo River Basin.

Developing an SSC rating curve is challenging because SSC samples are typically limited in number and scattered around the rating curve. Scatter contributes to uncertainty of derived rating curves (Porterfield, 1972). Glysson (1987) illustrated many possible causes that could lead to variability in rating curves, such as seasonality and asynchrony of sediment peaks in relation to discharge peaks. Colby (1956) discretized the rating curve with partial-year records when seasonal variations were obvious. Different SSC values could be expected at equivalent $Q_w$ in the rising and falling limbs of a storm hydrograph (hysteresis effect) (Ahanger et al. 2013; Baca, 2008). Considerations for deriving a meaningful at-site SSC rating curve may include (1) the coverage of the ranges of discharge and SSC to be estimated (that is, avoid extrapolation beyond the range of measured data), (2) the amount of measured data at specific flow ranges of interest for an application, and (3) exclusion of extreme sediment-transport rates from mixed populations of sediment-production processes (such extremes might occur after a dredging or dam removal).

Physiography and human activity (such as roads and structures) are common factors in the sediment concentration regimes. With the sediment availability and delivery governed by watershed and channel (hydraulic) characteristics, the parameters $a$ and $b$ (equation 1) are unique at individual sites. There have been

attempts to attribute physical meaning to the parameters *a* and *b*. For example, Morgan (1995) considered that the intercept, *a*, represents an index of erosion severity, and slope parameter *b* indicates the extent to which new sediment sources become available as discharge increases. Based on sediment characteristics in the Lower Yellow River, Mai et al. (1990) interpreted *a* to characterize the boundary conditions, such as the incoming sediment composition, and *b* to characterize the sediment carrying capacity. Asselman (2000) did not find these parameters to have any physical meaning.

Table 1 Rivers included in the study and their drainage areas and streamflow gage status in upstream to downstream order. Drainage areas for ungaged locations are calculated at the confluence with the Kalamazoo River.

| ***Station Number or Ungaged*** | ***Site Name*** | ***Drainage Area, $mi^2$*** |
|---|---|---|
| 04103500 | Kalamazoo River at Marshall, MI | 449 |
| Ungaged | Talmadge Creek, MI | 3.3 |
| Ungaged | Bear Creek, MI | 14.8 |
| Ungaged | Minges andHarper Creek, MI | 54.9 |
| 04105000 | Battle Creek at Battle Creek, MI | 241 |
| 04105500 | Kalamazoo River near Battle Creek, MI | 824 |
| Ungaged | Wabascon Creek, MI | 43.1 |
| Ungaged | Sevenmile Creek, MI | 16.4 |
| 04105700 | Augusta Creek near Augusta, MI | 38.9 |
| 04105800 | Gull Creek at 37th Street near Galesburg[1], MI | 38.1 |
| 04105990 | Comstock Creek at E. Main Street near Kalamazoo[2], MI | 18.3 |
| 04106000 | Kalamazoo River at Comstock, MI | 1,100 |

1. Gull Creek at 37th Street near Galesburg (04105800) has daily streamflow records between 10/01/1964 and 02/02/1973.
2. Comstock Creek at E. Main Street near Kalamazoo (04105990) has 28 field discharge measurements between 02/06/1964 and 09/03/2002.

## MEASURED DATA AND ASSESSMENT

**Data collected during the project:** The USGS collected SSC data in August 2012, January through April 2013, and in March 2014. For each round of water samples, SSC samples were collected at five gaged sites (table 2) in the study reach. Samples were not collected at the two historical gage sites on Gull and Comstock Creeks.

Table 2 Description of data collection stations and suspended-sediment data availability

| ***Station Number*** | ***Site Name*** | ***Number of Project samples*** | ***Number of Historical samples*** |
|---|---|---|---|
| 04103500 | Kalamazoo River at Marshall, MI | 6 | 0 |
| 04105000 | Battle Creek near Battle Creek, MI | 6 | 0 |
| 04105500 | Kalamazoo River near Battle Creek, MI | 6 | 0 |
| 04105700 | Augusta Creek near Augusta, MI | 6 | 4 |
| 04105800 | Gull Creek at 37th Street near Galesburg, MI | 0 | 4 |
| 04105990 | Comstock Creek at E. Main Street near Kalamazoo, MI | 0 | 4 |
| 04106000 | Kalamazoo River at Comstock, MI | 6 | 4 |

**Historical data:** SSC data collected in the mid-1980s from 29 sites covering the main stem and tributaries of the Kalamazoo River were retrieved (C. Hoard, USGS, written communication, February, 2013). Four of the 29 sites are in the study reach and each of the four sites has four samples. Table 2 summarizes the sites and SSC data points available for the study and table 3 lists the data. Hereafter, the gaged sites will be referred to by their station numbers.

Table 3 List of available suspended sedimentation concentrations (milligrams per liter, mg/l) according to the location, date, discharge (in cubic feet per second, cfs), and water temperature (in Celsius). [SSC: suspended sediment concentration]

| Station Number | Sample Date | Instantaneous discharge, in cfs | SSC, in mg/l | Water Temperature, in ℃ |
|---|---|---|---|---|
| 04103500 | 8/16/2012 | 243 | 20 | 21.72 |
| 04103500 | 1/15/2013 | 422 | 23 | 1.3 |
| 04103500 | 2/1/2013 | 575 | 18 | 0.11 |
| 04103500 | 3/18/2013 | 259 | 51 | 3.15 |
| 04103500 | 4/22/2013 | 1150 | 25 | 11.18 |
| 04103500 | 3/31/2014 | 826 | 27 | 7.0 |
| 04105000 | 8/16/2012 | 57 | 9 | 20.34 |
| 04105000 | 1/15/2013 | 273 | 8 | 0.67 |
| 04105000 | 2/1/2013 | 398 | 17 | 0.06 |
| 04105000 | 3/18/2013 | 422 | 45 | 1.48 |
| 04105000 | 4/22/2013 | 1410 | 48 | 9.07 |
| 04105000 | 3/31/2014 | 937 | 23 | 3.2 |
| 04105500 | 8/16/2012 | 436 | 23 | 21.02 |
| 04105500 | 1/15/2013 | 813 | 22 | 0.87 |
| 04105500 | 2/1/2013 | 1500 | 29 | 0.03 |
| 04105500 | 3/18/2013 | 1040 | 48 | 2.42 |
| 04105500 | 4/22/2013 | 3000 | 91 | 9.1 |
| 04105500 | 3/31/2014 | 2060 | 14 | 5.1 |
| 04105700 | 8/1/1986 | 39 | 35 | 20.5 |
| 04105700 | 10/7/1986 | 104 | 7 | 10.5 |
| 04105700 | 6/15/1987 | 27.3 | 44 | 21.2 |
| 04105700 | 9/91987 | 28 | 45 | 18 |
| 04105700 | 8/16/2012 | 24 | 20 | 18.1 |
| 04105700 | 1/15/2013 | 46 | 18 | 0.22 |
| 04105700 | 2/1/2013 | 111 | 14 | 0.1 |
| 04105700 | 3/18/2013 | 37 | 24 | 2.85 |
| 04105700 | 4/22/2013 | 89 | 22 | 8.7 |
| 04105700 | 3/31/2014 | 75 | 6 | 4.7 |
| 04105800 | 7/31/1986 | 47 | 6 | 27 |
| 04105800 | 10/7/1986 | 102 | 3 | 15.5 |
| 04105800 | 6/15/1987 | 15.4 | 8 | 27 |
| 04105800 | 9/9/1987 | 30.7 | 5 | 24 |
| 04105990 | 7/31/1986 | 7.6 | 3 | 25.5 |
| 04105990 | 10/71986 | 19.5 | 3 | 17 |
| 04105990 | 6/15/1987 | 4.54 | 5 | 30 |
| 04105990 | 9/9/1987 | 6.24 | 1 | 25 |
| 04106000 | 7/31/1986 | 778 | 8 | 26 |
| 04106000 | 10/9/1986 | 3100 | 7 | 13.5 |
| 04106000 | 6/17/1987 | 580 | 11 | 27 |
| 04106000 | 9/11/1987 | 762 | 39 | 22 |
| 04106000 | 8/16/2012 | 445 | 18 | 22.5 |
| 04106000 | 1/15/2013 | 598 | 22 | 2.2 |
| 04106000 | 2/1/2013 | 2090 | 9 | 0.1 |
| 04106000 | 3/18/2013 | 1440 | 31 | 2.6 |
| 04106000 | 4/22/2013 | 3750 | 74 | 8.2 |
| 04106000 | 3/31/2014 | 2290 | 5 | 5.0 |

**Timing of collected data:** The SSC data were collected near the storm peaks or slightly afterward during the falling limbs of the hydrograph (Fig. 2). The magnitudes of SSC collected on March 31, 2014 were much lower than those for samples collected previously. As part of the oil-mitigation work, sediment from the channel upstream of the Ceresco Dam, located approximately 3.75 miles downstream from the confluence of Talmadge Creek and the Kalamazoo River, was dredged and removed. Additionally, the channel was shaped to a wide floodplain channel and the Ceresco Dam (near Ceresco in Fig. 1) was notched in October 2013. Because of this dredging and channel alteration, the March 31, 2014 SSC data at sites 04105500 and 04106000 were not included in this analysis.

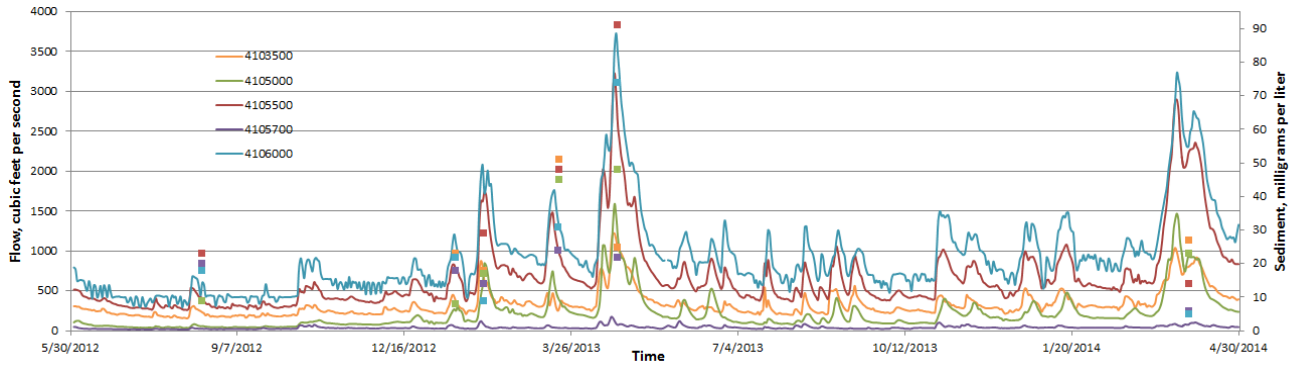


Figure 2 Timing of suspended sediment concentration data collection in relation to flow from June 1, 2012, to April 30, 2014. (Solid lines represent the hydrographs and dots show suspended sediment concentrations.)

**Flow regimes of collected data**: Both project and historical SSC data are plotted in relation to the flow duration curves (FDCs) to determine how well they represented the full streamflow regime. The FDCs were developed using mean-daily streamflow records from water years (WY) 2001 to 2014. The flow exceedance probability used for plotting the SSC data was computed based on the instantaneous discharge reported with each sample, assuming the differences between mean daily discharge and instantaneous discharge are not appreciable. The SSC data spanned a wide range of flow duration at each site (Fig. 3).

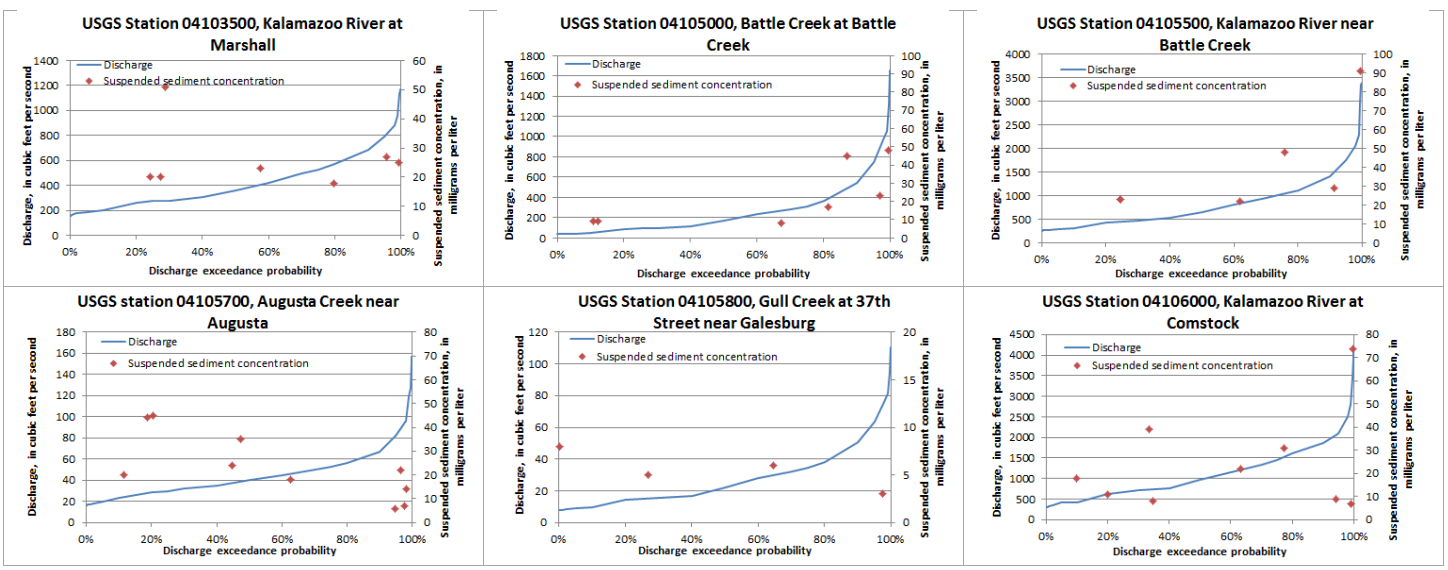


Figure 3 Coverage of suspended sediment concentration data in relation to discharge exceedance probability (flow-duration curve). Note as discussed in the "Timing of Collected Data" section, the March 31, 2014 SSC data at Kalamazoo River near Battle Creek (04105500) and Kalamazoo River at Comstock (04106000) were not included in this analysis.

The FDC for site 04105990 was not developed because the site has only 28 historical miscellaneous streamflow measurements. However, based on the 28 streamflow measurements, the range of flows for Comstock Creek is from 1.76 to 19.5 cfs, and the SSC measurements are considered to have covered the range of flows reasonably well.

## AT-SITE SSC RATING CURVES AND SITE CHARACTERISTICS

**At-site SSC rating curves**: Figure 4 shows log-log plots of $Q_w$ and SSC data for each site, along with the rating curve obtained from OLS regression. All data except for the two samples collected on March 31, 2014 at sites 04105500 and 04106000, were used in developing the at-site rating curves. Each at-site SSC rating curve was obtained from OLS regression between all remaining $\log_{10}(Q_w)$ and $\log_{10}(SSC)$ data pairs. Although the dataset sizes were limited, the trend of the resulting rating curves was considered representative because the sampled SSC data spanned much of the respective FDCs.

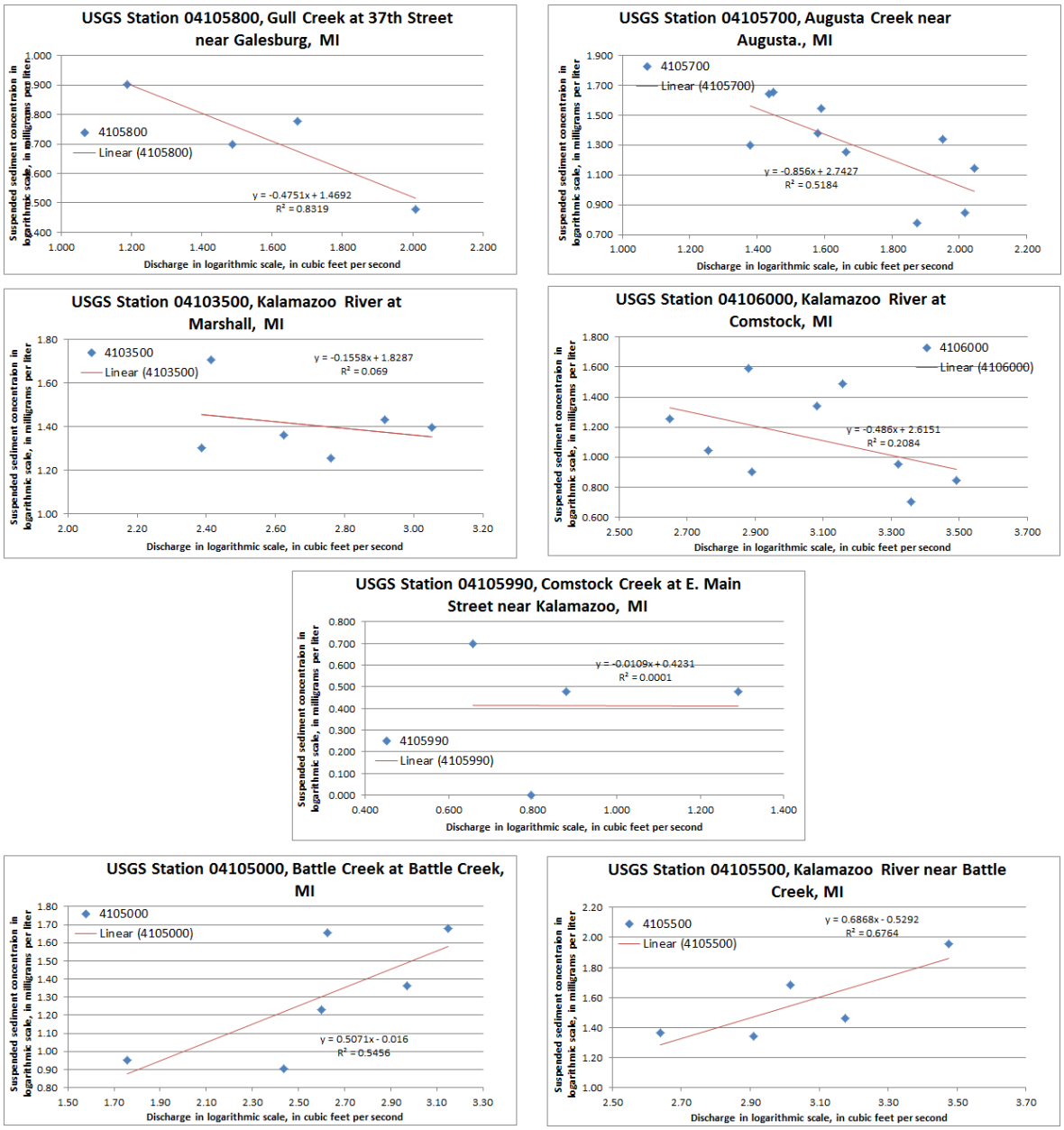


Figure 4 Relations of suspended sediment concentration (SSC) to discharge ($Q_w$) in logarithmic plots and SSC rating curves developed for seven study sites. [y stands for $\log_{10}$SSC, x stands for $\log_{10}Q_w$, and $R^2$ is the coefficient of determination]

The regression analysis resulted in negative SSC-rating slope estimates at sites 04105700 and 04105800; and weakly negative slopes at sites 04103500 and 04106000. In contrast, the positive slope estimates at sites 04105000 and 04105500 are more typical, in that SSC increases as $Q_w$ increases (Porterfield, 1972). The SSC-rating slope at site 04105990 is difficult to assess with the scatter in the limited data points. Physically, decreasing SSC at increasing $Q_w$ indicates that either the amount of sediment supply is similar at all flow rates, exhausted after early season flushing, or became supply-limited after the early part of each hydrograph pulse; or the transport of sediment is limited because of hydraulic carrying capacities. To understand whether the sediment transport is supply-limited or transport-limited, additional information on the amount and particle sizes of sediment is needed for analysis. The challenges to resolve for the present study are to: (1) use the available samples to improve the at-site analysis, and (2) use the at-site results to estimate SSC at ungaged locations.

**Temperature effect on SSC:** Some of the SSC data were collected between January and March at water temperatures between 5°C and 0°C and their values were higher than other samples collected at those sites in warmer weather (table 3). Barton and Albertson (1953) experimentally demonstrated that the depth-averaged SSC increases with a decrease in water temperature, and Colby (1956) documented that for finer sediment in the size range from 0.016 to 0.062 millimeter, there was a 57 percent increase in SSC as temperature dropped from 80 °F (26.7°C) to 40 °F (4.4°C). Plots made of the two subsets of the at-site data--those with water temperature above 5°C, and those with water temperature below 5°C--suggested a seasonal effect may exist in the study area as indicated by the different rating slopes in the two subsets at sites with adequate data.

**Dam effects versus free-flowing reaches:** There are several transverse (across the river) structures in the study reach including decommissioned dams (upper structure removed), a low-head dam, and hydropower dams. These transverse structures slow current velocity and cause coarse-grained sediment to settle. Depending on the incoming flow and incoming sediment magnitudes and particle sizes, in general the run-of-river conditions in these impoundments will not prevent fine sediment from being transported downstream. Therefore, SSC measured downstream from some of these dams could rise rapidly when streamflow increases from low to high discharges (i.e., a steeper rating-curve slope). In free-flowing channels, sediment deposits along the low-gradient reaches can produce similar effects. At regulated sites, the incoming flows and dam operations at the time of measurements can alter the relation between measured SSC and flow.

Among the gaged sites, the Kalamazoo River at Marshall and the Kalamazoo River at Comstock are located downstream from hydropower dams. Marshall has a small hydropower station by its dam that receives water from the Marshall pool through a side-channel. About 8 miles downstream from Marshall is a decommissioned dam at Ceresco. The operational rules at Morrow Dam are designed to release the amount of discharge flowing into its pool, as estimated from flows reported at the Kalamazoo River near Battle Creek gage, when discharges are above 1,000 cfs. Battle Creek is one of the largest tributaries of the Kalamazoo River, and the gage at Battle Creek at Battle Creek is located about 2.9 miles upstream from a low-head dam. Also, the gage on the Kalamazoo River near Battle Creek is located about 0.35 miles downstream from the low-head dam on Battle Creek.

**Monthly hydrographs:** Mean monthly streamflow hydrographs for six of the gaged sites are presented in figure 5 using data from water years (WYs) 1987 to 2011 except for the Gull Creek site, which used data from WYs 1964 to 1972. In general, streamflow rises from base flow in October to annual peaks in March or April, and then declines through August and remains low through September. Hydrograph bars in figure 5 are coded with two colors; the orange bars are those whose hydrograph patterns are clear and with low base flows in August to October; the blue ones are those with comparatively higher base-flow magnitudes and with monthly volumes fluctuating in the higher discharge period (signifying greater groundwater and surface water exchange). The hydrographs with blue bars are also associated with sampling sites that have negative SSC-rating-curve slopes. The monthly discharges were graphed using per unit area values, and it was observed that peak magnitudes for those coded with blue generally have lower values than those that are coded with orange.

**<u>Watershed and stream characteristics</u>:** Watershed characteristics such as the basin relief and geology (soil erodibility and permeability, and sediment delivery and storage), geomorphology of the channel (channel sinuosity, narrow or floodplain channels, bank and bed erodibility), and land-cover changes are factors affecting sediment yield from a watershed. On a large scale, most of these factors are also affecting streamflow from the watershed. Therefore, the streamflow patterns can serve as a surrogate for analyzing the sediment yields. On this basis, the watershed and stream characteristics that could serve as indictors for explaining SSC rating curves at the gaged sites and help extending the results of gaged sites to ungaged sites were sought.

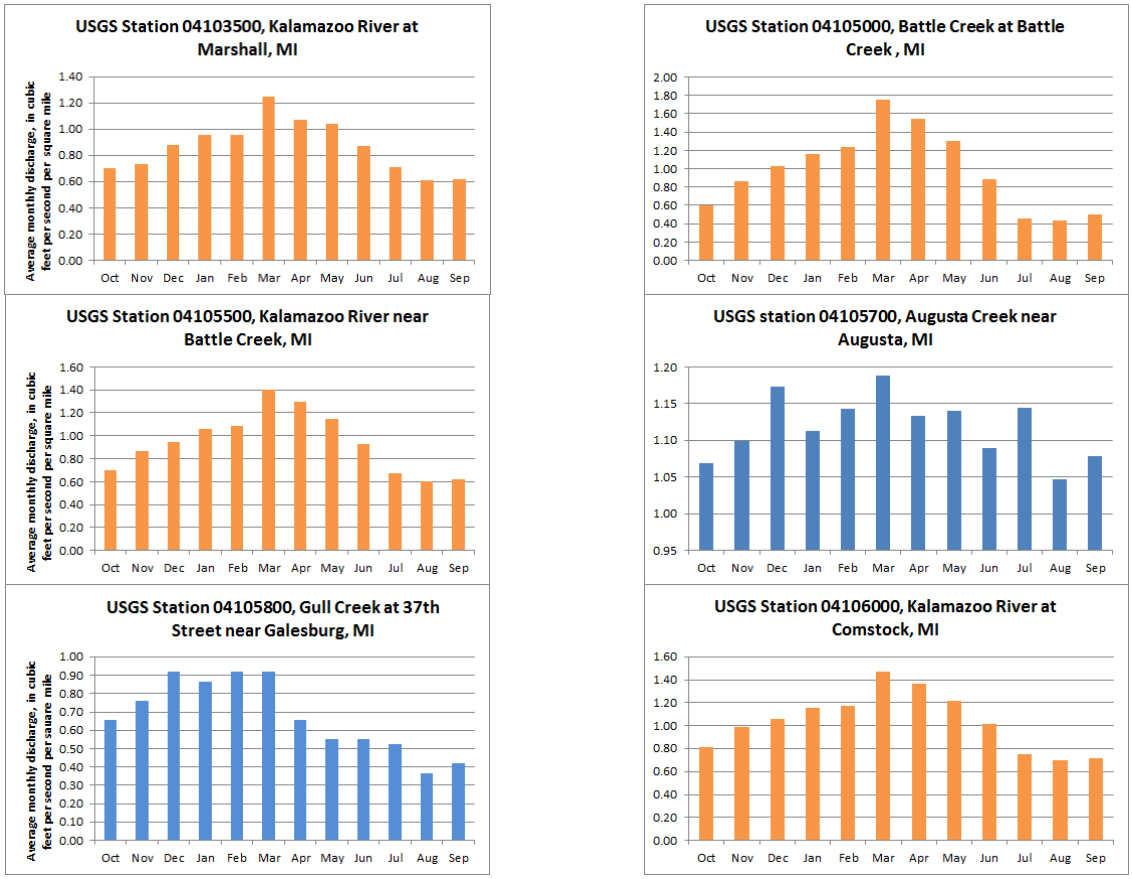


Figure 5 Mean monthly streamflow hydrograph patterns for sites in the study reach that have suspended sediment samples. Hydrographs coded in orange are considered to have clear yearly seasonal rising and falling patterns and with low base flows in August to October; those coded in blue have comparatively higher base-flow magnitudes and large monthly volumes fluctuations in the remaining months. Statistics were computed for water years (WYs) 1987 to 2011 except for the Gull Creek site, which used data from WYs 1964 to 1972.

Wesley (2005) used a "flow stability" index to classify the streamflow patterns of a watershed. A stream with more stable flows is characterized by lower peak flows and higher base flows than a stream with less stable flows. One component of the flow stability index (Wesley 2005) was the ratio of mean high flow to mean low flow. The dominance of stable streams (streams with low flow stability ratios) is mainly due to abundance of permeable surficial soils and geology, which promote groundwater inflow and outflow (Wesley, 2005). Groundwater dominated streams generally have cooler water temperatures than surface-water dominated streams. Surface-water dominated streams generally have relatively warmer water temperatures and higher flow-stability ratios because of faster responses to rainfall or snowmelt than groundwater dominated streams (Wesley, 2005). Less permeable soils, land-use changes (agriculture or development of less pervious surfaces), and channelization contribute to higher stream flow stability ratios. However, wetlands and lakes, wide

floodplains that create channel storage also contribute to low flow-stability ratios. Wesley (2005) suggested that a ratio between 1.0-2.0 indicates a typical self-sustaining cold-water trout stream, between 2.1-5.0 indicates warm-water streams, between 5.1-10.0 indicates somewhat flashy warm-water rivers, and >10.0 represents very flashy warm-water rivers.

Relevant characteristics found in Wesley (2005) for describing the watershed and stream and the flow-stability index of the gaged and ungaged sites in the study reach are presented in table 4. The high urban land cover in the Comstock Creek watershed might have caused the inconsistency in SSC data collected at the Comstock Creek site. For sites where such information is unavailable, the stream temperature class, defined as cold- or warm-water as described in Wesley (2005), is used as the indicator. A cold-water stream (groundwater dominated) has a low flow-stability index and the annual hydrographs are typical of those coded in blue in figure 5; the warm-water streams (surface-water dominated) have more diverse flow-stability indexes and annual flow patterns, most likely due to channel patterns.

Table 4 Watershed and stream characteristics and flow stability index for study sites along the main stem and tributaries used in hydrodynamic modeling work. [GW: groundwater; SW: surface water]

| ***River Reach*** | ***Stability Index*** | ***Watershed and stream characteristics (Wesley, 2005)*** | ***Classification*** |
|---|---|---|---|
| Marshall pool above the Marshall Dam on the Kalamazoo River at Marshall, MI | 4.4 | Heavily influenced by inflows from Rice Creek, which is groundwater dominated and comes in from upstream of the Marshall Dam. The measurement site is downstream of Marshall Dam. | Mixed |
| Talmadge Creek, MI | N/A | A cold-water stream; with gravel and coarse sand substrate. | GW dominated |
| Bear Creek, MI | N/A | A cold-water stream, having gravel and cobble substrate. | GW dominated |
| Minges and Harper Creek, MI | N/A | A cold-water stream. | GW dominated |
| Battle Creek, MI | 7.0 | A surface-water dominated stream, has channelization near the mouth, drainage includes urban area; located at upstream of Battle Creek Dam. | SW dominated |
| Kalamazoo River above the junction with Battle Creek, MI | 3.4 | Located downstream of Battle Creek Dam which is an urban area. | SW dominated |
| Wabascon Creek, MI | N/A | A warm-water stream. Drains a mixture of moderate-relief plains. Flows through several lakes and swamps. | Mixed |
| Sevenmile Creek, MI | 1.6 | A cold-water stream; substrate features gravels overlain by sand. | GW dominated |
| Augusta Creek, MI | 2.2 | A cold-water stream; features a series of wetlands and reservoirs. The substrate dominated with gravel and cobbles. | GW dominated |
| Gull Creek, MI | N/A | A warm-water stream. Gull Lake is located at headwater and Gull Creek flows through several lakes and swamps. Substrate: gravel and cobble. | Mixed |
| Comstock Creek, MI | N/A | A warm-water stream, drains through a few small lakes. 85 percent is in an urban area. | Mixed |
| Kalamazoo River near Comstock, MI | 2.9 | Located downstream of Morrow dam, whose release has been controlled by gates and turbine operations. | Regulated |

## DEVELOPING SSC RATING CURVES FOR GAGED AND UNGAGED SITES

Supplemental measures to improve the accuracy of at-site SSC rating curves are needed because of the small number of samples collected at each site. Furthermore, the distinctive SSC rating slopes could be caused by effects of water temperature, dam, and watershed and stream characteristics individually or in combination. The modeling challenges include determining the at-site SSC rating curves by incorporating these factors and then estimating SSCs for the ungaged sites.

**Panel regression with fixed-effect analysis for gaged sites:** The SSC data presented in table 3 were pooled as panel data for regression analysis, and the fixed-effects model was applied to analyze the panel data. Data were grouped in the analysis according to the causative factors: dammed or free-flowing reaches, winter or non-winter seasons, and surface-water or groundwater dominated watersheds. An assumption made was that the slope parameter *b*-the sediment source term-was similar for sites in each of the five subgroups, but the intercept, parameter *a*, varied from site to site. The assumption was based on reasoning that the magnitude of SSC is a function of channel erosive power and conveyance capacity. The following five subgroupings were tested and the goodness of fit between measured and estimated SSC was evaluated using the quantitative statistics presented in table 5.

- Group 1: Results from at-site linear regression analysis; i.e., no groups, no panel regression. This is the baseline condition.
- Group 2: The free-flowing and dammed reaches partition. Sites 04105700, 04105800, and 04105990 belong to the free-flowing reaches, and sites 04103500, 04105000, 04105500, 04106000 belong to the dammed reaches.
- Group 3: The groundwater and surface-water dominated reaches partition. Sites 04105000 and 04105500 belong to the surface-water dominated group, the remaining 5 sites belong to the groundwater-dominated group.
- Group 4: A further partition of Group 3 into winter (January through March) and non-winter months (the rest of the year).
- Group 5: Similar to Group 4, but the at-site SSC rating curve is used for site 04103500 and this site is not used in the panel analysis. An additional constraint is imposed at site 04106000: when Qw <= 1000 cfs (up to four turbines opened) the data are classified under groundwater-dominated stream (the dam effectively traps sediment), and when Qw is larger than 1000 cfs, the data are classified under surface-water dominated streams.

Table 5 Quantitative statistics of estimated suspended sediment concentrations for the five groupings studied. [$R^2$, coefficient of determination; PBIAS: ratio of deviation of simulated from measured data; NSE: Nash-Sutcliffe efficiency; and RSR: ratio of the root-mean-square error to the standard deviation of measured SSC data. Moriasi et al. (2007) recommended the use of the latter three statistics.]

| *Parameter* | *Group 1* | *Group 2* | *Group 3* | *Group 4* | *Group 5* |
|---|---|---|---|---|---|
| $R^2$ | 0.77 | 0.72 | 0.72 | 0.76 | 0.78 |
| PBIAS | -0.11 | -0.13 | -0.13 | -0.11 | -0.11 |
| NSE | 0.57 | 0.47 | 0.49 | 0.55 | 0.60 |
| RSR | 0.65 | 0.73 | 0.71 | 0.67 | 0.64 |

Group 5 results had a better fit and the least variance among the groups; therefore, parameters *a* and *b* (table 6) for that group were used to construct the SSC rating curves at specified gaged locations.

**Estimation of parameters *a* and *b* for ungaged sites**: For ungaged tributary sites, it was assumed that parameter *a* is a function of basin characteristics and that parameter *b* can be transferred from gaged sites that have similar watershed and channel characteristics.

Parameter *a* for ungaged sites was obtained using the assumption that they can be transferred from gaged sites to ungaged sites based on the criterion of whether the stream is groundwater or surface-water dominated. Table 7 lists the two parameters used for the ungaged study sites.

## CONCLUSIONS

Suspended sediment concentration (SSC) rating curves for gaged and ungaged sites in the Kalamazoo River and its tributaries from Marshall to Morrow Dam were developed. Despite the paucity of measured SSC data, the developed rating curves adequately covered the range of flows at each study site. Several sites had negative

SSC rating curve slopes, in contrast to the typical SSC rating curve pattern in which SSC increases as streamflow increases. This variability added an additional challenge to the SSC rating curve analysis for this study. By pooling at-site data as panel data and grouping them according to possible causative factors, a fixed-effects model analysis found classifying study sites according to their groundwater or surface-water dominance yielded better quantitative statistics than other groupings tested. For ungaged sites in the study area, it was assumed the parameters of SSC rating curves could be transferred from gaged sites reasonably well, based on the similarity in watershed and channel characteristics.

Table 6 Parameters *a* and *b* for estimating suspended sediment rating curves at sites with measured data. Winter was designated as January 1 through March 31, and non-winter period was designated as April 1 through December 31.

| ***River Reach*** | ***Season*** | ***a*** | ***b*** |
|---|---|---|---|
| Marshall pool above the Marshall Dam on the Kalamazoo River at Marshall, MI | Winter | 1.943 | -0.203 |
| Marshall pool above the Marshall Dam on the Kalamazoo River at Marshall, MI | Non-winter | 1.943 | -0.203 |
| Battle Creek, MI (tributary) | Winter | 0.554 | 0.277 |
| Battle Creek, MI (tributary) | Non-winter | -0.161 | 0.603 |
| Kalamazoo River above the junction with Battle Creek, MI | Winter | 0.654 | 0.277 |
| Kalamazoo River above the junction with Battle Creek, MI | Non-winter | -0.184 | 0.603 |
| Augusta Creek, MI (tributary) | Winter | 2.02 | -0.432 |
| Augusta Creek, MI (tributary) | Non-winter | 2.279 | -0.544 |
| Gull Creek, MI (tributary) | Winter | 0.554 | 0.277 |
| Gull Creek, MI (tributary) | Non-winter | 1.579 | -0.544 |
| Comstock Creek, MI (tributary) | Winter | 0.554 | 0.277 |
| Comstock Creek, MI (tributary) | Non-winter | 1.064 | -0.544 |
| Kalamazoo River near Comstock, MI when Q>1000 | Winter | 0.379 | 0.277 |
| Kalamazoo River near Comstock, MI when Q>1000 | Non-winter | -0.773 | 0.603 |
| Kalamazoo River near Comstock, MI when Q<=1000 | Winter | 0.379 | 0.277 |
| Kalamazoo River near Comstock, MI when Q<=1000 | Non-winter | 2.719 | -0.544 |

Table 7 Parameters *a* and *b* for estimating suspended sediment rating curves at ungaged sites used in hydrodynamic modeling. Winter was designated as January 1 through March 31, and the non-winter period was designated as April 1 through December 31.

| ***River Reach*** | ***Time period*** | ***a*** | ***b*** |
|---|---|---|---|
| Talmadge Creek, MI (tributary) | Winter | 0.554 | 0.277 |
| Talmadge Creek, MI (tributary) | Non winter | -0.161 | 0.603 |
| Bear Creek, MI (tributary) | Winter | 0.554 | 0.277 |
| Bear Creek, MI (tributary) | Non-winter | -0.161 | 0.603 |
| Minges and Harper Creek, MI (tributaries) | Winter | 0.554 | 0.277 |
| Minges and Harper Creek, MI (tributaries) | Non-winter | -0.161 | 0.603 |
| Wabascon Creek, MI (tributary) | Winter | 2.02 | -0.432 |
| Wabascon Creek, MI (tributary) | Non-winter | 2.279 | -0.544 |
| Sevenmile Creek, MI (tributary) | Winter | 0.554 | 0.277 |
| Sevenmile Creek, MI (tributary) | Non-winter | -0.161 | 0.603 |

Tributaries with negative SSC-rating slopes were found to come from watersheds that are characterized by lower stream temperatures and permeable surficial soils and geology indicative of groundwater-flow dominated systems. Such streams generally have low flow stability indices. However, surface-water dominated watersheds can also have a lower flow stability index if the channels have abundant storage. Classification of the watershed and channel characteristics as described in this paper improves the estimation of the SSC-rating curve at both gaged sites and ungaged sites. This identification can be an important consideration for the analysis and modeling of watershed streamflow and sediment.

## REFERENCES CITED


Ahanger, M.A., Asawa, G.L., and Lone, M.A. (2013). Hysteresis effect on sediment rating curves, J. Acad, Indus. Res. V1(8), pp: 481-484.

Asselman, N.E.M. (2000). Fitting and interpretation of sediment rating curves. Journal of Hydrology V.234 (2000), pp: 228-248.

Baca, P. (2008). Hysteresis effect in suspended sediment concentration in the Rybarik basin, Slovakia; Hydrological Science-Journal-des Sciences Hydrologiques, 53(1) February 2008; p 224-235.

Barton J.R., and Albertson, M.L. (1953). Temperature, seepage, and turbulence as factors affecting suspended sediment concentration: Colorado State University, Agricultural and Mechanical College, Department of Civil Engineering, AgrReport No. CE 53JBR12, 83 p.

Colby, B.R. (1956). Relationship of sediment discharge to streamflow: USGS Open File Report, prepared by Quality of Water Branch – April 1956, 184 p.

Dollhopf, R.H., Fitzpatrick, F.A., Kimble, J.W., Capone, D.M., Graan, T.P., Zelt, R.B., Johnson, R. (2014). "Response to heavy, non-floating oil spilled in a Great Lakes river environment: a multiple-lines-of-evidence approach for submerged oil assessment and recovery," Proceedings, 2014 International Oil Spill Conference, Savannah, GA, pp 434-448.

Ferguson, R.I. (1986). River loads underestimated by rating curves, Water Resources Research, 22(1), pp 74-76.

Fitzpatrick, F.A., Johnson, R., Zhu, Z.D., Waterman, D., McCulloch, R.D., Hayter, E.J., Garcia, M.H., Boufadel, M., Dekker, T., Hassan, J.S., Soong, D.T., Hoard, C., and Lee, K. (this volume). Integrated modeling approach for fate and transport of submerged oil an oil-particle aggregates in a freshwater riverine environment: (manuscript published in this proceedings).

Glysson, G.D. (1987). Sediment transport curves; U.S. Geological Survey, Open-File Report 87-218, Reston, Virginia, 47 p.

Helsel, D.R., and Hirsch, R.M. (1992). Statistical methods in water resources: U.S. Geological Survey, Water Resources Division, Reston, Virginia, 22092. 522 p.

Holtschlag, D.J., and Croskey, R.M. (1984). Statistical models for estimating flow characteristics of Michigan streams; U.S. Geological Survey Water-Resources Investigations Report 84-4207, 81 p.

Mai, Q.W., Zhao, Y.A., Pan, X.D., and Fan, Z.I. (1990). Feature of flow-sediment regime and regularities of siltation – scour on the lower Yellow River, *in* Sedimentation and Soil Conservation, Collected Research Papers, Vol. 2. Yellow River Conservancy Commission. Zhengzhou, China. p. 100-146.

Morgan, R. P.C. (1995). Soil Erosion and Conservation (2nd edition), Longman, London, 320 P.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., and Veith, T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulation: Transaction of American Society of Agricultural and Biological Engineers, v. 50, no. 3, p. 885– 900.

Porterfield, G. (1972). Techniques of water-resources investigations of the United States Geological Survey; Chapter 3, Computation of fluvial-sediment discharge, U.S. Geological Survey, Book 3, Applications of Hydraulics, 66 P.

Singh, K.P., and Durgunoglu, A. (1989). Developing accurate and reliable stream sediment yields: Sediment and the environment, IAHS publication, Wallingford, 184. Proceedings of the Baltimore symposium, May 1989: pp. 193-199.

Wesley, J.K. (2005). Kalamazoo River assessment, State of Michigan, Department of Natural Resources, Number 35, 377 P.