Appendix A - U.S. Army Corps of Engineers Publication, Lower Susquehanna River Watershed Assessment, Maryland and Pennsylvania, Phase 1

Calibration of a One-Dimensional Hydraulic Model (HEC-RAS) for Simulating Sediment Transport through Three Reservoirs, Lower Susquehanna River Basin, 2008-2011

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Cover – Susquehanna River at Conowingo Dam

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Conversion Factors

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
ton per year (ton/yr)	0.9072	metric ton per year
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

GLOSSARY – the purpose of this glossary is to provide definitions in general terms for the reader. They are not meant to be complete scientific definitions.

Cohesive sediments – sediments that are less than 0.063 mm in size that represent silts and clays. As the particle size becomes smaller, electrostatic properties of the clays tend to act as a cohesive bond.

Critical Shear Stress – the shear stress required to mobilize and transport sediments. In general, when the shear exceeds the critical shear stress, sediments are mobilized. Conversely, when the shear is less than the critical shear, sediments will deposit. The critical shear varies by particle size, bed embeddedness, and other factors.

Dynamic equilibrium – used in this report to describe the reservoir sediment storage condition. In this condition, little to no sediment storage remains; however, scour events will increase sediment storage for a short period of time, resulting in a reduction in sediment load in the Upper Chesapeake Bay for a short time. In the long-term, sediment will continue to deposit in the reservoirs and be removed with scour-producing flow events.

Fall velocity – the downward velocity of a particle caused by gravity. The velocity is related to the density and viscosity of the fluid, and the density, size, shape, and surface texture of the particle.

Mass Wasting –the down-slope movement of sediment material. As used in this report, mass wasting refers to the process when the bed starts to erode in mass chunks. In this report, this threshold was assumed to occur with flows greater than 390,000 cubic feet per second.

One-dimensional (1-D) modeling – assumes all water flows in the longitudinal direction only. One-dimensional models represent the terrain as a sequence of cross sections and simulate flow to estimate the average velocity and water depth at each cross section.

Shear Stress – the force exerted by water on the sediments in the banks and bottom surface, usually expressed in pascals (standard unit of pressure or stress, English units - pounds per square inch).

Stage-Discharge Rating –A graph showing the relation between the stage and the amount of water flowing in a channel (discharge) that is developed by obtaining a continuous record of stage, making periodic discharge measurements, establishing and maintaining a relation between the stage and discharge, and applying the stage-discharge relation to the stage record to obtain a continuous record of discharge.

Two-dimensional (2-D) modeling – two-dimensional models, water is allowed to move both in the longitudinal and lateral directions, while velocity is assumed to be negligible in the vertical direction. Unlike one-dimensional models, two-dimensional models represent the terrain as a continuous surface through a finite element mesh.

Calibration of a One-Dimensional Hydraulic Model (HEC-RAS) for Simulating Sediment Transport through Three Reservoirs in the Lower Susquehanna River Basin, 2008-2011

By Michael J. Langland and Edward H. Koerkle

Abstract

The U.S. Geological Survey developed a one-dimensional sediment-transport (1-D) model to simulate transport through three reservoirs in the Lower Susquehanna River basin. The primary objective was to produce boundary condition data (daily streamflow, sediment load, and particle size) at a site monitored just upstream of the reservoirs and at the upper end of Conowingo Reservoir. The 1-D model was calibrated with sediment data collected from the downstream site at Conowingo Dam and to bathymetric changes from 2008-2011. The boundary condition data were provided to the U.S. Army Corps of Engineers for use in the calibration and simulation of reservoir dynamics using a two-dimensional model. Due to model limitations identified in this study, two 1-D model simulations were produced, one for the entire modeling period 2008-2011 (representing net deposition) and a second for a high streamflow event September 7-13, 2011 from Tropical Storm Lee (representing net scour). Each simulation used the same model data inputs; however, model parameters were changed to produce results similar to the measured calibration data. The depositional model resulted in a net deposition of 2.1 million tons, while the scour model resulted in a net loss of 1.5 million tons of sediment. The results indicate a difference of about 54 and 57 percent less sediment load, respectively, when compared to the calibration data.

1.0 Introduction

The U.S. Geological Survey (USGS), the Lower Susquehanna River Watershed Assessment (LSRWA) team, and a consortium of federal, State, and private organizations, collaborated on a project to comprehensively forecast and evaluate sediment and associated nutrient loads through a system of three hydroelectric dams located in the lower Susquehanna River above the Chesapeake Bay. The LSRWA team is comprised of staff from the U.S. Army Corps of Engineers (USACE), Baltimore District, the Maryland Department of the Environment, the Maryland Department of Natural Resources, the Susquehanna River Basin Commission, and The Nature Conservancy.

The Susquehanna River is the largest tributary to the Bay and transports about one-half of the total freshwater input and substantial amounts of sediment, nitrogen, and phosphorus to the Bay (Langland, 2009). The loads transported by the Susquehanna River to the Bay are substantially affected by the deposition of sediment and nutrients behind three hydroelectric dams on the lower Susquehanna River near its mouth (Reed and Hoffman, 1996). The three consecutive reservoirs (Lake Clarke, Lake Aldred, and Conowingo Reservoir) that formed behind the three dams (Safe Harbor, Holtwood, and Conowingo) involve nearly 32 miles of the river and have a combined design storage capacity of 510,000 acre-feet (acre-ft) at their normal pool elevations (figure 1). The model area extends just above the pool of the most upstream dam near Marietta, Pennsylvania, to just below the most downstream dam at Conowingo, Maryland, approximately 33 miles. The normal pool elevation is the height in feet above sea level at which a section of a river is to be maintained behind a dam. A fourth dam (York Haven) is located approximately 44 miles above Conowingo Dam. Because of the low head (28 feet) and low storage area (7,800 acre-ft) the sediment retention at York Haven is substantially less than the dams located downstream and is not considered in this project. Safe Harbor Dam, built in 1931 with a dam height of 80 feet, forms the uppermost reservoir with a design capacity of about 150,000 acre-ft and is considered to have reached the capacity to store sediment in the early 1950's (Reed and Hoffman, 1996). Holtwood Dam, built in 1910 with a dam height of 60 feet, is the smallest of the three dams, with a design capacity of about 60,000 acre-ft and is considered to have reached the capacity to store sediment in the mid-1920's (Reed and Hoffman, 1996). Both Lake Clarke and Lake Aldred are considered in dynamic equilibrium. Conowingo Dam is the largest and most downstream; built in 1928 with a dam height of 110 feet, it has a design capacity of about 300,000 acre-ft. Conowingo Reservoir has limited capacity to store sediment and may be in dynamic equilibrium.

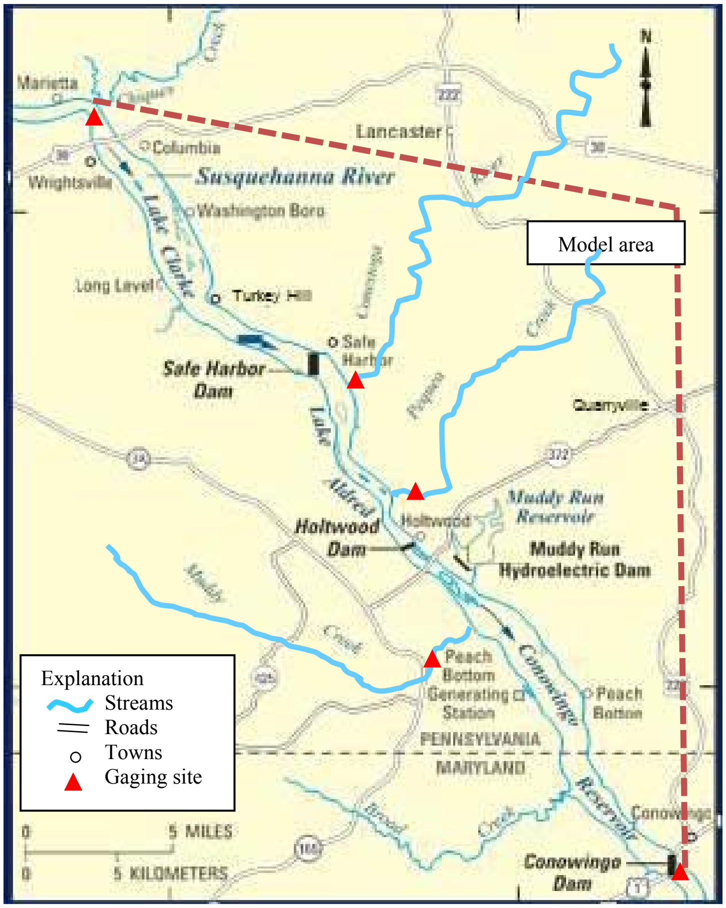

Figure 1. Location map of river reach for the one-dimensional sediment-transport model including the three major reservoirs in the Lower Susquehanna River basin—Lake Clarke, Lake Aldred, and Conowingo Reservoir.

2.0 Background and Previous Studies on the Three Reservoirs

The District of Columbia, the six states with water draining into the Chesapeake Bay (Maryland, Pennsylvania, Virginia, New York, West Virginia, and Delaware), the Chesapeake Bay Commission, and the U.S. Environmental Protection Agency (USEPA) have agreed to a plan to reduce nutrient loads to the Chesapeake Bay in an attempt to restore and protect the estuarine environment of the Bay. The USEPA has established a total maximum daily load (TMDL) which mandates sediment and nutrient allocation goals for each of the six states draining into the Chesapeake Bay (USEPA, 2010).

Previous studies by Ott and others (1991), Hainly and others (1995), Reed and Hoffman (1996), Langland and Hainly (1997), Langland (2009), URS Corporation and Gomez and Sullivan (2012) have documented important information on the lower Susquehanna River reservoirs, including the reservoirs' bottom-sediment profiles, reduced storage capacity, and trap efficiency. Several studies also have determined sediment chemistry (Hainly and others, 1995; Langland and Hainly, 1996; and Edwards, 2006) and the effects of large storm events on the removal and transport of sediment out of the reservoir system and into the upper Chesapeake Bay (Langland and Hainly, 1996; Langland, 2009; URS Corporation and Gomez and Sullivan, 2012). Information from previous reports was useful for the development and calibration of the model for this study.

Langland (2009) provided a historical perspective to reservoir filling rates and projected when sediment storage capacity may be reached in the Conowingo Reservoir. When storage capacity is reached, a dynamic-equilibrium condition will exist between incoming and outgoing sediment and nutrient loads discharged through the reservoir system to the Chesapeake Bay. In the dynamic-equilibrium condition, constituent loads may increase from high flow scour events, thereby affecting the sediment and nutrient allocation TMDL goals set by USEPA and the state of Maryland’s water-quality standards for dissolved oxygen, water-clarity, and chlorophyll A. With respect to TMDLs, increased loads may have a greater impact on sediment and phosphorus which tend to be transported in the particulate (solid) phase and less of an impact on nitrogen which tends to transported in the dissolved phase. However, in this dynamic equilibrium condition, loads may also decrease due to increased deposition from a preceding scour event. Hirsch (2012) concludes that the reservoirs are very close to this equilibrium state, and that nutrient and sediment concentrations and loads have been increasing at the Conowingo Dam (the furthest downstream and closest to the Chesapeake Bay) for the past 10-15 years. The report implies increasing concentrations and loads are due to the loss of storage capacity and from a possible decrease in the scour threshold. Reasons for this increase are not certain but likely involve changes in particle fall velocities, increased water velocity, transport capacities, and bed shear.

Dams create a change in hydrological reservoir dynamics affecting sediment transport and deposition. All reservoirs are a sink resulting in hydraulic conditions that reduce the velocity of flows within the reservoir. Due to flow deceleration as the water enters the reservoir, sediment-transport capacity decreases, and the coarser-size fractions of the incoming sediment are trapped and deposited near the upstream end of the reservoir forming a delta near the entrance to the reservoir (figure 2). As the water and sediment continue to flow into the reservoir, the delta continues to extend in the direction of the dam, eventually filling the entire sediment storage volume. The process is usually slow, governed by the amount of incoming sediment, sediment particle size, and flow variability. Generally, low flow results in deposition, while during higher flows some of the sediment is scoured from the upper end of the reservoir and transported downstream with a portion transported out of the reservoir. Large reservoirs receiving runoff with substantial sediment from natural and/or anthropogenic sources typically fill in 50 to 100 years (Mahmood, 1987).

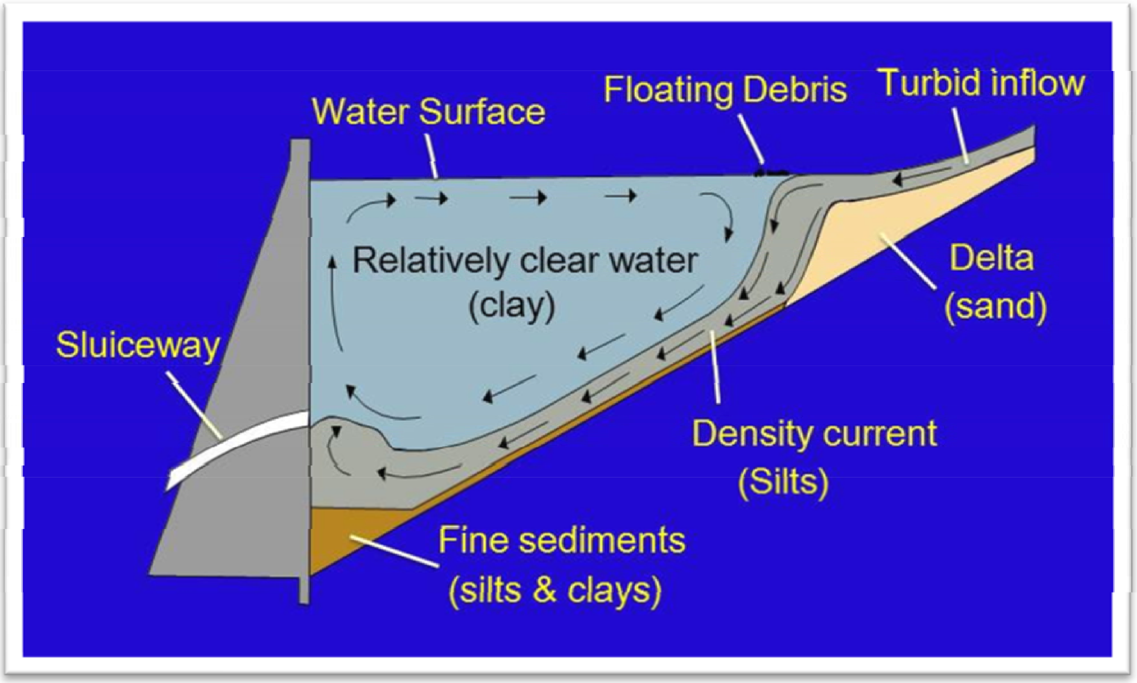

Figure 2. Idealized schematic of a reservoir and the dynamic of circulation and deposition (adapted from Sloff,1997).

3.0 Purpose and Scope

For this study, the primary objective was to produce boundary condition data (daily streamflow, sediment load, and particle size) between the Susquehanna River at Marietta, Pennsylvania streamgage (01576000) and the Susquehanna River at Conowingo, Maryland streamgage (01578310), January 1, 2008 - December 31, 2011. To capture the impacts of transport events on the sediment supply, the USGS selected, developed, and applied a one-dimensional (1-D) U.S. Army Corps of Engineers' **H**ydrologic **E**ngineering **C**enter **R**iver **A**nalysis **S**ystem (HEC-RAS) model to predict sediment discharge, as well as scour and deposition with daily streamflow as an input parameter. The selection was based on existing data, costs to construct and operate the model, new developments in HEC-RAS, and project timeline. This report 1) describes how streamflow and sediment boundary- condition data were developed using the 1-D HEC-RAS model, 2) presents model output to examine calibration and performance, and 3) discusses model limitations. The products of this study were provided to the USACE for the development of a two-dimensional (2-D) model to predict scour and deposition zones, sediment transport, and scenario development for the Conowingo Reservoir and upper Chesapeake Bay. Both the USGS 1-D model and the USACE 2-D model are designed to provide data on reservoir hydrodynamics and sediment transport in the Susquehanna River and to be the basis for sediment inputs into the Chesapeake Bay Program's Chesapeake Bay Environmental Model Package to predict impacts to water quality in the Chesapeake Bay.

4.0 Model Description and Development

Mathematical models have been developed to simulate sediment behavior in reservoirs. All computer sedimentation models include three major components: water routing, sediment routing and special function modules (such as graphical and GIS interfaces). Most models include the option of selecting alternative sediment-transport formulas, but rarely provide the criteria for making that selection. The sediment-transport calculations are performed by grain size fraction thereby allowing the simulation of hydraulic sorting and armoring of the bed. Most 1-D models are based in a rectilinear coordinate system and solve the differential conservation equation of mass and momentum of flow along with the sediment mass continuity equation by using the finite-differences method to predict the parameters of a particular channel, including the velocity, water-surface elevation, bed elevation change, and sediment-transport load (Abood and others, 2009). In addition, many 1-D models also predict the total sediment load and grain size distribution of sediment passing a given cross section.

HEC-RAS is a 1-D movable boundary open-channel flow model designed to simulate and predict changes in river profiles resulting from scour and/or deposition over moderate time periods (years), although single flood events can also be modeled (U.S. Army Corps of Engineers, 2010b). A new beta release of the model was tested for this study (HEC-RAS 4.2 beta 2012-07-19). When paired with a hydrologic record, the model handles hydraulics in a quasi-steady-state mode, which runs as a series of sequential steady-state periods. The HEC-RAS model is largely an enhanced HEC-6 model (U.S. Army Corps of Engineers, 1993) with new and revised algorithms for reservoir simulations and GIS (geographic information system) input/output capabilities using HEC-GeoRAS. HEC-GeoRAS is a GIS extension that provides the user with a set of procedures, tools, and utilities for the preparation of GIS data for import into HEC-RAS and generation of GIS data from RAS output.

The HEC-RAS 1-D model (referred to hereafter as the model) simulates the capability of a stream to transport sediment, both bed and suspended load, based on the yield from upstream sources and current composition of the bed. Using the hydraulic properties of the streamflow and the characteristics of the sediment material (for this study determined by analyzing sediment and core samples), the model can compute the rate of sediment transport. This is accomplished by the user partitioning a continuous streamflow record into a series of steady flows of variable discharges and durations. For each flow, a water-surface profile is calculated thereby providing energy slope, velocity, depth, etc., at each cross section. Potential sediment-transport rates are then computed at each section. These rates, combined with the duration of the flow, permit a volumetric accounting of sediment within each reach. The amount of scour or deposition at each section is then computed and the cross section adjusted accordingly. The computations then proceed to the next flow in the sequence and the cycle is repeated beginning with the updated geometry (U.S. Army Corps of Engineers, 2010b, p. 17-20).

The model calculates sediment-transport rates for 20 particle size classes for grain sizes up to 2048 millimeters (mm). Not all 20 particle size classes are required in the model. If sediment sizes larger than 2048 mm (equivalent to 6.7 feet) exist in the bed, they are used for sorting computations but are not transported. For this study, particle size from sediment core data indicated the largest sediment class to be 8 mm. The user chooses from seven sediment-transport functions (table 1) for bed material load (U.S. Army Corps of Engineers, 2010a). Each transport function was developed based on specific assumptions such as bed type (sand, gravel), hydraulic conditions, and grain size transport. Several transport functions were tested, but Laursen (Copeland) was selected because the dominant particle size in the bed and being transported is silt (discussed later in report).

Bed sorting and armoring methods include Exner 5 and active layer. Exner 5 is a three-layer active bed method capable of forming an armored bed to limit erosion (scour) of deeper material.

Active layer is a two-layer active bed approach with no bed armoring to help increase potential scour (Duan and others, 2008).

Table 1. HEC-RAS 4.1 Sediment-transport functions and general use.

Sediment-Transport Function	General use and Applicability
Ackers-White	Total load function developed for sand to fine gravel. Suspended sediment is a function of shear velocity and bedload is a function of shear stress.
Engelund_Hansen	Total load function developed and limited to sandy rivers.
Laursen (Copeland)	Total sediment load predictor based on excess shear stress and the ratio of excess shear and fall velocity. It outperforms the other transport functions in the silt range.
Meyer-Peter Muller	Designed for bed load transport and not useful for this study
Toffaleti	A modified Einstein total load model generally applicable to sand and gravel beds but tested in large rivers with high suspended sediment loads.
Yang	Developed assuming stream power is dominant factor more useful for sands up to gravel.
Wilcock	Bedload transport function

For deposition and erosion of clay and silt sizes up to 0.0625 mm, fine particle transport can be computed using the selected sediment-transport equation or use of Krone's (1962) method for deposition and Ariathurai and Krone's (1976) adaptation of Parthenaides (1965) method for scour. Additional cohesive sediment data are required when using the above-referenced methods (discussed later in report). The model’s default procedure for clay and silt computations allows only deposition using a method based on fall velocity. Cohesive particles are small enough that electrochemical surface forces dominate their behavior more than gravity (fall velocity). The Krone's and Parthenaides methods are functions used to quantify the deposition and erosion of cohesive material in a single process (U.S. Army Corps of Engineers, 2010a).

4.1 Model data

The basic types of data needed to simulate sediment transport are streamflow, bed composition, and the geometric and hydraulic framework, together creating the boundary conditions. The acquisition, development, and assembly of these data are discussed in this section.

4.1.1 Discharge

Continuous (recorded every 15 minutes) and daily-mean streamflow (discharge) data for the Susquehanna River at Marietta, Pennsylvania (USGS 01576000) and the Susquehanna River at Conowingo, Maryland (USGS 01578310) streamgages were obtained from the USGS National Water Information System (NWISWeb) (U.S. Geological Survey, 2002). The Marietta gage served as the upstream boundary condition and the Conowingo gage served as the downstream boundary condition for the period of study and simulation, January 2008-December 2011. A stage-discharge rating curve also was constructed using all available data and both the rating curve and actual discharge values were used in model calibration (figures 3 and 4). Discharge over the 4-year simulation period (figure 5) indicated normal to less than normal flows for the first 3 years with only one daily-mean discharge exceeding 300,000 cubic feet per second (cfs), and flow with a return interval of two years (annual exceedence probability (AEP) of 0.5). The fourth year (2011) was above normal with 8 days exceeding a daily-mean discharge of 300,000 cfs and 4 of those 8 days exceeding 400,000 cfs, the estimated average bed scour threshold (figure 5). The average return interval for flows of 400,000 cfs is every 5 years (AEP 0.2).

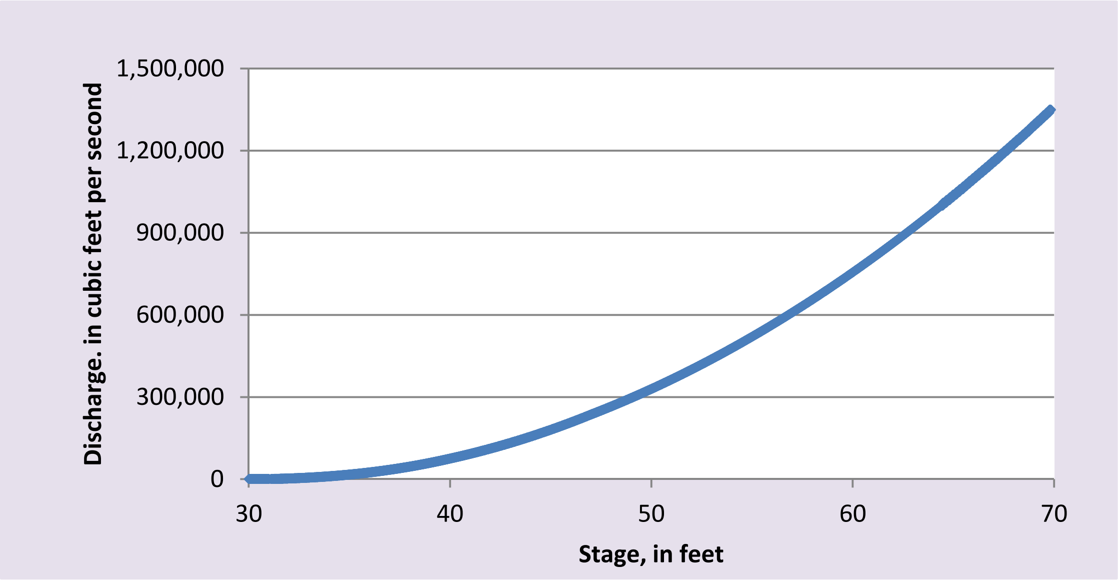

Figure 3. Stage-discharge rating curve for Susquehanna River at Marietta, Pennsylvania (01576000).

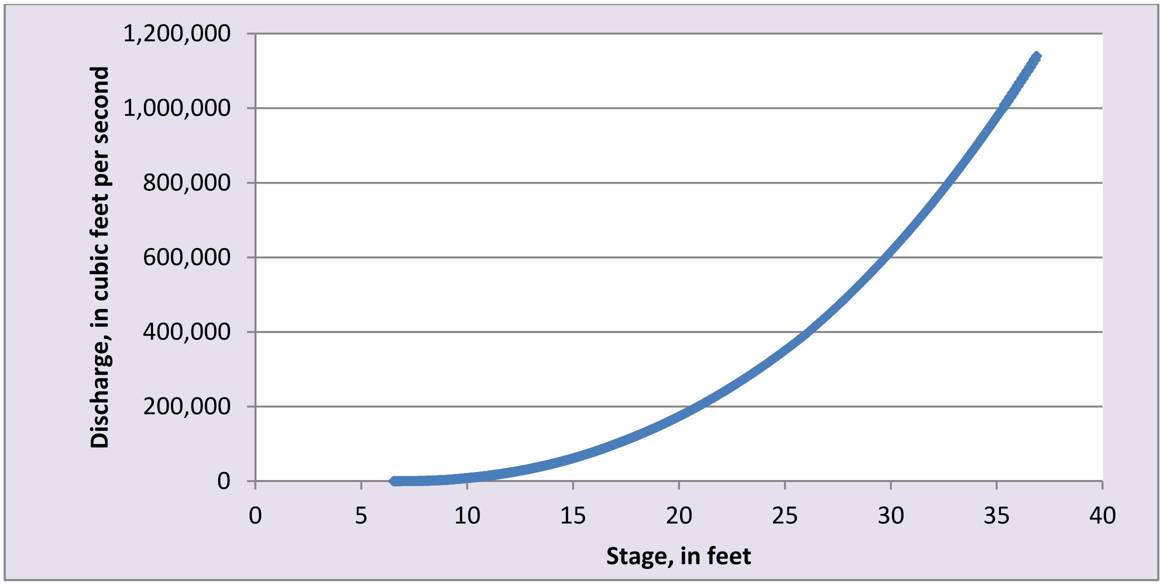

Figure 4. Stage-discharge rating curve for Susquehanna River at Conowingo, Maryland (01578310).

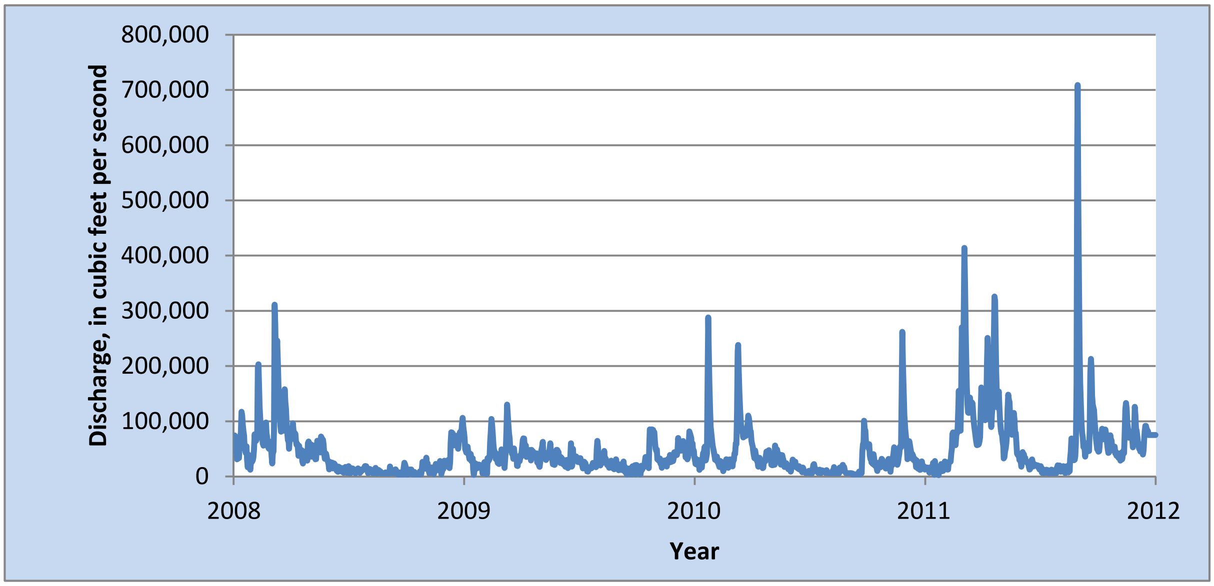

Figure 5. Discharge for Susquehanna River at Conowingo, Maryland (01568310), 2008-2011.

4.1.2 Sediment

Predicting sediment transport through a reservoir is a complex problem. Sediment input, deposition and scour rates in a reservoir mainly depend on water velocities, particle size distribution, and bed shear. Knowledge of sediment particle size distributions in incoming and outgoing water columns, as well as in bottom sediment, aids in the development of a successful sediment-transport model.

Sediment loads entering and leaving a reservoir can be determined from a sediment-rating (transport) curve or from actual concentration data from upstream and/or downstream site(s). In this study, instantaneous suspended-sediment concentrations from above the reservoir system (Susquehanna River at Marietta, Pennsylvania; 01576000) and below the reservoirs (Susquehanna River at Conowingo, Maryland; 01578310) were used to construct sediment transport curves. The sediment-transport curve and actual discharge/concentration data were tested and used in the model calibration (figures 6 and 7). Both figures indicate the occurrence of outliers, the largest being from the September 2011 storm event. Using the R^2 values included in figures 6 and 7, approximately 70 and 61 percent of the variance, respectively, is explained by the equations at the sites. It is important to mention that first, the highest values represented in the graph may need be the “true” maximum concentration because only a small percentage of the storm flow is sampled and second, a direct comparison between the two sediment ratings cannot be made, due to the trapping and release (scour) of the sediments in the three reservoirs.

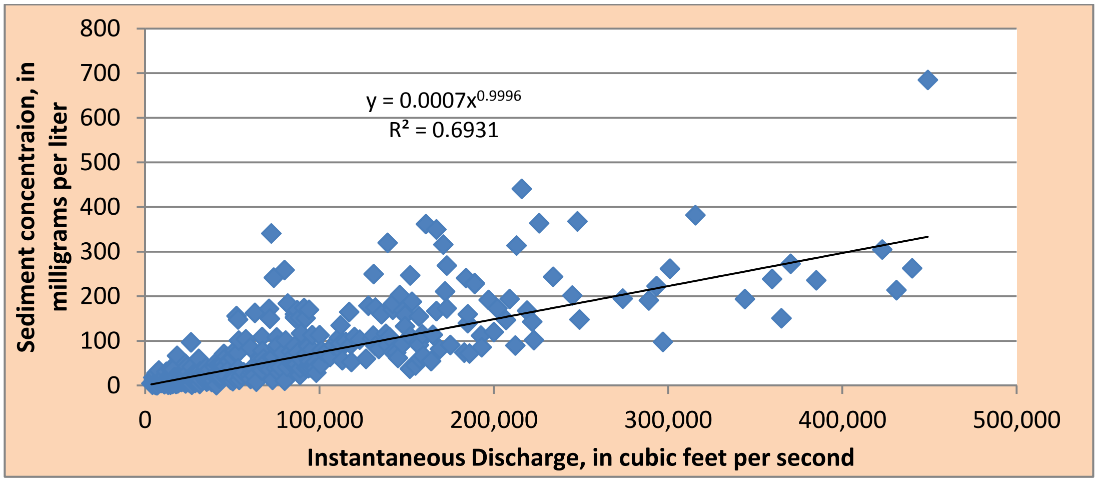

Figure 6. Sediment-transport curve for Susquehanna River at Marietta, Pennsylvania (1987-2011).

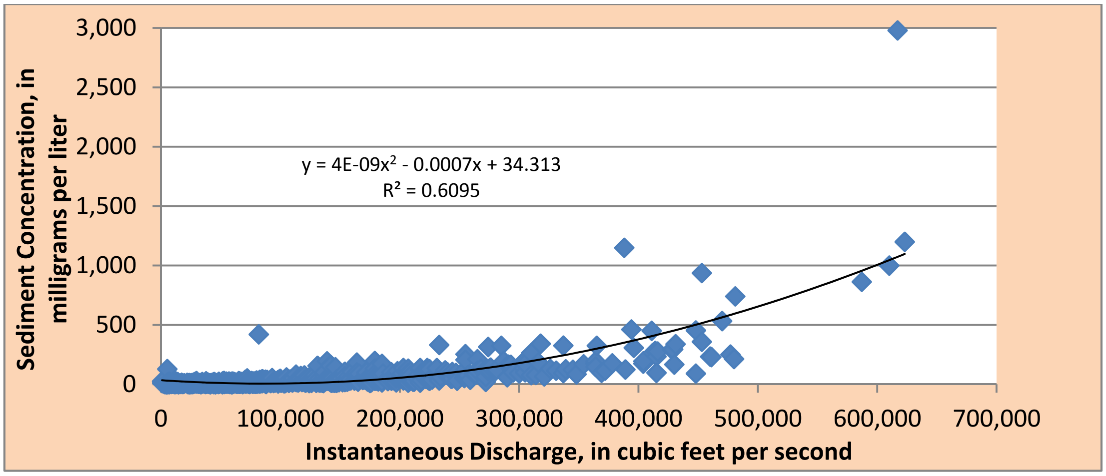

Figure 7. Sediment-transport curve for Susquehanna River at Conowingo, Maryland (1979-2011).

Data on stream bed particle size distributions from sediment corings are available from Hainly and others (1995), Reed and Hoffman (1996), and Edwards (2006) (see attachment B). These data were compiled and analyzed for spatial patterns in each reservoir. Particle size distributions from the 1990-91 and 2000 core data indicated good agreement with size ranges and distributions by depth in all three reservoirs except in the lower portion of Conowingo Reservoir, an area with remaining trapping capacity. Based on sediment cores and historic transport data, 12 particle size classes were simulated in the model, ranging from about 8 mm to less than 0.004 mm. The 1990-91 and 2000 core datasets were averaged and grouped into a total of 12 distinct spatial locations (figure 8), each with unique particle size distributions and bed thickness. The average percentage of sand, silt, and clay for each reservoir is presented in table 2. The percent silt in Lake Aldred was most likely affected by the smaller reservoir size and the dredging of silt-sized coal lasting for several decades until 1972.

Table 2. Average percentage of sediment by sediment type for three reservoirs in the Lower Susquehanna River Basin.

Reservoir	Sand	Silt	Clay
	(Percent)		
Lake Clark	27	44	29
Lake Aldred	61	24	15
Conowingo	16	52	32

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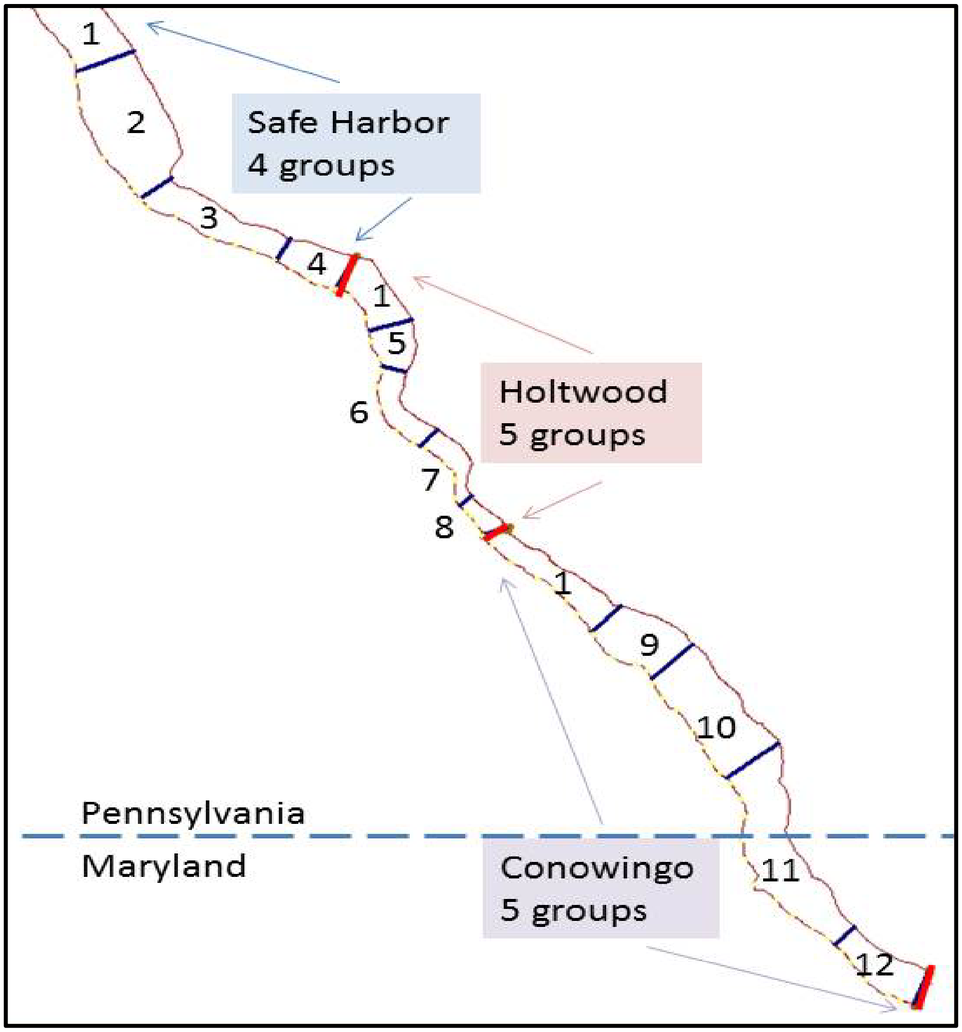


Figure 8. Selected spatial locations (based on particle size and bed thickness) where particle size distribution curves were created for use in the HEC-RAS sediment-transport model

The distribution of particle size classes for each grouping is presented in table 3. Group number 1 is the most sandy and is common at the uppermost portions of each reservoir resulting in three of the locations having equivalent particle size distributions (labeled as group 1), equaling the 12 groups depicted in figure 8 and table 2. Moving downstream within a reservoir, the percent sand generally becomes less, while fines increase due to reservoir transport dynamics (see figure 2, background section) and stratification of the sediments. The data in table 2 were used to construct a continuous particle size distribution curve for each group that was subsequently assigned to corresponding river cross sections in that group. As discussed previously, the HEC-RAS transport equations (table 1) are designed mainly for sand and coarser particles. The bed sediments exhibit a wide variability in the particle size distributions, with sand (greater than 0.0625 mm) as the dominant sediment type in 7 of the 12 groups, generally in the upper and middle sections of each reservoir, and silt (less than 0.0625 mm but greater than 0.004 mm) as the dominant sediment type in the other 5 groups, generally in the lower sections of each reservoir and most prone to be scoured.

Table 3. Particle size distribution for each of the groups used in the HEC-RAS modeled area presented in figure 8. Particle sizes are in percent finer. Group 1 (upper) is used at the uppermost portion of each reservoir. Groups are color coded to match figure 8.

Sediment Type	Particle Size class (mm)	Group Number											
		Upper	Lake Clarke			Lake Aldred				Conowingo Reservoir			
		1	2	3	4	5	6	7	8	9	10	11	12
clay	< .004	2	16	33	20	17	20	5	26	3	16	31	36
silt	< .008	2	23	47	27	23	27	7	35	4	23	42	51
silt	< .016	3	29	61	37	30	35	9	49	4	32	55	70
silt	< .031	3	38	76	48	37	45	11	63	5	42	73	88
silt	< .0625	6	46	87	55	42	58	13	76	7	53	85	96
sand	< .125	21	52	93	62	46	71	20	87	10	63	93	99
sand	< .25	61	60	96	83	59	85	40	96	39	75	97	100
sand	< .5	88	81	99	94	81	95	63	100	70	93	99	100
sand	< 1	98	95	100	99	96	98	78	100	90	97	100	
sand	< 2	100	99	100	100	99	98	88		94	99	100	
pebble	< 4		100		100	100	99	93		98	100		
pebble	< 8						100	100		100			
	Summary												
	Sand	90	38	13	45	58	42	87	24	93	47	15	4
	silt	6	54	54	36	25	37	8	50	3	37	54	60
	clay	2	16	33	20	17	20	5	26	4	16	31	36

4.1.3 Water Temperature

According to Stokes Law, water temperature has a direct effect on the fall velocity (settling) rate of sediment in a reservoir water column (Sullivan and others, 2007). As the temperature decreases, the water becomes more viscous and the fall velocity decreases thereby effecting the distribution of sediment in the water column. In addition, the more viscous (denser) the water becomes, the greater the potential for increase in bed erosion. Therefore, a daily time series of water temperature was generated. Available water temperature data consisted of irregularly spaced measurements during 2005-2011 (165 measurements at Susquehanna River at Marietta, Pennsylvania, 01576000; 105 measurements at Susquehanna River at Conowingo, Maryland, 01578310). Better continuity and distribution of water temperature data was available from Marietta than from Conowingo, but the range of temperatures at the 2 sites was similar. Therefore, the Marietta data was used as the basis for the modeled temperature series (figure 9). A fourth order polynomial (algebraic expression with exponents) was fit to an annual time series of the observed temperature data for the period 2008-2011. Fit of the observed data to the equation was generally within 3 degrees with a few exceptions. Discontinuity in the fit at the December-January boundary was smoothed using the interpolation feature in RAS.

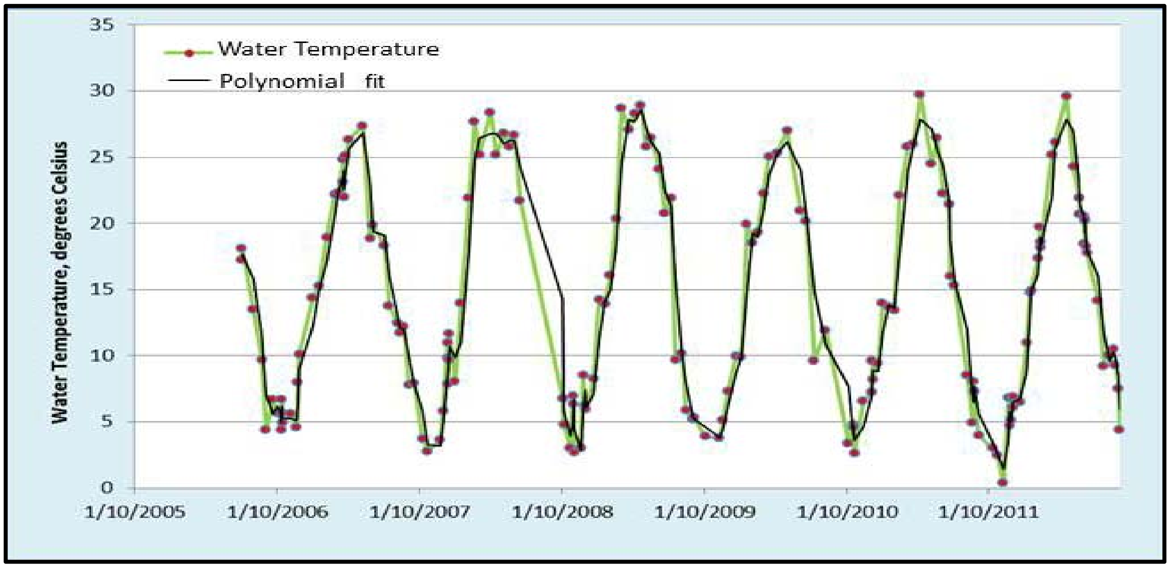


Figure 9. Water temperature data from the Susquehanna River at Marietta, Pennsylvania streamgage used to construct the daily time series for the one-dimensional model.

4.2 Geometry and Hydraulic data

Geometry and flow data are used to calculate steady, gradually varied flow water-surface profiles from energy loss computations (U.S. Army Corps of Engineers, 2010a). Model geometry is specified by a series of channel cross sections and the dam structures. For this study, three options were considered. The options included: (1) using a previous USGS HEC-6 model, (2) converting a flood insurance study (FIS) model completed using HEC-2, and (3) constructing a new model. Due to data limitations, the USGS selected option 3 and assembled new geometry data. Advantages to creating a new model included being able to align cross sections with current bathymetry using the model, using geometry that is better suited for the sediment model (fewer cross sections, no structures), and using Lidar-derived topography for channel banks.

A total of 83 cross sections were developed from the 2008 bathymetry (Langland, 2009) to represent the river system from the Marietta gage to just below Conowingo Dam (figure 10). Each cross section was assigned a numerical identification based on river distance (feet) above the most downstream point and was limited to a maximum of 600 lateral points. The average USGS 2008 bathymetry cross section was 8,000 points. A thinning routine was developed that deleted points based on change over a specific distance while retaining as much detailed bathymetry as possible; however, some loss in detail was unavoidable. Because HEC-RAS is a 1-D model, this loss was considered insignificant. Furthermore, because the river channels are narrow and steep sided, there was little concern for overbank (floodplain) flow.

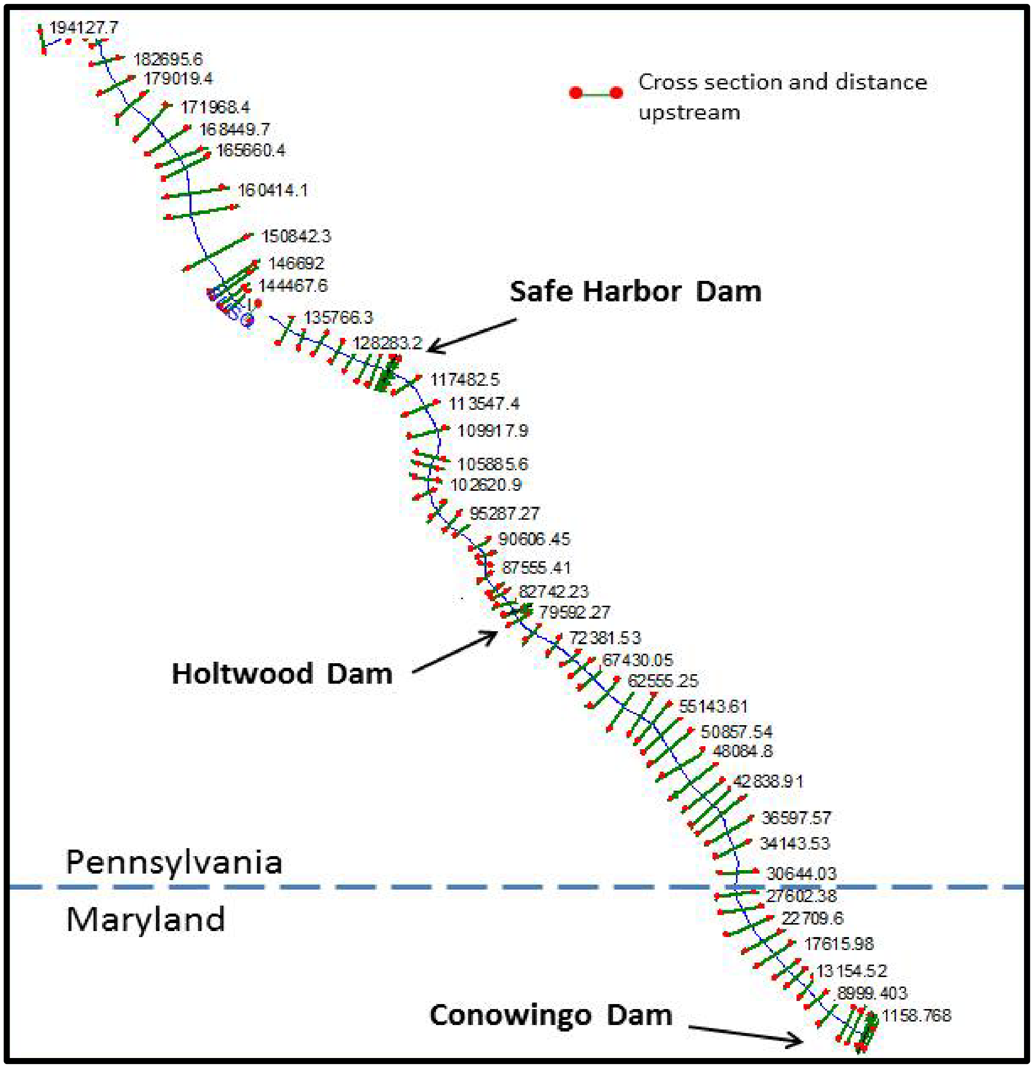


Figure 10. Locations of the cross sections aligned with bathymetry results to produce the geometry files for the HEC-RAS model (river distances in feet).

Flood control gates are designed to release additional water to assist in storage regulation (floods, maintenance) so flow specifications and related changes in reservoir pool elevations need to be considered in the model geometry data. Safe Harbor and Conowingo Dams have flood gates capable of controlling pool elevations over a range of flows. The 31 gates for Safe Harbor and 53 gates for Conowingo (one gate with single flow and 26 gates with flow doubled) were modeled using pass through areas and published gate elevations. There is very limited control of pool elevation at Holtwood (turbine pass through rate and 4.75 feet (ft) high inflatable dam sections are the only controls) therefore, the spillway was simulated as a weir.

Model inputs for the hydraulic simulations included normal water-surface pool elevations with dynamic changes through time representing a hydrograph as levels fluctuate due to power generation, routine maintenance, and changes in incoming water discharge. Gate openings to maintain approximately constant pool elevations for Safe Harbor and Conowingo Dams were determined by multiple steady-state runs covering a range of flows in the 2008-11 period. Gate ratings were subsequently developed and used to estimate gate openings for every day in the 2008-11 simulation period. The bed roughness coefficient (Manning's n) has a major effect on water-surface elevations and is usually one of the primary calibration hydraulic parameters. Several options were available for initial estimates of Manning's n —HEC-RAS defaults, values from a previous USGS HEC-6 model, and values from other HEC 1-D models.

5.0 Model Calibration

The next step in model development is calibration. Calibration can be considered a continuous process. The input parameters that control modeled processes are adjusted during calibration to obtain better agreement between model output and actual observations. For this study, model iterations were made to improve predictions. Prior to calibration, initial boundary conditions were established for discharge, sediment, and geometric and hydraulic parameters.

The streamflow boundary conditions were established using the actual daily-value discharge hydrograph for the Susquehanna River at Marietta, Pennsylvania streamgage as the upstream boundary condition and a stage-discharge rating for daily-value streamflows from the Susquehanna River at Conowingo, Maryland gage as the downstream boundary condition (figure 4). As previously mentioned, instantaneous and daily-mean discharges files and stage-discharge-rating curves were retrieved or developed. Each file was tested in the model and the simulation result that yielded the best hydraulic performance (matching normal pool elevations) was selected. Internal boundaries for the dams were set using time-series of gate openings. Lateral inflows from Conestoga River at Conestoga, Pennsylvania (01576754) and Pequea Creek at Martic Forge, Pennsylvania (01576787) were included. Although other smaller lateral inflows exist (e.g., Muddy Run, Deer Creek, Broad Creek, Conowingo Creek), only Conestoga River and Pequea Creek inflows were included in the model due to their greater volume and agricultural sediment inputs compared to other smaller streams like Muddy Run and Deer Creek.

For the hydraulic boundary conditions, the initial Manning's n values were modified during calibration based on examination of cross section bed movement. Although water-surface elevations respond to changes in n values, sediment transport tends to be fairly insensitive to changes in channel Manning's n values in HEC-RAS (personal communication, Stan Gibson, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, October, 2012). The average Manning's n for 80 cross sections was 0.034, ranging from 0.012 (level beds) to 0.3 (very rough bedrock and boulders near channel banks and just downstream of each dam). These 80 cross sections, along with the three cross sections representing the dam structures, total 83 modeled cross sections, as previously mentioned.

The target (normal) pool elevations were 227 ft at Safe Harbor, 169.75 ft at Holtwood, and 108.5 ft at Conowingo, all National American Vertical Datum of 1988 (NAVD88). Exact matches to selected (target) normal pool elevations were not achieved in the model on a daily basis with most days differing by less than 5 percent during the 4 year simulation period. In general, gate openings for Safe Harbor and Conowingo were set to produce slightly increasing pool elevations with increasing discharge in lieu of an exact target elevation.

During the 2008-11 simulation period, the largest daily-mean flow event occurred on September 9, 2011 (figure 11). Because Holtwood Dam does not have control gates for pool elevation control, the discharge was simulated to reach the normal and maximum pool elevations. The maximum pool elevation for Holtwood Dam on September 9, 2011 was approximately 183 ft (personal communication, Chris Porse, Pennsylvania Power and Light, 2012). The exact height is uncertain because the water rose higher in the forebay than could be recorded. What is certain is that the elevation did not exceed 184.5 ft, the height of the crestwall. At a height of 183 ft, the water over the spillway would be approximately 17 ft; the calibrated hydraulic simulation resulted in a height of 17.1 ft.

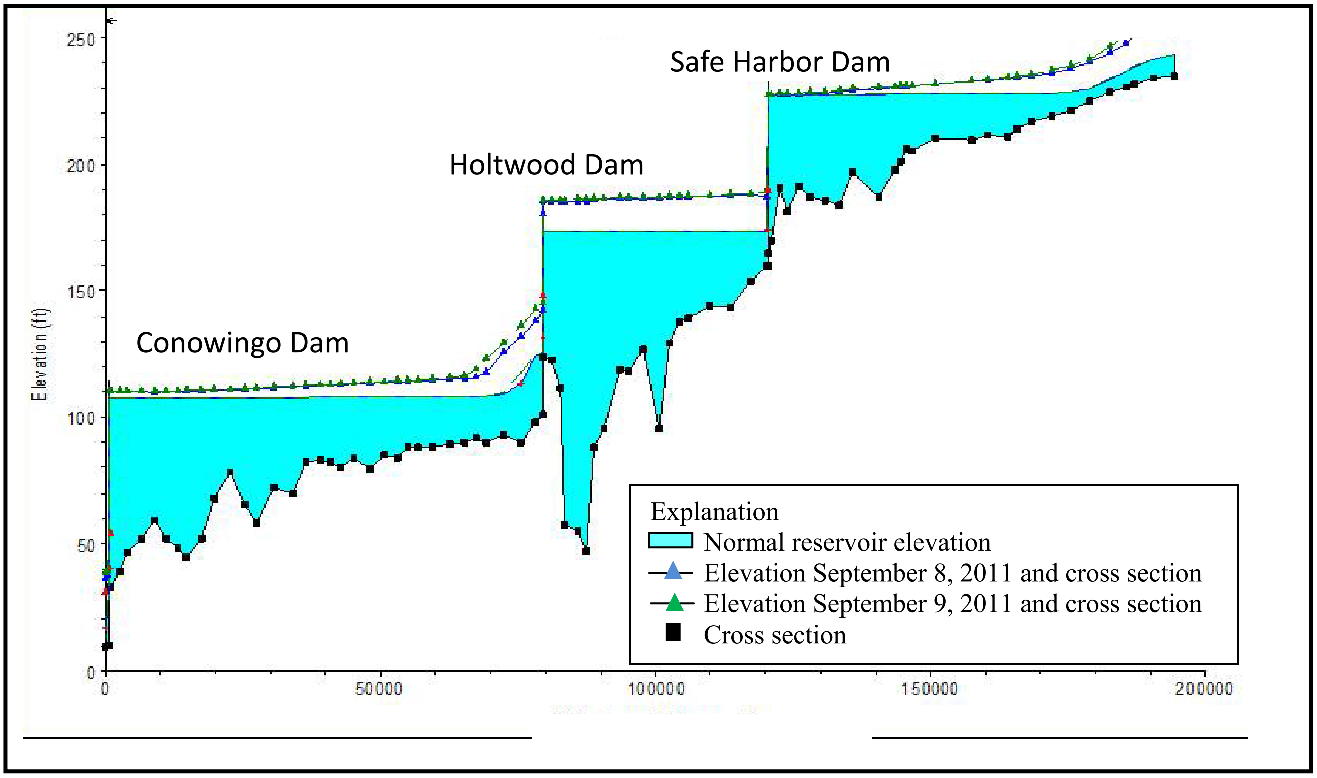


Figure 11. Calibrated water-surface profiles for the three reservoirs at normal pool elevations (light blue shading) and maximum elevation on September 8, 2011 (blue line above shaded areas) and maximum elevations on September 9, 2011 (green line above shaded areas). The dots and triangles represent the model cross sections.

Sediment input boundary conditions were specified at 3 locations in Pennsylvania, Susquehanna River at Marietta, Conestoga River at Conestoga and Pequea Creek at Martic Forge. Together, these three locations account for an average of approximately 97 percent of the monthly inflow into the reservoirs. The boundary conditions consist of daily time series of suspended sediment (USGS parameter code 80154) and loads from the USGS ESTIMATOR model (Cohn and others, 1989). The ESTIMATOR model is a 7-parameter log linear regression model with parameters for flow, season, and time. Although Conestoga and Pequea have much smaller streamflows than the Susquehanna River, the large agricultural sediment loads coming from Conestoga and Pequea add up to 5-10 percent of the total suspended-sediment load entering the reservoirs (figure 12). Note the generally inverse relation between the percentage of the total sediment load from the Conestoga River and Pequea Creek tributaries to the total load transported into the reservoirs, indicating increased influence from the Susquehanna River watershed at higher flows.

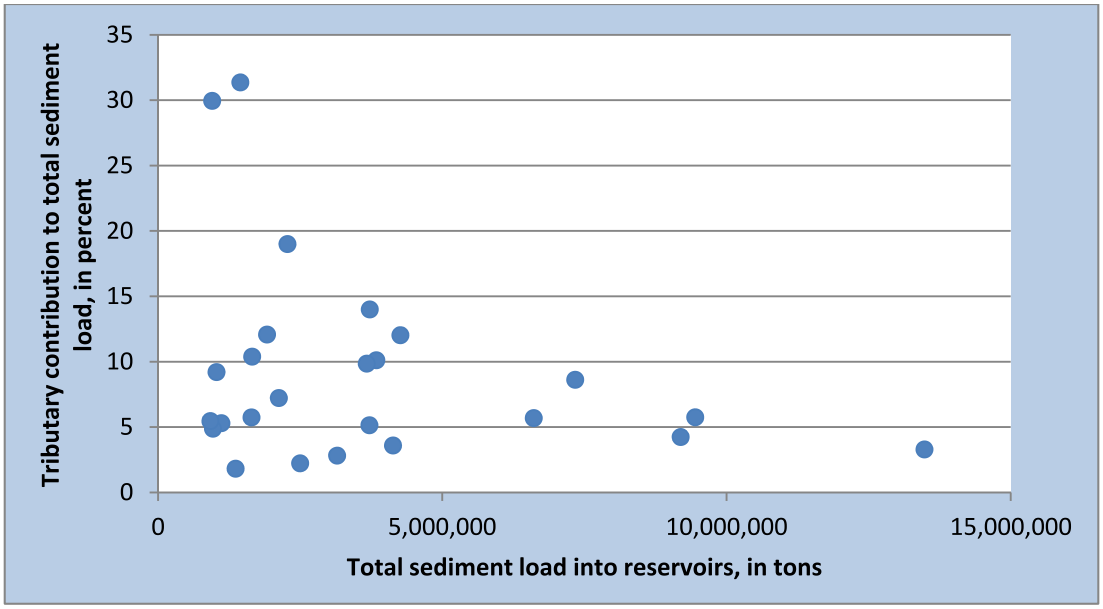


Figure 12. The percent of the total sediment load from the Conestoga River and Pequea Creek tributaries compared to the total sediment load transported into the reservoir system.

A model is calibrated if there is good agreement between model predictions and observed (measured) conditions over the simulation period. Model output was compared to volume changes based on bottom surface profiles from the 2008 and 2011 bathymetry studies, actual daily streamflows and sediment loads for the model time period, and particle size transport data determined from discrete sediment samples collected above and below the reservoirs. Interaction, evaluation, and feedback of boundary-condition data provided to the USACE for the 2-D model also aided in model calibration. The calibration process involved many iterations, each involving some adjustment to one or more model algorithm‘s or parameters and assumptions. For example, the initial model runs indicated scour at low velocities with little to no scour at high velocities, regardless of the critical shear stress resulting in low sediment concentrations and transport. Adjustments were made by changing transport functions and adding cohesive sediment properties.

The sediment-transport analysis in HEC-RAS requires the selection of sediment-transport formulas, maximum erodible depth, sediment bed sorting method, fall velocity method, upstream boundary (flow and sediment) conditions, Manning’s n, information on particle size fractions and additional detailed and specific information on sediment properties. Three of the seven sediment-transport functions were evaluated and Laursen (Copeland) was selected as best predictor. Erodible depths ranged from 0 feet just downstream of each dam where the bed is composed of gravels, boulders, and bed rock to 20 feet in the deepest sediment accumulation areas. Final calibration (input) parameters for each model are presented in table 4. Two simulations (depositional and scour) were performed using different model parameters but the same boundary condition data (more in Results section).

Table 4. Input parameters for the HEC-RAS depositional and scour simulations.

Parameter	HEC-RAS Depositional	HEC-RAS Scour
Sediment-transport function	Laursen (Copeland)	Laursen (Copeland)
Fall velocity method	Ruby	Van Rijn
Cohesive shear (pounds/square ft)	0.018	0.018
Erodible depth (feet)	Variable 0 to 20 ft	Variable 0 to 20 ft
Manning's n	Variable 0.012 to 0.3 (average 0.03)	Variable 0.012 to 0.3 (average 0.03)
Number of size fractions	12	12
Bed sorting	Exner 5	Active Method
Upstream discharge condition	Daily-mean discharge	Daily-mean discharge
Downstream discharge condition	Stage-discharge rating	Stage-discharge rating
Upstream sediment condition	Estimated daily loads	Estimated daily loads
Downstream sediment condition	Calibrate to the estimated daily loads	Calibrate to the estimated daily loads
Length of time steps	1 hour	1 hour
Water temperature	Daily time series	Daily time series

The Laursen (Copeland) transport function was selected as the best total sediment load transport predictor based on performance to transport silt, the most common particle size class in the bed sediments and suspended-sediment data; the selection of sorting methods varied depending on amount of deposition or scour; and the fall velocity method was selected based on temperature compensation and performance with other methods. The fall velocity of a particle depends on the density and viscosity of the fluid, and the density, size, shape, and surface texture of the particle. The "Ruby" method is appropriate for silt, sand, and gravel size grains, while the "van Rijn" method tends to hold the cohesive sediments and fine sands in suspension longer thereby increasing transport capacity (Van Rijn, 1984).

Cohesive critical shear threshold (force needed to initiate movement) and mass wasting thresholds (sediment moved downslope due to gravity) were first run using model defaults and were changed based on sediment data from the USACE SEDflume studies (Perky and others, 2013) using average values and bed mixing routines that were changed between models due to resistance to bed erosion. The Krone/Parthenaides option was selected which requires additional data input to quantify the deposition and erosion of cohesive material in a single process. Final cohesive parameter settings for the 12 groups (presented earlier in report) for bed sediment gradations are presented in table 5. An important model limitation is the model can only accept one non-varying series of cohesive parameters for all 12 groups, although the SEDflume data indicated a wide variability in the parameters.

Table 5. Cohesive parameter settings for bed gradations for the 12 bed sediment groupings.

[lb/ft^{2,} pounds per square foot; lb/ft^2/hr, pounds per square foot per hour];

	Critical Shear Threshold (lb/ft^2)	Erosion Rate (lb/ft^2/hr)	Mass Wasting Threshold (lb/ft^2)	Mass Wasting Rate (lb/ft^2/hr)
Cohesive Parameters	0.0183	33.1	0.31	134.3

In addition, several model computational and tolerance options related to performance (cross section expansion and contraction, critical depth computation, conveyance and energy slope analysis, and number of iterations) were set based on advice from Stan Gibson (personal communication, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, October 4, 2012). The output was daily and the model was run in one hour time steps from January 01, 2008 to December 31, 2011. A sensitivity check was made by using a time and flow varying time step (higher flows equal smaller time steps, with time steps ranging from 24 hours to 1 minute). Because the largest change in hourly flow was only 9,000 cfs in the Conowingo Reservoir, results from time steps less than 1 hour were not discernible.

6.0 Model Uncertainty and Limitations

Because models only approximate natural conditions, they are inherently inexact. The mathematical description can be imperfect and/or understanding of processes may be incomplete. Mathematical parameters used in models to represent real processes are often uncertain because the parameters are empirically determined and represent multiple processes and central tendencies (averages). Additionally, the initial conditions or the boundary conditions in a model may not be well known. The following limitations were observed and documented during this project.

1. Most models include the option of selecting alternative sediment-transport formulas, but few provide the criteria for making that selection. This usually results in many trial and error scenarios, relying on knowledge of the model parameter constraints or additional data collection to help in the validation process, or both. For this study, the selection of the sediment-transport function, Laursen (Copeland), was based on the most common sediment class (silt) in the bed sediments and transported over the Conowingo Dam.
2. Increasing the critical shear resulted in an increase in scour in some cross sections (contradictory effect). In other cross sections, the shear stress exceeded the mass wasting threshold which normally should produce scour, however, only minor scour was indicated. Project staff were not able to resolve these issues.
3. The model is one-dimensional, and while scour and deposition can be simulated in different time steps on the bed surface in each cross section, the model assumes the change occurs evenly across the entire cross-sectional movable bed. Bathymetry data from 2008 and 2011 indicate both deposition and scour occur in the same cross section (figure 13).

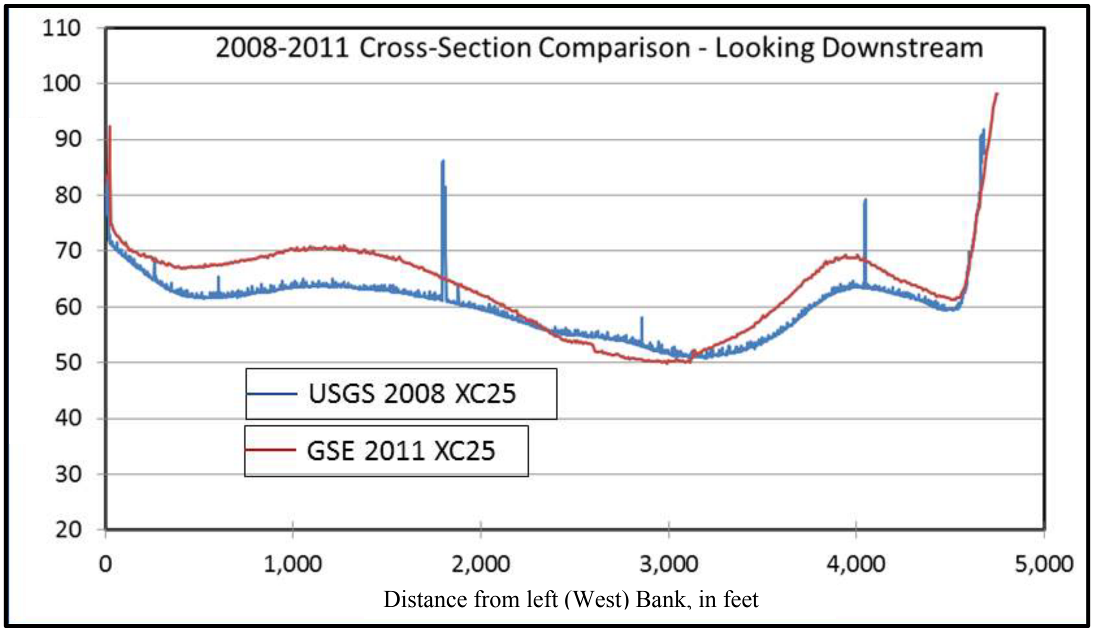


Figure 13. Comparison of cross section 25 (XC25) showing both deposition (red line above blue line) and scour (red line below blue line) for the 2008 U.S. Geological Survey (USGS) and 2011 URS Corporation URS Corporation and Gomez and Sullivan (GSE) bathymetries.

4. There was a lack of information of regarding flocculation size. This could have contributed in modeled fall velocity of the silts and clays being about two times lower (lack of deposition) than expected from literature values and the USACE 2-D model and fall velocity values had limited adjustment capability in the model.
5. The model only allows for one critical shear stress value for cohesive sediments; USACE SEDflume core stress data indicated the potential for wide variability, (Perky and others, 2013).
6. There were substantial differences in particle size distributions across many cross sections. The model cannot account for this lateral variation.
7. The model does not simulate the bed load and suspended load separately, but solves as total load.
8. The model is designed for non-cohesive (sands and course silts) sediment transport with limited capability to simulate processes of cohesive (generally medium silts to fine clays) sediment transport, which may not be suitable for all reservoir simulations, especially in areas of highly variable bed shear, active scour and deposition, and particle size.

7.0 Results

Calibration of the 1-D HEC-RAS model for this application was difficult due to model limitations and the complexity of the system being modeled. Model results were compared to other estimated loads in and out of the reservoir system using the USGS ESTIMATOR model (Cohn and others, 1989). As previously mentioned, the HEC-RAS model is designed for long-term (years) simulations (U.S. Army Corps of Engineers, 2010b), with potential applications to a single, high-flow event. For this study, there was a need to simulate the 2008-11 period and a specific flood event in September 2011. As the calibration proceeded, it became apparent that developing a single model to accurately simulate both deposition and scour was not possible. Therefore, two versions of the model were developed —one to simulate the net depositional change indicated by the 2008 and 2011 bathymetries and another to simulate the net scour that that was estimated to have occurred September 7-13, 2011 (Tropical Storm Lee).

As previously mentioned, bathymetry results indicated net deposition over the simulation period; therefore, model parameters were set to help ensure sediment deposition (Table 4. Many parameter combinations were tested with numerous iterations and calibration checks performed during the simulations (see Calibration section).

Estimated model output was compared to the bathymetry and sediment data, and to estimated data for loads from the USGS ESTIMATOR model and USGS scour regression equation model (table 6 and Attachment A). Using the net deposition model for the simulation period 2008-2011, approximately 22.3 million tons of sediment entered the reservoir system and approximately 20.2 million tons were transported into the upper Chesapeake Bay, resulting in approximately 2.1 million tons (10 percent of total load) being deposited in the reservoirs, with the majority deposited in Conowingo Reservoir (Table 6. The deposition simulated for the period 2008-2011 using the HEC-RAS model was very close (difference less than 5 percent) to the results obtained by summing the estimated annual loads from the USGS ESTIMATOR model for 2008-2011and about 54 percent less the volume when compared to the computed volume difference between the 2008 and 2011 bathymetries. Despite this poor agreement with the estimated change in bathymetry, due to limitations previously discussed, these results are consistent with previously published results from the Rillito River in Arizona (Duan and others, 2004). Duan and others (2004) compared five 1-D models (including two HEC-RAS) to the results based on the bathymetry change, and found all models substantially under predicted the actual deposition. The HEC-RAS model using the Laursen (Copeland) transport equation performed the best, under predicting by about one-half.

Results from the HEC-RAS net deposition model for the high-flow event (Tropical Storm Lee, September 7-13), indicated 200,000 tons of sediment were scoured in the upper two reservoir systems with 500,000 tons deposited in Conowingo. The depositional model results were quite different than results predicted by the USGS ESTIMATOR model (table 6) and the USGS scour equation (Table 6. and attachment A), both of which indicated scour (-3.55 and -3.50 million tons, respectively). The difference in estimates prompted the need for a second simulation for the high flow event in 2011.

Table 6. Results for sediment load transport IN and OUT of the Lower Susquehanna River reservoir system by model type. Numbers in black represent deposition; numbers in red represent scour.

Model	Calendar Year 2008-2011 (tons)	Difference (tons)	Tropical Storm Lee (Sept 7-13, 2011) (tons)	Difference (tons)
HEC-RAS (depositional)				
Marietta IN	22,300,000	--	9,900,000	--
Conowingo IN	22,100,000	200,000	10,100,000	-200,000
Conowingo OUT	20,200,000	1,900,000	9,600,000	500,000
Net change	2,100,000	2,100,000	300,000	300,000
HEC-RAS (scour)				
Marietta IN	22,300,000	--	9,900,000	--
Conowingo IN	24,400,000	-2,100,000	10,300,000	-400,000
Conowingo OUT	25,200,000	-800,000	11,400,000	-1,100,000
Net change	-2,900,000	-2,900,000	-1,500,000	-1,500,000
USGS ESTIMATOR				
Marietta IN	22,300,000	--	9,900,000	--
Conowingo OUT	20,100,000	2,200,000	13,500,000	-3,550,000
USGS Scour Regression Equation	--	--	--	-3,500,000
Bathymetry Change (2008-2011)	**--**	4,500,000	**--**	--

Changes in the bed surface elevations based on the HEC-RAS depositional model suggest deposition occurred in all three reservoirs (figure 14) generally in the middle and lower reaches. The simulated change in bed surface is greatest (between 1.0 and 1.5 feet, areas shown in orange and brown in figure 14) near Safe Harbor and Conowingo Dams. Scour (negative deposition, areas shown in pink and red in figure 14) is indicated in the upper reaches of Safe Harbor Reservoir (Lake Clarke) and in the lower reaches of Holtwood Dam Reservoir (Lake Aldred). No scour was indicated in the Conowingo Reservoir. Little to no change in bed elevation is evident in many areas. Areas mapped in figure 14 correspond well to the 2011 bathymetry for Conowingo in terms of spatial change (deposition) but the modeled sediment mass data is less than predicted when compared to the bathymetry for many cross sections.

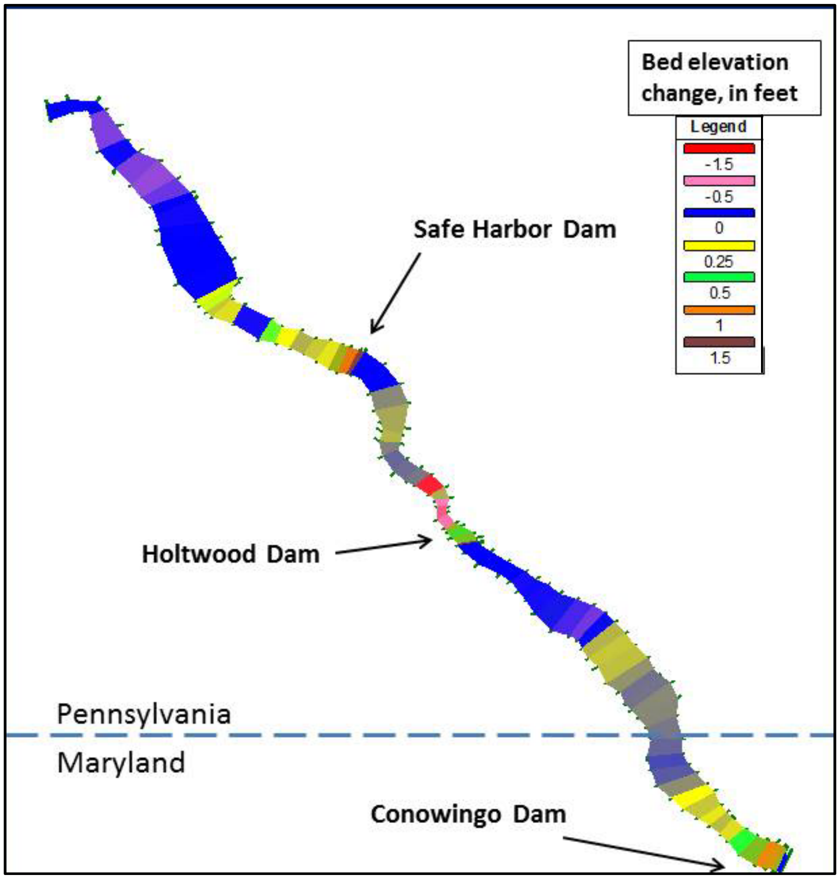


Figure 14. Changes in bed elevation using a HEC-RAS depositional model, 2008-2011.

A second 1-D model simulation (a scour model) was developed using the same 2008-2011 input boundary data to estimate the total scour from the reservoir system for the period September 7-13, 2011. The model parameters for the scour simulation are given in tables 3 and 4. The bed sorting method was changed to an algorithm that was less resistant to erosion and the fall velocity method changed to decrease settling to bed surface, thereby potentially increasing the mass to be scoured (Table 6). For the simulation period September 7-13, 2011, approximately 9.9 million tons of sediment entered the reservoir system (about 44 percent of the entire four year model simulation incoming sediment load) and approximately 11.4 million tons were transported into the upper Chesapeake Bay, resulting in approximately 1.50 million tons being scoured in the reservoirs, the majority (1.1 million tons or approximately 73 percent) was estimated to be from Conowingo Reservoir (Table 6. The simulated scour volume from the HEC-RAS scour model for the high flow event is about 57 percent of the volume computed from the USGS scour prediction and the daily summed USGS ESTIMATOR model loads for September 7-13, 2011. For the 2008-2011 simulation period, the net scour model indicated about 2.9 million tons scoured during the 2008-2011 period, with about 40 percent estimated to originate in Conowingo Reservoir. The net bed elevation change based on the 2008 and 2011 bathymetries indicated 4.5 million tons of deposition.

Changes in the bed surface elevations based on the HEC-RAS scour model indicate scour occurred in all three reservoirs (figure 15), generally occurring throughout the majority of the reservoir cross sections. The greatest change in bed surface elevation depicting scour (about -1.5 ft, areas shown in red in figure 15) occurs in several areas in all three reservoirs, generally related to a natural constriction in the river channel. These large scour spatial areas and depositional areas near Safe Harbor and Conowingo Dams (about 1 to 1.5 ft, areas shown in orange or brown in figure 15) suggest that in all three reservoirs, sediment is both scoured and deposited even at dynamic-equilibrium storage capacity and the upper two reservoirs could contribute one-fourth to one-half of the total scour load from the reservoir system.

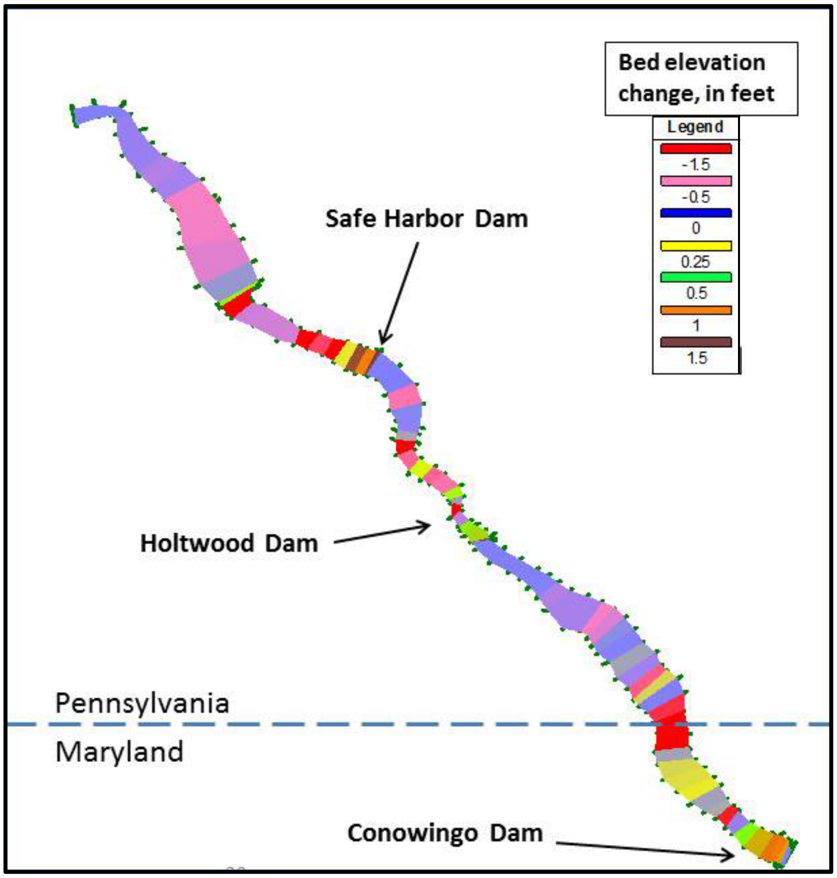


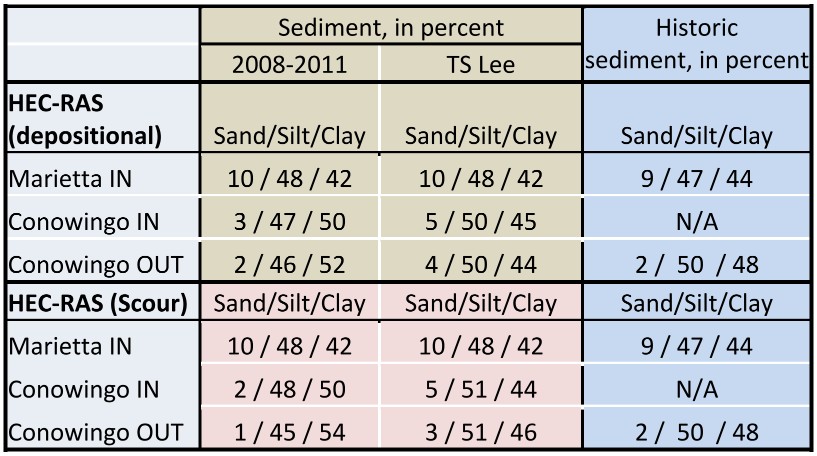
Figure 15. Changes in bed elevation using a HEC-RAS scour model, 2008-2011.

Particle size results from the models for scour and deposition for the 2008-2011 simulation period were compared to historic sediment (sand, silt, and clay) transport (table 7). Twelve sediment particle sizes (7 sand, 4 silt, and 1 clay, from table 2) were used in the bed sorting and sediment-transport routines. The percentages of sediment (sand, silt, and clay) transported in and out of the reservoir system, as simulated in both the depositional and scour models, are in close agreement with historic percentages of sediment transported (table 7). Generally, both simulations suggest little sand is transported to the upper Chesapeake Bay while silts comprise the greater percent of the transported sediment.

The model output data (boundary condition) containing the daily sediment loads by particle size and individual cross sections along with the streamflow data for Susquehanna River at Marietta, Pennsylvania and Conowingo, Maryland were provided to the USACE for use as input or calibration for the 2-D model (Berger and others, 2010). An additional model simulation was completed with no inflowing sediment to the reservoir system in an attempt to quantify the contribution of sediment from the upper two reservoirs. Additional information provided to the USACE included the 2008 and 2011 bathymetries, bed sediment particle size characteristics, temperature data, and Manning's n values for each cross section.

Table 7. Summary of HEC-RAS sediment (sand, silt, and clay) transported into the Susquehanna reservoir system (Marietta), and into and out of the Conowingo Reservoir compared to historic sediment transport.

[N/A; not available]



	Sediment, in percent		Historic sediment, in percent
	2008-2011	TS Lee	
HEC-RAS (depositional)	Sand/Silt/Clay	Sand/Silt/Clay	Sand/Silt/Clay
Marietta IN	10 / 48 / 42	10 / 48 / 42	9 / 47 / 44
Conowingo IN	3 / 47 / 50	5 / 50 / 45	N/A
Conowingo OUT	2 / 46 / 52	4 / 50 / 44	2 / 50 / 48
HEC-RAS (Scour)	Sand/Silt/Clay	Sand/Silt/Clay	Sand/Silt/Clay
Marietta IN	10 / 48 / 42	10 / 48 / 42	9 / 47 / 44
Conowingo IN	2 / 48 / 50	5 / 51 / 44	N/A
Conowingo OUT	1 / 45 / 54	3 / 51 / 46	2 / 50 / 48

8.0 Summary

Boundary-condition data for daily flow, sediment transport, and particle size fractions were constructed from a one-dimensional (1-D) sediment-transport model using two simulations (deposition and scour) and were provided to the USACE for input to the two-dimensional (2-D) model used to simulate processes in the Conowingo Reservoir and output to the upper Chesapeake Bay. The depositional simulation resulted in a net deposition of 2.1 million tons for the 2008-2011 period, while the scour simulation resulted in a net loss of 1.5 million tons of sediment for the Tropical Storm Lee event. The results indicate a difference of about 54 and 57 percent less, respectively, when compared to the calibration data. Each simulation provided a range of probable conditions and also provided a range of uncertainty in the boundary-condition data. The simulations also provide insights into the reservoir sediment dynamics, indicating all three reservoirs are active with respect to scour and deposition even at dynamic-equilibrium storage capacity as is the case in the upper two reservoirs. Silt is the dominate particle size transported from the reservoir system, with little sand (less than 5 percent) transported to the upper Chesapeake Bay. Model limitations were identified and include underestimation of fall velocity, use of non-varying (average) shear, and non-varying cohesive settings to represent highly variable sediment characteristics. These limitations most likely resulted in 1) less than expected deposition for the 2008-2011 simulation and 2) less than expected erosion (scour) for the Tropical Storm Lee seven day event simulation, when compared to other approaches and estimates. In conclusion, because the 1-D model is designed primarily for non-cohesive (sands and course silts) sediment transport with additional but limited capability to simulate processes of cohesive (generally medium silts to fine clays) sediment transport, the model may not be suitable for all reservoir simulations, especially in areas of highly variable bed shear, active scour and deposition, and a lack of information on flocculation size. The boundary-condition data from the 1-D model were helpful in the calibration of the USACE 2-D model, especially by improving information on the inputs into Conowingo Reservoir.

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