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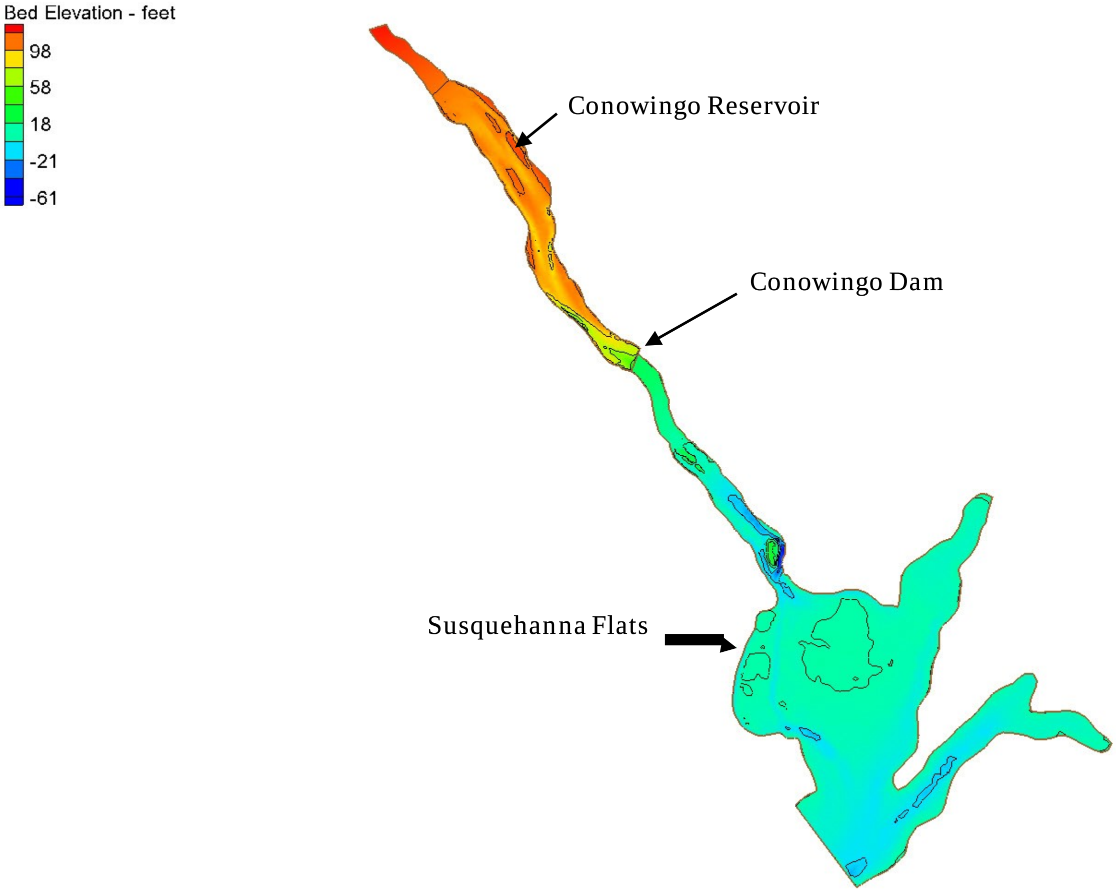
Sediment Transport Characteristics of Conowingo Reservoir

Stephen H. Scott and Jeremy A. Sharp

February 2014



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ERDC DRAFT
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Sediment Transport Characteristics of Conowingo Reservoir

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Abstract

Three consecutive dam and reservoir systems are located on the lower Susquehanna River; Lake Clarke (uppermost), Lake Aldred, and Conowingo Reservoir (lowermost). The dams associated with these reservoirs produce hydroelectric power for the region. The dams were constructed over the time frame of 1910 – 1931. With the passage of time, Lake Clarke and Lake Aldred have filled with inflowing sediments. These reservoirs are considered to be at full sediment storage capacity, thus they no longer efficiently trap nutrients and sediment. The lowermost reservoir, Conowingo, has very little sediment storage capacity remaining, and is currently near a state of dynamic equilibrium in which sediment transport through the reservoir over time will remain relatively constant.

The Lower Susquehanna River Watershed Assessment (LSRWA) is being conducted by the Baltimore District of the Corps of Engineers to address the sedimentation issues of these lower reservoirs as well as water quality of the lower Susquehanna River and Chesapeake Bay. The Maryland Departments of the Environment and Natural Resources were the non-federal sponsors for the watershed assessment, with The Nature Conservancy and the Susquehanna River Basin Commission as technical contributors. The study described in this report is one of a number of studies sponsored by the LSRWA for evaluating the impacts of sediment and nutrient transport on the water quality of Chesapeake Bay. This report describes the results from a two-dimensional (2D) sediment transport model of Conowingo Reservoir. The impacts of large storms on bed scour were simulated, as well as a number of sediment management alternatives including conventional dredging and agitation dredging. A number alternatives were investigated to evaluate the change in sediment transport in Conowingo over time. Three reservoir bathymetries (1996, 2008, and 2011) were used in the model to evaluate temporal sediment transport trends. Model inflowing sediment boundary conditions were provided by a HECRAS one dimensional model of the three lower Susquehanna River reservoirs developed by the United States Geological Survey (USGS) under the LSRWA effort. Model results indicate reservoir bed scour increases for large storms as the reservoir fills, with decreasing reservoir sedimentation as storage capacity is lost. Additionally, model results indicate that Conowingo Reservoir is near full sediment storage capacity and that it is

currently in a state of dynamic equilibrium. This implies that although the reservoir scours and stores sediment during flood and non-flood periods, overall the net reservoir sediment storage capacity does not change appreciably over time. Thus the bay may be currently experiencing maximum sediment inflows from Conowingo during periodic large flood events.

The 2D modeling results only describe the transp0rt of sediment solids and do not imply a relationship exists between solids transport and fate with nutrient loads.

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Preface

This study was conducted for the U.S. Army Corps of Engineers, Baltimore District under project identification "Sediment Transport Characteristics of Conowingo Reservoir." The Baltimore District team included the study manager Anna Compton, the project manager Claire O'Neill, with technical team members Bob Blama, Tom Laczo, Chris Spaur, and Danielle Szimanski. The Maryland Departments of the Environment and Natural Resources were the non-federal sponsors for the watershed assessment, with The Nature Conservancy and the Susquehanna River Basin Commission as technical contributors.

The work was performed by the River Engineering Branch of the Flood and Storm Protection Division, U.S. Army Engineer Research and Development Center – Coastal and Hydraulics Laboratory. At the time of publication, Dr. Loren L. Wehmeyer was chief of the River Engineering Branch; Dr. Ty V. Wamsley was chief of the Flood and Storm Protection Division; and Mr. Bill Curtis was the technical director for the Flood and Storm Protection Division. The deputy director was Richard Styles and the director was Mr. Jose E. Sanchez.

COL Kevin J. Wilson was the commander and executive director of the U.S. Army Corps of Engineers, Engineer Research and Development Center, and Dr. Jeffery P. Holland was the director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
microns	1.0 E-06	meters
miles (US statute)	1,609.347	meters
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.88026	pascals
pounds (mass)	0.45359237	kilograms
square feet	0.09290304	square meters
square yards	0.8361274	square meters
tons (long) per cubic yard	1,328.939	kilograms per cubic meter
tons (2,000 pounds, mass)	907.1847	Kilograms
yards	0.9144	Meters

1 Introduction

The Susquehanna River flows through south central New York, central and southern Pennsylvania, and northeastern Maryland, draining a watershed of approximately 27,000 square miles. Three hydroelectric dams and the associated reservoirs are located in series on the lower Susquehanna River within a 35-mile span of the river upstream of Chesapeake Bay. The upper most reservoir, Lake Clarke, is impounded by Safe Harbor Dam located approximately 32 miles upstream of Chesapeake Bay. It was constructed in 1931, with a design water storage capacity of approximately 150,000 acre-feet. The middle reservoir, Lake Aldred, was impounded by Holtwood Dam in 1910, with a water storage capacity of approximately 60,000 acre-feet. It is located approximately 25 miles upstream of Chesapeake Bay. The lowermost reservoir, Conowingo Reservoir, was constructed in 1928 with a water storage capacity of approximately 300,000 acre-feet. Conowingo Dam is located approximately 10 miles upstream of the bay.

Inflowing sediments from the watershed have been depositing in these reservoirs since construction. The inflowing sediment load is dependent on many factors including watershed area, land use, and regional hydrology. In addition to the natural sediment load, coal entered the Susquehanna River system through mining and processing operations. These coal sediments comprise approximately 10 percent of the sediment deposited in the reservoirs (Hainly and others, 1995).

The Susquehanna River is a major tributary to Chesapeake Bay, delivering a substantial amount of sediment and nutrients to the bay. High inflowing nutrient loads, some of which are attached to sediment particles, have resulted in the Chesapeake Bay being listed as water quality impaired under the federal Clean Water Act (CWA). In an effort to mitigate these negative impacts, regulatory agencies responsible for implementing the federal CWA required a TMDL (total maximum daily load) limit for nutrient releases into the bay (USEPA, 2011). To meet the TMDL requirements, sediment and nutrient releases from all Chesapeake Bay tributaries, including the Susquehanna River and the associated Conowingo Dam, must be controlled. If sedimentation processes within the three upstream reservoirs were currently in a steady state condition, a TMDL standard could possibly be enforced. However, the dam/reservoir system has altered the river's hydrology such that sediment deposition and erosion throughout the system is in flux. The top two reservoirs have reached a dynamic equilibrium sediment transport condition in that the capacity to store sediments has been significantly reduced (Langland and others, 2009). In the absence of large flow events, the majority of sediments that enter the two upstream reservoirs transport to the lowermost Conowingo Reservoir. However, large flood events will scour and transport bed sediment deposits in these reservoirs, thus temporarily restoring some incoming sediment storage capacity. Conowingo Reservoir currently is approaching a dynamic equilibrium state and continues to store inflowing sediments during non-flood periods. However, the storage capacity of Conowingo will decrease over time similar to the upstream reservoirs. Eventually, it is assumed that all three reservoirs will be in a dynamic equilibrium condition where the system's overall capacity to store sediments has been significantly reduced and larger flow events cause more frequent sediment scour sediment scour and transport events that temporarily restores some sediment storage capacity. Thus, as the storage capacity decreases over time, the amount of sediment and nutrients delivered to the bay may increase to some degree.

The hydrodynamic and sediment transport processes in the reservoirs are complex and unsteady in nature. Thus a thorough understanding of both sediment deposition and erosion processes is required for evaluating how the system currently functions and how it will function in the future. Although sediment transport in Conowingo Reservoir is dominated by deposition during low flow periods, bed scour does occur during large flow events, and significant amounts of sediment can potentially be scoured, mobilized, and transported through the reservoir system and ultimately into the bay. To facilitate analysis of the reservoir system, a 2D numerical model of reservoir hydrodynamics and sediment transport was developed and utilized to evaluate sediment transport through the reservoir, as well as evaluate sediment management alternatives necessary to control or mitigate sediment releases.

This report presents a description of the model, how it was applied, and model results for a number of sediment transport scenarios designed to evaluate storm scour potential and sediment management alternatives. The 2D modeling results only describe the transp0rt of sediment solids and do not imply a relationship exists between solids transport and fate with nutrient loads.

2 Background

The USGS has performed a number of significant sediment transport and bathymetric studies on the three reservoirs. Their study findings indicate that top two reservoirs are in a dynamic equilibrium status, with Conowingo Reservoir currently having some capacity to store incoming sediment load. The USGS predicts that Conowingo Dam has approximately 10 to 15 years of sediment storage capacity remaining (USGS 2009). Data presented by the USGS studies show the average inflowing sediment into the reservoir system as well as the Conowingo Reservoir deposition rate over time. Figure 1 presents the average sediment delivery to the system by decade, along with the estimated sediment deposition in Conowingo Dam. The estimated sediment deposition in Conowingo was determined by interpolating data presented in the 2009 USGS publication referenced above.

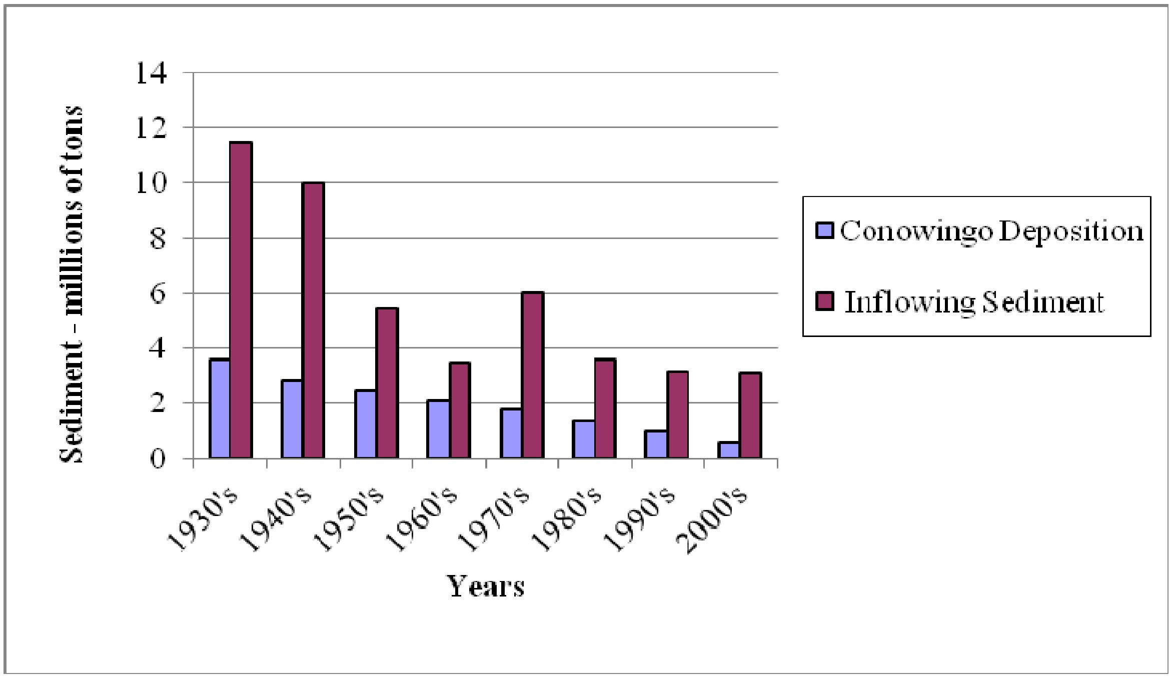


Figure 1 Average annual Inflowing sediment into the lower Susquehanna along with Conowingo Reservoir deposition (provided by USGS)

From 1929 to 1959, all three reservoirs were actively trapping sediments. (USGS, 2009) The inflowing loads from the watershed during that period were much higher. By approximately 1959, the two uppermost reservoirs had become less efficient in trapping sediment, and the inflowing sediment load to Conowingo Reservoir remained relatively constant at about 3.2 million tons per year, with the exception of the 1970's which was impacted by Hurricane Agnes. During this time of relatively constant average sediment inflow (1960 to present), the average deposition of sediment in Conowingo Reservoir has been decreasing. A constant sediment inflow combined with a reduction in sediment deposition indicates a possible decrease in trap efficiency with a resulting increase in sediment outflow from the reservoir.

The USGS estimates that the average inflow of sediment is about 3.2 million tons per year into Conowingo Reservoir, with deposition ranging from 1.0 to 2.0 million tons per year. A similar reservoir with adequate storage capacity can have a trap efficiency ranging from 70 to 80 percent. Although the data indicate that, on the average, the trap efficiency of Conowingo Dam is decreasing, large flow events can temporarily increase trap efficiency by scouring existing bed sediments out of the reservoir into the bay. The USGS indicates that flow events on the order of 400,000 cfs (cubic feet per second) will result in scour of reservoir bed sediments. This flow is approximately a 5-year return flood (Figure 2). To put this flow in perspective, a 1-year return flood on the lower Susquehanna is approximately 130,000 cfs, with a 100-year return flood approaching 900,000 cfs.

Two sediment transport numerical modeling studies were conducted on the lower Susquehanna reservoirs. In 1995, the USGS conducted a HEC-6 one dimensional model study (Hainly and others 1995). The modeling results indicated that the HEC-6 model significantly under-predicted the trap efficiency (35 percent as opposed to the measured efficiency of 76 percent). They found that the model was capable of reproducing the measured trap efficiency if the inflowing sediment size classes included more coarse grained sediments. In addition, Exelon Corporation revised the USGS HEC-6 model and conducted a series of simulations to evaluate scour potential of the three reservoirs (Exelon, 2012 RSP 3.15). Their results indicated that for flood flows greater than 400,000 cfs (scour threshold flows), Conowingo Reservoir was net depositional. A summary of both studies is presented in the Exelon report cited above.

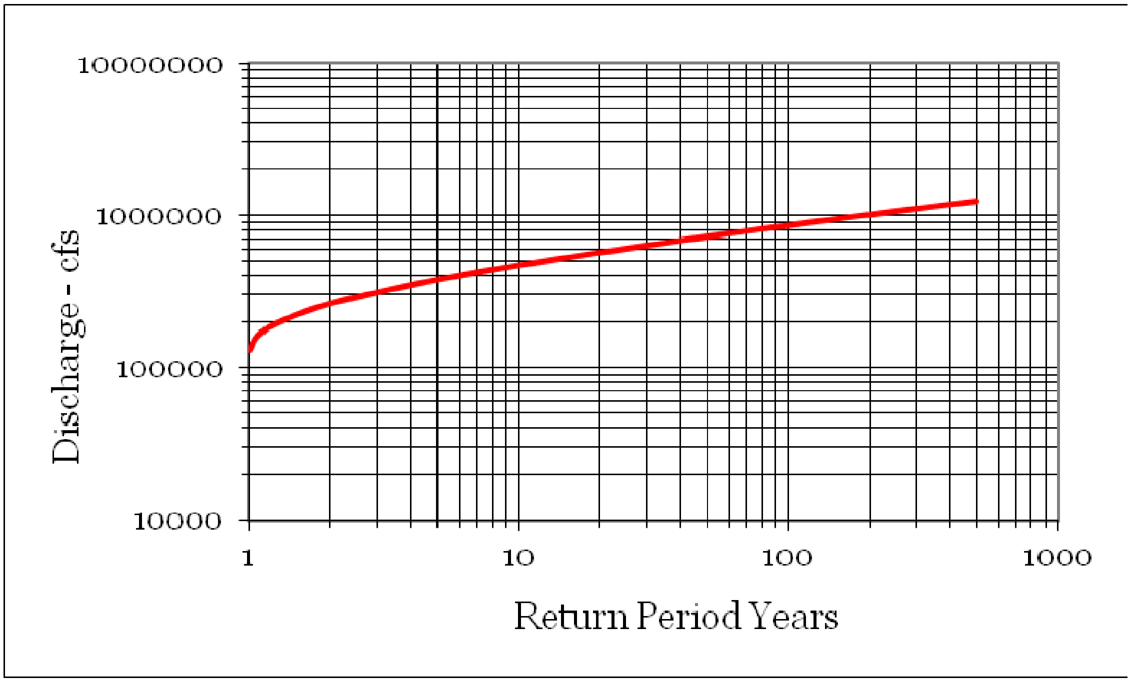


Figure 2 Return flood flows for the Susquehanna River

3 Study Approach and Goals

For this study, the 2D model was used to simulate a number of alternatives that were designed to provide an estimate of the impact of low, moderate, and flood flows on sediment transport dynamics in Conowingo Reservoir. The complexity of reservoir hydrodynamics and sediment transport dictate that a physics-based model be applied to the problem. The appropriate model must contain either physical or empirical formulations that will adequately simulate the processes found in the domain. The 2D Adaptive Hydraulics (AdH) numerical model developed by the ERDCWES is a finite element, implicit scheme model utilizing an unstructured mesh (Berger, 2012). It provides a fully unsteady solution of system hydrodynamics and sediment transport. The sediment transport model is capable of simulating coarse sediment transport (sand size or greater), fine sediment transport (silt and clay sizes) or mixed sediment transport. Multiple bed layers can be simulated, with sorting of mixed load due to variable erosion and deposition processes. The model contains sediment transport capacity functions for the coarse sediment transport. However, silt and clay deposits in reservoirs will most likely display cohesive behavior due to consolidation. Functions that describe the prototype sediment behavior can be directly input into AdH to describe the erosion and deposition characteristics. For the LSRWA study, the bed sediments in the reservoirs were sampled and analyzed in the laboratory to develop erosion rate functions specific to the sediments in the reservoir. The AdH model utilizes this data to compute the erosion rate and critical shear stress for erosion of the cohesive fine sediment bed.

The AdH numerical mesh used for the Conowingo study consisted of approximately 20,000 elements and 10,000 nodes. The mesh density for the entire Conowingo Reservoir is depicted in Figure 3, with Figure 4 presenting the mesh density in the lower reach of the reservoir. The mesh was designed to provide an adequate number of computational elements and associated nodes to capture details of the reservoir bathymetry and to provide highly resolved model results. The model solution is generated at the computational nodes and interpolated across the element area to create a solution over the entire problem domain. For this study, a number of reservoir surveys were mapped to the mesh for analysis. The USGS provided reservoir surveys from 1996 and 2008, with Exelon

Corporation providing the most recent 2011 survey. The 2011 survey was modified by the USGS to represent a full sediment capacity condition.

The model simulations were designed to provide insight into how the reduction in sediment storage capacity over time affects sediment discharge from Conowingo Dam, and determine the effectiveness of proposed sediment management techniques designed to reduce the overall sediment load to Chesapeake Bay. The model output parameters of interest include net reservoir sedimentation, net bed scour as a function of sediment grain size, and total load to the bay. All simulations were conducted with the same Susquehanna River flow and inflowing sediment boundary conditions. The 4-year flow period from 2008 to 2011 was simulated in the model. The flow and sediment entering the upstream model boundary (channel below the dam on Lake Aldred) were provided by the USGS from HEC-RAS (Hydrologic Engineering Center-River Analysis System) model simulations of the 4-year flow record. These simulations included all three reservoirs, thus the sediment output from HEC-RAS included bed sediment scour from the upper two reservoirs. The sediment rating curve in the HEC-RAS simulations was developed by the USGS from suspended sediment measurements in the Susquehanna River above the reservoir system.

The following were the six main study goals:

- Evaluate the uncertainty associated with applying a 2D model to Conowingo Reservoir;

- Measure the critical shear stress and erosion rate of bed sediments in Conowingo Reservoir for input into the 2D model;

- Evaluate how Conowingo Reservoir sediment transport responds to low, moderate, and flood flows for different reservoir bathymetries representing temporal changes in sediment storage capacity (1996, 2008, and 2011 years);

- Determine how Conowingo Reservoir sediment transport responds to low, moderate, and flood flows for a full reservoir capacity scenarios;

- Evaluate how effective sediment management techniques would be for reducing sediment loads passing through Conowingo into Chesapeake Bay (conventional dredging, agitation dredging, and sediment bypassing impacts);

- Provide model output to the CBEMP (Chesapeake Bay Environmental Modeling Package) which will evaluate the impact of the 2D AdH output on water quality in Chesapeake Bay.

Figure 3 Numerical Mesh of Conowingo Reservoir

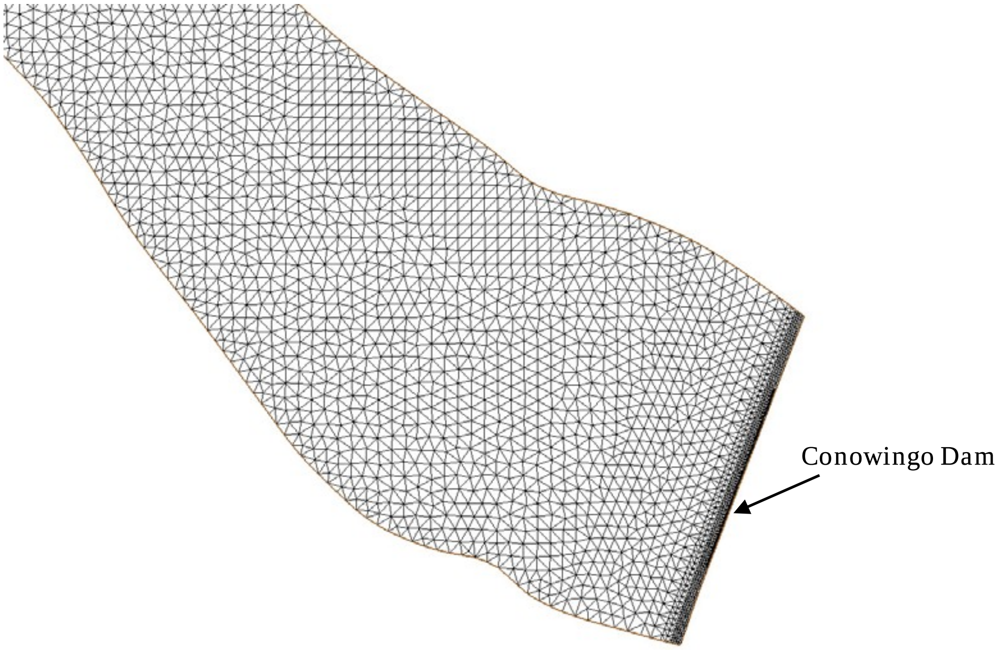


Figure 4 Detail of numerical mesh in lower Conowingo Reservoir

4 Description of Modeling Uncertainties

Numerical models are valuable tools for describing complex flow and sediment interactions. However, as with any analytical method, they contain a number of uncertainties that can influence results. The decision of which model to use depends on many factors, including problem dimensionality and required resolution. One dimensional models are typically utilized when depth and laterally averaged conditions can provide adequate resolution to the problem. When lateral sediment transport conditions need to be resolved, a 2D model is more appropriate. In this case, the model results are depth averaged, with model results available throughout the domain area. The most complex model to apply to a problem is the 3D model. It provides problem resolution in all three dimensions (depth, lateral, and longitudinal). However, these models are computationally intensive and require long periods of simulation time to run relatively short problem durations.

4.1 Modeling uncertainties

Hydrodynamic and sediment transport numerical models have a number of inherent uncertainties. The mathematical computation methods add uncertainty, with additional uncertainties due to bathymetry surveys used to populate the model and field data used for model boundary conditions. The choice of a sediment transport model to apply to reservoirs depends on the conditions that will be modeled. If the goal of a particular study is to better understand reservoir stratification in low flow, low turbulence conditions, then a three-dimensional model (3D) will be required to differentiate the vertical properties. However, if the item of interest in the reservoir occurs during well-mixed, turbulent conditions, a 2D depth-averaged model will be adequate. A 3D model can also be applied to well-mixed problems, but the computational requirements (run time) are excessive. Two dimensional models can be used to simulate sediment transport over years or decades, thus they are better suited for long-term simulations.

Reservoirs are primarily depositional at low to moderate flows. When a reservoir is initially constructed the sediment trap efficiency is high, approaching 80 percent or more. As the reservoir fills with sediment, coarser sediments begin to deposit in the upper reaches of the reservoir, with the finer fractions depositing in the downstream reaches or passing through the dam. Over time, the upper reservoir reach becomes shallower due to deposition, thus the transport capacity increases with inflowing sediment transporting further downstream. Eventually a delta forms within the reservoir at its upstream end that encroaches on the deeper, lower reaches of the reservoir and gradually decreases sediment storage capacity (Sloff, 1997). When the reservoir no longer has sediment storage capacity, it is assumed to be in equilibrium in that sediment that flows into the reservoir eventually is passed through the dam. Reservoir equilibrium is not a static condition, rather an ongoing dynamic change of state. The sediment deposits during low flows and scours during flood flows, and the net result is that the sediment entering the reservoir eventually leaves the reservoir. The changes in hydrology created by the dam thus changes both the timing and the quantity of sediment transport below the dam.

Modeling such a dynamic system requires an extensive set of model boundary conditions such as suspended sediment inflow concentrations and fine sediment bed properties. Suspended fine sediments can either exist as primary silt and clay particles, or in low energy systems such as reservoirs, form larger particles in the water column due to flocculation. Particles that flocculate are larger and have higher settling velocities, thus their fate in the reservoir can be quite different than the lighter primary particles (Ziegler, 1995).

When fine sediment particles deposit on the reservoir bed, they compact consolidate over time. As they consolidate, the yield stress increases, meaning that the resistance to erosion becomes greater. Higher flows and subsequent bed shear stresses are required to scour the consolidated bed. Laboratory results show that sediments that erode from consolidated beds may have larger diameters than the primary or flocculated particles (Banasiak, 2006). Scour may result in re-suspension of large aggregates that re-deposit in the reservoir and do not pass through the dam. To add to the complexity of this phenomenon, the large aggregate particles scoured from the bottom during a high flow event can break down to smaller particles in highly turbulent conditions. Thus the fate of inflowing sediment particles in the reservoir is highly variable and difficult to capture with current modeling techniques.

Reservoir dam operations can significantly impact the fate of inflowing sediments. Conowingo Reservoir discharges water through the power plant on the western end of the dam. At a flow greater than 86,000 cfs, the 52 flood gates that span the dam begin to open (Exelon, 2012 RSP 3.29). Each flood gate generally has the capability to pass up to about 15,000 cfs. The power plant water intake is located near the reservoir bed whereas the flood gates remove near surface waters. With the lower elevation water intake, the power plant has the potential to pass coarser materials that transport near the bottom whereas the flood gates may pass finer materials. Reservoir surveys indicate that during floods, the bed scours just upstream of the power plant intake and the adjacent flood gates. During a large flood that requires the majority of the gates to open, the spatial distribution of discharge shifts from the western side of the dam where the power plant resides, to the center of the channel. This shift in flow distribution and subsequent sediment load causes the sediment load on the eastern side of the reservoir to increase resulting in a high deposition rate in this area. Thus depending on the reservoir inflows, the spatial and quantitative fate of sediment in Conowingo Reservoir can be quite variable and difficult to simulate with current modeling methods.

In summary, of all the modeling uncertainties that exist, three are most critical for interpreting the Conowingo Reservoir modeling results. These include the potential for flocculation of sediments flowing into the reservoir, the potential for large sediment aggregates to erode from cohesive beds, and dam operations. Because of these uncertainties the AdH model may potentially over-predict to some degree transport of scoured bed sediment through the dam.

A report was prepared for the LSRWA effort that discusses modeling uncertainties. This report is attached in Attachment B-1.

5 Model Flow and Sediment Boundary Conditions

5.1 Susquehanna River inflows

The Susquehanna River inflows for all but one of the AdH simulations used flows from the four year time period from 2008 to 2011. The model inflow and downstream water surface elevation were the same for each simulation for comparison purposes. The sediment management simulation for agitation dredging used a number of steady state flows ranging from 30,000 to 400,000 cfs.

The 2008-2011 time period was chosen for the model simulations because it included periods of low flows where sediment was depositing in the reservoir, medium flows that transport more sediment to the lower reaches of the reservoir, and high flood flows that scour the bed. The first two years of flow allowed the bed to build whereas the last two years had flows that reached or surpassed the scour threshold flow of 400,000 cfs.

The simulation flow data are presented in Figure 5. The first 2 years of this flow record contained relatively low flows with peak flows of approximately 300,000 cfs, whereas the final 2 years had flows exceeding 400,000 cfs, which is considered the approximate bed scour threshold discharge. The scour threshold discharge indicates when mass bed erosion occurs, not low erosion rates of thin surface layers of low density material. The top layer of Conowingo Reservoir sediments consists of a low density unconsolidated layer that may mobilize at lower flows. Tropical Storm Lee occurred in September 2011 with a peak discharge of approximately 700,000 cfs. The downstream water surface elevation boundary condition at the dam was 109.0 feet for all simulations.

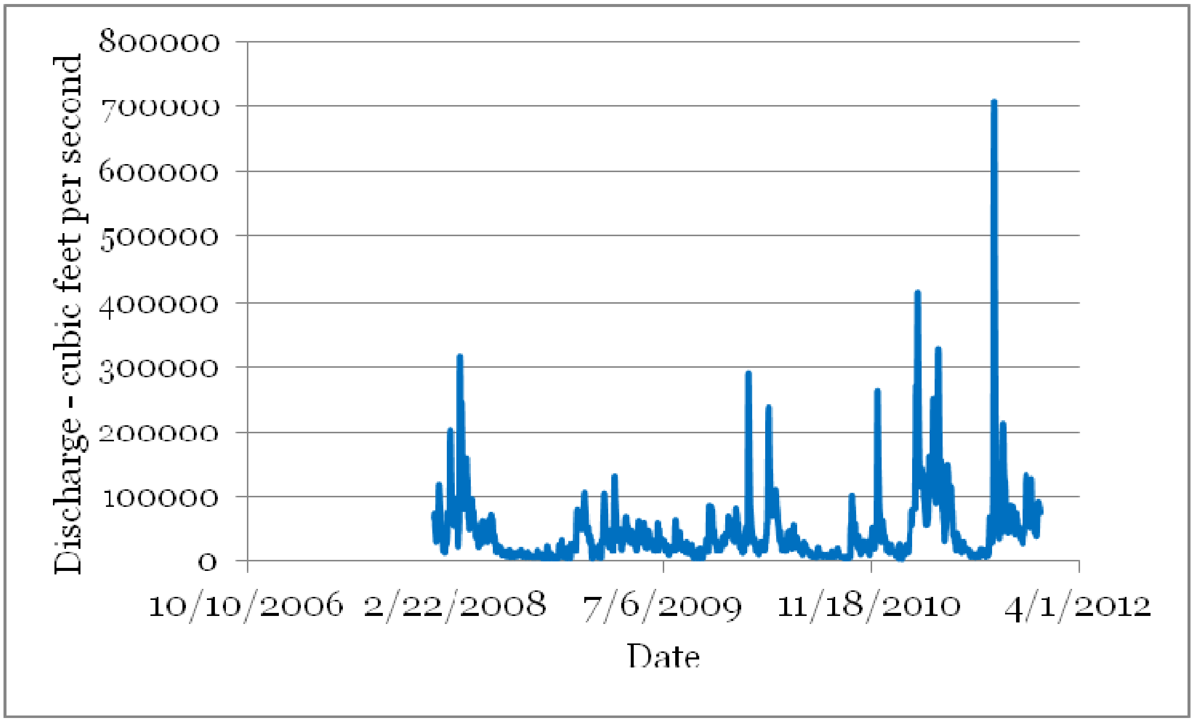


Figure 5 Flow boundary condition for AdH simulations

5.2 HECRAS output sediment rating curve / AdH input

The USGS provided the inflowing sediment load for the AdH model by simulating sediment transport through all three reservoirs with the HEC-RAS one-dimensional (1D) model. The USGS created a sediment rating curve for the Susquehanna River based on historical suspended sediment measurements for 10 sediment grain sizes. The HEC-RAS model was run for the 4-year flow record, 2008 to 2011. Hydraulic and sediment output data from HEC-RAS just below Lake Aldred (upstream boundary of Conowingo Reservoir) was used as input to the 2D model of Conowingo Reservoir based on maximum scour potential from Lake Clarke and Lake Aldred.

The HECRAS simulations produced two sediment inflow scenarios. The first scenario indicated no scour from the upper two reservoirs. The total inflow into Conowingo for this scenario was approximately 22.0 million tons. The second scenario was for approximately 1.8 million tons of scour from the upper two reservoirs, for a total Conowingo inflow load of approximately 24 million tons. For the AdH model runs, the maximum scour load from the upper two reservoirs is needed because the maximum load may influence transport capacity in Conowingo, and thus impact bed scour potential. Therefore the 24 million ton HECRAS load was increased by 10 percent to reflect a potential maximum scour load from the upper reservoirs . Thus the total sediment load entering Conowingo Reservoir was 26.2 million tons for the 4-year flow event simulation in the 2D model. The inflowing sediment rating curve for AdH is presented in Figure 6, with the clay, silt, and sand fraction in Figure 7 for the 2008 – 2011 inflow. Figures 6 and 7 show loads increasing exponentially after the 400,000 cfs scour threshold, with clay sediments dominating the inflow at lower discharges, with coarser sediments (silts and sands) increasing with flow. The USGS 1D model effort is summarized in a separate report to the LSRWA.

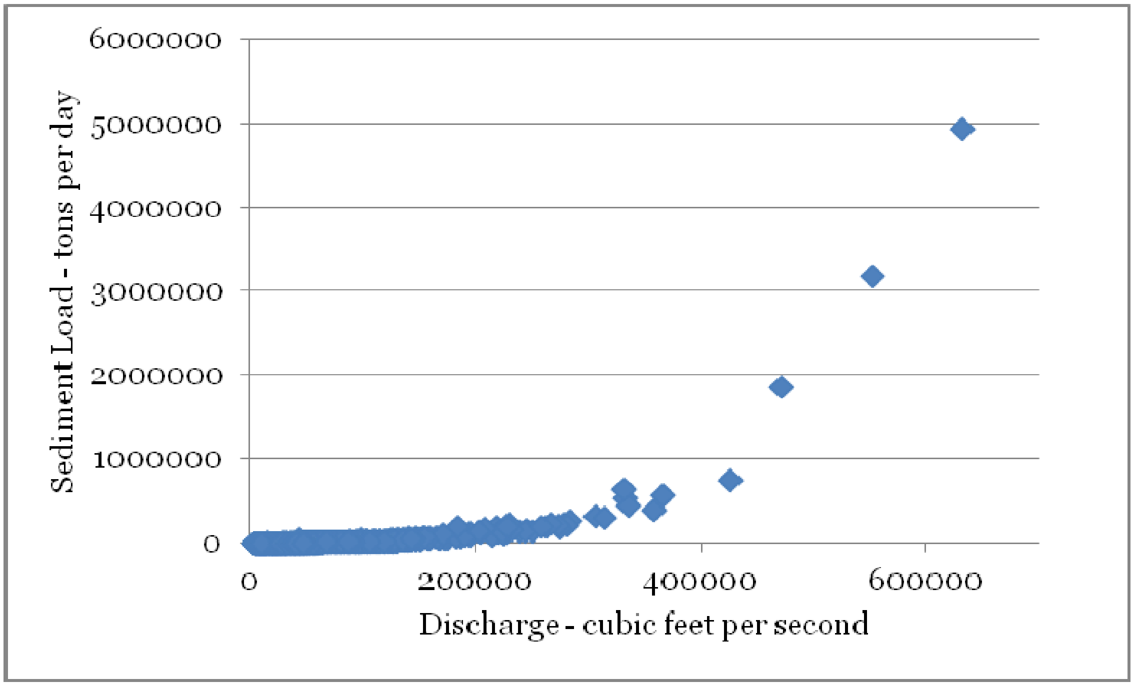


Figure 6 AdH input sediment rating curve

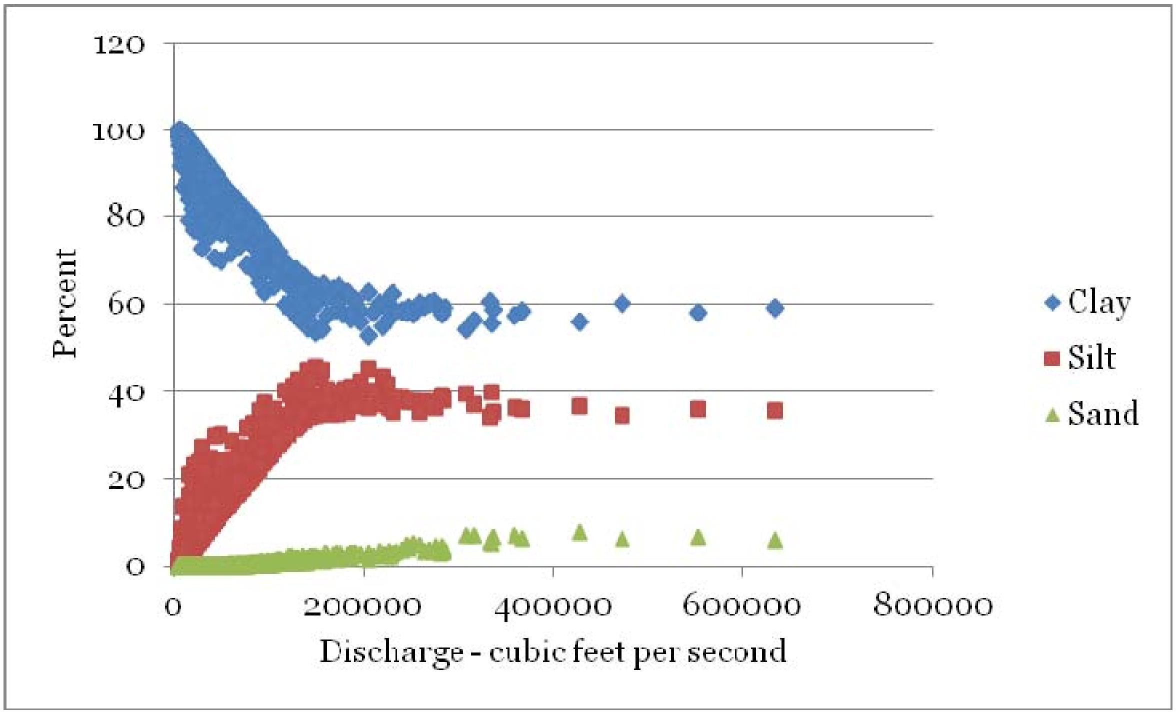
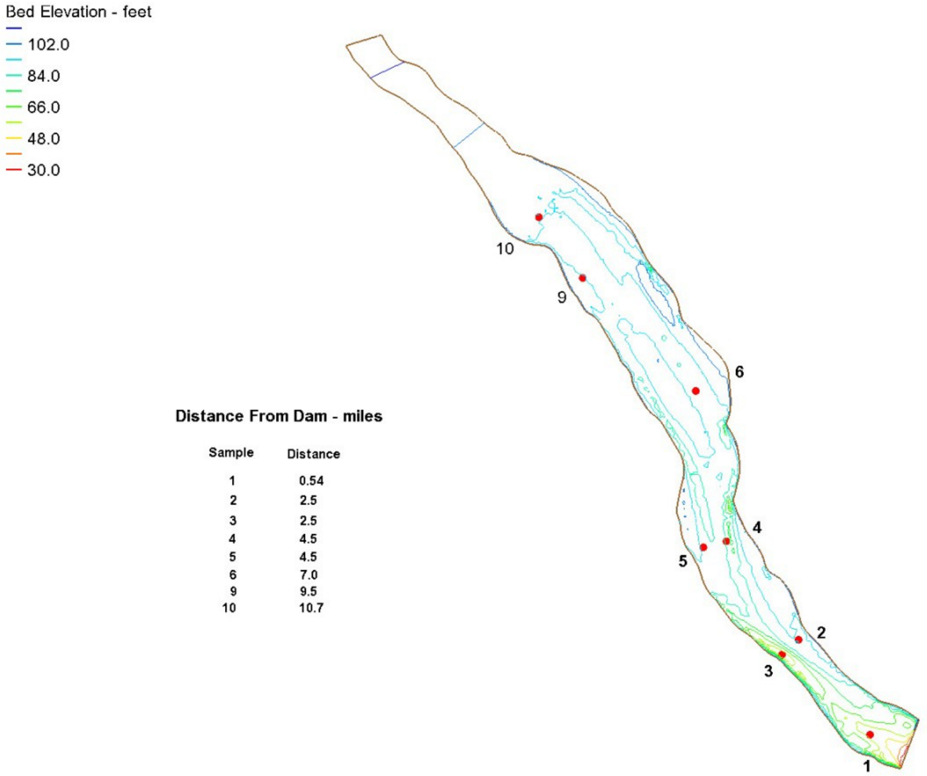


Figure 7 Percent of clay, silt, and sand in Conowingo inflow

5.3 SEDflume analysis of bed sediments

The AdH sediment model requires bed sediment properties for each layer in the bed. If the sediment bed has more than 10 percent fines (silts and clays), it is considered cohesive. For fine sediments, these properties include sediment bulk density, sediment particle size fraction, critical shear stress for erosion, and erosion rate.

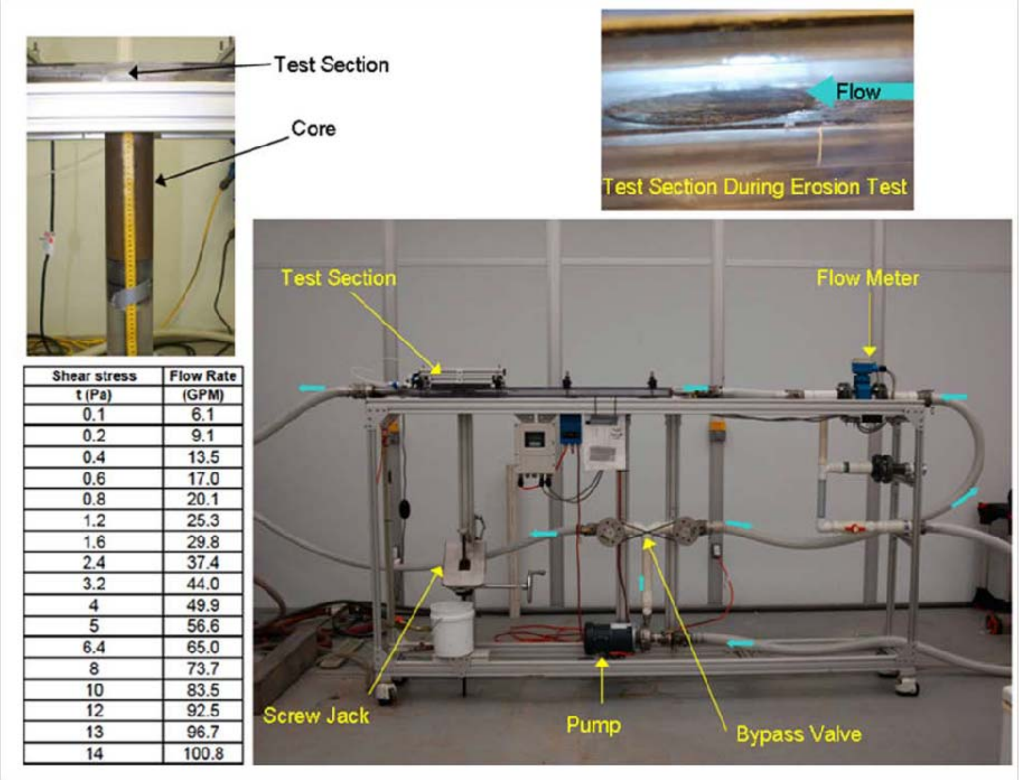
Eight bed core samples were taken from Conowingo Reservoir for analysis (Figure 8). The sample locations were determined through evaluation of potential scour and deposition areas, as well as spatial considerations (distance from the dam). The bed was sampled to a maximum depth of only one foot because the resistance of the more consolidated sediments at deeper depths. These samples were analyzed in the SEDflume, a laboratory-scale flume that subjects the core samples to varying flows to determine the inception of erosion (critical shear stress for erosion), and the erosion rate. The SEDflume apparatus is presented in Figure 9, with the full SEDflume laboratory report and bed property summary found in Attachment B-2. The SEDflume data developed in the Laboratory was used to populate the model bed. Six material zones were established in the model (Figure 10). For each of the zones, critical bed shear stress for erosion and erosion rates were defined based on the laboratory data.



Distance From Dam - miles

Sample	Distance
1	0.54
2	2.5
3	2.5
4	4.5
5	4.5
6	7.0
9	9.5
10	10.7

Figure 8 Core sample locations in Conowingo Reservoir for SEDflume studies



Shear stress t (Pa)	Flow Rate (GPM)
0.1	6.1
0.2	9.1
0.4	13.5
0.6	17.0
0.8	20.1
1.2	25.3
1.6	29.8
2.4	37.4
3.2	44.0
4	49.9
5	56.6
6.4	65.0
8	73.7
10	83.5
12	92.5
13	96.7
14	100.8

Figure 9 SEDflume apparatus

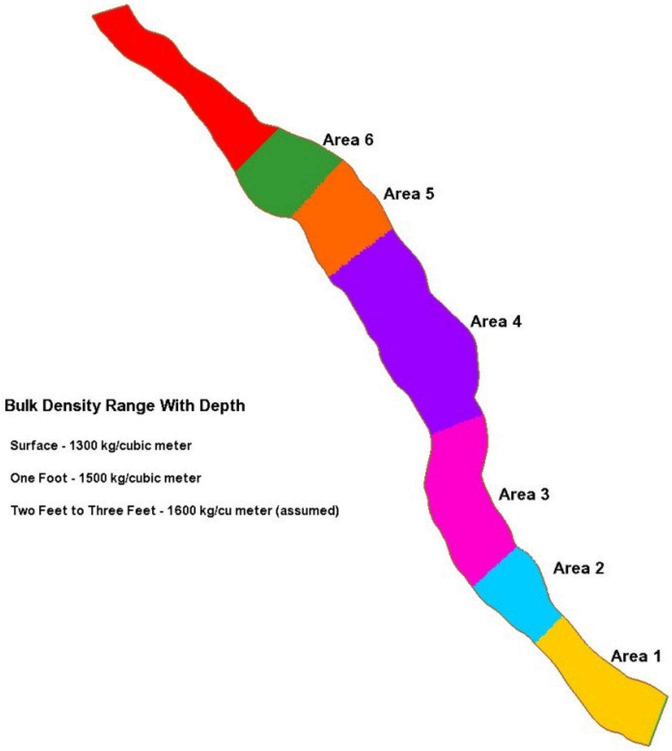


Figure 10 AdH sediment model material zones for assigning bed properties

6 Model Validation

Generally, there are two methods for evaluating model capability for reproducing field conditions; model calibration or model validation. Model calibration is conducted by comparing model output to a set of measured boundary conditions such as water surface elevations, velocity measurements, and inflowing and out-flowing sediment concentrations. The model parameters are then set to match, within reason, the actual data that was measured over a range of flows. A calibrated model can then be used to predict outcomes into the future. This is the preferable model application, however, large field data sets are often times non-existent, difficult to collect, and prohibitively expensive, or they cannot be collected within the timeframe of the project.

The alternative to a fully calibrated model is a model validation exercise. This is the method used for this AdH 2D modeling effort. Generally, a sediment transport model validation insures that the model can adequately replicate sediment transport characteristics of the system for which it is applied. Typically, a model validation is conducted when there are minimal or no directly measured boundary conditions. The model is compared to either analytical or empirical study results such as historical suspended sediment loads collected by the USGS below Conowingo dam. Model parameters are varied accordingly to generally match the results. Typically, a range of model parameters are varied to determine a lower and upper bound for sediment transport characteristics. This type of model is better suited for comparing existing and alternative project conditions rather than predicting model results into the future.

Minimum amounts of data were available for this modeling effort. The inflowing sediment load into Conowingo was provided from HEC-RAS output and not direct measurements. Suspended sediment samples were collected below the dam over time, however, very few were taken over the Tropical Storm Lee flood event simulated in the model. A total of eight bed sediment samples were taken from Conowingo Reservoir for analysis of critical bed shear stress for erosion and erosion rate. The maximum sample depth was only about 12 inches due to highly consolidated sediments in deeper layers preventing penetration of the sampling tube. In addition to the uncertainty of bed sediment erosion properties and inflowing sediment load, dam operations could not be simulated in the model. Efforts were made to simulate power plant discharge as well as flood discharge through the 52 flood gates. The hydrodynamics of the flood gate system was successfully modeled; however, sediment transport through the dam was not successful and could not be implemented for this project. Thus sediment transport characteristics (scour and deposition) near the dam may not be representative.

Because of the uncertainty of measured model boundary conditions, the AdH 2D model was validated by comparing model output to the total suspended sediment sample measurements below Conowingo Dam, the empirical studies of sediment mass balance through Conowingo Reservoir by the USGS, the fraction of sand, silt, and clay in the outflow below Conowingo Dam, and the scour and deposition change in Conowingo computed from surveys taken in 2008 and 2011. The bed roughness was 0.03 Manning's n for the reservoir with the exception of the upper 3.0 miles of the reservoir where the roughness ranged from 0.05 to 0.04 Manning's n. The Manning's n is a coefficient that describes the roughness of the bed, which is directly related to the computed water surface elevations and velocities.

6.1 Validation model description

For the validation exercise, the AdH model bathymetry was based on the 2008 survey. The USGS sediment rating curve was utilized as the inflowing sediment for the period 2008–2011 (26.2 million tons), with bed material properties taken from the SEDflume laboratory study. Generally, the sand, silt, and clay fractions ranged from about 10, 80, and 10 percent, respectively, near the dam, to about 50, 44, and 6 percent, respectively, in the upper reaches of the reservoir about 7 to 11 miles above the dam (Figure 11). The critical shear stress for erosion ranged from a low of 0.006 pounds per square foot (psf) within the top 0.5 inch of the core to a maximum of about 0.04 psf at a core depth of 1 foot. Most of the cores were less than 1 foot in length. The sampling tube could not penetrate the substrate indicating highly consolidated sediments. Although the samples only represented the top foot of material, the sediment bed in the AdH model was approximately 3 feet. The properties of the lower two feet were estimated from literature values. The general trend in bed properties was a coarsening of sediment size and subsequent increasing critical shear stress with distance from the dam. Although the bulk of sand was found in the upper reach of the reservoir, layers of sand were found in the cores taken in the lower reaches indicating transport of sand during high flow events to lower reaches of the reservoir.

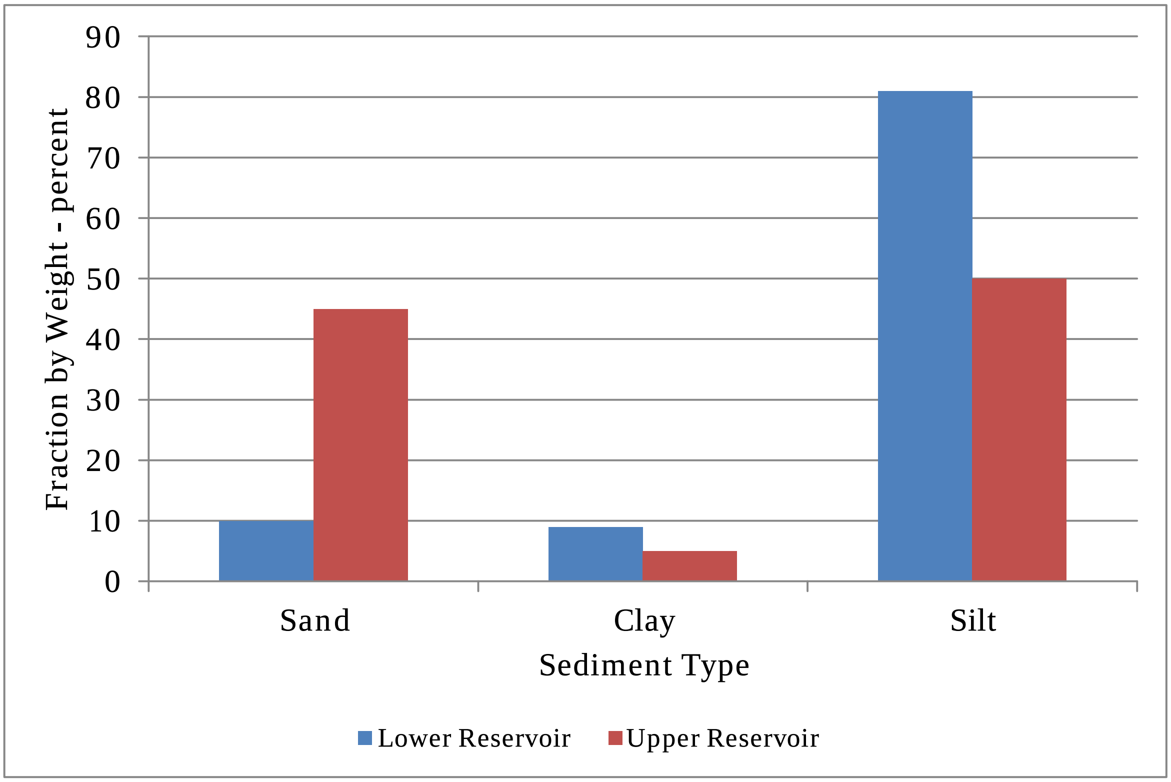


Figure 11 General particle size distribution for upper and lower Conowingo Reservoir

6.2 Total suspended solids measurements below Conowingo Dam

The measured suspended sediment data are presented in Figure 12 (USGS, 2011). The data show an increasing scatter with discharge indicating the effects of high flows. For a storm hydrograph, the magnitude of a suspended sediment measurement is highly dependent on when the measurement is taken. The highest suspended sediment concentrations are found on the ascending leg of the hydrograph, whereas the descending leg typically has lower values. This is referred to as the hysteresis effect. As the flow increases during the ascending leg, the available sediment is scoured and mobilized with peak sediment discharge. On the descending leg of the hydrograph, sediment supply is less, thus suspended sediment concentrations are lower. The peak concentration on Figure 11 was one data point taken on the ascending leg of the Tropical Storm Lee hydrograph (about 600,000 cfs). No further data could be collected because of dangerous conditions adjacent to the dam. Because large storms are more difficult and dangerous to sample, and occur less frequently, few suspended sediment samples are included in the data set for the higher flow ranges.

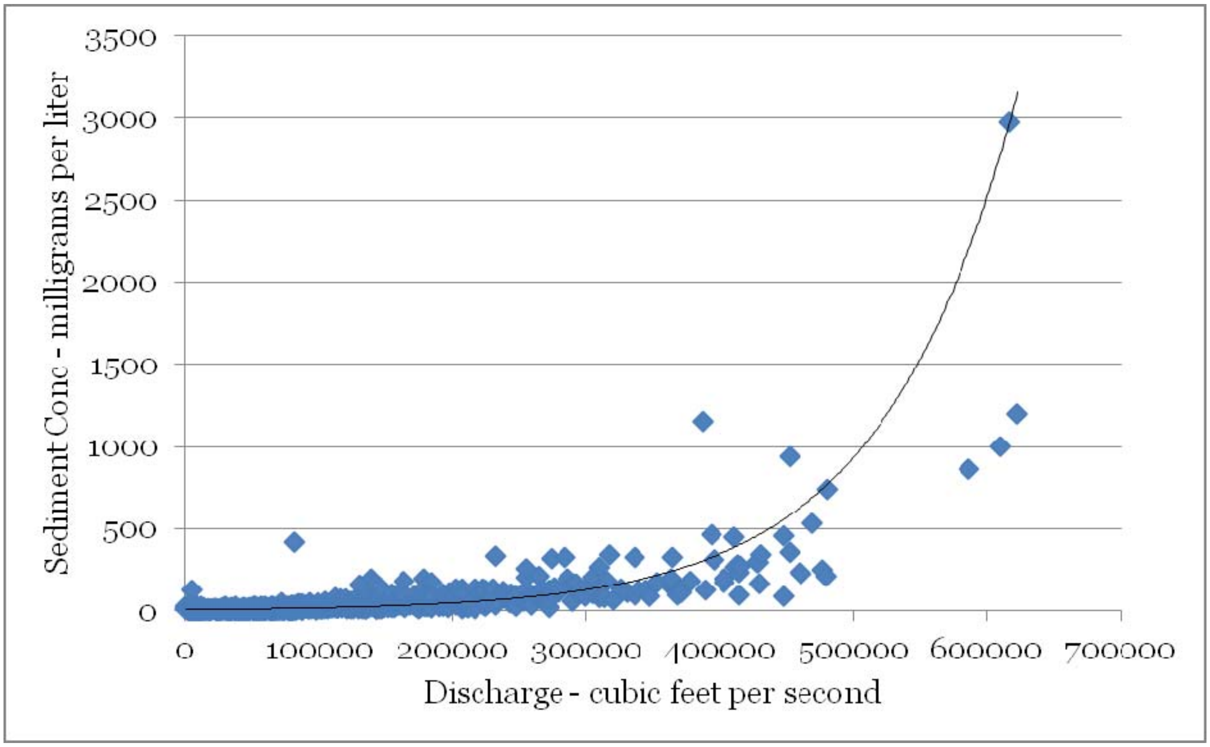


Figure 12 Suspended sediment concentrations measured below Conowingo Dam

6.3 USGS estimation of bed scour as a function of discharge

The USGS has performed numerous studies on changes in sediment storage capacity of Conowingo Reservoir (summarized in Langland and others, 2009). Based on these studies, they developed a scour prediction curve which estimates the amount of bed scour load that will occur in the lower Susquehanna River reservoirs as a function of mean daily discharge. The prediction curve is presented in Figure 13 along with upper and lower bounds. Note that at 630,000 cfs (mean daily flow for Tropical Storm Lee), the predicted scour load is about 3.3 million tons.

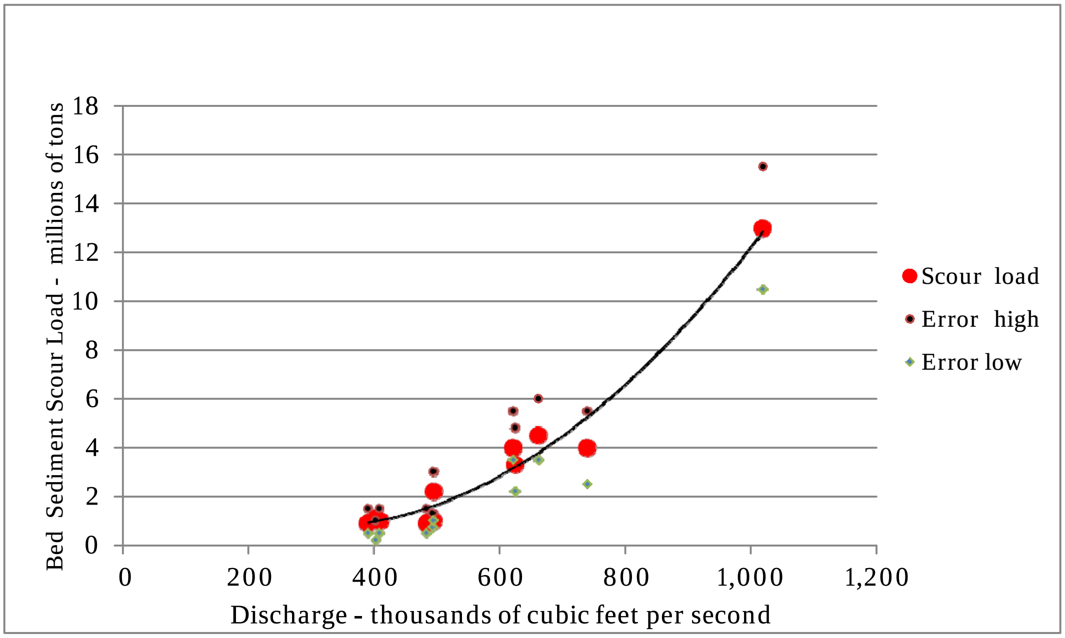


Figure 13 USGS predicted scour as a function of discharge in Conowingo Reservoir (provided by USGS)

6.4 Suspended sediment grain size distribution measurements

The total suspended sediment samples collected below Conowingo Dam were analyzed for sand, silt, and clay fractions. Figure 14 presents the data as a function of discharge (USGS 2001). Generally, at low flows, clay is the dominant sediment that is scoured. However, the silt fraction increases with increasing flow, along with the sand fraction. This reflects the increasing transport capacity with discharge. Overall, the sand fraction is less than 10 percent. These data were from suspended sediment samples taken below the dam and not computed by the model.

6.5 Change in deposition and bed scour from survey comparisons

Bathymetric surveys of Conowingo Reservoir were taken in 2008 and 2011. The 2011 survey was taken just after Tropical Storm Lee occurred. The impact of Tropical Storm Lee can be determined from evaluating the bed elevation change between the surveys. A computational mesh was created in the graphical user interface for the AdH model, the Surface Water Modeling System (SMS). This mesh contained 25,000 nodes and 48,000 elements. Each survey was interpolated to the mesh, with the 2008 mesh subtracted from the 2011 mesh. The difference is change in bed elevation, with positive change reflecting deposition and negative change reflecting bed scour. A summary report of these computations is provided in Attachment B-3. Approximately 8.6 million tons of sediment deposited between 2008 and 2011, with 5.4 million tons of scour. The reservoir was net depositional 3.2 million tons. The major trend was that most of the scour (50 percent) occurred in the upper one third of the reservoir (7-10 miles from the dam), with decreasing scour in the lower reaches of the reservoir. These sediments contained up to 50% sand. Approximately 120,000 tons scoured from the dam to a point one mile upstream. Deposition increased with distance from the upper reservoir to the dam, with 69 percent of deposition occurring in the lower half of the reservoir (from the dam to about 5 miles upstream). A significant amount of sediment was deposited just upstream of the Eastern end of the dam. This deposit contained approximately 26 percent of the total deposition in about 3 percent of the reservoir area.

Although the change in survey computations do not address how much scour material leaves Conowingo dam, they do show the potential for re-deposition of bed scour within the reservoir. The area with the maximum bed scour contains 50 percent sand. Samples taken below Conowingo dam indicate sand concentrations of 10 percent or less passing through the dam for large floods, thus the potential is high for these sandy sediments to re-deposit and not leave through the dam. The high depositional area found on the eastern side of the dam may be the result of dam operations during floods. The flood gates re-align the sediment laden flow to the middle of the reservoir, with low velocity circulation occurring upstream of the Eastern side of the dam. This low velocity circulation will encourage sedimentation in this area during the flood.

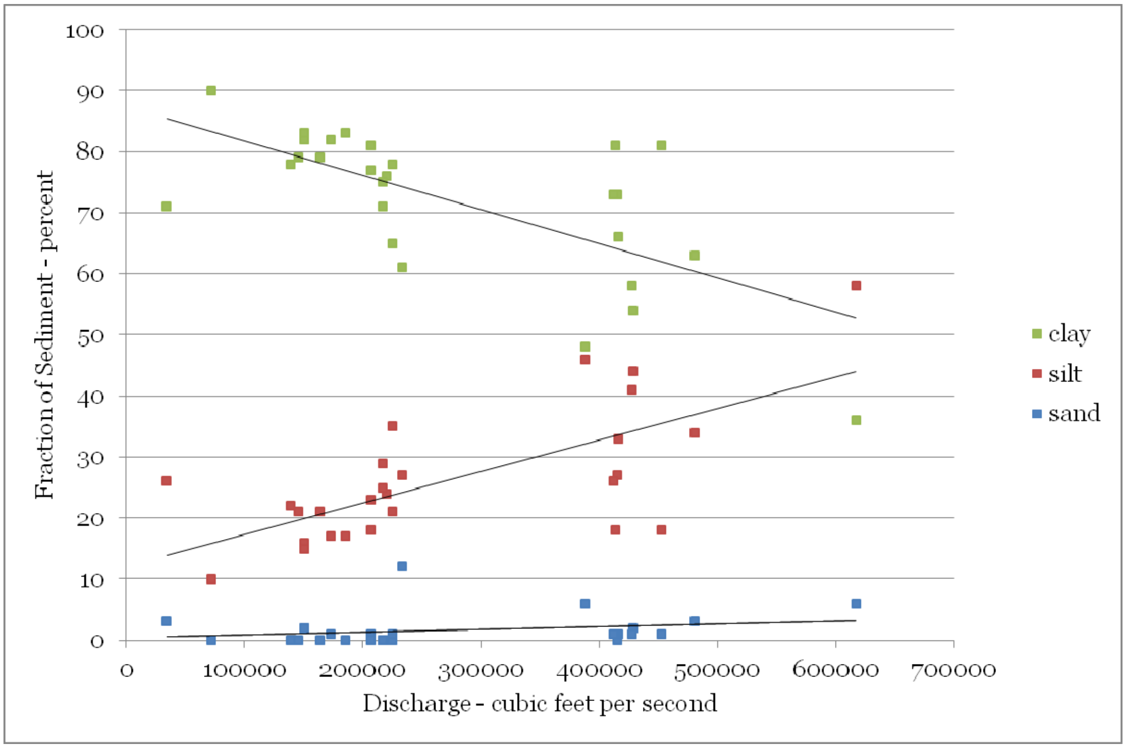


Figure 14 Measured clay, silt, and sand fractions as a function of discharge below Conowingo Dam

6.6 AdH model validation simulations and comparisons

A relatively small number of bed samples were taken from Conowingo Reservoir. Eight samples were used to represent the entire domain. Analysis of these samples revealed how the sediment size distribution coarsened with distance from the dam, and the subsequent variation of the critical shear stress and erosion rate. With such a small data set, it was necessary to conduct a parametric model study in which the variables were varied or adjusted to reflect the potential variation in bed properties. Variables include bed bulk density, critical bed shear stress, erosion rate, and depth of available bed sediment. After each parametric model run, the data were compared to the USGS scour load prediction, sediment size distribution of samples collected below the dam, and the change in survey computations. Each run was made with the same hydraulic and sediment boundary conditions (2008–2011 Susquehanna River flow and inflowing sediment rating curve). Ultimately, the most representative model formulation would reflect a net deposition of 3.0 to 4.0 million tons over the 2008 – 2011 simulation period, sediment retention of about 1.0 to 1.5

million tons per year during the non-storm periods, and outflow of 10 percent or less sand from the reservoir.

The model calculated a bed scour load through the model ranging from 5. 5 million tons to 2.0 million tons based on simulations containing varying estimates of critical shear stress, bed bulk density, erosion rate, and available bed material.

The upper range, 5.5 million tons, was within the upper error bound of the USGS scour prediction curve, however, the simulation resulted in a net scour bathymetry, which is not in agreement with the change in survey calculations. Additionally, sand fractions higher than 10 percent passed through the model.

Estimated increases in critical bed shear stress for erosion for deeper bed layers resulted in a calculation of 4.0 million tons of bed scour passing through the model with a net depositional bathymetry of about 1.0 million tons. This net deposition is somewhat lower than that computed by the change in survey calculations. Additionally, sand fractions greater than 10 percent passed through the model.

Higher critical shear stress values from literature were assigned to the model based on the bulk density of the sediments (Whitehouse, 2000). This simulation calculated a bed scour load of 2.9 million tons, with a net depositional bathymetry of 4.4 million tons, which is in approximate agreement with the change in survey computations, with sand fractions passing through the dam less than 10 percent (Figure 15). The average annual non-storm deposition during the initial years of simulation (2008 – 2010) was about 1.3 million tons.

To obtain a lower end estimate of bed scour passing through the dam, the depth of sediment available for scour was limited to one foot which represents the sampling depth limit. Approximately 2.0 million tons of sediment passed through the model.

The AdH model and USGS scour predictions are found in Figure 16, with SEDflume parameters used in the simulations summarized in Table1 (full description in Attachment B-2).

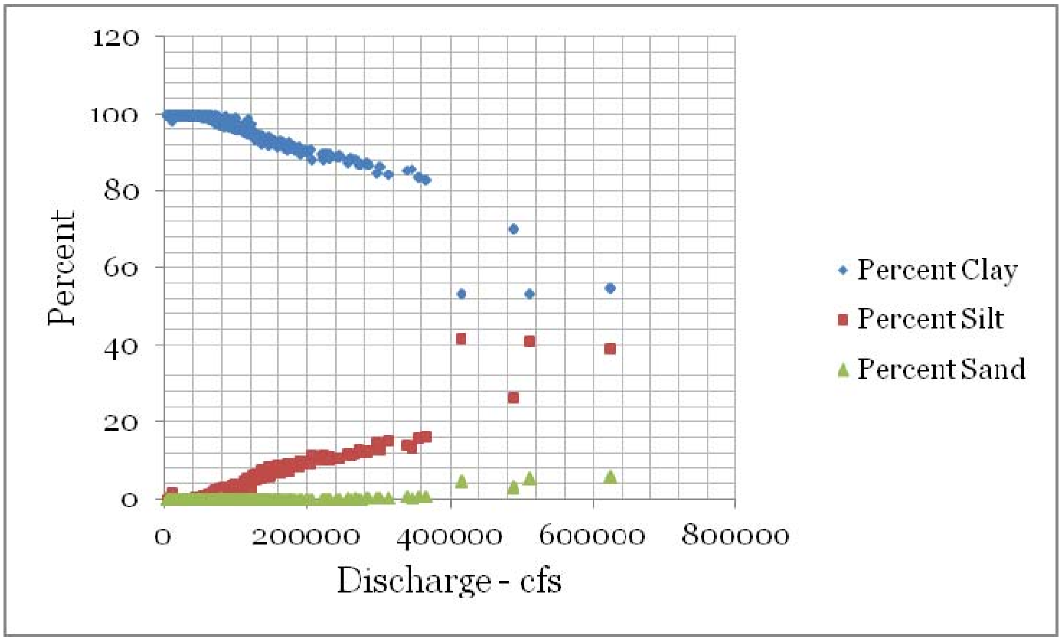


Figure 15 Model output of clay, silt, and sand fractions passing through Conowingo Dam

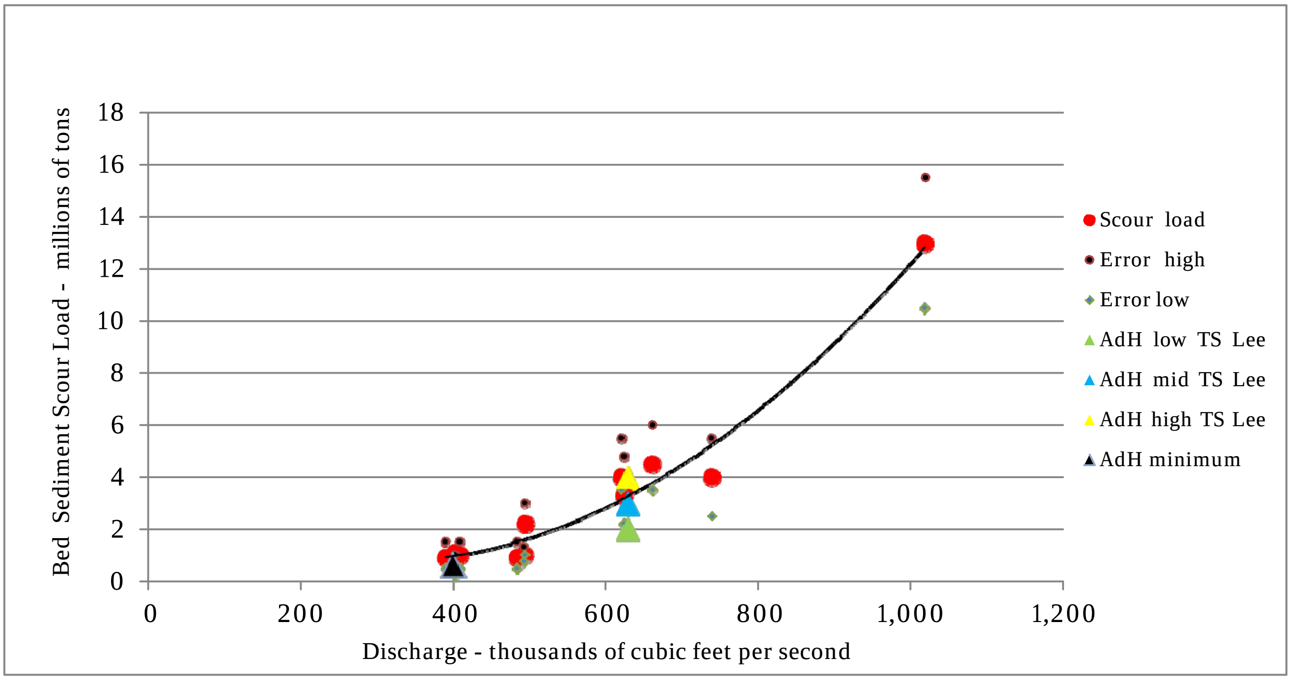


Figure 16 Scour load predictions by the USGS with AdH model results

The parameters in Table 1 are used to compute erosion rate from the following equation:

$$E = M\left(\frac{\tau}{\tau_c} - 1\right)^n$$

With τ_c the critical bed shear stress for initiation of erosion, τ the bed shear stress calculated by the model, M the erosion coefficient and n the exponent.

Table 1. SEDflume data for validation simulations – scour load in millions of tons

Simulation	**Bed Depth - ft**	**Critical Shear – lb/ft²**	**Coefficient M**	**Exponent n**	**Scour Load**
1	0-1	0.005 – 0.04	0.01-0.08	1.0 – 1.3	5.5
	1-2	0.04	0.08	1.3	
	2-3	0.04	0.08	1.3	
2	0-1	0.005 – 0.04	0.01-0.08	1.0 – 1.3	4.0
	1-2	0.06	0.08	1.3	
	2-3	0.10	0.08	1.3	
3	0-1	0.03 – 0.06	0.01-0.08	1.0 – 1.3	2.9
	1-2	0.10	0.08	1.3	
	2-3	0.14	0.08	1.3	
4	0-1	0.03 – 0.06	0.01 – 0.08	1.0 – 1.3	2.0

6.7 Discussion

Based on the AdH validation simulations, along with the computed changes in the 2008 and 2011 bed surveys, it is estimated that the potential range of bed scour that leaves the reservoir during the Tropical Storm Lee event is within the range of 2.0 to 4.0 million tons, with this bed scour range based on the impact of varying the bed bulk density, critical shear stress for erosion of bed layers, and the quantity of bed material available for erosion.

Based on the above model runs and analysis, the model formulation that predicts 2.9 million tons of bed scour load was chosen for the following alternative simulations. It is a more conservative calculation that better correlates bed scour and deposition to system hydraulics.

7 Model Simulations – Impact of Temporal Change in Sediment Storage Capacity

The AdH model was utilized to investigate a number of scenarios designed to provide guidance on how variations in sediment storage capacity impacts sediment transport through Conowingo reservoir. Although significant uncertainty exists with the model simulations, the uncertainty is reduced to a manageable level by comparing existing versus alternative model simulations. With this approach, an existing condition simulation is performed for a given problem. Then a change is made to the model to represent the alternative condition. This could be a change to the model bathymetry such as removing sediment representing a dredging operation. All of the other variables remain the same as for the existing condition. The alternative condition is simulated and directly compared to the existing condition simulation to evaluate the impact of the change in condition.

Three reservoir bathymetries were simulated in the model for comparison purposes (1996, 2008, and 2011). For all three simulations, the same sediment and flow boundary conditions were utilized (the 2008–2011 flow record with USGS sediment inflows). Each simulation contained the same model variables with the exception of the model bathymetry. The cumulative change in sediment storage in the reservoir over the 4-year timeframe was computed by subtracting the sediment load discharged from the reservoir from the inflowing sediment load. A positive loading trend represents deposition with a negative loading trend representing a reduction of storage due to bed scour. For all of the sediment storage plots, the Tropical Storm Lee flood event occurred on day 1348 (significant decrease in sediment storage trend). The bed scour load passing through the dam was computed, along with net sedimentation in the reservoir. The reservoir sediment storage was then compared for each of the simulations (1996, 2008, 2011, and full reservoir storage).

7.1 General flow and bed shear distribution in Conowingo Reservoir

Before presenting the sediment transport results, it is informative to show system hydrodynamics for two flow events, a 150,000 cfs flow which approximately represents a one year return flow event for the

Susquehanna River, and a 400,000 cfs flood event which represents a five year return flow event. Model hydrodynamic output are presented in Figures 17-20 which describe the distribution of flow and bed shear stress for both events. The bathymetry used for this simulation was based on the most recent 2011 reservoir survey. The 150,000-cfs flow event is presented in Figures 17 and 18. The upper 3.0 miles of the reservoir has the steepest channel slope (0.001 feet/feet) thus it had the highest velocity and bed shear. This channel was not included in the bathymetry surveys (USGS and Exelon), however, some bathymetric data were available that described the general channel shape and slope. At 150,000 cfs, the maximum velocity in the reservoir is about 1.0 foot per second, with a bed shear less than the critical bed shear stress for erosion from the SEDflume studies (0.004 psf) over much of the reservoir. Generally, the flow distribution and velocity are highest in the deeper channels within the reservoir. The 400,000-cfs event is presented in Figures 19 and 20. Velocities in the reservoir exceed approximately 3.0 feet per second over much of the reservoir area, with bed shear stresses exceeding the critical shear stress for erosion as defined by the SEDflume studies. The 400,000 cfs event is considered the threshold for mass erosion of the reservoir bed.

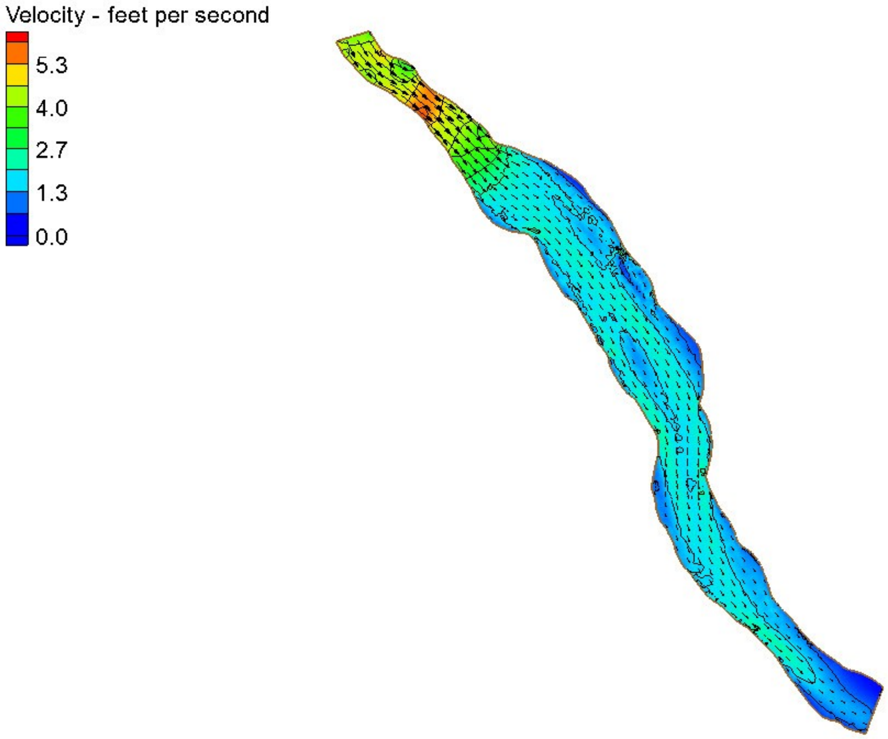


Figure 17 Conowingo Reservoir velocity at a discharge of 150,000 cfs

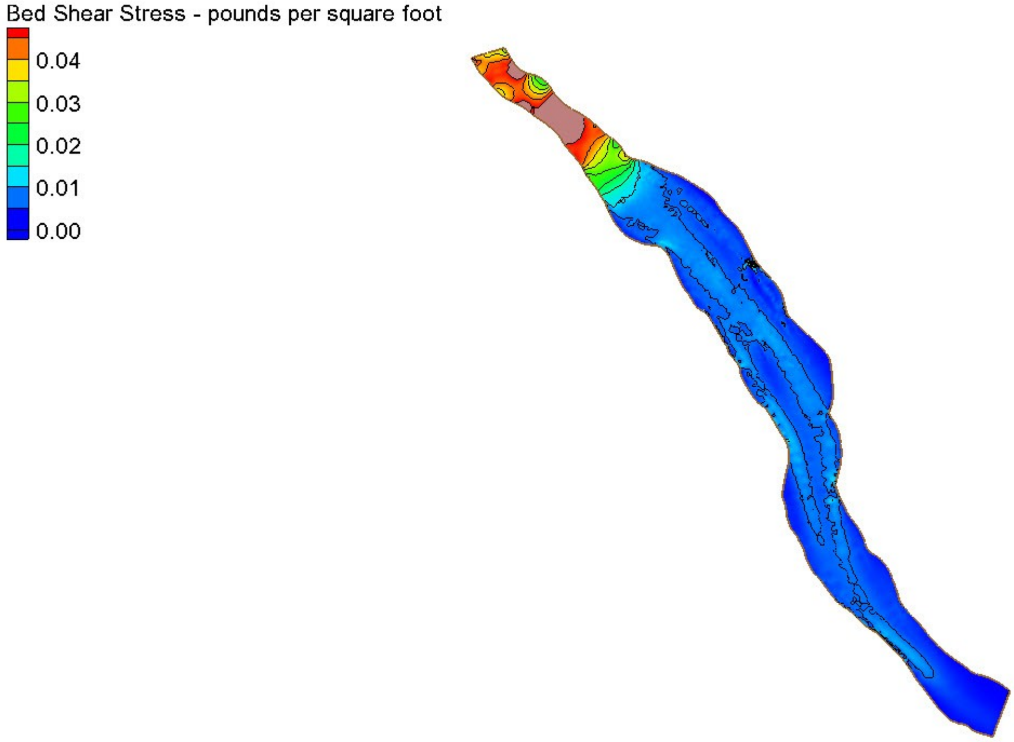


Figure 18 Conowingo Reservoir bed shear stress for a discharge of 150,000 cfs

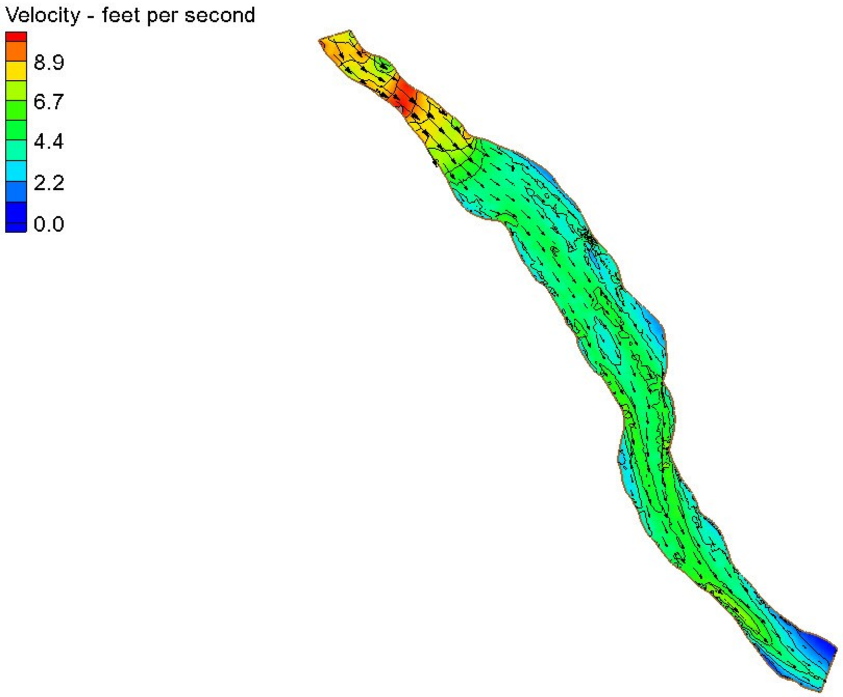


Figure 19 Conowingo Reservoir velocity for a discharge of 400,000 cfs

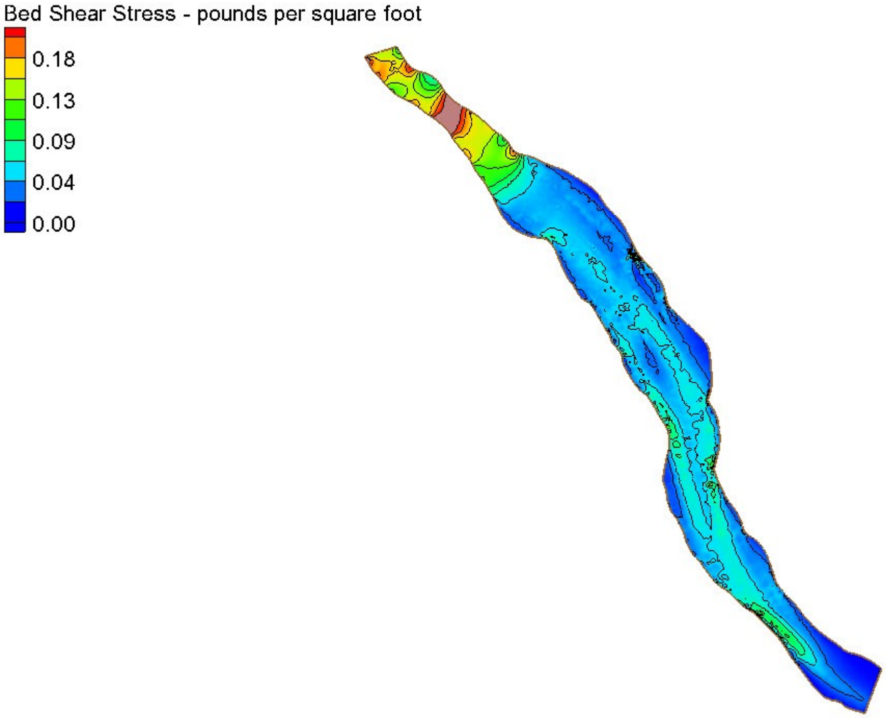


Figure 20 Conowingo Reservoir bed shear stress at a discharge of 400,000 cfs

7.2 Sediment Transport Simulation Utilizing the 1996 bathymetry

The 1996 bathymetry was simulated in the AdH model for the 4-year flow record (2008–2011). The cumulative change in sediment storage in the reservoir is presented in Figure 21. The total sediment load discharged below the dam was 20.3 million tons, with bed scour from Tropical Storm Lee comprising 9.0 percent of the load (1.8 million tons). The net deposition in the reservoir was 6.0 million tons. The 1996 bathymetry is depicted in Figure 22.

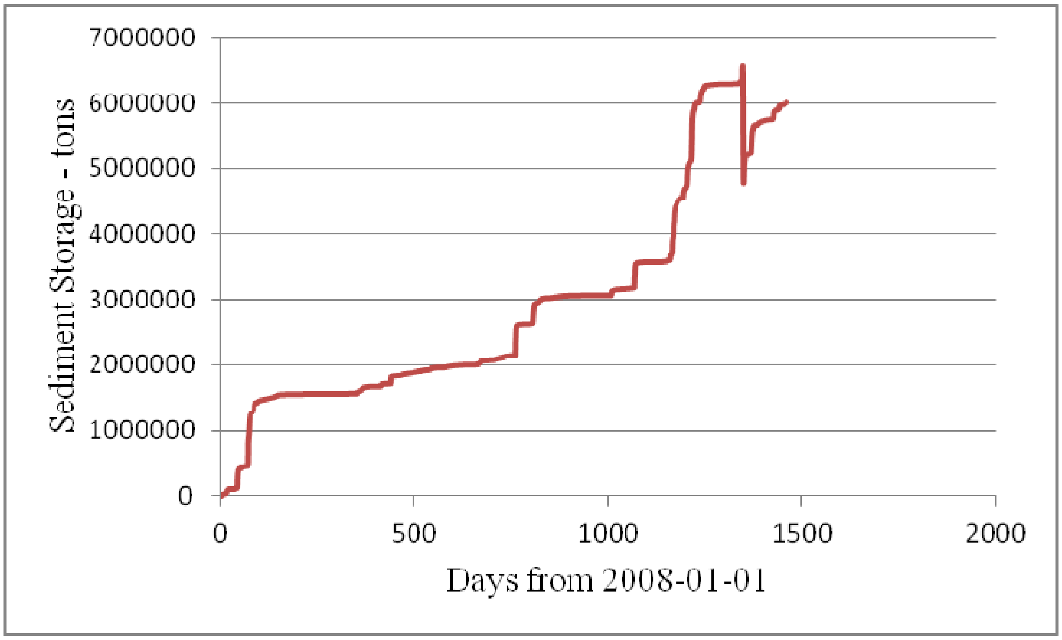


Figure 21 Sediment storage in Conowingo Reservoir for the 1996 bathymetry simulation

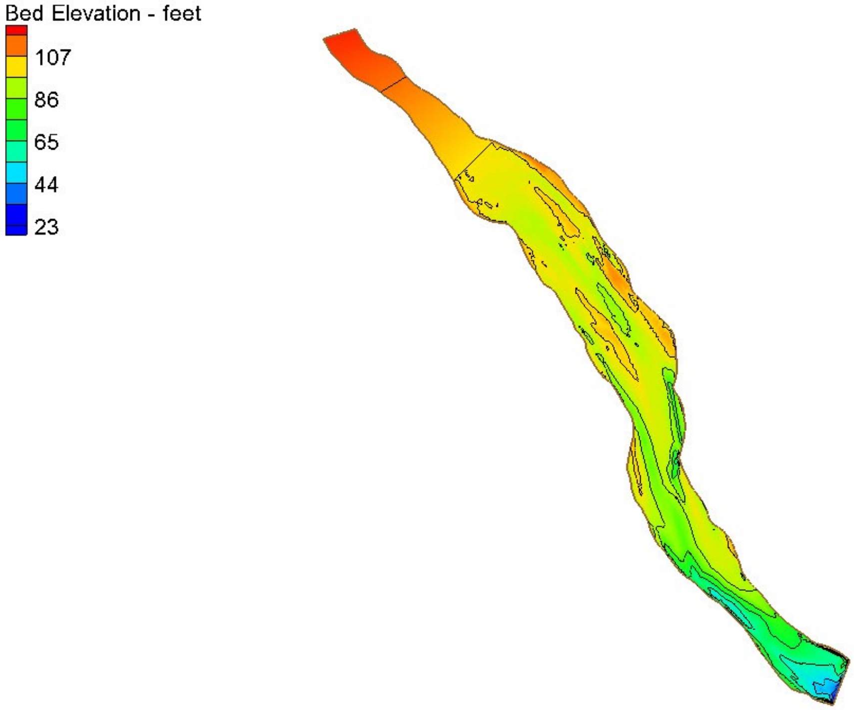


Figure 22 The 1996 model bed elevation

7.3 Simulation of the 2008 bathymetry

The 2008 bathymetry was simulated in the AdH model for the 4-year flow record (2008–2011), with the cumulative storage of sediment presented in Figure 23. The total sediment load discharged below the dam was 21.9 million tons, with a Tropical Storm Lee scour load of 2.9 million tons (13 percent of the total load). The net deposition in the reservoir was 4.4 million tons. The 2008 bathymetry is depicted in Figure 24.

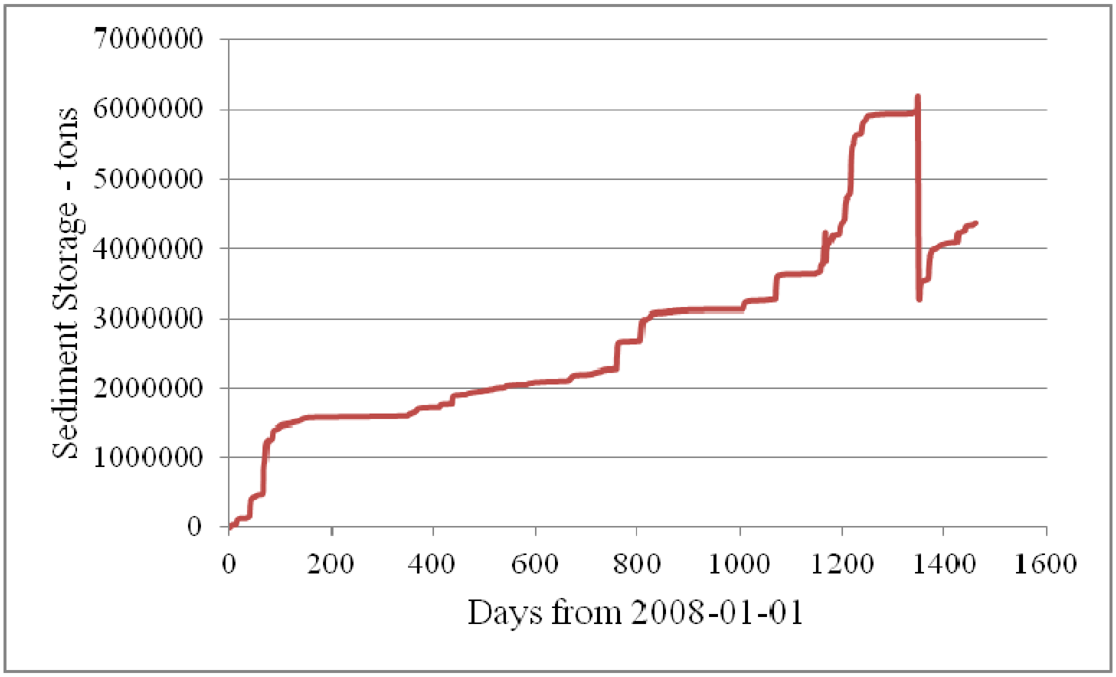


Figure 23 Sediment storage in Conowingo Reservoir for the 2008 bathymetry simulation

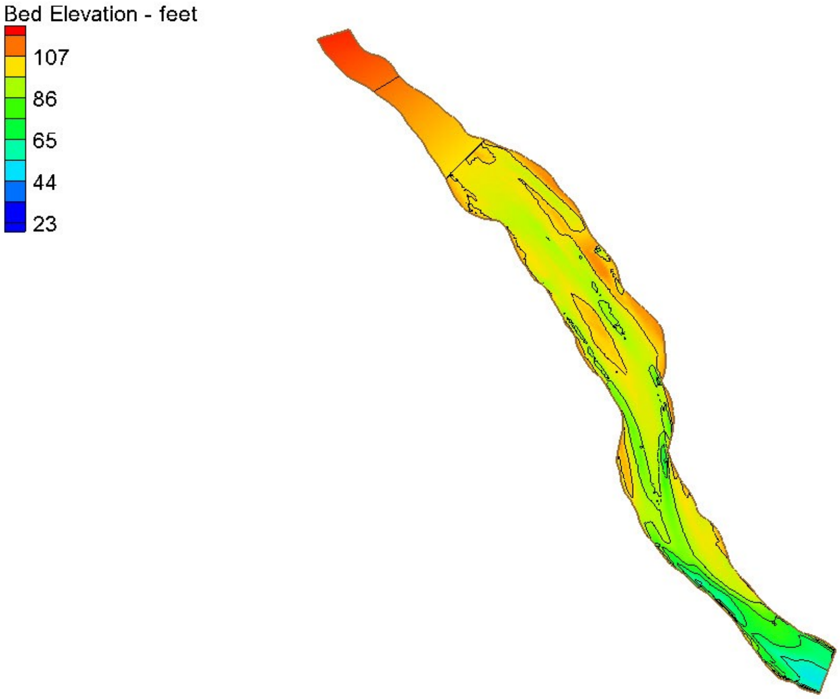


Figure 24 The 2008 model bed elevation

7.4 Simulation of the 2011 bathymetry

The 2011 bathymetry was simulated in the AdH model for the 4-year flow record (2008-2011). The cumulative storage of sediment is presented in Figure 25. The total sediment load discharged below the dam was 22.3 million tons, with a Tropical Storm Lee scour load of 3.0 million tons (13 percent of the total load). The net deposition in the reservoir was 4.0 million tons. The 2011 bathymetry is depicted in Figure 26.

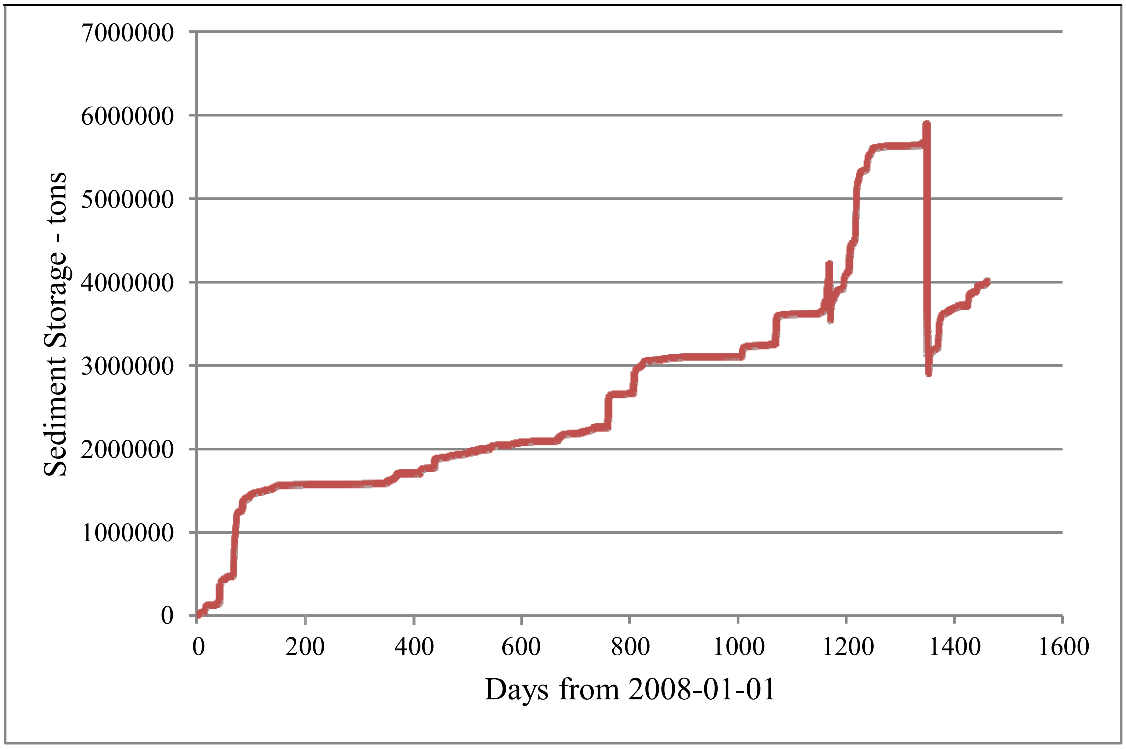


Figure 25 Sediment storage in Conowingo Reservoir for the 2011 bathymetry

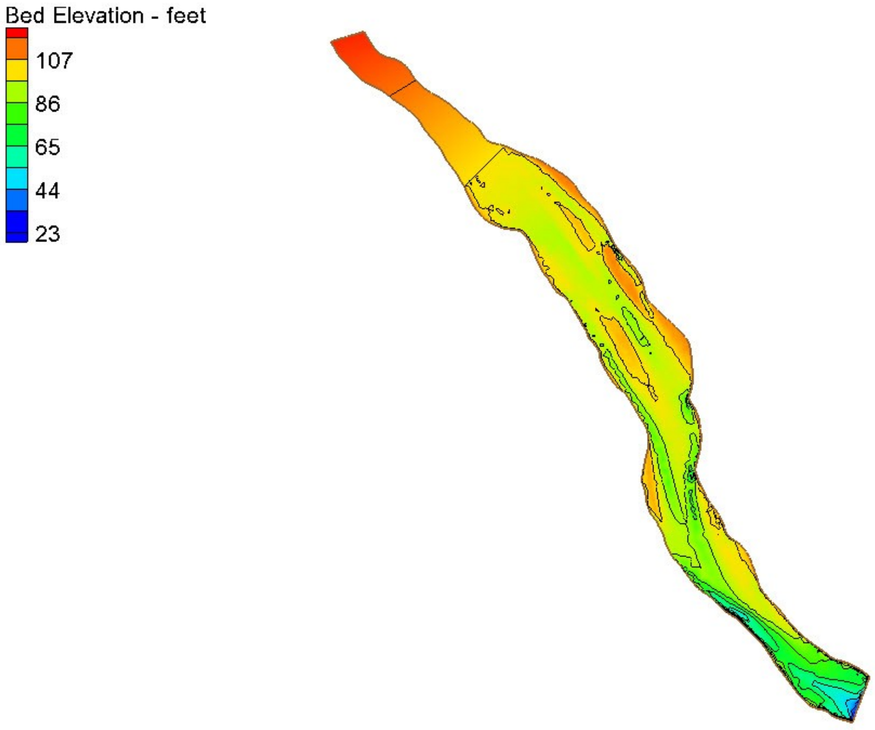


Figure 26 The 2011 model bed elevation

7.5 Simulation of the full reservoir bathymetry

The 2011 bathymetry was modified to reflect a full reservoir condition with minimum remaining sediment storage capacity. The USGS provided the remaining reservoir storage volume which was added to the 2011 model bathymetry. The cumulative storage of sediment is presented in Figure 27, with the full storage bathymetry presented in Figure 28. The location and magnitude of this additional volume (approximately 7.0 million cubic yards) is presented in Figure 29. This full reservoir condition model was simulated for the 4-year flow record. The results indicate an outflow load of 22.2 million tons, with a Tropical Storm Lee scour load of 3.0 million tons (13 percent of the total load). The net deposition in the reservoir was 4.1 million tons.

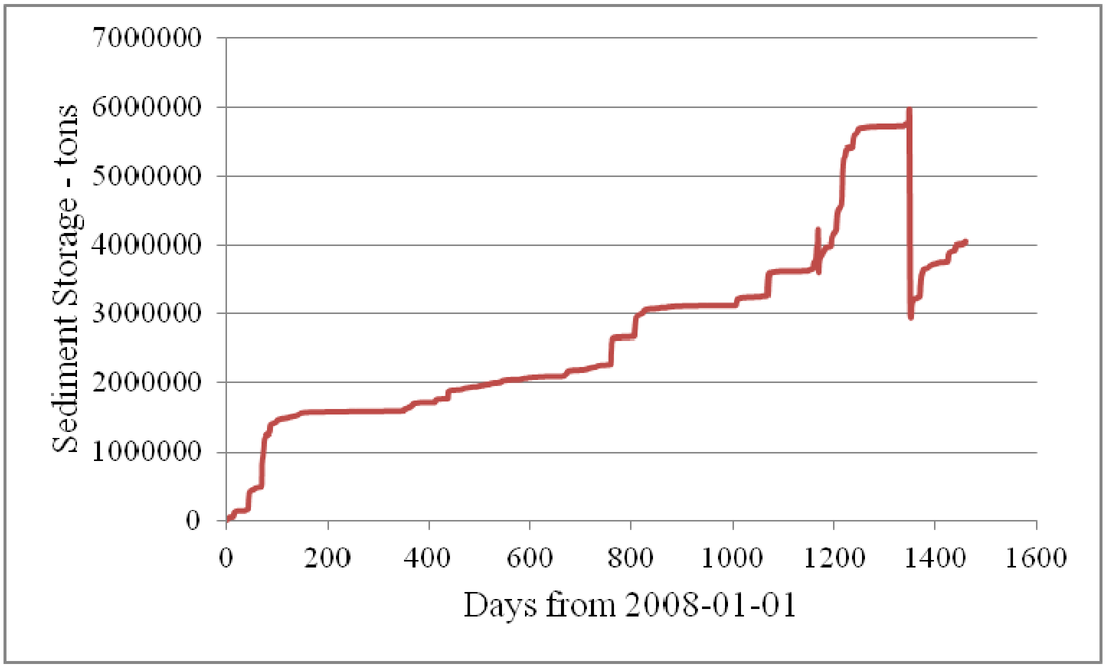


Figure 27 Sediment storage in Conowingo Reservoir for the full reservoir simulation

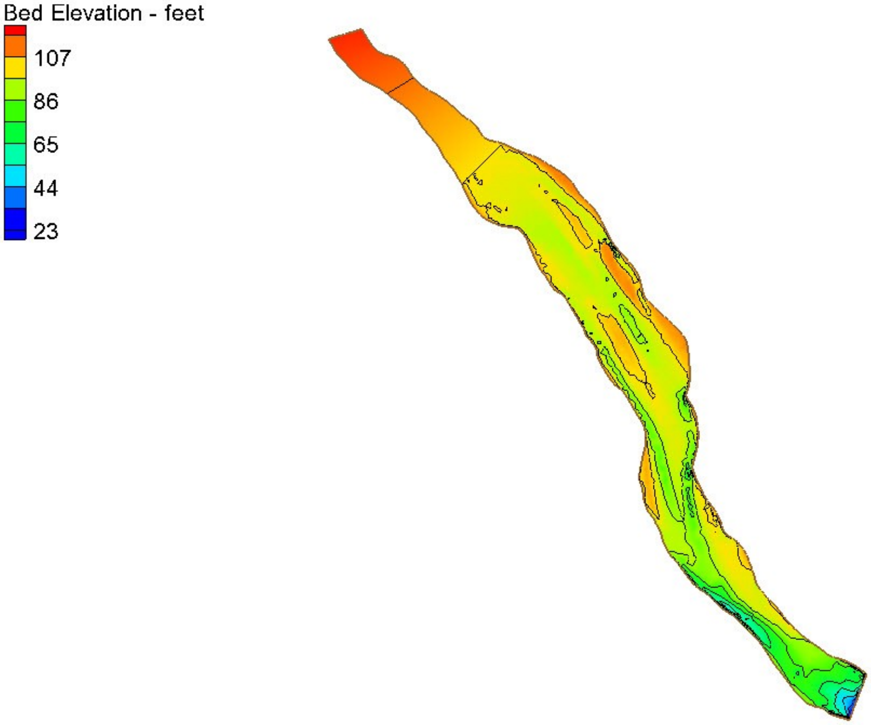


Figure 28 The full reservoir model bed elevation

Figure 29 Additional sediment depth added to the 2011 bathymetry for the full reservoir simulation

7.6 Discussion

Summary data for the four bathymetric simulations are found in Table 2. The impact of decreasing sediment storage capacity with time on sediment transport is revealed by a comparison of the 1996 and 2011 model results. A comparison of the 1996 and 2011 surveys not presented in this report indicate that approximately 25 million tons of sediment have deposited in Conowingo Reservoir between 1996 and 2011 (approximately 31 million cubic yards assuming a consolidated bulk density of 1600 kilograms per cubic meter). The model results for this 4-year simulation indicate that the decrease in reservoir capacity has resulted in a 10-percent increase in total load to the bay (20.3 to 22.3 million tons), a 66-percent increase in bed scour (1.8 to 3.0 million tons), and a 33-percent decrease in reservoir sedimentation (6.0 to 4.0 million tons).

Table 2 Summary of AdH 2D Model Simulation (Millions of Tons)

Bathymetry	Inflow Load	Outflow Load	Bed Scour Load	Net Deposition
1996	26.3	20.3	1.8	6.0
2008	26.3	21.9	2.9	4.4
2011	26.3	22.3	3.0	4.0
Full Condition	26.3	22.2	3.0	4.1

The reservoir will have more storage capacity, however, the large periodic storms like Tropical Storm Lee will continue to transport large quantities of sediment to the Bay which are much higher than the reduced scour loads resulting from sediment removal operations.

Results for the 2011 and full bathymetry model runs indicate minimal differences in bed scour and net sedimentation, indicating that Conowingo Reservoir is currently at or very near the maximum sediment storage capacity. The additional storage capacity in Conowingo Reservoir is within a reach two miles upstream of the dam. This is a deep area, with relatively lower velocities and bed shear stress, thus the potential for bed scour is low. These simulations reinforce the opinion that Conowingo Reservoir is currently in a dynamic equilibrium state.

The impact of Tropical Storm Lee on total load passing through the dam is shown in Table 3. For all simulations, Tropical Storm Lee provided about 65 percent of the total outflow load for the four year simulation (about 14.5 million tons of the 22.3 million-ton 2011 bathymetry outflow load). The scour load during Tropical Storm Lee comprises about 20 percent of the Tropical Storm Lee total load (about 3.0 million tons of the 14.5 million tons). For the total outflow load to the bay, bed scour passing through

Conowingo Dam comprises 13 percent of the total load, with 87 percent of the load originating from the watershed and the reservoirs upstream of Conowingo.

These results are based on a maximum scour load potential from the upper two reservoirs (26.3 million ton inflow load over the 2008 – 2011 time period). For a lower Conowingo inflow load scenario, the outflow load will be less, along with the Tropical Storm Lee load, thus the scour fraction presented in Table 2 can potentially be as high as 30 percent of the Tropical Storm Lee load.

Table 3 Summary of AdH 2D Model Simulation –Tropical Storm Lee (loads in millions of tons)

Bathymetry	Outflow Load	Total Lee Load	Lee Percent of Outflow	Scour Load	Scour Percent of Lee
1996	20.3	13.1	65	1.8	14
2008	21.9	14.4	66	2.9	20
2011	22.3	14.5	65	3.0	21
Full Condition	22.2	14.6	66	3.0	21

8 Simulation of Sediment Management Alternatives

Three sediment management modeling scenarios were simulated. The first alternative was simulated to evaluate the impact of sediment removal in a sediment deposition area upstream of the dam. The goal of the simulation was to determine how effective dredging would be for reducing scour during storms and reducing the overall total sediment transport to the bay. The second management scenario investigated the potential application of agitation dredging to Conowingo Reservoir. The goal of this simulation was to determine the minimum flow condition for which agitation dredging would be effective for transporting sediments through the dam. The third scenario was designed to evaluate the impact of bypassing sediments below the dam.

8.1 Dredging alternative

The impact of sediment removal activities on reservoir sediment transport was investigated with the model. It was assumed that 3.0 million cubic yards (2.4 million tons) were removed by dredging from an area above the dam that is depositional for all flows (Figure 30). The 2011 model bathymetry was lowered approximately 5.0 feet in this area to simulate a post-dredging bed elevation. The altered 2011 bathymetry was simulated over the same 4-year flow record and compared back to the unaltered 2011 simulation. The cumulative reservoir storage plots are found in Figure 31. The total outflow load to the bay was reduced by about 1.4 percent from 22.3 to 22.0 million tons, the scour load decreased by 10 percent (from 3.0 to 2.7) and the net reservoir sedimentation increased by about 5.0 percent (4.1 to 4.3 million tons). For this simulation, the scour load decreased approximately 3.3 percent for every million cubic yards removed.

Although changing the dredging area location will likely influence model results, removing such a relatively small quantity of sediment will have a minimal impact on total load delivered to the Bay when large flood events occur.

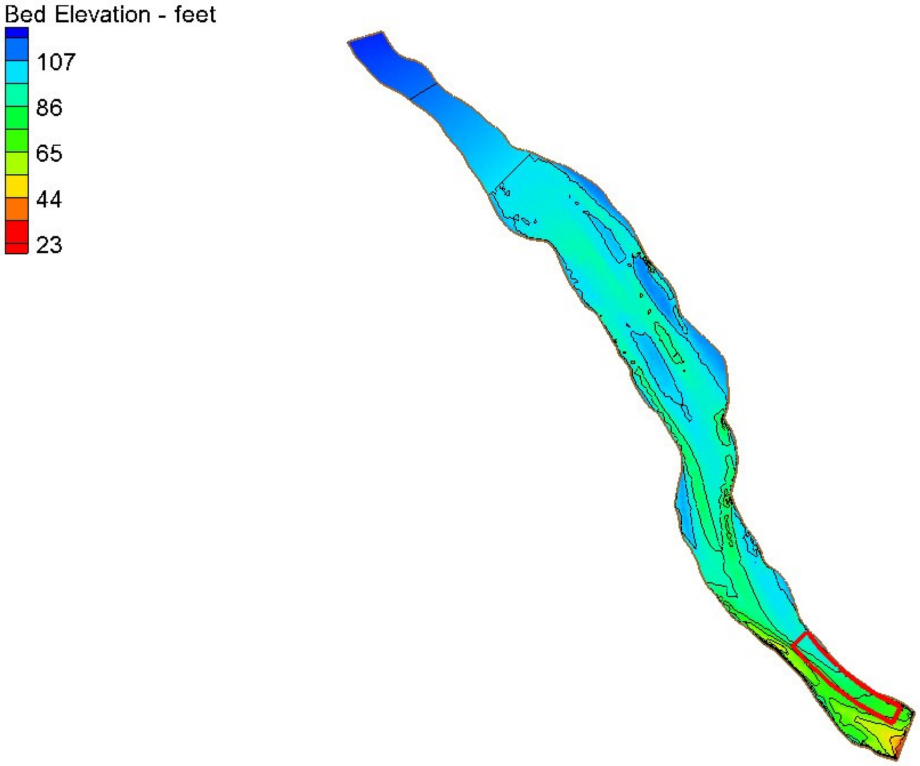


Figure 30 Area of reservoir for dredging simulation (outlined in red)

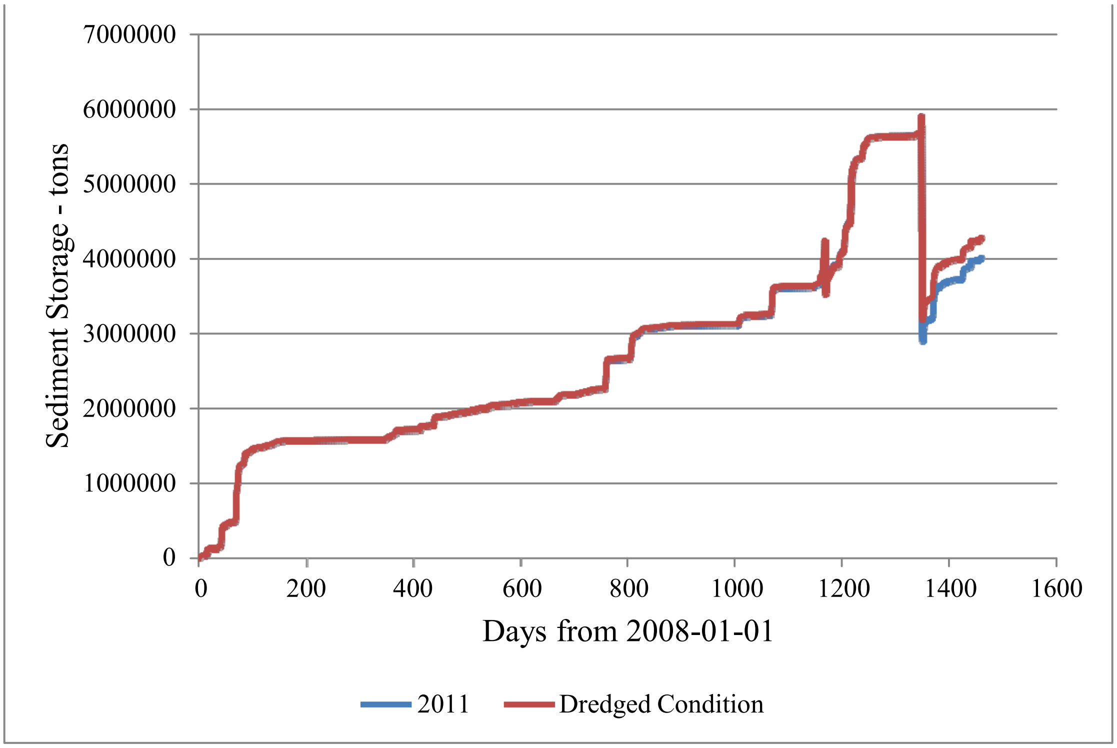


Figure 31 Comparison of pre-dredge and dredged reservoir sediment storage

8.2 Agitation dredging alternative

An alternative to dredging bed sediments and transporting them out of the reservoir is agitation dredging. Agitation dredging is mechanically or hydraulically re-suspending bed sediments which are then entrained in the water column and transported out the dam with the currents. For this sediment removal technology to be successful, adequate flow velocities in the reservoir are required to transport the re-suspended sediments through the system. The AdH model was used to evaluate the feasibility of such a system in Conowingo Reservoir. A number of steady state discharges were simulated in the model to evaluate the flow velocity and turbulence required to transport re-suspended sediments through Conowingo Dam. A flow range from 30,000 cfs to 400,000 cfs was investigated. A mean sediment grain size 0f 0.1 mm (millimeters) was assumed based on the size distribution in the reservoir bed and the potential size of cohesive bed sediment agitated from the bed. The potential for sediment to transport as a function of turbulence and particle fall velocity was determined. The study results indicated that a minimum flow of 150,000 cfs was required to transport agitated sediment through the dam. A report on the agitation dredging analysis is found in Attachment B-4.

8.3 Sediment bypassing alternative

The sediment bypassing study was not conducted with the AdH 2D model. It was a desk study with sediment bypassing quantities provided by the Baltimore District. The study consisted of two parts. Part 1 assumed that 2.4 million tons of sediment were transported below the dam and discharged into the channel over a 90-day period. Part 2 of the study assumed that 2.4 million tons of sediment were transported below the dam and discharged into the channel over a 270-day period. The goal of the studies was to determine the impact to suspended sediment concentrations below the dam.

The total suspended sediment load for the bypassing study consisted of the total Susquehanna River load passing through the dam plus the bypassed sediment load from the dredging operation. It was assumed that the average Susquehanna River flow during the winter months was 60,000 cfs, approximately twice that of the median flow of about 30,000 cfs. At

60,000 cfs, the average suspended sediment measurement below the dam was assumed to be about 12.0 milligrams per liter, which equates to about 1490 tons of sediment passing per day through the dam.

The dredging load discharged below the dam for the 90-day period was 26,700 tons per day with a dredge discharge of about 61.0 cubic feet per second. The dredging load discharged below the dam for the 270-day period was 8,900 tons per day. Thus the total solids loading per day below the dam for the 90- and 270-day scenarios was 28,200 and 10,400 tons, respectively. Analysis indicates that the 90 day loading resulted in an increase in total solids concentration from 12 to 174 milligrams per liter, whereas the 270 day loading resulted in an increase in concentration from 12 to 66 milligrams per liter.

8.4 Discussion

The dredging scenario results indicate a relatively small reduction in scour load (3.0 percent per million cubic yards removed), with a 1.4-percent reduction in total load to the bay (scour reduction and slight increase in reservoir deposition). Although the bed scour load is reduced, it is a relatively small contribution to the overall total load dominated by watershed and upstream dam sources. The previous comparison of the 1996 and 2011 bathymetry simulations indicated that removal of 31.0 million cubic yards produced only a 10.0-percent reduction in total sediment to the bay for the 4-year simulation, therefore dredging relatively small amounts will have a minimal impact to total sediment discharged to the bay.

The agitation dredging scenario is only effective for flows of 150,000 cfs or greater. These flows occur on the average 12 days out of the year. Although agitation dredging is feasible, operations will be limited due to flow restrictions and will not be effective for significantly reducing overall sediment transport to the bay.

Bypassing sediment around Conowingo Dam will increase suspended sediment loading to the lower channel and Susquehanna Flats, with the 90-day bypass scenario increasing suspended sediment concentrations by a factor of 15 (12 to 174 milligrams per liter) and the 270-day bypass scenario increasing concentrations by a factor of 5 (12 to 64 milligrams per liter).

9 Impact of Conowingo Reservoir Water and Sediment Releases on Susquehanna Flats

An AdH model of the lower Susquehanna River channel and Susquehanna Flats area was constructed. The model domain bathymetry is presented in Figure 32. The model contains approximately 16,000 elements and 8,600 nodes. Bathymetric surveys of approximately 4 miles of channel below Conowingo Dam were provided by Exelon Corporation from a previous 2D model water quality study (Exelon, 2012 RSP 3.16). The remaining bathymetry data in the model was digitized from NOAA depth charts, with bed elevation converted from water depth to mean low lower water elevations, and then finally to the Maryland State Plane coordinate system.

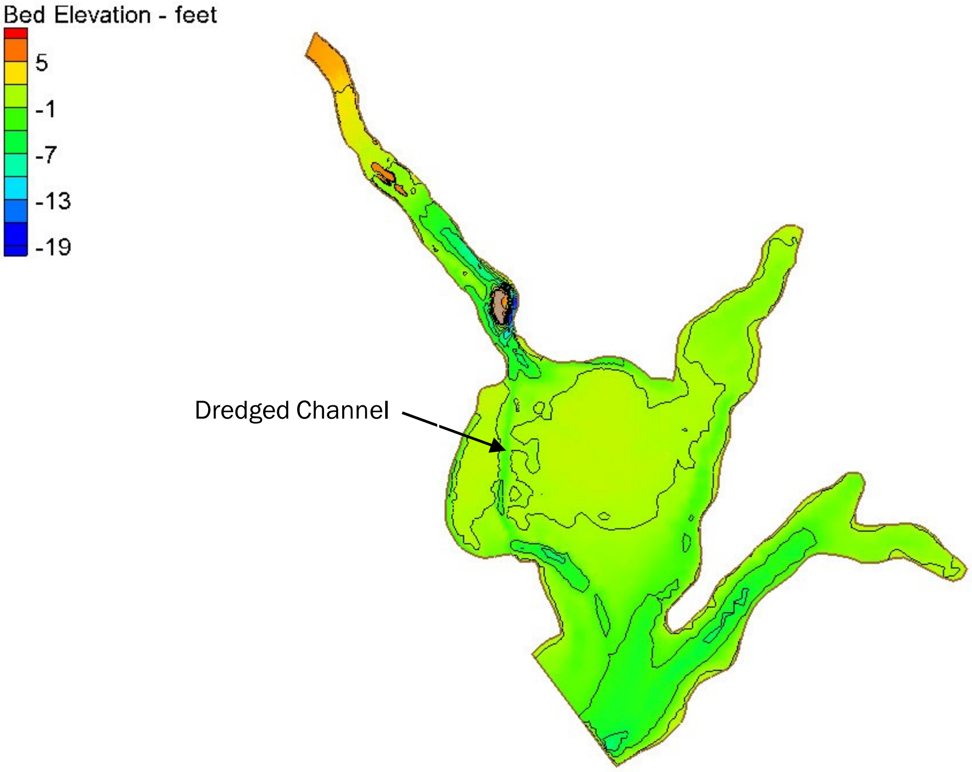


Figure 32 Lower Susquehanna River and Flats bathymetry

The model contains the Susquehanna Flats area. The submerged aquatic vegetation (SAV) in the flats is represented in the model. The SAV areas were defined from maps provided by Virginia Institute for Marine Sciences (Orth, 2012) and are presented in Figure 33. The SAV presence is seasonal, occurring from about April through October. These areas were defined as specific material types in the model mesh with specific properties. The AdH model has the capability to simulate the influence of both submerged and unsubmerged aquatic vegetation on total roughness (resistance to flow). The relationship of submerged vegetation height and water depth to total roughness is found in Figure 34. Bed size gradations were determined from samples taken in the lower channel and flats area by the Maryland Department of Natural Resources.

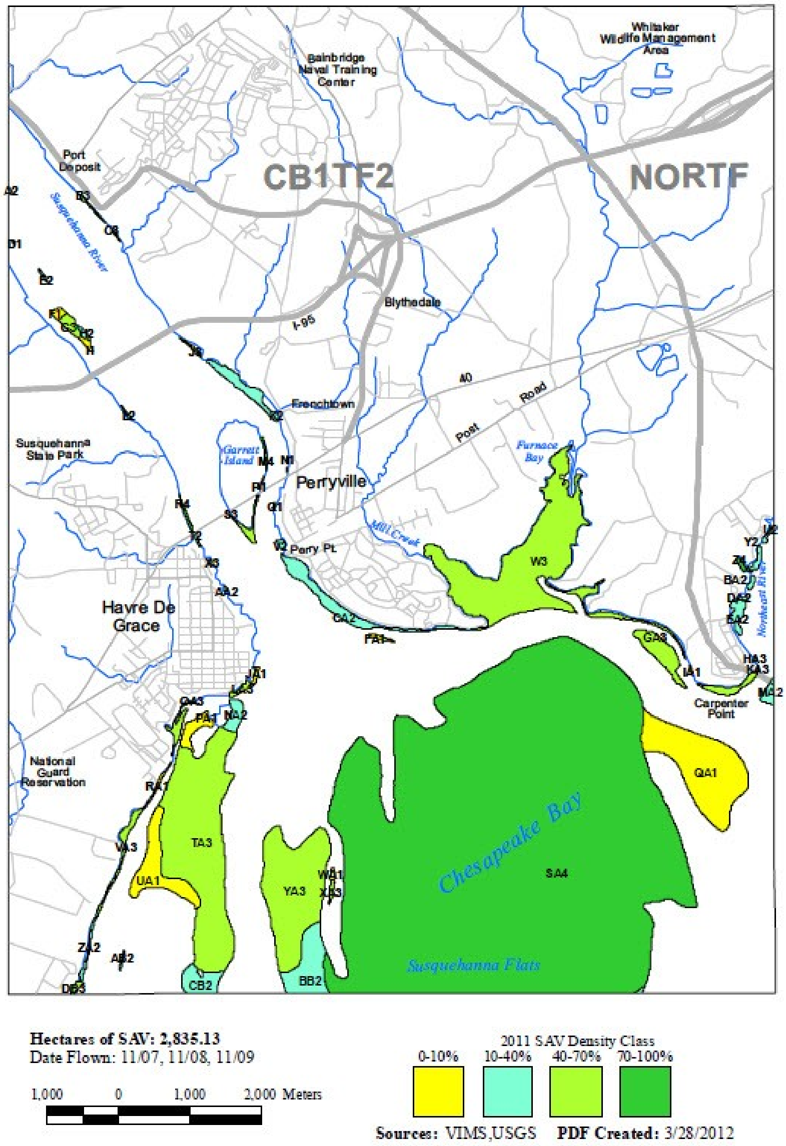


Figure 33 Submerged aquatic vegetation (SAV) areas in Susquehanna Flats

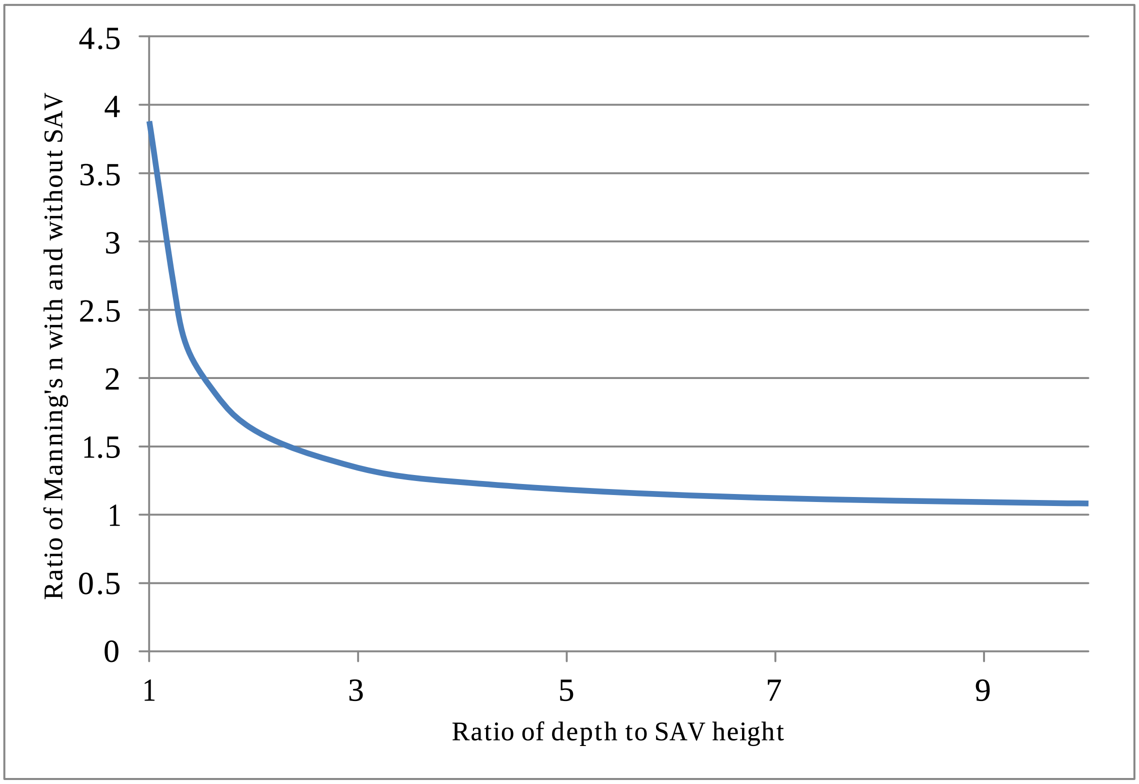


Figure 34 Ratio of Manning's n roughness coefficient with and without SAV to the ratio of water depth to SAV height (Berger et al, 2012)

9.1 Hydrodynamic modeling results

An inflow similar to the Tropical Storm Lee event was applied to the model. Figure 35 presents the flow velocity near the peak of the event (600,000 cfs). Velocities exceed 5.0 feet per second in the channel below the dam, however, in the flats area, flow is routed around the shallow flats through the dredged channel. Velocities in the dredged navigation channel below Havre de Grace are approximately 5.0 feet per second.

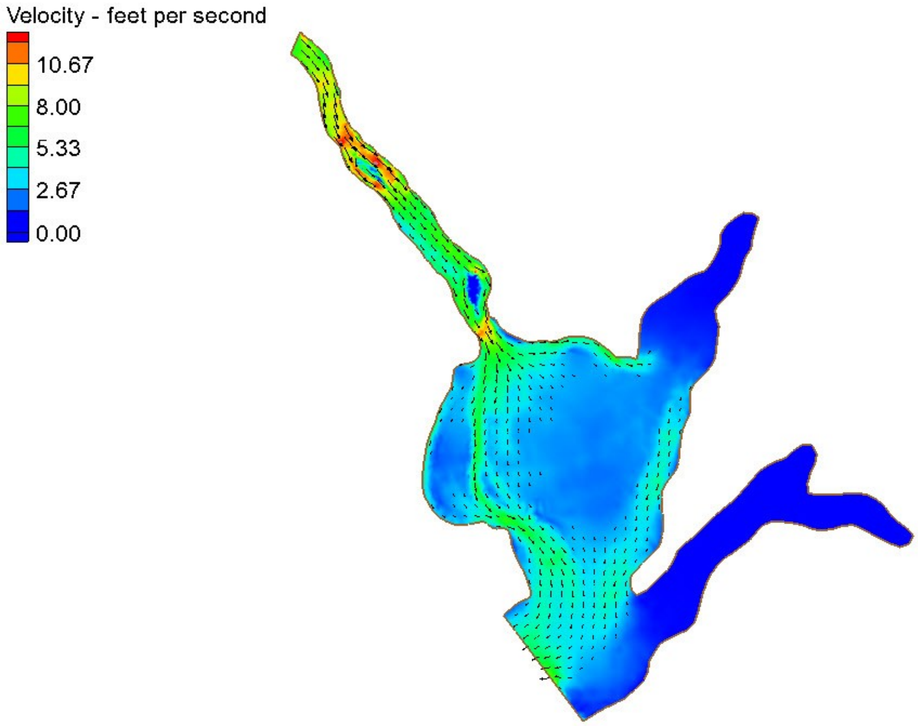


Figure 35 Velocity in Susquehanna Flats for a discharge of 600,000 cfs

9.2 Sediment modeling results

Bed scour at the peak flow of the simulation is presented in Figure 36. The bed scour and deposition pattern reflects the routing of flow around the flats area due to the resistance of flow from the relatively shallow SAV area containing vegetation.

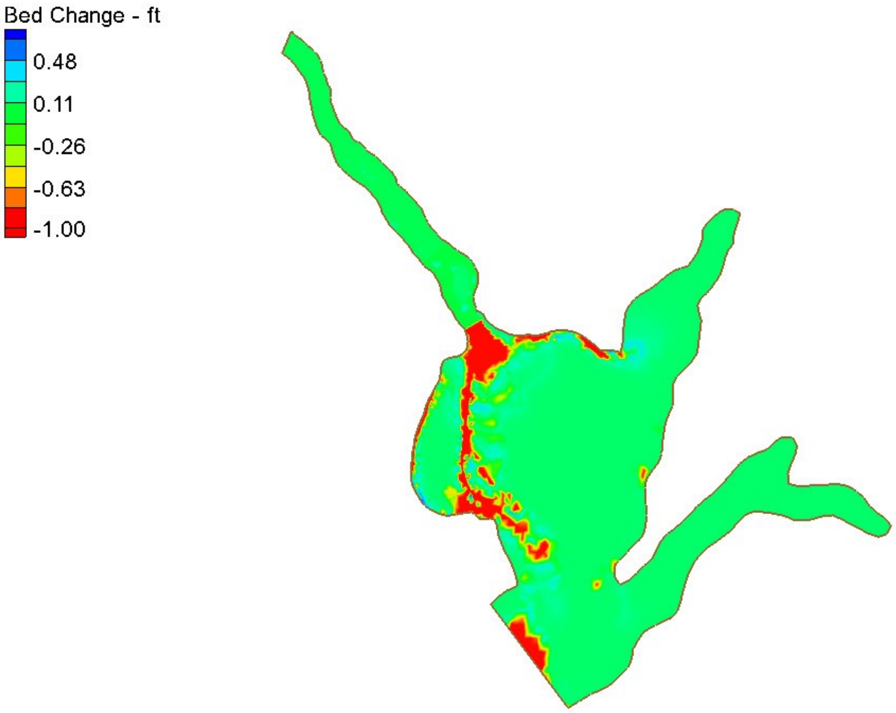


Figure 36 Bed change in Susquehanna Flats area for 600,000 cfs

9.3 Discussion

The SAV in the Susquehanna Flats area will increase resistance to flow thus change the specific discharge through the area, with the highest concentration of flow in the dredged channel. Inflowing sediment will be routed around the flats, with scour occurring in the dredged channel at high flows. When the SAV dies back in the winter, the flats area will be vulnerable to higher flows and possibly scour. However, the relatively higher bed roughness of the shallow flats will tend to continue to route the majority of the flow through the dredged navigation channel below Havre de Grace. Thus, discharge of sediment from Conowingo Dam due to bypassing or flushing operations will have minimal impact on the flats area, with sedimentation occurring in the dredged navigation channel or below the flats area.

10 Conclusions

A number of conclusions can be drawn from the modeling study. Although the uncertainty of the modeling is high due to the uncertainty of sediment boundary conditions and model limitations, the existing versus alternative approach to the simulations revealed the relative change in sediment transport based on the alternative condition scenario. The conclusions are as follows:

10.1 Modeling to evaluate temporal changes in sediment transport

The simulation and comparison of the various model bathymetries (1996, 2008, and 2011) for the Susquehanna flow record of 2008–2011 revealed an increase in scour and decrease in reservoir sedimentation in the 15-year period between 1996 and 2011. The bed scour load increased by 66 percent (1.8 million tons to 3.0 million tons) while deposition decreased by 33 percent (6.0 million tons to 4.0 million tons). The results imply that if 31 million cubic yards were removed from the present day reservoir (back to the 1996 condition), the reduction of total sediment discharged to the bay would be about 10.0 percent due to a reduction in bed scour and increase in net sedimentation). Although the scour increase from 1996 to 2011 appears significant, it only represents a relatively small fraction of the total load resulting from Tropical Storm Lee.

A comparison of the present day (2011 bathymetry) model results with the projected full bathymetry model results indicates that sediment transport through Conowingo Reservoir does not appreciably change, indicating that the reservoir is currently in a state of dynamic equilibrium in which the net change in sedimentation (deposition during low flows and scour during floods) will remain relatively constant into the future. This implies that the bay is currently experiencing the maximum periodic sediment loading from Conowingo Reservoir.

Tropical Storm Lee contributed approximately 65 percent of the total load discharged to the bay over the 2008–2011 flow record (14.5 of 22.3 million tons); with bed scour contributing about 20 percent of the total Tropical Storm Lee load. These results imply that the watershed and upstream reservoirs are providing 80 percent of the load during Tropical Storm Lee.

Overall, bed scour contributes about 13 percent of the total load to the bay based on the 4-year model simulation (3.0 of 22.3 million tons) with the remaining 87 percent originating from the watershed and upstream reservoirs. The estimated range of bed scour load that passed through the model for the Tropical Storm Lee event is 2.0 to 4.o million tons which is within the prediction error of the USGS scour regression curve.

10.2 Modeling to evaluate dredging (removing sediment out of the reservoir)

Dredging limited quantities from depositional areas in the reservoir has a minimal impact on total sediment load transported to the bay. Model results for the 2008 – 2011 flow scenario indicate that for 3.0 million cubic yards removed, a 10-percent reduction of scour is achieved (from 3.0 million tons to 2.7 million tons). This reduction represents only a 1.4-percent reduction of total load delivered to the bay (reduction of bed scour and increase in net sedimentation) over the 2008 – 2011 simulation period. Large periodic flood flows dominate sediment transport dynamics in Conowingo Reservoir. The amount of sediment passed through the dam during floods is significantly higher than the estimated bed scour load, thus small reductions in bed scour due to dredging operations will not provide any substantial benefit to the bay over time.

10.3 Modeling to evaluate agitation dredging effectiveness

Agitation dredging is possible in Conowingo Reservoir, but it requires sufficient currents for transporting re-suspended sediments through the dam. Model and analytical results indicate that a Susquehanna River flow of 150,000 cfs is required to maintain re-suspended sediments in suspension and transport them out of the reservoir. The 150,000 flow occurs approximately 12 days out of the year thus there is a narrow window for operations.

10.4 Sediment bypassing impacts to sedimentation below Conowingo Dam

Bypassing sediment around Conowingo Dam will temporarily increase suspended sediment concentrations below the dam. Assuming an average Susquehanna River flow of 60,000 cfs and concentration of 12 milligrams per liter, bypassing 2.4 million tons of sediment below the dam over a 90-day period will result in an increase in average suspended sediment concentration from 12.0 to 174.0 milligrams per liter. If the same mass of sediment is bypassed over 270 days, the increase is from 12.0 to 64.0 milligrams per liter.

10.5 Susquehanna Flats sedimentation impacts

The Susquehanna flats area is shallow and contains submerged aquatic vegetation. These characteristics increase resistance to flow. Because of these characteristics, the deeper dredged navigation channel to the east of the flats passes the majority of the flow and sediment, and thus is most vulnerable to sedimentation impacts (erosion and sedimentation).

10.6 Interpretation of AdH sediment transport model results

The AdH sediment transport model results only estimate the transport and fate of sediments that enter the reservoir and scour from the bed. The model does not predict nutrient transport and does not imply any predictive relationship exists between nutrients and sediment transport.

11 Recommendations to Improve Future Modeling Efforts

This model study contains significant uncertainty due to limited sediment boundary conditions as well as limited model representation of dam operations. The initial plan for the model was to simulate dam operations by releasing flows less than or equal to 86,000 cfs through the power plant (western side of the dam), with the 52 flood gates releasing water based on their operations rating curve. The hydrodynamics were successfully implemented in AdH; however, the model was not capable of passing sediment through the gates, therefore, for this study the dam was modeled as an open boundary with downstream control represented by the water surface elevation at the dam. This limitation impacted how sediment was spatially distributed in the lower reach of Conowingo Reservoir near the dam. It is recommended that dam operations be incorporated in the Conowingo model for future studies.

Sediment transport models in general do not have a sophisticated approach to simulate fine sediment flocculation. The AdH model has the capability to relate flocculation to concentration, but not to other variables such as shear stress which determine flock particle size and overall fate. The ability to predict flocculation dynamics is critical to track the fate of sediment in a reservoir system. More sophisticated methods need to be developed to provide this capability.

Field data collection needs to continue both upstream and downstream of Conowingo Dam to provide more information on reservoir mass balance. Currently, the suspended sediment samples are collected from one location near the power plant. Because of the danger of sampling during large storms, samples are not currently collected for the peak of the largest storms. Field methods are required for sampling storm concentrations or turbidity over the entire storm hydrograph to verify estimations of bed scour during large storms.

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