Attachment B-1

Evaluation of AdH Model Simplifications in Conowingo Reservoir Sediment Transport Modeling

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Lower Susquehanna River Watershed Assessment

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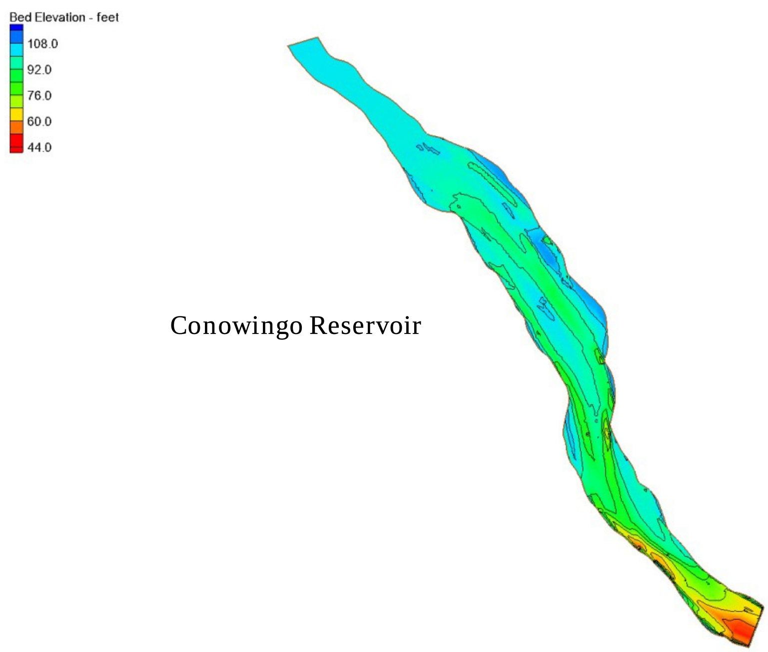

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1.0 STUDY GOAL

The goal of this paper is to detail the uncertainties involved with the simulation of hydrodynamics and sediment transport through Conowingo Reservoir. Uncertainties in the modeling process include approximation of reservoir bathymetry and estimation of hydrodynamic and sediment modeling parameters. However, the type (dimensionality) of model to apply is based primarily on the model's ability to capture the dominant hydrodynamic and sediment transport mechanisms. Reservoirs are typically exposed to both low and high inflow conditions that will impact the transport and fate of inflowing sediments. The ability of a sediment particle to transport suspended in the water column or transport near or along the bed is determined by the ratio of the force that tends to cause the particle to settle (gravity) and the force that tends to keep it in suspension (turbulence). Depending on the inflow condition, the sediments may be stratified in the water column (low flow, low turbulence) or well mixed (high flow, high turbulence). This paper presents the potential uncertainties involved in modeling varying reservoir conditions, along with the potential impact of Conowingo Dam operations. Model capabilities are presented, with discussion of the application of one, two, and three dimensional models for reservoir sediment transport modeling.

2.0 INTRODUCTION

The basic governing equations involved in modeling reservoir sedimentation processes are the same as for river or estuarine systems. However, other factors unique to reservoirs may influence the distribution of inflowing sediments and re-distribution of bed sediments during large flow events.

The circulation of water and sediment in reservoirs is generally multi-dimensional, non-uniform, and unsteady in nature (USBR 2006). It can be affected by a number of processes including river inflow rates, wind driven circulation, density gradients in the water column due to temperature stratification, ice and debris, and dam operations during low flow and flood events. Cooler water is denser and will displace the warmer, less dense water. Sediment concentrated in these higher density layers will displace with the water, resulting in vertical sediment stratification. All these effects may have an impact on sedimentation processes, sediment trap efficiency, and distribution of sediments in the reservoir.

Sediment transport processes are highly dependent on hydrodynamics. Reservoir hydraulics directly influences the transport, deposition, and scour of sediment consisting of widely varying grain sizes (clay to sand sizes). Generally, coarse sediments such as gravels (greater than 4 mm) will only transport as bed load. Sand-sized material can transport as both suspended load and bed load, while the finer sediments such as silts and clays primarily transport as suspended load. The flow velocity in reservoirs is the primary sediment transport mechanism. The ability of a sediment particle to stay in suspension is directly proportional to the degree of turbulence generated by the flow within the system. However, for low flow conditions in reservoirs with low flow velocities, the dominant transport processes may not be due to inflows. Wind driven events may increase surface velocities and influence spatial deposition patterns. Vertical density stratification due to temperature differences in the water column may also induce currents that will transport suspended sediments in the form of density currents. This gravity-driven sediment transport is the result of temperature difference in the impounded and inflowing waters.

The type of sediment transport model to apply to reservoirs is based on the expected flow distribution and sediment mixing potential. Two-dimensional (2D) and one-dimensional (1D) models are generally used for engineering applications which include computing total sediment discharge along with scour and deposition potential within the reservoir. For relatively narrow reservoirs where flow is channelized and is generally well mixed, 1D models are applicable. However, if the reservoir pool is wide with a widely varied lateral flow distribution, the multi-dimensional model is more applicable (Haun 2012). If 3D effects are a significant aspect of the study, a 3D model may be applicable. However, 3D models are computationally intensive and thus have limited capability for long term simulations (simulation of years of record). Generally, these models are applied to very specific areas to evaluate the effects of 3D water circulation (vertical velocities and accelerations). For example, hydrodynamics and sediment transport in the immediate vicinity of a dam where vertical circulation is expected and complex sediment deposition and scour patterns may occur.

3.0 BACKGROUND

The Engineering Research and Development Center at Waterways Experiment Station is applying the 2D Adaptive Hydraulics model (AdH) to Conowingo Reservoir for the Lower Susquehanna River Watershed Assessment. The goal of the sediment transport modeling is to simulate sediment transport processes within the reservoir for widely varying flow conditions, including very low flows that typically occur during the summer months, and large flood flows due to inland storm events and occasional coastal storm events that influence the watershed.

There are areas and flow conditions in the reservoir that can impact the spatial distribution of sediment deposits. The flow patterns in the vicinity of Conowingo Dam vary due to dam operations, power plant water intake, and other potentially 3D flows near structures. Additionally, in Conowingo reservoir there are low inflow conditions where flow velocity is at a minimum, water residence time is high, and sediments are stratified in the water column. However, during these low flow periods, sediment transport into the reservoir is at a minimum. Thus, although forces other than advection may be a factor in how sediment moves through the reservoir and ultimately deposits, the amount of sediment under this influence has been determined to be negligible for low flow conditions.

The following sections will discuss the effects of various modeling simplifications and quantify the low flow sediment load into Conowingo Reservoir.

4.0 IMPACT OF CONOWINGO DAM ON HYDRAULICS AND SEDIMENT TRANSPORT

The presence of the dam creates a backwater effect, reducing the energy slope, thus reducing velocities and encouraging sedimentation. In the area adjacent to Conowingo dam, circulation of water and sediment is directly impacted by both the dam face and how the water is discharged through the dam. For low flows less than 86,000 cfs, the water is released through the power plant on the eastern side of the dam. The reservoir pool is generally maintained at an elevation of 109.2 feet NGVD 29, with the power plant intakes located over a depth range of 58 feet (from elevation 11.2 to 69.2 feet NGVD 29). For flows exceeding 86,000 cfs, both the power plant and flood gates pass flow. There are 53 flood gates with a crest elevation of 89.2 feet NGVD 29. Both the power plant and floodgates pass flow up to approximately 400,000 cfs. At higher flows the power plant is shut down with all flow passing through the gates.

For lower flows with less turbulence and more sediment stratification in the water column, the higher near-bed sediment concentrations will pass through the power plant. Density currents that flow through the reservoir may display this type of behavior.

These currents are formed from inflows that are cooler and denser than the reservoir waters. These sediment laden flows transport through the reservoir below the warmer, less dense water. For low turbulence conditions, these flows may remain near the bed, and transport through the power plant intake.

For higher, more turbulent flows, flow passes through both the power plant intake and through flood gates which have a crest elevation approximately 67 feet above the power plant intake. Under these flow conditions, the majority of the sediment transports as suspended load with the water column considered well mixed. However, the power plant intake that is located near to the bed will likely pass higher concentrations of sand bed load.

The presence of the dam, flood control gates, and hydropower intakes will result in changes in hydrodynamics and sediment transport. The stream-wise transport of bed-load is impeded by the dam, with 3D flows occurring adjacent to the structures. Both scour and deposition are possible near the dam due to dam operations.

5.0 SIGNIFICANCE OF LOW FLOW SEDIMENT TRANSPORT

During low inflow conditions, sediment may be stratified in the water column and forces other than stream-wise flow velocity may act to re-distribute sediment in the reservoir. Wind and wave action may impact how sediment moves through the reservoir system. However, during low flow conditions, the sediment inflow is generally low.

To evaluate the sediment transport potential for Conowingo Reservoir during low flow conditions, the Susquehanna River flow duration and sediment inflow must be analyzed, along with consideration of Conowingo Reservoir water residence time.

The water residence time or flushing rate can be defined as the time that it takes for a particle of water entering the reservoir to exit out the dam. For Conowingo Reservoir, the residence time is described by Figure 1. These data were generated by the Exelon Corporation during a study of Conowingo Dam operations (Exelon 2009). This figure indicates an exponential drop in residence time with flow, ranging from a high of 80 days for a river discharge of 1,000 cubic feet per second (cfs) to 1 day for a discharge of 100,000 cfs.

The flow-duration curve for the Susquehanna River at Marietta, Pennsylvania, is presented in Figure 2 (USGS station 0157600). This curve was created from 40 years of flow record from 1970 to 2010. The flow duration curve is a plot that shows the percentage of time that flow in a river is likely to equal or exceed a specific discharge (volumetric flow rate of water). The median Susquehanna River flow (50 percent exceeded) is approximately 26,000 cfs, and has a residence time of six days in Conowingo Reservoir.

Generally, the sediment load entering a river or reservoir is described with a sediment rating curve which represents the sediment load in tons per day as a function of discharge. A sediment rating curve was developed for the Susquehanna River from previous sediment transport studies conducted by the USGS (USGS 1994). Recently, Exelon Corporation used this rating curve to evaluate sediment transport through the lower three Susquehanna River reservoirs (Lake Alred, Lake Clark, and Conowingo Reservoir) (Exelon 2011). This curve is presented in Figure 3. For example, the inflowing sediment load for the median flow of 26,000 cfs is approximately 2500 tons of sediment per day.

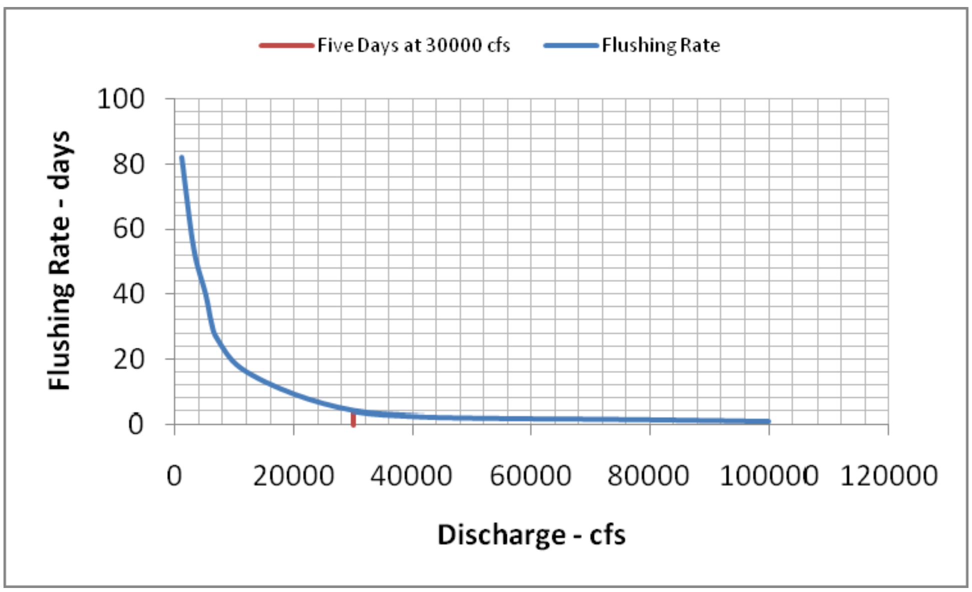

Figure 1. Residence time for Conowingo Reservoir

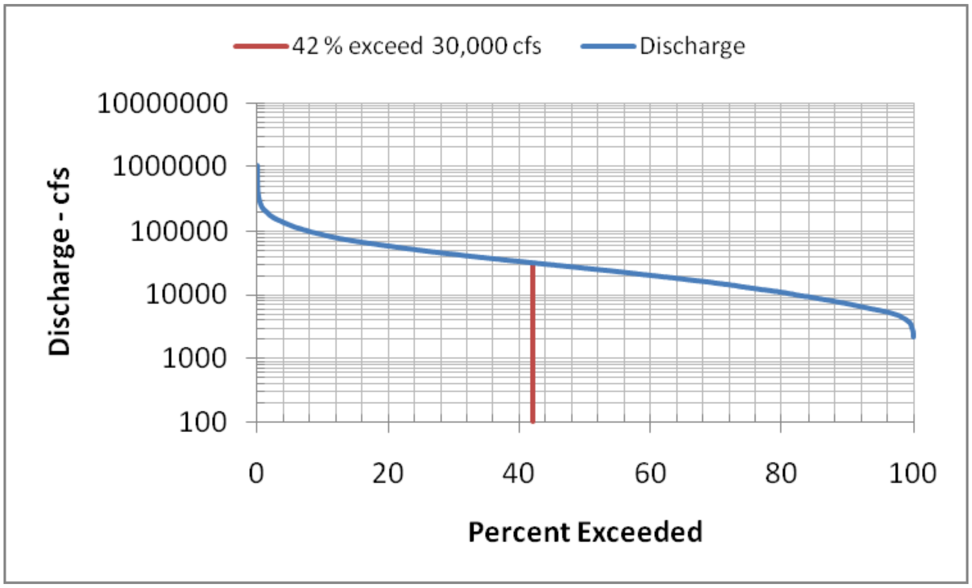

Figure 2. Flow duration curve for the Susquehanna River at Marietta, Pennsylvania

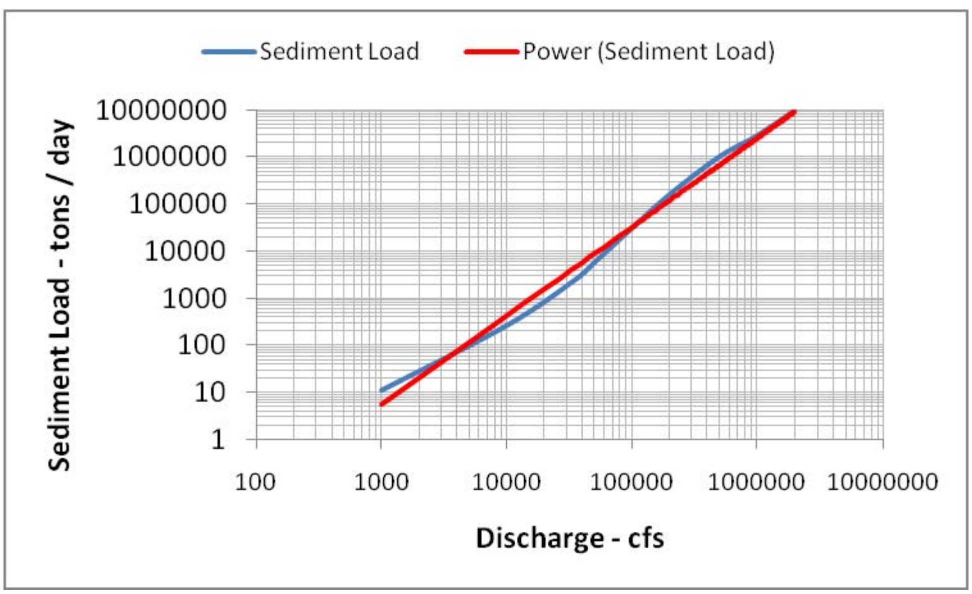

Figure 3. Sediment rating curve for the lower Susquehanna River

5.1 Sediment Delivery Analysis

To determine the annual sediment yield delivered by the Susquehanna River to the three lower reservoirs, the flow duration curve is integrated with the sediment rating curve. The flow duration curve is a graphical representation of the percentage of time in the historical record that a flow of any given magnitude has been equaled or exceeded. Integrating this curve with the sediment rating curve will provide not only the total estimated annual sediment yield, but will also demonstrate the cumulative sediment yield to the lower reservoirs as a function of discharge. The result of this integration is presented in Figures 4 and 5. Figure 4 shows the cumulative annual sediment yield in tons as a function of discharge and Figure 5 presents the cumulative percentage of annual sediment yield as a function of discharge. The total estimated annual sediment yield delivered to the downstream reservoirs is approximately 4,200,000 tons.

From the Conowingo Reservoir water residence time plot (Figure 1), a river discharge of 30,000 cfs requires approximately four days to transit through the reservoir. If one assumes all flows less than the median flow of 30,000 cfs to be low flows with a potentially higher degree of sediment stratification in the water column, the cumulative percent of delivered sediment per year for these low flows is approximately 5 percent. In other words, only 5 percent of the total annual sediment load is delivered during these low flow periods. Thus sediment delivery during median to low Susquehanna River flows is not significant to the overall sediment delivery into the system of reservoirs on the lower Susquehanna River.

The analysis presented in the following section will provide insight on sediment stratification as a function of discharge in Conowingo Reservoir.

5.2 Analysis of Transport Capability at 30,000 cfs – Rouse Number Calculation

The ability of a sediment particle to transport suspended in the water column or transport near or along the bed is determined by the ratio of the force that tends to cause the particle to settle (gravity) and the force that tends to keep it in suspension (turbulence). Small particles such as silts and clays require less flow-generated turbulence to keep particles in suspension, whereas sand-size particles require higher flows to maintain in suspension. Clay and fine silt-sized particles less than 10 microns in diameter may remain in suspension and pass through the system as wash load without interacting with the bed.

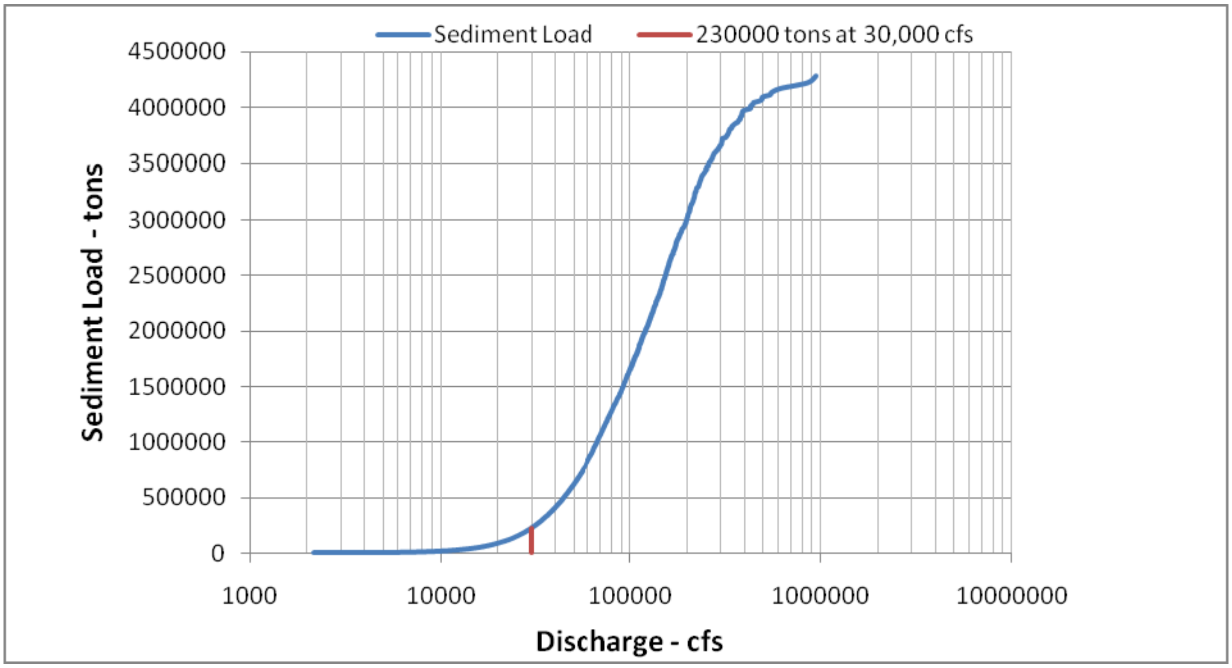

Figure 4. Annual cumulative sediment yield for the lower Susquehanna River

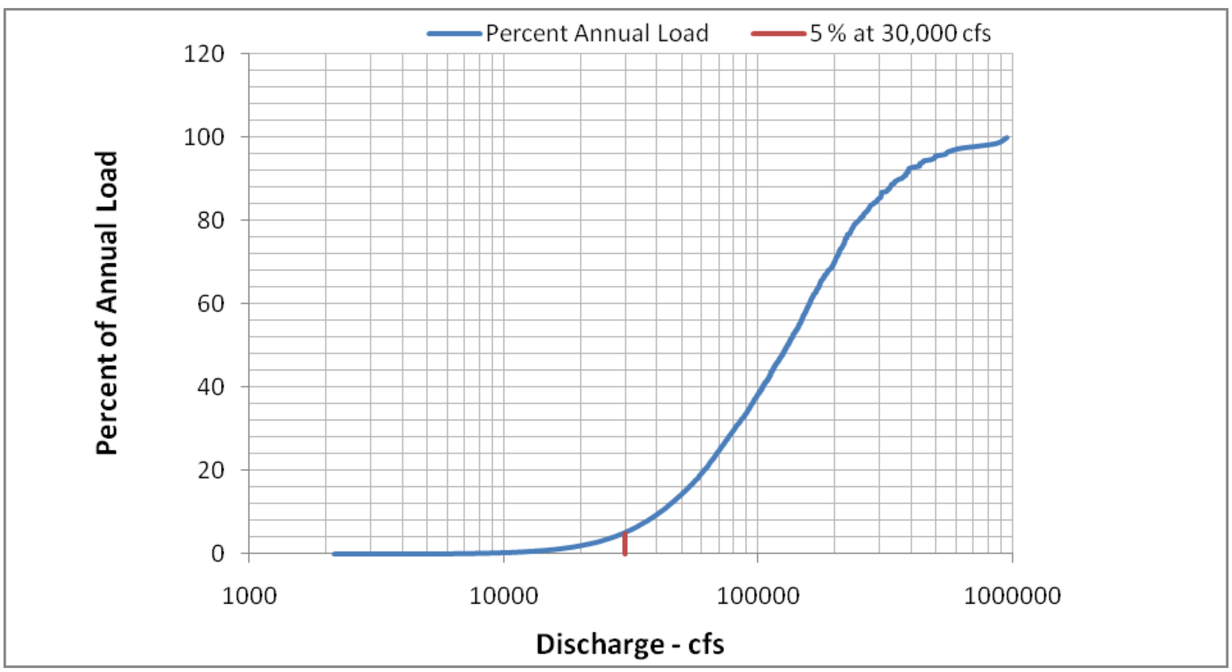

Figure 5. Percent of average annual yield for the lower Susquehanna River

The Rouse Number is a dimensionless number that is used to evaluate the potential of sediment to stratify in the flow (Rouse 1937). It is the ratio of the sediment fall velocity and the shear velocity which is a function of bed shear stress:

$$R = \frac{U_p}{k\left(\frac{\tau_b}{\rho}\right)^{0.5}}$$

With U_p the particle fall velocity, k the Von Karman Constant, τ_b bed shear stress, and ρ the water mass density.

The AdH 2D model was used to evaluate the sediment transport capability for a discharge of 30,000 cfs in Conowingo Reservoir. The bed shear stress resulting from the calculation was used to calculate the Rouse Number across the entire model domain assuming a medium silt particle size (Figure 6). A silt sediment particle size was chosen for the analysis because the silt fraction of the incoming load represents approximately 60 percent of the total load. The results indicate that velocity and subsequent bed shear stress is high enough to maintain a medium silt in suspension throughout the lower reaches of the reservoir (Rouse number of < 0.8). Only in the upper reach of the reservoir (blue contour on Figure 6) is the flow velocity and bed shear low enough for stratification (50% settled out, 50% in suspension). These Rouse Number simulation results validate the assumption that flows greater than 30,000 cfs will have sufficient velocity to transport silt sized sediments and that any three dimensional affects due to secondary flow processes will potentially be negligible in comparison.

5.3 AdH Model Treatment of Suspended Sediment Profiles

Due to the way AdH treats Suspended Sediment Profiles, the uncertainty due to stratification is not as great as it might have been. Suspended sediment transport is an inherently three dimensional process (Brown 2010). In low flow conditions with little or no sand transport, fine sediments such as silts can stratify vertically in the water column. During higher, more turbulent flows, the fines are generally well mixed in the profile, with larger, sand sized sediments exhibiting some degree of stratification in the water column. Typically 2D models utilize a general depth averaged advection diffusion equation to account for suspended sediment transport. To account for this 3D stratification, AdH computes a correction factor to simulate quasi 3D suspended sediment transport. These correction factors, based on work by Rouse (1937), yield an approximate concentration profile for both equilibrium and non-equilibrium conditions. This profile is then integrated to compute mass flux, with a mass flux correction factor applied assuming a logarithmic velocity profile. In addition, when transport equations are depth averaged, the dispersion of sediment concentration based on varying velocities within the vertical profile is not accounted for. To correct for this, AdH assumes a logarithmic velocity profile, and computes a correction factor by integrating the difference in the velocity at a given depth and the depth averaged velocity.

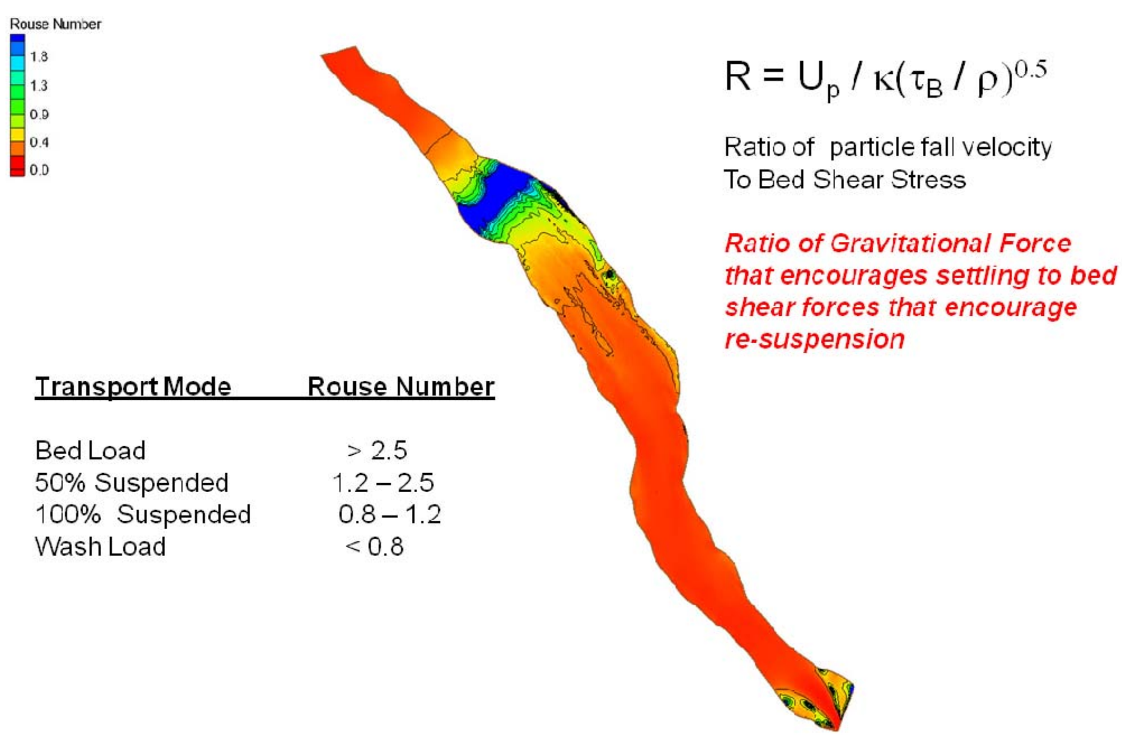

Figure 6. Rouse Number calculation for a medium silt sediment particle at 30,000

6.0 DISCUSSION AND CONCLUSIONS

The transport of sediments through Conowingo Reservoir can be affected by a number of phenomena including stratification due to temperature, wind-driven circulation, and dam operations. Conowingo Dam passes all flows less than 86,000 cfs through the power house on the western edge of the dam, with high flows passing through flood gates along the dam length. Thus reservoir operations add additional uncertainties to the modeling process, with highly variable sediment processes (scour and deposition) likely in the vicinity of the flood gates, hydropower intake, and the dam itself.

This sediment load analysis indicates that approximately 5 percent of the total annual load is accounted for by flows equal to or less than 30,000 cfs. Thus the bulk of the annual sediment load is passed into the reservoir for the higher flows for which the water column is relatively well mixed and stream-wise velocity is the dominant transport process. For this flow condition, 1D and 2D models can provide adequate resolution of sediment processes.

Based on the findings of this study, the application of the AdH 2D sediment transport model to Conowingo reservoir is adequate for simulating general reservoir sediment scour and deposition modeling scenarios (flows that define the reservoir morphology). Although there are 3D effects in the reservoir that occur during certain flow conditions and dam operations, they are not significant enough to warrant a 3D model application.

7.0 REFERENCES

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