Application of the Chesapeake Bay Environmental Model Package to Examine the Impacts of Sediment Scour in Conowingo Reservoir on Water Quality in Chesapeake Bay

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Abstract

The Susquehanna River empties into the northernmost extent of Chesapeake Bay and provides more than half of the freshwater flow to the estuarine system. A series of dams and reservoirs at the lower terminus of the river regulates flow and influences dissolved and suspended material loads into the Bay. Considerable sedimentation has occurred in the reservoirs since the dams were constructed. The two upper-most reservoirs have lost all sediment storage capacity while Conowingo Reservoir, situated immediately upstream of the Bay, was reported to have lost 60% to 70% of its storage capacity by 1997. Loss of the remaining sediment storage could have environmental consequences for the Chesapeake Bay, especially the portion immediately below the dam. Sediments which pass over the dam and enter the Bay, instead of settling to the reservoir bottom, may increase light attenuation, with adverse consequences for submerged aquatic vegetation. Nutrients associated with the sediments may contribute to ongoing eutrophication. Loss of storage may counter or negate load reductions planned under a recently-completed total maximum daily load (TMDL) program which assumes continued deposition in Conowingo Reservoir at the rate which prevailed from 1991 to 2000.

This report examines the impact of reservoir filling on water quality in Chesapeake Bay. Emphasis is placed on three quantities which form the basis of Bay water quality standards: chlorophyll, water clarity, and dissolved oxygen. Scenarios are presented which examine the impact of scour from a large storm on the Bay and which examine benefits from potential sediment management efforts. The Chesapeake Bay Environmental Model Package was the primary tool used to complete these investigations. Scenarios examined the impact of scour under alternate reservoir bathymetries, the effect of storms occurring at different times of the year, the potential ecosystem benefits of the dam, the potential benefits of removing sediments from the reservoir, and the potential impact of sediment bypassing. One over-arching conclusion from the scenarios is that the suspended solids loads are not the major threat to Bay water quality. For most conditions examined, solids scoured from the reservoir bottom settle out before the period of the year during which light attenuation is critical. The nutrients associated with the solids are more damaging. The nutrients settle to the estuary bottom and are mineralized in bottom sediments. The nutrients are recycled to the water column and stimulate algal production. Subsequent decay of algal organic matter consumes oxygen in the classic eutrophication cycle.

The computed impact of storm scour associated with a January 1996 flood event on TMDL conditions is small in magnitude relative to projected ambient conditions although the area affected may be extensive. Averaged over the SAV growing season, the median increase in growing-season light attenuation is less than 0.01 m^{-1}. Computed chlorophyll increases by 0.1 to 0.3 mg m^{-3} over a widespread area extending into the lower Potomac River and below the mouth of the Potomac in the mainstem bay. Bottom-water dissolved oxygen declines up to 0.2 g m^{-3} although the decline is 0.1 g m^{-3} or less when averaged over the summer season.

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1 Introduction

The Susquehanna River empties into the northernmost extent of Chesapeake Bay and provides more than half of the freshwater flow to the estuarine system. A series of dams and reservoirs (Figure 1-1) at the lower terminus of the river regulates flow and influences dissolved and suspended material loads into the Bay. The most upstream reservoir, Lake Clarke, forms behind Safe Harbor Dam. Holtwood Dam forms Lake Aldred which sits below Lake Clarke. Conowingo Reservoir, the largest of the three, forms behind Conowingo Dam which is situated roughly six kilometers above the Chesapeake Bay head of tide.

Considerable sedimentation has occurred in the reservoirs since the dams were constructed circa 1910 – 1930. Lakes Clarke and Aldred have filled to the extent that they are in equilibrium with sediment loads coming down the river. Gravitational particle settling is balanced by erosion in these shallow systems so that no net accumulation of sediments occurs. The quantity of suspended solids entering each reservoir is essentially balanced by the quantity leaving. Conowingo Reservoir was reported to have lost 60% to 70% of its storage capacity by 1997 (Langland and Hainly, 1997). At that time, the period for the reservoir to fill to capacity was estimated at roughly 17 years. The Langland and Hainly report projected substantial increases in loadings of sediment and sediment-associated phosphorus to Chesapeake Bay resulting from loss of storage capacity in the reservoir. Recent analysis of loads from the reservoir to the Bay associated with the 2011 Tropical Storm Lee event suggest storm-generated loads are now substantially higher than in previous years (Hirsch, 2012). The increase in loadings projected in 1997 may be presently in effect.

Loss of sediment storage in Conowingo Reservoir could have environmental consequences for the Chesapeake Bay, especially the portion immediately below the dam. Sediments which pass over the dam and enter the Bay, instead of settling to the reservoir bottom, may increase light attenuation, with adverse consequences for submerged aquatic vegetation. Nutrients associated with the sediments may contribute to ongoing eutrophication. Loss of storage may counter or negate load reductions planned under a recently completed total maximum daily load (TMDL) program (USEPA, 2010) which assumes continued deposition in Conowingo Reservoir at the rate which prevailed during the hydrologic period used in determination of the TMDL (1991 to 2000).

The U.S. Army Corps of Engineers, Baltimore District (USACE), and the state of Maryland (MDE) have entered into a cost-share agreement to conduct Phase I of the Lower Susquehanna River Watershed Assessment (LSRWA). Phase I will:

- Forecast and evaluate sediment loads to the system of hydroelectric dams located on the Susquehanna River,
- Analyze hydrodynamic and sedimentation processes and interactions within the lower Susquehanna River watershed,
- Consider structural and non-structural strategies for sediment management, and
- Assess cumulative impacts of future conditions and sediment management strategies on Chesapeake Bay.

Critical components of the Phase I Watershed Assessment (USACE, 2011) include:

- Identification of watershed-wide sediment management strategies,
- Use of engineering models to link incoming sediment and associated nutrient projections to in-reservoir processes at the hydroelectric dams and forecast impacts to living resources in the upper Chesapeake Bay,
- Use of the Chesapeake Bay Environmental Model Package (CBEMP), a cooperative effort of the US Environmental Protection Agency Chesapeake Bay Program and the US Army Engineer Research and Development Center, to assess cumulative impacts of the various sediment management strategies to the upper Chesapeake Bay, and
- Integration of the Maryland and Pennsylvania Watershed Implementation Plans for nitrogen, phosphorus, and sediment reduction, as required to meet Chesapeake Bay TMDL's.

The present document reports on the use of the CBEMP in partial fulfillment of the goals stated above.

The Model Suite

This investigation involves the use of numerous predictive environmental models and the transfer of information between the models (Figure 1-2). Various and, occasionally, alternate acronyms are used to describe the individual models and combination of models. Water quality in the Bay is computed by the CBEMP which consists of three independent models: a watershed model (WSM), a hydrodynamic model (HM), and a water quality or eutrophication model (WQM). The WSM (Shenk and Linker, 2013) incorporates the entire Chesapeake Bay watershed and provides daily computations of flow, solids loads, and nutrient loads at the Conowingo outfall, at the heads of other tributaries and along the shoreline below the tributary inputs. Daily flows from the WSM are one set of inputs to the Computational Hydrodynamics in Three Dimensions (CH3D) hydrodynamic model (Johnson et al., 1993; Kim, 2013). CH3D computes surface level, three-dimensional velocities, and vertical diffusion on a time scale measured in minutes for the tidal Chesapeake Bay system. Daily nutrient and solids loads from the WSM and hourly transport processes from CH3D drive the Corps of Engineers Integrated Compartment Water Quality Model (CE-QUAL-ICM or simply ICM) of the Bay and tributaries (Cerco et al., 2010). ICM computes, in three dimensions, physical properties including suspended solids, algal production, and elements of the aquatic carbon, nitrogen, phosphorus, silica, and oxygen cycles. These are computed on time scales of minutes although computations averaged up to longer time periods, hours to one day, are more representative of observations. A predictive sediment diagenesis component (DiToro, 2001), a submerged aquatic vegetation component (Cerco and Moore, 2001), and a bivalve filtration component (Cerco and Noel, 2010) are attached to and interact with the model of the water column.

The HM and the WQM operate on a 50,000-cell computational grid which extends from the mouth of the Bay to the heads of tide of the Bay and major tributaries (Figure 1-3). Computational cells are quadrilateral (≈1 km x ≈1 km x 1.5m) and vary in number from 1 to 19 in the vertical in order to represent bathymetric variations. The primary application period for the two models covers the decade from 1991 to 2000. The 1991 to 2000 hydrologic record is retained for this study and the hydrodynamics for all but a few model runs are transferred directly from Cerco et al. (2010). (Two additional hydrodynamic simulations were completed as described in a subsequent chapter of this report.) The WQM is exactly as calibrated and described by Cerco at al. (2010) and as employed by the EPA Chesapeake Bay Program in development of the 2010 TMDL (USEPA, 2010).

WSM Phase 5.3.2, the most recent implementation, provided daily solids and nutrient loads for this study. The WSM provided two series of outputs for subsequent use in the WQM. The "2010 Progress Run" was based on land use, management practices, waste-loads, and atmospheric deposition from the year 2010 and represented current conditions. The "TMDL" run employed projected land use, management practices, waste-loads, and atmospheric deposition upon which the TMDL was based. The TMDL was developed from WSM Phase 5.3.0, however, so small differences exist between the loads used herein and the published regulatory TMDL.

Two other models were associated with this study and provided information utilized directly or indirectly in the CBEMP. A detailed Adaptive Hydrodynamics (ADH) model computed two-dimensional hydrodynamics and sediment transport in Conowingo Reservoir (Scott and Sharp, 2013). Sediment erosion or scour from the bed of Conowingo under various conditions was computed in ADH and added to the loads at Conowingo computed by the WSM and employed by the WQM. Since the ADH application period was 2008 to 2011 while the CBEMP application period was 1991 to 2000, an algorithm described in a subsequent chapter was applied to adjust calculated scour from the ADH application for use in the CBEMP. Solids loads to Conowingo Reservoir, for use in the ADH model, were based on a "rating curve" which was informed by an application of the Hydrologic Engineering Center River Analysis System (HEC-RAS) to the three-reservoir system from Lake Clarke through Conowingo (Langland, 2013).

A Word about Units

This report employs SI units throughout, with rare exceptions. Tons comprise 1,000 kg unless "English" tons, 1000 lbs., are specified.

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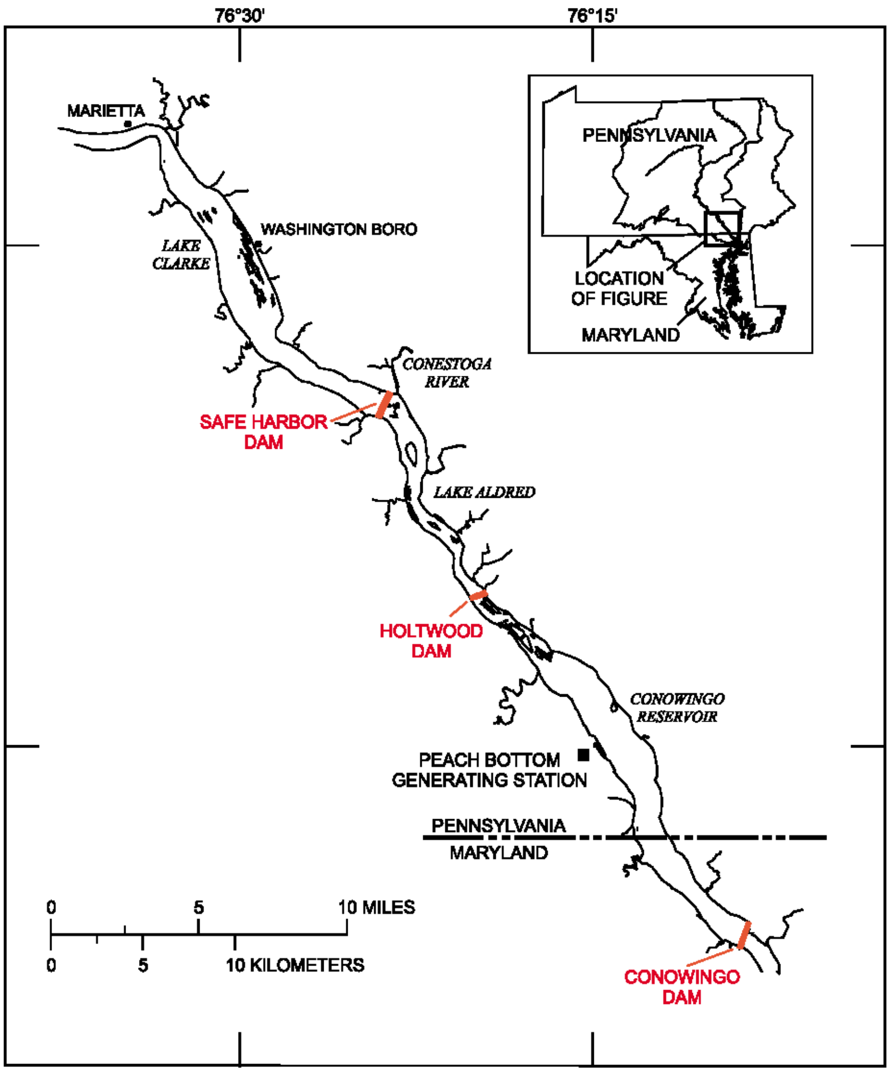

Figure 1-1. Lower Susquehanna River reservoir and dam system (extracted from USGS, 2003).

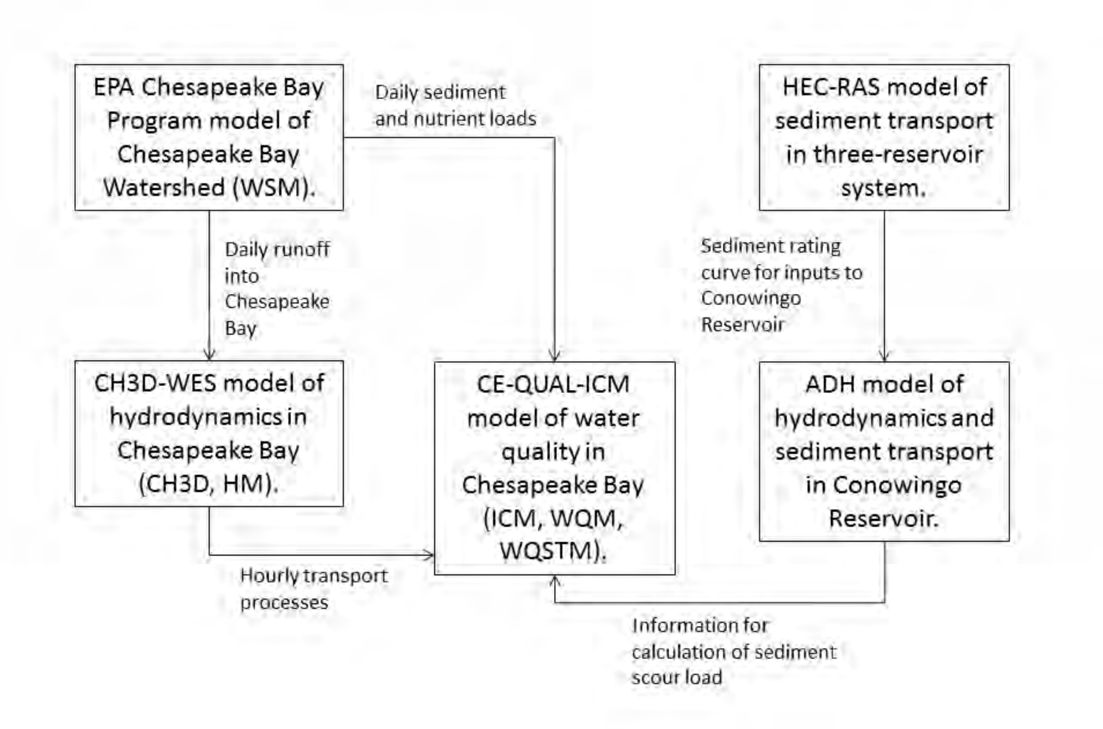

Figure 1-2. Flow chart for models applied in this study.

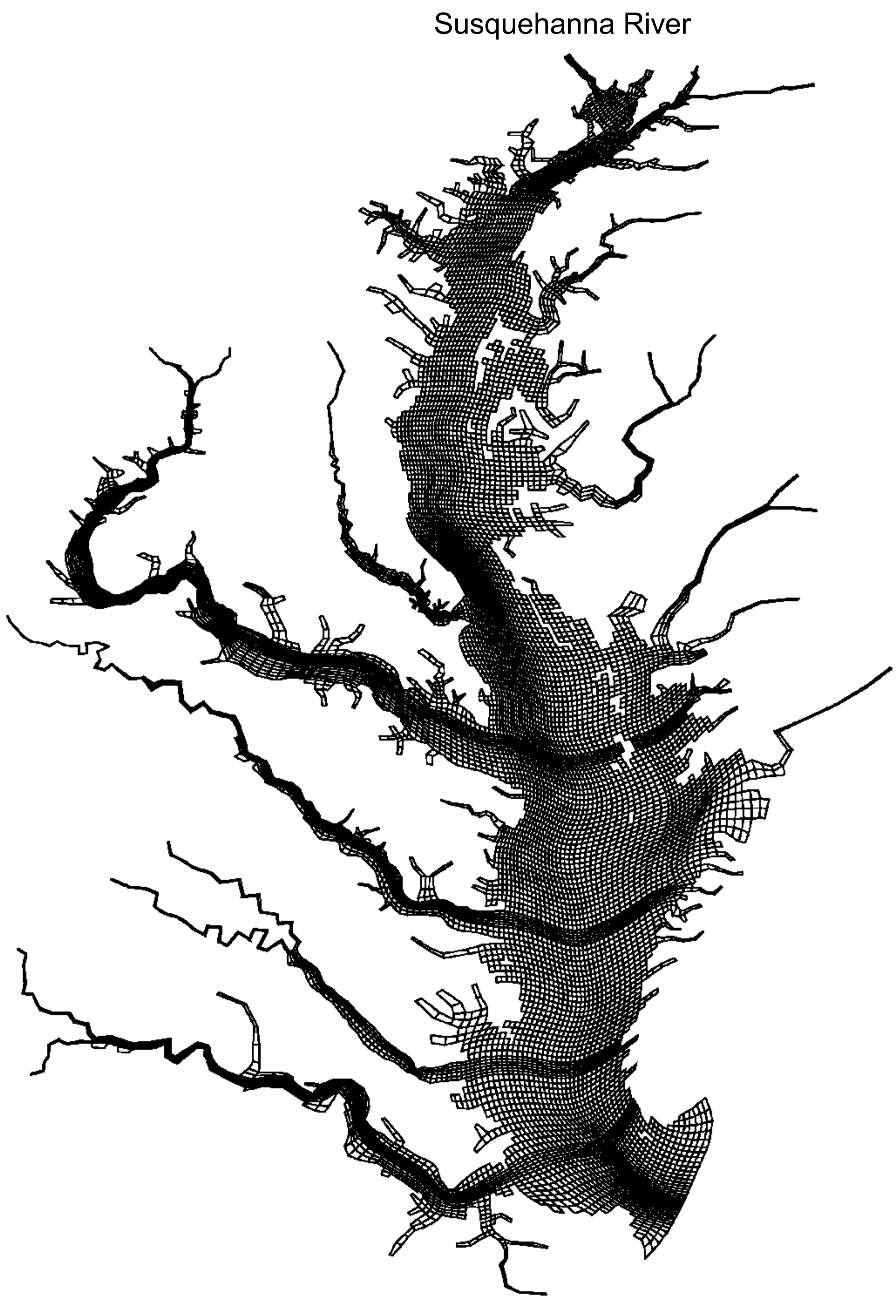

Figure 1-3. Plan view of the Chesapeake Bay computational grid.

2 Analytical and Conceptual Models

Suspended solids transport through the Conowingo Reservoir is a dynamic process involving flow and storage in the water column and erosion, deposition, and storage in the sediment bed. Realistic simulation of suspended solids transport in this system requires application of complex hydrodynamic and sediment transport models. While these models can be highly accurate, interpretation of model results is complicated by the myriad processes represented in the model framework. The application of basic analytical models provides insight which aids in understanding of complex model results. We developed the analytical model below to aid in interpretation of model results presented in succeeding chapters. The analytical model leads to the presentation of a conceptual model of suspended solids transport in and out of the reservoir.

Analytical Model

Consider the reservoir to be a well-mixed system at steady state and containing sediments of a single size class (Figure 2-1). Sources of sediment to the water column include loading from the watershed and erosion from the bottom. Sediment sinks are reservoir discharge and deposition. At steady state, reservoir volumetric inflow must equal volumetric outflow and sediment sources must equal sediment sinks:

$$Q \cdot Cin + E \cdot A = Q \cdot C + W \cdot A \cdot C \qquad (2\text{-}1)$$

in which:

Q = volumetric flow (L^3/T)
Cin = inflow solids concentration (M/L^3)
E = erosion rate ($M/L^2/T$)
A = surface area (L^2)
C = solids concentration in water column (M/L^3)
W = settling velocity (L/T)

Solving for C yields:

$$C = \frac{Cin + \frac{E \cdot A}{Q}}{1 + \frac{W \cdot A}{Q}} \qquad (2\text{-}2)$$

At this level of analysis, solids concentration is independent of reservoir depth. Rather, the dimension of importance is surface area.

Consider erosion to be proportional to excess bottom shear stress:

$$E = B \cdot \frac{\tau - \tau c}{\tau c} \qquad \text{for } \tau > \tau c \tag{2-3}$$
$$E = 0 \qquad \text{otherwise}$$

in which:

B = base erosion rate ($M/L^2/T$)
τ = bottom shear stress ($M/L/T^2$)
τc = critical shear stress required to initiate erosion ($M/L/T^2$)

Bottom shear stress is the product of shear velocity, u_*, and fluid density, ρ:

$$\tau = \rho \cdot u_*^2 \tag{2-4}$$

Shear velocity is considered proportional to mean velocity in the water column:

$$u_* = \alpha \cdot u \tag{2-5}$$

in which:

u = velocity in water column
α = proportionality constant

Velocity is not a property of the well-mixed reactor. In an open channel, mean velocity would be obtained by dividing flow by cross-sectional area, width x depth. Consider a characteristic width to be proportional to the square root of surface area. In that case, a characteristic velocity is:

$$u = \frac{Q}{H \cdot \sqrt{A}} \tag{2-6}$$

in which:

H = depth (L)

The expression for bottom shear stress becomes:

$$\rho \cdot u_*^2 = \rho \cdot \left[\frac{\alpha \cdot Q}{H \cdot \sqrt{A}}\right]^2 = \varepsilon \cdot \frac{Q^2}{H^2 \cdot A} \tag{2-7}$$

The constant ε incorporates the density and the proportionality constant between bulk velocity and shear velocity.

Substituting the relationship for bottom shear stress, Equation 2-7, into the relationship for erosion rate, Equation 2-3, yields:

$$E = \frac{B \cdot \frac{\varepsilon \cdot Q^2}{H^2 \cdot A} - \tau c}{\tau c} \tag{2-8}$$

and the solution for concentration, Equation 2-2, becomes:

$$C = \frac{Cin + \frac{B \cdot A}{Q} \cdot \left[\frac{1}{\tau c} \cdot \frac{\varepsilon \cdot Q^2}{H^2 \cdot A} - 1\right]}{1 + \frac{W \cdot A}{Q}} \quad (2\text{-}9)$$

Parameter Values

Parameter values for use in Equation 2-9 were obtained from publications on Conowingo Reservoir and from values used in other lakes. Table 2-1 presents parameter values, their source, and brief explanations.

The value for τc is obtained by noting, from Eq. 2-9, that erosion occurs when

$$\frac{1}{\tau c} \cdot \frac{\varepsilon \cdot Q^2}{H^2 \cdot A} > 1 \quad (2\text{-}10)$$

Then

$$\tau c = \frac{\varepsilon \cdot Qe^2}{H^2 \cdot A} \quad (2\text{-}11)$$

in which:

Qe = volumetric flow at which bottom erosion is initiated (L^3/T)

The value of Qe is widely recognized to be ≈ 11,000 $m^3\ s^{-1}$ (Hirsch, 2012 and references therein). Substitution of appropriate parameter values (Table 2-1) in Equation 2-11 yields τc = ≈ 0.7 P.

Results from Analytical Model

The expression for concentration, Equation 2-9, has multiple independent variables. The solution is illustrated (Figure 2-2) for continuous values of Q and discrete values of H. Concentration is normalized by a characteristic value of Cin, 10 g m^{-3}. When the ratio C/Cin > 1, reservoir concentration is greater than inflowing concentration, indicating the occurrence of net erosion.

The following insights can be gleaned from the derivation of the analytical model and from the illustrated solution:

When volumetric flow is below the erosion threshold, the solids concentration in the reservoir is independent of depth. This result is derived from Equation 2-2 with E = 0. The reservoir concentration, and hence the outflowing concentration, is always less than the inflowing concentration. The difference between inflowing and outflowing sediment loads is deposition which is also independent of depth. By this analysis, deposition is continuous and the reservoir is never full. This situation cannot continue indefinitely, however.

As reservoir depth decreases, the flow required to initiate erosion, Qe, diminishes. This result follows from Equation 2-11 which can be rearranged to yield:

$$Qe = H \cdot \sqrt{\frac{A}{\varepsilon} \cdot \tau c} \qquad (2\text{-}12)$$

The flow required to initiate erosion is linearly proportional to depth. This result can also be seen in Figure 2-2. For a reservoir of 9 m depth, flow required to initiate erosion is ≈ 13,000 $m^3\ s^{-1}$ versus ≈ 7,000 $m^3\ s^{-1}$ at 5 m depth.

When the erosion threshold is exceeded, the sediment concentration in the outflow is inversely proportional to depth. Effectively, for any flow rate sufficient to initiate erosion, more sediment will flow from a shallow reservoir than a deep reservoir. This result can be readily seen from Figure 2-2. At a flow rate of 12,000 $m^3\ s^{-1}$, the ratio of C/Cin is ≈ 2 for a reservoir of 7 m depth; the ratio increases to C/Cin ≈ 7 at the same flow rate for a reservoir of 5 m depth.

Conceptual Model

Insights from the analytical model as well as from numerous reports on the reservoir system allow for the formulation of a conceptual model of Conowingo Reservoir (Figure 2-3). One significant insight is that the reservoir is never completely filled. Solids accumulate continuously until an erosion event occurs. As the reservoir fills, however, the flow threshold to initiate an erosion event diminishes. Erosion events become more frequent and severe.

The concept of equilibrium between solids loads into and out of Conowingo Reservoir is used in this report and elsewhere although the precise definition of the equilibrium condition is lacking. Equilibrium does not imply equality of suspended solids inflows and outflows on a daily basis or similar time scale. As used here, equilibrium implies a balance between suspended solids inflows and outflows over a time period defined by erosion events. Solids which accumulate between events are washed away after which accumulation begins anew. No net storage or filling occurs in the reservoir. The conventional threshold for erosion of ≈ 11,000 $m^3\ s^{-1}$ has a recurrence interval of five years (Langland, 2013) implying the equilibrium exists over roughly that period. If we believe the threshold for erosion is below 11,000 $m^3\ s^{-1}$, then the recurrence interval and the equilibrium tine scale are shorter. The concept of equilibrium remains applicable over a period of years, however, rather than an instantaneous equality between inflows and outflows.

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Table 2-1
Parameter Values for Analytical model

Parameter	Value	Derivation	References
A	33×10^6 m^2	Reported as 12.8 mi^2.	Hainly et al., 1995
Volume	2.34×10^8 m^3	Reported capacity in 1990 was 190,000 acre-feet.	Hainly et al., 1995
H	7.3 m	Obtained from volume divided by area.	
ε	10 kg m^{-3}	The density of water is 1000 kg m^{-3}. Shear velocity is 10% of mean velocity.	Fisher et al., 1979
τc	0.688 P (= kg m m^{-2} s^{-2})	Bottom erosion occurs at 11,000 m^3 s^{-1} (400,000 ft^3 s^{-1}). See text. Critical shear stress measured in cores collected from Conowingo is 0.19 to 2.87 P.	Hirsch, 2012; Scott and Sharp, 2013
B	0.019 g m^{-2} s^{-1}	Typical values for lakes range from 500 to 10,000 g m^{-2} d^{-1}.	Luettich et al., 1990; Bailey and Hamilton, 1997; Hawley and Lesht, 1992; Janes et al., 2004a; James et al., 2004b
W	1.16×10^{-4} m s^{-1}	Order of magnitude range for lakes is 10^0 to 10^2 m d^{-1}.	Luettich et al., 1990; Bailey and Hamilton, 1997; Hawley and Lesht, 1992; Janes et al., 2004a; James et al., 2004b

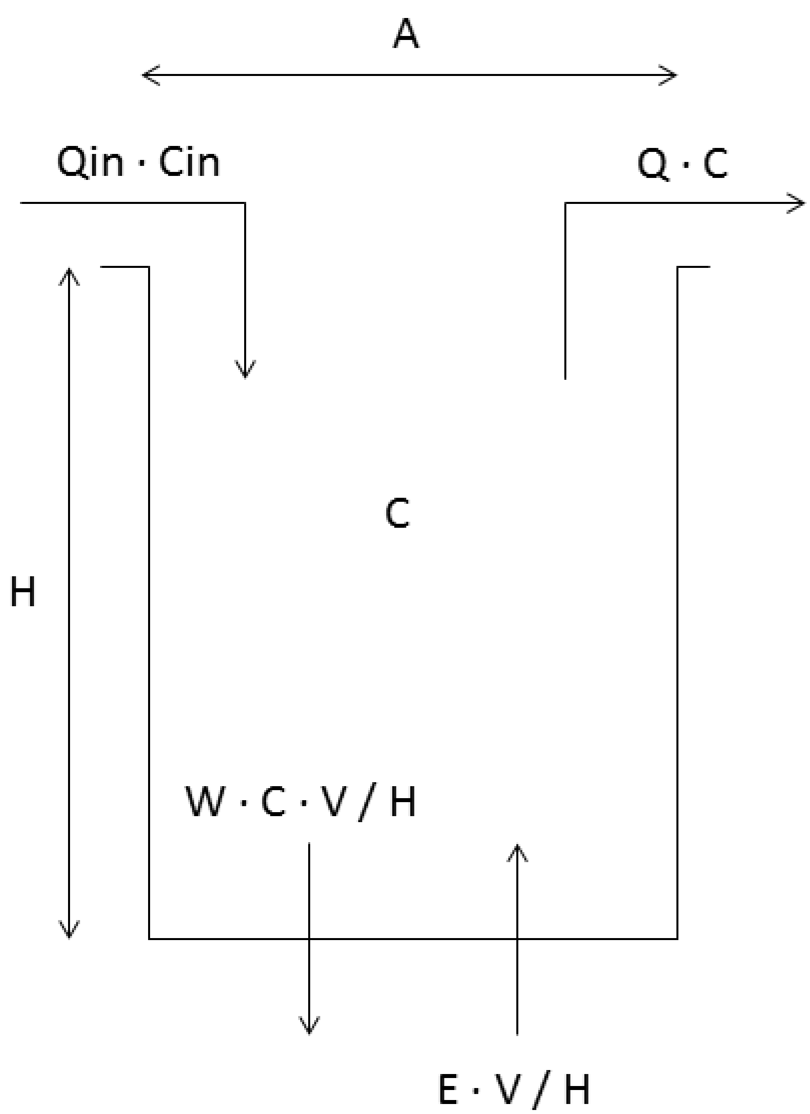

Figure 2-1. Schematic diagram for the Conowingo Reservoir represented as a well-mixed system of depth H, surface area A, and volume V. Note that concentration within the reservoir is equivalent to outflowing concentration.

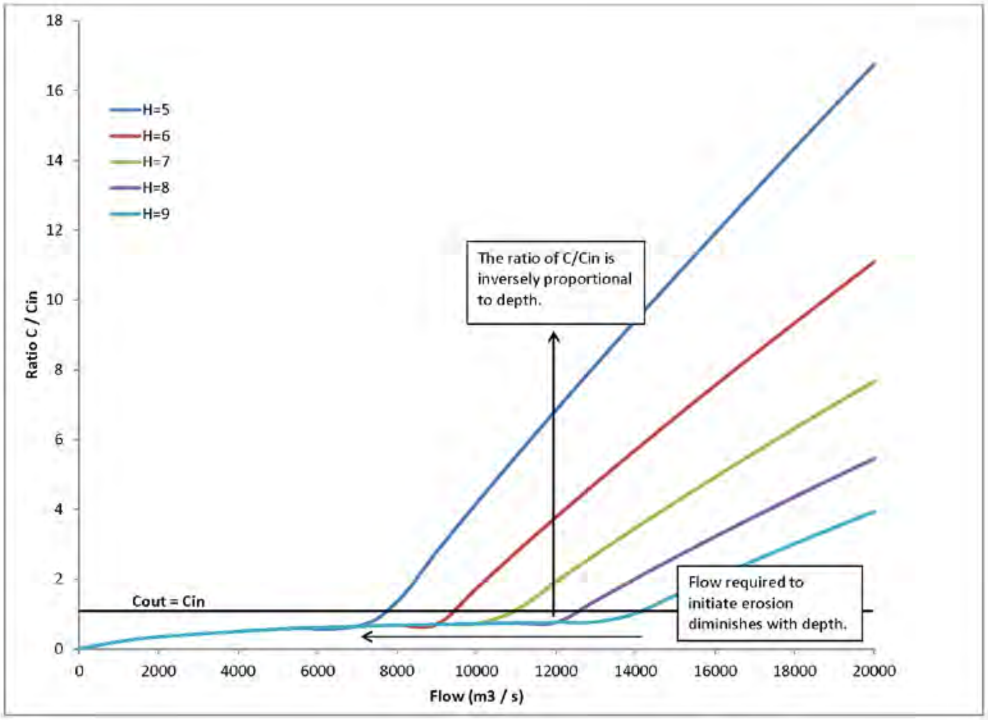

Figure 2-2. Analytical solution (Equation 2-9) for sediment concentration, C, as a function of flow and depth, H.

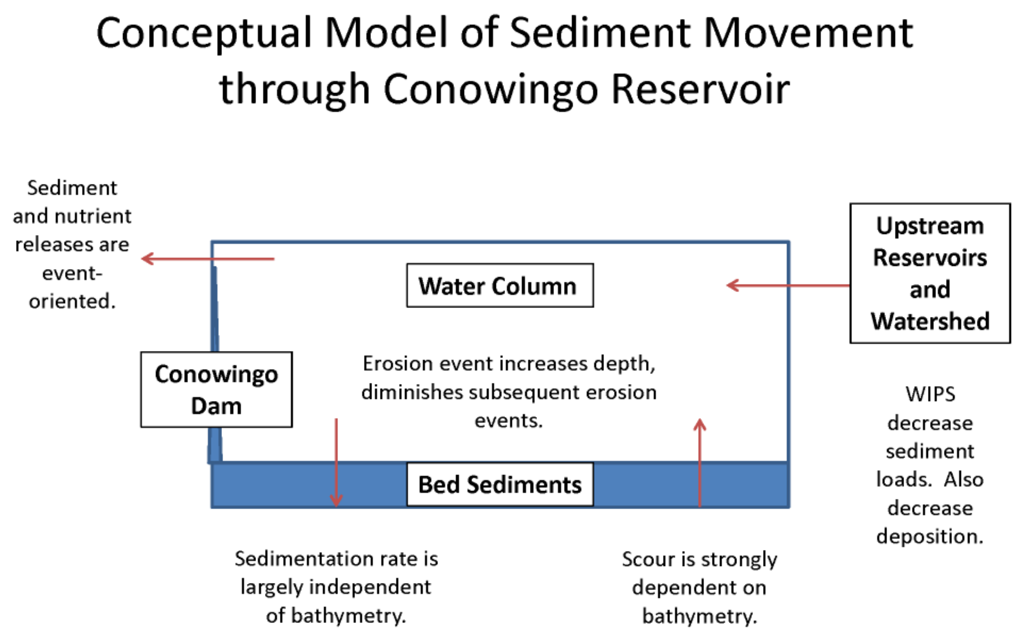

Figure 2-3. Conceptual model for solids transport and erosion in Conowingo Reservoir.

3 Scenario Procedure and Listing

Overview

The LSRWA makes use of existing tools and methodologies as well as new tools and applications developed specifically for this study. The use of existing models and practices is advantageous to the study since these tools could not be developed within the time and budget limitations of the LSRWA. The individual models within Chesapeake Bay Environmental Model Package (Watershed Model, Hydrodynamic Model, and Water Quality Model) are documented, have been extensively reviewed, and have lengthy application histories. The use of these existing tools provides some disadvantages and constraints, however, notably in the period emphasized in their application.

The ADH model, which computed sediment fate and transport in the Conowingo Reservoir, was a new application created especially for this study. ADH was applied over the period 2008 – 2011, in order to take advantage of recent data collected in the reservoir. The application included the Tropical Storm Lee event, which resulted in notable scour and provided an excellent opportunity for model calibration and validation. This period was not represented in the CBEMP, however, for which the primary application period was 1991 – 2000. The resources necessary to acquire raw observations, create model input decks, execute and validate the individual models within the CBEMP for the years 2008 – 2011 was beyond the scope of the LSRWA. Consequently, means were required to transfer information from the 2008 – 2011 ADH application to the 1991 – 2000 CBEMP. The crucial transfer involved combining scour computed by ADH for TS Lee with watershed loads computed by the WSM model for a January 1996 flood and scour event represented by the CBEMP.

The WSM provides computations of volumetric flow and associated sediment and nutrient loads throughout the watershed and at the entry points to Chesapeake Bay. Flow computations are based on precipitation, evapotranspiration, snow melt, and other processes. Loads are the result of land use, management practices, point-source wasteloads and additional factors. The loads computed for 1991 – 2000 are no longer current and are not the loads utilized in the TMDL computation. To emphasize current conditions, a synthetic set of loads was created from the WSM based on 1991 – 2000 flows but 2010 land use and management practices. The set of loads is designated the “2010 Progress Run.” The TMDL loads are a second set of synthetic loads created with the WSM. In this case, the 1991 – 2000 flows are paired with land uses and management practices sufficient to meet the TMDL limitations.

The ADH model provides computations of sediment load due to bottom scour, but not the load of associated nutrients. Limited observations of sediment-associated nutrients are available at the Conowingo outfall during the 1996 flood event. The composition of solids eroded from the bottom are difficult to glean from these observations, however, since samples at the outfall represent the mixture of solids washed down from the watershed and eroded from the bottom. And, as with the watershed loads, these observations may no longer represent current conditions. Consequently, the nutrients associated with scoured solids for use in scenarios was derived from observations of nutrients in the bottom sediments of Conowingo Reservoir.

Major storm events occur at different times of the year. In order to examine the effect of seasonality of storm loads on Chesapeake Bay, the January 1996 storm was moved, within the model framework, to June and to October. The loads were moved directly from January to the other months. No adjustment was made for the potential effects of seasonal alterations in land uses. New Chesapeake Bay hydrodynamic model runs were completed based on the revised flows, to account for alterations in flow regime and stratification within the Bay.

Scenario Procedure

Scenarios that examine the effect on Chesapeake Bay of sediment erosion in Conowingo Reservoir are ten years in duration and incorporate the hydrologic record that occurred from 1991 to 2000. This record consists of daily freshwater flows at the heads of all tributaries as well as runoff from the adjacent watershed directly to Bay and tributary waters. All freshwater flows are provided by the CBP WSM. This is the record employed in calibration of the CBEMP and incorporates the critical years 1993 to 1995. The TMDL was determined based on maintenance of water quality standards during these three years. The record (Figure 3-1) includes a major scour event in Conowingo Reservoir which occurred in January 1996 (Figure 3-2). The January 1996 event included the second highest daily flow observed at Conowingo since the inception of the modern management era in 1985, 17,600 $m^3 s^{-1}$, as well as three of the top ten daily flows in that period. The 11,000 $m^3 s^{-1}$ (400,000 $ft^3 s^{-1}$) threshold for scour was exceeded on January 20, 21, and 22. The threshold for scour was also exceeded in early April 1993 although the peak flow, 13,200 $m^3 s^{-1}$, was lower and the event did not receive the notoriety of the 1996 event.

The 1996 flood was caused by an unusual convergence of events (Langland, 1998). Heavy rainfall and warm temperature enhanced melting of snow cover which had accumulated in the Susquehanna watershed. The combined volume of rain and snowmelt caused a rapid rise in river level and breakup of ice cover in the Susquehanna River and tributaries. Ice jams caused even greater rise in river level and accumulation of large volumes of water behind the jams. When the jams broke, an enormous volume of water pushed through the reservoir system and was released through Conowingo Dam. Peak instantaneous flow was 25,000 $m^3 s^{-1}$ (Langland, 1998).

Runoff at major tributary inputs, lesser distributed flows, solids loads and nutrient loads for the scenarios all originate with the CBP WSM. These are input to the CBEMP on a daily basis, according to the watershed area contributing to each surface cell in the CBEMP computational grid. The hydrologic record is the same in all scenarios with the exception of alterations to examine the effects of seasonality of storm events. Solids and nutrient loads are based on alternate combinations of land use in the watershed. Loads computed in the 2010 Progress Run are based on 2010 land uses and management practices and represent current loading conditions. Loads computed in the TMDL scenario are based on projected future land uses and management practices which meet the loading restrictions imposed by the TMDL.

Each scenario is preceded by a ten-year spin-up sequence. The spin-up is required to generate initial conditions in the water column and in the sediment bed. The spin-up is a ten-year repetition of hydrodynamics, daily flows, and daily loads for the year 1992, a year of typical hydrology in the Susquehanna River. Following the spin-up, conditions in the water column and sediments are considered to be in equilibrium with the imposed sediment and nutrient loads.

The scenarios incorporate scour loads from Conowingo Reservoir generated based on alternate bathymetry configurations. Most scenarios employ the "existing" bathymetry, based on a 2008 survey. The "equilibrium" bathymetry is the bathymetry projected to result when sediment loads in and out of the reservoir are in dynamic equilibrium and no net deposition occurs. The "1996" bathymetry is based on a survey completed after the scour event and represents a reservoir with enhanced volume relative to present conditions. The "dredged" bathymetry is derived from existing bathymetry less 2.3×10^6 m^3 (3×10^6 yd^3) of material removed as a management action.

Roughly thirty scenarios were conducted although all are not reported here. A number of scenarios conducted early in the study were supplanted as improved information and understanding developed. The significant scenarios are listed in Table 3-1. Space considerations limit the information presented in this report. An appendix entitled "Individual Results for each Chesapeake Bay Environmental Model Package Scenario" is available upon request from the first author or from the Planning Division, US Army Engineer District, Baltimore.

References

Langland, M. (1998). "Changes in sediment and nutrient storage in the three reservoirs in the lower Susquehanna River basin and implications for the Chesapeake Bay," USGS Fact Sheet 003-98, USGS Pennsylvania Water Science Center, Lemoyne PA.

Table 3-1
Scenario List

Code	Land Use	Bathymetry	Description
LSRWA_4	2010 Progress	Existing	The base scenario for the 2010 Progress Run. No scouring in Conowingo.
LSRWA_3	TMDL	Existing	The base TMDL scenario. No scouring in Conowingo.
LSRWA_5	2010 Progress	Existing	The 2010 Progress Run with Conowingo Reservoir removed from the system. Loads computed by the WSM to the reservoir are routed directly to Chesapeake Bay. This scenario examines the role of Conowingo Reservoir under existing conditions.
LSRWA_6	TMDL	Existing	The TMDL scenario with Conowingo Reservoir removed from the system. Loads computed by the WSM to the reservoir are routed directly to Chesapeake Bay. This scenario examines the role of Conowingo Reservoir under projected TMDL conditions.
LSRWA_20	2010 Progress	Existing	The 2010 Progress Run with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_21	TMDL	Existing	The TMDL scenario with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_31	TMDL	1996	The TMDL scenario with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_18	2010 Progress	Equilibrium	The 2010 Progress Run with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_30	TMDL	Equilibrium	The TMDL scenario with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_22	TMDL	Existing	The TMDL scenario with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during the January 1996 scour event.
LSRWA_23	TMDL	Existing	The TMDL scenario with the January 1996 storm removed from the hydrologic record, from the load record, and from the hydrodynamics.
LSRWA_24	TMDL	Existing	The TMDL scenario with the January 1996 storm moved to June 1996. The transfer includes the hydrologic record, the load record, and the hydrodynamics. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.

LSRWA_25	TMDL	Existing	The TMDL scenario with the January 1996 storm moved to October 1996. The transfer includes the hydrologic record, the load record, and the hydrodynamics. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_26	TMDL	Existing	The TMDL scenario with the January 1996 storm moved to June 1996. The transfer includes the hydrologic record, the load record, and the hydrodynamics. The nutrients associated with the solids are based on observations collected during the January 1996 scour event.
LSRWA_27	TMDL	Existing	The TMDL scenario with the January 1996 storm moved to October 1996. The transfer includes the hydrologic record, the load record, and the hydrodynamics. The nutrients associated with the solids are based on observations collected during the January 1996 scour event.
LSRWA_28	TMDL	Dredged	The TMDL scenario with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011.
LSRWA_29	TMDL	Dredged	The TMDL scenario with added solids and nutrient loads from scour in Conowingo Reservoir. The nutrients associated with the solids are based on observations collected during Tropical Storm Lee in 2011. Three million cubic yards of solids and associated nutrients, assumed to be the by-product of dredging, are bypassed during the months of December – February for each of ten scenario years.

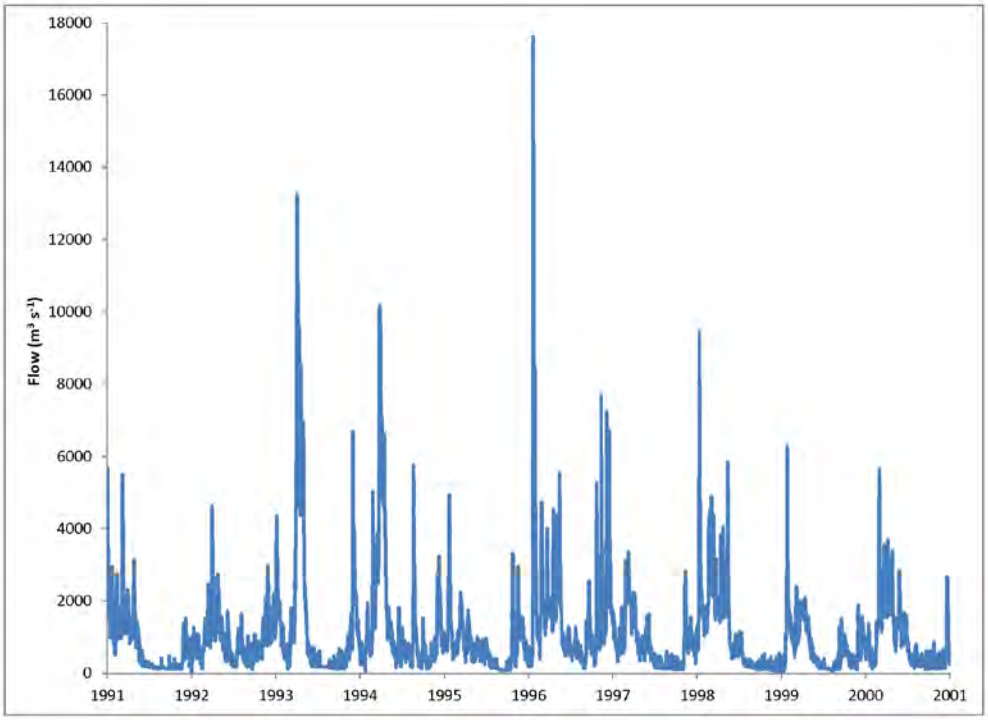

Figure 3-1. Observed flows at Conowingo Dam outfall 1991 – 2000. Scour occurs at ≈ 11,000 m^3 s^{-1}.

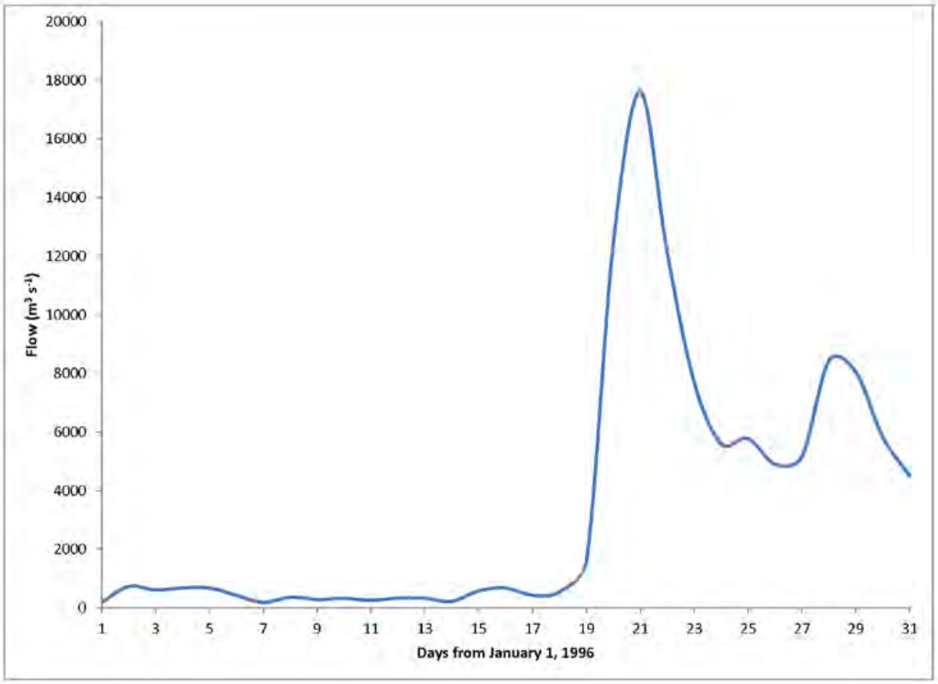

Figure 3-2. Observed flows at Conowingo Dam outfall, January 1996. Scour occurs at ≈ 11,000 m^3 s^{-1}.

4 Load Computation and Summary

Loads from the Watershed

Sediment and nutrient loads from the Susquehanna River employed in Chesapeake Bay scenario runs are influenced by hydrology, by land use and management practices in the watershed, and by the configuration of the reservoir system at the watershed terminus. Loads from the watershed are calculated by the CBP WSM for two configurations: existing conditions (2010 Progress Run) and total maximum daily load (TMDL). The WSM routes watershed loads computed above the three reservoirs through Lake Clarke, Lake Aldred, and Conowingo Reservoir. The loads at the head of the reservoir system are supplemented by inputs from the local watersheds immediately adjacent to the reservoirs. The routing process includes calculation of the effects of settling, erosion, and biological transformations within the reservoirs. Several scenarios were completed in which the calculated loads to Conowingo Reservoir were routed directly to Chesapeake Bay without modeling of processes in the reservoir. These scenarios were originally conducted as “reservoir full” scenarios based on the supposition that under reservoir-full conditions material would pass through the reservoir swiftly and completely. This supposition was supplanted as an improved picture of the reservoir under equilibrium between inputs and outputs became available. The scenario results are retained, however, since they provide an illustration of the conditions expected if the river emptied directly into the bay. A summary of loads to the bay from the Susquehanna River, with and without the dam, calculated for the period 1991 – 2000 is presented in Table 4-1.

The WSM represents multiple nitrogen forms including ammonium, nitrate, and organic nitrogen. The individual forms have been combined into total nitrogen here and in subsequent tables. The organic nitrogen variable is also reported individually since scoured nutrient loads are incorporated into this classification. The WSM represents multiple phosphorus forms including dissolved inorganic phosphorus, particulate inorganic phosphorus, and organic phosphorus. The individual forms have been combined into total phosphorus here and in subsequent tables. The organic phosphorus and particulate inorganic phosphorus variables are also combined and reported as particulate phosphorus since scoured nutrient loads are incorporated into this classification.

Coupling the Bay Model and the Watershed Model

Particulate nutrients suspended in Susquehanna River water and eroded from the bottom of Conowingo Reservoir exist in multiple organic and inorganic forms. No definitive laboratory analysis or suite of analyses describes all these forms. Neither is there a universal suite of model variables for the particulate nutrients. The state variable suite in the WSM differs from the WQM. In particular, the WQM incorporates a more elaborate suite of organic and inorganic particles. WSM variables are "mapped" into WQM variables during preparation of the WQM input files. Nutrients associated with solids eroded from the Conowingo Reservoir bed are routed into WQM variables in the same process. The mapping procedure is sketched in Figure 4-1 and quantified in Table 4-2. Details are found in Cerco and Noel (2004) and Cerco et al. (2010).

Loads from Bottom Erosion

The WSM incorporates algorithms to calculate particle settling and erosion in Conowingo Reservoir. The algorithms are parameterized empirically to optimize agreement between computed and observed sediment and nutrient concentrations flowing over Conowingo Dam. During the course of this study, we determined that little or no scouring of bottom material was calculated during the January 1996 flood event. As a consequence, computed solids concentrations (Figure 4-2) and, potentially, particulate nutrient concentrations were less than observed. Solids and nutrient loads from erosion were calculated independently, based on computations from the ADH model for Conowingo Reservoir, and added to the WSM loads for this event.

The terms "erosion" and "scour" are used interchangeably in this report. A significant point to remember is that both these terms refer to net erosion or scour. "Net scour" is the amount of material scoured from the bottom of Conowingo Reservoir and carried over the Conowingo outfall. Net scour does not include material scoured from the bottom and re-deposited within the reservoir. Net scour is computed on a daily basis as the excess of suspended solids leaving via the outfall over suspended solids entering the reservoir.

Solids Loads from Bottom Erosion

The ADH application period, 2008 – 2011, differed from the WQM application period, 1991 – 2000. A procedure to apply ADH calculations to the 1996 storm was developed based on the volumetric flow in excess of the threshold for scour, ≈ 11,000 $m^3 s^{-1}$. The year 2011 contained two erosion events, an un-named event in March and Tropical Storm Lee, in late August. The excess volume (Figure 4-3) for each event was computed by integrating flow over time for the period during which flow exceeded 11,000 $m^3 s^{-1}$. The amount of solids eroded during each event was taken as the difference between computed loads entering and leaving Conowingo Reservoir. Solids loads leaving the reservoir in excess of loads entering were taken as evidence of net erosion from the bottom. Net erosion for January 1996 was calculated by linear interpolation of the two 2011 events, using excess volume as the basis for the interpolation (Figure 4-4). The analysis was conducted for three major sediment classes employed in the WQM: clay, silt, and sand. The total scour load for the 1996 event was apportioned to individual days based on flows and inspection of the 2011 record. The solids concentrations resulting from the combination of WSM loads and estimated erosion showed remarkable agreement with solids concentrations observed at the dam outfall in January 1996 (Figure 4-2).

Nutrient Loads from Bottom Erosion

Nutrient loads associated with bottom erosion were calculated by assigning a fractional nitrogen and phosphorus composition to the eroded solids. The initial fractions assigned, 0.3% nitrogen and 0.1% phosphorus, were based on analyses of sediment cores removed from the reservoir (Cerco, 2012). These fractions were consistent with data collected at the Conowingo outfall during 2011 as part of this study (Table 4-3). We found, however, that addition of these nutrient loads to the WSM loads resulted in nutrient concentrations in excess of values observed in January 1996 (Figures 4-5, 4-6, Table 4-4).

The solids nutrient fractions observed at Conowingo in 2011 were determined via direct particle analysis. No direct analyses were conducted in 1996 but nutrient fractions can be obtained by differencing of filtered and unfiltered samples:

$$\%N = 100 \cdot \frac{(TKNw - TKNf)}{SS} \tag{4-1}$$

in which:

%N = nitrogen associated with sediment particles (% mass fraction)
TKNw = whole total Kjeldahl nitrogen (g m^{-3})
TKNf = filtered total Kjeldahl nitrogen (g m^{-3})
SS = suspended sediment (g m^{-3})

An analogous relationship holds for the particulate phosphorus fraction, %P.

Comparison of the particle composition in 1996 (Table 4-4) and 2011 (Table 4-3) indicates the compositions are distinctly different and the nutrient fractions are much less in 1996 than in 2011 (Figures 4-7, 4-8). The reason (or reasons) for the differences cannot be definitively identified. The 1996 and 2011 storms occurred in different seasons (January versus August) and differences in properties of material washed from the land surface are expected. The mechanisms behind the floods also differed. The 2011 flood was primarily a meteorological event while the 1996 flood was partly due to the build-up and release of water trapped behind ice dams. The unique origin of the 1996 flood and the dam operation intended to release the flood waters may have caused bottom erosion from a different portion of the reservoir than in 2011.

Employment of the 1996 nutrient composition to characterize the nutrients associated with sediment eroded in 1996 results in reasonable agreement between observed and computed nutrients at the Conowingo outfall (Figures 4-5, 4-6) but presents a dilemma. Which nutrient fractions should be used in subsequent scenario analysis? The 1996 composition, which accompanied the 1996 event and was observed during the 1991 – 2000 scenario period? Or the 2011 composition which is more recent and characterizes a typical tropical storm event? In view of the dilemma, several key scenarios have been run with alternate composition, presenting a range of potential outcomes.

Erosion Loads under Different Bathymetries

The amount of material scoured from the bottom of the reservoir depends, in part, upon the reservoir bathymetry. Observations (Langland and Hainly, 1997) and theory (Chapter 2) indicate scour is inversely related to reservoir depth. The ADH model was run for several bathymetry sets including:

- Existing (2008) bathymetry
- Equilibrium bathymetry
- Bathymetry following 1996 storm
- Bathymetry resulting from dredging 2.3 x 10^6 m^3 (3 million cubic yards)

The existing bathymetry was based on surveys conducted in 2008. The equilibrium bathymetry was based on the estimated configuration after the reservoir achieves long-term equilibrium between solids inflows and outflows. The bathymetry following the 1996 storm was also based on surveys. Following the erosion associated with this event, the reservoir volume was 21 x 10^6 m^3 (28 million cubic yards) greater than existing volume. This configuration allowed assessment of depth effects on scour and served as an endpoint for dredging scenarios. The bathymetry resulting from dredging 3 million cubic yards from a depositional area near the dam was employed in sediment management scenarios.

In all cases, the procedure for determining the scour load followed the same steps:

- Solids loads into and out of Conowingo Reservoir using the hydrologic record for the period 2008 to 2011were provided by the ADH model.
- Solids scour for two events in 2011 was determined by the excess of outflowing solids loads over inflowing solids loads.
- Scour for the 1996 hydrologic record was estimated by interpolation based on excess volume.
- Nutrient composition was assigned to the scoured solids based on 2011 observations.
- For key scenarios, an alternate set of nutrient loads was constructed based on 1996 observed nutrient fractions.

The scour loads for alternate bathymetric configurations and solids composition are presented in Table 4-5.

References

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Table 4-1 Summary of Watershed Model Loads from the Susquehanna River for 1991 to 2000 Hydrologic Record

		Flow, $m^3 s^{-1}$	Total Nitrogen, kg d^{-1}	Organic Nitrogen, kg d^{-1}	Total Phosphorus, kg d^{-1}	Particulate Phosphorus, kg d^{-1}	Total Suspended Solids, kg d^{-1}
2010 Progress Run	1991 to 2000 daily average	1,170	147,949	62,931	6,314	5,222	3,056,623
	daily maximum	13,382	1,981,500	1,387,800	154,330	116,028	181,910,000
TMDL	1991 to 2000 daily average	1,175	104,067	46,058	4,718	3,872	2,307,352
	daily maximum	13,367	1,421,600	1,010,300	113,490	86,797	134,960,000
2010 Progress Run, No Conowingo Efffects	1991 to 2000 daily average	1,171	161,569	73,648	7,697	6,495	4,113,782
	daily maximum	13,415	2,093,500	1,498,200	268,870	263,249	483,100,000
TMDL, No Conowingo Effects	1991 to 2000 daily average	1,183	114,959	53,757	5,779	4,818	3,196,639
	daily maximum	13,411	1,603,500	1,125,100	227,470	222,041	393,000,000
2010 Progress Run, January 1996 Storm	January 19 to 25 daily average	9,292	1,178,697	496,847	100,562	71,920	74,115,571
	storm total	65,041	8,250,880	3,477,930	703,931	503,440	518,809,000
TMDL, January 1996 Storm	January 19 to 25 daily average	9,260	842,820	354,771	73,726	49,248	57,837,429
	storm total	64,822	5,899,740	2,483,400	516,081	344,739	404,862,000

Table 4-2 Routing WSM Variables into WQM Variables		
Watershed Model	**goes to**	**Water Quality Model**
Organic Nitrogen		Up to 0.16 g m^{-3} is considered Dissolved Organic Nitrogen. The remainder is considered Refractory Particulate Organic Nitrogen.
Organic Phosphorus plus Particulate Inorganic Phosphorus		Up to 0.005 g m^{-3} is considered Dissolved Organic Phosphorus. 58% of the remainder is considered Particulate Inorganic Phosphorus. 42% of the remainder is considered Refractory Particulate Organic Phosphorus.
Clay		Up to 4 g m^{-3} is considered fine clay. The remainder is clay.

Table 4-3 Particle Composition Observed at Conowingo Outfall 2010 to 2011[1]

Date	Flow, $m^3 s^{-1}$	Phosphorus, ppm	Fe, %	Mn, ppm	TOC,%	PN, %	Susp. Sediment, $g\ m^{-3}$
10/3/2010	2861	1500	3.6	2500			
12/3/2010	7819	1400	4.7	3000	4.1	0.47	141
3/8/2011	7762	1400	5	3400	4.2	0.4	129
3/12/2011	12833	1200	4.2	2100	5.1	0.36	937
3/12/2011	12833	1200	4.4	2200	4.9	0.34	937
9/8/2011	17479	1100	4.4	1900	3.2	0.26	2980
9/8/2011	17479	1100	4.3	2000	3.2	0.27	2980
9/10/2011	13626	900	5.3	1900	2.2	0.18	741
9/11/2011	10992	960	4.9	1800	2.5	0.2	1150
9/12/2011	6600	940	5.4	1800	1.9	0.19	332
avg	11028	1170	4.6	2260	3.5	0.30	1147
max	17479	1500	5.4	3400	5.1	0.47	2980
min	2861	900	3.6	1800	1.9	0.18	129

[1]Data provided by Jeffrey Chanat, USGS MD-DE-DC Water Science Center. The samples from September 2011 reflect Tropical Storm Lee.

Table 4-4 Observed and Derived Concentrations at Conowingo Outfall, January 1996[2]

Date	Flow, $m^3 s^{-1}$	Total Nitrogen, $g\ m^{-3}$	Ammonium + Organic Nitrogen, whole, $g\ m^{-3}$	Ammonium + Organic Nitrogen, filtered, $g\ m^{-3}$	Phosphorus, whole, $g\ m^{-3}$	Phosphorus, filtered, $g\ m^{-3}$	Suspended Sediment, $g\ m^{-3}$	Organic Carbon, $g\ m^{-3}$	Particulate Nitrogen, $g\ m^{-3}$	Particulate Phosphorus, $g\ m^{-3}$	Particulate Nitrogen, %	Particulate Phosphorus, ppm
1/17/96	431	2.4	0.2	0.3	0.02	0.011	3	3.6		0.009		3000
1/20/96	12436	2.3	0.6	0.4	0.09	0.021	194	5.5	0.2	0.069	0.10	356
1/21/96	17620	2.8	1.3	0.7	0.29	0.007	1200	9.7	0.6	0.283	0.05	236
1/21/96	17620						1000					
1/21/96	17620	2.8	1.3	0.7	0.29	0.007	863		0.6	0.283	0.07	328
1/22/96	12125	2.0	0.6	0.4	0.13	0.013	533	7.0	0.2	0.117	0.04	220
1/22/96	12125	2.1	0.7	0.3	0.20	0.008	462	11.0	0.4	0.192	0.09	416
1/22/96	12125	2.0	0.6	0.3	0.13	0.009	451	12.0	0.3	0.121	0.07	268
1/23/96	7705	1.8	0.4	0.3	0.10	0.024	315	4.3	0.1	0.076	0.03	241
1/23/96	7705	1.9	0.5	0.3	0.11	0.01	254	4.3	0.2	0.100	0.08	394
1/24/96	5609						105					
1/24/96	5609	2.0	0.6	0.2	0.20	0.01	118	3.8	0.4	0.190	0.34	1610
1/25/96	5779						111					
1/25/96	5779	1.9	0.3	0.3	0.06	0.01	87	4.9	0	0.050	0.00	575
1/26/96	4901	2.1	0.5	0.3	0.15	0.016	96	3.7	0.2	0.134	0.21	1390
1/29/96	8045	2.3	0.6	0.4	0.17	0.023	130	4.1	0.2	0.147	0.15	1131
1/31/96	4504	2.0	0.4	0.2	0.08	0.01	63	7.6	0.2	0.070	0.32	1111

avg		2.2	0.6	0.4	0.1	0.0	352	6.3	0.3	0.132	0.12	805
max		2.8	1.3	0.7	0.3	0.0	1200	12.0	0.6	0.283	0.34	3000
min		1.8	0.2	0.2	0.0	0.0	3	3.6	0.0	0.009	0.00	220

[2]Data provided by Joel Blomquist, US Geological Survey, Baltimore MD. Particulate nitrogen and phosphorus are derived from the original data as described in the text.

Table 4-5 Scour Loads Computed for January 1996 as a Result of Alternate Reservoir Bathymetries

Bathymetry	**Clay, metric ton**	**Silt, metric ton**	**Sand, metric ton**	**Total Suspended Solids, metric ton**	**Particulate Nitrogen, metric ton**	**Particulate Phosphorus, metric ton**
Existing	1,143,996	1,117,128	110,926	2,372,050	7,116	2,372
Equilibrium	1,154,277	1,106,496	106,557	2,367,330	7,102	2,367
After Dredging 2.3 x 10^6 m^3 (3 million cubic yards)	1,015,964	554,083	34,975	1,605,021	4,815	1,605
After 1996 Scour Event	754,660	531,278	27,934	1,313,872	3,942	1,314
Existing, 1996 Nutrient Composition	1,143,996	1,117,128	110,926	2,372,050	1,637	712

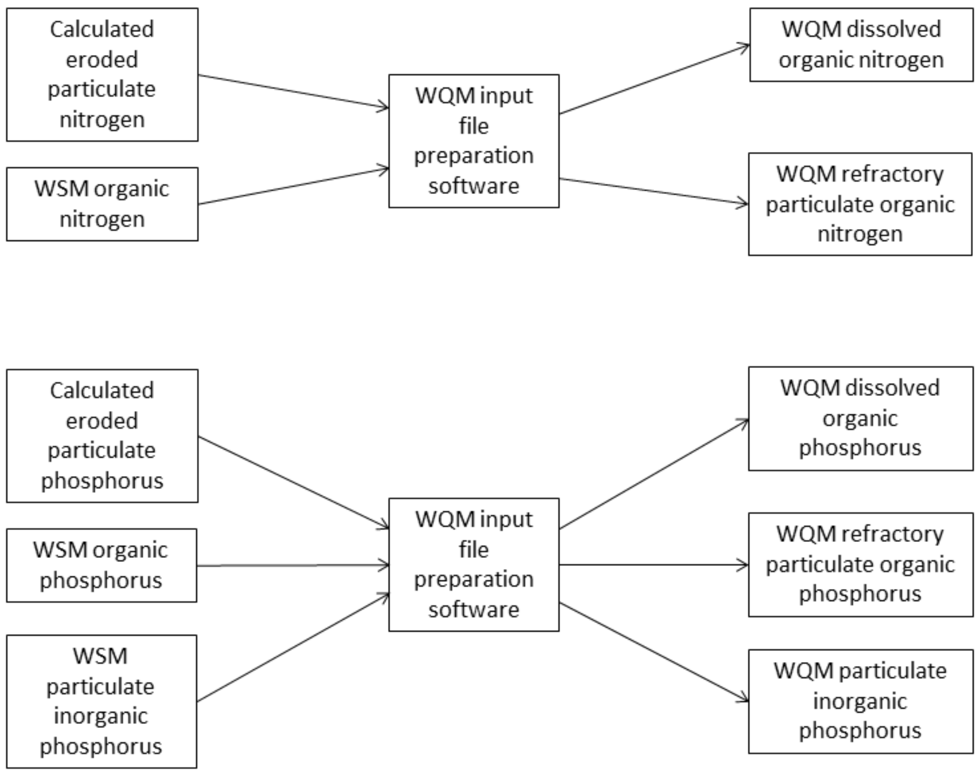

Figure 4-1. Routing of particulate nutrients at Conowingo outfall into WQM state variables.

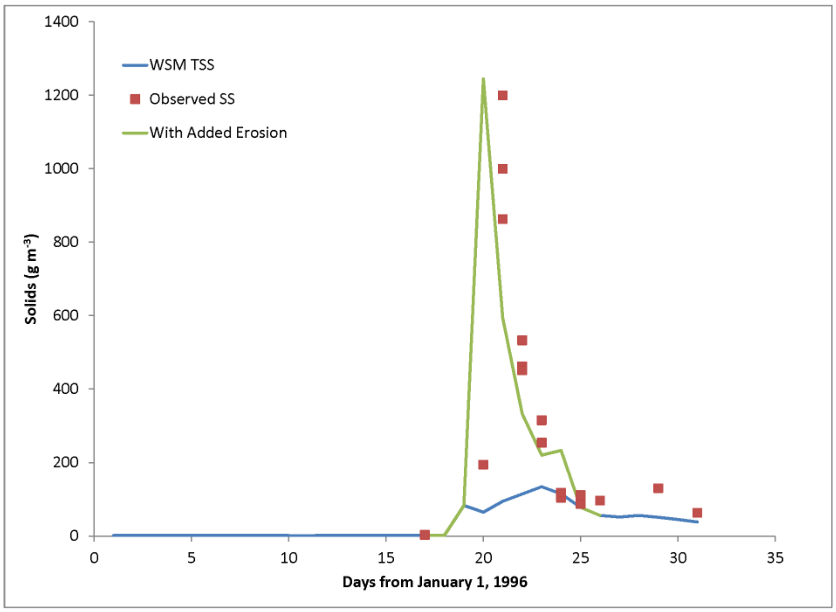

Figure 4-2. Observed and computed suspended solids at the Conowingo outfall, January 1996. Computations are shown for the WSM alone and for the WSM with additional erosion load.

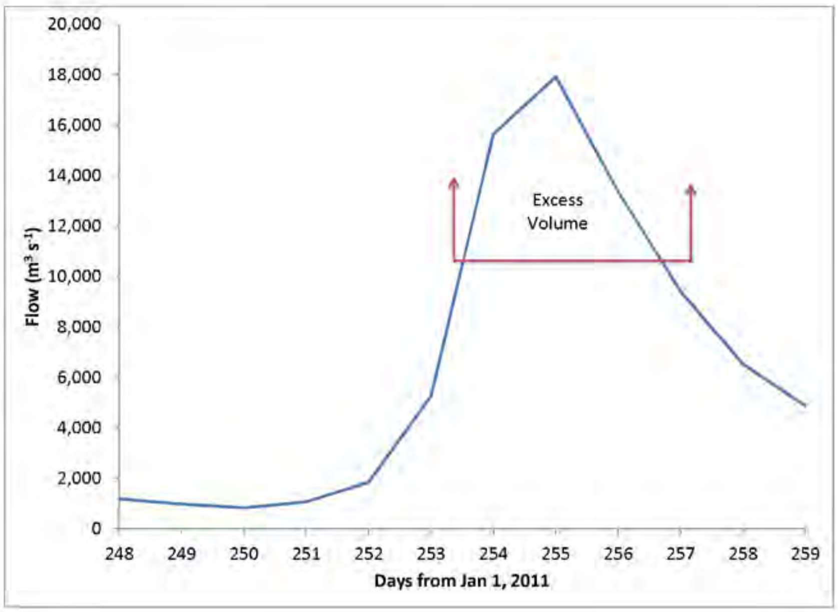

Figure 4-3. Excess volume during Tropical Storm Lee. The excess volume is the volume in excess of the 11,000 $m^3\ s^{-1}$ (400,000 $ft^3\ s^{-1}$) threshold for bottom scour.

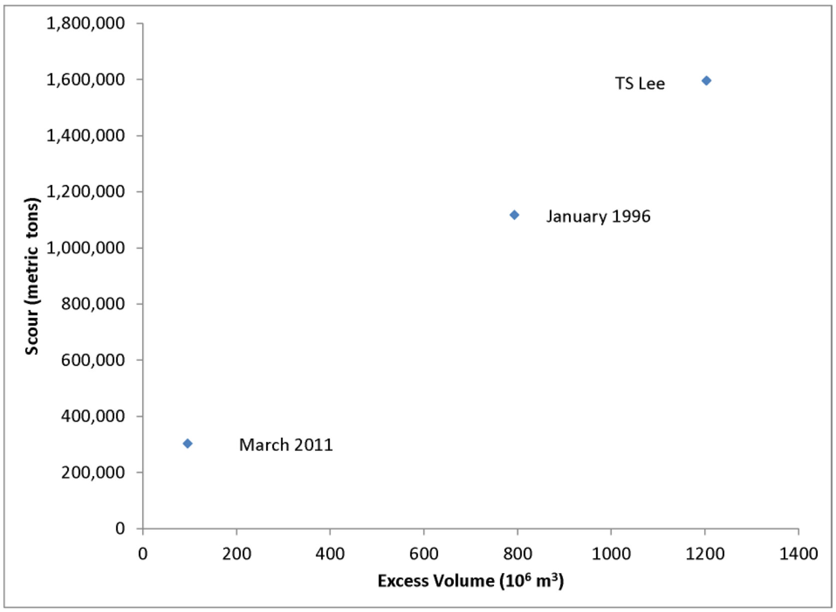

Figure 4-4. Linear interpolation of solids load based on excess volume. This figure shows the determination of silt loading for January 1996.

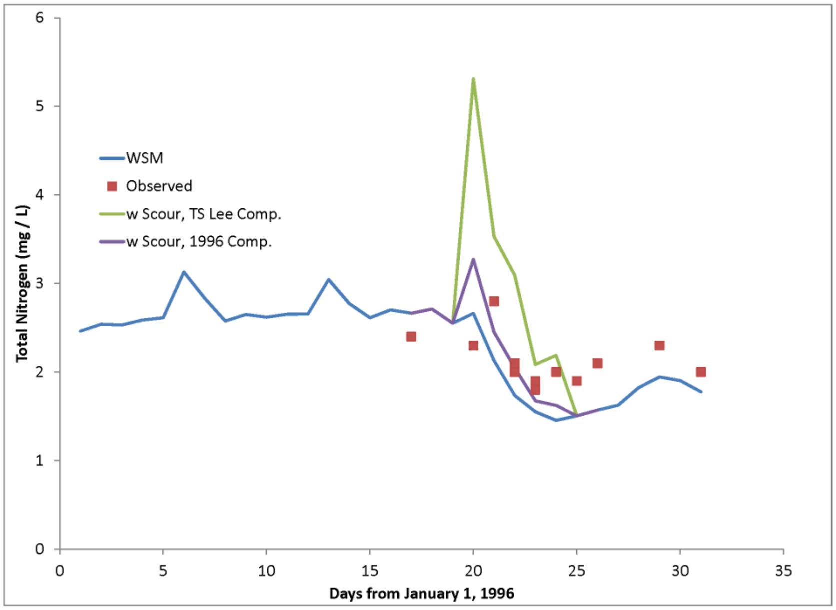

Figure 4-5. Observed and computed total nitrogen concentration at Conowingo Outfall, January 1996. Computations are shown for the WSM alone and for the WSM supplemented with alternate nutrient composition for scoured solids.

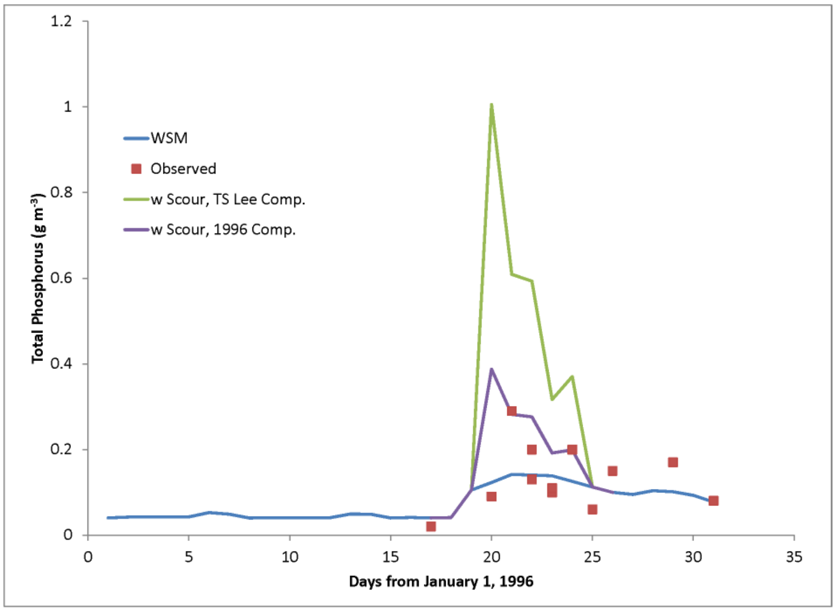

Figure 4-6. Observed and computed total phosphorus concentration at Conowingo Outfall, January 1996. Computations are shown for the WSM alone and for the WSM supplemented with alternate nutrient composition for scoured solids.

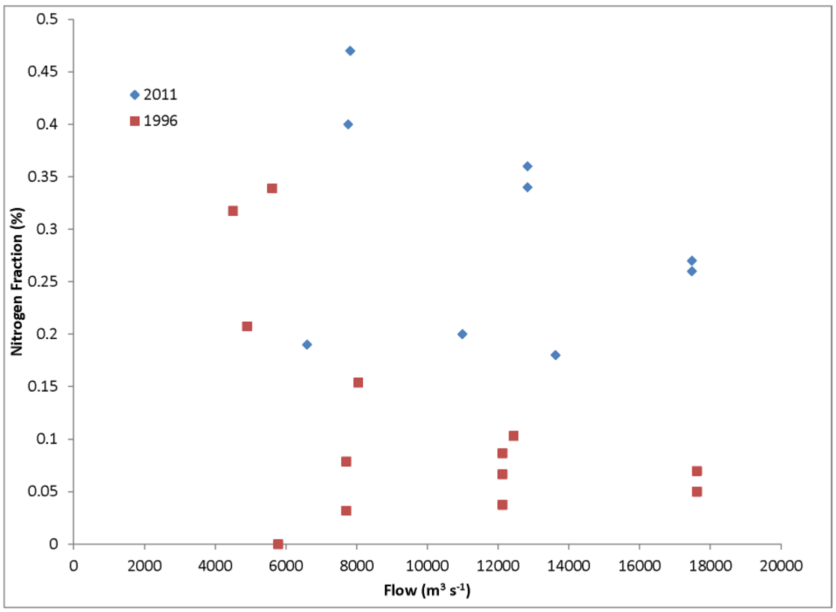

Figure 4-7. Solids nitrogen fraction versus flow at the Conowingo outfall. The 2011 observations are primarily greater than the 1996 observations.

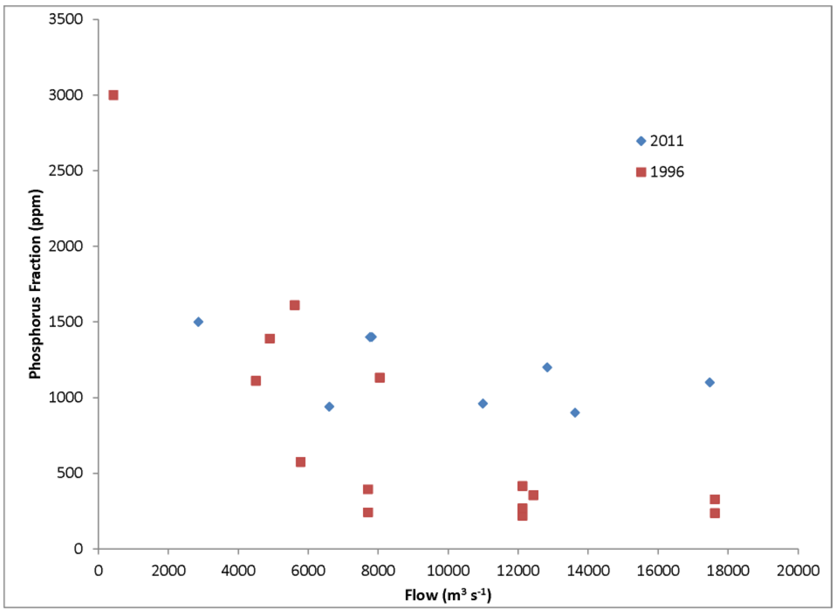

Figure 4-8. Solids phosphorus fraction versus flow at the Conowingo outfall. The 2011 observations are primarily greater than the 1996 observations.

5 Output Formats

The volume of information produced during each ten-year scenario is enormous and requires summarizing and formatting to facilitate assessment. Material presented in this report is limited primarily to results of scenarios conducted for the LSRWA and to runs related to the TMDL. A separate, supplemental, publication is planned to describe results of scenarios conducted for the EPA Chesapeake Bay Program (CBP).

The Total Maximum Daily Loads (USEPA, 2010) are specified to meet criteria in three areas: water clarity, chlorophyll (CHL) concentration, and dissolved oxygen (DO) concentration (Tango and Batiuk, 2013). Water clarity is quantified in the model as the coefficient of diffuse light attenuation (KE) and has units of inverse depth (m^{-1}). DO is quantified in concentration units of g m^{-3} (equivalent to mg/L or ppm). CHL is quantified in concentration units of mg m^{-3} (equivalent to µg/L). Model results are presented for these three criteria, supplemented by total suspended solids (TSS concentration as g m^{-3} or mg/L) which result, in part, from external loading and which contribute to poor water clarity.

Results are presented for the base TMDL conditions, as computed by the CBEMP. Results for the remaining scenarios are presented as difference plots which illustrate the difference between the scenario and base condition. Difference plots are calculated as [Scenario – Base]. Negative differences indicate scenario conditions are less than base conditions. Positive differences indicate scenario conditions are greater than base conditions. Results are presented as time series at five CBP monitoring stations (Figure 5-1) along the axis of the upper bay and as spatial plots for the entire bay. The selected monitoring stations are situated in the portion of the bay expected to show the greatest reaction to scour events and, in several cases, are situated in regions that are critical to meeting DO water quality standards. The time series plots are limited to the last five years of the scenario, 1996 – 2000, to emphasize the effect of the 1996 storm and scour event. Time series are presented for the surface and bottom at all stations and at mid-depth for the deeper stations. Spatial plots are presented for the year 1996, 1997, and 1999. The year 1996 is the storm year. The year 1997 contains the first SAV growing season and summer hypoxic interval following modelled storm events which occur late in 1996. The year 1999 is a drought year emphasized in previous presentations of model results (Cerco et al., 2010). The spatial plots for surface CHL and KE are averaged over the submerged aquatic vegetation growing season, April – October, and correspond to the period specified in the water clarity criteria. The spatial plots for DO show the bottom 1.5 m of the water column and are averaged over the months of June – August. These plots illustrate the occurrence of bottom-water hypoxia during the months when the condition is prevalent. Note, however, that in shallow portions of the bay, the bottom 1.5 m of the water column will be close to or may correspond to the surface.

The colors on the difference plots are configured so that the color red indicates a change towards undesirable conditions. The numeric scales are selected to emphasize differences which are of various magnitudes depending on constituent and scenario. The scales do not refer to specific water quality criteria. The reader may find the following frames of reference useful in judging the magnitude of differences, however. The water quality standard for "deep-channel seasonal refuge use" requires an instantaneous DO minimum > 1 mg/L from June to September; the deep water seasonal fish and shellfish use" requires an instantaneous minimum > 1.7 mg/L (Tango and Batiuk, 2013). The water clarity criteria are a complex combination of observed SAV acreage and percent light through water. A useful guideline is that SAV restoration to the 2m depth in tidal fresh and oligohaline water requires light attenuation < 0.8 m^{-1} (USEPA CBP, 1992). No quantitative chlorophyll criteria apply to upper Bay waters. However, concentrations less than 10 to 15 mg m^{-3} are recommended to avoid DO impairments (Tango and Batiuk, 2013).

Summary tables, as well as graphical presentations, are provided for CHL, KE, and DO. Results are for Chesapeake Bay Program Segments (CBPS) in the upper bay (Table 5-1, Figure 5-2). The CBPS are regions defined by the CBP and distinguished by physical configuration and salinity. Surface CHL and KE are averaged over the growing season. DO is quantified by the anoxic volume days (AVD) statistic. AVD is a spatial and temporal integration of the volume of water with DO concentration less than 1 g m^{-3}:

$$AVD = \sum_{i=1}^{n} \sum_{j=1}^{m} V_i \cdot \Delta t \quad (5\text{-}1)$$

in which:

AVD = anoxic volume days (m^3 d)
n = number of model computational cells in CBPS
m = number of integration time steps in simulated year (d)
V_i = volume of computational cell with DO < 1 g m^{-3} during time step Δt
Δt = integration time step (d)

Various DO concentrations are employed to define hypoxia, anoxia, and similar terms. The 1 g m^{-3} criteria has been defined as the threshold for "severe hypoxia" and used in multiple analyses of DO trends in Chesapeake Bay (Hagy et al., 2004; Murphy et al., 2011; Cerco and Noel, 2013).

Scenarios Presented

Results for each scenario or difference are included as individual pdf files attached to this report. Significant figures and statistics are pulled into the body of the report in subsequent chapters. The scenarios and differences are as follows:

Concentration plots for LSRWA_3. This is the base TMDL run with no scouring.

Difference plots for LSRWA_21 – LSRWA_3. LSRWA_21 is the TMDL run with scouring adapted from ADH for the January 1996 storm. This run shows the effect of scouring on the TMDL.

Difference plots of LSRWA_21 – LSRWA_23. LSRWA_21 is the TMDL run with scouring adapted from ADH for the January 1996 storm. LSRWA_23 is the TMDL run with the January storm removed. This run shows the effect of a January storm on the TMDL.

Difference plots of LSRWA_24 – LSRWA_23. LSRWA_24 is the TMDL run with the January storm flows, loads, and scour moved to June. LSRWA_23 is the TMDL run with the January storm removed. This run shows the effect of a June storm on the TMDL.

Difference plots of LSRWA_25 – LSRWA_23. LSRWA_25 is the TMDL run with the January storm flows, loads, and scour moved to October. LSRWA_23 is the TMDL run with the January storm removed. This run shows the effect of an October storm on the TMDL.

Difference plots for LSRWA_3 – LSRWA_6. LSRWA_3 is the base TMDL run. LSRWA_6 is the base TMDL run with Conowingo removed. This run shows the effect of processes in the Conowingo Reservoir on the TMDL.

Difference plots of LSRWA_30 – LSRWA_21. LSRWA_30 is the TMDL run with scouring for the January 1996 storm adapted from ADH with the reservoir at equilibrium bathymetry. LSRWA_21 is the TMDL run with scouring for the 1996 storm adapted from ADH storm with 2008 (existing) bathymetry. This run shows the effect of reservoir filling on the TMDL.

Difference plots of LSRWA_28 – LSRWA_21. LSRWA_28 is the TMDL run with scouring adapted from ADH based on the removal of 3 million cubic yards (mcy) by dredging. LSRWA_21 is the TMDL run with scouring based on existing bathymetry. This run shows the effect of dredging 3 mcy on the TMDL.

Difference plots of LSRWA_31 – LSRWA_30. LSRWA_31 is the TMDL run with scouring adapted from ADH based on 1996 bathymetry. LSRWA_30 is the TMDL run with scouring adapted from ADH based on equilibrium bathymetry. LSRWA_31 serves two purposes. Here it is employed as a representation of the bathymetry resulting from dredging back to 1996 conditions. The amount of material removed to restore the 1996 bathymetry depends on the base bathymetry utilized. The amount is 28 mcy based on 2008 bathymetry. Due to subsequent sedimentation, the amount is 31 mcy based on 2011 bathymetry. The amount would be grater still if the equilibrium bathymetry is used as a base.

Difference plots of LSRWA_29 – LSRWA_28. LSRWA_29 is a run with additional sediment and nutrient loads resulting from “sediment bypassing.” Bypassing is the practice of dredging sediment and releasing it downstream, past the dams. The bypassing loads are 3 mcy of dredged sediment spread over the interval December to February of each scenario year. LSRWA_28 is the TMDL run with scouring based on bathymetry with 3 mcy removed by dredging.

Dredging and bypassing for ten years eventually result in the 1996 bathymetry. The January 1996 storm happens at some intermediate, unknown bathymetry. To represent this condition, we used the bathymetry and scour produced by the dredging of 3 mcy. This run shows the effect of bypassing dredged material on the TMDL.

References

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Table 5-1
Chesapeake Bay Program Segments Selected for Summation

CBPS	Quantities[1]	CBPS	Quantities
NORTF	CHL, KE	WSTMH	CHL, KE
CB1TF	CHL, KE, AVD	CB4MH, AVD	CHL, KE
BSHOH	CHL, KE	PAXMH, AVD	CHL, KE
GUNOH	CHL, KE	POTMH, AVD	CHL, KE
CB2OH	CHL, KE, AVD	CB5MH, AVD	CHL, KE
MIDOH	CHL, KE	LCHMH, AVD	CHL, KE
BACOH	CHL, KE	CHOMH1, AVD	CHL, KE
PATMH	CHL, KE, AVD	CHOMH2, AVD	CHL, KE
CB3MH	CHL, KE, AVD	EASMH, AVD	CHL, KE
MAGMH	CHL, KE	CHSMH, AVD	CHL, KE
SEVMH	CHL, KE	SASOH	CHL, KE
SOUMH	CHL, KE	BOHOH	CHL, KE
RHDMH	CHL, KE	ELKOH, AVD	CHL, KE

[1]AVD is quantified only for CBPS with substantial volume below the pycnocline.

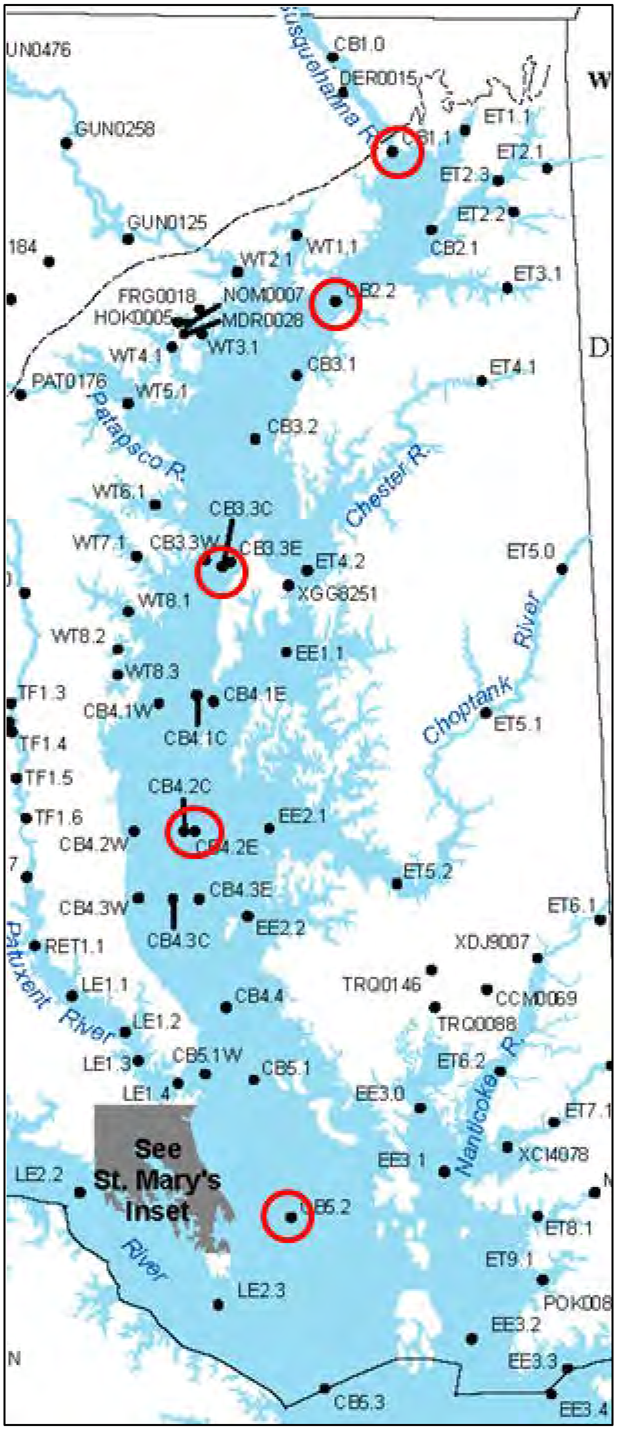

Figure 5-1. CBP monitoring stations (circled in red) selected for time series plots.

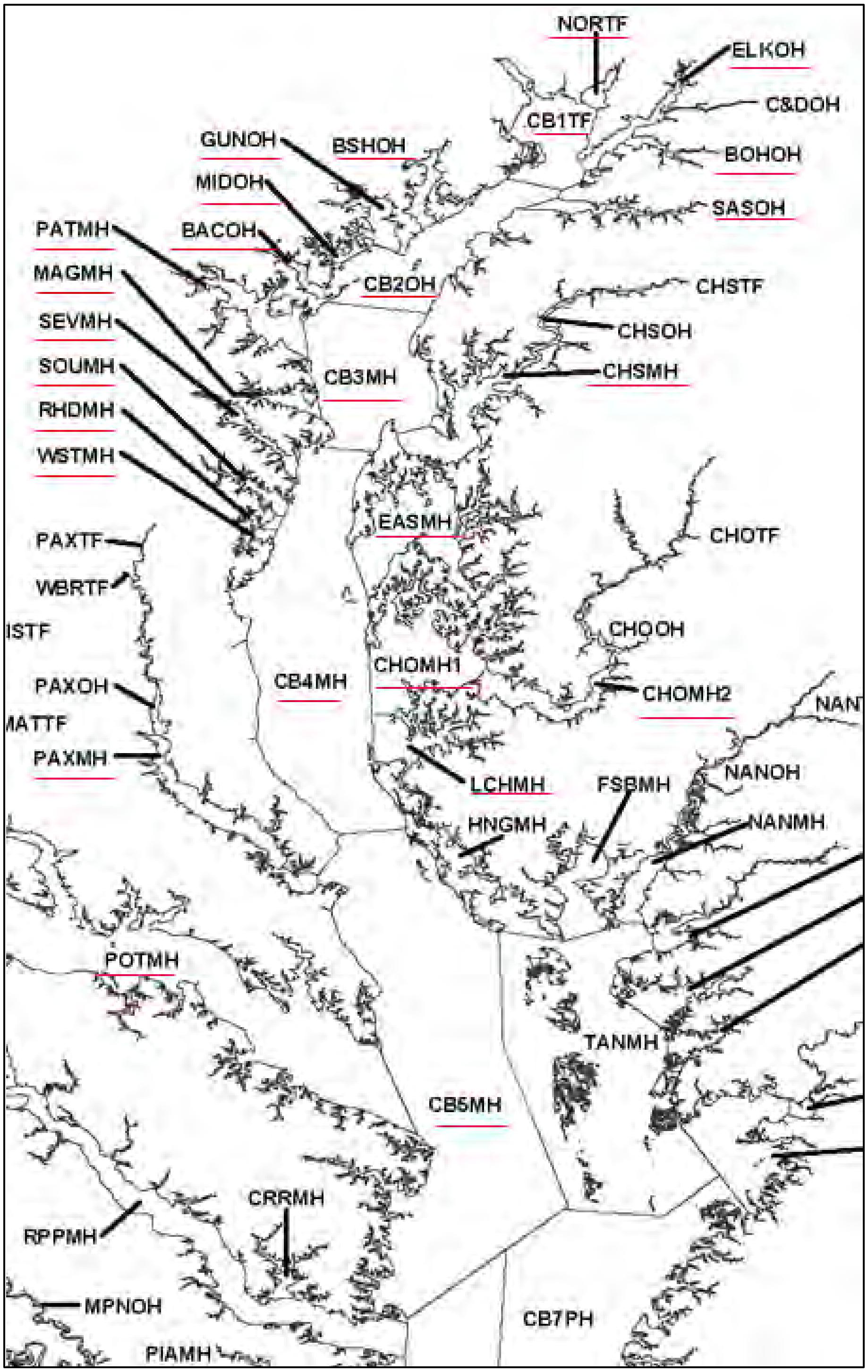

Figure 5-2. Chesapeake Bay Program Segments (underlined in red) selected for summation.

6 Scenario Results

Base Scenario

The Base Scenario consists of a ten-year hydrologic sequence, 1991 – 2000, with watershed solids and nutrient loads from the Chesapeake Bay Program (CBP) Watershed Model (WSM), based on Total Maximum Daily Load (TMDL) conditions. As calibrated and employed here, the WSM provides watershed loads but little or no scour in the Conowingo Reservoir for the January 1996 storm.

The year 1996 is characterized by high flow at the Conowingo outfall, not only in January but throughout the months prior to and during the period of summer hypoxia (Figure 6-1). The year 1996 is followed by 1997 and 1999, respectively, in terms of flow volume during the spring and summer months. The relative ranking of freshwater inflow is reflected in computed stratification (Cerco and Noel, 2013). Summer stratification is strongest in 1996, moderate in 1997, and weakest in 1999. Stratification in the three years influences the magnitude and extent of computed anoxia. (Anoxia is defined here as dissolved oxygen (DO) concentration < 1 g m^{-3}.) DO concentration during the summer months of 1996 is lower, for a longer period, than in 1997 or 1999 (Figures 6-2 to 6-5). Computed anoxic volume days (AVD) also follow the sequence from greatest volume in 1996 to least volume in 1999 (Figure 6-6).

Phytoplankton are quantified in the model as carbonaceous biomass. Their computed concentration is reported both as carbon and as chlorophyll, however, since phytoplankton observations are usually reported as chlorophyll concentration. The saline portions of Chesapeake Bay are subject to no chlorophyll standard. Phytoplankton are a crucial influence, however, on whether bay waters meet DO and water clarity standards. Oxygen consumption associated with the decay of organic carbon fixed by phytoplankton is the primary mechanism for the occurrence of bottom-water hypoxia. Light attenuated by the chlorophyll pigment and by particulate organic matter contributes to poor water clarity.

Phytoplankton in the saline portions of Chesapeake Bay exhibit two recurrent annual phenomena. The first is the spring diatom bloom which occurs roughly from January through May. The bloom is characterized by high chlorophyll concentration but low primary productivity. The second phenomenon is the period of maximum productivity which takes place in summer. Although the warmer months are more productive than spring, the chlorophyll concentration may be lower than during the diatom bloom. The two phytoplankton intervals overlap with the submerged aquatic vegetation (SAV) growing season which is considered to be April – October for the species which occupy the upper bay. This is also the period for application of water clarity standards (Tango and Batiuk, 2013). Due to the variability in chlorophyll through the growing season, time series plots (e.g. Figure 6-7) are difficult to interpret with regard to the role of phytoplankton in light attenuation during the critical period. For this purpose, spatial plots of surface chlorophyll, averaged over the growing season are superior (Figures 6-8 to 6-10).

Light attenuation by colored dissolved organic matter, chlorophyll pigment, fixed (mineral) solids, and volatile (organic) solids all contribute to the total attenuation coefficient in Chesapeake Bay. The relative contribution of individual substances varies with location and season throughout the bay (Cerco et al., 2013). Several useful guidelines can be discerned, however. The first is that fixed solids (FSS) originate primarily in the watershed or from shoreline erosion. The major source of volatile solids (VSS), however, is primary production in the water column rather than external loading. The fraction of fixed solids in the total solids concentration illustrates the role of external loading in light attenuation. As noted, the fraction varies spatially and temporally but it can be less than half of the total solids concentration in portions of the upper bay (Figure 6-11). The period of greatest light attenuation in the upper bay coincides with the period of greatest runoff, usually winter and spring (Figure 6-12). When averaged over the growing season, the region of greatest light extinction extends from nearly the head of the bay down to the Patapsco River (Figures 6-13 to 6-15). This region encompasses the turbidity maximum in which suspended particles are concentrated by estuarine circulation (Schubel, 1968) as well as the region of highest chlorophyll concentration in the mainstem portion of the bay (Figures 6-8 to 6-10).

The Effect of Storm Scour

The Relative Role of Net Scour Loads

Scour in Conowingo Reservoir for the January 1996 storm was computed as described in Chapter 4. Summarizing material presented in that chapter results in the comparison of loads at the Conowingo outfall presented in Table 6-1. The table shows TMDL watershed loads, summed over the interval of peak storm flows, total net scour loads, and total TMDL watershed loads for the winter and spring months. The watershed loads are computed by the WSM and do not include significant scour. The net scour loads are the predominant source of solids and nutrients during the storm interval. For solids and phosphorus, the scour loads are the predominant source over the entire winter-spring period. The relative importance of the scour loads is magnified, in this instance, by comparison to the TMDL watershed loads. These loads are considerably less than estimated 2010 loads (Table 4-1) or loads which occurred in 1996. The relative importance of the nutrient loads is also magnified through use of the 2011 particle composition for this scenario (Table 4-3) rather than 1996 composition (Table 4-4).

The predominant role of net scour loads, reported here, is in contrast to the companion reports to this one (Scott and Sharp, 2013; Langland, 2013) in which scour is assigned a lesser fraction of the total storm loads. Scott and Sharp, for example, report the scoured sediment load is ≈ 20% of the total sediment load computed for Tropical Storm Lee. The relative magnitude of the scour load depends on multiple factors including:

- The nature of the storm event,
- How the scour load is determined,
- Where the watershed loads are specified, and
- How the watershed loads are determined.

We must recognize that the 1996 and 2011 storm events were fundamentally different. Tropical Storm Lee was a tropical storm event which passed over the lower portion of the Susquehanna Watershed. This portion of the entire watershed contains several sub-watersheds which produce notably high sediment loads. The 1996 flood was generated, in part, by snowmelt which is relatively "clean" with regard to sediment content. Therefore, we expect the ratio of watershed load to scour load to differ for these two events.

One method to quantify scour is by comparison of bathymetry measurements obtained before and after the event. This was the method used in one of the earliest studies of scour in Conowingo Reservoir (Langland and Hainly, 1997) and resulted in an estimate in which scour was the predominant source of solids loading during the January 1996 event. An alternate methodology compares loads entering and leaving the system. An excess of loads leaving over loads entering implies the occurrence of net scour. The loads may be obtained from a statistical model based on observations (Hirsch, 2012) or from a mechanistic model such as ADH.

The watershed loads can be specified at the head of the reservoir system, at the entry to Conowingo Reservoir, or at the Conowingo outfall. Conditions at the entry to Conowingo are not monitored. Consequently, calculations which employ observed loads entering the system are based on observations at Marietta, the head of the reservoir system, and the differencing process incorporates all three reservoirs. For the ADH estimates, watershed loads are taken at the Conowingo entrance. The estimates in this report use watershed loads at the Conowingo outfall.

Watershed loads cannot be perfectly observed. They require calculation based on interpolation of observations (Cohn et al., 1989; Hirsch, 2012) or come from a mechanistic model calibrated to observations. For ADH, the watershed loads entering Conowingo are obtained from the HEC-RAS application to the three-reservoir system (Langland, 2013). For the CBEMP application, watershed loads are from the CBP WSM.

Clearly, the relative magnitude of scour loads compared to watershed loads is variable and subject to uncertainity. Estimates will vary depending on characteristics of the storm event and on the methodology employed in deriving the comparison. While the relative magnitude of scour is uncertain, the absolute net scour loads reported here are consistent with the companion reports and with the latest estimates. Scott and Sharp (2013) report net solids scour for Tropical Storm Lee as 3.0×10^6 English tons and Langland (2013) reports net solids scour for the January 1996 event as 4.0×10^6 English tons. Both reports are consistent with the load of 2.37×10^6 tons reported here for January 1996 (Table 6-1).

The Effect of Scour Computed for January 1996

The scour loads produce a tremendous increase in computed light attenuation during the January storm (Figure 6-16). During the 1996 SAV growing season (Figure 6-17) and in later years, however, the change in light attenuation resulting from storm scour is negligible. The median increase in growing-season attenuation in any year is less than 0.01 m^{-1}, compared to median base light attenuation ≈ 0.8 m^{-1}. By the time growing season arrives, most of the solids associated with the storm have settled out. There are a few CBPS, notably NORTF and BACOH, where an increase in TSS of 0.4 to 0.6 g m^{-3} persists into the 1996 growing season (Figure 6-18). For most segments, however, the computed increase in growing-season TSS is less than 0.1 g m^{-3}. The origin of the increase varies. In the upper bay, the increase in TSS is largely in the fixed fraction (Figure 6-18) indicating solids remaining in suspension following the scour event. Further down the bay, the increase in FSS is a small fraction of the increase in TSS indicating an indirect mechanism where scoured nutrients stimulate phytoplankton, which produce organic matter which attenuates light.

Computed surface chlorophyll decreases during the scour event (Figure 6-19), most likely due to increased light attenuation from scoured solids. Computed chlorophyll increases, however, in the first growing season following the event. The extent of the increase is widespread with an average increase of 0.1 to 0.3 mg m^{-3} extending into the lower Potomac River and below the mouth of the Potomac in the mainstem bay (Figure 6-20). The increase in chlorophyll persists into subsequent years although the magnitude of the increase diminishes with time. The pathway for nutrients scoured in winter to stimulate phytoplankton in summer leads through bottom sediments. Particulate nutrients associated with scoured solids settle to the bottom. During the warmer months, diagenesis in the bottom sediments releases the nutrients to the water column (Figure 6-21, 6-22) where they stimulate phytoplankton production. Over time, processes including burial and washout remove the sediment nutrients from the active surface sediment layer and the stimulus provided by additional sediment nutrient release diminishes.

Bottom DO declines by up to 0.2 g m^{-3} as a result of the storm scour (6-23). The mechanism is the classic eutrophication mechanism in Chesapeake Bay. The additional nutrients, made available via sediment diagenesis, stimulate algal production. Organic matter produced by phytoplankton settles to the bottom waters and sediments of the bay and consumes oxygen as it decays. The effect on DO diminishes with time, similar to chlorophyll and sediment nutrient release. The time series and seasonal-average plots (Figures 6-24, 6-25) indicate, however, that the decrease of DO in 1997 exceeds the decrease in 1996. This phenomenon is an artifact of the different base DO concentrations in the two years (e.g. Figure 6-2). The generally higher bottom DO concentrations which prevail in the 1997 base case can fall farther than the bottom DO concentrations in the 1996 base case. In most segments, the anoxic volume in 1996, immediately following the scour event, is greater than in 1997 (Figure 6-26). The anoxic volume indicates an increase in anoxia throughout the water column that is not illustrated in plots of bottom DO.

Storm Seasonal Effects

Runoff events with flows sufficient to scour reservoir sediments occur at various times of the year. Floods occur in the Susquehanna River in late winter and early spring due to precipitation and snowmelt. Tropical storm events are most common during late summer and early fall although the notorious Tropical Storm Agnes occurred in June 1972 (CRC, 1976). The effect of the storm-generated loads, from the watershed and from reservoir scour, will vary depending on the period of storm occurrence. To investigate the effect of storm season, scenarios were completed with the January 1996 Susquehanna storm flows and loads moved to June and October 1996. These were compared to a base scenario with the storm removed. For this base case, the storm was removed completely, both watershed load and storm scour. The scenarios with the storm included both watershed loads and scour. Revised hydrodynamics were completed for the three new scenarios (June Storm, October storm, no storm) to capture the effects of circulation and stratification as well as loading. As with the previous scenarios, results are presented in the form of difference plots which highlight the influence of scenario conditions. Time series plots are presented here for Station CB3.3C. This station is located at the head of the deep trench which forms the natural channel in the upper bay and, consequently, this station is among those with the lowest ambient bottom-water DO concentration. CB3.3C also ranks among the main-channel stations with the greatest summer surface chlorophyll concentration and the highest light attenuation.

Light Attenuation

All three storm events, January, June and October, demonstrate an enormous, immediate response in light attenuation due to solids loads (Figure 6-27). The January response is shortest-lived. In this instance, the high flows which prevail even with the storm removed flush solids downstream and out of the system. The influence of the solids load on attenuation persists for ≈ 90 days for the June and October storms. For both the January and October storms, the fixed solids are virtually gone prior to the subsequent SAV growing season. The increase in light attenuation is primarily due to stimulation of primary production by storm-generated nutrient loads. The June storm occurs during the SAV growing season and the light-attenuating effects of fixed solids loads are incorporated into the seasonal-average light attenuation computation (Figure 6-28). The seasonal-average results indicate the spatial extent of increased attenuation is greater for the June storm than for the January or October storm.

Chlorophyll

Computed surface chlorophyll concentration decreases immediately as the storm flows pass (Figure 6-29). Nutrients introduced by the storm stimulate chlorophyll production in each subsequent SAV growing season. The resulting chlorophyll concentration is highest for the June storm and least for the October storm (Figure 6-29). The region of increased chlorophyll concentration is also most extensive for the June storm (Figure 6-30). This effect is promoted by the introduction of nutrients at the beginning of the season of maximum production. For the January storm, roughly five months pass between the loading and the summer production season. For the October storm, eight months pass, allowing time for the added nutrients to be flushed from the system or buried to deep, inactive bottom sediments.

Dissolved Oxygen

As with chlorophyll, the initial effect of the storm on DO is a decrease as the storm passes (Figure 6-31). For the January and October storms, DO rebounds, then decreases due to oxygen demand associated with additional production and decay of organic matter stimulated by storm-generated nutrient loads. For the June storm, the decrease associated with storm flow nearly connects to the decrease caused by respiration. As a result, the decrease during the summer following the storm is of larger magnitude than for a January or October storm. The spatial plots (Figure 6-32) indicate the effect of the June storm on bottom DO is much more extensive than for the alternate storms. In particular, DO depletion moves up the flanks of the deep trench into water which is usually well aerated. In the shallow shoals, computed DO actually increases due to oxygen production which accompanies the enhanced algal primary production.

Equilibrium Bathymetry

Conowingo bathymetry for most scenarios was based on surveys conducted in 2008. Several scenarios were completed with alternate representations of Conowingo Reservoir. One was the “Reservoir Full” or “Equlibrium Bathymetry” scenario. This scenario employs bathymetry estimated to prevail when the reservoir achieves long-term equilibrium between sediment loads in and sediment loads out. Note that this condition does not imply that loads in and out are always equal. Rather, the reservoir will be in a depositional state punctuated by frequent scour events such that loads in equal loads out when averaged over time scales of a few years or less. The equilibrium bathymetry was based on the estimated configuration after the reservoir achieves long-term equilibrium between solids inflows and outflows.

Figure 6-33 shows the difference between solids loads into Conowingo and solids loads out of Conowingo for 2008 – 2011 with equilibrium bathymetry. The loads are from the ADH model and were provided for use in the CBEMP. The condition when loads in exceed loads out indicates deposition; the condition when loads out exceed loads in indicates erosion. Despite the equilibrium state, deposition is computed up to the March 2011 erosion event and resumes until the Tropical Storm Lee event. Computation of deposition is consistent with the analytical model of Chapter 2 in which deposition is independent of depth, as long as the threshold for erosion is not exceeded. As noted in Table 4-5, the erosion computed for the equilibrium bathymetry is virtually identical to the erosion computed for the existing bathymetry. Effectively, the reservoir had achieved equilibrium by the 2008 – 2011 period.

Owing to the nearly identical loads, the scenario results for the equilibrium bathymetry are virtually identical to the results for the base scenario with scouring (Figures 6-34 – 6-36).

The “No Conowingo” Scenario

A scenario was run with Conowingo Reservoir removed from the system. This was accomplished by routing directly to the bay the calculated WSM loads into Conowingo Reservoir. This routing eliminated settling and other processes computed by the WSM in the reservoir. This run has multiple interpretations. The initial intent was to simulate a reservoir-full condition. In this interpretation, loads to the reservoir would pass directly through in the absence of deposition. This interpretation was superseded by a revised conceptual model in which settling occurs even under reservoir-full conditions. In the revised conceptual model, the reservoir-full or equilibrium condition implies the occurrence of frequent scour events that remove deposited material so that there is no net accumulation of solids in the reservoir. The scenario retains value, however. The difference between the “No Conowingo” scenario and the TMDL scenario shows the effect of computed processes in the reservoir on the calculated TMDL conditions. The difference between the two scenarios may also be interpreted as a quantification of the effect of Conowingo Dam on Chesapeake Bay water quality when the reservoir is in a depositional state.

The difference plots are interpreted so that a difference greater than zero indicates concentrations are higher with the reservoir than without the reservoir. A difference less than zero indicates that concentrations are lower with the reservoir than without the reservoir. This interpretation is readily viewed in a time series plot of TSS at Station CB3.3C (Figure 6-37). Computed solids concentrations in the bay are lower with the reservoir in place than without the reservoir. Lower concentrations of suspended solids result in reduced light attenuation. Benefits of 0.1 to 0.2 m^{-1} are evident at Station CB3.3C (Figure 6-38). The maximum benefit is in winter and spring, however, during periods of peak solids loading. During the SAV growing season, reductions in attenuation due to solids and nutrient retention in the reservoir are lower, ≈ 0.025 m^{-1} (Figure 6-39).

Reservoir processes result in both higher and lower computed chlorophyll concentrations in the bay, depending on season. During winter to spring, higher concentrations are computed (Figure 6-40). Apparently, solids retention leads to lower light attenuation which leads to a larger spring algal bloom. During summer, however, computed chlorophyll concentrations are lower with the reservoir in place. For this season, nutrient retention in the reservoir contributes to nutrient limitation of algal production and biomass. The influence on chlorophyll of nutrient retention in the reservoir can be seen throughout the bay (Figure 6-41).

As a result of nutrient retention and algal limitation, computed bottom DO concentrations are uniformly higher with the reservoir than without (Figure 6-42). Peak benefits of 0.1 to 0.2 g m^{-3} are evident at CB3.3C. The benefits are spatially extensive, corresponding to the expansive chlorophyll benefits although the magnitude of the DO benefit, when averaged over the summer months, is less than the peak computations (Figure 6-43).

Sediment Management – Dredging 3 Million Cubic Yards

Several scenarios were conducted to examine sediment management actions. The first was an examination of one-time removal of 3 million cubic yards (mcy, equivalent to 2.3×10^6 m^3) of material from Conowingo Reservoir. This scenario was compared to the TMDL scenario with 2008 bathymetry. The sole difference in loading between the two conditions was during the January 1996 scour event. Computed scouring of solids and nutrients was reduced by 32% as a result of the dredging (Table 4-5).

The dredging has little effect on computed conditions in the bay. Computed surface chlorophyll increases immediately following the scour event (Figure 6-44) as a result of reduced solids loading and reduced light attenuation (Figure 6-45). In the first summer following the storm event, surface chlorophyll is reduced a maximum of 0.1 mg m^{-3} (Figure 6-44, 6-46) with the effect diminishing over time. The influence of the dredging on computed light attenuation during the SAV growing season is negligible (Figure 6-47). Changes in CHL and KE were tabulated by CBPS for the first SAV growing season following the storm (Tables 6-2, 6-3). For both variables, the change induced by the dredging is much less than 1%.

Bottom DO improves by 0.01 to 0.04 g m^{-3} (Figure 6-48). The improvement is perhaps better in summer 1997 than summer 1996. Averaged over the summer season, however, the improvement is roughly 0.02 g m^{-3} and of limited spatial extent (Figure 6-49). The improvement was quantified using the AVD statistic (Table 6-4). The reduction in anoxia in the summer following the storm event ranged from effectively zero to 12% in various CBPS. Overall reduction in AVD was 1.7%.

Sediment Management – Dredging Back to 1996 Bathymetry

The ADH run with 1996 bathymetry was originally completed to examine the effects of a major scour event on subsequent scour events. (The 1996 bathymetry survey was completed after the January scour event.) The scour computed with this bathymetry can also be viewed as the scour that would take place if 28 mcy, relative to the 2008 bathymetry, were removed from the reservoir by dredging. This scour load (Table 4-5) can be combined with appropriate watershed loads to produce a scenario with TMDL loading and 28 mcy dredging, relative to 2008 bathymetry. To examine limiting cases, this scenario is compared to the scenario with TMDL loads and equilibrium bathymetry as the base. Computed scouring of solids and nutrients is reduced by 45% by dredging back to 1996 bathymetry compared to the equilibrium bathymetry.

The nature of the response to removal of 28 mcy is similar to the response to the removal of 3 mcy although the magnitude of the effects is greater, especially for CHL and DO. There is, again, an initial increase in computed surface chlorophyll (Figure 6-50), prompted by a reduction in solids load and an improvement in computed water clarity (Figure 6-51). By summer, the improvement in water clarity is nearly indistinguishable (Figure 6-52) as the storm-generated solids settle out of the water column. Surface chlorophyll concentration is reduced by peak values of 0.1 to 0.2 mg m^{-3} during the SAV growing season due to reduction in nutrient loads that accompany scour (Figure 6-50). Averaged over the 1996 growing season, the improvements in CHL are roughly 0.05 mg m^{-3} (Figure 6-53, Table 6-5). Improvements in seasonal-average surface chlorophyll approach 1% in some CBPS while improvements in KE are limited to less than 0.5% (Table 6-6).

During the summer months, the instantaneous improvement in calculated bottom DO is nearly double the improvement from dredging 3 mcy (Figure 6-54). Instantaneous improvements of 0.05 g m^{-3} are calculated for several years following the scour event and extend along the upper bay and into the lower Potomac River (Figure 6-55). Quantified as AVD, anoxia is reduced by up to 15% in some CBPS and by 2.8% overall.

Sediment Management – Sediment Bypassing

Material dredged from the reservoir has to be placed elsewhere. One option is to "bypass" the sediment. That is, pass the material over or around the Conowingo dam and into the bay during a period when biological activity is minimal. The potential for this disposal method was examined in a scenario in which 3 mcy of sediment was bypassed during the months of December – February of each scenario year. This scenario was compared to a base condition of TMDL loads with 3 mcy removed from the reservoir. Although the bypassing was simulated for ten years, the results are shown for five years, 1996 – 2000, for consistency with previous results.

As expected, sediment bypassing results in increased suspended solids computed in the bay during the bypass period. At Station CB3.3C, the increase is usually 1 to 2 g m^{-3} (Figure 6-56). As demonstrated in the scour scenarios, the bypassed solids settle quickly after the source is eliminated. A secondary solids increase occurs during the summer when nutrients that accompany the bypassed sediments stimulate the production of algae and associated organic matter. The net effect on light attenuation during the SAV growing season is small, however. The greatest increase in any CBPS (CB2OH) averages ≈ 0.1 m^{-1} and the typical increase is ≈ 0.025 m^{-1} (Figure 6-57).

As a result of the continuous discharge of nutrients associated with the bypassed sediments, computed increases in surface chlorophyll are extensive (Figure 6-58) and cover most of the bay as well as the lower portions of several tributaries. Averaged over the growing season, increases in surface chlorophyll of 1 mg m^{-3} are computed in multiple CBPS and increases of ≈ 0.5 mg m^{-3} occur in most segments. The enhanced algal production increases computed bottom DO in some shoal areas but the overwhelming effect is diminished DO. The resulting decrease of DO is extensive and of greater magnitude than seen as a result of scour events (Figure 6-59). Decreases of 0.2 to 0.3 g m^{-3} in summer average DO are widespread and an overall increase of 30% is computed for AVD (Table 6-8).

A Caveat

The scenarios reported above use TMDL watershed loads and examine results computed in the bay under TMDL conditions. Conclusions regarding the impact of reservoir scour and of mitigation efforts on Bay water quality standards should not be drawn from this chapter, however. The primary years for development of the TMDL were 1993 – 1995, years not impacted by storm scour and not reported here. In addition, the CBP conducts a detailed procedure to relate computed conditions to observations (Keisman and Shenk, 2013). The CBP has a series of "stop-light" plots which illustrate the effect of various scenarios on standards. The sole authority on the Bay water quality standards is the EPA Chesapeake Bay program.

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Table 6-1 Computed TMDL Loads at the Conowingo Outfall

	Flow, m^3	Total Nitrogen, kg	Organic Nitrogen, kg	Total Phosphorus, kg	Particulate Phosphorus, kg	Total suspended Solids, kg
Watershed Jan 19 - 25, 1996	64,822	5,899,740	2,483,400	516,081	344,739	404,862,000
January 1996 Scour			7,116,000		2,372,000	2,372,050,000
Watershed Jan - May, 1996	362,934	32,756,318	14,235,853	1,742,474	1,357,043	990,407,321

Table 6-2 Calculated Surface Chlorophyll ($mg\ m^{-3}$) for 1996 SAV Growing Season With and Without Dredging 3 mcy

Region	Dredge 3 mcy	2008 Bathymetry	Change	Percent Change
NORTF	5.68	5.69	-0.007	-0.12
CB1TF	3.56	3.56	-0.002	-0.06
BSHOH	5.06	5.06	-0.003	-0.06
GUNOH	2.54	2.55	-0.003	-0.12
CB2OH	6.28	6.30	-0.018	-0.29
MIDOH	2.72	2.73	-0.005	-0.18
BACOH	6.82	6.82	0.001	0.01
PATMH	11.78	11.82	-0.037	-0.31
CB3MH	9.57	9.61	-0.041	-0.43
MAGMH	5.80	5.84	-0.044	-0.75
SEVMH	4.98	5.01	-0.024	-0.48
SOUMH	6.02	6.06	-0.041	-0.68
RHDMH	6.10	6.14	-0.04	-0.65
WSTMH	2.53	2.55	-0.018	-0.71
CB4MH	8.95	9.00	-0.052	-0.58
PAXMH	6.18	6.20	-0.021	-0.34
POTMH	9.11	9.12	-0.018	-0.20
CB5MH	7.64	7.67	-0.034	-0.44
LCHMH	2.43	2.45	-0.019	-0.78
CHOMH1	3.84	3.86	-0.019	-0.49
CHOMH2	8.41	8.43	-0.018	-0.21
EASMH	3.46	3.49	-0.027	-0.77
CHSMH	7.02	7.05	-0.034	-0.48
SASOH	6.60	6.61	-0.015	-0.23
BOHOH	4.18	4.19	-0.008	-0.19
ELKOH	4.10	4.10	-0.007	-0.17

Table 6-3 Calculated Light Attenuation (m^{-1}) for 1996 SAV Growing Season With and Without Dredging 3 mcy

Region	Dredge 3 mcy	2008 Bathymetry	Change	Percent Change
NORTF	1.94	1.95	-0.006	-0.31
CB1TF	1.46	1.46	0	0.00
BSHOH	1.03	1.03	-0.001	-0.10
GUNOH	0.96	0.96	-0.002	-0.21
CB2OH	1.42	1.42	-0.001	-0.07
MIDOH	1.23	1.23	-0.002	-0.16
BACOH	3.12	3.13	-0.01	-0.32
PATMH	1.60	1.61	-0.004	-0.25
CB3MH	1.02	1.02	-0.003	-0.29
MAGMH	1.41	1.41	-0.002	-0.14
SEVMH	0.99	0.99	0	0.00
SOUMH	0.94	0.94	-0.002	-0.21
RHDMH	0.80	0.80	-0.002	-0.25
WSTMH	0.44	0.44	-0.001	-0.23
CB4MH	0.75	0.76	-0.002	-0.26
PAXMH	0.65	0.65	-0.001	-0.15
POTMH	0.72	0.72	0	0.00
CB5MH	0.55	0.55	-0.001	-0.18
LCHMH	0.58	0.58	0	0.00
CHOMH1	0.58	0.58	-0.001	-0.17
CHOMH2	0.80	0.80	0	0.00
EASMH	0.52	0.52	-0.001	-0.19
CHSMH	0.70	0.70	-0.001	-0.14
SASOH	1.37	1.37	-0.001	-0.07
BOHOH	1.13	1.13	-0.002	-0.18
ELKOH	0.97	0.97	0	0.00

Table 6-4 Calculated Anoxic Volume Days (10^6 m^3 d) for June - August 1996 With and Without Dredging 3 mcy

Region	Depth	Dredge 3 mcy	2008 Bathymetry	Change	Percent Change
PATMH	6.7 < d < 12.8	8724	8788	-64	-0.73
PAXMH	6.7 < d < 12.8	128	135	-8	-5.54
PAXMH	12.8 < d	32	34	-2	-5.06
POTMH	6.7 < d < 12.8	2229	2388	-159	-6.64
POTMH	12.8 < d	1469	1531	-62	-4.03
CB5MH	6.7 < d < 12.8	11627	12117	-490	-4.04
CB5MH	12.8 < d	12352	12691	-339	-2.67
CB4MH	6.7 < d < 12.8	22582	23281	-699	-3.00
CB4MH	12.8 < d	88097	89423	-1326	-1.48
LCHMH	6.7 < d < 12.8	2111	2113	-2	-0.10
CB3MH	6.7 < d < 12.8	12095	12317	-222	-1.80
CB3MH	12.8 < d	10211	10279	-69	-0.67
CB2OH	6.7 < d < 12.8	38	43	-6	-12.67
CHOMH1	6.7 < d < 12.8	936	938	-2	-0.21
CHOMH1	12.8 < d	684	688	-4	-0.60
CHOMH2	6.7 < d < 12.8	3729	3771	-42	-1.10
EASMH	6.7 < d < 12.8	14359	14512	-153	-1.05
EASMH	12.8 < d	8063	8099	-35	-0.44
CHSMH	6.7 < d < 12.8	10129	10211	-82	-0.80
CHSMH	12.8 < d	3382	3384	-2	-0.06
ELKOH	6.7 < d < 12.8	91	93	-2	-2.47
TOTAL	12.8 < d	213068	216836	-3767	-1.74

Table 6-5. Calculated Surface Chlorophyll (mg m-3) for 1996 SAV Growing Season With Dredging Back to 1996 Bathymetry

Region	Dredge Back to 1996	Equilibrium Bathymetry	Change	Percent Change
NORTF	5.67	5.67	0	0.00
CB1TF	3.56	3.56	-0.003	-0.08
BSHOH	5.06	5.06	-0.004	-0.08
GUNOH	2.54	2.55	-0.005	-0.20
CB2OH	6.27	6.30	-0.029	-0.46
MIDOH	2.72	2.73	-0.007	-0.26
BACOH	6.81	6.82	-0.002	-0.03
PATMH	11.76	11.82	-0.061	-0.52
CB3MH	9.54	9.60	-0.067	-0.70
MAGMH	5.77	5.83	-0.069	-1.18
SEVMH	4.97	5.00	-0.038	-0.76
SOUMH	6.00	6.06	-0.063	-1.04
RHDMH	6.08	6.14	-0.064	-1.04
WSTMH	2.52	2.55	-0.029	-1.14
CB4MH	8.91	9.00	-0.084	-0.93
PAXMH	6.16	6.20	-0.032	-0.52
POTMH	9.09	9.12	-0.028	-0.31
CB5MH	7.62	7.67	-0.053	-0.69
LCHMH	2.42	2.45	-0.029	-1.19
CHOMH1	3.82	3.85	-0.03	-0.78
CHOMH2	8.39	8.42	-0.028	-0.33
EASMH	3.44	3.48	-0.044	-1.26
CHSMH	6.99	7.05	-0.056	-0.79
SASOH	6.59	6.61	-0.023	-0.35
BOHOH	4.18	4.19	-0.012	-0.29
ELKOH	4.09	4.11	-0.014	-0.34

Table 6-6 Calculated Light Attenuation (m^{-1}) for 1996 SAV Growing Season With Dredging Back to 1996 Bathymetry

Region	Dredge Back to 1996	Equilibrium Bathymetry	Change	Percent Change
NORTF	1.94	1.94	-0.004	-0.21
CB1TF	1.46	1.46	0	0.00
BSHOH	1.03	1.03	-0.002	-0.19
GUNOH	0.96	0.96	-0.004	-0.42
CB2OH	1.42	1.42	-0.003	-0.21
MIDOH	1.23	1.23	0	0.00
BACOH	3.13	3.13	-0.004	-0.13
PATMH	1.60	1.61	-0.004	-0.25
CB3MH	1.02	1.02	-0.003	-0.29
MAGMH	1.41	1.41	-0.002	-0.14
SEVMH	0.99	0.99	-0.001	-0.10
SOUMH	0.94	0.94	-0.003	-0.32
RHDMH	0.80	0.80	-0.002	-0.25
WSTMH	0.44	0.44	-0.001	-0.23
CB4MH	0.75	0.76	-0.003	-0.40
PAXMH	0.65	0.65	-0.001	-0.15
POTMH	0.72	0.72	0	0.00
CB5MH	0.55	0.55	-0.002	-0.36
LCHMH	0.58	0.58	0	0.00
CHOMH1	0.58	0.58	0	0.00
CHOMH2	0.80	0.80	-0.001	-0.12
EASMH	0.52	0.52	-0.001	-0.19
CHSMH	0.70	0.70	-0.002	-0.28
SASOH	1.37	1.37	-0.002	-0.15
BOHOH	1.13	1.13	-0.002	-0.18
ELKOH	0.98	0.98	-0.001	-0.10

Table 6-7 Calculated Anoxic Volume Days (10^6 m^3 d) for June - August 1996 With Dredging Back to 1996 Bathymetry

Region	Depth	Dredge Back to 1996	Equilibrium Bathymetry	Change	Percent Change
PATMH	6.7 < d < 12.8	8684	8789	-105	-1.20
PAXMH	6.7 < d < 12.8	126	135	-10	-7.09
PAXMH	12.8 < d	29	34	-5	-14.88
POTMH	6.7 < d < 12.8	2142	2386	-244	-10.22
POTMH	12.8 < d	1427	1531	-104	-6.80
CB5MH	6.7 < d < 12.8	11313	12107	-794	-6.56
CB5MH	12.8 < d	12145	12683	-538	-4.24
CB4MH	6.7 < d < 12.8	22216	23270	-1054	-4.53
CB4MH	12.8 < d	87208	89407	-2199	-2.46
LCHMH	6.7 < d < 12.8	2107	2113	-6	-0.30
CB3MH	6.7 < d < 12.8	11956	12314	-358	-2.90
CB3MH	12.8 < d	10172	10279	-107	-1.04
CB2OH	6.7 < d < 12.8	37	43	-6	-14.52
CHOMH1	6.7 < d < 12.8	934	938	-4	-0.43
CHOMH1	12.8 < d	680	688	-8	-1.19
CHOMH2	6.7 < d < 12.8	3703	3767	-64	-1.70
EASMH	6.7 < d < 12.8	14248	14508	-260	-1.79
EASMH	12.8 < d	8028	8099	-71	-0.87
CHSMH	6.7 < d < 12.8	10079	10213	-134	-1.32
CHSMH	12.8 < d	3370	3384	-14	-0.41
ELKOH	6.7 < d < 12.8	90	93	-3	-3.12
TOTAL	12.8 < d	210691	216780	-6089	-2.81

Table 6-8 Calculated Anoxic Volume Days (10^6 m^3 d) for June - August 1996 With and Without Sediment Bypassing

Region	Depth	With Bypassing	Without Bypassing	Change	Percent Change
PATMH	6.7 < d < 12.8	10600	8724	1875	21.5
PAXMH	6.7 < d < 12.8	232	128	104	81.1
PAXMH	12.8 < d	78	32	46	143.9
POTMH	6.7 < d < 12.8	5365	2229	3137	140.7
POTMH	12.8 < d	2824	1469	1355	92.2
CB5MH	6.7 < d < 12.8	18941	11627	7314	62.9
CB5MH	12.8 < d	18334	12352	5982	48.4
CB4MH	6.7 < d < 12.8	33690	22582	11108	49.2
CB4MH	12.8 < d	109774	88097	21677	24.6
LCHMH	6.7 < d < 12.8	2288	2111	177	8.4
CB3MH	6.7 < d < 12.8	16021	12095	3926	32.5
CB3MH	12.8 < d	11717	10211	1506	14.7
CB2OH	6.7 < d < 12.8	132	38	94	248.3
CHOMH1	6.7 < d < 12.8	1070	936	133	14.2
CHOMH1	12.8 < d	765	684	81	11.9
CHOMH2	6.7 < d < 12.8	4664	3729	935	25.1
EASMH	6.7 < d < 12.8	16741	14359	2382	16.6
EASMH	12.8 < d	8849	8063	786	9.7
CHSMH	6.7 < d < 12.8	11748	10129	1619	16.0
CHSMH	12.8 < d	3766	3382	384	11.3
ELKOH	6.7 < d < 12.8	212	91	121	133.3
TOTAL	12.8 < d	277810	213068	64741	30.4

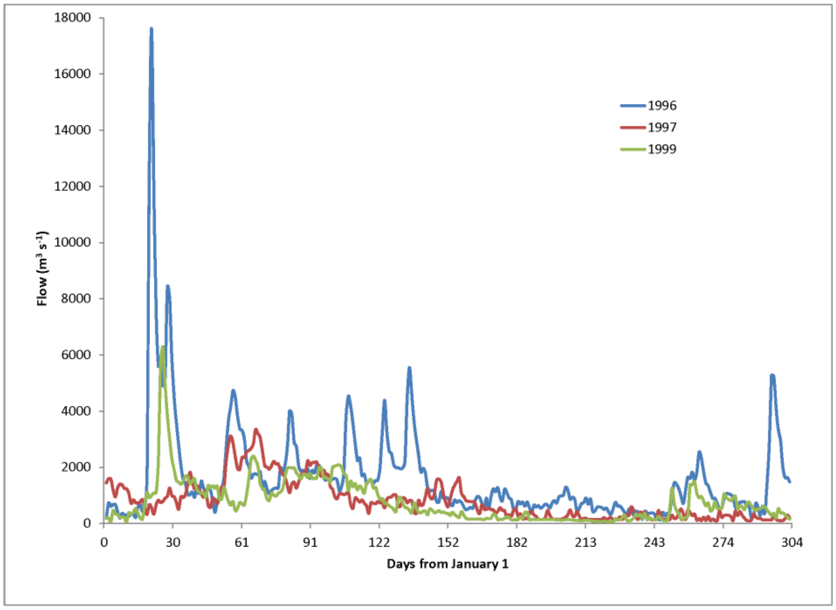

Figure 6-1. Gauged flow at the Conowingo outfall for the months January – October 1996, 1997, 1999.

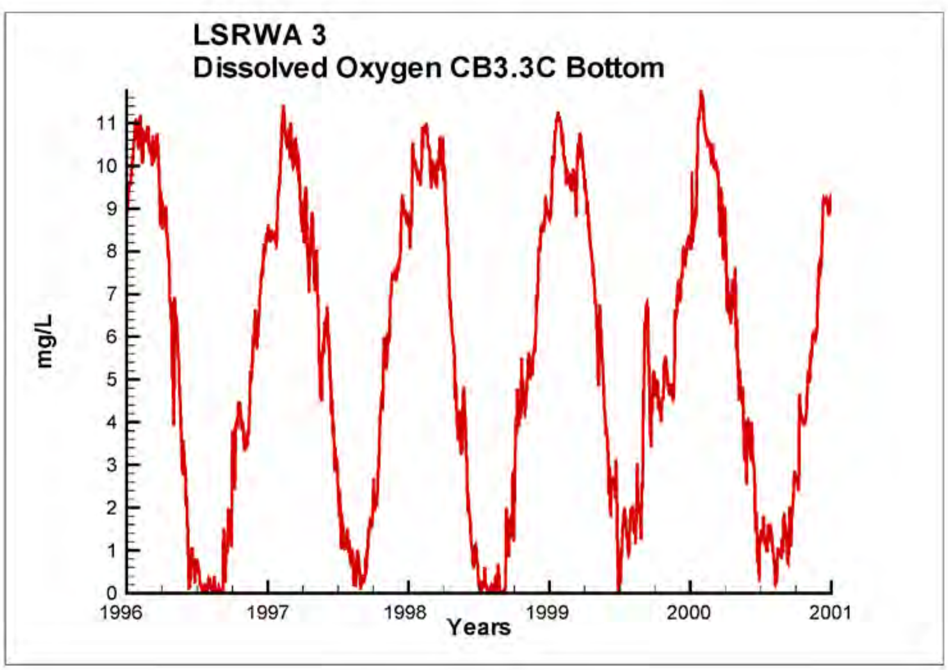

Figure 6-2. Computed DO concentration for the base scenario at the bottom of Station CB3.3C (Figure 5-1), located at the head of the deep trench where hypoxia is most intense.

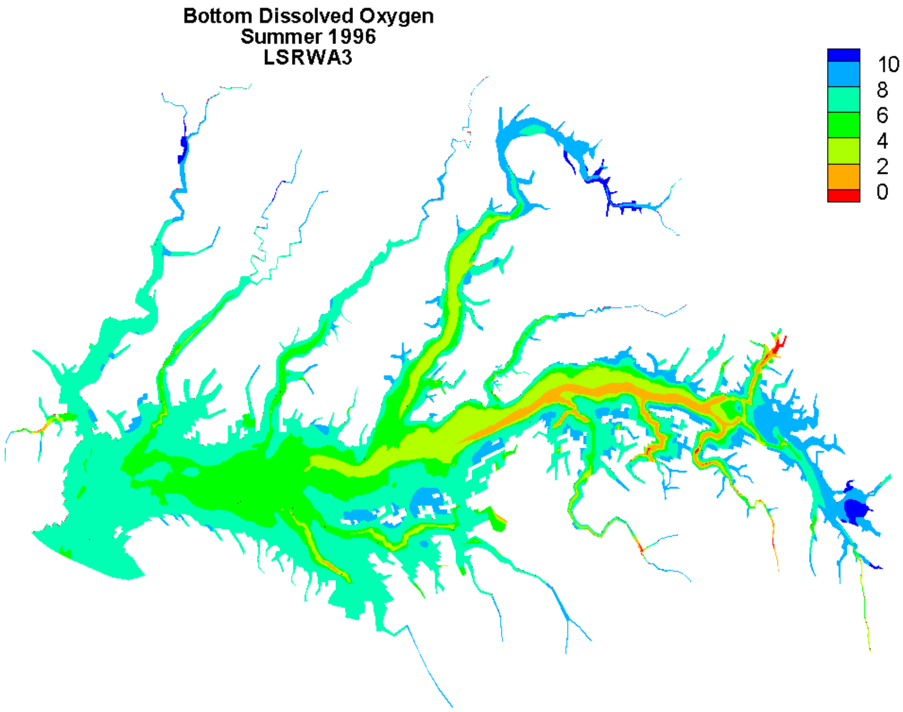

Figure 6-3. Computed bottom DO concentration (g m^{-3} or mg/L) for the base scenario, averaged over June – August 1996.

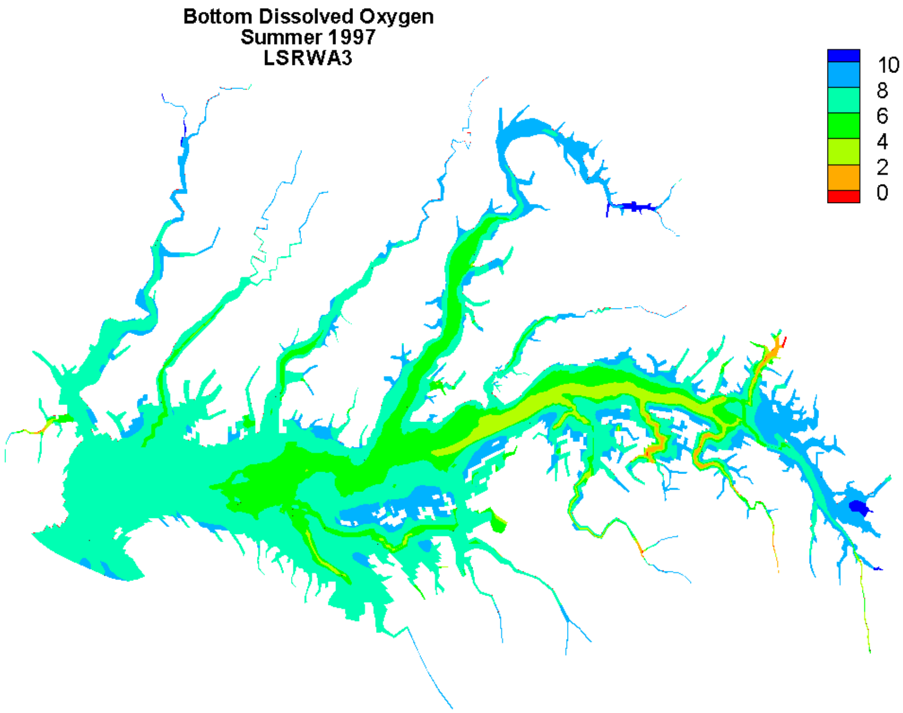

Figure 6-4. Computed bottom DO concentration (g m^{-3} or mg/L) for the base scenario, averaged over June – August 1997.

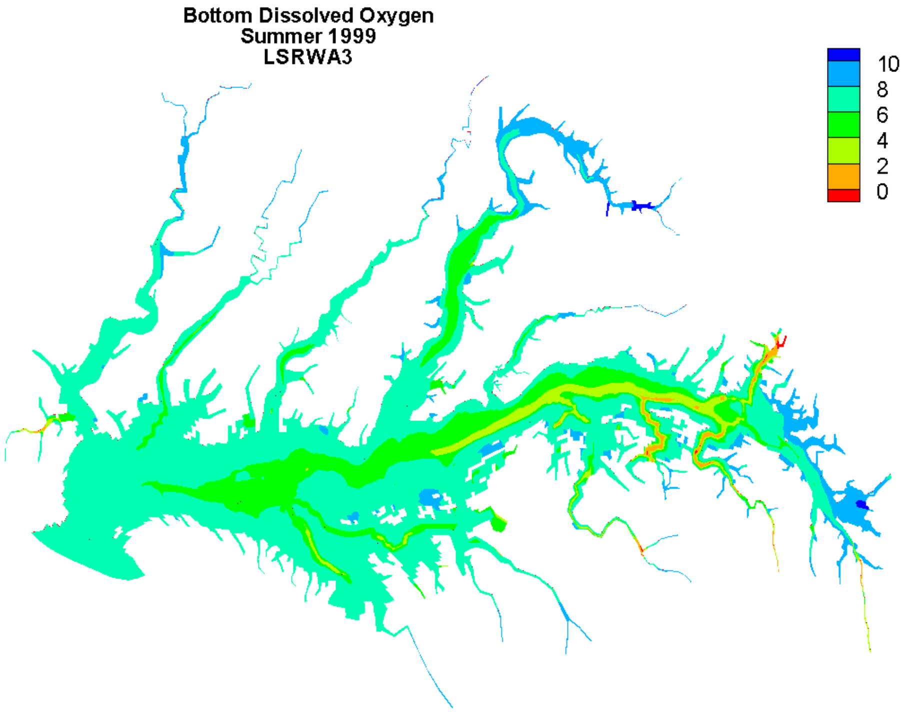

Figure 6-5. Computed bottom DO concentration (g m^{-3} or mg/L) for the base scenario, averaged over June – August 1999.

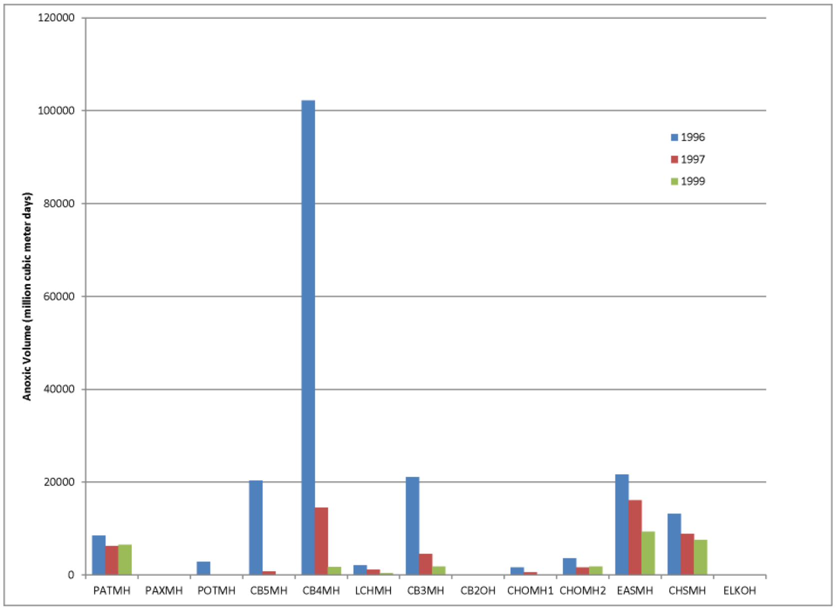

Figure 6-6. Computed anoxic volume days for the base scenario for three years: 1996, 1997, 1999.

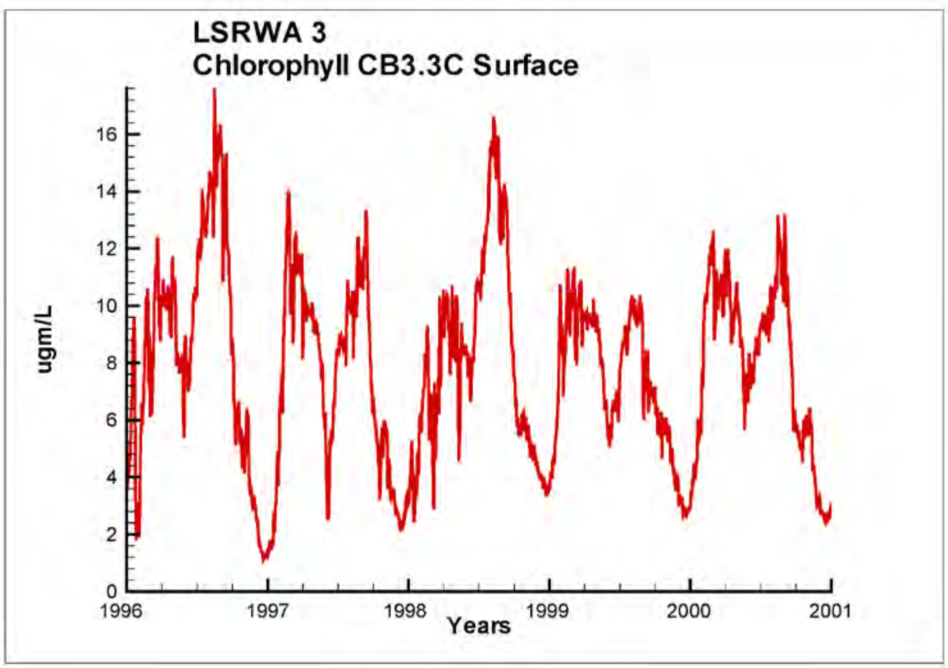

Figure 6-7. Computed chlorophyll concentration for the base scenario at the surface of Station CB3.3C (Figure 5-1).

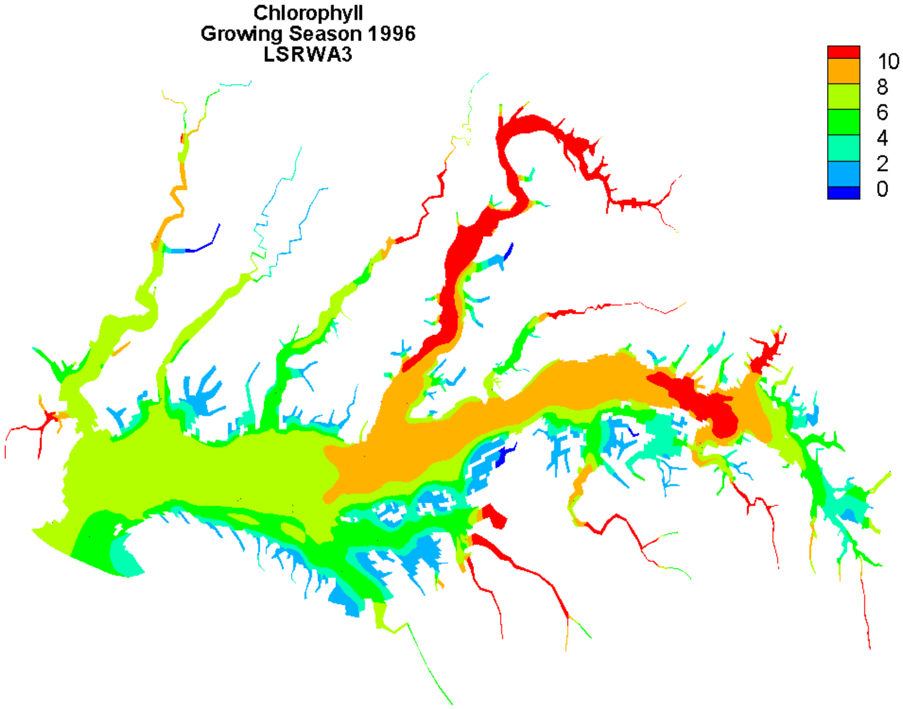

Figure 6-8. Computed surface chlorophyll concentration (mg m^{-3} or µg/L) for the base scenario, averaged over the SAV growing season April – October 1996.

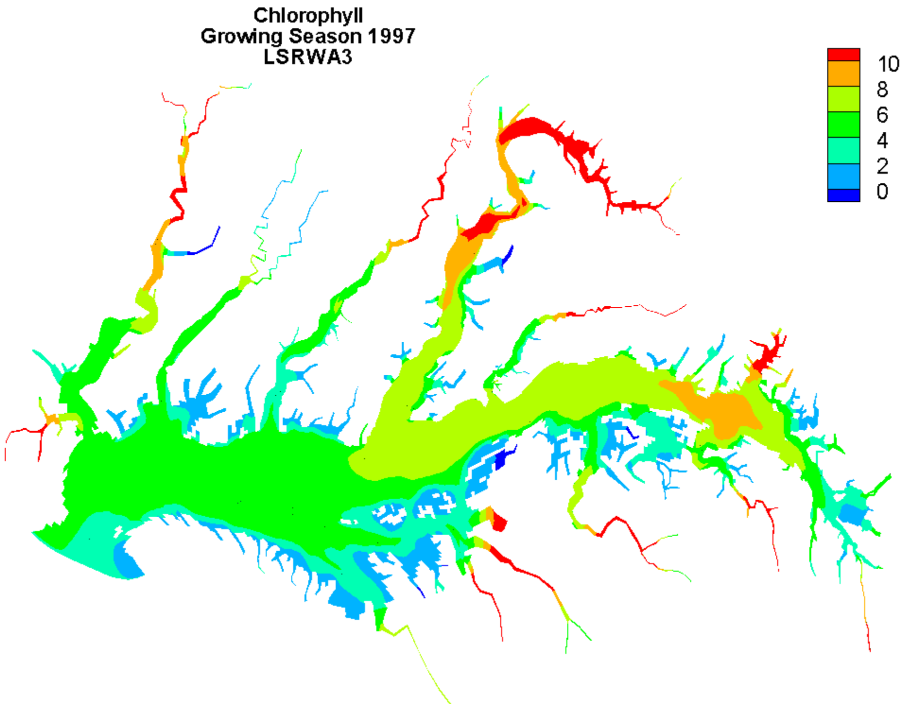

Figure 6-9. Computed surface chlorophyll concentration (mg m^{-3} or µg/L) for the base scenario, averaged over the SAV growing season April – October 1997.

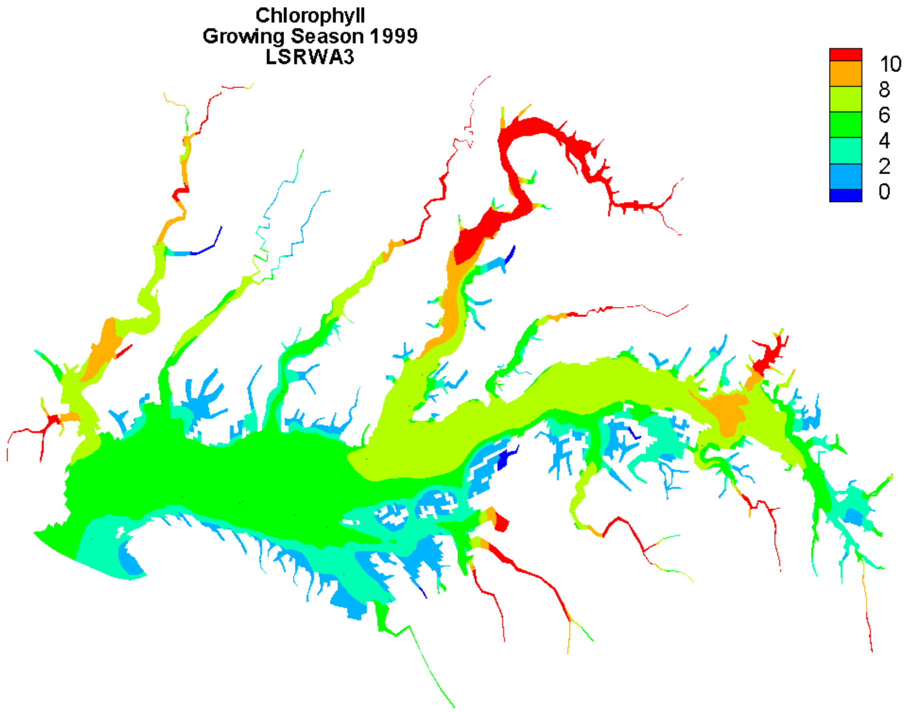

Figure 6-10. Computed surface chlorophyll concentration (mg m^{-3} or µg/L) for the base scenario, averaged over the SAV growing season April – October 1999.

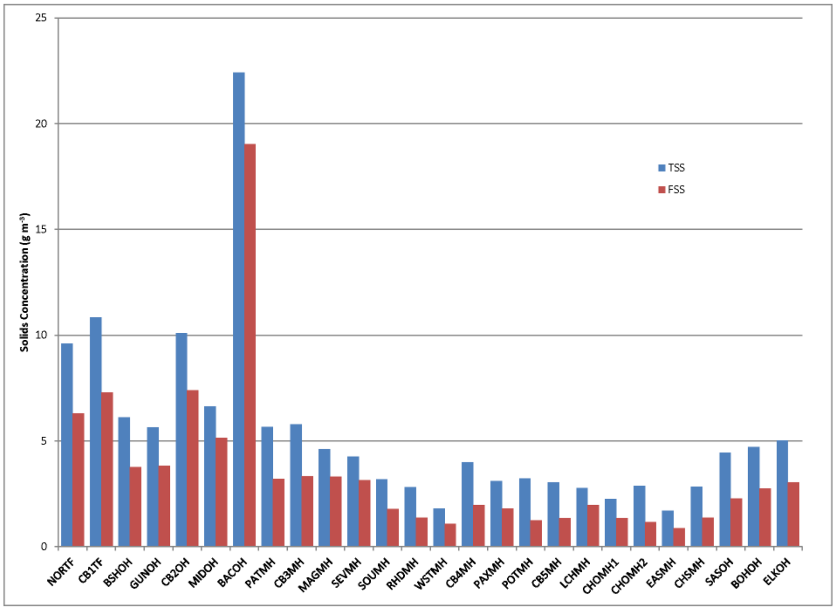

Figure 6-11. Computed total and fixed suspended solids in upper bay CBPS for the base scenario. Results are averaged over the SAV growing season, April – October, 1996.

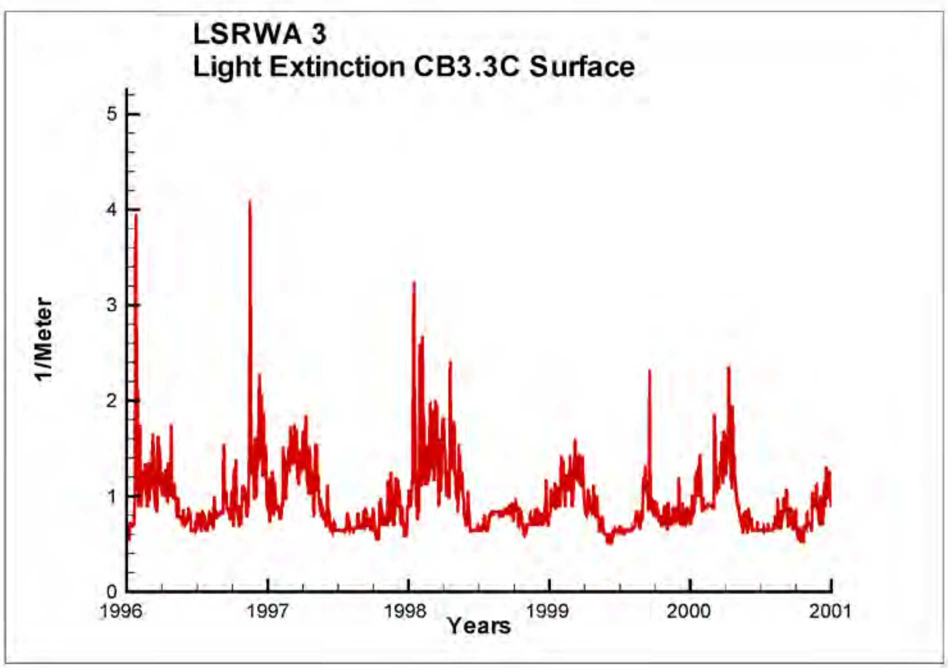

Figure 6-12. Computed light attenuation for the base scenario at the surface of Station CB3.3C (Figure 5-1).

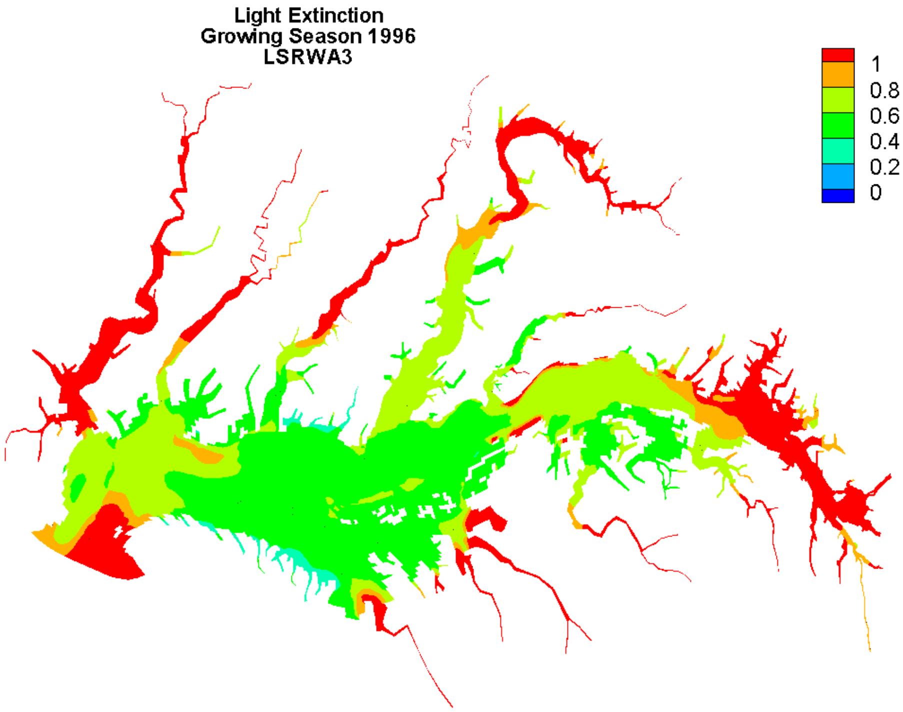

Figure 6-13. Computed light attenuation (m^{-1} or 1/m) for the base scenario, averaged over the SAV growing season April – October 1996.

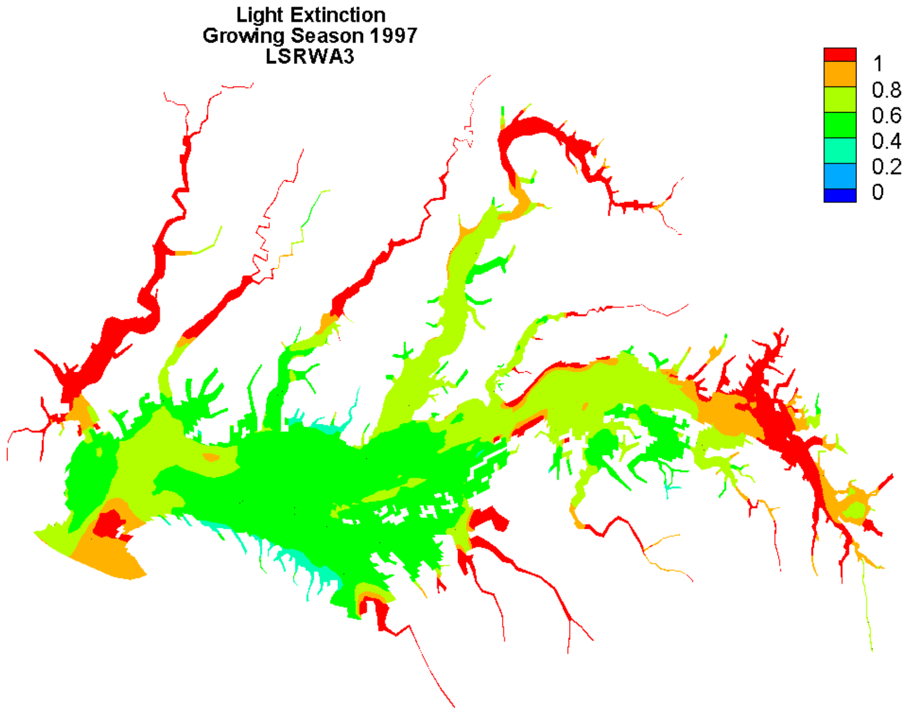

Figure 6-14. Computed light attenuation (m^{-1} or 1/m) for the base scenario, averaged over the SAV growing season April – October 1997.

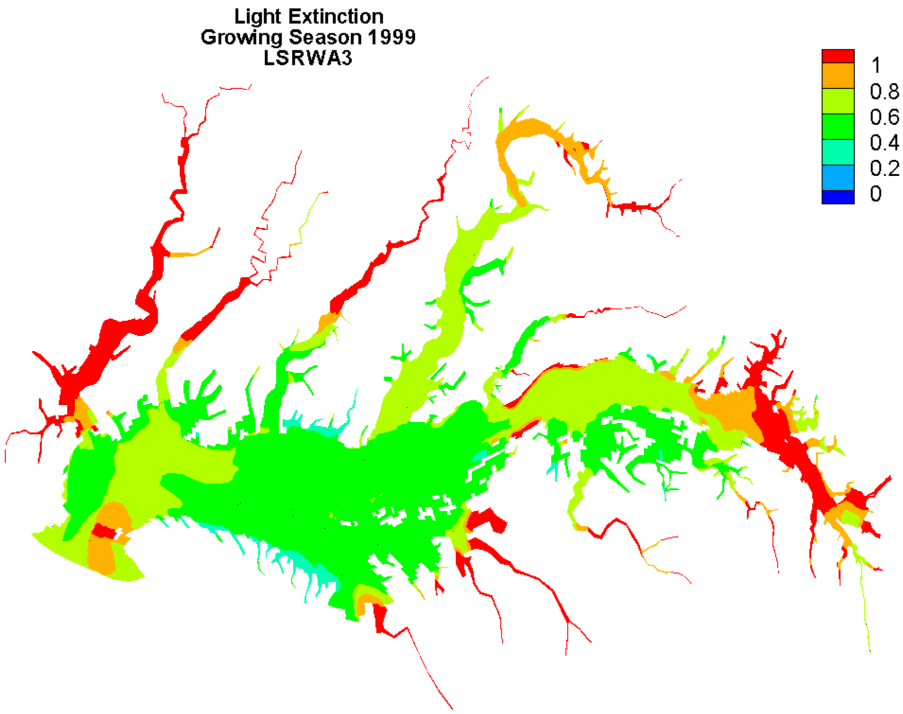

Figure 6-15. Computed light attenuation (m^{-1} or 1/m) for the base scenario, averaged over the SAV growing season April – October 1999.

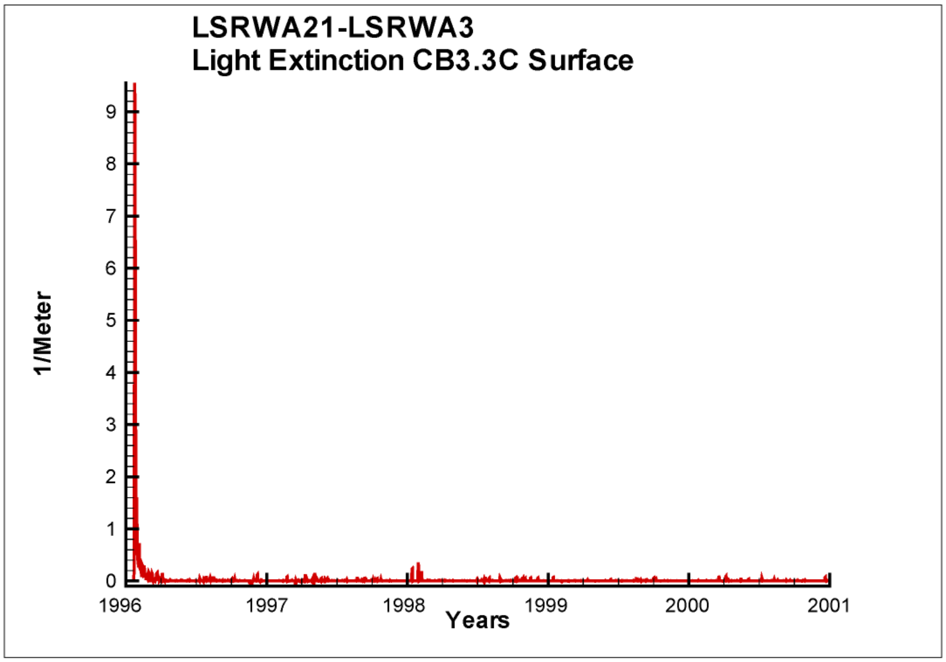

Figure 6-16. Additional light attenuation computed at Station CB3.3C as a result of January 1996 storm scour. Positive values indicate an increase in attenuation relative to the base scenario.

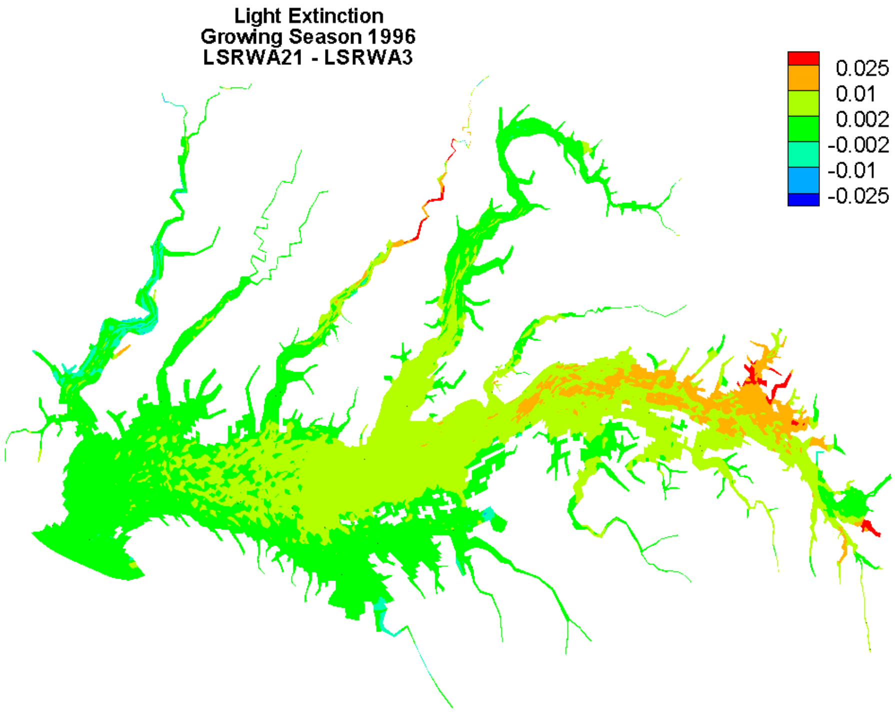

Figure 6-17. Computed additional light attenuation (m^{-1} or 1/m) as a result of January 1996 storm scour, averaged over 1996 SAV growing season. Positive values indicate an increase in attenuation relative to the base scenario.

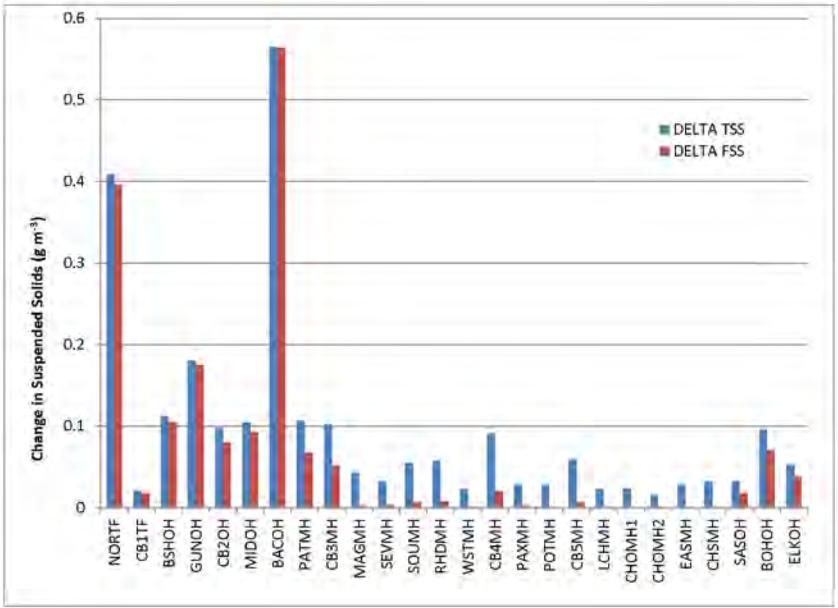

Figure 6-18. Computed additional total and fixed solids resulting from the January 1996 scour event. Results are shown for upper bay CBPS, averaged over the 1996 SAV growing season.

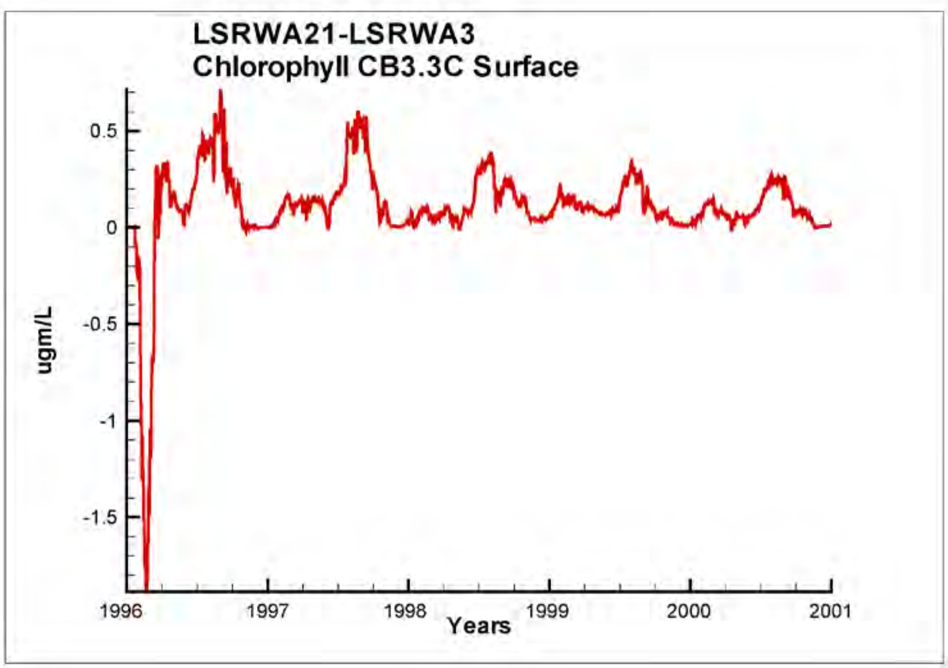

Figure 6-19. Computed change in surface chlorophyll at Station CB3.3C resulting from January 1996 scour event. Positive values indicate an increase relative to the base case; negative values indicate a decrease.

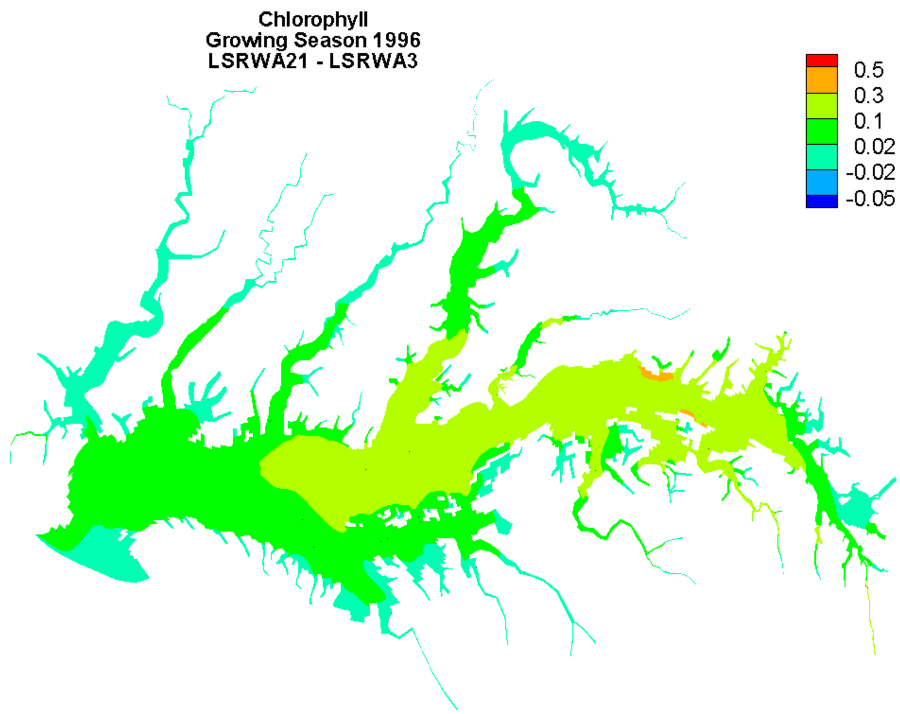

Figure 6-20. Computed additional surface chlorophyll (mg m^{-3} or µg/L) as a result of January 1996 storm scour, averaged over 1996 SAV growing season. Positive values indicate an increase relative to the base scenario.

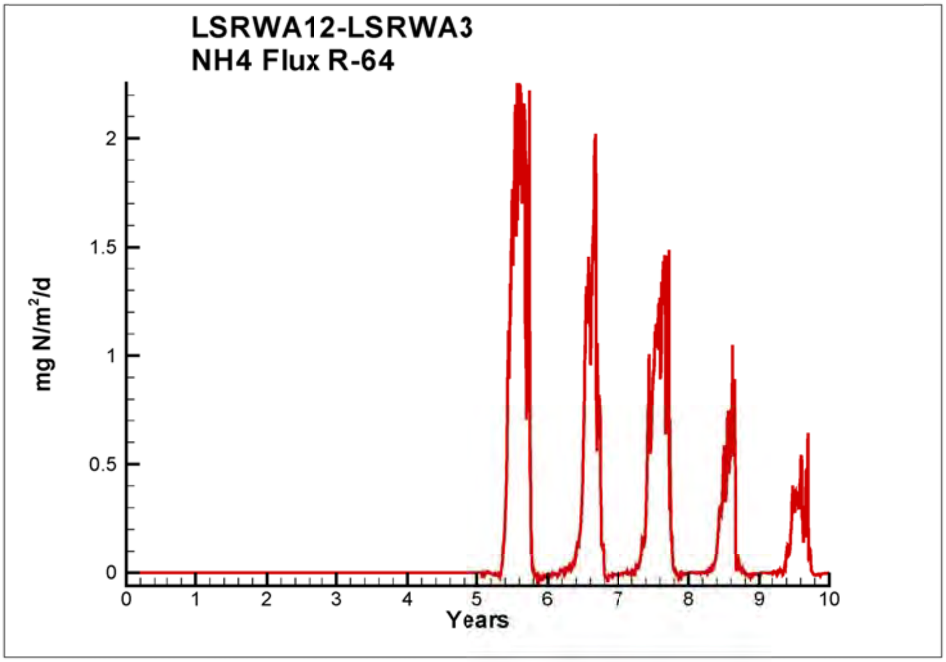

Figure 6-21. Computed additional sediment ammonium release as a result of January 1996 storm scour. Results are shown for SONE station R-64 which is adjacent to CB4.2C (Figure 5-1). The horizontal axis includes the years 1991 – 1995 (Years 0 – 5) and 1996 – 2000 (Years 5 – 10). Positive values indicate an increase in nutrient release relative to the base scenario. The release increases by 16.2% over the base value in the first summer following the storm.

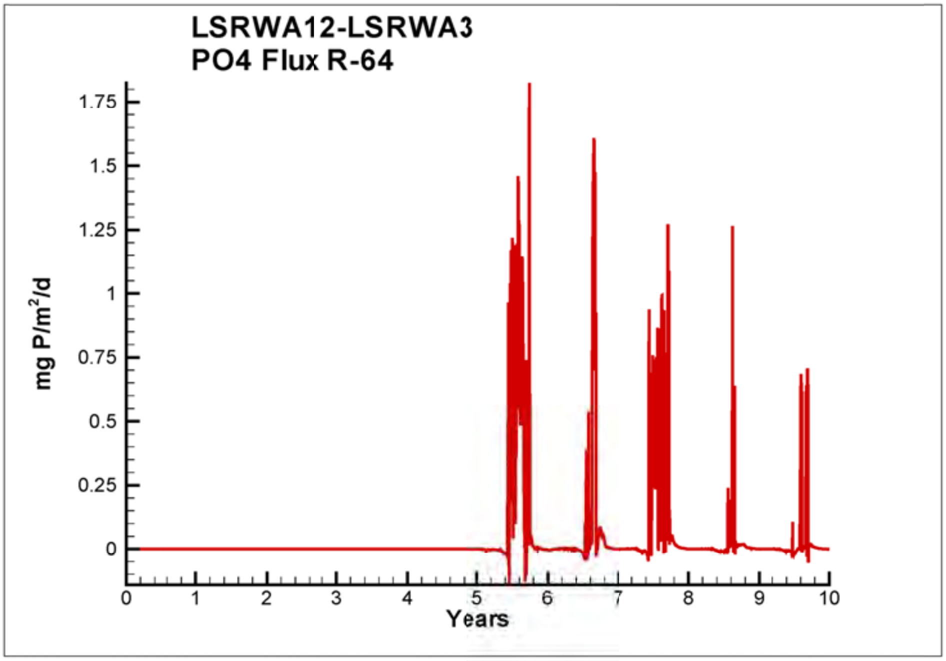

Figure 6-22. Computed additional sediment phosphate release as a result of January 1996 storm scour. Results are shown for SONE station R-64 which is adjacent to CB4.2C (Figure 5-1). The horizontal axis includes the years 1991 – 1995 (Years 0 – 5) and 1996 – 2000 (Years 5 – 10). Positive values indicate an increase in nutrient release relative to the base scenario. The release increases by 7.8% over the base value in the first summer following the storm.

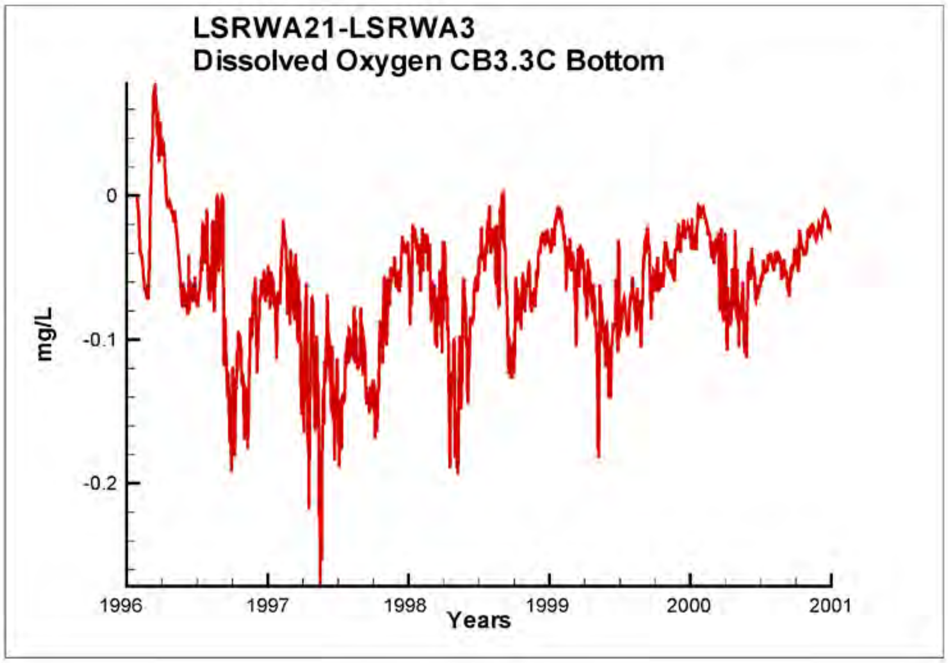

Figure 6-23. Computed change in bottom DO at Station CB3.3C resulting from January 1996 scour event. Positive values indicate an increase relative to the base case; negative values indicate a decrease.

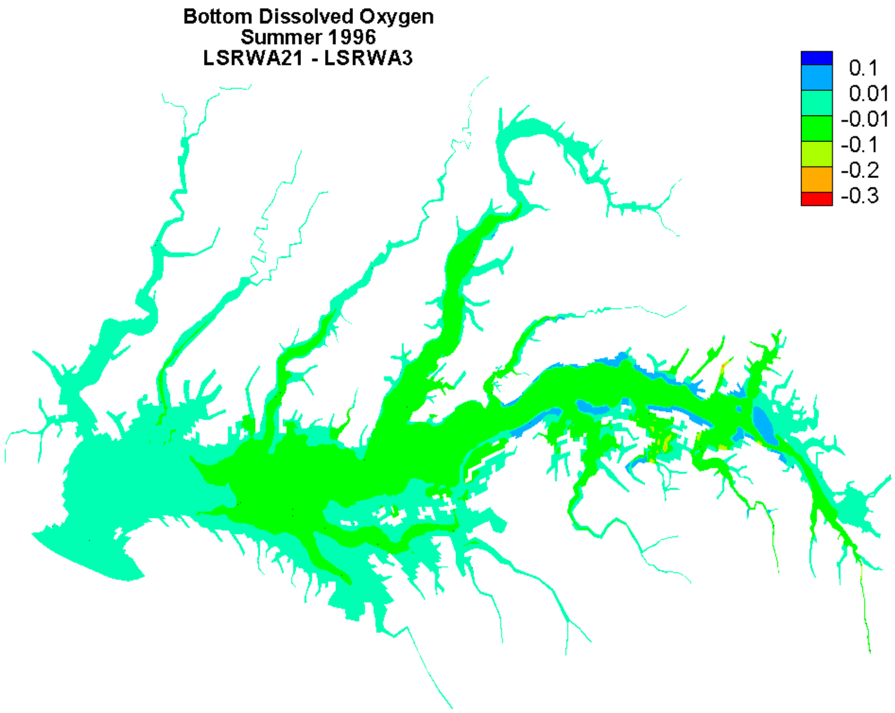

Figure 6-24. Computed change in bottom DO concentration (g m^{-3} or mg/L) as a result of January 1996 storm scour, averaged over June – August 1996. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease.

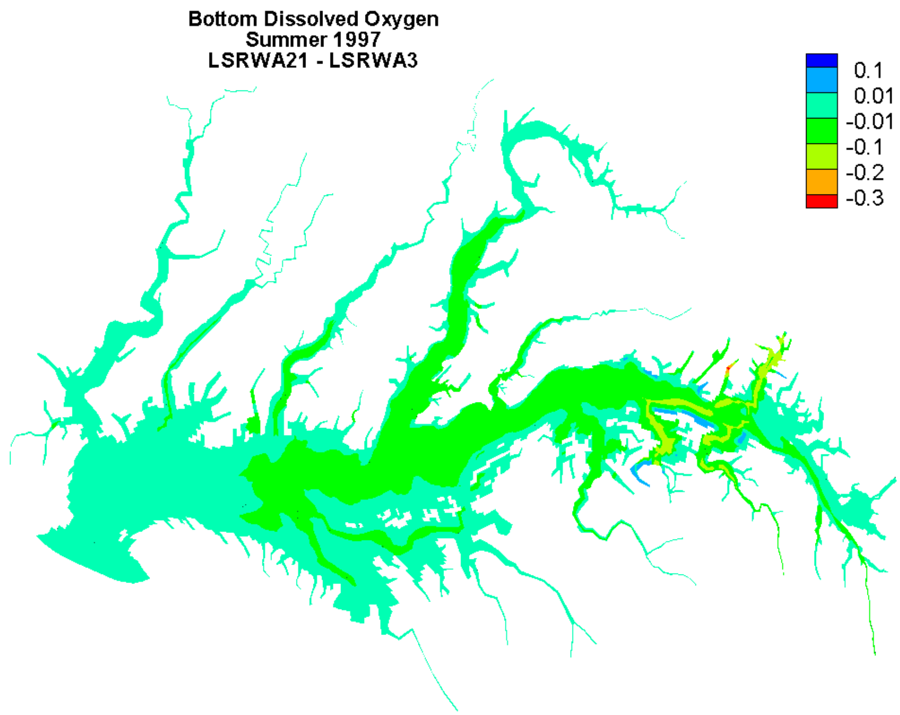

Figure 6-25. Computed change in bottom DO concentration (g m^{-3} or mg/L) as a result of January 1996 storm scour, averaged over June – August 1997. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease.

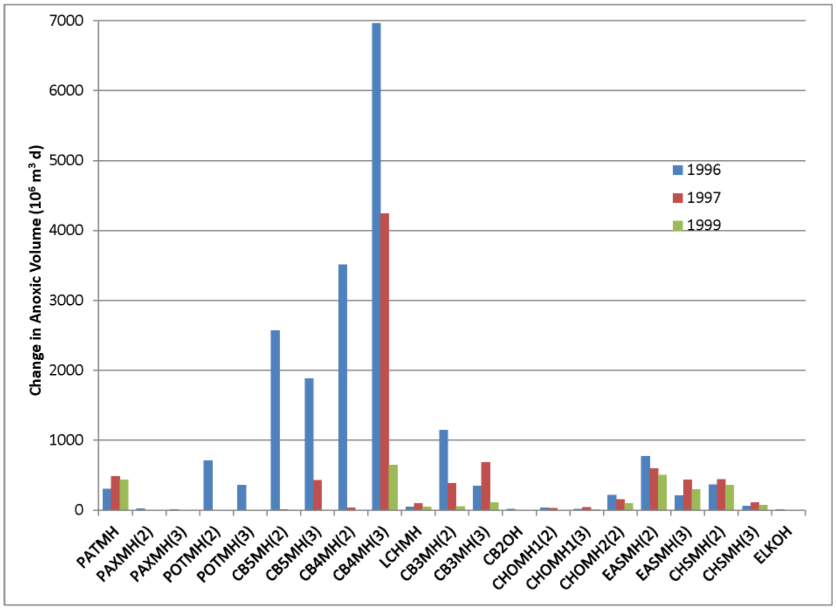

Figure 6-26. Computed additional anoxic volume days as a result of January 1996 storm scour. (2) indicates the pycnocline region between 6.7 and 12.8 m depths. (3) indicates deep water greater than 12.8 m. Note that in 1996, anoxia moves up from deep water into the pycnocline for several CBPS.

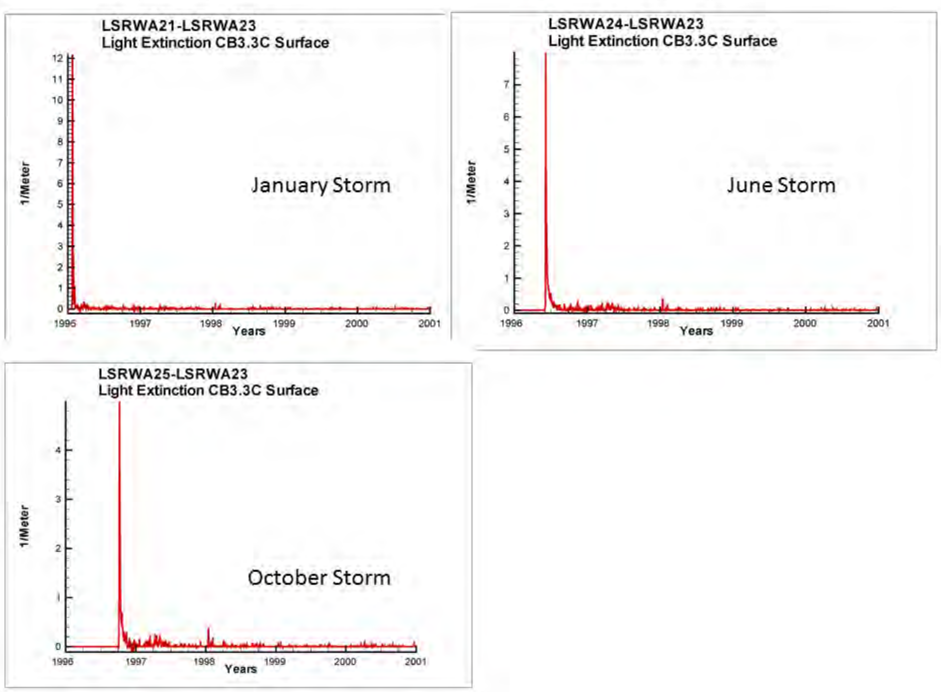

Figure 6-27. Computed increase in light attenuation at Station CB3.3C resulting from storm events in January, June, and October. Results are compared to a base case with no storm.

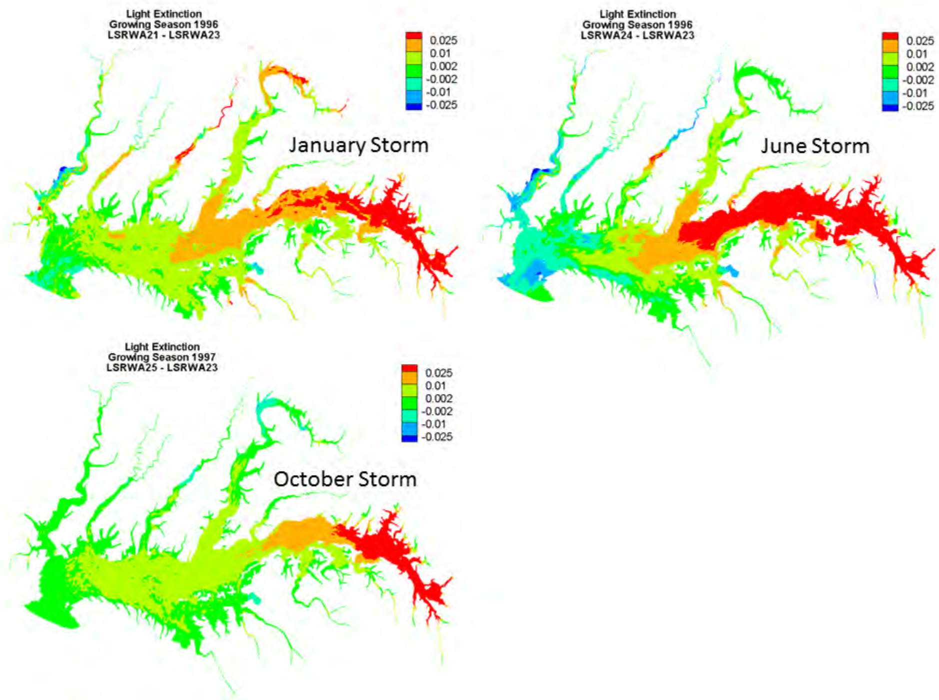

Figure 6-28. Computed change in light attenuation (m^{-1} or 1/m) resulting from storms in January, June, and October, averaged over SAV growing season. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease. Note that the results for the October 1996 storm are shown for 1997 since the storm occurs at the end of the 1996 SAV growing season.

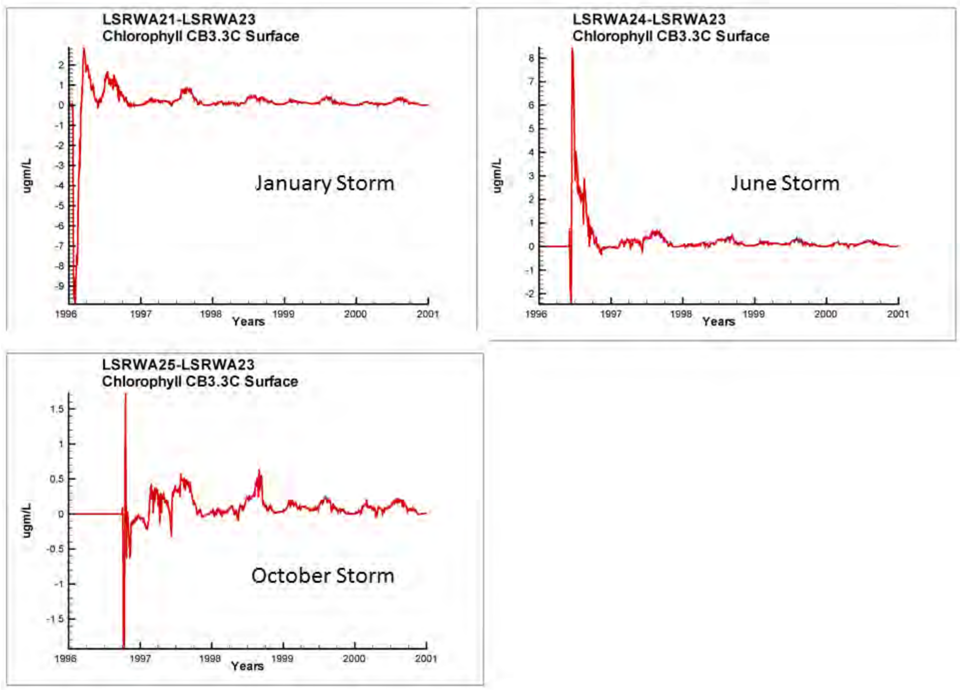

Figure 6-29. Computed change in surface chlorophyll at Station CB3.3C resulting from storm events in January, June, and October. Results are compared to a base case with no storm. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease.

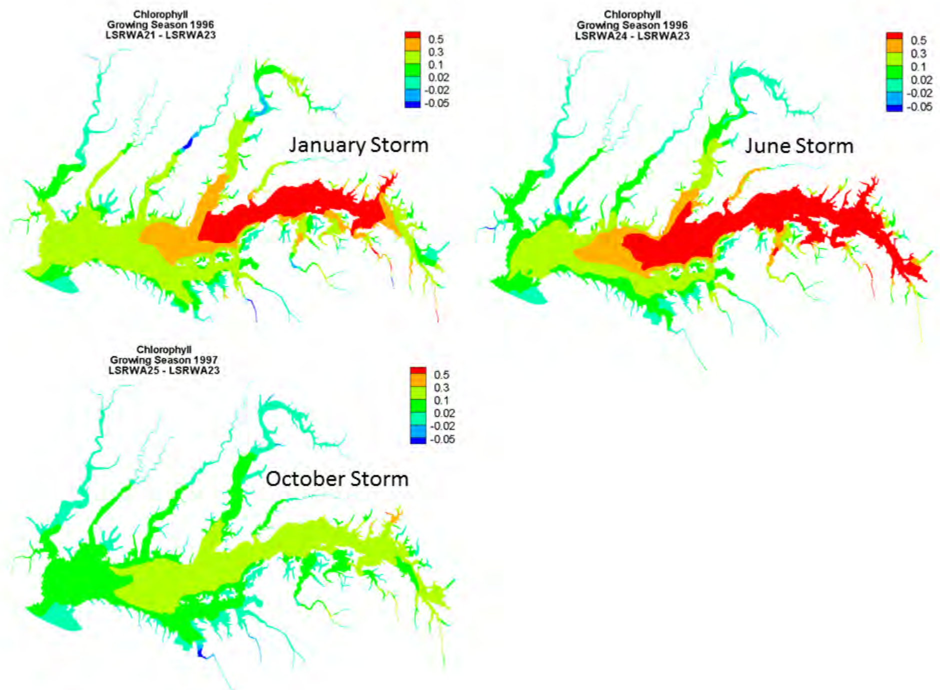

Figure 6-30. Computed change in surface chlorophyll (mg m^{-3} or µg/L) resulting from storms in January, June, and October, averaged over SAV growing season. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease. Note that the results for the October 1996 storm are shown for 1997 since the storm occurs at the end of the 1996 SAV growing season.

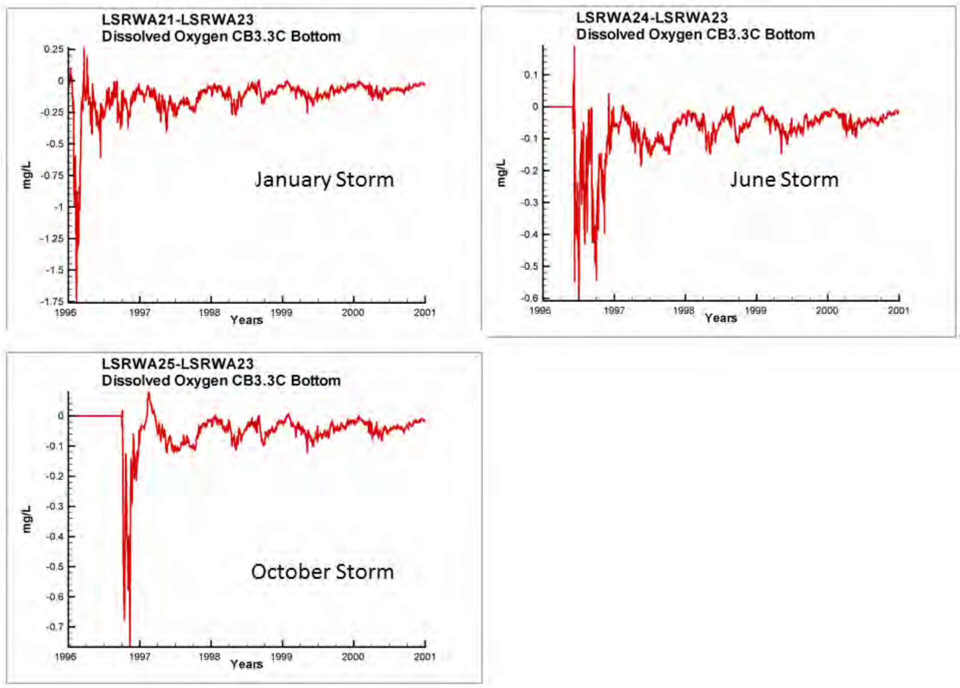

Figure 6-31. Computed change in bottom DO at Station CB3.3C resulting from storm events in January, June, and October. Results are compared to a base case with no storm. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease.

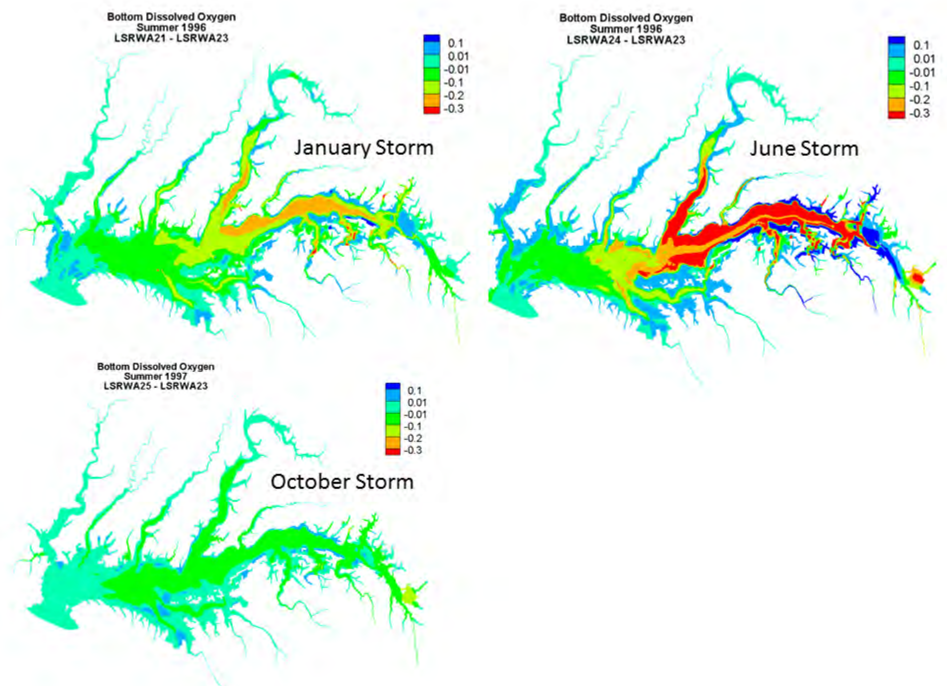

Figure 6-32. Computed change in bottom DO concentration (g m^{-3} or mg/L) resulting from storms in January, June, and October, averaged over June - August. Positive values indicate an increase relative to the base scenario; negative values indicate a decrease. Note that the results for the October 1996 storm are shown for 1997 since the storm occurs at the end of the 1996 SAV growing season.

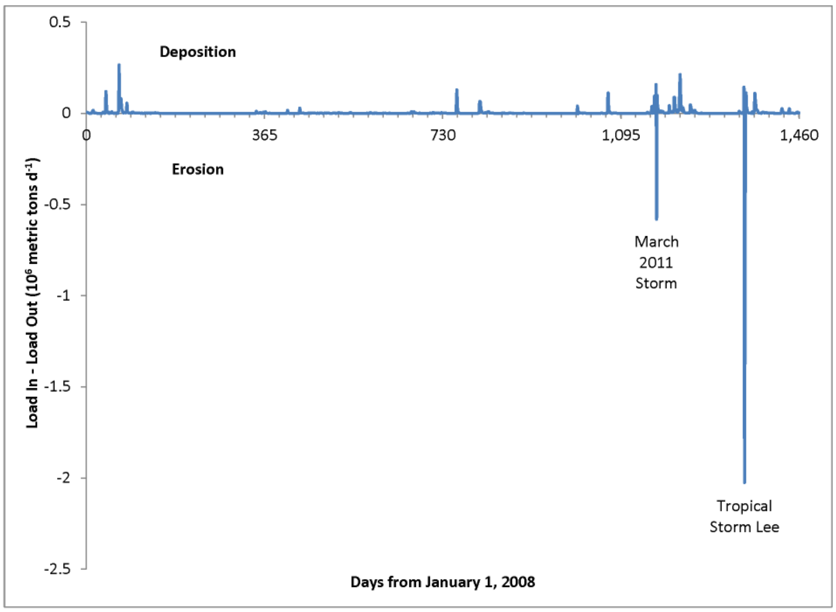

Figure 6-33. Difference between modeled solids loads into Conowingo Reservoir and modeled solids loads out for "Equilibrium Bathymetry." The reservoir is depositional up to the 2011 scour events despite the equilibrium bathymetry.

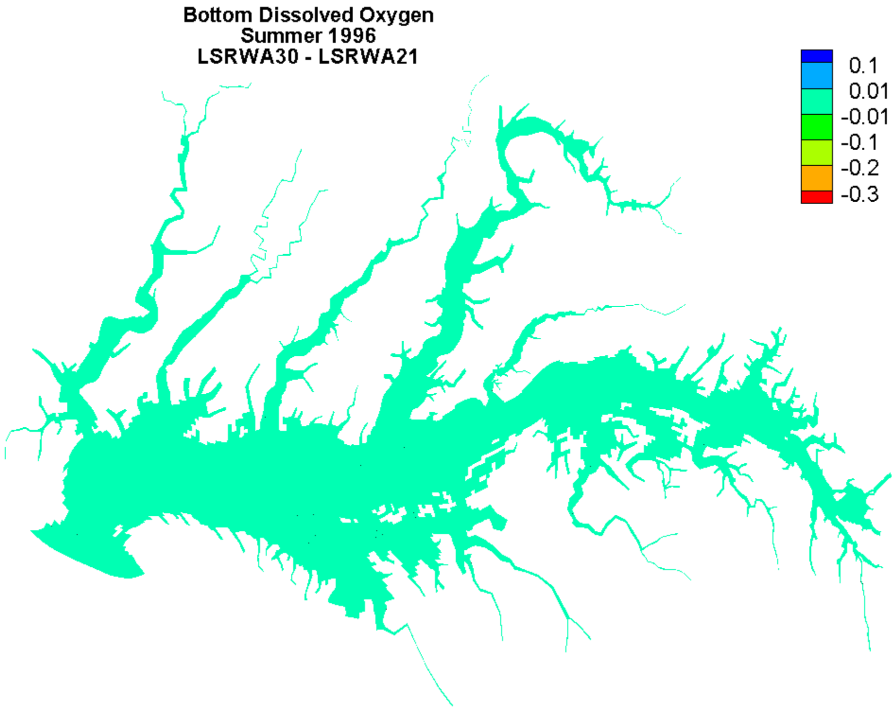

Figure 6-34. Computed change in bottom DO concentration (g m^{-3} or mg/L) when reservoir scour is computed based on equilibrium bathymetry. The base scenario has scour based on 2008 bathymetry. Results are averaged over June – August 1996. Computed differences are negligible.

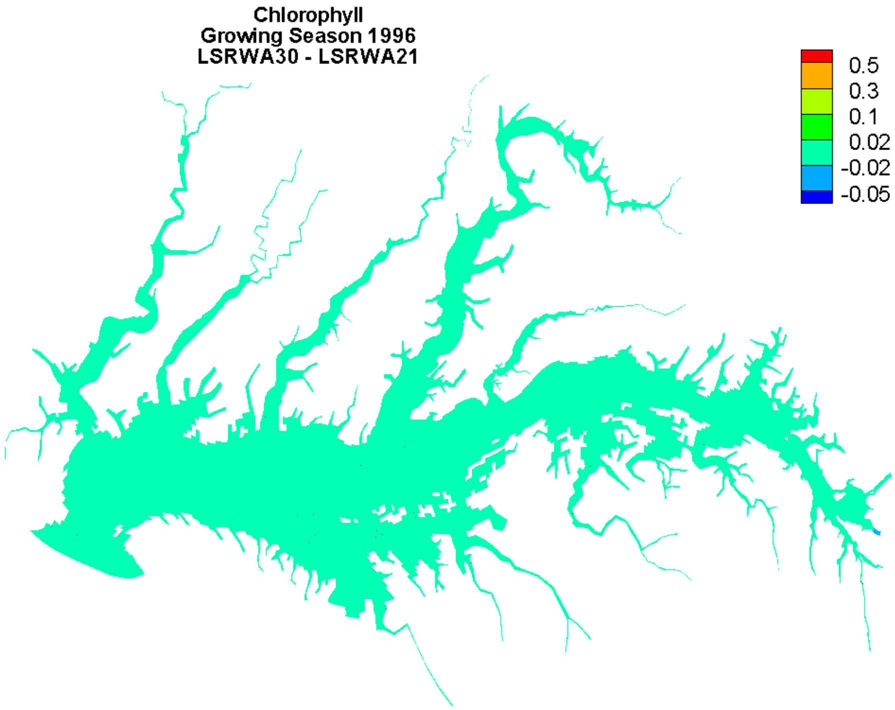

Figure 6-35. Computed change in surface chlorophyll concentration (mg m^{-3} or µg/L) when reservoir scour is computed based on equilibrium bathymetry. The base scenario has scour based on 2008 bathymetry. Results are averaged over the SAV growing season for 1996. Computed differences are negligible.

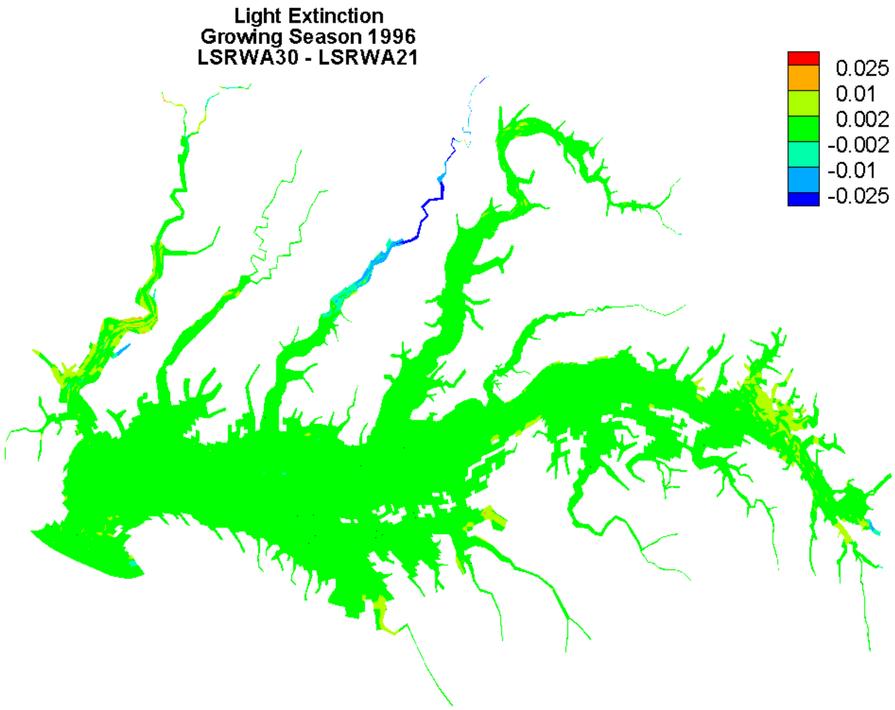

Figure 6-36. Computed change in light attenuation (m^{-1} or 1/m) when reservoir scour is computed based on equilibrium bathymetry. The base scenario has scour based on 2008 bathymetry. Results are averaged over the SAV growing season for 1996. Computed differences are negligible.

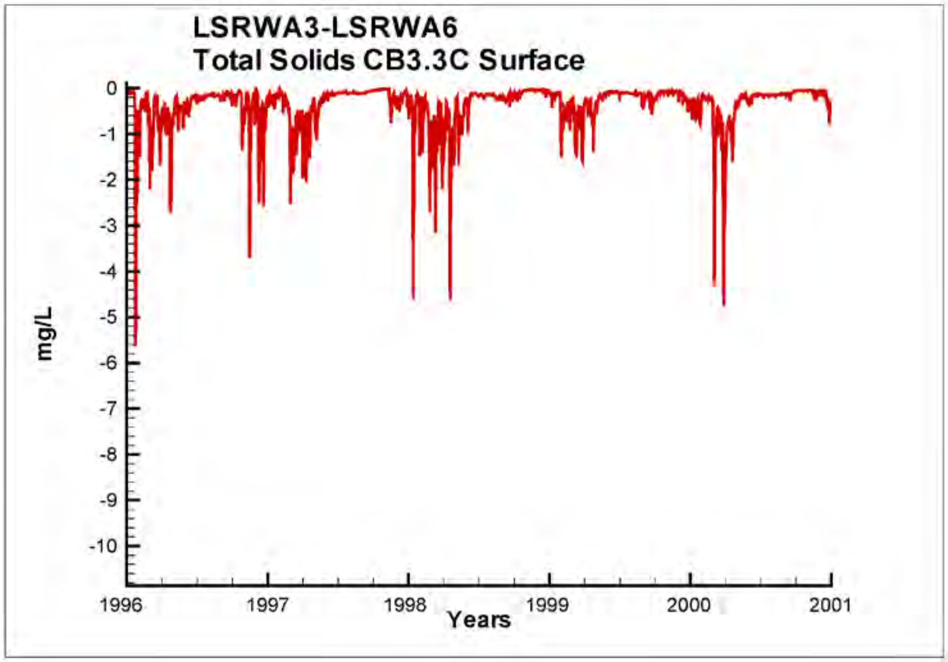

Figure 6-37. Computed effect of processes in Conowingo Reservoir on surface TSS at Station CB3.3C in Chesapeake Bay. Negative values indicate concentrations are lower as a result of reservoir processes.

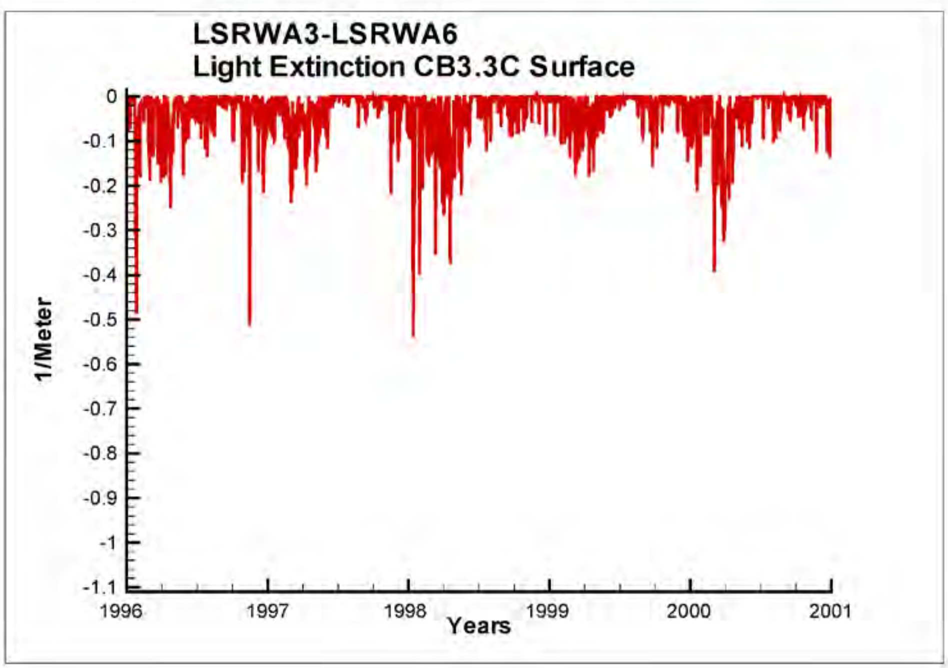

Figure 6-38. Computed effect of processes in Conowingo Reservoir on light attenuation at Station CB3.3C in Chesapeake Bay. Negative values indicate attenuation is lower as a result of reservoir processes.

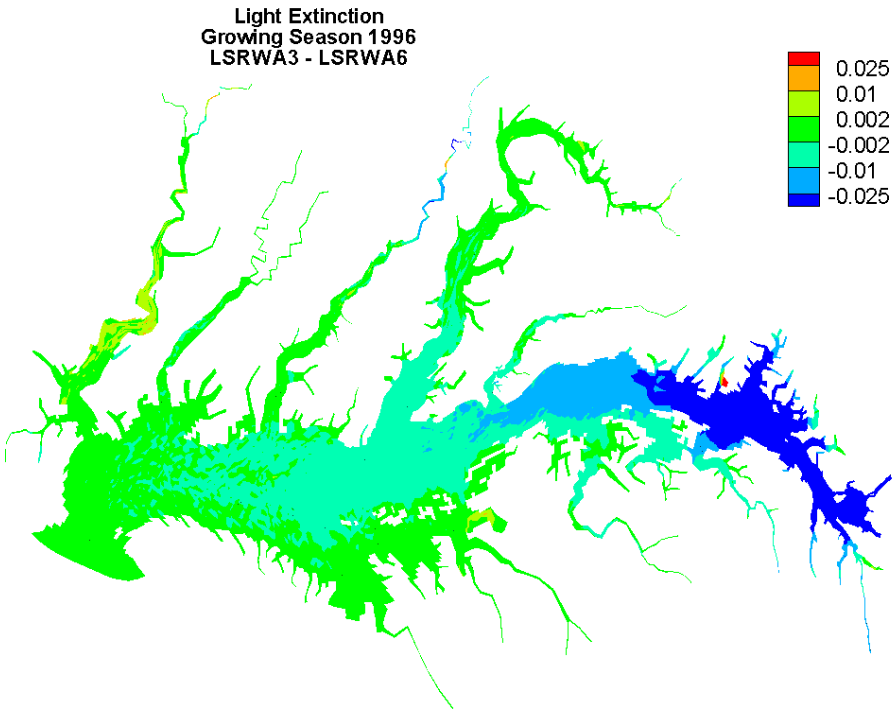

Figure 6-39. Computed effect of processes in Conowingo Reservoir on light attenuation (m^{-1} or 1/m) in Chesapeake Bay, averaged over 1996 SAV growing season. Negative values indicate attenuation is lower as a result of reservoir processes.

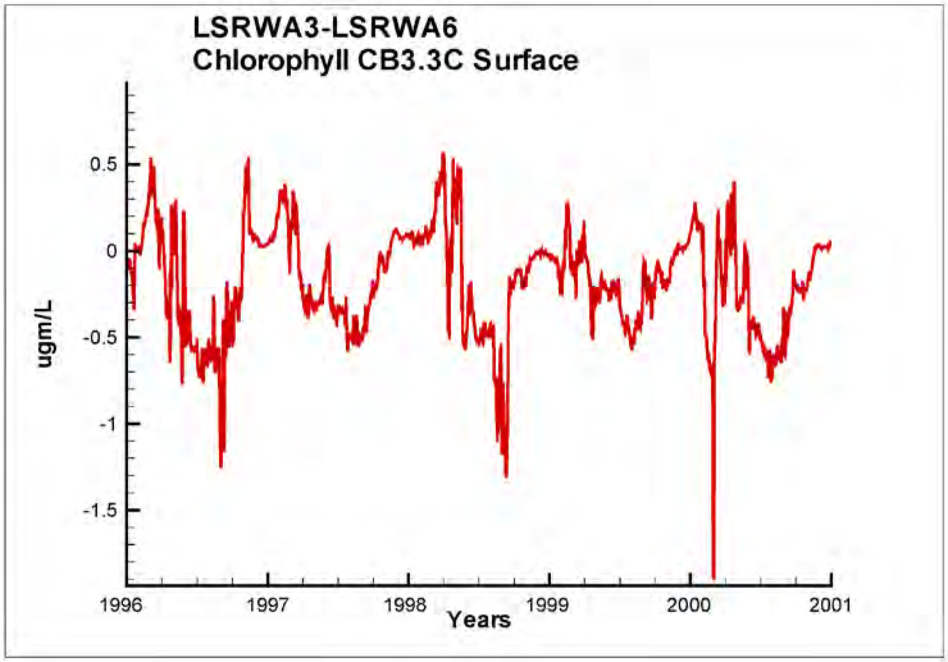

Figure 6-40. Computed effect of processes in Conowingo Reservoir on surface chlorophyll at Station CB3.3C in Chesapeake Bay. Negative values indicate chlorophyll is lower as a result of reservoir processes; positive values indicate chlorophyll is higher as a result of reservoir processes.

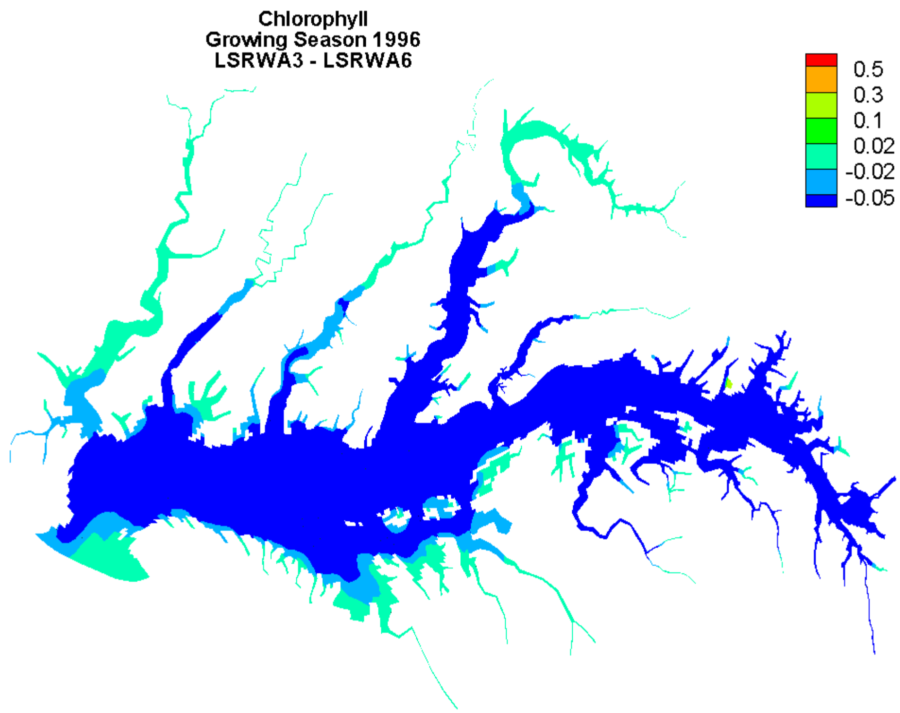

Figure 6-41. Computed effect of processes in Conowingo Reservoir on surface chlorophyll (mg m^{-3} or µg/L) in Chesapeake Bay, averaged over 1996 SAV growing season. Negative values indicate chlorophyll is lower as a result of reservoir processes.

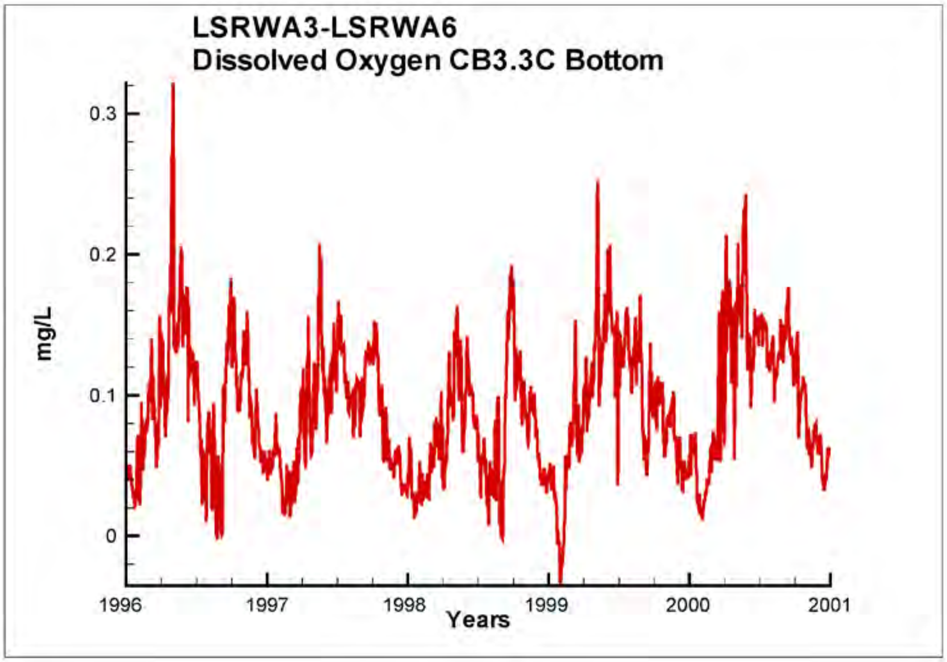

Figure 6-42. Computed effect of processes in Conowingo Reservoir on bottom dissolved oxygen at Station CB3.3C in Chesapeake Bay. Positive values indicate DO is higher as a result of reservoir processes.

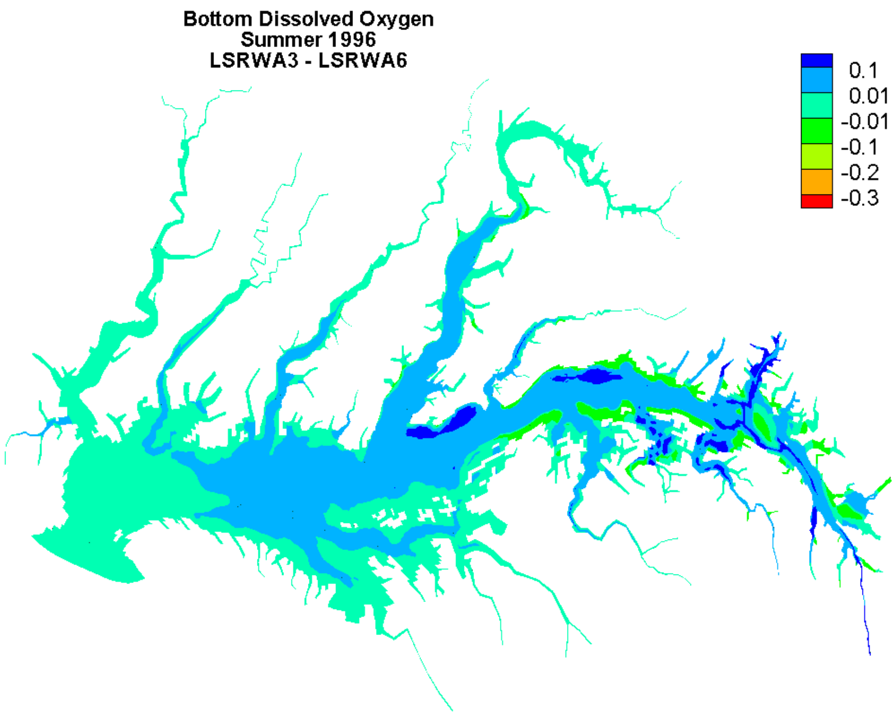

Figure 6-43. Computed effect of processes in Conowingo Reservoir on bottom dissolved oxygen concentration (g m^{-3} or mg/L) in Chesapeake Bay, averaged over June – August 1996. Positive values indicate DO is higher as a result of reservoir processes.

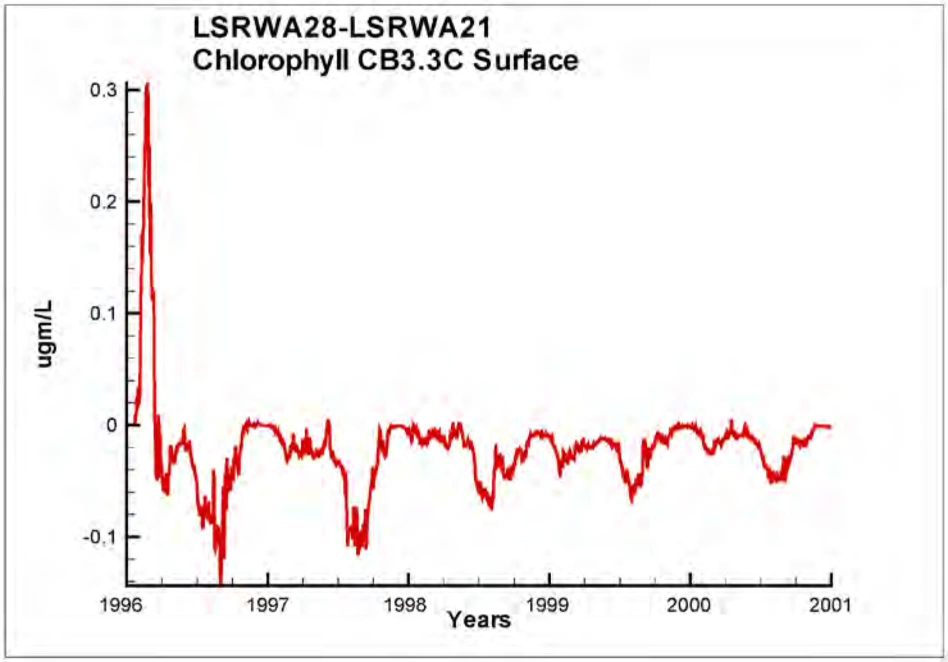

Figure 6-44. Computed effect of dredging 3 mcy from Conowingo Reservoir on surface chlorophyll at Station CB3.3C in Chesapeake Bay. Negative values indicate chlorophyll is lower as a result of dredging.

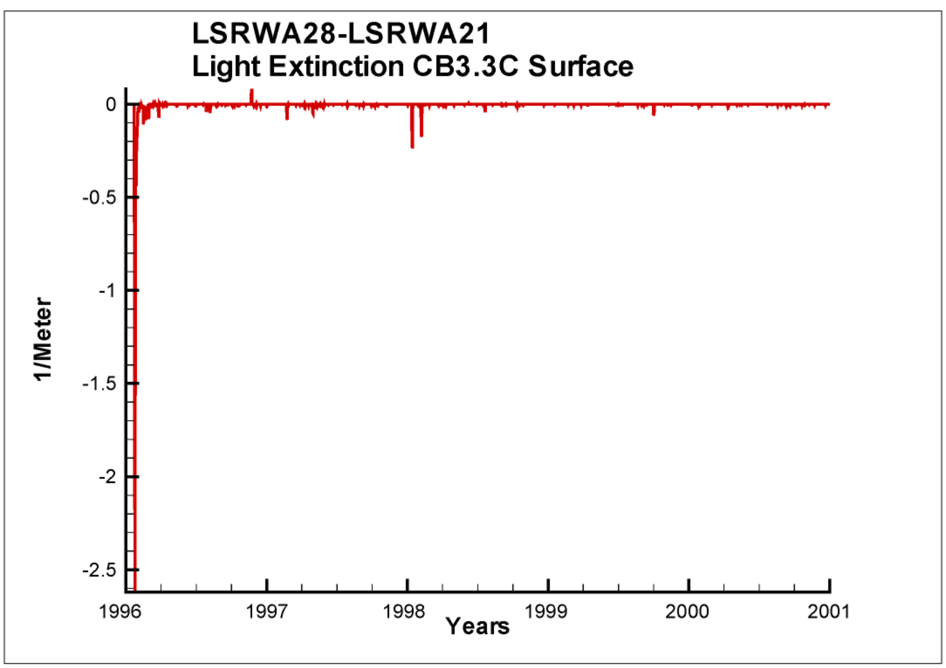

Figure 6-45. Computed effect dredging 3 mcy from Conowingo Reservoir on light attenuation at Station CB3.3C in Chesapeake Bay. Negative values indicate light attenuation is lower as a result of dredging.

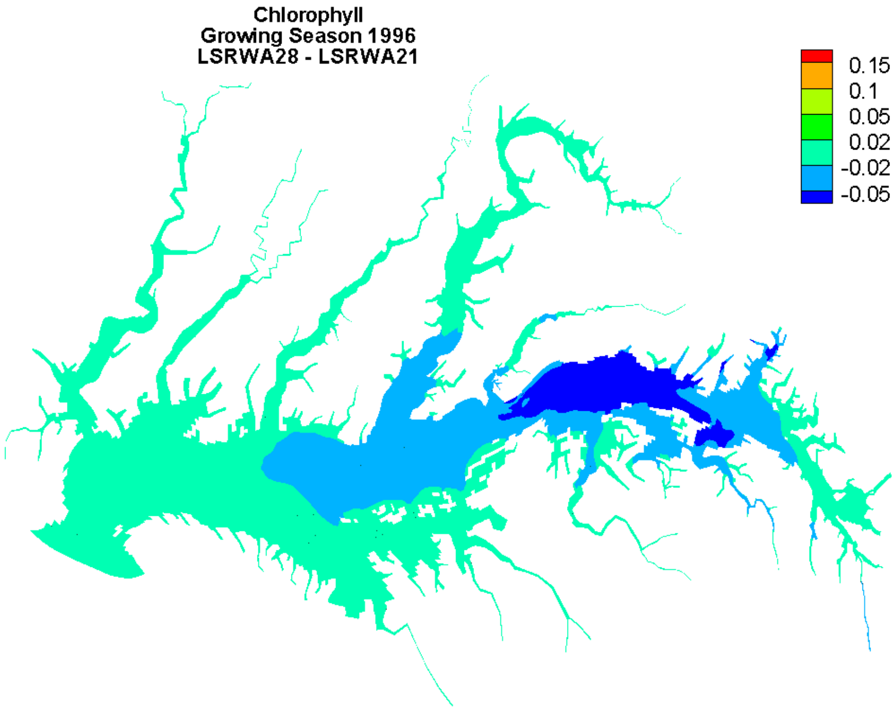

Figure 6-46. Computed effect of dredging 3 mcy from Conowingo Reservoir on surface chlorophyll (mg m^{-3} or µg/L) in Chesapeake Bay, averaged over 1996 SAV growing season. Negative values indicate chlorophyll is lower as a result of dredging.

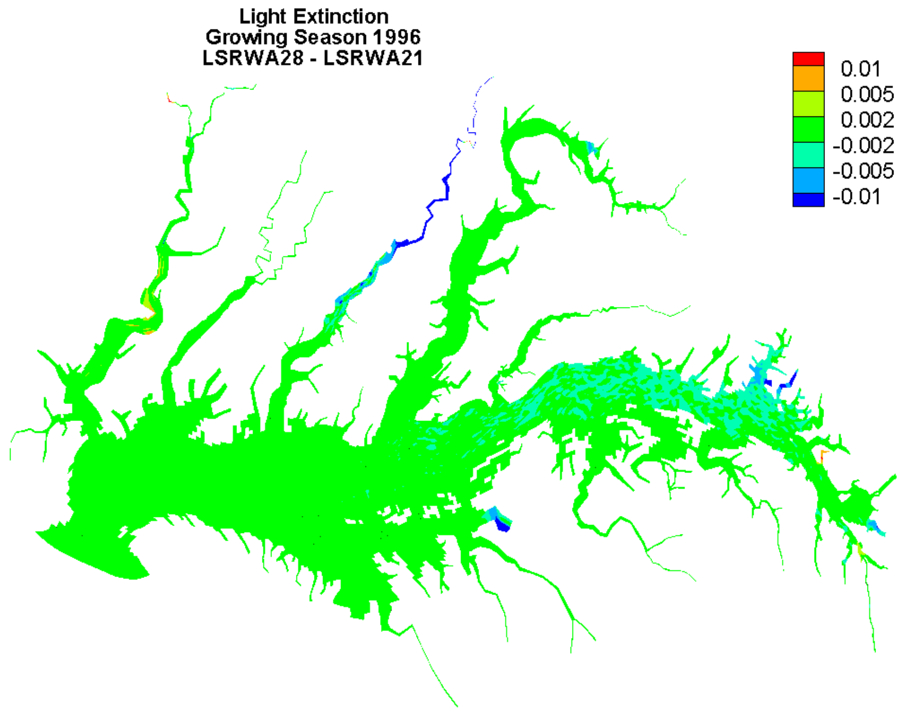

Figure 6-47. Computed effect of dredging 3 mcy from Conowingo Reservoir on light attenuation (m^{-1} or 1/m) in Chesapeake Bay, averaged over 1996 SAV growing season. Negative values indicate attenuation is lower as a result of dredging.

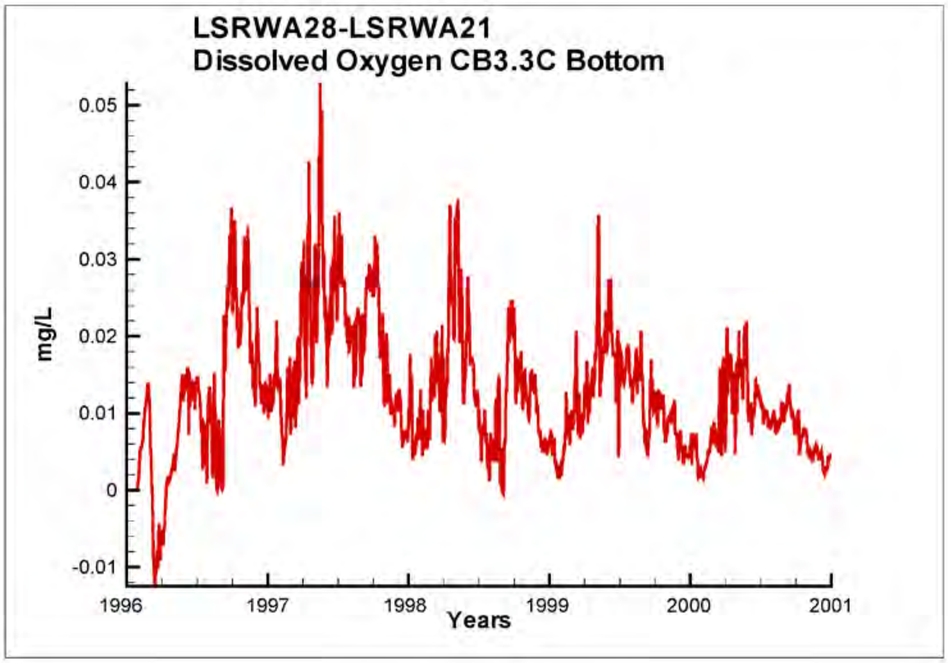

Figure 6-48. Computed effect of dredging 3 mcy from Conowingo Reservoir on bottom dissolved oxygen at Station CB3.3C in Chesapeake Bay. Positive values indicate DO is higher as a result of dredging.

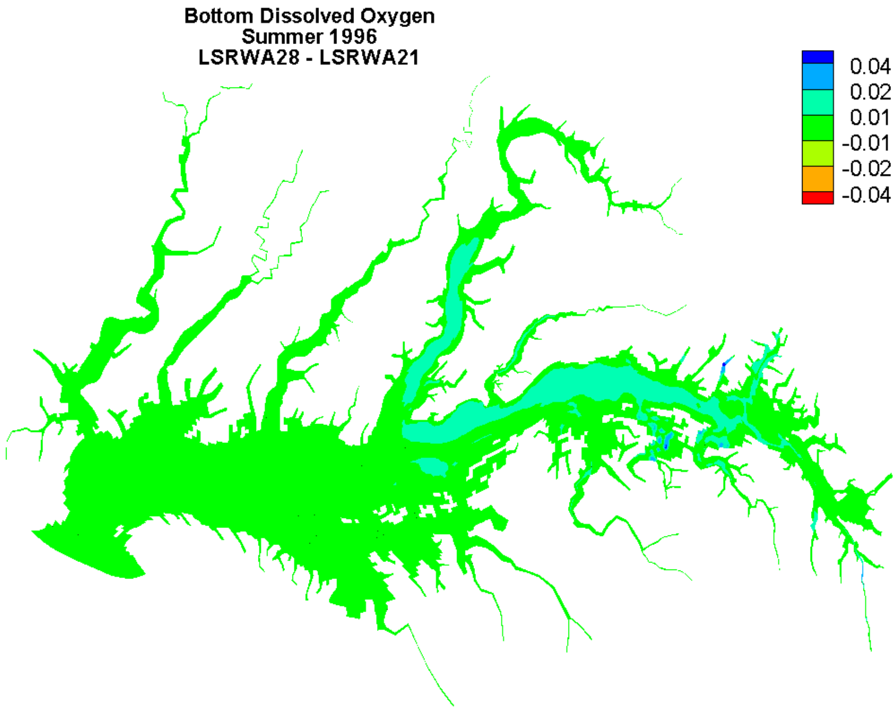

Figure 6-49. Computed effect of dredging 3 mcy from Conowingo Reservoir on bottom dissolved oxygen concentration (g m^{-3} or mg/L) in Chesapeake Bay, averaged over June – August 1996. Positive values indicate DO is higher as a result of dredging.

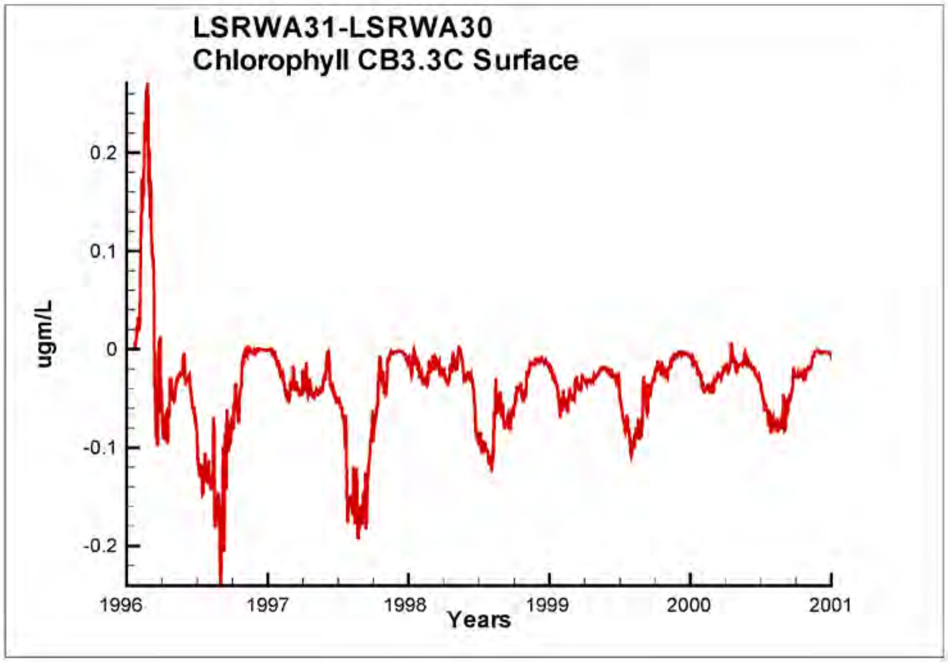

Figure 6-50. Computed effect of dredging back to 1996 bathymetry on surface chlorophyll at Station CB3.3C in Chesapeake Bay. Negative values indicate chlorophyll is lower as a result of dredging.

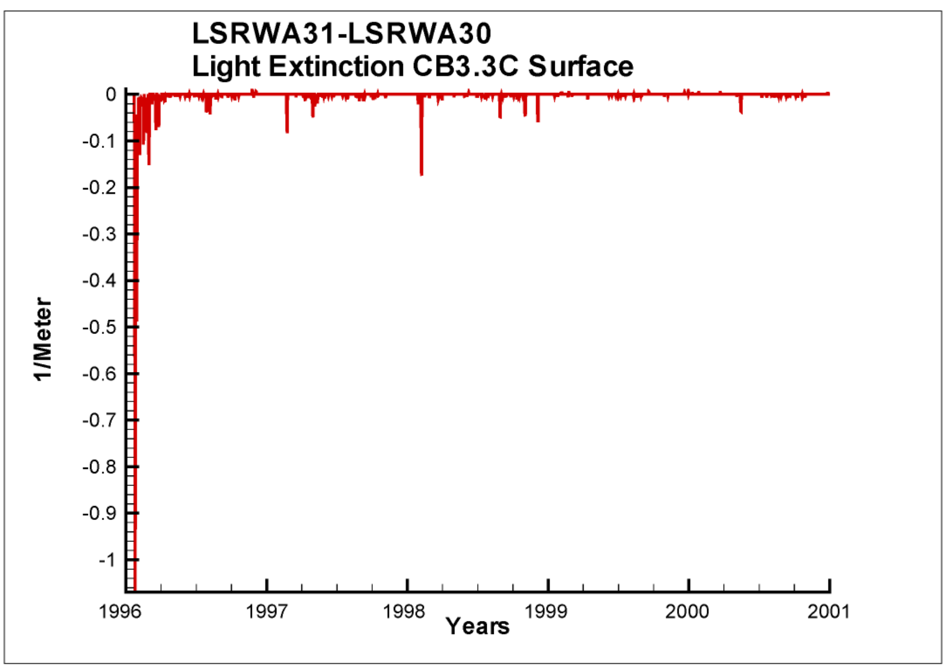

Figure 6-51. Computed effect of dredging back to 1996 bathymetry on light attenuation at Station CB3.3C in Chesapeake Bay. Negative values indicate attenuation is lower as a result of dredging.

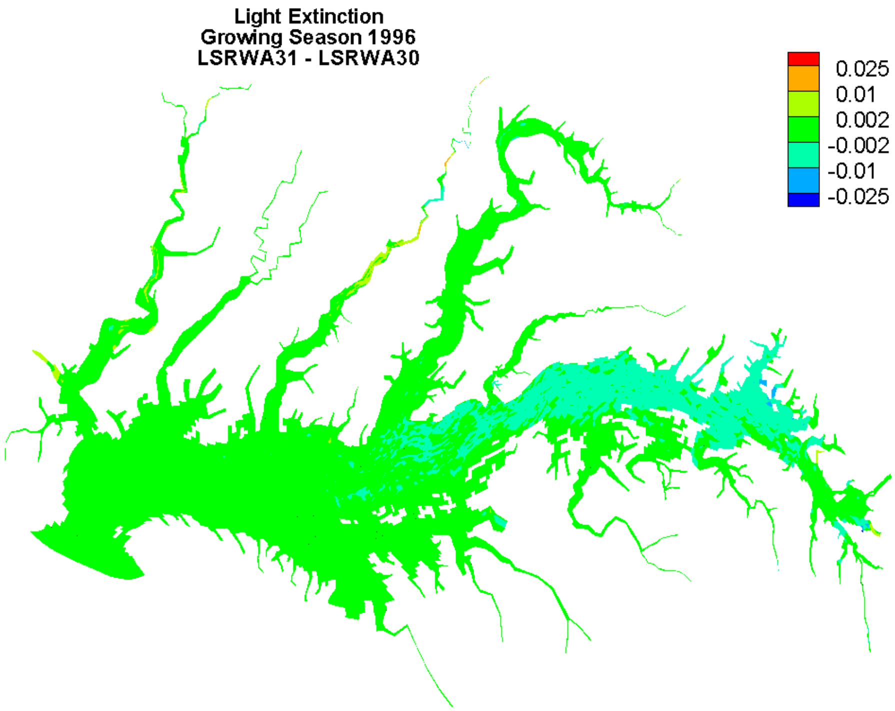

Figure 6-52. Computed effect of dredging back to 1996 bathymetry on light attenuation (m^{-1} or 1/m) in Chesapeake Bay, averaged over 1996 SAV growing season. Negative values indicate attenuation is lower as a result of dredging.

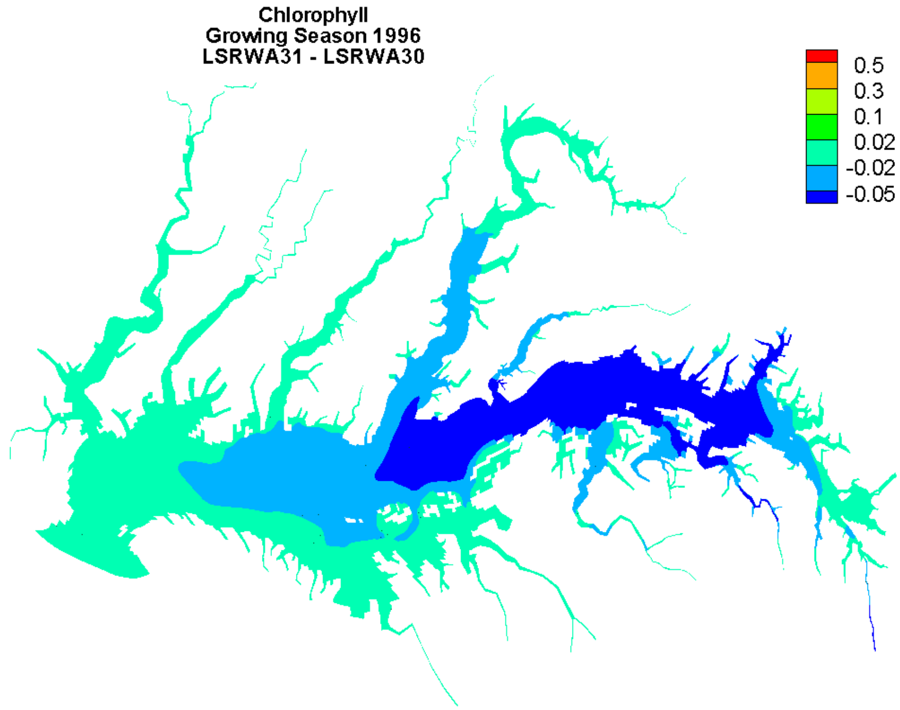

Figure 6-53. Computed effect of dredging back to 1996 bathymetry on surface chlorophyll (mg m^{-3} or µg/L) in Chesapeake Bay, averaged over 1996 SAV growing season. Negative values indicate chlorophyll is lower as a result of dredging.

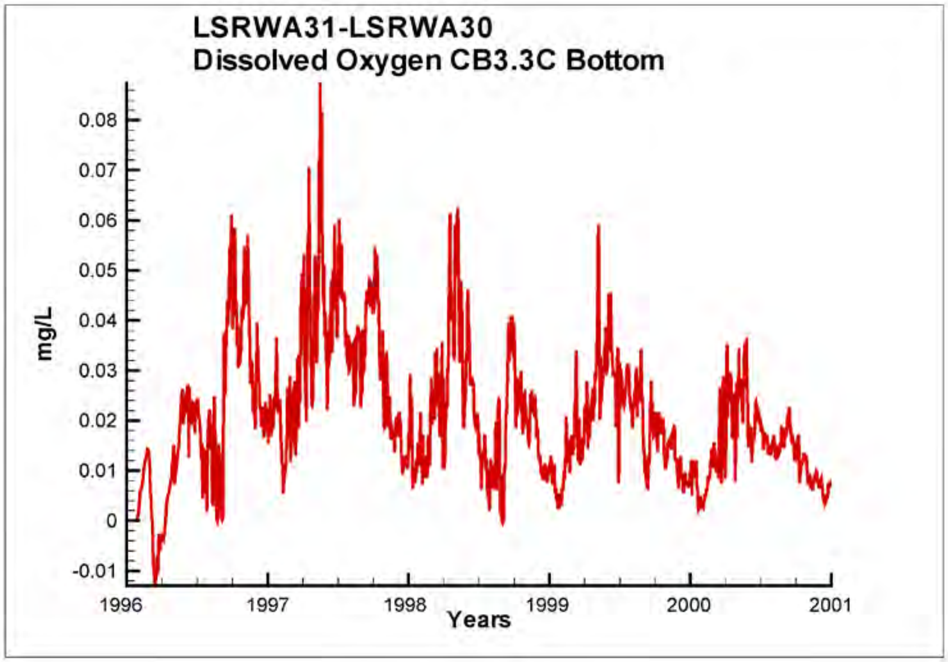

Figure 6-54. Computed effect of dredging back to 1996 bathymetry on bottom dissolved oxygen at Station CB3.3C in Chesapeake Bay. Positive values indicate DO is higher as a result of dredging.

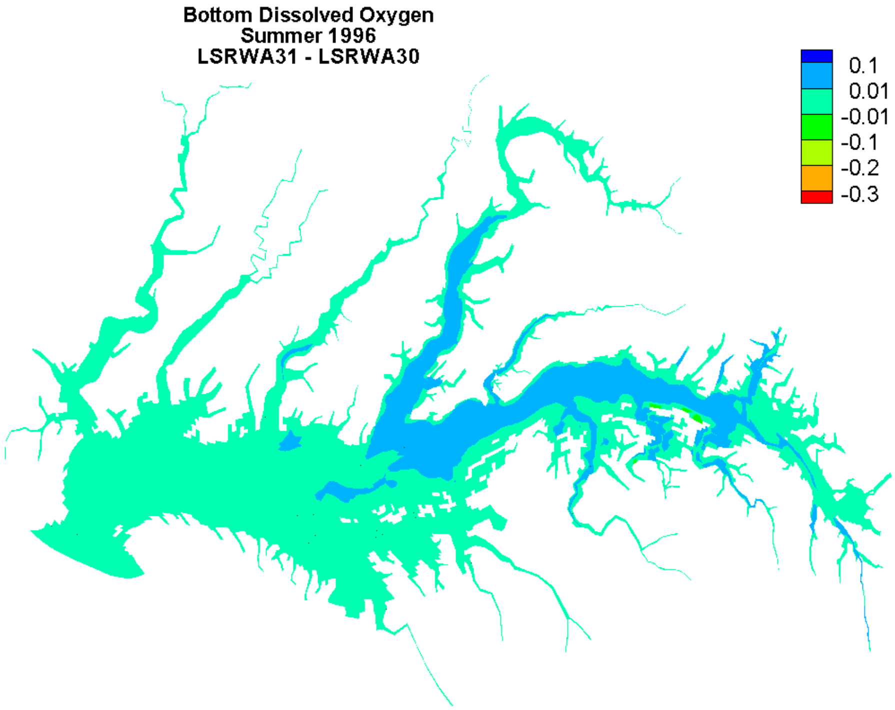

Figure 6-55. Computed effect of dredging back to 1996 bathymetry on bottom dissolved oxygen concentration (g m^{-3} or mg/L) in Chesapeake Bay, averaged over June – August 1996. Positive values indicate DO is higher as a result of dredging.

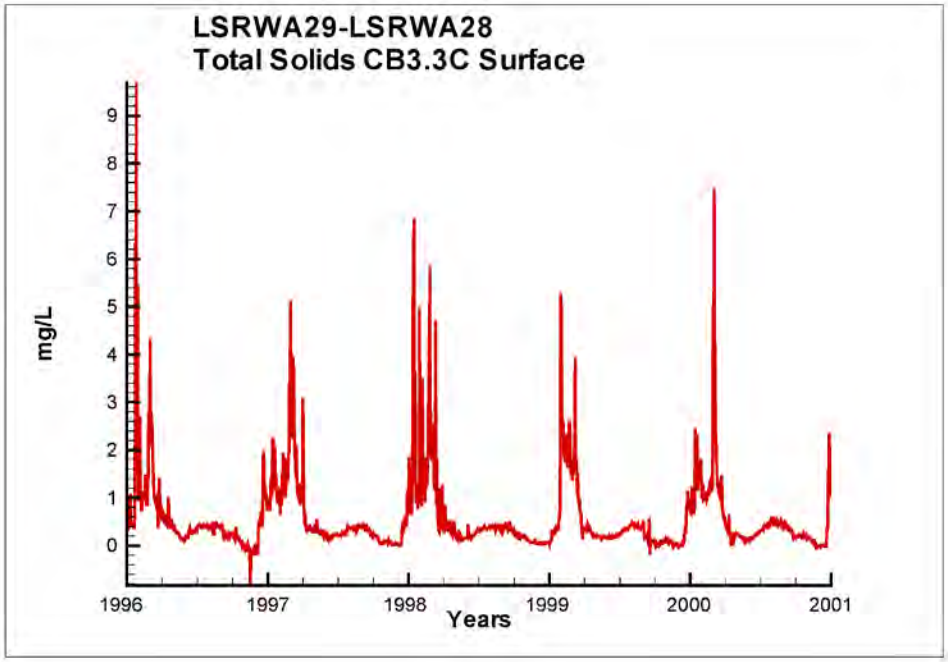

Figure 6-56. Computed increase in surface TSS at Station CB3.3C in Chesapeake Bay resulting from bypassing 3 mcy sediment per annum.

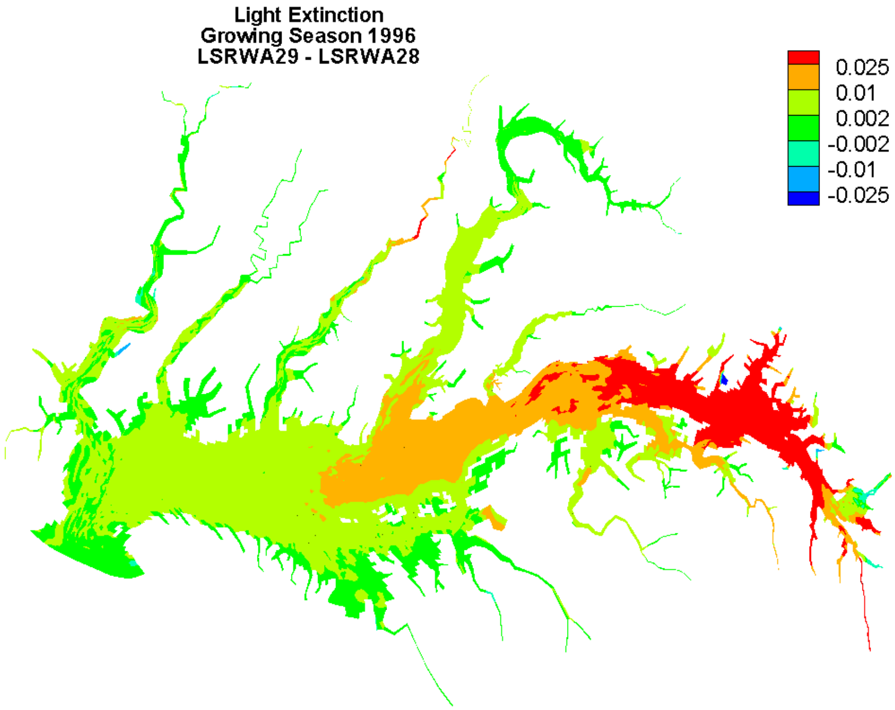

Figure 6-57. Computed increase in light attenuation (m^{-1} or 1/m) in Chesapeake Bay, averaged over 1996 SAV growing season, resulting from bypassing 3 mcy sediment per annum.

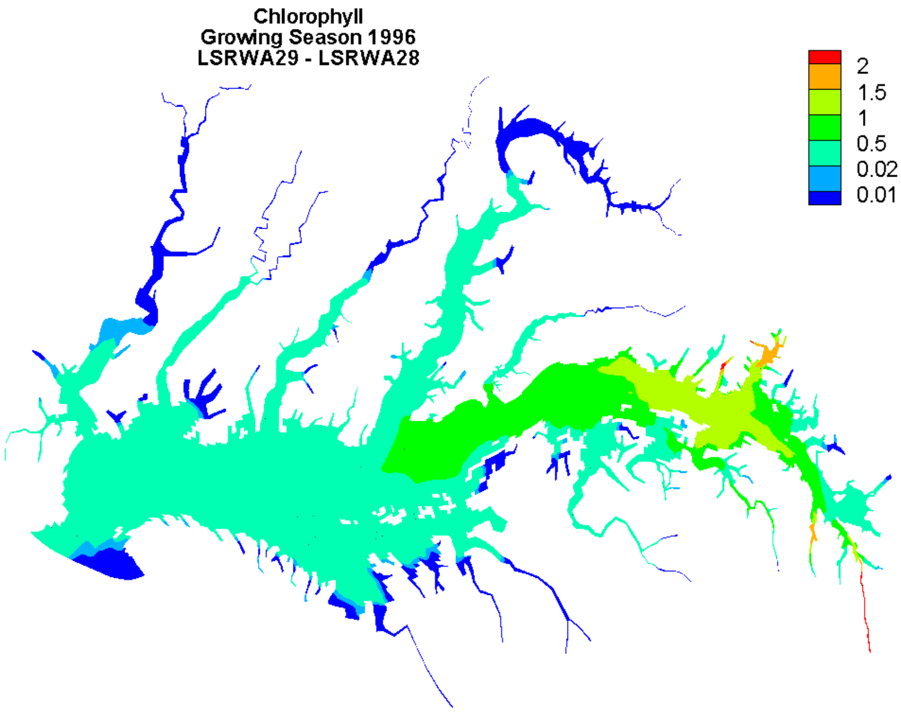

Figure 6-58. Computed increase in surface chlorophyll (mg m^{-3} or µg/L) in Chesapeake Bay, averaged over 1996 SAV growing season, resulting from bypassing 3 mcy sediment per annum.

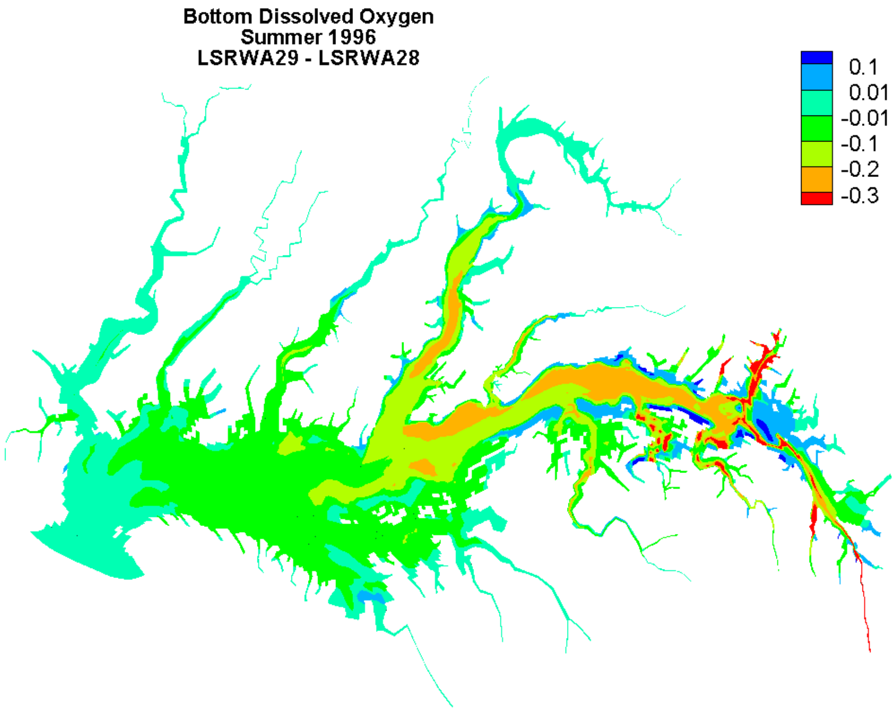

Figure 6-59. Computed effect of bypassing 3 mcy sediment per annum on bottom dissolved oxygen concentration (g m^{-3} or mg/L) in Chesapeake Bay, averaged over June – August 1996. Positive values indicate DO is higher as a result of dredging. Negative values indicate DO is lower.

7 Summary and Conclusions

Introduction

The Susquehanna River empties into the northernmost extent of Chesapeake Bay and provides more than half of the freshwater flow to the estuarine system. A series of dams and reservoirs at the lower terminus of the river regulates flow and influences dissolved and suspended material loads into the bay. Considerable sedimentation has occurred in the reservoirs since the dams were constructed circa 1910 – 1930. Conowingo Reservoir, situated immediately upstream of the bay, was reported to have lost 60% to 70% of its storage capacity by 1997. Recent analysis of loads from the reservoir to the bay associated with the 2011 Tropical Storm Lee event suggest storm-generated loads are now substantially higher than in previous years.

Loss of sediment storage could have environmental consequences for the Chesapeake Bay, especially the portion immediately below the dam. Sediments which pass over the dam and enter the bay, instead of settling to the reservoir bottom, may increase light attenuation, with adverse consequences for submerged aquatic vegetation. Nutrients associated with the sediments may contribute to ongoing eutrophication. Loss of storage may counter or negate load reductions planned under a recently-completed Total Maximum Daily Load (TMDL) program which assumes continued deposition in Conowingo Reservoir at the current rate.

The U.S. Army Corps of Engineers, Baltimore District (USACE), and the state of Maryland (MDE) have entered into a cost-share agreement to conduct Phase I of the Lower Susquehanna River Watershed Assessment (LSRWA). Phase I will:

- Forecast and evaluate sediment loads to the system of hydroelectric dams located on the Susquehanna River,
- Analyze hydrodynamic and sedimentation processes and interactions within the lower Susquehanna River watershed,
- Consider structural and non-structural strategies for sediment management, and
- Assess cumulative impacts of future conditions and sediment management strategies on Chesapeake Bay.

This report emphasizes examination of the impact of reservoir filling on the Chesapeake Bay. Scenarios are presented which examine the impact of scour from a large storm on the bay and which examine benefits from potential remediation efforts. The Chesapeake Bay Environmental Model Package (CBEMP) was the primary tool used to complete these investigations.

The Chesapeake Bay Environmental Model Package

The CBEMP consists of three independent models: a watershed model (WSM), a hydrodynamic model (HM), and a eutrophication model (WQM). The WSM provides daily computations of flow, solids loads, and nutrient loads at the heads of major tributaries and along the shoreline below the tributary inputs. Flows from the WSM are one set of inputs to the Computational Hydrodynamics in Three Dimensions (CH3D) hydrodynamic model. CH3D computes surface level, three-dimensional velocities, and vertical diffusion on a time scale measured in minutes. Loads from the WSM and transport processes from CH3D drive the Corps of Engineers Integrated Compartment Water Quality Model (ICM). ICM computes, in three dimensions, physical properties including suspended solids, algal production, and elements of the aquatic carbon, nitrogen, phosphorus, silica, and oxygen cycles. These are computed on time scales of minutes although computations averaged up to longer time periods, hours to one day, are more representative of observations.

Insights from an Analytical Model

An analytical model was developed of solids transport in Conowingo Reservoir. The model treated the reservoir as a well-mixed system at steady state. Insights from the model included:

1. When volumetric flow is below the erosion threshold, the solids concentration in the reservoir is independent of depth.

2. As reservoir depth decreases, the flow required to initiate erosion, Qe, diminishes.

3. When the erosion threshold is exceeded, the sediment concentration in the outflow is inversely proportional to depth.

The first conclusion is the most significant. This conclusion implies the reservoir is never completely filled. Solids will continue to accumulate until an erosion event occurs. As the reservoir fills, however, the flow threshold to initiate an erosion event diminishes. Erosion events become more frequent and severe.

Scenario Procedure

Chesapeake Bay scenarios are ten years in duration and incorporate the hydrologic record that occurred from 1991 to 2000. This is the record employed in calibration of the CBEMP and incorporates the critical years 1993 – 1995 used in development of the TMDL. The record includes a major scour event in Conowingo Reservoir which occurred in January 1996. Each scenario is preceded by a ten-year spin-up sequence. The spin-up is required to generate initial conditions in the water column and in the sediment bed. Following the spin-up, conditions in the water column and sediments are considered to be in equilibrium with the imposed sediment and nutrient loads.

The scenarios incorporate scour loads from Conowingo Reservoir generated based on alternate bathymetry configurations. Most scenarios employ the “existing” bathymetry, based on a 2008 survey. The “equilibrium” bathymetry is the bathymetry projected to result when sediment loads in and out of the reservoir are in dynamic equilibrium and no net deposition occurs. The “1996” bathymetry is based on a survey completed after the scour event and represents a reservoir with enhanced trapping capacity relative to present conditions. The “dredged” bathymetry is derived from existing bathymetry less 2.3×10^6 m^3 (3×10^6 yd^3) of material removed as a management action.

Roughly thirty scenarios were conducted although all are not reported here. The scenarios described here emphasize examination of the impact of a major storm event. Scenarios were also conducted, under the auspices of the CBP, which examined successive, lesser scour events. These are reported in a document subsequent to this one.

Load Computation

Loads for Chesapeake Bay scenario runs are influenced by hydrology, by land use and management practices in the watershed, by the presence of Conowingo dam, and by the storage capacity of Conowingo Reservoir. Loads from the watershed are calculated by the CBP WSM. The WSM routes watershed loads through Conowingo Reservoir, in which processes including settling, erosion, and transformation are calculated.

The WSM incorporates algorithms to calculate particle settling and erosion in Conowingo Reservoir. The algorithms are parameterized empirically to optimize agreement between computed and observed sediment and nutrient concentrations flowing over Conowingo Dam. During the course of this study, we determined that little or no scouring of bottom material was calculated during the January 1996 flood event. As a consequence, computed solids concentrations and, potentially, particulate nutrient concentrations were less than observed. For the scenarios, solids loads from erosion were calculated independently, based on computations from the ADH model for Conowingo Reservoir, and added to the WSM loads for this event. Nutrient loads associated with bottom erosion were calculated by assigning a fractional nitrogen and phosphorus composition to the eroded solids.

Solids and nutrient loads from bottom scour were computed for a range of bathymetric conditions and solids nutrient composition. Considering TMDL loads calculated for the watershed, solids scour calculated for January 1996, and observed 2011 sediment composition, scour loads comprise the majority of the total storm-generated solids and nutrient loads calculated at the Conowingo Dam. In fact, for solids and phosphorus, the scour loads are the predominant source over the entire winter-spring period. These proportions represent our best estimates for the 1996 flood event under described loading conditions. The proportions of watershed and scour for alternate events, notably Tropical Storm Lee, and alternate loading conditions may be substantially different. One significant finding from the computed loads is that scoured solids contain three times the concentration of nitrogen as phosphorus. Since dissolved nitrogen is a large fraction of the watershed load, however, particulate nitrogen is a smaller fraction of the total, compared to the fraction of particulate phosphorus in the total.

Uncertainty Analysis

Model results can be reported with extensive precision, consistent with the precision of the computers on which the models are executed. Despite the precision, model results are inherently uncertain for a host of reasons including uncertain inputs, variance in model parameters, and approximations in model representations of prototype processes. The uncertainty in model results can be described in quantitative and qualitative fashions. Quantitative measures are usually generated through multiple model runs with alternate sets of inputs and/or parameters. The number of model runs quickly multiplies so that this type of quantitative uncertainty analysis is impractical for complex models with numerous parameters and extensive computational demands. A qualitative, descriptive uncertainty analysis is the practical alternative in these instances.

One source of uncertainty is the use of the WSM to provide solids and nutrient loads at the Conowingo outfall. In fact, the WSM is the sole means for projecting watershed loads once the watershed implementation plans (WIPS) are in place. The WSM also presents the sole means for estimating loads under various hydrologic sequences given existing land uses and management practices (2010 Progress Runs). Still, two sources of uncertainty are inherent in the loading record employed in this study. The first is due to the uncertainties in the WSM itself. The second arises from the unknown hydrologic sequence which will actually occur in the future. The WSM loads, as well as the WQM hydrodynamics, are based on a design hydrologic record that occurred from 1991 to 2000. This exact sequence will not repeat itself in the future.

A second source of uncertainty is in the nutrient loads carried over Conowingo as a result of sediment scour from the reservoir bottom. Two alternative sets of observations were presented here, one based on observations at the outfall in January 1996 (Table 4-4) and one based on observations collected at Conowingo during Tropical Storm Lee in September 2011 (Table 4-3). The nutrients associated with suspended solids differ in the two events with 1996 being lower. In fact, both data sets represent a mixture of solids from the watershed and solids scoured from the bottom so that neither exactly represents the composition of scoured material alone. The 2011 observations are consistent with samples collected in the reservoir bed (see the data summaries presented by Cerco, 2012), are more recent, and represent a typical tropical storm event rather than the anomalous circumstances of January 1996. For this reason, nutrient composition observed at Conowingo in 2011 is preferred to characterize the future and is emphasized in this report. Several key scenarios were repeated with 1996 composition, however, to quantify the uncertainty inherent in the composition of solids scoured from the reservoir bottom.

This study reports that the nitrogen loads associated with the scoured solids exceed the phosphorus loads. While the magnitude of the loads is uncertain, the excess of nitrogen over phosphorus is not. The excess of nitrogen over phosphorus in Conowingo bottom sediments can be seen in in the results of multiple surveys, independent of any model calculations (see the data summaries presented by Cerco, 2012). The ratio of nitrogen to phosphorus in the sediments indicates nitrogen load will exceed phosphorus load any time bottom material is scoured, regardless of the quantity of bottom material.

A third source of uncertainty lies in the reactivity and biological availability of the nutrients scoured from the reservoir bottom. The majority of particle analyses at the Conowingo outfall and in the reservoir bottom sediments quantify simply particulate nitrogen and particulate phosphorus without further defining the nature of the nitrogen or phosphorus. Long experience with the WQM provides guidelines to partition particulate nitrogen and phosphorus into model state variables. Subsets of the available data (e.g. Durlin and Schaffstall, 1997) provide additional analyses including splits between organic and inorganic phosphorus and plant-available phosphorus. In view of the sporadic nature of the additional analyses and the passage of time since the data collection, we opted to maintain the accepted, consistent particle composition we have employed throughout the WQM application. Still, we must acknowledge the uncertainty in the particle composition and, consequently, the processes by which particulate nutrients are transformed into biologically available forms.

One remaining source of uncertainty lies in the nature of scour events at this time and into the future. This report is oriented towards the analysis of a single large event. Recent reports suggest that the trend of recent scour events is for smaller, more frequent events (Hirsch, 2012). This result is not without controversy. For example, direct physical observations of scour at flows less than the commonly accepted threshold of 11,300 $m^3 s^{-1}$ are absent. The amount of material available to be scoured will also decrease into the future as watershed implementation plans come into effect. Still, the potential for the future alternative of smaller, more frequent scour events cannot be ignored. Scenarios based on this assumption were conducted for the EPA CBP and are the subject of an upcoming report.

Scenario Results

Reporting concentrated on scenarios involving TMDL loads in combination with bottom scour. Scenarios examined the impact of scour under alternate reservoir bathymetries, the potential ecosystem benefits of the dam, the potential for remediation of scour impacts, and the potential impact of sediment bypassing. One over-arching conclusion from the scenarios is that the solids loads are not the major threat to bay water quality. For most conditions examined, solids from bottom scour settle out before the period of the year during which light attenuation is critical. The nutrients associated with the solids are more detrimental. The particulate nutrients settle to the bottom and are mineralized in bottom sediments. The mineralized nutrients are recycled to the water column in dissolved form and stimulate algal production. Algal organic matter decays and consumes oxygen in the classic eutrophication cycle. As a consequence, dissolved oxygen is diminished by reservoir scour events.

Effect on TMDL Conditions

The TMDL for Chesapeake Bay is aimed at attaining and maintaining desirable conditions of chlorophyll concentration, water clarity, and dissolved oxygen concentration. The computed impact of storm scour associated with the January 1996 flood event on TMDL conditions is small in magnitude relative to projected ambient conditions. Averaged over the SAV growing season, the median increase in growing-season light attenuation in any year is less than 0.01 m^{-1}. Computed chlorophyll increases by 0.1 to 0.3 mg m^{-3} over a widespread area extending into the lower Potomac River and below the mouth of the Potomac in the mainstem bay. Bottom-water dissolved oxygen declines up to 0.2 g m^{-3} although the decline is 0.1 g m^{-3} or less when averaged over the summer season. Although this decline is small in magnitude, the implications could be significant for the TMDL in regions where the projected DO concentration, in the absence of scour, just meets the standards. Determination of the significance of the decline depends on analyses from the CBP which are part of this project.

Scour events can occur at various times of the year, depending on the mechanism behind the flood event. Model computations indicate that an autumn event has the least detrimental impact on Bay water quality. A late spring storm has the greatest impact.

One-time dredging of 3 mcy (2.3×10^6 m^3) of material from Conowingo Reservoir reduces scour of solids and nutrients by 32% relative to conditions computed for the January 1996 event and 2011 bathymetry. The impact of this reduction on computed chlorophyll and light attenuation, averaged over the SAV growing season, is less than 1%. Computed bottom DO improves by 0.01 to 0.04 g m^{-3}. Averaged over the summer season, however, the improvement is roughly 0.02 g m^{-3} and of limited spatial extent. Overall reduction in anoxia (DO < 1 g m^3) is 1.7%.

The nature of the response to removal of 28 mcy is similar to the response to the removal of 3 mcy although the magnitude of the effects is greater, especially for CHL and DO. Surface chlorophyll concentration is reduced by peak values of 0.1 to 0.2 mg m^{-3} during the SAV growing season. Averaged over the 1996 growing season, the improvements in CHL are roughly 0.05 mg m^{-3}. During the summer months, the instantaneous improvement in calculated bottom DO is nearly double the improvement from dredging 3 mcy. Instantaneous improvements of 0.05 g m^{-3} are calculated for several years following the scour event and extend along the upper bay and into the lower Potomac River. Anoxia is reduced by up to 15% in some segments of the system and by 2.8% overall.

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Durlin, R., and Schaffstall, W. (1997). "Water Resources Data Pennsylvania Water Year 1996," Vol. 2 Susquehanna and Potomac River Basins. US Geological Survey, Lemoyne PA.

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Scott, S., and Sharp, J. (2013). “Sediment transport characteristics of Conowingo Reservoir,” prepared for U.S. Army Corps of Engineers Baltimore District by Engineer Research and Development Center, Vicksburg MS.

Attachment C-1:
Data Assembly for Application of the CBEMP in the Lower Susquehanna River Watershed Assessment