# Appendix D:
# Estimated Influence of Conowingo Infill on the Chesapeake Bay Water Quality

# Estimated Influence of Conowingo Reservoir Infill on Chesapeake Bay Water Quality

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## INTRODUCTION

As part of the Lower Susquehanna River Watershed Assessment (LSRWA), the influence of the Conowingo Reservoir infill on Chesapeake water quality was assessed using Delaware, District of Columbia, Maryland, and Virginia's water quality standards that were developed and adopted into state water quality regulations to protect Chesapeake Bay living resources. The Susquehanna River basin, sitting at the headwaters of Chesapeake Bay, is the Bay's largest watershed and drains an area of 27,500 square miles, 43 percent of the Chesapeake Bay's total watershed, covering half of Pennsylvania, and portions of New York and Maryland. The Susquehanna River delivers about 41 percent of the nitrogen loads, 25 percent of the phosphorus loads, and 27 percent of the suspended solids loads on an annual average basis (CBPO, 2012 Phase 5.3.2 Watershed Model 1991-2000 simulation period). The infill condition of the three lower Susquehanna River reservoirs contributes a portion of the nutrient and sediment loads delivered to Chesapeake Bay (Hirsch, 2012; Zhang et al., 2013).

The Chesapeake Bay Program (CBP) Partnership, a state-federal partnership, is an ongoing effort in restoring the national treasure which is the United States' largest estuary. Chesapeake Bay restoration work has now been underway for three decades, and in 2010 a new tool was added to the restoration effort when the nation's most extensive Total Maximum Daily Load (TMDL) program was established for the Chesapeake Bay watershed (USEPA, 2010a). The Chesapeake Bay TMDL was required under the federal Clean Water Act and responded to consent decrees in Virginia and the District of Columbia from the late 1990s. By 2007, an assessment of nutrient loads found that estimated nutrient and sediment load reductions by 2010 would be insufficient to avoid a Chesapeake Bay TMDL, and work began in 2008 to ensure completion of the TMDL allocations by 2010 (USEPA, 2008a).

The Clean Water Act sets an overarching environmental goal that all waters of the United States be "fishable" and "swimmable." Specifically, it requires the Chesapeake Bay states and the District of Columbia to establish appropriate uses for their waters, adopt water quality standards that are protective of those uses, and list waterways that are impaired by pollutants causing them to fail to meet water quality standards. For waterways on the impaired list, a TMDL must be developed which identifies the maximum amount of pollutants the waterway can receive and still meet water quality standards. Most of Chesapeake Bay and its tidal tributary and embayment waters are impaired because of excess nitrogen, phosphorus, and sediment (USEPA, 2010a). These pollutants enter the water from agricultural operations, urban and suburban stormwater runoff, wastewater facilities, air pollution, septic systems, and other sources.

More than 49,000 TMDLs have been completed across the United States, but the Chesapeake Bay TMDL is the most extensive and complex thus far (Linker et al., 2013a) . It is designed to achieve significant reductions in nitrogen, phosphorus, and sediment pollutant loads throughout a 64,000-square-mile watershed. The Chesapeake watershed has a population of over 17 million people and includes portions of Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia, and all of the District of Columbia (USEPA, 2010a). The Chesapeake Bay TMDL is a combination of 276 individual TMDLs—separate nitrogen, phosphorus, and sediment TMDLs for each of the 92 Chesapeake Bay tidal segments shown in Figure 1.

The Chesapeake Bay TMDL incorporates several key elements. Water quality standards that are scientifically-based and publically understandable are among the most important. The Chesapeake Bay water quality standards are based on requirements for the Bay's living resources to thrive, including adequate dissolved oxygen (DO) in deep-water habitats, appropriate levels of chlorophyll as a source of food at the base of the estuarine food web, and good water clarity in the shallow waters necessary for growth of underwater grasses which provide habitat for juvenile fish and crabs (USEPA, 2010c). Other elements include a time and space accounting of estimated water quality impairments (Keisman and Shenk, 2013) and a quantifiable TMDL 2010 Chesapeake allocation process for the Chesapeake that ensures achievement of all tidal water quality standards while assessing equitable levels-of-effort in reducing nutrients and sediments across all seven watershed jurisdictions (Linker et al., 2013a).

Developing the 2010 Chesapeake Bay TMDL and associated allocations involved the selection of a 10-year average hydrologic period that had an equitable distribution of high and low flow periods across the major basins (USEPA, 2010a; 2010b). This hydrologic period was then used to set the average long-term watershed allocation loads. Within the 10-year average period, a particular 3-year critical period was chosen that would serve as the assessment period of the tidal water quality standards. The 3-year period was selected as representative of a 10-year return frequency of high flows and loads (USEPA, 2010b). The 10-year average hydrologic period chosen was 1991-2000 and the key 3-year critical period for DO was 1993-1995 (USEPA, 2010a; 2010b). A time and space approach was used to assess the water quality standards, which allowed the comparison of observed and model simulated water quality conditions to criteria and reference conditions in healthy living resource sites, to determine if Delaware, District of Columbia, Maryland, and Virginia's Chesapeake Bay water quality standards were achieved (USEPA, 2003, 2010a, 2010b; Keisman and Shenk, 2013).

The 2010 Chesapeake Bay TMDL sets watershed-wide limits of 186 million pounds (84.3 million kilograms) of nitrogen, 12.5 million pounds (5.67 million kilograms) of phosphorus, and 6.46 billion pounds (2.93 billion kilograms) of sediment per year (USEPA, 2010a). Implementation of the nutrient and sediment limits is through the seven watershed jurisdictions' Watershed Implementation Plans (WIPs), which detail how and when the six Chesapeake Bay watershed states and the District of Columbia will complete implementation of management actions sufficient to meet their assigned pollution allocations.

The infill of the Conowingo Reservoir with the increased sediment and associated nutrient loads delivered to Chesapeake Bay creates a potential challenge in meeting the jurisdictions' Chesapeake Bay water quality standards with the nutrient and sediment reduction goals already set in the 2010 Chesapeake Bay TMDL allocations. A major Midpoint Assessment of the Chesapeake Bay TMDL and its progress to date is planned for 2017 (CBP Partnership, 2012). During the 2017 Midpoint Assessment, decisions will be made by the CBP Partnership regarding any necessary adjustments to the Chesapeake Bay TMDL and the jurisdictions' WIPs in order to account for Conowingo Reservoir infill and offset any additional sediment and associated nutrient pollutant loads to Chesapeake Bay and their impact on the jurisdictions' Chesapeake Bay water quality standards attainment.

## THE CBP PARTNERSHIP'S MODELING SYSTEM

The collaborative work and decision making of hundreds of representatives from state, federal, and local agencies, universities, and non-governmental organizations was required for the development of the Chesapeake Bay TMDL (USEPA, 2010a). Decisions were supported by decades of scientific discovery as well as the application of a suite of integrated environmental models. Models of the Chesapeake Bay airshed (Community Multi-scale Air Quality Model – CMAQ, watershed (Watershed Model (WSM) Phase 5.3.2), and tidal Bay water quality (Water Quality and Sediment Transport Model – WQSTM) were applied to develop the 2010 Chesapeake Bay TMDL allocations (Cerco, 2000; Cerco et al., 2002; Cerco and Noel, 2004; Linker et al., 2000; Linker et al., 2008; Cerco et al., 2010; Shenk and Linker, 2013; Linker et al., 2013; Cerco and Noel, 2013).

The CBP Partnership's airshed, watershed, and Bay tidal water quality models that were used to develop the Chesapeake Bay TMDL were used in the LSRWA study to predict water quality conditions for the more than 30 Conowingo Reservoir infill loading scenarios. The Chesapeake Bay Watershed Model provided the estimated Susquehanna River watershed loads in the LSRWA study (Shenk and Linker, 2013) and the Chesapeake Bay WQSTM model was a key element to the assessment of Chesapeake Bay water quality responses (Cerco et al. 2013). Interposed between the Watershed Model of the Susquehanna River watershed and the WQSTM model of the Chesapeake Bay were the HEC-RAS and ADH models of the Lower Susquehanna reservoirs described in Appendices A and B. The Chesapeake Bay airshed model provided atmospheric nitrogen deposition loads to the Chesapeake watershed and tidal waters. Atmospheric deposition is one of the largest nitrogen sources to the Chesapeake Bay (Linker et al., 2013).

It was necessary to compare the Chesapeake Bay WQSTM model results with the applicable jurisdictions' Chesapeake Bay water quality standards regulations to determine estimated compliance with the standards. In general, to determine the degree of water quality standard achievement, model scenarios were run representing different Conowingo Reservoir infill management conditions using the CBP Partnership's suite of models (Linker et al., 2013; Shenk and Linker, 2013 Cerco et al., 2013). The resultant combined model simulated nitrogen, phosphorus, and sediment loadings were used as input into the Bay WQSTM to evaluate the response of critical water quality parameters, specifically DO, submerged aquatic vegetation (SAV), and water clarity.

To quantify the degree to which the different Conowingo Reservoir infill analysis scenarios' estimated Bay water quality conditions were projected to meet the jurisdictions' Chesapeake Bay DO and SAV-clarity water quality standards, the Bay WQSTM's simulated tidal water quality responses for DO, SAV, and water clarity were compared to the corresponding observed monitoring values collected during the same 1991-2000 hydrological period as described in Keisman and Shenk (2013). In other words, the Chesapeake Bay WQSTM was primarily used to estimate the *change* in water quality that would result from various modeled loading scenarios. Figure 2 provides an overall representation of the CBP Partnership's Modeling System.

The full simulation period of the key Chesapeake Bay airshed, watershed, and estuary water quality models used in the Chesapeake Bay TMDL allocation analysis were from 1985 to 2005, but the hydrologic period chosen to represent the long-term hydrologic conditions for the Chesapeake Bay watershed in the Chesapeake TMDL was for the ten years of 1991-2000 (USEPA, 2010b). The ten year period provided average long-term simulation conditions for each state jurisdiction of the Chesapeake Bay watershed and the Bay's tidal waters so that all Bay watershed states had a representative mix of point and nonpoint loads under a wide range of high to low river flows. The selection of a representative hydrologic averaging period was determined by examining the statistics of long-term flow relative to each 10-year period at nine key USGS gauging stations, which measure the discharge of the major rivers flowing to the Bay (USEPA, 2010b). The 10-year average period was used to set 10-year average loads in the 2010 Chesapeake Bay TMDL allocations.

## KEY HYDROLOGIC PERIODS

Within the 10-year hydrologic period a 3-year critical period was chosen, which was used as the assessment period of the water quality standards in the tidal Bay. The critical period was based

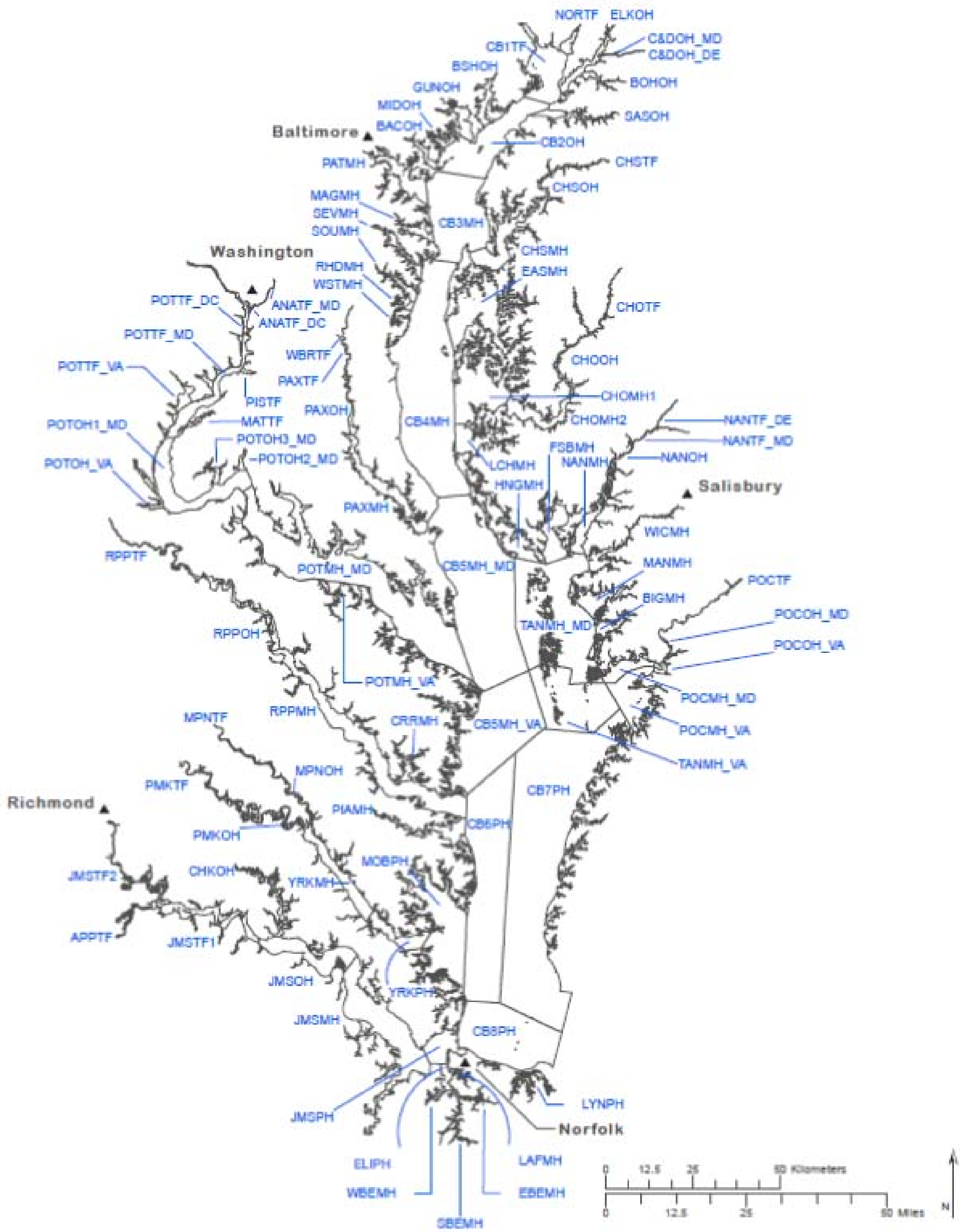


Figure 1. The 92 Chesapeake Bay TMDL segments.

Source: USEPA 2004a, 2005, 2008b

on key environmental factors, principally rainfall and streamflow, which influenced the DO water quality standard in the deep-water and deep-channel habitats of the Chesapeake Bay. The critical period and conditions determined major design conditions of the Chesapeake Bay TMDL [40 CFR 130.7(c)(1)] (CFR, 2011), in particular the period of loads, flows, and other environmental conditions during which the water quality standards were assessed in the tidal waters.  The 3-year period selected as the critical period was 1993-1995, which was the second highest flow period of all the eight 3-year contiguous periods contained in the 1991-2000 record. In Chesapeake Bay, high flows bring high levels of nutrient and sediment loads, resulting in more DO and SAV-clarity impairments. The 1993–1995 critical period was chosen because it experienced stream flows that historically occurred about once every 10 years, which is typical of the return frequency for hydrological conditions employed in developing TMDLs in the Chesapeake Bay region (USEPA, 2010b). While the modeling for the Chesapeake Bay TMDL consisted of an assessment of the entire hydrologic period of 1991–2000 for many aspects of the allocation, including the 10 year average loads of the basin-jurisdictions, the water quality conditions during the 1993–1995 critical period was specifically used to assess attainment of the four jurisdictions' Chesapeake water quality standards.

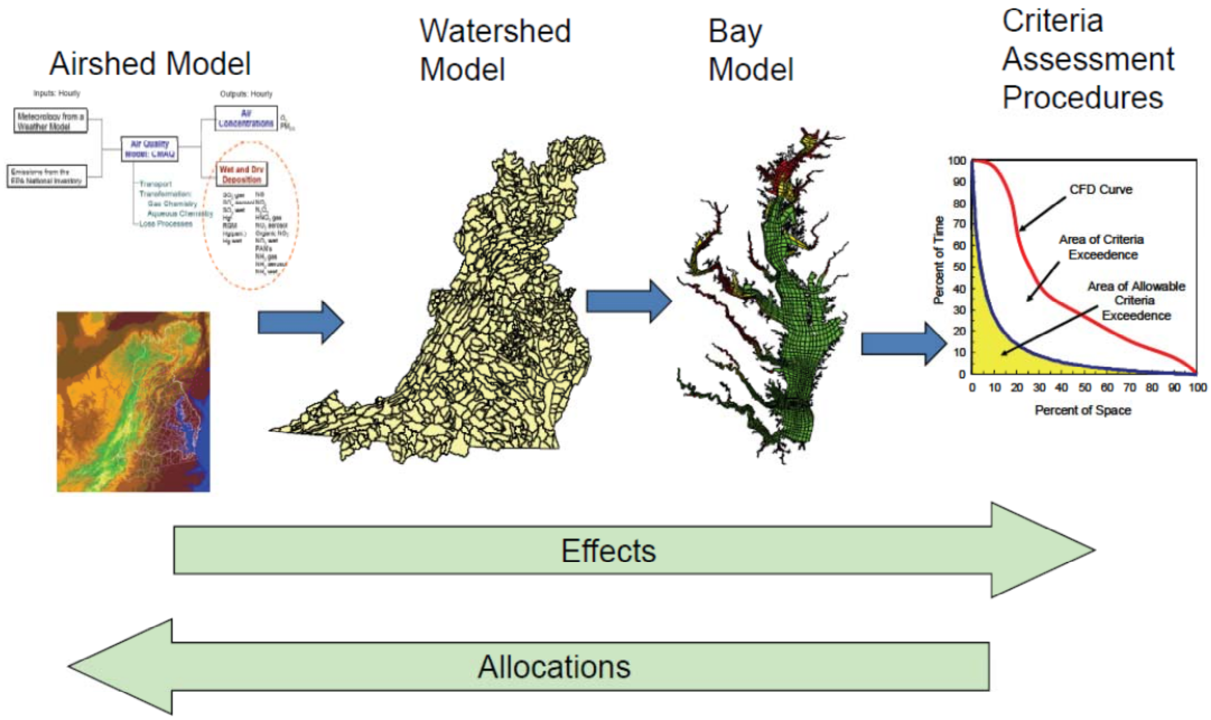


Figure 2. CBP Partnership decision-support simulation system including the Chesapeake Bay airshed, watershed and estuary models along with the criteria assessment procedures for water quality standard assessment.

Source: USEPA 2010a.

The highest 3 year flow and load period contained the January 1996 Susquehanna extreme flow event of the *Big Melt*, an event that was brought about by a rain event during a warming trend on existing snow pack in the lower Susquehanna. The Big Melt occurred in January 1996, which led to extreme flows and flooding because of a period of warmer weather and extensive rain on snowpack, as well as the formation and subsequent breaching of an ice dam (SRBC, 2006). For January 1996, precipitation over the entire Susquehanna River basin was above average, with the upper portion of the basin receiving more than 75 percent above normal. Snowpack over the upper portion of the basin through January 12 averaged 8 to 10 inches. Mild temperatures, combined with a precipitation event of 0.75 to 1.50 inches, caused the January 1996 flood event (SRBC, 2006). The January 1996 event was used extensively in the LSRWA scenarios described in this report because it is the highest observed and simulated flow within the 10 year simulation period of the CBP Partnership's models used in the LSRWA assessment. The January 1996 event was outside the 1993-1995 Chesapeake Bay TMDL critical period, so adjustments to the criteria assessment procedures of the Chesapeake Bay water quality standards were applied as described below to compare water quality results in the 1996-1998 three-year period.

## CHESAPEAKE BAY WATER QUALITY STANDARDS

A good TMDL is based on scientifically sound and publically understandable water quality standards (Tango and Batiuk, 2013). In 2003, the Chesapeake Bay Program partners worked with the U.S. Environmental Protection Agency to develop and publish ambient water quality criteria protective of five specific Chesapeake Bay tidal water designated uses along with assessment procedures for dissolved oxygen, SAV, water clarity, and chlorophyll *a* criteria (USEPA, 2003a; b). The adoption of these criteria, designated uses, and assessment procedures into Delaware, District of Columbia, Maryland, and Virginia's water quality standards regulations ultimately provided the basis for developing the 2010 Chesapeake Bay TMDL (USEPA, 2010a). Table 1 lists the Chesapeake Bay DO criteria. The SAV-clarity criteria can be found in USEPA (2010c). The chlorophyll *a* water quality standard has little bearing on the analysis of Conowingo Reservoir infill because the only numeric chlorophyll standards are in the tidal fresh waters of the District of Columbia and in the tidal James River in Virginia (USEPA, 2010a). Both are tidal bodies of water that are too far removed from the Conowingo Reservoir to be influenced by it.

Water quality criteria are usually numerical, although sometimes narrative, values of environmental parameters (chemical, biological, and physical) which reflect concentrations, levels, or conditions protective of desired aquatic life species and communities. Water quality standards, on the other hand, are the combination of criteria, designated uses (defining the desired human and/or aquatic life uses of the subject water body), and antidegradation statements (commitments not to degrade the current water quality conditions) promulgated and adopted into states' water quality standard regulations through a public process and final approval by U.S.

EPA. In the case of the four Chesapeake Bay jurisdictions with tidal waters of the Chesapeake Bay within their respective jurisdiction, i.e., Delaware, the District of Columbia, Maryland, and Virginia, their water quality standards regulations also include descriptions of, and references to, more detailed criteria attainment assessment procedures (USEPA, 2010c).

The DO criteria were designed to be protective of living resources in all major habitat regions of the Chesapeake including regions of open surface waters, migratory fish spawning areas, deep-water habitats, and deep-channel areas (Batiuk et al., 2009; USEPA, 2003a; 2003d; Tango and Batiuk, 2013). The SAV-clarity criteria were protective of the shallow water regions of the Chesapeake (USEPA, 2003a, 2003b, 2004, 2007a; Kemp et al., 2004; Tango et al., 2013). The DO, chlorophyll-*a*, and SAV-clarity criteria were adopted into water quality standard regulations by all of the tidewater Chesapeake Bay Program jurisdictions of Virginia, Maryland, Delaware, and the District of Columbia (USEPA, 2003a, 2003b, 2003c, 2007a, 2007b, 2010a).

Under simulated conditions of the estimated 1985 nutrient and sediment loads the water quality standard violations of surface Open-Water, Deep-Water, and Deep-Channel DO criteria, and chlorophyll *a* spring and summer criteria were estimated by the WQSTM to be widespread, particularly in the Deep-Water and Deep-Channel of the mainstem, with 110 violations (USEPA, 2010a). Under the 2009 model estimated load conditions, in which nutrient loads were reduced about half way toward the Chesapeake TMDL load levels, the number of total DO water quality criteria violations decreased to 34. By the time the estimated nutrient and sediment loads of the 2010 Chesapeake Bay TMDL were achieved, the model simulation the number of water quality criteria violations was estimated by the WQSTM to be zero (USEPA, 2010a).

## TIME AND SPACE ASSESSMENT OF STANDARDS ATTAINMENT

The degree of achievement of the Chesapeake Bay water quality standards was assessed through quantitative analyses of the WQSTM scenario results for each Chesapeake Bay segment (see Figure 1). The same methods used for the 2010 Chesapeake Bay TMDL were used for the analysis of the Conowingo Reservoir LSRWA scenarios and consisted of an assessment of the percent of time and space that the modeled water quality results exceeded the allowable criterion concentration as described in USEPA, 2003a, 2004a, 2007a, 2008b, 2010c; and Keisman and Shenk, (2013).

| Designated Use | Criteria Concentration/Duration | Protection Provided | Temporal Application |
|---|---|---|---|
| **Migratory fish spawning and nursery use** | Seven-day mean ≥6mg/l (tidal habitats with 0-0.5 ppt salinity | Survival and growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species | February 1-May 31 |
| | Instantaneous minimum ≥ 5 mg/l | Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species | |
| | Open-water fish and shellfish designated use criteria apply | | June 1-January 31 |
| **Shallow-water Bay grass use** | Open-water fish and shellfish designated use criteria apply | | Year-round |
| **Open-water fish and shellfish use** | 30-day mean ≥5.5 mg/l (tidal habitats with 0-0.5 ppt salinity) | Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species | Year-round |
| | 30-day mean ≥5 mg/l (tidal habitats with >0.5 ppt salinity) | Growth of larval, juvenile, and adult fish and shellfish; protective threatened/ endangered species | |
| | Seven-day mean ≥ 4 mg/l | Survival of open-water fish larvae | |
| | Instantaneous minimum ≥ 3.2 mg/l | Survival of threatened/ endangered sturgeon species | |
| **Deep-water seasonal fish and shellfish use** | 30-day mean ≥ 3 mg/l | Survival and recruitment of Bay anchovy eggs and larvae | June 1-September 30 |
| | One-day mean ≥ 2.3 mg/l | Survival of open-water juvenile and adult fish | |
| | Instantaneous minimum ≥ 1.7 mg/l | Survival of Bay anchovy eggs and larvae | |
| | Open-water fish and shell designated use criteria apply | | October 1-May 31 |
| **Deep-channel seasonal refuge use** | Instantaneous minimum ≥ 1 mg/l | Survival of bottom-dwelling worms and clams | June 1-September 30 |
| | Open-water fish and shellfish designated use criteria apply | | October 1-May 31 |

**Table 1**. Chesapeake Bay dissolved oxygen criteria (mg/L = milligrams per liter; ppt = parts per thousand salinity)
Source: USEPA 2003a

Figure 3 is a graphical representation of the water quality standards assessment in a Chesapeake Bay segment. The green reference curve represents the maximum allowable exceedance of the criterion concentration in space and time. The reference curve is based on observations of healthy ecosystem habitats for the assessed criterion where those observations exist with a default reference curve used in other areas.  If any part of the blue assessment curve is above the reference curve, the segment is considered to be violation of the standard.  The yellow area represents the fraction of space and time that are allowable exceedances of the criterion concentration.  The red area represents unallowable exceedances and the unshaded area represents non-exceedances.

The same approach of considering the time and space of the critical hydrologic conditions is applied in the assessment of the water quality standards achievement with observed monitoring data.  Ultimately, the time and space of water quality criteria exceedances are assessed against a reference curve derived from healthy living resource communities to determine the degree of water quality standard attainment (USEPA, 2007; Tango and Batiuk, 2013).  Other more detailed aspects of the 2010 Chesapeake Bay TMDL, including consideration of daily loads and margins of safety, are described in the extensive Chesapeake Bay TMDL documentation and supporting appendices (USEPA, 2010a; b).

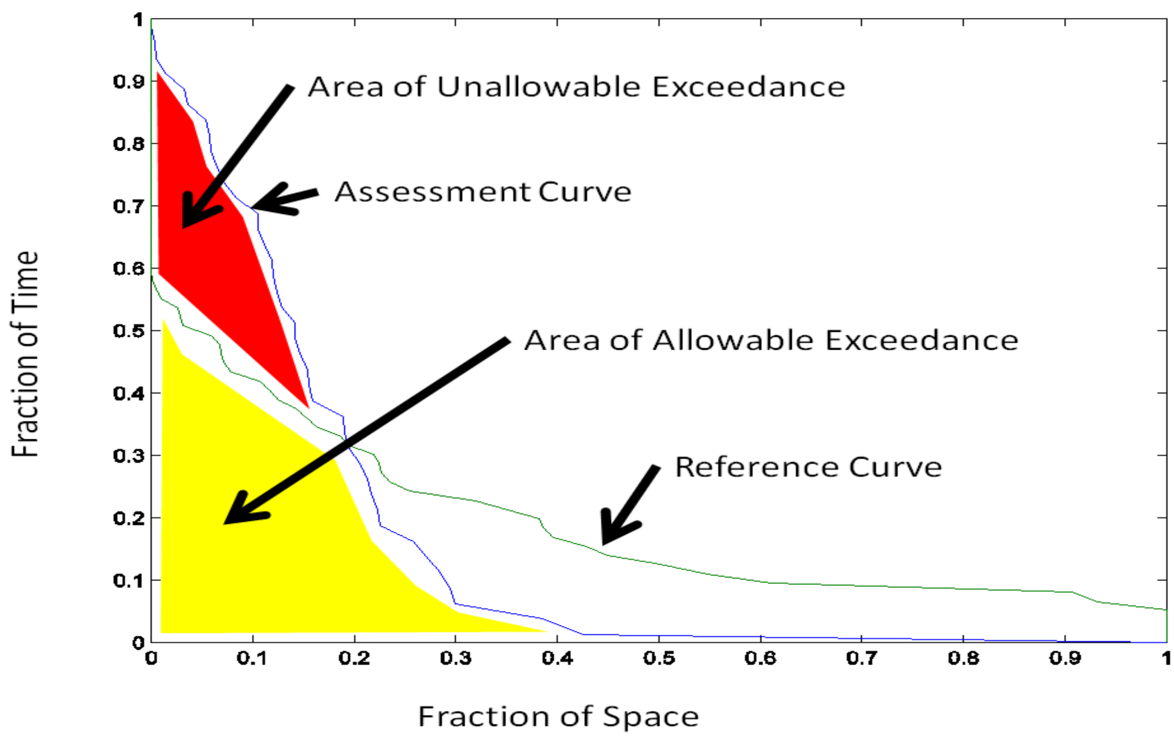


**Figure 3**. The analysis applied for each TMDL CB segment to determine the percent time and space that the simulated Chesapeake Bay water quality results exceeded the allowable concentration.

Source: USEPA 2003a.

## RESULTS

### *Scenarios Employed In the LSRWA Study*

A series of scenarios were employed in the LSRWA study. The scenarios applied different loading conditions in the Susquehanna River watershed, different bathymetries of the Conowingo Reservoir, different management actions to mitigate Conowingo infill conditions, and used different simulation tools. A list of the LSRWA scenarios described in the section below is adapted from Appendix C.

**LSRWA-3** This is the base TMDL Watershed Implementation Plan (WIP) Scenario which represents the future conditions when all of the point source, nonpoint source, and atmospheric emission controls are in place in order to achieve the 2010 Chesapeake Bay TMDL in 2025. The LSRWA-3 Scenario uses only the HSPF simulation of scouring in the Conowingo and was developed solely with the Chesapeake Bay Watershed Model Phase 5.3.2. See Figure 4-2 of Cerco and Cole, Appendix D (this report) to see the observed and computed suspended solids at the Conowingo outfall during January 1996 for the WSM alone and for the WSM with additional erosion load.

**LSRWA-4** This is the estimated existing current condition scenario which applies the simulation conditions of the estimated 2010 Chesapeake Bay watershed land use, management actions, populations, point source loads and atmospheric deposition loads. The LSRWA-4 Scenario uses only the HSPF simulation of scouring in the Conowingo and was developed solely with the Chesapeake Bay Watershed Model Phase 5.3.2. See Figure 4-2 of Cerco and Cole, Appendix D (this report) to see the observed and computed suspended solids at the Conowingo outfall during January 1996 for the WSM alone and for the WSM with additional erosion load.

**LSRWA-21** This is the WIP Scenario (LSRWA-3) with scouring adapted from ADH for the January 1996 storm. This run shows the effect of scouring on the Chesapeake Bay TMDL allocations. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models. The ADH model employed the Conowingo Reservoir bathymetry based on surveys conducted in 2011. The nutrients associated with the solids scoured from the Conowingo Reservoir were based on observations collected during Tropical Storm Lee in 2011.

**LSRWA-22** This is the WIP Scenario (LSRWA-3) with scouring adapted from ADH for the January 1996 storm. This scenario is the same as LSRWA-21 except that the nutrients associated with the solids scoured from the Conowingo Reservoir were based on observations collected during the January 1996 scour event.

**LSRWA-23** This is the WIP Scenario (LSRWA-3) with the January storm removed. The scenario was developed solely with the Chesapeake Bay Watershed Model Phase 5.3.2 model.

**LSRWA-24** This is the LSRWA-21 Scenario with the January 1996 storm flows, loads, and scour moved to the June timeframe. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models. The ADH model employed the Conowingo

Reservoir bathymetry based on surveys conducted in 2011. The nutrients associated with the solids were based on observations collected during Tropical Storm Lee in 2011.

**LSRWA-25** This is the LSRWA-21 Scenario with the January 1996 storm flows, loads, and scour moved to the October timeframe. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models. The ADH model employed the Conowingo Reservoir bathymetry based on surveys conducted in 2011. The nutrients associated with the solids were based on observations collected during Tropical Storm Lee in 2011.

**LSRWA-26** This is the LSRWA-21 Scenario with the January 1996 storm flows, loads, and scour moved to the June timeframe. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models. The ADH model employed the Conowingo Reservoir bathymetry based on surveys conducted in 2011. The nutrients associated with the solids scoured from the Conowingo Reservoir were based on observations collected during the January 1996 scour event.

**LSRWA-27** This is the LSRWA-21 Scenario with the January 1996 storm flows, loads, and scour moved to the October timeframe. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models. The ADH model employed the Conowingo Reservoir bathymetry based on surveys conducted in 2011. The nutrients associated with the solids scoured from the Conowingo Reservoir were based on observations collected during the January 1996 scour event.

**LSRWA-28** This is the LSRWA-21 Scenario with scouring adapted from the ADH model based on the removal of 3 million cubic yards (mcy) by dredging. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models. The ADH model employed the Conowingo bathymetry based on surveys conducted in 2011 combined with the removal of the removal of 3 million cubic yards (mcy) from high depositional regions in the Conowingo Reservoir.

**LSRWA-29** This is the LSRWA-21 Scenario representing sediment and associated nutrient loads delivered to the tidal Chesapeake Bay equivalent to bypassing 3 mcy of dredged sediment during December – February of each year. Dredging and bypassing eventually result in the 1996 bathymetry at some period between one and two decades because of ongoing infill (followed presumably by continuous dredging operations to maintain 1996 bathymetry). Because the high flow event is assumed to happen at some intermediate, unknown bathymetry, the January 1996 high flow condition is represented by the bathymetry and scour produced by the dredging of 3 mcy scenario (LSRWA-28). The LSRWA-29 Scenario shows the effect of bypassing dredged material on sediment and associated nutrient loads to the tidal Chesapeake and resultant estimated Chesapeake Bay water quality conditions. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models.

**LSRWA-30** This is the LSRWA-21 Scenario with scouring for the January 1996 storm adapted from the ADH model with the Conowingo Reservoir at equilibrium bathymetry. Equilibrium bathymetry is the representation when the Conowingo Reservoir is full. The scenario employs bathymetry estimated to prevail when the reservoir achieves long-term equilibrium between sediment and associated nutrient loads in and sediment and associated nutrient loads out. Equilibrium bathymetry is equivalent to the 2011 bathymetry in the scour and discharge behavior of sediment and associated nutrients from the Conowingo Reservoir. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models.

**LSRWA-31** This is the LSRWA-21 Scenario with scouring adapted from the ADH model based on 1996 Conowingo Reservoir bathymetry. The LSRWA-31 scenario is a representation of the bathymetry resulting from dredging 27 mcy from the current (2011) reservoir bathymetry conditions back to the 1996 bathymetry conditions. This run shows the effect of removing 27 mcy of sediment and associated nutrient loads from the Conowingo Reservoir and the resultant estimated Chesapeake Bay water quality conditions. The scenario was developed with the Chesapeake Bay Watershed Model Phase 5.3.2 and ADH models.

### *DO Water Quality Standard Results*

The process used for determining the influence of Conowingo Reservoir infill on the achievement of the jurisdictions' DO water quality standards in the Bay's Deep-Channel, Deep-Water, and Open-Water habitats was to apply the system of Chesapeake Bay simulation models, which are the Watershed Model (Phase 5.3.2) and the WQSTM of the tidal Bay (Figure 2). The ADH and HEC-RAS models of the lower Susquehanna River were also applied in specific scenarios as described above and in Appendices B and C.

The scenario representing current conditions was the 2010 Scenario (LSRWA-4). This scenario was run with a simulation period of 1991 to 2000 and is representative of the state of Conowingo Reservoir infill of the mid-1990s. The 2010 Scenario used estimated 2010 Chesapeake Bay land uses, animal numbers, manure and fertilizer loads, atmospheric deposition, point source and septic loads, and nonpoint source management actions. This was the base scenario of current conditions that all other model scenarios representing the Conowingo Reservoir infill condition could be compared to with respect to attainment of the jurisdictions' Chesapeake Bay water quality standards. The 2010 Scenario (LSRWA-4) is the fourth scenario listed in Tables 2a and 2b.

Similarly, the Watershed Implementation Plan (WIP) Scenario (LSRWA-3) represents the future conditions when all of the point source, nonpoint source, and atmospheric emission controls are in place in order to achieve the Chesapeake Bay TMDL in 2025 (but not including watershed and estuary lag times that could delay the ultimate achievement of the Chesapeake Bay water quality standards). The WIP Scenario represents the estimated Chesapeake Bay water quality conditions when all management actions called for in the seven watershed jurisdictions' WIPs—New York, Pennsylvania, West Virginia, Maryland, Delaware, the District of Columbia, and Virginia—are fully implemented (USEPA, 2010a). The WIP Scenario (LSRWA-3) is the fifth scenario listed in Tables 2a and 2b.

The assessment of Chesapeake Bay water quality standard attainment estimated in Tables 2a and 2b required consideration of restoration variances and application of the 2010 Chesapeake Bay TMDL Allocation decision rules.  A restoration variance is the percentage of an allowable exceedance of an established water quality standard based on water quality modeling which incorporates the best available data and assumptions on achievable water quality conditions. The restoration variances, adopted into a state's water quality standards regulations, are temporary, and are reviewed, at a minimum every three years, as required by the Clean Water Act and EPA regulations. Currently, EPA has approved restoration variances in Maryland's water quality standards regulations of 7 percent in CB4MH and PATMH Deep-Water. This means that time and space occurrences of DO failing to meet Deep-Water criterion must be greater than 7 percent of the allowable exceedance before measures of nonattainment are actually reached.  The CB4MH and EASMH Deep-Channel designated uses each have a restoration variance of 2 percent, and the CHSMH Deep-Channel has a variance of 16 percent[1], all approved by EPA.  In addition, the 2010 Chesapeake Bay TMDL allocation decision rules allowed rounding to the nearest whole number of nonattainment and allowed a one-time 1 percent nonattainment for uncertainties in the overall allocation analysis procedure (USEPA, 2010a).

To illustrate how Chesapeake Bay water quality responds to changes in nutrient and sediment loads, several key scenarios and loads used in the development of the 2010 Chesapeake TMDL are tabulated in Table 2a illustrating percent non-attainment of the Deep-Channel DO water quality standard USEPA, 2010a).  The scenarios in Table 2a are ordered from the highest to the lowest nutrient and sediment loads and were all run on the Chesapeake Bay Watershed Model Phase 5.3.2. The Deep-Channel DO has a criterion of at least 1 mg/l DO concentration which is required to be met at all times (except for the time and space area of allowable exceedances as shown in Figure 3). All of the Chesapeake Bay segments that have a Deep-Channel designated use are listed in Table 2a, and the location of the Chesapeake Bay segments can be seen in Figure 1. The greatest estimated loads are in the No Action Scenario, which is a "what if" scenario representing the 2010 conditions of land use and population with no management actions in place anywhere in the Chesapeake Bay watershed.  In order of decreasing nutrient and sediment loads from the No Action Scenarios are the scenarios of 1985, 2007, and 2010, all of which estimate the loads under the land use, population, and estimated management actions extant in the Chesapeake Bay watershed in those years.  As described previously, the 2010 Scenario and the WIP Scenario in Tables 2a and 2b are the same scenarios applied in the LSRWA analysis and are also described as LSRWA-4 and LSRWA-3, respectively.

Among the final three lowest loading scenarios in Table 2a is the WIP Scenario representing the loads under full implementation of the Chesapeake Bay TMDL as represented by the seven Chesapeake Bay watershed jurisdictions' Phase II Watershed Implementation Plans.  Even lower load scenarios include the E3 Scenario, which is a full implementation of all management actions

[1] Maryland COMAR 26.08.02.03-3

by “everyone, everywhere, doing everything”, and the All Forest Scenario, in which the estimated load conditions represent the forest land use as the sole land use across the entire Chesapeake Bay watershed.

As nutrient and sediment loads decrease, the level of estimated nonattainment of the Chesapeake Bay water quality standards, quantified in red font, decreases. Attainment of the Deep-Channel DO standard of 1.0 mg/l is displayed in green font. Deep-Channel DO is estimated to reach full attainment under the WIP Scenario conditions (Table 2a). Table 2b describes the estimate of water quality nonattainment for Deep-Water, a region of the water column within the pycnocline and above the Deep-Channel designated use. The Deep-Water DO criterion is a 30-day mean of 3 mg/l (USEPA, 2003a). All of the Deep-Water DO segments are estimated to achieve full attainment under the WIP Scenario conditions (Table 2b). Table 2b lists all of the Deep-Water Chesapeake Bay segments.

In Tables 2a and 2b attainment is estimated to further increase as loads are reduced beyond the WIP Scenario. This can be seen by the estimated response under the E3 and All Forest Scenarios in the cases of Deep-Channel DO in the CB segments of CB4MH, EASMH, and CHSMH where restoration variances are currently in place within Maryland’s water quality standards regulations (Table 2a).

The scenarios in Tables 2a and 2b assume the Conowingo Reservoir conditions of relative net deposition (Hirsch, 2012) during the 1991-2000 period. This is because the calibration period of the Phase 5.3.2 Watershed Model used to simulate the Tables 2a and 2b scenarios was 1985 to 2005, and the calibration centered on the 1991-2000 TMDL application period (Shenk and Linker, 2013). These periods had relative net deposition of sediment and particulate nutrients in the Conowingo Reservoir.

All of the scenarios of Tables 2a and 2b were run for the 10 years of the 1991-200 hydrology period and the 10 year annual average loads are listed with each scenario in millions of pounds total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). The DO water quality standard percent non-attainment levels for the Chesapeake Bay TMDL critical period of 1993-1995 are shown in Tables 2a and 2b (USEPA, 2010a).

| CB Segment | Scenario→ Year → State | No Action (N-Based) Scenario 371 TN, 37.6 TP, 10630TSS '93-'95 DO Deep Channel | 1985 Scenario 353 TN, 24.6 TP, 10100 TSS '93-'95 DO Deep Channel | 2007 Scenario 269 TN, 19.5 TP, 8770 TSS '93-'95 DO Deep Channel | 2010 (LSRWA-4) Scenario 263 TN 19.4 TP 8360 TSS '93-'95 DO Deep Channel | WIP (LSRWA-3) Scenario 191 TN 15 TP 6675 TSS '93-'95 DO Deep Channel | E3 (2010 N-Based) Scenario 135 TN, 10.4 TP, 4850 TSS '93-'95 DO Deep Channel | All Forest Scenario 54 TN, 2.6 TP, 1340 TSS '93-'95 DO Deep Channel |
|---|---|---|---|---|---|---|---|---|
| CB3MH | MD | 22% | 17% | 12% | 5% | 0% | 0% | 0% |
| CB4MH | MD | 54% | 49% | 40% | 23% | 1.49% | 0% | 0% |
| CB5MH | both | 22% | 17% | 10% | 0% | 0% | 0% | 0% |
| CHSMH | MD | 45% | 39% | 36% | 28% | 15.01% | 5% | 0% |
| EASMH | MD | 38% | 29% | 24% | 14% | 1.09% | 0% | 0% |
| PATMH | MD | 46% | 42% | 25% | 18% | 0% | 0% | 0% |
| POTMH | both | 27% | 20% | 13% | 0% | 0% | 0% | 0% |
| RPPMH | VA | 29% | 23% | 6% | 0% | 0% | 0% | 0% |

**Table 2a.** Assessment of Chesapeake Bay DO Deep-Channel water quality standard nonattainment for key scenarios.

The Open-Water DO standard has a designated use of all tidal waters of the Chesapeake above the pycnocline (USEPA, 2010a). The Open-Water DO criterion is a 30-day mean of 5.0 mg/l (USEPA, 2003a). Generally, the Open-Water DO standard was relatively easily achieved in the 2010 Chesapeake Bay TMDL because the Open-Water designated use is in contact with the atmosphere and reaeration is rapid. Under all LSRWA Conowingo scenario conditions the Open-Water DO standard was achieved for all Chesapeake Bay segments.

The findings of the 2010 Chesapeake Bay TMDL were that Deep-Channel and Deep-Water DO water quality standards were difficult to achieve, and the CBP Partnership found that achievement of these two water quality standards largely drove the magnitude of nutrient pollutant load reductions in setting the 2010 Chesapeake Bay TMDL allocations (USEPA, 2010a). This was also the case with the LSRWA scenarios of Conowingo Reservoir infill. Deep-Channel DO and Deep-Water DO were the most sensitive water quality standards to estimated Conowingo Reservoir infill conditions, i.e., were the water quality standards most likely to go into nonattainment with increases in sediment and the associated nutrient loads.

The jurisdictions' Chesapeake Bay SAV-clarity water quality standards of were largely attained through sediment reductions associated with required nutrient reductions brought about by farm plans, conservation tillage, and other management actions in the Chesapeake Bay watershed (USEPA, 2010a). In addition, the 2010 Chesapeake TMDL also applies a water quality standard for chlorophyll-*a* in the tidal James River in Virginia and in the tidal waters of the District of Columbia (USEPA, 2007b), but the chlorophyll standards applied in the tidal James River and tidal fresh waters of the District are too far removed from the Susquehanna River and are uninfluenced by Conowingo Reservoir infill conditions.

| CB Segment | Scenario → Year → State | No Action (N-Based) Scenario 371 TN, 37.6 TP, 10630TSS '93-'95 DO Deep Water | 1985 Scenario 353 TN, 24.6 TP, 10100 TSS '93-'95 DO Deep Water | 2007 Scenario 269 TN, 19.5 TP, 8770 TSS '93-'95 DO Deep Water | 2010 (LSRWA-4) Scenario 263 TN, 19.4 TP, 8360 TSS '93-'95 DO Deep Water | WIP (LSRWA-3) Scenario 191 TN, 15 TP, 6675 TSS '93-'95 DO Deep Water | E3 (2010-N Based) Scenario 135 TN, 10.4 TP, 4850 TSS '93-'95 DO Deep Water | All Forest Scenario 54 TN, 2.6 TP, 1340 TSS '93-'95 DO Deep Water |
|---|---|---|---|---|---|---|---|---|
| CB3MH | MD | 4% | 2% | 2% | 1% | 0% | 0% | 0% |
| CB4MH | MD | 28% | 22% | 17% | 11% | 4.7% | 3% | 0% |
| CB5MH | both | 7% | 5% | 3% | 2% | 0% | 0% | 0% |
| CB6PH | VA | 1% | 1% | 0% | 0% | 0% | 0% | 0% |
| CHSMH | MD | 39% | 32% | 21% | 11% | 0% | 1% | 0% |
| EASMH | MD | 34% | 14% | 4% | 2% | 0.90% | 0% | 0% |
| PATMH | MD | 31% | 21% | 11% | 6% | 0% | 0% | 0% |
| PAXMH | MD | 23% | 12% | 2% | 0% | 0% | 0% | 0% |
| POTMH | both | 9% | 5% | 2% | 0% | 0% | 0% | 0% |
| RPPMH | VA | 13% | 8% | 3% | 0% | 0% | 0% | 0% |
| SBEMH | VA | 5% | 3% | 0% | 0% | 0% | 0% | 0% |
| YRKPH | VA | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

**Table 2b.** Assessment of Chesapeake Bay DO Deep-Water water quality standard nonattainment for key scenarios.

The assessments of Chesapeake Bay DO water quality standard attainment in Table 2a and Table 2b provide background and context for the Conowingo Reservoir infill scenarios presented in Table 3. In Table 3, the 2010 Scenario is in column 1 (also designated as Scenario LSRWA-4). The scenario when the Watershed Implementation Plans (WIPS) are in full effect, Scenario LSRWA-3 corresponding to the WIP Scenario in Tables 2a and 2b, is in column 2. As described previously in Table 2a, the level of Deep-Channel DO attainment is relatively low in the 2010 Scenario. Tables 2a and 2b quantify the degree of nonattainment in all Deep-Channel and Deep-Water segments for the 2010 Scenario (LSRWA-4) and the WIP Scenario (LSRWA-3).
As a graphical representation of Deep-Channel DO nonattainment, Figure 4 shows the extent of nonattainment under estimated 2010 Scenario conditions (LSRWA-4). The segments of CH3MH, CB4MH, EASMH, and CHSMH are in a region of contiguous Deep-Water and Deep-

Channel waters. These CB segments have similar depths so that advection from gravitational circulation as well as tidal dispersion plays a role in the continuous area of hypoxia among these Chesapeake Bay segments. Under WIP Scenario conditions (LSRWA-3), full attainment (with restoration variances in place) of the Deep Channel DO standard is estimated.

***LSRWA Results: Non-Management Scenarios***

The LSRWA-21 Scenario represents the Conowingo Reservoir infill condition represented by the ADH Model simulation of the 2011 Conowingo Reservoir bathymetry (see Appendix B and C, this report) and with the seven watershed jurisdictions' WIPs are fully implemented.

In the LSRWA-21 Scenario, the high flow event occurs in January 1996 making the 1993-1995 critical period of the TMDL impractical for comparison purposes because the January 1996 event is outside the 1993-1995 simulation period. Therefore, the 1996-1998 period of the LSRWA-3 Scenario was used for comparison. The key difference between LSRWA-21 and LSRWA-3 scenarios is that the January 1996 high flow event was simulated in the LSRWA-21 Scenario using the ADH Model scour of sediment resulting in an improved estimate of storm scoured sediment and associated particulate nutrients. The estimates of particulate nutrients scoured by the storm were determined by observations made during Tropical Storm Lee in 2011 (Appendix C, this report). The nutrient and sediment loads estimated by Cerco (2014) using the ADH model replaced the nutrient and sediment loads estimated by the Chesapeake Bay Watershed Model Phase 5.3.2 for this event. The estimated response in the Deep-Channel DO standards under the LSRWA-21 Scenario was an increase of 1 percent nonattainment over the Base WIP Scenario (LSRWA-3) for CB4MH, EASMH, and CHSMH as shown in Figure 5. For the LSRWA-22 Scenario with estimated particulate nutrients scoured by the storm determined by observations made during the 1996 January Big Melt (Appendix C, this report), attainment of water quality standards was higher due to less scoured particulate nutrients estimated for the January 1996 event and only CB4MH was in 1% Deep-Channel nonattainment.

Scenario LSRWA-18 represents the current (2010) condition, with Conowingo Reservoir infilled and a winter scour event. As in the LSRWA-21 Scenario, the event occurs in January 1996 making the 1993-1995 critical period of the Chesapeake Bay TMDL impractical for comparison purposes. Therefore, the 1996-1998 period of LSRWA-4 Scenario was used for comparison. The difference between LSRWA-18 and LSRWA-4 is inclusion of a January 1996 high flow event simulated with an ADH Model estimate of sediment scour and by an estimate of associated nutrient loads as determined by observations made during Tropical Storm Lee (see Appendix B, this report for details of nutrient scour associated with the 1996 Big Melt event). The estimated response in the Deep-Channel DO standards under the LSRWA-18 Scenario was an increase of 1 percent nonattainment for CB4MH, and PATMH compared to the LSWRA-4 Scenario.

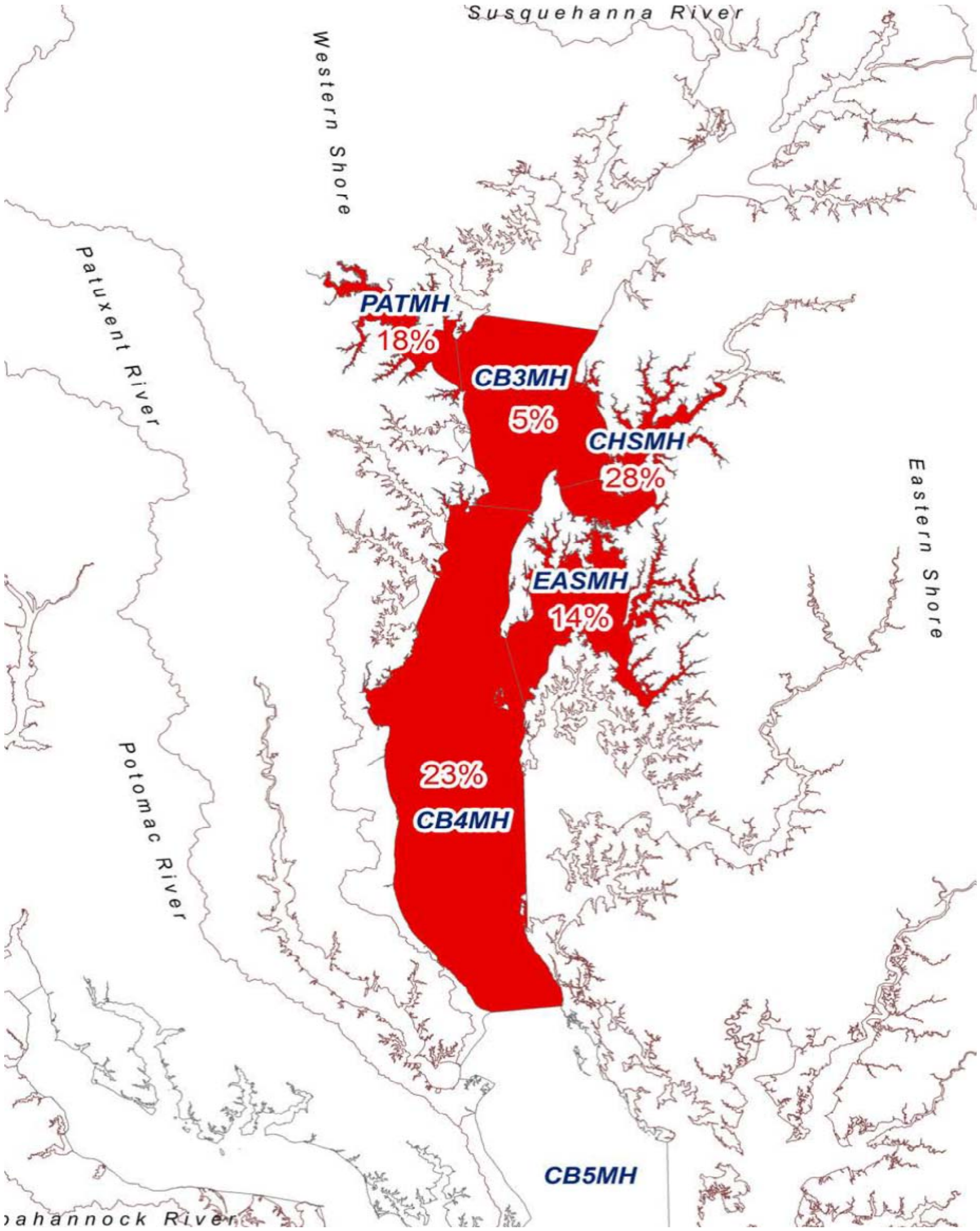


**Figure 4.** Estimated nonattainment of the Deep-Channel DO standard in Chesapeake Bay segments CB3MH, CB4MH, EASMH, PATMH, and CHSMH under the 2010 Scenario (LSRWA-4).

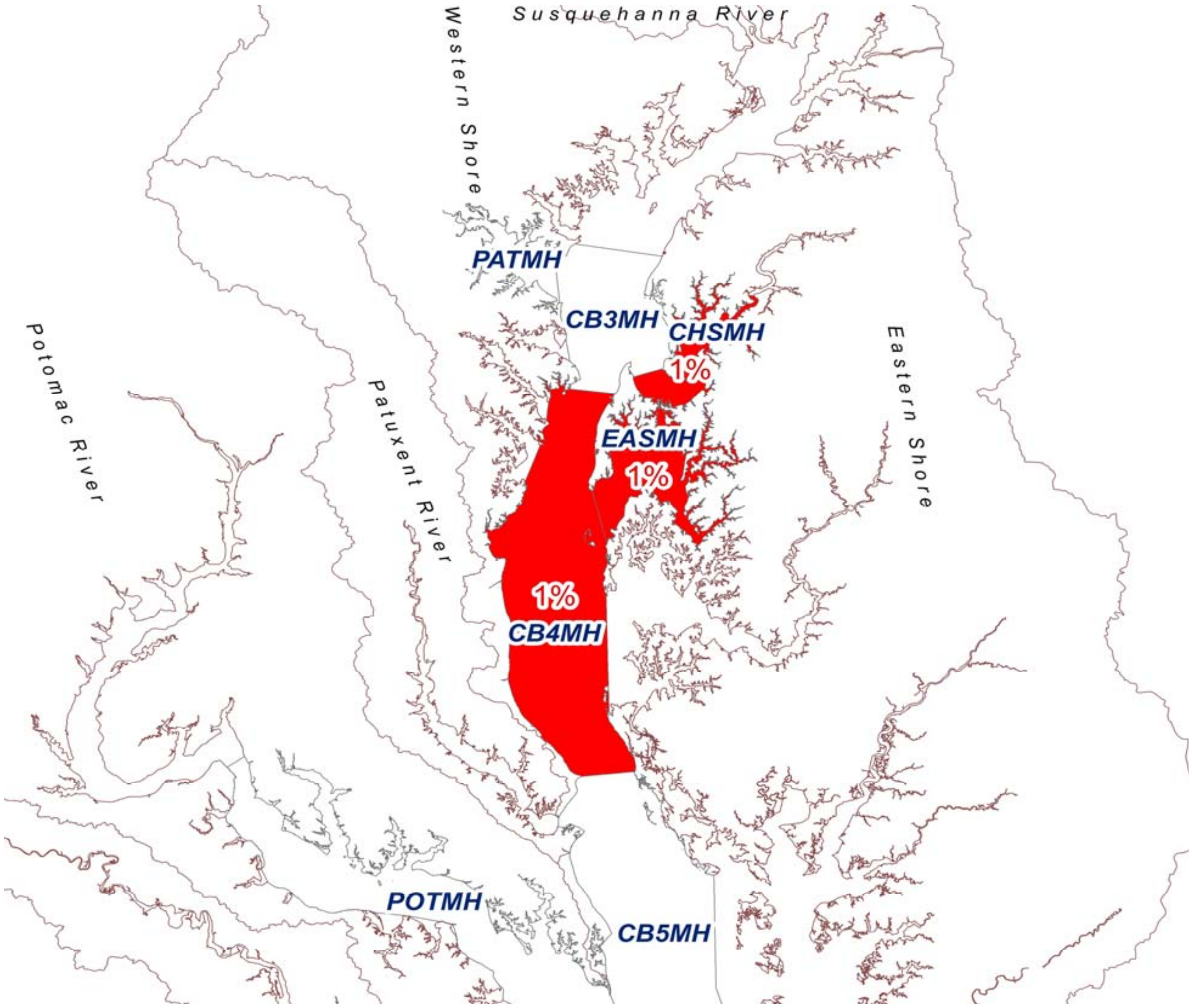


**Figure 5.** An estimated 1 percent increase of nonattainment of the Deep-Channel DO standard in Chesapeake Bay segments CB4MH, EASMH, and CHSMH under the LSRWA-21 Scenario compared to the LSRWA-3 Scenario using the 1996-1998 hydrology period.

The LSRWA-30 Scenario represents the Chesapeake Bay system's water quality condition when seven jurisdictions' WIPs are in full effect, the Conowingo Reservoir is in-filled at an equilibrium bathymetry, and there is a January 1996 scour event. As in the LSRWA-21 and LSRWA-18 scenarios, the event occurs in January 1996 and therefore, 1996-1998 hydrologic period of the LSRWA-3 Scenario was used for comparison. Again, the difference between LSRWA-30 and LSRWA-3 scenarios is the January 1996 high flow event was simulated with ADH model scour of sediment and by an improved estimate of associated scoured nutrients as determined by observations made during Tropical Storm Lee (see Appendix C for details of nutrient scour associated with the 1996 Big Melt). The estimated response in the Chesapeake

Bay Deep-Channel DO water quality standards was an increase of 1 percent nonattainment over the Base WIP Scenario (LSRWA-3) for Chesapeake Bay segments CB4MH, and CHSMH respectively (Table 3). There is little difference in Chesapeake Bay low dissolved oxygen response between the LSRWA-21 and LSRWA-30 scenarios because the sole difference between the two is that LSRWA-21 applies a 2011 Conowingo Reservoir bathymetry and LSRWA-30 applies an estimated equilibrium bathymetry and there is little difference between the two's scoured sediment and nutrient loads, i.e., the 2011 bathymetry is essentially the equilibrium bathymetry.

Finally, to examine the influence of a high flow scour event in different seasons of the year, the January 1996 Big Melt estimated flows and loads, along with the Chesapeake Bay hydrodynamics as modified through the CH3D Hydrodynamic Model, were moved to the June 1996 (LSRWA-24 Scenario) and October 1996 (LSRWA-25 Scenario) time periods. The LSRWA-24 and LSRWA-25 scenarios were run with the seven watershed jurisdictions' WIPs in full effect and Conowingo Reservoir trapping sediment at a level consistent with the LSRWA-21 Scenario (2011 bathymetry). Consistent with the published findings of Wang and Linker (2005), a June high flow storm event has the most detrimental influence on Deep-Channel DO water quality standard attainment followed by a storm of the same magnitude in January and then October time periods. The "no large storm" condition (LSRWA-23 Scenario) was used as a point of comparison with the seasonal January (LSRWA-21), June (LSRWA-24), and October (LSRWA-25) scenarios. The LSRWA-23 Scenario had the January storm removed and was developed solely with the Chesapeake Bay Watershed Model Phase 5.3.2 model. A counterpoint to the LSRWA-24 and LSRWA-25 scenarios were the LSRWA-26 and LSRWA-27 Scenarios which were like the previous two scenarios in every way except that the nutrients associated with the solids scoured from the Conowingo Reservoir were based on observations collected during the January 1996 scour event.

**June Event**

The June high flow event scenario (LSRWA-24 Scenario) had an estimated increase in Chesapeake Bay Deep-Channel DO water quality standard nonattainment of 1 percent, 4 percent, 8 percent, and 3 percent in segments CB3MH, CB4MH, CHSMH, and EASMH, respectively when compared to the LSRWA-23 Scenario in the 1996-1998 hydrology period. Likewise, the LSRWA-24 Scenario had an estimated increase in Deep-Water DO water quality standard nonattainment of 1 percent in segments CB4MH and SEVMH, when compared to the LSRWA-23 Scenario in the 1996-1998 hydrology period resulting in relatively higher estimated levels of both Deep-Water and Deep-Channel DO nonattainment than for other LSRWA scenarios. For the LSRWA-26 Scenario, the degree of Deep-Channel nonattainment was only 2 percent for segment CB4MH but was otherwise unchanged for Deep-Channel and Deep-Water DO nonattainment compared to LSRWA-24.

**October Event**

The estimated Deep-Channel DO water quality conditions from the October high flow event (LSRWA-25 Scenario) compared to the LSRWA-23 Scenario (which represents the no storm condition), using the 1996-1998 hydrology period, was increased nonattainment of 2 percent and 1 percent in the lower Chester River (CHSMH) and Severn River segments (SEVMH), respectively. The estimated Chesapeake Bay Deep-Water DO water quality standard achievement for the October high flow event (LSRWA-25) was increased nonattainment of 1 percent in the Severn River segment (SEVMH), compared to the LSRWA-23 Scenario. The Deep-Water segment of CB4MH showed a negligible impact from an October event. For the LSRWA-27 Scenario the degree of Deep-Channel nonattainment was only 1 percent for segment CHSMH but was otherwise unchanged for Deep-Channel and Deep-Water DO nonattainment compared to the LSRWA-24 Scenario.

**January Event**

The January condition (LSRWA-21 Scenario) had had an estimated increase in Chesapeake Bay Deep-Channel DO water quality standard nonattainment of 1 percent, 1 percent, 2 percent, and 2 percent in segments CB3MH, CB4MH, CHSMH, and EASMH, respectively when compared to the LSRWA-23 Scenario in the 1996-1998 hydrology period. The Deep-Water DO water quality standard attainment levels of LSRWA-21 Scenario were estimated to be 1 percent in segments CB4MH and SEVMH, when compared to the LSRWA-23 Scenario in the 1996-1998 hydrology period.

**Summary of Seasonal Impact of a Major Event**

The severity of the DO hypoxia response estimated by the degree of nonattainment of the Deep-Channel and Deep-Water DO standards was greatest in the June storm scenario followed by the January and October storm scenarios. The seasonal differences in water quality response, despite the same magnitude of nutrient and sediment loads in the LSRWA-24 (June storm), LSRWA-25 (October storm), and LSRWA-21 (January storm) scenarios, is thought to be because of the fate and transport of nutrients in the different seasons. In June, the pulse of delivered nutrient loads contribute directly to ongoing primary production as they are taken up to produce more algae. As a consequence, these loads contribute to Deep-Channel and Deep-Water DO nonattainment when the increased production of June algal biomass sinks to the bottom and generate sediment and water column oxygen demand. The water quality effects in the October and January periods are diminished because of colder temperatures and decreased primary productivity, resulting in less interception of nutrient loads by algae. In the fall and winter, a greater portion of the storm pulsed nutrient load is transported down the Bay to be discharged at the ocean boundary or is lost though denitrification or deep burial in sediments. The long-term impacts of the October Storm on DO were estimated to be less than the January storm (see Main Report Figure 6-31). This is because the simulated January storm load of particulate nutrients scoured from the Conowingo Reservoir was processed during that summer and cycled through the system, while much of the simulated October 1996 storm load was buried or discharged out of the Chesapeake over the simulated 1996-97 winter before the particulate nutrient load was ultimately expressed as a depression of DO in the simulated 1997 summer.

Table 4 provides an evaluation of Deep-Water DO and Open-Water DO water quality standards attainment results consistent with the Table 3 results. The Deep-Water DO findings are similar to the Deep-Channel DO findings. However, the Open-Water DO standard is relatively insensitive to the load changes estimated under the Conowingo Reservoir infill conditions. The Open-Water DO standard was estimated to be in full attainment under the WIP Scenario (LSRWA-3) and remained unchanged from this condition of full attainment under all estimated scenario loads of Conowingo Reservoir infill. The Open-Water designated use is relatively easier to achieve than the Deep-Channel or Deep-Water designated uses because it is in contact with the atmosphere, reaeration is rapid, and there is no pycnocline barrier to reaeration as there is in the other DO designated use habitats.

### *LSRWA Results: Management Scenarios*

Table 5 contains the estimated Chesapeake Bay dissolved oxygen water quality standards attainment under a series of three management scenarios aimed at removing sediment from the Conowingo Reservoir by different means. Three management scenarios were examined with the full simulation of the WQSTM and were, as a result, available for water quality standard assessment.

| | 1. What is the system's current (existing) condition? **Scenario LSRWA-4** | 2. What is the system's condition if the WIPs are in full effect and reservoirs are still trapping? Scenario **LSRWA-3** | 3. What is the system's condition when WIPS are in full effect, reservoirs are still trapping sediments and a scour event occurs during winter? **Scenario LSRWA-21** | 4. What is the system's condition when WIPS are not in effect, reservoirs are full and there is a winter scour event? Scenario **LSRWA-18** | 5. What is the system's condition when WIPs are in full effect, the reservoirs are full and there is a winter scour event? **LSRWA-30** | 6. What is the system's condition if WIPs are in full effect, reservoirs are full and a large scour event occurs during summer **(LSRWA-24)**, fall **(LSRWA-25)** or winter **(LSRWA-21)?** |
|---|---|---|---|---|---|---|
| Deep Channel DO Water Quality Standard Achievement for Total Maximum Daily Load (TMDL) | Widespread nonattainment of TMDL of Deep Channel DO. Nonattainment of 23% in the CB4 mainstem, 14% in Eastern Bay, and 28% in the Lower Chester River was estimated. This and other areas of nonattainment in the Deep Channel amounted to more than half of the Deep Channel habitat. | Complete attainment of the Deep Channel DO standard was estimated. | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, an increase of 1% nonattainment over the Base TMDL Scenario (LSRWA-3) was estimated for CB4MH, EASMH, and CHSMH. | Using for comparison, the scenario of the systems current condition (LSRWA-4), an increase of 1% nonattainment for CB4MH, and PATMH was estimated. | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, an increase of 1% nonattainment over the Base TMDL Scenario (LSRWA-3) was estimated for CB4MH, EASMH, and CHSMH. | Generally, a June high flow storm event has the most detrimental influence on Deep Channel DO followed by a storm of the same magnitude in January and then October. |

Table 3. Assessment of the Chesapeake Bay Deep-Channel DO water quality standards attainment for key scenarios in the Conowingo Reservoir infill analysis.

**Strategic Dredging**

The LSRWA-28 Scenario examines the application of strategic dredging which simulated the removal of 3 million cubic yards of material from regions in the Conowingo Reservoir most susceptible to scour. Using the 1996-1988 period to capture the January 1996 "Big Melt" event, an improvement in water quality characterized by a decrease of 0.2 percent nonattainment in the Deep-Channel DO water quality standard over the LSRWA-21 Scenario for segments CB3MH and CB4MH, and a decrease of 0.1 percent nonattainment in segment EASMH was estimated (Table 5). The LSRWA-21 Scenario is the Chesapeake Bay system's condition when seven watershed jurisdictions WIPs are in full effect, the Conowingo Reservoir 2011 bathymetry is simulated, and a major scour event occurs during winter. The LSRWA-21 Scenario was used to provide a consistent point of comparison for all three of the management scenarios listed in Table 5 which were all based on additional reservoir sediment removal under LSRWA-21 simulated conditions. A water quality improvement of 0.1 percent over LSRWA-21 conditions was also found for Deep-Water DO water quality standard in CB4MH (Table 5).

| | 1. What is the system's current (existing) condition? **Scenario LSRWA-4** | 2. What is the system's condition if the WIPs are in full effect and reservoirs are still trapping? Scenario **LSRWA-3** | 3. What is the system's condition when WIPS are in full effect, reservoirs are still trapping sediments and a scour event occurs during winter? **Scenario LSRWA-21** | 4. What is the system's condition when WIPS are not in effect, reservoirs are full and there is a winter scour event? Scenario **LSRWA-18** | 5. What is the system's condition when WIPs are in full effect, the reservoirs are full and there is a winter scour event? **LSRWA-30** | 6. What is the system's condition if WIPs are in full effect, reservoirs are full and a large scour event occurs during summer **(LSRWA-24),** fall **(LSRWA-25)** or winter **(LSRWA-21)?** |
|---|---|---|---|---|---|---|
| Deep Water DO Water Quality Standard Achievement for TMDL | Widespread nonattainment of TMDL of Deep Water DO. Estimated nonattainment of 11% in the CB4 mainstem, 2% in Eastern Bay, and 11% in the Lower Chester River. | Complete attainment of the Deep Water DO standard was estimated to be attained. | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, an increase of 1% nonattainment over the Base TMDL Scenario (LSRWA-3) was estimated for CB4MH and CB5MH. | Using for comparison, the scenario of the systems current condition (LSRWA-4), an increase of 1% nonattainment for CB3MH and PAXMH was estimated. | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, an increase of 1% nonattainment over the Base TMDL Scenario (LSRWA-3) was estimated for CB4MH and CB5MH. | Generally, a June high flow storm event has the most detrimental influence on Deep Channel DO followed by a storm of the same magnitude in January and then October. |
| Open Water DO Water Quality Standard Achievement for TMDL | Widespread, but not complete attainment of the Open Water DO standard was estimated to be attained. | Complete attainment of the Open Water DO standard was estimated. | Complete attainment of the Open Water DO standard was estimated. | Complete attainment of the Open Water DO standard was estimated. | Complete attainment of the Open Water DO standard was estimated. | Complete attainment of the Open Water DO standard was estimated. |

**Table 4**. Assessment of the Chesapeake Bay Deep-Water and Open-Water DO water quality standards attainment for key scenarios in the Conowingo Reservoir infill analysis.

**Sediment By-Pass**

The scenario examining the effects of passing sediment downstream for three winter months, over-time for a period of 10 years, was the LSRWA-29 Scenario. The LSRWA-29 Scenario released sediment from the bottom of the Conowingo Reservoir during a time of the year (December-February) when there was no adverse influence by sediment on achievement of the SAV-clarity water quality standard in Chesapeake Bay. Unfortunately this approach had the effect of increasing nutrient loads delivered to Chesapeake Bay by 6,545 metric tons/year of total nitrogen and 2,182 metric tons/year of total phosphorus because of the nutrients associated with the released sediment. This scenario was estimated to increase Chesapeake Bay Deep-Channel DO water quality standards nonattainment by an estimated 4 percent, 5 percent, 3 percent, 4 percent, and 2 percent over the comparative LSRWA-21 Scenario for segments CB3MH, CB4MH, CHSMH, EASMH, and PATMH, respectively.

| | What are the effects of strategic dredging? **LSRW-28** | What are the effects of passing sediment downstream for 3 winter months, over-time for a period of 10 years? **LSRWA-29** | What are the effects of extreme long-term removal out of system) restoring to 1996 bathymetry? **LSRWA-31** |
|---|---|---|---|
| **Deep-Channel DO Water Quality Standard Achievement for Total Maximum Daily Load (TMDL)** | Using the 1996-1988 period to capture the January 1996 "Big Melt" event, water quality was estimated to be improved by a decrease of 0.2% nonattainment over the Base WIP (**LSRWA-21)** Scenario for CB3MH and CB4MH and a 0.1% decrease in attainment in EASMH. | Using the 1996-1988 period to capture the January 1996 "Big Melt" event, water quality was estimated to increase nonattainment by an estimated 4%, 5%, 3%, 4%, and 2% over the comparative LSRWA-21 Scenario for CB3MH, CB4MH, CHSMH, EASMH, and PATMH, respectively. | Using the 1996-1988 period to capture the January 1996 "Big Melt" event, water quality was estimated to be improved by a decrease of 0.3%, 0.5%, and 0.2% nonattainment over the Base WIP (**LSRWA-21)** Scenario for CB3MH, CB4MH and EASMH, respectively. |
| **Deep-Water DO Water Quality Standard Achievement for TMDL** | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, nonattainment in CB4MH was estimated to decrease by 0.1% over the Base WIP Scenario (**LSRWA-21)** | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, nonattainment in CB4MH was estimated to decrease by 0.2% over the Base WIP Scenario (**LSRWA-21)** | Using the 1996-1998 period to capture the January 1996 "Big Melt" event, nonattainment in CB4MH was estimated to decrease by 0.2% over the Base TMDL Scenario (**LSRWA-21)** |
| **Open-Water DO Water Quality Standard Achievement for TMDL** | Complete attainment of the Open Water DO standard was estimated. | Complete attainment of the Open Water DO standard was estimated. | Complete attainment of the Open Water DO standard was estimated. |

**Table 5**. Assessment of the Deep-Channel DO, Deep-Water DO, and Open-Water DO water quality standard for key management scenarios in the Conowingo infill analysis.

**Long-Term Sediment Removal**

The scenario examining the effects of long-term sediment removal (out of system) and restoring the Conowingo Reservoir to its 1996 bathymetry is LSRWA-31. This scenario further extended the estimated water quality benefits of LSRWA-21. The Chesapeake Bay Deep-Channel DO water quality standards nonattainment was estimated to be improved by a decrease of 0.3 percent, 0.5 percent, and 0.2 percent in nonattainment over the comparative LSRWA-21 Scenario for segments CB3MH, CB4MH, and EASMH, respectively (Table 5). The Chesapeake Bay Deep-Water DO water quality standard attainment is also estimated to be improved by a decrease in nonattainment of 0.2 percent in segment CB4MH.

### *SAV-Clarity Water Quality Standard Results*

During the 2010 Chesapeake Bay TMDL allocation development widespread attainment of the jurisdictions' Chesapeake Bay SAV-clarity water quality standards was found at the Chesapeake Bay TMDL allocation levels of nutrient and sediment loads sufficient to achieve the respective DO standards. In this sense, the SAV-clarity water quality standards were not the drivers behind the established 2010 Chesapeake Bay TMDL allocations that the DO water quality standards were. The nutrient reductions needed to achieve the DO water quality standards were often accompanied by reductions in sediment loads given implementation of management practices such as farm plans and conservation tillage. Together, the nutrient and sediment load reductions were sufficient to achieve the jurisdictions' Chesapeake Bay SAV-clarity water quality standards (USEPA, 2010a).

Across all the LSRWA scenarios referenced in this report and described in this appendix, model simulated sediment and associated nutrient loads above the full application of the seven watershed jurisdictions' Phase II WIPs resulted in estimates of full attainment of the SAV-clarity water quality standards in the upper Chesapeake Bay. There were estimated detrimental impacts of sediment. For example, light attenuation during the Big Melt event storm moved to the June time period was estimated to be greater than 2 1/m for 12 days, a level of light attenuation insufficient for long-term SAV growth and survival (Figure 6). These results are consistent with relatively high coverage and density of SAV observed on the Susquehanna Flats just downstream of the Conowingo Dam and Reservoir.

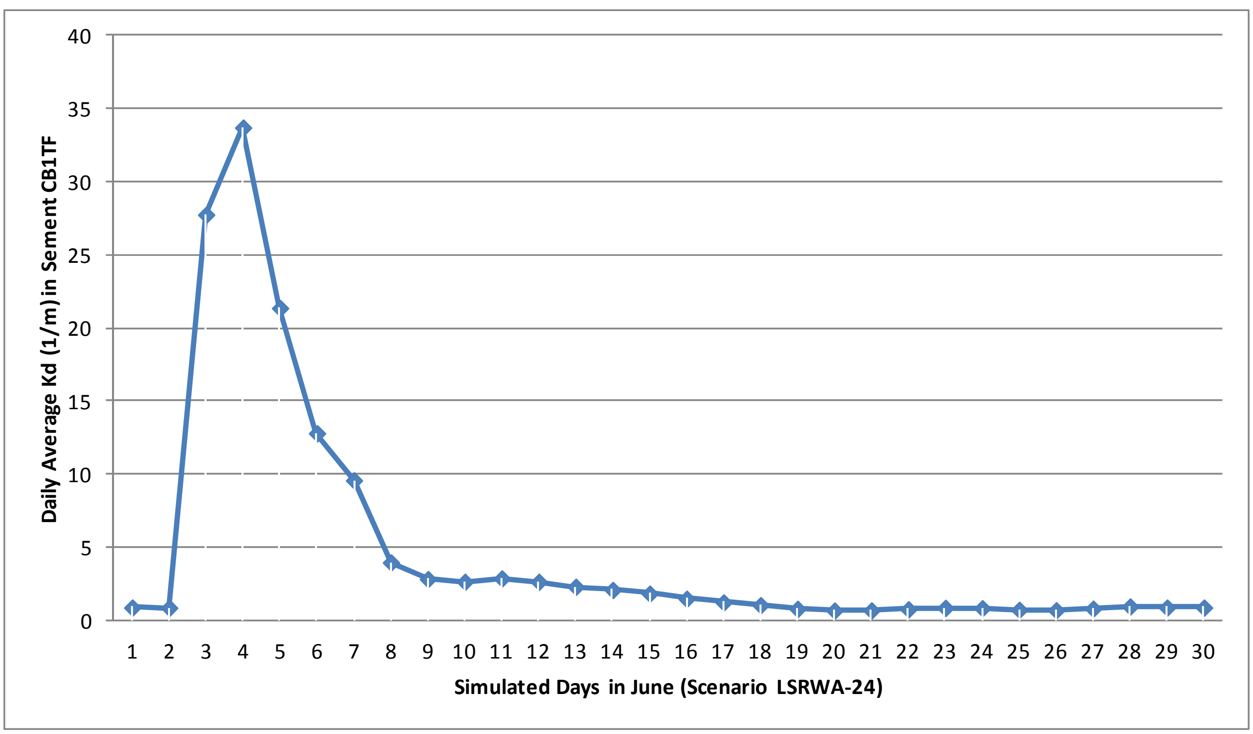

**Figure 6.** Estimated average daily light attenuation (1/m) in the Susquehanna Flats (CB1TF) for the June high flow event scenario (LSRWA-24).

## CONCLUSIONS

The 2010 Chesapeake Bay TMDL sets watershed-wide loads limits of 186 million pounds (84.3 million kilograms) of total nitrogen, 12.5 million pounds (5.67 million kilograms) of total phosphorus, and 6.46 billion pounds (2.93 billion kilograms) of total suspended solids per year (USEPA, 2010a) – a 25 percent reduction in nitrogen, 24 percent reduction in phosphorus, and 20 percent reduction in sediment from 2010 estimated loads, and a 46 percent reduction in nitrogen, 48 percent reduction in phosphorus, and 33 percent reduction in sediment from estimated 1985 loads. These pollution limits were further divided by basin-jurisdictions on the basis of the CBP Partnership's model scenario analysis findings, extensive monitoring data, peer-reviewed science, and close interaction with the jurisdictional partners (USEPA, 2010a). In the 2010 Chesapeake Bay TMDL assessment by the CBP partners, the Conowingo Reservoir sediment and associated nutrient delivery was simulated over the 1991-2000 period, which was a condition prior to the current dynamic equilibrium state of sediment infill of the Conowingo Reservoir (USEPA 2010a).

The Deep-Water and Deep-Channel DO water quality standards are on a knife-edge of attainment with full implementation of the seven watershed jurisdictions' Watershed Implementation Plans (WIPS). Achieving the Deep-Water and Deep-Channel DO standards in the 2010 Chesapeake Bay TMDL was difficult and required management actions that went far beyond what was needed for estimated attainment of the jurisdictions' SAV-clarity and chlorophyll (except in the case of the tidal James River) water quality standards. The annual difference in DO generally ranges from about 12 mg/l in the winter to near hypoxia/anoxia conditions in the summer in the Deep-Water and Deep-Channel regions of the Chesapeake largely due to DO solubility differences with temperature and also due to the summertime presence of the pycnocline. But it is the summer hypoxic period that is of concern and small difference in DO during this period make big differences to living resources as reflected in the development of the DO water quality standards (USEPA 2003a; Batiuk et al. 2009).

Appendix T of the Chesapeake Bay TMDL report projected that there would be future increased nutrient and sediment loads under the conditions of the current dynamic equilibrium state of the Conowingo Reservoir (USEPA, 2010d). In a TMDL, any increase in pollutant loads that result in a failure to achieve of water quality standards must be addressed and offset so as to ensure full attainment of the applicable water quality standards.

The LSRWA study has found that as the Conowingo Reservoir has filled, the minimum discharge required for sediment and associated nutrient scour decreases as the reservoir becomes shallower. The Conowingo Reservoir was evaluated under the estimated 1996 and 2011 bathymetries with the ADH model to determine the minimum discharge for erosion to commence. For the 1996 reservoir bathymetry, the minimum discharge for erosion to commence was estimated to be 427,000 cfs. For the 2011 reservoir bathymetry, the minimum discharge for erosion to commence was estimated to be 333,000 cfs. The scour threshold has been reduced by 22 percent between 1996 and 2011 (Scott, S. - personal communication 11-20-13 email). As a consequence, more of bottom sediment and associated nutrient loads from the Conowingo Reservoir are estimated to be available for transport to the tidal Chesapeake Bay due to the higher frequency of river flows reaching the lower scour thresholds.

Of these increased pollutant loads, nutrients are most important from a Chesapeake Bay water quality perspective. Sediment loads from a Conowingo Reservoir in dynamic equilibrium infill condition are estimated to have relatively little influence on achievement of the jurisdictions' Chesapeake Bay SAV-water clarity water quality standards attainment. Additional evidence for the relative insensitivity of Chesapeake water quality conditions to episodic high flow sediment load events is the existence of the large SAV bed in the Chesapeake Segment CB1TF (the Susquehanna Flats) which has often exceeded Maryland's SAV-clarity standard for segment CB1TF in recent years.

Nutrient loads are another matter. Consistent with the 2010 Chesapeake Bay TMDL findings, water quality impairments estimated to be caused by the Conowingo Reservoir infill condition are the increased nutrient loads associated with increased sediment scour. The Chesapeake Bay water quality standards most sensitive to increased nutrient loads generally, including the increased nutrient loads estimated under Conowingo infill conditions, are the Deep-Channel and Deep-Water DO water quality standards (USEPA, 2010a). Nutrient loads are estimated to be decreased somewhat under conditions of strategic dredging of 3 million cubic yards (LSRWA-28 Scenario) and as a consequence the Deep-Channel and Deep-Water DO standard were estimated to be slightly improved under this condition. Further slight improvements were estimated when the Conowingo Reservoir was simulated at its 1996 bathymetry condition in the LSRWA-31 Scenario. Conversely, Deep-Channel DO and Deep-Water DO water quality were estimated to be seriously degraded by passing sediment downstream for three winter months over-time for a period of 10 years because of the release of nutrients from the bed of the Conowingo Reservoir associated with sediment by-pass.

From the perspective of the 2010 Chesapeake Bay TMDL, a key finding of the LSRWA is that concurrent with the problem of Conowingo infill is the estimated increase in nutrient releases from the Conowingo Reservoir sediments under the current infill condition of equilibrium bathymetry. At equilibrium bathymetry, the Conowingo Reservoir is full, and there is long-term equilibrium between sediment and associated nutrient loads in, and sediment and associated nutrient loads out. During episodic high flow scouring events, large nutrient loads are delivered to Chesapeake Bay, while at the same time storage capacity in the reservoir is increased which allows for more deposition sediment and the associated nutrient which, in turn, can fuel another episodic high flow, high nutrient and sediment load release. The relative importance of nutrient loads impacts due to Conowingo Reservoir infill is a finding that provides nutrient management and mitigation options that could be more cost effective and provide more management flexibility than solely relying on reservoir dredging as a management option.

To provide a first order estimate of the degree of Susquehanna River watershed nutrient pollutant load reduction needed to avoid estimated increases in DO nonattainment due to Conowingo Reservoir infill, Table 2a can be used to assess the degree of attainment under different scenario loads of nutrients. Using the loads in Table 2a for the scenarios that produce some non-attainment, the Deep-Channel DO percent attainment for CB4MH was found to be related to the estimated nitrogen and phosphorus loads for the entire Bay. Using the slope of the lines relating TN and TP to percent non-attainment of CB4MH Deep-Channel, a rough estimate of the load reduction needed Bay-wide to offset 1 percent nonattainment is about 4.4 million pounds of total nitrogen and 0.41 million lbs of total phosphorus. Scoping scenarios provide an estimate of the nitrogen and phosphorus pollutant load reductions from the Susquehanna River watershed needed to offset the increase in DO nonattainment. In this case, a nutrient reduction solely from the Susquehanna River watershed to offset a 1 percent increase in Deep-Channel DO nonattainment from Conowingo Reservoir infill would be about 2.4 million pounds of nitrogen, or alternately, a reduction of 0.27 million pounds of phosphorus.

The 2010 Chesapeake Bay TMDL report's Appendix T points out that in developing the Chesapeake Bay TMDL, an array of factors that affected the loadings to the Chesapeake Bay were accounted for and the Chesapeake Partnership worked to appropriately assign load allocations to each state (USEPA, 2010d). A large influencing factor in sediment and nutrient loads to the Chesapeake Bay are the major dams of the lower Susquehanna River (Safe Harbor, Holtwood, and Conowingo) which retain large quantities of sediment and nutrients in their reservoirs. Appendix T describes the case where "future monitoring shows that the trapping capacity of the reservoir has been reduced" and suggests that then the Chesapeake Bay Program Partners will need to consider adjusting the Pennsylvania, Maryland, and New York 2-year milestone loads based on the new delivered loads to ensure that all are meeting their target load obligations.

### *Future Research Needs*

Going forward, further research and analysis is needed to provide a refined assessment of the influence of Conowingo Reservoir infill on Chesapeake Bay water quality, including an improved understanding of the fate and transport of particulate organic and inorganic nutrients associated with scoured sediment from the Conowingo Reservoir. Refinements in monitoring, research, and model simulation of the particulate organic and inorganic nutrients associated with Conowingo Reservoir sediment, their fate when scoured with sediment from the Conowingo

Reservoir, and their subsequent transport to the Chesapeake Bay along with their diagenesis and utilization in tidal waters would advance considerably the understanding of the influence Conowingo Reservoir infill has on Chesapeake water quality.

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