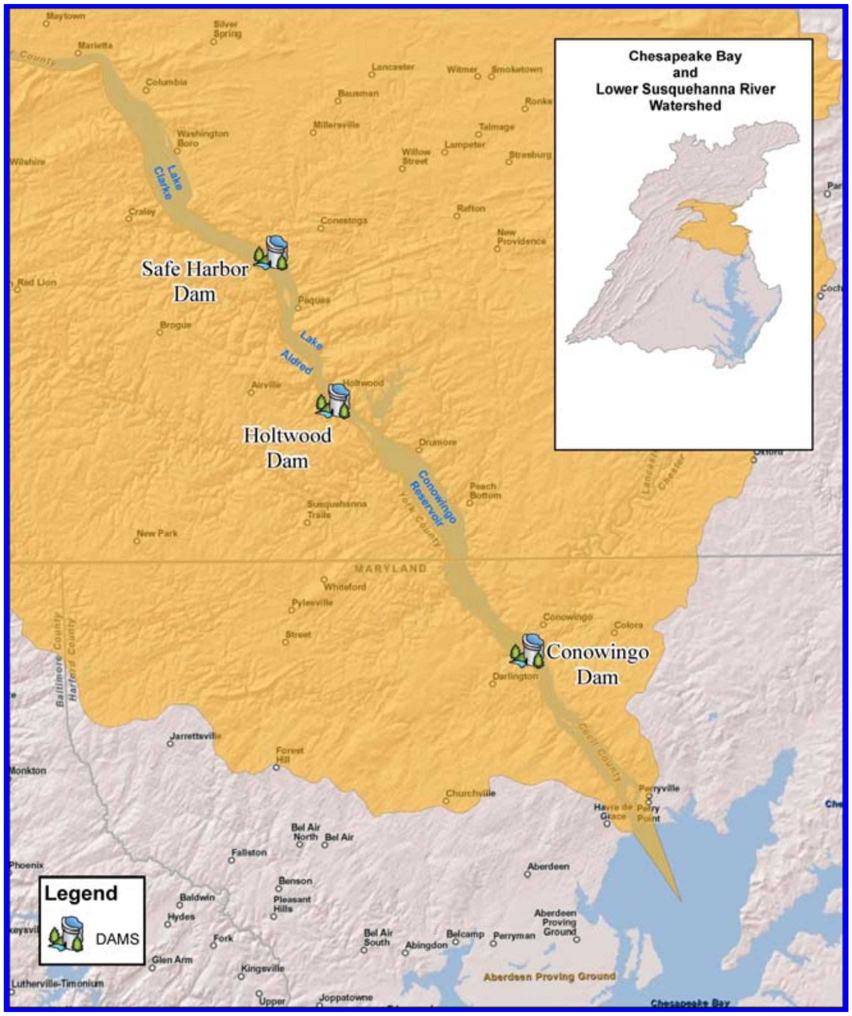
LOWER SUSQUEHANNA RIVER WATERSHED ASSESSMENT, MARYLAND AND PENNSYLVANIA



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Back of Title Page

Executive Summary

The U.S. Army Corps of Engineers, Baltimore District (USACE), and the Maryland Department of the Environment (MDE) partnered to conduct the Lower Susquehanna River Watershed Assessment (LSRWA). This report presents assessment efforts and documents findings.

The purpose of this assessment was to analyze the movement of sediment and associated nutrient loads within the lower Susquehanna watershed through the series of hydroelectric dams (Safe Harbor, Holtwood, and Conowingo) located on the lower Susquehanna River to the upper Chesapeake Bay. Critical components of this watershed assessment included: (1) use of hydrologic, hydraulic, and sediment transport models to link incoming sediment and associated nutrient projections to in-reservoir processes at the dams and to estimate impacts to living resources in the upper Chesapeake Bay; (2) identification of watershed-wide sediment management strategies; and (3) assessment of cumulative impacts from sediment management strategies on the upper Chesapeake Bay ecosystem. This assessment represents an increase in understanding that may be used to inform stakeholders undertaking efforts to manage the lower Susquehanna River watershed and restore the Chesapeake Bay.

Environmental History

The Chesapeake Bay ecosystem is substantially degraded today from historic conditions by human activities. Erosion of farmland, mined land, and logged areas in the watershed delivered immense quantities of sediment to rivers. Bay sediment loads peaked in the late 1800s and early 1900s, and then subsequently declined. Some increase in algal blooms and reduction in water clarity began to occur in the Bay at about the time of peak sediment loads. Following World War II, nutrient loads increased substantially (largely from fertilizer) causing eutrophication, and Bay oxygen levels underwent a precipitous decline. Over the last several decades, between 15 and 25 percent of the Bay water volume has severely low levels of oxygen annually in warm water months, greatly reducing its quality as habitat for aquatic life.

Oyster populations which formerly filtered Bay waters are reduced to less than 1 percent of historic levels from overharvesting through the 19th and 20th centuries, and mortality from exotic diseases that began in the 1950s (NOAA, 2015). Diminished oyster populations no longer produce sufficient shell to maintain oyster beds, which then are gradually buried by sediment and become unsuitable for oyster reestablishment. Loss of oyster filtration contributed to worsening of water clarity. Oysters are naturally vulnerable to impacts of large freshwater inputs to the Bay from major storms.

Submerged aquatic vegetation (SAV) declined in the 1960s accompanying worsening water clarity from eutrophication and oyster loss, and then underwent dramatic decline from impacts of Hurricane Agnes in 1972. The timing of Hurricane Agnes was particularly devastating, as its massive influx of freshwater occurred during the growing season for the aquatic grasses. SAV recovered somewhat in subsequent decades to occupy between about 20 to 50 percent of its historic bottom area in accompaniment with Bay and watershed environmental management efforts. SAV shows substantial interannual variation driven by variation in precipitation and nutrient and sediment loading.

Watershed is the Principal Source of Sediment

Sediment and associated nutrients from the lower Susquehanna River watershed have been transported and stored in the areas (reservoirs) behind the dams over the past century. The dams have historically acted as sediment traps, reducing the amount of sediment and associated nutrients reaching the Chesapeake Bay. The Chesapeake Bay ecosystem is impacted both physically and biologically by the delivered sediment load from the Susquehanna River basin. These impacts are exacerbated by large storm and flood events which scour additional sediment and associated nutrients from behind the dams on the lower Susquehanna River and adversely affect the Chesapeake Bay ecosystem.

However, while the impacts of all three dams and reservoirs on the Chesapeake Bay ecosystem are important, this assessment estimates that the majority of the sediment load from the lower Susquehanna River entering the Chesapeake Bay during storm events originates from the watershed rather than from scour from the reservoirs. But, storm characteristics are highly variable and variations in track, timing, and duration can alter the amount of sediment entering the system from both the watershed and from behind the dams. Consequently, the relative proportion of sediment originating from reservoir scour versus from watershed contributions also varies. Additionally, the proportion of sediment sources is not universal to all storms, but the estimate described below provides a good sense of magnitude.

It was estimated that during a major storm event, that is, one that occurs on average every 4 to 5 years, approximately 20 to 30 percent of the sediment that flows into Chesapeake Bay from the Susquehanna River is from scour of bed material stored behind Conowingo Reservoir, and the rest is from the upstream watershed (which includes scour from behind Holtwood and Safe Harbor Dams). During lower flow periods, the three reservoirs act as a sediment trap and, in essence, aid the health of the Bay until the next high-flow event occurs. Given the often smaller contribution of the sediment load to the Bay from Conowingo Reservoir scour in comparison to the watershed (under most hydrologic conditions), the primary impact to aquatic life in the Bay is from sediment and nutrients from the Susquehanna River watershed and the rest of the Chesapeake Bay watershed. However, both sources of sediment and nutrient loads, reservoir scour and watershed load, should be addressed to protect aquatic life in Chesapeake Bay.

The seven Chesapeake Bay watershed jurisdictions (Delaware, District of Columbia, Maryland, New York, Pennsylvania, Virginia, and West Virginia) have developed watershed implementation plans (WIPs), which detail how each of the Bay watershed jurisdictions will meet their assigned nitrogen, phosphorus, and sediment load allocations as part of the Chesapeake Bay total maximum daily loads (TMDLs), and achieve all dissolved oxygen (DO), water clarity, SAV, and algae (measured as chlorophyll) levels required for healthy aquatic life. Implementation of the WIPs was estimated to have a far larger influence on the health of Chesapeake Bay in comparison to scouring of the lower Susquehanna River reservoirs.

Modeling done for this assessment estimated that currently more than half of the deep-channel habitat in the Bay is frequently not suitable for healthy aquatic life. However, it was estimated that even with full implementation of the WIPs and subsequent achievement of the reduced nitrogen, phosphorus, and sediment loads documented in the Chesapeake Bay TMDL (which should yield 100 percent suitable habitat for aquatic life), DO levels required to protect aquatic life in the Bay's deeper northern waters will not be achieved (in 3 of the 92 Bay segments). An increased frequency of scour and the amount of scoured sediment and associated nutrients from behind the dams on the lower Susquehanna River is a major contributor to these results.

Loss of Long-Term Trapping Capacity

Since the 1990s, scientists raised concerns over impacts to Chesapeake Bay from the lower Susquehanna River dams filling to capacity, and consequent increased delivery of sediments and associated nutrients to the Bay. These concerns were founded on the large total quantities of sediments and nutrients that would be transported. This scientific information supported a widely held view among government agencies, academics, and the public that once Conowingo Dam filled to capacity, severe downstream impacts to Chesapeake Bay would occur. These concerns served as the impetus for conducting this assessment. Only limited consideration was given to the relative bio-availability of nutrients contained in these riverine sediments versus the nutrients delivered to the Bay in other forms in these earlier risk analyses. Findings of this assessment, and other recent scientific investigations referenced in the report, reexamine these earlier scientific views.

This assessment concludes that each of the three reservoirs' sediment trapping capacity is greatly reduced and that each reservoir has reached an end state of sediment storage capacity. The evaluations carried out through this assessment demonstrate that Conowingo Dam and Reservoir, as well as upstream Safe Harbor and Holtwood Dams and their reservoirs, are no longer trapping sediment and the associated nutrients over the long term. Instead, the reservoirs are in a state of dynamic equilibrium.

In this dynamic equilibrium state, sediment and associated nutrients will continue to accumulate in the reservoirs until an episodic flood (scouring) event occurs. That is, there is no absolute capacity or point at which the reservoir is "full" and will no longer trap sediment and associated nutrients. Storage capacity will increase after a scouring event, allowing for more deposition within the reservoir in the short term. This state is a periodic "cycle" with an increase in sediment and associated nutrient loads to the Bay from scour also resulting in an increase in storage volume (capacity) behind the dam, followed by reduced sediment and associated nutrient loads transported to the Chesapeake Bay due to reservoir deposition within that increased capacity.

Dynamic equilibrium does not imply equality of sediment inflow and outflow on a daily, monthly, or even annual basis, or similar time scale. It implies a balance between sediment inflow and outflow over a long time period (years to decades) defined by the frequency and timing of scouring events. Sediment and associated nutrients that accumulate between high-flow events are scoured away during storm events, whereby accumulation begins again. Over time, there is no net storage or filling occurring in the reservoirs.

The reservoirs are trapping a smaller amount of the incoming sediment and associated nutrient loads from the upstream watersheds, and scouring more frequently in comparison to historical amounts. For example, upon comparing 1996 bathymetry data to 2011 data, this study estimated that the decrease in reservoir sediment trapping capacity from 1996 to 2011 (within the Conowingo Reservoir) resulted in a 10-percent increase in total sediment load to the Bay (20.3 to 22.3 million tons), a 67-percent increase in bed scour (1.8 to 3.0 million tons), and a 33-percent decrease in reservoir sedimentation (6.0 to 4.0 million tons) over the period of analysis. These additional loads, due to the loss of sediment and associated nutrient trapping capacity in the Conowingo Reservoir, are causing adverse impacts to the Chesapeake Bay ecosystem. These increased loads need to be prevented or offset to restore the health of the Chesapeake Bay ecosystem.

Nutrients, Not Sediment, Have the Greatest Impact on Bay Aquatic Life

Modeling work completed for this assessment estimated that the sediment loads comprised of sand, silt, and clay particles from scouring of Conowingo Reservoir during storm events, are not the major threat to Chesapeake Bay water quality and aquatic life. For most conditions examined, the sediment scoured from the reservoir behind the dam generally settle out on the bottom of the Bay within a period of days to weeks and generally before the period of the year during which light levels in the Bay's shallow waters are critical for the growth of underwater bay grasses or SAV. If a storm event occurs during the SAV-growing season, burial and light attenuation impacts could occur causing damage to SAV.

Conversely, the nutrients associated with the scoured sediment were determined to be more harmful to Bay aquatic life than the sediment itself. The particulate nutrients settle to the bottom and are recycled back up into 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, DO in the Bay's deep-water habitat is diminished following Conowingo scour events.

Additionally, increased algal growth (living and then dead) create murky waters that impede water clarity limiting growth of SAV. The primary impact to Bay aquatic life from the Susquehanna River watershed and the high river flows moving through the series of dams and reservoirs is lower dissolved oxygen concentrations and reduced water clarity from increased algal growth. It is the nutrients associated with the sediment that are the most detrimental factor from scoured loads to healthy Bay habitats and aquatic life versus sediment alone. Study findings are in accordance with scientific developments recognizing the effects of nutrients and algae upon suspended sediments (and water clarity) in the Bay, and emerging consensus that excess sediment independent of nutrients is a lower level stressor to the Bay than was previously thought (CBP STAC, 2007; CBP STAC, 2014).

Sediment Management Strategy Analysis

This assessment included a survey-level screening of management strategies to address the additional loads to Chesapeake Bay from scour. Sediment management in aquatic environments is a USACE agency mission activity. The focus was managing and evaluating sediment loads with the understanding that there are nutrients associated with those sediment loads; thus, in managing sediment, one is also managing nutrients. Potential sediment management measures were formulated in accordance with long-established concerns over potential impacts of excess sediments from the Susquehanna River impacting Chesapeake Bay, as described previously.

A variety of sediment management strategies were considered to reduce the amount of sediment available for a future storm (scour) event. Sediment management strategies were broadly divided into: (1) reducing sediment yield from the Susquehanna River watershed (reducing sediment inflow from upstream of the three reservoirs above what is required for the jurisdictions' WIPs); (2)

minimizing sediment deposition within the reservoirs (routing sediment around or through the reservoir storage); and (3) increasing or recovering volume in the reservoirs.

Additional management strategies for reducing sediment yield from the Susquehanna River watershed beyond the WIPs appear to be higher in cost, and ultimately, have a low influence on reducing the amount of sediment available for a storm event. This is because the majority of the effective lower cost opportunities to manage sediment are already being pursued in Pennsylvania, New York and Maryland's WIPs to meet the Chesapeake Bay TMDL mandated by the U.S. Environmental Protection Agency (USEPA, 2010a).

Sediment bypassing (minimizing sediment deposition behind the dams), defined here as routing sediment around reservoirs and downstream, appears to be lower in cost in comparison to other management strategies, but ultimately increases the total sediment and associated nutrient loads to the Bay and has high adverse impacts to the Chesapeake Bay ecosystem. As a result of the continuous discharge of nutrients associated with the bypassed sediment, conditions with lower DO concentrations would be produced. Increased algae levels are roughly 10 times greater than the benefits gained from reducing future scour from the Conowingo Reservoir.

Increasing or recovering storage volume of reservoirs via dredging or other methods is possible, but the Chesapeake Bay ecosystem benefits are minimal and short-lived, and the costs are high. When sediment is strategically removed from the reservoirs behind the dams, there was a predicted minor influence on scour load (reduction) and sediment deposition (increase); there was also a predicted minor reduction in adverse impacts to Chesapeake Bay ecosystem health for a future similar storm event. Scour events would still occur, but lower amounts of sediment and associated nutrients were estimated to be mobilized during these events.

However, Chesapeake Bay ecosystem benefits from sediment removal are short-lived due to the constant deposition of sediment and associated nutrients that originate throughout the Susquehanna River watershed in this very active system, as well as the unpredictable nature of storms (i.e., it is impossible to reduce all impacts from all storm events and it is unknown exactly when the next storm will occur as well as the magnitude of that storm). Sediment removal would be required annually, or on some similar regular cycle, to achieve any actual net improvement to the health of the Bay. This positive influence is minimized due to sediment loads coming from the Susquehanna River watershed during a flood event.

The estimated cost range for the suite of sediment management strategies evaluated was $5 to $90 per cubic yard of sediment removed. The removal of the specific amount of 3 million cubic yards (an estimated 2.4 million tons) of sediment which is estimated to be slightly more than what deposits and is temporarily stored behind the dams entering the Conowingo reservoir on an annual basis (average for 1993-2012), would cost $15 to $270 million annually (all strategies considered). For the dredging strategies investigated, the cost was estimated to be $16 to $89 per cubic yard, or $48 to $267 million annually for removal of 3 million cubic yards (an estimated 2.4 million tons) of sediment. Costs for reductions in sediment yield from the watershed were on the order of a one-time cost of $1.5 to $3.5 billion which is estimated to annually prevent approximately 117,000 cubic yards (an estimated 95,000 tons) of sediment from reaching the Chesapeake Bay.

The conclusion that the primary impact to living resources in Chesapeake Bay from reservoir scour was from nutrients associated with the sediments and not the sediment itself, was not determined until late in the assessment process. Further study on this is warranted. Management opportunities in the Chesapeake Bay watershed to reduce nutrient delivery are likely to be more effective than sediment reduction opportunities at reducing impacts to the Chesapeake Bay water quality and aquatic life from scour events, but these management opportunities were not investigated in detail during this assessment. The relative importance of nutrient load impacts from the lower Susquehanna River reservoirs is a finding that indicates that nutrient management and mitigation options could be more effective and provide more management flexibility, than solely relying on sediment management options only.

It should be noted that the LSRWA effort was a watershed assessment and not a detailed investigation of a specific project alternative(s) proposed for implementation. That latter would likely require preparation of a NEPA (National Environmental Policy Act) document. The evaluation of sediment management strategies in the assessment focused on water quality impacts, with some consideration of impacts to SAV. Other environmental and social impacts were only minimally evaluated or not evaluated at all. A full investigation of environmental impacts would be performed in any future, project-specific NEPA effort.

Future Needs and Opportunities in the Watershed

Based on these LSRWA findings, specific recommendations were identified to provide state, federal, and local decision makers with the additional information needed to take further actions to protect water and living resources of the lower Susquehanna River watershed and Chesapeake Bay.

1. Before 2017, quantify the full impact on Chesapeake Bay aquatic resources and water quality from the changed conditions in the lower Susquehanna River's dams and reservoirs.

2. The U.S. Environmental Protection Agency (EPA) and the Bay watershed jurisdictional partners should integrate findings from the LSRWA into their ongoing analyses and development of the seven watershed jurisdictions' Phase III WIPs as part of the Chesapeake Bay TMDL 2017 midpoint assessment.

3. Develop and implement management options that offset impacts to the upper Chesapeake Bay ecosystem from increased sediment-associated nutrient loads.

4. Commit to enhanced long-term monitoring and analysis of sediment and nutrient processes in the lower Susquehanna River and upper Chesapeake Bay to promote adaptive management.

Table of Contents

List of Tables

List of Figures

Organization and Purpose of Report

This Lower Susquehanna River Watershed Assessment (LSRWA) report includes a main document that discusses the assessment activities and findings. Appended to this main report are 11 appendices with various attachments that discuss more detailed technical findings as well as provide extensive and detailed back-up documentation to information and findings laid out in the main document.

The purpose of this report organization is to provide an overview of LSRWA activities and findings in the main report document, and also to have detailed discussion of technical analyses findings available to the reader in the appendices.

List of Appendices

Chapter 1. Introduction

The U.S. Army Corps of Engineers, Baltimore District (USACE), and the Maryland Department of the Environment (MDE) partnered to conduct the Lower Susquehanna River Watershed Assessment (LSRWA; the contents are herein).

1.1 PROJECT AUTHORIZATION

The LSRWA was conducted under several authorities. The first study authority comes from a resolution of the U.S. Senate Committee on Environment and Public Works, dated 23 May 2001 – Chesapeake Bay Shoreline Erosion. This resolution reads:

> "The Secretary of the Army is requested to review the report of the Army Corps of Engineers on the Chesapeake Bay Study, dated September 1984, and other pertinent reports, with a view to conducting a comprehensive study of shoreline erosion and related sediment management measures which could be undertaken to protect the water and land resources of the Chesapeake Bay watershed and achieve the water quality conditions necessary to protect the Bay's living resources. The study shall be conducted in cooperation with other federal agencies, the State of Maryland, the Commonwealth of Virginia, and the Commonwealth of Pennsylvania, and their political subdivisions and agencies and instrumentalities thereof; and the Chesapeake Bay Program, and shall evaluate structural and nonstructural environmental enhancement opportunities and other innovative protection measures in the interest of ecosystem restoration and protection, and other allied purposes for the Chesapeake Bay."

In addition, the fiscal year 2002 Energy and Water Appropriations Act conference report provided funding "…for a Chesapeake Bay shoreline erosion study, including an examination of management measures that could be undertaken to address the sediment behind the dams on the lower Susquehanna River." USACE received appropriations from the 2009 Omnibus Appropriations Act (House Appropriations Committee, H.R. Public Law 111-8) to sign a feasibility cost-sharing agreement with a non-federal sponsor to "examine management measures that could be undertaken to address the sediment behind the dams on the Lower Susquehanna River."

As a watershed assessment, this effort was conducted under Section 729 of the Water Resources Development Act (WRDA) of 1986, as amended. Guidance has been provided in USACE memoranda dated 29 May 2001, 7 March 2008, and 15 January 2012 for watershed planning under Section 729 of WRDA 1986, as amended, and other specifically authorized watershed planning authorities.

1.2 PROJECT SPONSORS AND PARTNERS

The assessment was led by USACE and MDE (non-federal sponsor). In addition, both the U.S. Geological Survey (USGS) and USACE's Engineer Research and Development Center (ERDC) participated in major technical portions of the study along with the Susquehanna River Basin Commission (SRBC), The Nature Conservancy (TNC), the U.S. Environmental Protection Agency's Chesapeake Bay Program Office (EPA-CBPO), and the Maryland Department of Natural Resources (MDNR, including the Maryland Geological Survey [MGS]). These agencies made up the LSRWA interagency team which was responsible for carrying out the day-to-day direction, management, and execution of the assessment and communication of its results.

Outside of the interagency team, there were various agencies, organizations, and businesses that attended LSRWA meetings regularly and provided feedback and information throughout the multi-year assessment process. These agencies included: Pennsylvania Department of Environmental Protection (PADEP), Pennsylvania Department of Conservation and Natural Resources, Pennsylvania Fish and Boat Commission (PFBC), Exelon, Lower Susquehanna Riverkeeper, the National Oceanic and Atmospheric Administration (NOAA), the University of Maryland Center for Environmental Science (UMCES), U.S. Fish and Wildlife Service (USFWS), Chesapeake Bay Commission (CBC), Chesapeake Bay Foundation, Chesapeake Conservancy, Chesapeake Research Consortium (CRC), Conservation Fund, Baltimore City agencies, the Pennsylvania governor's office, and the Maryland governor's office.

1.3 STUDY AREA

The Susquehanna River basin, encompassing 27,510 square miles, is the largest watershed draining to the Chesapeake Bay; it contains nearly 30,000 miles of streams, or 60,000 miles of streambanks (SRBC, 2006a). As such, the Susquehanna River is the single largest source of fresh water to the Chesapeake Bay, providing more than half of the freshwater flow into the estuarine system. It originates at Otsego Lake in Cooperstown, NY, flows through New York, Pennsylvania, and Maryland, and eventually empties into the Chesapeake Bay at Havre de Grace, MD, a distance of 444 miles (SRBC, 2006a).

The lower Susquehanna River's northern boundary is considered to be at the confluence of the mainstem Susquehanna River and the West Branch Susquehanna River at Sunbury, PA, as shown in Figure 1-1. The watershed crosses into Maryland and eventually empties into the Chesapeake Bay. There are four hydroelectric dams on the lower Susquehanna River below Harrisburg, PA, each creating a reservoir. Located from north to south, the dams are York Haven, Safe Harbor, Holtwood, and Conowingo. York Haven Dam forms Lake Frederick. York Haven Dam, which does not fully cross the river, is significantly smaller than the other dams, and does not trap sediment to a significant degree; consequently, it will not be addressed in this assessment. Additionally, the Muddy Run hydroelectric pump storage facility is located near the top eastern portion of the Conowingo Reservoir along Muddy Run, and the Peach Bottom Atomic Power Station is located approximately 7 miles upstream of Conowingo Dam (URS and Gomez and Sullivan [GSE], 2012a).

The three downstream reservoirs, Lake Clarke, Lake Aldred, and Conowingo Reservoir, are formed behind the southernmost three dams, Safe Harbor, Holtwood, and Conowingo, respectively, as illustrated in Figure 1-2. These three reservoirs involve nearly 33 miles of the river and have a combined storage capacity of 510,000 acre-feet at their normal pool elevations, while providing an estimated 1,148 megawatts of energy. General information pertaining to each dam is summarized in Table 1-1.

Figure 1-1. Lower Susquehanna River Watershed

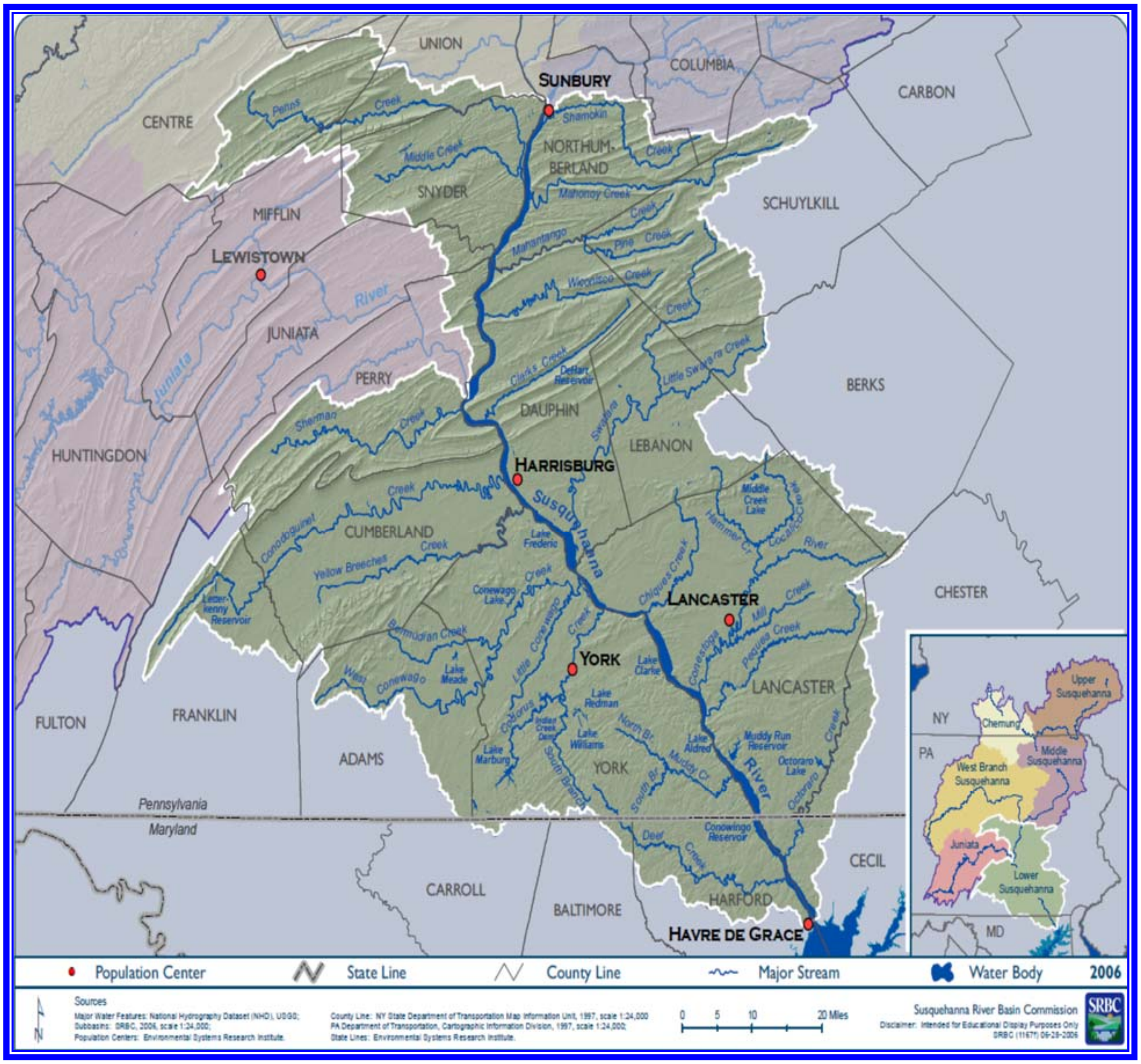


Figure 1-2. LSRWA Detailed Study Area

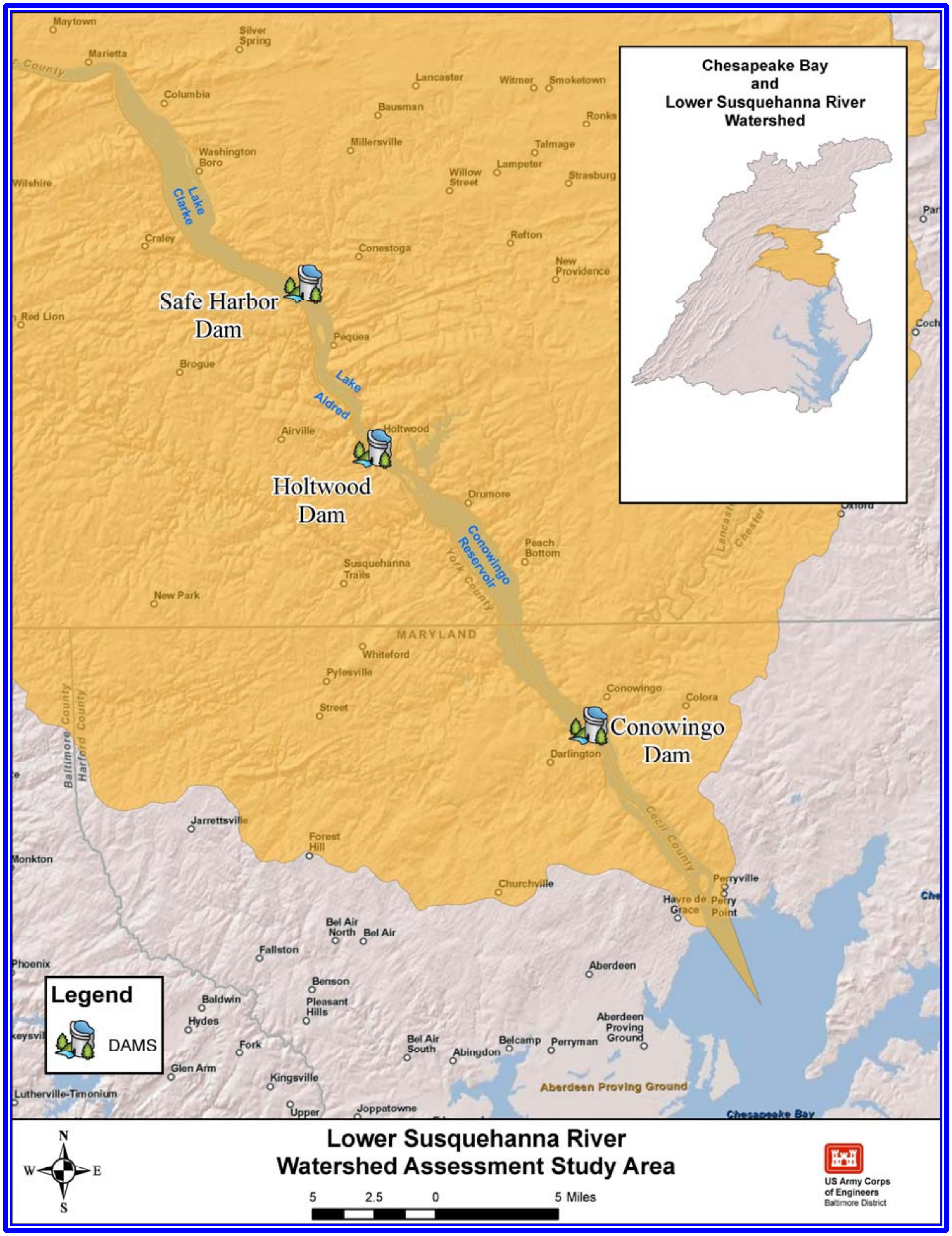


Table 1-1. Information on the Lower Susquehanna Hydroelectric Dams

Dam	Reservoir Name	Construction Date	Owner/ Operator	Dam Height (feet)	Design Capacity (acre-feet)	Sediment Trapping Capacity Status
York Haven, PA[1]	Lake Frederick	1904	Metropolitan Edison Company	28	7,800	N/A
Safe Harbor, PA	Lake Clarke	1931	Safe Harbor Water Power Corporation	75	150,000	Dynamic equilibrium reached in the 1950's
Holtwood, PA	Lake Aldred	1910	PPL Holtwood LLC	55	60,000	Dynamic equilibrium reached in the 1920's
Conowingo, MD	Conowingo Reservoir	1928	Exelon	94	300,000	Dynamic equilibrium reached in the 2000's, very limited capacity remaining [2]

Notes: [1] York Haven does not fully cross the river, is significantly smaller than the other dams, and does not trap sediment to a significant degree; thus, it is not addressed in this assessment.

[2] This LSRWA effort provides updated information on the sediment trapping capacity status of Conowingo.

Source: Hainly et al., 1995.

1.4 PURPOSE AND NEED

The purposes of this assessment were to estimate and evaluate sediment and associated nutrient loads from the series of hydroelectric dams and reservoirs located on the lower Susquehanna River, analyze hydrodynamic and sedimentation processes and interactions within the lower Susquehanna River watershed, consider structural and nonstructural strategies for sediment management, and assess cumulative impacts of future conditions and sediment management strategies on the upper Chesapeake Bay. The need for this assessment was to understand how to better protect water quality and aquatic life in the lower Susquehanna River and Chesapeake Bay.

This assessment concludes with this watershed assessment report to better inform all stakeholders undertaking efforts to restore Chesapeake Bay.

Critical components of this watershed assessment, along with their report locations, within this report, were:

- The identification of watershed-wide sediment management strategies (Chapter 5);
- The use of hydrologic and hydraulic and sediment transport models to link incoming sediment and associated nutrient loads to in-reservoir processes at the dams and reservoirs and estimate impacts to living resources in the upper Chesapeake Bay (Section 4.2);
- The use of the Chesapeake Bay Program Partnership's environmental model suite to assess cumulative impacts of the various sediment management strategies on upper Chesapeake Bay water quality and aquatic life (Section 4.2); and
- The integration of Maryland, New York, and Pennsylvania's watershed implementation plans (WIPs) for implementing management actions leading to nitrogen, phosphorus, and sediment pollutant load reductions, as required to meet the Chesapeake Bay total maximum daily load (TMDL) (Section 5.2).

1.5 SIGNIFICANCE

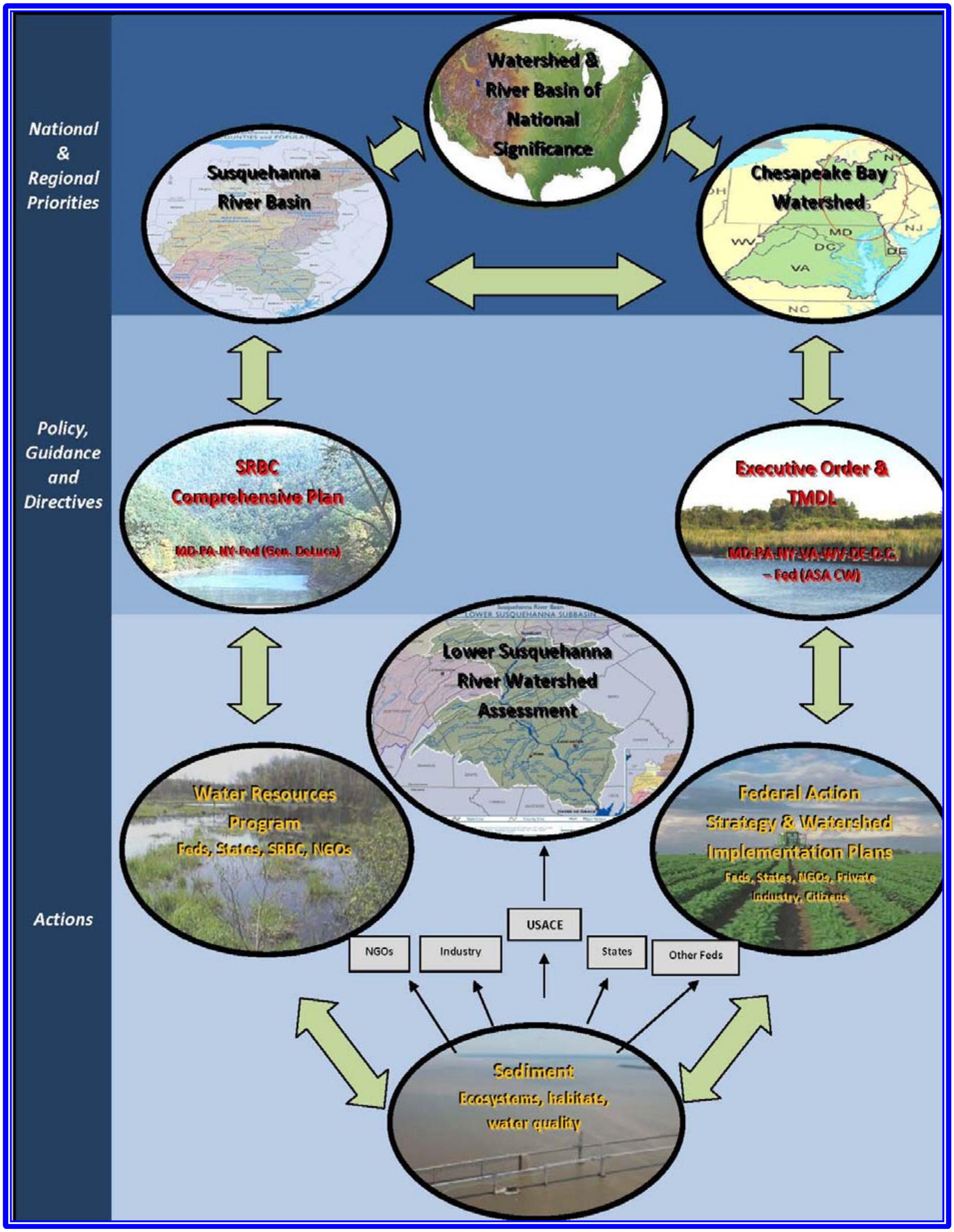
The Susquehanna River is the nation's 16th largest river, and the largest source of fresh water for and the largest single source of sediment and nutrients pollutant loads to the Chesapeake Bay (CBP, 2013).

There are many ongoing restoration activities in the watershed and Chesapeake Bay. Federal agencies share a renewed commitment to restore the Chesapeake Bay embodied in President Obama's Executive Order 13508, Chesapeake Bay Protection and Restoration (Obama, May 12, 2009). This executive order established the Federal Leadership Committee, which in turn, developed the Federal Action Strategy that set goals and objectives to be accomplished by the federal government, working closely with state, local, and non-governmental agencies, to protect and restore the health of the Chesapeake Bay (Federal Leadership Committee for Restoring the Chesapeake Bay, 2010).

In 2010, the nation's most extensive and comprehensive TMDL program was established for the Chesapeake Bay watershed. The Chesapeake Bay TMDL was required under the federal Clean Water Act (CWA) because most of the Chesapeake Bay and its tidal tributary and embayment waters are impaired due to excess nitrogen, phosphorus, and sediment pollutants (U.S. Environmental Protection Agency [EPA or USEPA], 2010a).

USACE and MDE, through collaboration with MDNR, MGS, Commonwealth of Pennsylvania, EPA, USGS, SRBC, TNC, and others seek to integrate water resources management in the lower Susquehanna River basin to ensure sustainable restoration of the Chesapeake Bay, the largest estuary in the United States. This process of integrated water resources management is depicted graphically in Figure 1-3.

Figure 1-3. Chesapeake Bay Significance and Integrated Water Resource Management



1.6 PROBLEM BACKGROUND

Historically, sediment from erosion in the Susquehanna River watershed, and nutrients associated with these sediments, were transported in the Susquehanna River and discharged directly into the Chesapeake Bay (Langland, 2001). Following construction of the dams on the lower Susquehanna River, a large amount of sediment and associated nutrients have been stored in the resulting reservoirs (Hainly et al., 1995).

Excess nutrients, primarily nitrogen and phosphorus, were identified as the principal stressor to the Bay ecosystem by the 1980s. Nitrogen and phosphorus occur in a number of different forms in the environment and these forms differ in their biological availability and effects on water quality. Phosphorus tends to bind to sediments which are then transported, whereas nitrogen is mostly transported in dissolved form. Excess sediment independent of phosphorus was also believed to be of substantial importance as a stressor. Dramatic sediment plumes often occur in the Bay at river mouths following storm events. Suspended sediments in the water column measurably contribute to water clarity reduction much of the year, and loss of substrate suitable to oysters from ongoing sedimentation is widely observed.

Studies released in 1995 by USGS and SRBC reported that both Safe Harbor's reservoir (Lake Clarke) and Holtwood's reservoir (Lake Aldred) had already reached their sediment trapping capacity, but that the Conowingo Reservoir still had capacity (Hainly et al., 1995). The studies raised substantial concerns about potential impacts to Bay living resources resulting from the filling of Conowingo Reservoir.

All reservoirs act as a sediment sink resulting in hydraulic conditions that reduce the velocity of flows within the reservoir. Due to flow deceleration as water enters the reservoir, sediment transport capacity decreases, and coarser fractions of the incoming sediment deposits in the reservoir forming a delta near the entrance to the reservoir. As the water and sediment continue to flow into the reservoir, the delta continues to extend in the direction of the dam, eventually filling the entire sediment storage volume. This process is usually slow, governed by the amount of incoming sediment, sediment type, and flow variability. Generally, low flow increases deposition, while during higher flows, deposition is reduced and some sediment may be resuspended, transported downstream, or conveyed out of the reservoir. Large reservoirs receiving runoff with substantial sediment from natural and/or anthropogenic sources can fill within 50 to 100 years (Mahmood, 1987).

The Chesapeake Bay is impacted both physically and biologically by the delivered sediment and associated nutrient loads from the Susquehanna River basin and the rest of the 64,000-square mile watershed. Associated impacts are exacerbated during large storm and high-flow events (such as the 1972 Tropical Storm Agnes), which increase inflow loads from the watershed, scour additional sediment from behind the dams on the lower Susquehanna River, and deliver large loads of sediment and associated nutrients to the tidal waters, adversely affecting the Chesapeake Bay ecosystem. Flooding occurs on a fairly regular basis in the Susquehanna River watershed; however, large storm and high-flow events are hard to predict, but occur infrequently (SRBC, 2006a).

The delivery of excess sediment to the Bay can have deleterious effects. Sediment contributed from the Susquehanna River to Chesapeake Bay could become part of the continual cycle of re-suspension and deposition. Excess sediment loads to the Bay deliver excess nutrients, increase maintenance dredging requirements of navigation channels, and can have adverse impacts to underwater bay grasses or submerged aquatic vegetation (SAV), bottom-dwelling (benthic) organisms, and fish (CBP STAC, 2000). Excess fine-grained sediment from rivers is more harmful to Bay water quality and aquatic life than coarse sediments, because fine sediments can remain suspended in the water degrading water clarity. Additionally, fine-grained sediments convey adsorbed nutrients and chemical contaminants into the Bay. Excess nutrients fuel additional algal growth in Bay waters, which drives eutrophication. However, sediment also has an important role in the Bay ecosystem. It creates and maintains valuable habitats, including shallow water and tidal wetlands. Appendix K contains additional information on nutrients and sediment and Bay environmental history.

In March 2000, the Chesapeake Bay Program Partnership's Scientific and Technical Advisory Committee (STAC, the entity charged with providing scientific and technical guidance on measures to restore the Bay to the larger partnership) conducted a workshop to assess the potential impact of increased sediment delivery to the Chesapeake Bay resulting from loss of sediment retention within the Susquehanna River's reservoirs. The workshop determined that a variety of detrimental impacts would occur, including increased loading of phosphorus in the middle Bay, increased need for dredging of navigation channels, adverse effects on SAV, adverse impacts to benthic organisms, and potential impacts on fish utilizing the upper Bay as a nursery area. The workshop report notes a likely 150-percent increase in sediment load, with a concomitant increase in phosphorus load (CBP STAC, 2000). In December 2000, the SRBC held a major workshop to address potential sediment load increases and impacts from loss of storage capacity (SRBC, 2001). In the workshop, it was reported that once the Conowingo Reservoir reaches equilibrium ("steady-state"), loads to the Bay would increase by 150 percent for suspended sediment, 2 percent for total nitrogen, and 40 percent for total phosphorus (SRBC, 2001).

Concern about the reduced trapping capacity of the reservoirs and increases in sediment and associated nutrient loads to the Chesapeake Bay, as well as implications for the management of these sediments served as the impetus for this study. More specifically, there were significant implications to the then ongoing development of the Chesapeake Bay TMDL by EPA working collaboratively with the six watershed states and the District of Columbia. In the 2010 Chesapeake Bay TMDL report, EPA and its seven partner watershed jurisdictions documented their assumption that the Chesapeake Bay TMDL allocations were based on the Conowingo Dam and Reservoir's sediment and associated nutrient trapping capacity in the mid-1990s, the midpoint of the 10 years of hydrology (1991-2000) used in the underlying model scenarios (USEPA, 2010a). EPA documented within its 2010 Chesapeake Bay TMDL main report and supporting technical appendix that if future monitoring shows the trapping capacity of the dam were reduced, then EPA would consider adjusting the Pennsylvania, Maryland, and New York sediment and associated nutrient load reduction obligations based on the new delivered loads to ensure that they were offsetting any new loads of sediment and associated nutrients being delivered to Chesapeake Bay (USEPA, 2010a)[1]. Chapter 2 provides further details on the Chesapeake Bay TMDL.

Various terms have been used to describe this reduced and/or end state of sediment and associated nutrient trapping capacity of the reservoirs. These terms include "full," "dynamic equilibrium," "quasi-equilibrium," "equilibrium," "steady state," "at capacity," and "at storage capacity." This report uses the term "dynamic equilibrium" for this condition. Estimating the time remaining until the reservoirs reach dynamic equilibrium is difficult because the amount of sediment transported and deposited in the reservoirs depends on such factors as sediment transport and delivery, sediment deposition, reservoir trapping efficiencies, and storm scour threshold. Transport and delivery can be altered by changing land use and management practices, as well as by climatic factors such as the timing and amounts of rainfall.

Previous studies by Ott et al. (1991), Hainly et al. (1995), Reed and Hoffman (1997), Langland and Hainly (1997), Langland (2009), and URS and GSE (2012b) have documented conditions of the lower Susquehanna River dams and reservoirs, including the reservoirs' bottom-sediment profiles, sediment storage capacity, and trapping efficiency. Several studies also have documented the sediment chemistry (Hainly et al., 1995; Langland and Hainly, 1997; and Edwards, 2006) and the effects of large storm events on the removal and transport of sediment out of the reservoirs and into the upper Chesapeake Bay (Langland and Hainly, 1997; Langland, 2009; URS and GSE, 2012b). Based on 2000-2008 trends, Langland (2009) found that the Conowingo Dam and Reservoir was trapping approximately 59 percent of sediment loads (3.1 million tons in, 1.2 million tons out) including 2 percent of the nitrogen load and 40 percent of the phosphorus load (1996-2008 period of evaluation). Langland (2009) also provided a historical perspective to reservoir filling rates, considering Holtwood and Safe Harbor to have already reached dynamic equilibrium decades ago, and projected when dynamic equilibrium would be reached for the Conowingo Dam and Reservoir.

In this dynamic equilibrium state, sediment and associated nutrient trapping will still occur. Storage capacity will increase after episodic flood (scouring) events, allowing for more deposition behind the dam within the reservoir in the short term. This state is a periodic "cycle" with an increase in sediment and associated nutrient load to the Bay from scour also resulting in an increase in storage volume (capacity) behind the dam, followed by reduced sediment and associated nutrient loads transported to Chesapeake Bay due to reservoir deposition. A recent study by Hirsch (2012) concludes that all the reservoirs in this reach appear very close to a dynamic equilibrium state, with the nutrient and sediment loads discharged from Conowingo Dam increasing since the mid-1990s. This LSRWA effort further investigated how close Conowingo Dam and Reservoir were to a dynamic equilibrium state (see Chapter 4 for additional details).

1.7 WATERSHED VISION

Watershed planning should provide a joint vision of a desired end state of the watershed of interest. The watershed vision developed for the LSRWA effort was:

[1] See pages 10-7 and 10-8 in USEPA, 2010a, and Appendix T in USEPA, 2010b.

- Managing land and water resources of the lower Susquehanna River watershed and Chesapeake Bay to achieve the water quality conditions necessary to protect the Chesapeake Bay's living resources.

1.8 GOALS

Based on the current needs of the lower Susquehanna River watershed and Chesapeake Bay, the specific goals and objectives[2] for the LSRWA effort were:

1. Generate and evaluate strategies to manage sediment and associated nutrient loads delivered to Chesapeake Bay.

   These strategies will incorporate input from Maryland, New York, and Pennsylvania's WIPs, will incorporate evaluations of sediment storage capacity in the reservoirs on the lower Susquehanna River, and will evaluate the types of sediment delivered and associated effects on Chesapeake Bay.

2. Generate and evaluate strategies to manage sediment and associated nutrients available for transport during high-flow storm events to reduce impacts on Chesapeake Bay.

3. Determine the effects to Chesapeake Bay due to the loss of sediment and associated nutrient storage within the reservoirs behind the dams on the lower Susquehanna River.

1.9 ASSESSMENT PRODUCTS

This assessment served as a tool to analyze sediment management strategies in the watershed, the loss of sediment storage capacity from the series of dams and reservoirs on the lower Susquehanna River, and the resultant impacts to the upper Chesapeake Bay ecosystem. Management strategies to reduce the impact, or potential impact, of sediment and associated nutrients were analyzed. The assessment included integrated modeling activities, data gathering, and development of broad, planning-level strategies, and evaluation of anticipated impacts and benefits to the upper Chesapeake Bay ecosystem.

The assessment produced numerous products that are available now to assist in future watershed planning and management efforts; these products are listed in Table 1-2. Based on the findings of this assessment, future needs and opportunities were identified by the study team. These were formulated into recommendations for state, federal, and local decision makers, and are detailed in Chapter 8.1. The assessment recommends the integration of this study's results into future watershed management policies and strategies, and identifies areas where further study is needed.

[2] It had been known for decades that excess nutrients were the most important stressor to Chesapeake Bay. Excess sediments independent of nutrient content were assumed to be a stressor of nearly equal importance. As this assessment evolved, that assumption was re-evaluated. For these reasons, management measures focused primarily or solely on nutrients were not considered in this assessment.

Table 1-2. LSRWA Major Products

Product Type	Product Description	Report Location
Dataset/ Analysis	2012 field sampling (core samples) and SEDflume analysis of bed sediment in the Conowingo Reservoir to characterize the erosion characteristics (erosion rate and critical shear stress) of fine sediment deposits.	Appendix B and Attachment B-2
Dataset/ Analysis	2011 field sampling and lab analysis of solids in the Conowingo Dam outflow at base flow and storm flow for multiple size classes (clay, very fine silt, fine silt, medium silt, coarse silt, sand), as well as nutrients.	Appendix F
Dataset/ Analysis	Computation of storm recurrence intervals, sediment scouring, and flow/sediment transport into and out of the reservoir system based on data collected from the Marietta and Conowingo USGS gages. These sites are considered to represent the flow and sediment input to and output from the reservoirs, respectively.	Appendix A, Attachment A-1
Dataset/ Analysis	Compilation of all sediment core data collected in Conowingo Reservoir by USGS, and analysis of historical particle size percentages and deposition rates	Appendix A, Attachment A-2
Dataset	2012 sediment sampling of the Susquehanna Flats for input into the Adaptive Hydraulics (AdH) model.	Appendix E
Dataset	Assembly of existing data (as of 2012) of physical properties and composition of solids flowing over the Conowingo Dam and of bed sediment within the Conowingo Reservoir.	Appendix C, Attachment C-1
Dataset	Assembly of existing data on the conditions of the Chesapeake Bay and Lower Susquehanna River Watershed.	Appendix K
Analysis	Computation of 100-percent capacity "full" Conowingo bathymetry utilizing recent 2008 and 2011 bathymetry data.	Appendix A, Attachment A-3
Analysis	Determination that a two-dimensional (2D) AdH model was appropriate to adequately estimate long-term sedimentation and hydrologic processes in Conowingo Reservoir.	Appendix B and Attachment B-3
Analysis	Development and evaluation of planning-level concepts and cost ranges for selected sediment management strategies.	Appendix J
Analysis	Literature review summarizing the management of watershed and reservoir sedimentation, both in the United States and internationally.	Appendix H

Product Type	Product Description	Report Location
Model Application	Utilization of the 2D AdH model to estimate the Conowingo Reservoir and Susquehanna Flats sediment transport response to low (less than 30,000 cubic feet per second [cfs]), moderate (30,000-150,000 cfs), and high (greater than 150,000 cfs) flows for different reservoir bathymetries (1996, 2008, 2011, and calculated "full") with an evaluation of results.	Appendix B and Attachment B-3
Model Application	Utilization of the Hydrologic Engineering Center's River Analysis System (HEC-RAS) model to estimate a range of probable conditions for flow, sediment transport, and particle size fractions between each of the reservoirs on lower Susquehanna River with an evaluation of results.	Appendix A
Model Application	Utilization of the 2D AdH model to estimate the effectiveness of various sediment management strategies to reduce sediment loads transported through Conowingo Reservoir and the Susquehanna Flats with an evaluation of results.	Appendix B and Attachment B-4
Model Application	Utilization of the Chesapeake Bay Environmental Model Package (CBEMP), to estimate the water quality impacts of selected watershed and land use conditions, reservoir bathymetries, and flows, with an evaluation of results.	Appendix C
Model Application	Utilization of CBEMP to estimate the water quality impacts under various sediment management strategies with an evaluation of results.	Appendix C
Model Application	Utilization of CBEMP and a criteria assessment procedure to assess if water quality standards developed and adopted to protect Chesapeake Bay living resources are met based on the estimated water quality impacts under various watershed and land use conditions, reservoir bathymetries, and flows. Note: any alterations to current TMDL requirements will be determined by EPA and its watershed jurisdictional partners as defined by the 2010 Chesapeake Bay TMDL, Appendix T, outside of this LSRWA effort.	Appendix D
Model Application	Development of a series of modeling tools and applications that can be utilized in the future to evaluate other sediment and nutrient management strategies, flows, land use, and reservoir conditions in the watershed.	Appendices A, B, C, and D

1.10 ASSESSMENT APPROACH

Application of the following series of tools was necessary to properly examine the behavior and properties of the sediment and associated nutrients for this assessment:

1. A one-dimensional (1D) HEC-RAS model computed hydraulic conditions and sediment transport in the reservoir system and sediment loads to Conowingo Reservoir for use in AdH (Adaptive Hydraulics model).

2. USACE's 2D AdH model computed detailed hydrodynamics and sediment transport within and out of Conowingo Reservoir, and the response of the reservoir and flats area to various sediment management scenarios and flows.

3. CBP Partnership's Watershed Model (WSM) computed loads from the watershed at key locations in the reservoir system including the Conowingo inflow and outflow. Watershed loads at the Conowingo outfall computed by the WSM were supplemented by bottom scour loads estimated through ADH and through data analysis. The WSM is considered part of the CBEMP (Chesapeake Bay Environmental Model Package).

4. CBP Partnership's CBEMP computed the impact of sediment and nutrient pollutant loads on light attenuation, SAV, chlorophyll, and dissolved oxygen (DO) in the Chesapeake Bay and its tidal tributaries and embayments. The unique components of the CBEMP include a hydrodynamic model and an estuarine eutrophication model. The eutrophication model is commonly referred to as the Water Quality Sediment Transport Model (CBP WQSTM).

5. CBP Partnership's Chesapeake Bay Water Quality Criteria Assessment Procedure, which utilizes CBEMP, assessed whether Maryland, Virginia, Delaware and the District of Columbia's water quality standards developed and promulgated into state regulations to protect Chesapeake Bay aquatic life are met in terms of time and space for all 92 Bay segments based on estimated water quality impacts under various watershed and land use conditions, reservoir bathymetries, and flows. This procedure was added to the LSRWA effort after the study commenced to provide context to the magnitude of water quality changes that were estimated from selected LSRWA scenarios and to understand the potential living resource impacts. Any alterations to current TMDL allocations will be determined by EPA and its seven watershed jurisdictional partners as defined by the 2010 Chesapeake Bay TMDL, Appendix T, through a collaborative decision making process outside of the scope of the LSRWA.

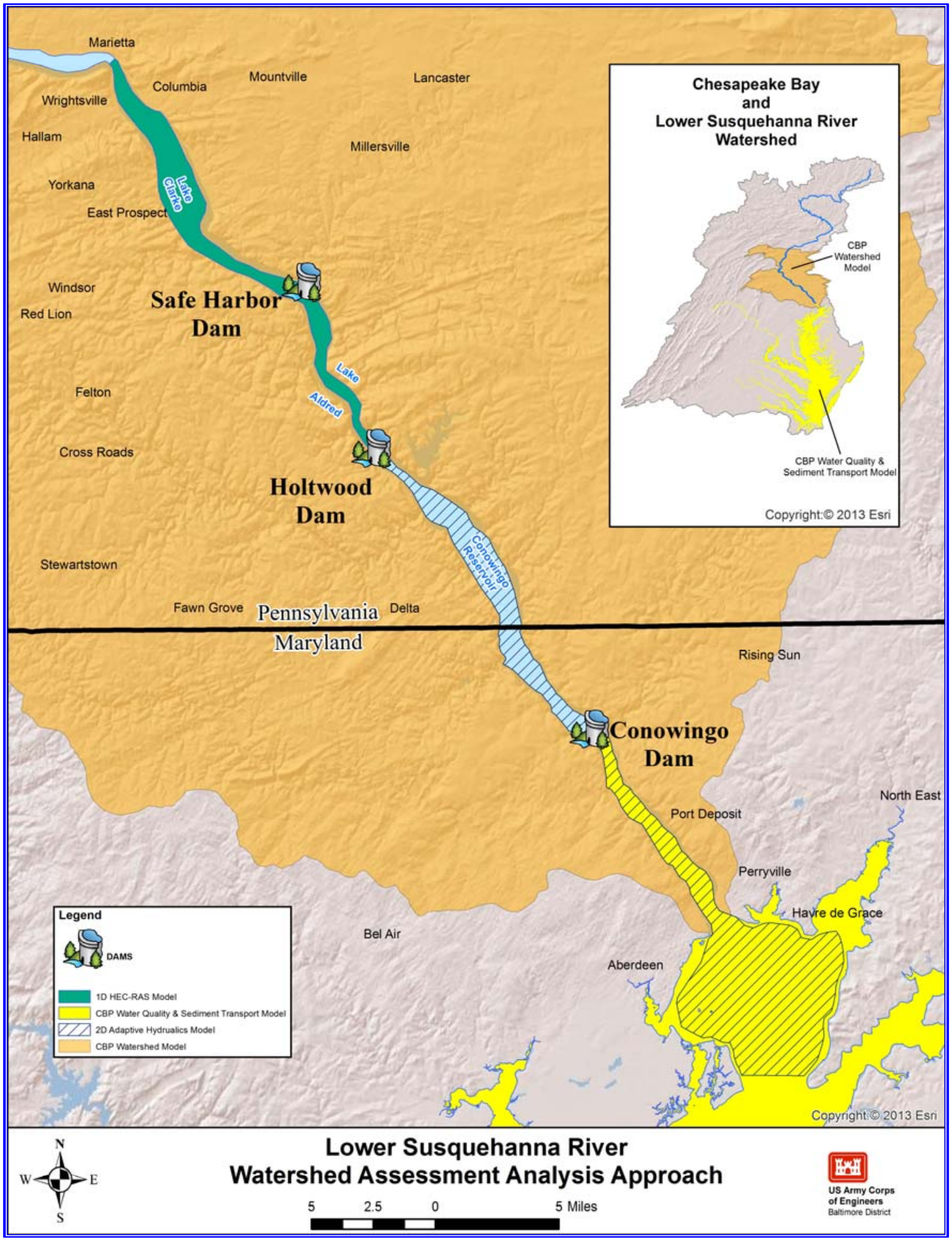
Figure 1-4 depicts the areas where these models were applied. Because of the importance of these modeling tools, Chapter 3 is devoted to further explanation of these modeling tools and how they were used in the LSRWA effort. The full modeling reports, which have extensive details of the modeling work and results, are appended to this main report, and are broken out as follows:

- Appendix A provides detailed documentation of the 1D HEC-RAS modeling development, scenario descriptions, results, and uncertainties.

- Appendix B provides detailed documentation of the 2D AdH modeling development, scenario descriptions, results, and uncertainties.
- Appendix C provides detailed documentation of the CBEMP modeling development, scenario descriptions, results, and uncertainties.
- Appendix D provides detailed documentation of the Chesapeake Bay Water Quality Criteria Assessment Procedure utilizing CBP Partnership's CBEMP to estimate attainment of the Chesapeake Bay water quality standards in terms of time and space for each Chesapeake Bay segment under different model scenarios. Documentation includes scenario descriptions and results.
- Attachment J-4 in Appendix J provides consolidated summary tables of major modeling scenarios and results.

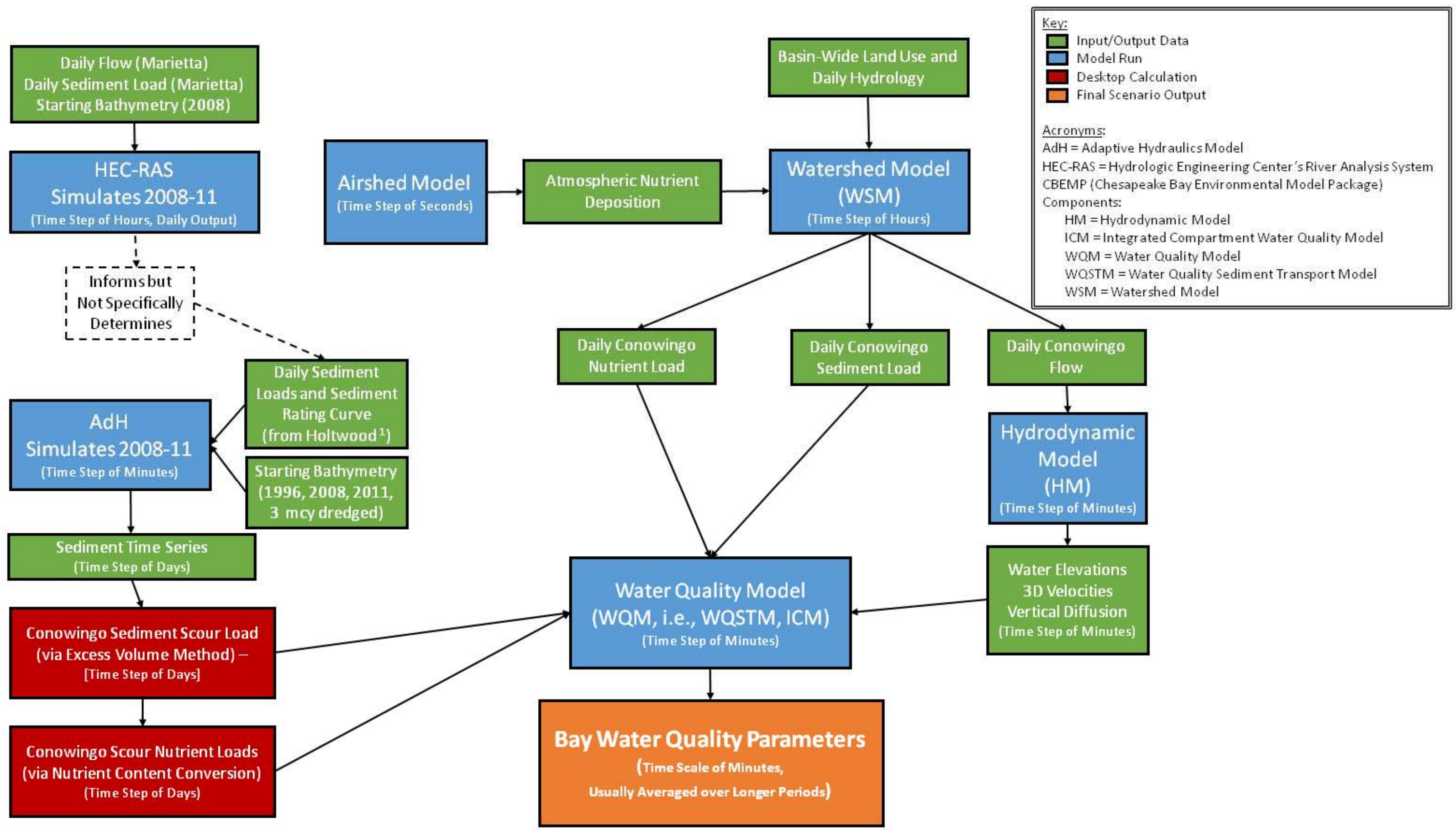
Figure 1-5 provides a flow chart of the modeling tools, their components, and application in this study, while Figure 1-6 depicts the overall LSRWA analytical approach. The LSRWA approach included identification of the sediment and nutrient loads into the reservoirs, routing of these loads through the reservoirs, routing of the outflowing loads down to the Susquehanna Flats and Chesapeake Bay, and identification of the impacts of these loads on critical parameters. This approach was followed for numerous modeling scenarios such as existing conditions, future conditions with the WIPs in effect, and with various sediment management scenarios. Following completion of these runs, the various modeling scenarios were compared to ascertain the impacts of the changes between scenarios. Based on modeling results, the sediment management strategies were analyzed and estimated conditions of the watershed described. An extensive discussion of the development of the modeling scenarios is provided in Section 3.4, with results in Chapters 4 and 5.

Figure 1-4. LSRWA Modeling Areas



Notes: This figure has been simplified to emphasize the lower Susquehanna River watershed. It should be noted that the CBP Watershed Model encompasses the entire Susquehanna River watershed.

Figure 1-5. Flow Chart of Modeling Components and Applications



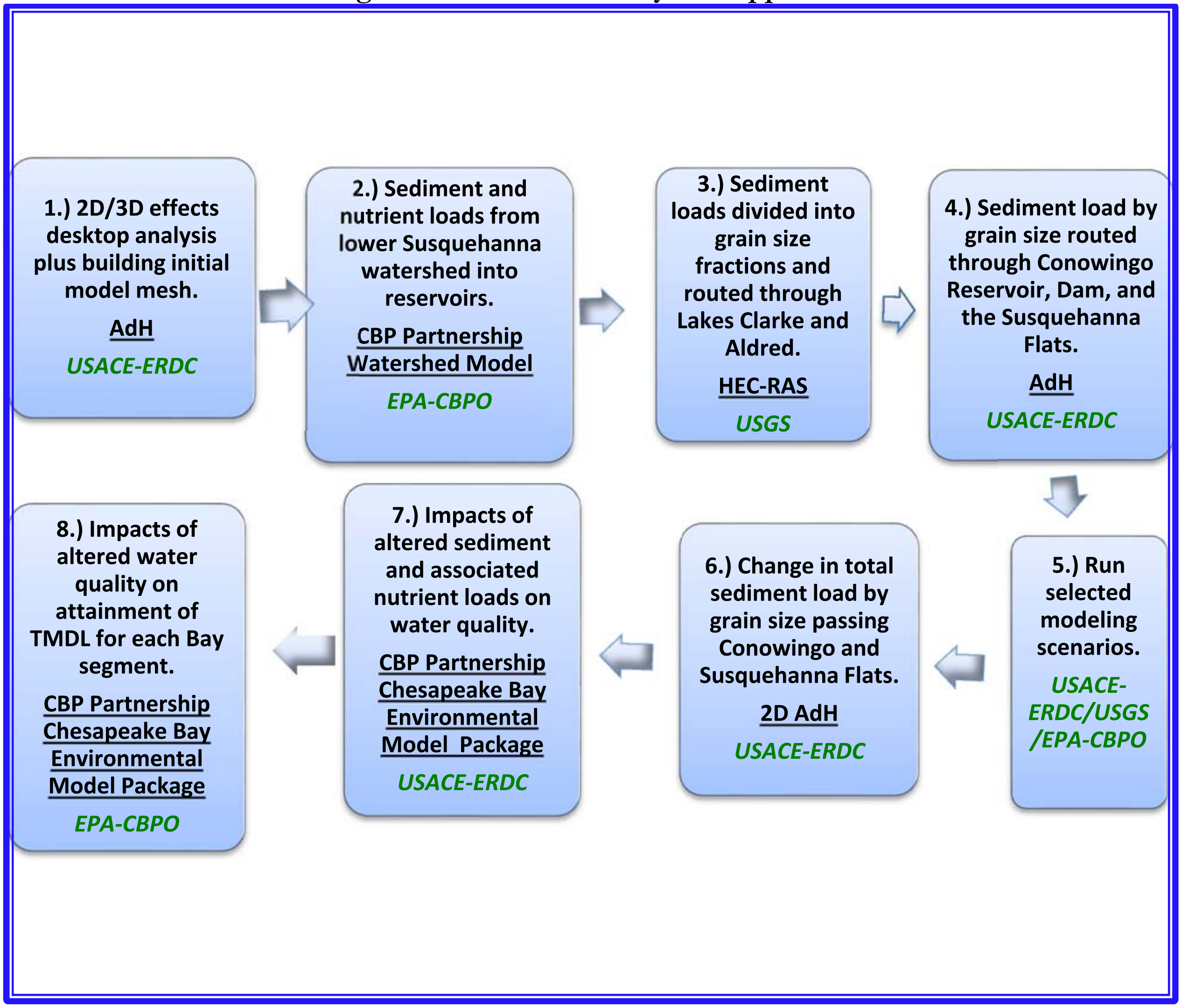
Notes:

[1] The Holtwood sediment outflows were calculated from the HEC-RAS model "scour" simulation, plus an additional 10 percent beyond the HEC-RAS predicted sediment load.

[2] The time steps noted for each model are the time element used in the numerical integration of the underlying differential equation. These do not necessarily indicate the significant time scale of the model, nor the time values of the inputs or outputs. Inputs are seldom available on the frequency of the model's time step, and outputs are generally averaged up to a more meaningful time scale. Daily loads from the WSM are input to the WQSTM on a daily basis.

[3] Scour loads for Lake Clarke and Lake Aldred are not explicitly represented in the WQM inputs; the WQM only "sees" what comes over the Conowingo outfall, with no identified origins to the mixture.

Figure 1-6. LSRWA Analytical Approach



Notes: The Chesapeake Bay Program Office modeling work was funded by EPA unlike other modeling efforts which were funded with LSRWA funds.

Step 8 was added to the LSRWA effort after the study commenced to provide context to the magnitude of water quality changes that were estimated from selected LSRWA scenarios to help understand potential Chesapeake Bay aquatic life impacts.

Chapter 2. Management Activities in the Watershed

Chesapeake Bay is a nationally significant multi-jurisdictional ecosystem. There are many management activities currently planned or ongoing within the Chesapeake Bay and lower Susquehanna River watershed that aim to continue the protection and restoration of this important ecosystem and maintain other public uses such as hydroelectric power, drinking water, recreation, and navigation. This section summarizes the regulatory and management framework that the LSRWA was working within to provide context for assessing and evaluating findings and implications of this effort and to meet the integrated water resources management approach of this LSRWA effort. Figure 2-1 provides a timeline of major ongoing and planned management activities in the watershed and the sections herein provide summary descriptions.

2.1 CHESAPEAKE BAY RESTORATION

2.1.1 Chesapeake Bay Agreements

The Chesapeake Bay Agreement of 1983 was signed by the governors of Maryland, Virginia, and Pennsylvania as well as the mayor of the District of Columbia, the EPA Administrator, and the Chairman of the CBC. This agreement led to the formation of the Chesapeake Executive Council. Following the ratification of the 1983 agreement, three additional agreements have been adopted since that time.

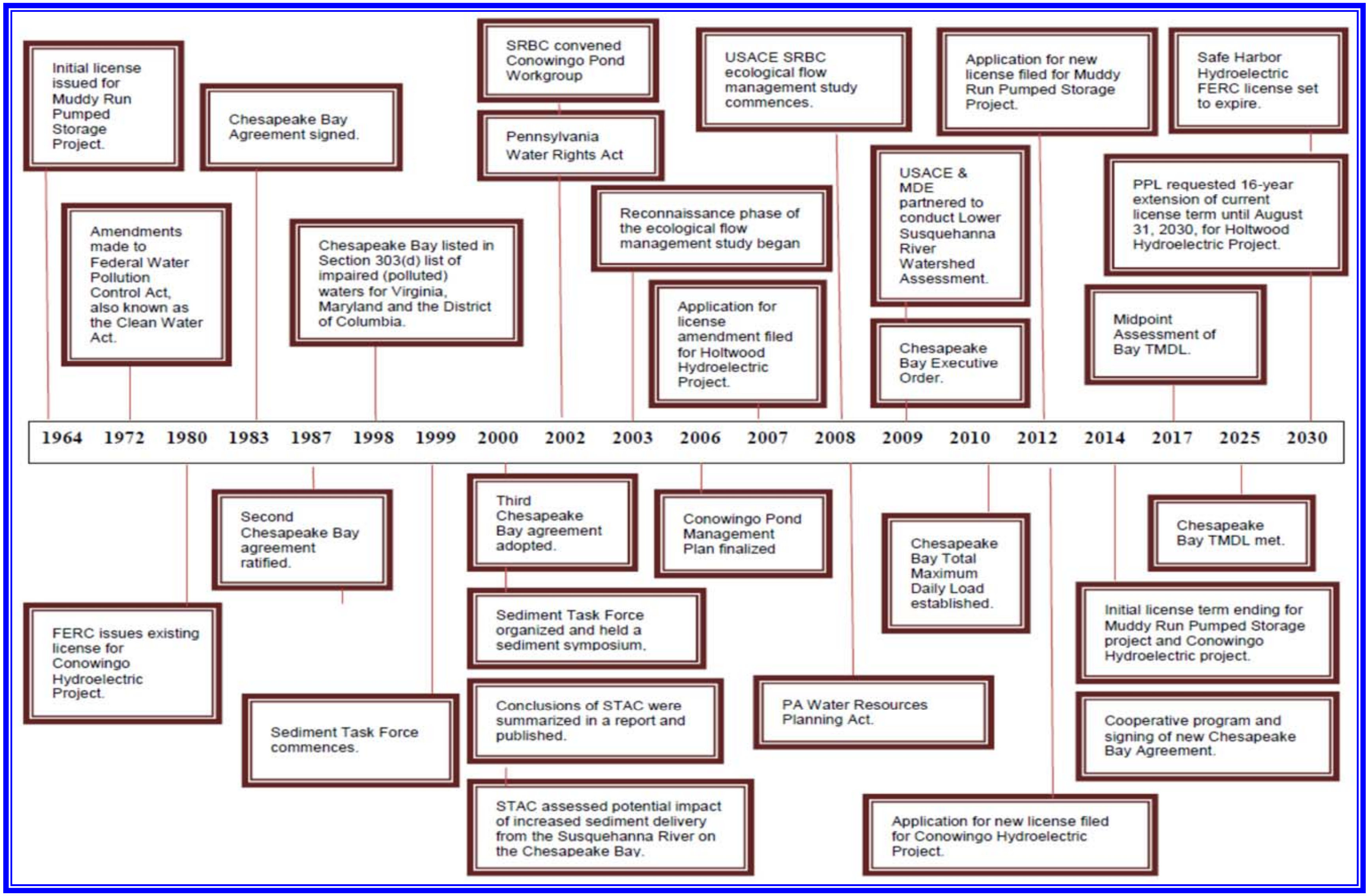
The second Chesapeake Bay agreement was ratified December 15, 1987, by the original signatories to the 1983 agreement. The goals of this non-binding agreement included:

- Provide for the restoration and protection of the living resources, their habitats, and ecological relationships;
- Reduce and control point and nonpoint sources of pollution to attain the water quality condition necessary to support the living resources of the Bay; and
- Plan for and manage the adverse environmental effects of human population growth and land development in the Bay watershed.

Among the objectives to achieve these goals was to develop, adopt, and begin implementation of a basin-wide strategy to achieve a 40-percent reduction of nitrogen and phosphorus entering the Bay by the year 2000. The primary objective in achieving this specific goal was to correct the nutrient and sediment-related problems of the Chesapeake Bay and its tidal tributaries in order to remove the Bay from the list of impaired (polluted) waters. This included determining the sediment load reductions necessary to achieve the water quality conditions that would protect and enhance aquatic living resources.

The Chesapeake Bay was listed in the 1998 Section 303(d) list of impaired waters for Virginia, Maryland, and the District of Columbia. This list is required to be submitted by the states under the CWA. Following the 1998 impaired water listing of the Chesapeake Bay, a third Chesapeake Bay agreement was adopted in 2000.

Figure 2-1. Major Watershed Management Activities



The third Chesapeake Bay agreement was also signed by Virginia, Maryland, Pennsylvania, the District of Columbia, the CBC, and the EPA (representing the federal agencies) in 2000. In 2014, a fourth Chesapeake Bay watershed agreement was signed which now included New York, West Virginia, and Delaware, as well as the original signatories, as full partners in the Chesapeake Bay Program Partnership and on the Chesapeake Executive Council. One of the many goals of all three 1987, 2000, and 2014 Chesapeake Bay agreements has been to continue to achieve and maintain the water quality necessary to support the aquatic living resources of the Bay and to protect human health.

2.1.2 Total Maximum Daily Load (TMDL)

The 1972 amendments to Federal Water Pollution Control Act are known as the Clean Water Act (CWA). These amendments provide the statutory basis for identifying and restoring impaired (polluted) waters. The CWA has set an environmental goal that all waters of the United States be fishable and swimmable, and requires that states develop and submit biennial lists of polluted waterways. Surface waters are classified as impaired (polluted) by identifying waters that are not meeting water quality standards. Under the CWA's Section 304, water quality standards are composed of: (1) designated uses that describe the intended use (or goal) of surface waters; (2) water quality criteria (numeric or narrative) that protect designated uses; and (3) an antidegradation policy that protects surface waters of higher quality.

Numeric water quality criteria consist of two separate but related components: magnitude and duration. Magnitude usually consists of specific concentrations of a toxin or pollutant known to affect aquatic life or human health. Duration is the time period over which the concentration of the toxin or pollutant is assessed, and is expressed in terms of acute (lethal) or chronic (affecting organism survival, growth or reproduction) effects. Water bodies with chemical contaminants, nutrients, sediment, or other pollutants that exceed acute or chronic water quality criteria are not achieving water quality standards, and therefore, are considered and labeled as impaired (polluted).

Total Maximum Daily Loads (TMDLs)

- The maximum amount of a pollutant that a water body can receive and still meet water quality standards
- Includes point, nonpoint, and natural background sources, plus a margin of safety
- Mandated by the Clean Water Act
- States have developed watershed implementation plans (WIPs) to achieve these loads.

Under Section 303(d) of the CWA, states and authorized tribes are required to list and develop TMDLs for any impaired (polluted) surface waters not meeting water quality standards. A TMDL is the maximum amount of a given pollutant that a water body can receive and still meet water quality standards. The mathematical expression of a TMDL is defined as the sum of the point sources of pollution (e.g., municipal wastewater treatment plants, industrial discharges, etc.) and nonpoint sources of pollution (e.g., stormwater, agricultural runoff, septic systems, atmospheric deposition, etc.), natural background sources, and a margin of safety (MOS). Natural background sources of sediment are considered to be those sources present in undisturbed areas with no anthropogenic influence. In the case of nutrients, natural background sources can also include atmospheric deposition loads during pristine air conditions. Other natural background sources include lightning, forest fires, and bacterial processes (USEPA, 2010a).

Point sources are assigned waste load allocations (WLAs) and nonpoint sources and natural background sources are assigned load allocations (LAs) using the following equation:

$$TMDL\ \ Allocation = \sum WLA + \sum LA + MOS$$

Simply, the TMDL allocation is the sum of all of the WLAs and the LAs, plus a safety factor. Despite extensive restoration efforts under the voluntary 1983 and 1987 Chesapeake Bay agreements, the Chesapeake Bay was listed in the 1998 Section 303(d) list of impaired (polluted) waters for Virginia, Maryland, and the District of Columbia. The pollutants impairing the Chesapeake Bay were identified as nitrogen, phosphorus, and sediment (EPA, 2010a).

The Chesapeake Bay TMDL has separate allocations for sediment, phosphorus, and nitrogen that are each based separately on the living resource needs in the Chesapeake Bay. Phosphorus is both sorbed and desorbed to sediment, essentially instantaneously, based on relative concentrations of the nutrients and environmental conditions, such as salinity and oxygen availability. This means that phosphorus and sediment can have independent sources within the watershed, yet be sorbed (or desorbed) repeatedly in watershed transport to the tidal Bay. The majority of phosphorus delivered to the Chesapeake Bay is sorbed to sediment, but the ecological influence of phosphorus and sediment is separable (EPA, 2010a; Bicknell et al., 1997).

Chesapeake Bay Water Quality Standards

The Chesapeake Bay Program partners published a set of Chesapeake Bay-specific water quality criteria guidance as committed to within the Chesapeake 2000 Agreement (Chesapeake Executive Council, 2000; USEPA, 2003a). These water quality criteria were derived using the best available scientific information and relate directly to the nitrogen, phosphorus, and sediment loads coming into Chesapeake Bay. The four tidal jurisdictions – Delaware, District of Columbia, Maryland, and Virginia – subsequently incorporated these water quality criteria into their state regulations.

The objective of these criteria is to protect the designated uses of the Chesapeake Bay. The CBP partners developed five separate designated uses:

- Migratory fish spawning and nursery use;
- Shallow-water bay grass use;
- Open-water fish and shellfish use;
- Deep-water seasonal fish and shellfish use; and
- Deep-channel seasonal refuge use.

These five designated uses identified the living resources and their supporting habitats that the Chesapeake Bay water quality criteria DO, SAV, water clarity, and chlorophyll *a* were developed to protect (Figure 1-CC in USEPA, 2003b). Because these designated uses vary seasonally, the criteria themselves also contain spatial and temporal components. For example, the deep-channel seasonal DO criteria apply only from June 1 to September 30 in certain areas of Chesapeake Bay (USEPA, 2003a).

Water quality criteria applied in each reach of the Susquehanna River and its tributaries are based on specific use designations identified in Pennsylvania and Maryland state code. The mainstem lower Susquehanna River is designated for warmwater fisheries and migratory fisheries uses. About 4,200 stream miles in the Susquehanna River basin are impacted by nutrients and/or sediment, with a large number of impacts occurring in the lower Susquehanna region (SRBC, 2013a).

Determination of TMDL Achievement

The Chesapeake Bay TMDL is considered achieved when each of the seven jurisdictions in the Chesapeake Bay watershed meets their nitrogen, phosphorus, and sediment allocations and the Maryland, Virginia, Delaware, and the District of Columbia's Chesapeake Bay water quality standards are achieved. The allocations were derived by modeling nutrient and sediment pollutant loads from the watershed and the airshed that result in achievement of each of the four jurisdictions' Chesapeake Bay water quality standards (USEPA, 2010a). The 2010 Chesapeake Bay TMDL allocations for nitrogen, phosphorus, and sediment are enumerated for each of the six watershed states and the District of Columbia in Table 2-1.

The anticipated degree of achievement (i.e., "attainment") of the Chesapeake Bay water quality standards under different management scenarios are estimated by EPA and its seven watershed jurisdictional partners by long-term monitoring of water quality parameters and using the WQSTM which estimates impacts to water quality in each Chesapeake Bay segment. This process and the Chesapeake Bay water quality criteria assessment procedures are described in detail in Section 3.3. More detailed descriptions of the approach, including consideration of daily loads and margins of safety, are described in the Chesapeake Bay TMDL documentation (USEPA, 2010a and 2010b).

Frequency of Allowable Exceedance of Water Quality Standards

Allowable water quality standard exceedances are already built into the criteria assessment procedures and resulting allocations using the following mechanisms: (1) establishment of allowable criteria exceedance resulting from natural ecological conditions; (2) allowance of 1 percent exceedance due to model uncertainty per the Chesapeake TMDL decision rules; and (3) allowances provided for restoration variances in specific Bay segments as promulgated into the states' water quality regulations (USEPA, 2010a).

Since allowable exceedances are already built into the criteria assessment procedures carried for each Chesapeake Bay segment, absolutely no further water quality standard exceedances are allowed.

Consequences for Not Meeting the TMDL Allocations

EPA has stated that it will take contingency actions where jurisdictions do not meet their Chesapeake Bay TMDL allocations (USEPA, 2010a). These contingency actions may include but are not limited to:

- Expanding coverage of National Pollution Discharge Elimination System (NPDES) permits to sources that are currently unregulated;
- Increasing oversight of state-issued NPDES permits;

Table 2-1. Chesapeake Bay TMDL Load Allocations by Jurisdiction

Jurisdiction	TMDL Load Allocation					
	Nitrogen		Phosphorus		Total Suspended Sediment	
	Tons per year	Million pounds per year	Tons per year	Million pounds per year	Tons per year	Million pounds per year
Delaware	1,500	3.0	150	0.3	28,900	57.8
District of Columbia	1,200	2.3	50	0.1	5,600	11.2
Maryland	19,600	39.1	1,400	2.7	609,000	1,218.9
New York	4,400	8.8	300	0.6	146,000	293.0
Pennsylvania	36,900	73.9	1,400	2.9	992,000	1,983.8
Virginia	26,700	53.4	2,700	5.4	1,289,000	2,578.9
West Virginia	2,800	5.5	300	0.6	155,000	310.9

Source: USEPA, 2010a.

- Requiring additional pollution reductions from point sources such as wastewater treatment plants;
- Increasing federal enforcement and compliance in the watershed;
- Prohibiting new or expanded pollution discharges;
- Redirecting EPA grants; and
- Revising water quality standards.

One of the primary mechanisms that will be used to meet the Chesapeake Bay TMDL allocations is the jurisdictions' WIPs. The WIPs provide a set of strategies that, when fully implemented, are predicted (based on current available science) to achieve the four jurisdictions' Chesapeake Bay water quality standards. The six Chesapeake Bay watershed states and the District of Columbia developed their own WIPs which detail how and when the individual states and the District of Columbia will meet their Chesapeake Bay TMDL allocations (USEPA, 2010a).

The Chesapeake Bay TMDL accountability process requires jurisdictions – including states and the federal government – to provide a reasonable assurance of implementation by establishing 2-year milestones to track progress toward reaching the TMDL goals (USEPA, 2010a). These milestones will demonstrate the effectiveness of the jurisdictions' WIPs by identifying specific near-term pollution reduction controls and a schedule for implementation. EPA will review these 2-year milestones to see if they are achieved and evaluate whether current strategies are sufficient to achieve necessary pollution reduction strategies. A midpoint assessment of the 2010 Chesapeake Bay TMDL process is planned for 2017 in order to make any necessary adjustments to the needed nutrient and sediment pollutant load reductions and management actions necessary to achieve those pollutant reductions.

Impacts of Conowingo Reservoir Filling with Sediment on the TMDL

Section 10.6 and Appendix T of the 2010 Chesapeake Bay TMDL report and technical appendices, respectively, specifically addressed the effect of Conowingo Reservoir sediment infill on the Chesapeake Bay TMDL[3] (USEPA, 2010a and 2010b). When developing the allocations for the seven watershed jurisdictions, EPA and its seven watershed jurisdictional partners assumed Conowingo Reservoir's pollution trapping capacity, defined in the Chesapeake Bay Program Partnership's models as levels observed and monitored in the mid-1990s[4], would remain constant through the Chesapeake Bay TMDL planning horizon (through 2025). Thus, the 2010 Chesapeake Bay TMDL allocations were developed assuming unchanging conditions within the Conowingo Reservoir. In addition, the seven watershed jurisdictions' Phase I and Phase II WIPs do not include strategies to increase sediment and nutrient reduction efforts to offset any increase in sediment and associated nutrient loads to Chesapeake Bay if Conowingo's sediment trapping efficiency declined. The 2010 Chesapeake Bay TMDL assumed that the reservoirs above Conowingo, Lake Clarke (Safe Harbor Dam) and Lake Aldred (Holtwood Dam) had no remaining sediment trapping capacity and have been in long-term equilibrium for 50 years or more (USEPA, 2010b).

EPA stated within Appendix T of the 2010 Chesapeake Bay TMDL that "if future monitoring shows the trapping capacity of the dam is reduced, then EPA would consider adjusting Pennsylvania, Maryland, and New York 2-year milestones loads based on the new delivered loads" (USEPA, 2010b). In practical terms, this means that nutrient and sediment loads from the Pennsylvania, Maryland, and New York portions of the Susquehanna River basin would have to be further reduced to offset the increase in sediment and associated nutrient loads in order to achieve the established 2010 Chesapeake Bay TMDL allocations and achieve the states' Chesapeake Bay water quality standards. Any future alteration to the 2010 Chesapeake Bay TMDL allocations will be determined by EPA working directly with its seven watershed jurisdictional partners through a collaborative decision making process outside of the LSRWA.

2.2 SEDIMENT MANAGEMENT INVESTIGATIONS

Prior to the development of the Chesapeake Bay TMDL, a combination of changing land use and the implementation of sediment erosion and runoff control BMPs in surrounding Bay states had reduced the amount of sediment entering the lower Susquehanna River reach, including Conowingo Reservoir. Several efforts have ensued in recent years to specifically address the concerns for sediment storage in the lower Susquehanna River reservoirs, as discussed below.

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[3] Appendix T of the 2010 Chesapeake Bay TMDL can be directly accesses at: http://www.epa.gov/reg3wapd/pdf/pdf_chesbay/FinalBayTMDL/AppendixTSusquehannaDams_final.pdf.

[4] This is the midpoint of the 1991-2000 hydrologic period selected by the CBP partners for development of the allocations documented within the 2010 Chesapeake Bay TMDL (USEPA, 2010a).

2.2.1 SRBC Sediment Task Force

Several regulatory entities have examined the issue of sediment storage behind the Susquehanna dams during the past two decades. The CBC, through its Pennsylvania delegation, provided grant funding to SRBC to organize and chair a multi-agency task force to review the technical aspects of the issue and make management recommendations to policymakers at the state, regional, and national level. The Sediment Task Force was organized in July 1999 by SRBC, with the following charge: (1) undertake a review of existing studies related to Susquehanna sediment transport and storage; (2) evaluate and make recommendations on management options to address the issue; (3) conduct a symposium to bring experts and policymakers together; and (4) recommend continued areas of study, research, or demonstration. The task force met for 18 months before organizing a sediment symposium, which was held in December 2000. The symposium, coupled with the ongoing deliberations of the Sediment Task Force, provided a forum for bringing together expertise on a wide range of sediment management issues in the Susquehanna River basin.

The effort culminated in a report, entitled *Sediment Task Force Recommendations* (SRBC, 2002). The report set forth a series of recommendations developed by the task force for riverine, upland, and reservoir management options in the basin. Riverine management recommendations focused on stream restoration and stabilization, riparian buffers, and natural and constructed wetlands. Upland recommendations addressed agricultural, forest, mining and urban lands, as well as transportation systems. Reservoir management recommendations included a feasibility study to determine if dredging the reservoirs is a viable option to maintain or reduce the volume of sediment currently trapped behind the dams. Other reservoir management alternatives, included sediment bypassing, sediment fixing, and modified dam operations, that were considered, but dismissed. The suites of recommendations were offered to provide guidance to policymakers in the Susquehanna River basin on the issue of sediment management. They could also serve as a foundation for management options elsewhere in the Chesapeake Bay watershed.

2.2.2 Scientific and Technical Advisory Committee (STAC)

On March 29, 2000, the Chesapeake Bay Program's STAC convened a group of experts to assess the potential impact of increased sediment delivery from the Susquehanna River on the Chesapeake Bay. The objective of the workshop was to survey the possible consequences of increased sediment delivery to Chesapeake Bay as a result of reduced sediment storage capacity in the reservoirs behind Conowingo Dam and the other upstream dams.

The conclusions of the STAC-sponsored workshop were summarized in a report published in May 2000 (CBP STAC, 2000). STAC acknowledged that the timing and intensity of scouring events is impossible to predict and therefore detailed predictions of impacts are not feasible. However, some consequences could be predicted with confidence including:

- Increased nutrient loading;
- Increased need for dredging to maintain navigation channels;
- Higher turbidity and faster sedimentation rates;
- Adverse effects on SAV recovery; and
- Adverse effects on benthic organisms and fish populations.

2.3 FEDERAL ENERGY REGULATORY COMMISSION RELICENSING

The sections below summarize recent and current Federal Energy Regulatory Commission (FERC) relicensing activities associated with applicable projects located on the lower Susquehanna River. As part of FERC's relicensing process for these projects, a number of federal and state agencies, non-governmental organizations, businesses, and other stakeholders have been actively engaged in study requests, report reviews, and advocating for proposed license terms and conditions. Management issues addressed through the process are extensive and comprehensive, including areas such as flow management, fish passage, sediment management, and recreation.

2.3.1 Safe Harbor Hydroelectric Station

Safe Harbor is currently operating in accordance with its FERC license (FERC Project No. 1025), which is set to expire in 2030.

2.3.2 Holtwood Hydroelectric Station

On December 20, 2007, PPL filed with FERC an application for a license amendment for its 108.4-MW Holtwood Project, FERC Project No. 1881 (PPL, 2009). PPL proposed to increase the installed capacity, increase the hydraulic capacity, and improve upstream fish passage at the project. The proposal included construction of a new powerhouse, installation of turbines, construction of a new skimmer wall, enlargement of the forebay, and reconfiguration of the project facilities to enhance upstream fish passage through modifications of the existing fishway and excavation in the tailrace channel. The installed capacity was increased by approximately 90 MW to 196 MW. Additionally, PPL requested a 16-year extension of Holtwood's current license term through August 31, 2030, for the project. The license amendment included provisions for minimum releases, drought operations, fish passage, and recreation. The amendment was granted, and construction is slated to be completed in 2014.

2.3.3 Muddy Run Pumped Storage Facility

On August 29, 2012, Exelon filed with FERC an application for a new license for its 800-MW Muddy Run Pumped Storage Project, FERC Project No. 2355 (URS and GSE, 2012b). The initial license for the project was issued by the Federal Power Commission, FERC's predecessor, to Susquehanna Power Company and Philadelphia Electric Power Company in September 1964. This license was set to expire on August 31, 2014. Project facilities and features of the existing FERC license for pump storage operation include the dam creating the Muddy Run upper reservoir, as well as three other structures: an east dike, a recreation reservoir dike, and an intake canal embankment. The project's lower reservoir is the Conowingo Reservoir.

For its new license, Exelon proposes to continue to operate the Muddy Run Pumped Storage Project as it has been operated historically. Exelon is not proposing any changes to the existing power production facilities or project operations. Exelon is proposing the implementation of several resource management plans and a comprehensive management and upgrade proposal for the recreational facilities at the Muddy Run project. FERC must decide whether to issue a new hydropower license to Exelon for the Muddy Run project and what conditions should be placed on any license issued. In addition to the power and developmental purposes for which licenses are issued, FERC is required to give equal consideration to the purposes of energy conservation, the protection of recreational opportunities, the preservation of other aspects of environmental quality, as well as the protection, mitigation of damage to, and enhancement of fish and wildlife (including related spawning grounds and habitat).

On June 3, 2014, PADEP issued a Section 401 water quality certification (WQC) for the Muddy Run project. On March 11, 2015, FERC issued a final environmental impact statement (EIS) for the relicensing of the York Haven, Muddy Run, and Conowingo projects. In the final EIS, FERC staff recommended the staff alternative, a combination of measures from Exelon's proposal, some mandatory conditions recommended by other groups, and additional measures developed by the FERC staff. As of May 2015, a new FERC license for the Muddy Run project is pending.

2.3.4 Conowingo Hydroelectric Station

On August 30, 2012, Exelon filed with FERC an application for a new license for its 573-MW Conowingo Hydroelectric Project, FERC Project No. 405 (URS and GSE, 2012b). The existing license for the project was issued by FERC to Susquehanna Power Company and Philadelphia Electric Power Company on August 14, 1980, for a term ending August 31, 2014.

Exelon intends to continue to operate the project as it has operated historically. FERC must decide whether to issue a new hydropower license to Exelon for the Conowingo project and what conditions should be placed on any license issued. Like the Muddy Run relicensing action, FERC will consider and balance the project's energy, recreation, fish and wildlife, and other environmental resources. On March 11, 2015, FERC issued a final EIS for the relicensing of the York Haven, Muddy Run, and Conowingo projects, recommending relicensing using the staff alternative. At the writing of this report, Exelon still needs to acquire a 401 WQC from MDE, and a new FERC license for the Conowingo project is pending.

2.4 WATER WITHDRAWAL AND CONSUMPTIVE WATER USE REGULATIONS

This section includes a summary of the current laws in place to oversee water withdrawal and water use in the lower Susquehanna River watershed.

There is an ongoing interface between the SRBC and Maryland, New York, and Pennsylvania state regulatory programs to ensure each meets its objectives with no duplication of work or inconsistencies. In general, SRBC regulates ground and surface water withdrawals of 100,000 gallons per day (gpd) or more (peak 30-day average), consumptive water uses and out-of-basin diversions of 20,000 gpd or more (peak 30-day average), and all in-basin diversions (SRBC, 2013b).

The SRBC consumptive use regulation contains specifications pertaining to mitigation requirements. The main purposes of the regulations are to avoid conflict among water users; protect public health, safety and welfare; manage and protect stream quality; consider economic development factors; protect fisheries and aquatic habitat; and protect the Chesapeake Bay (SRBC, 2013b). Examples of SRBC-regulated projects located in the lower Susquehanna River watershed include the Baltimore City water supply, Peach Bottom consumptive water use, Chester Water Authority's water supply, York Energy Center's water withdrawal for power production, and Holtwood Hydroelectric Generating Station's water withdrawal for power production. SRBC regulates water withdrawals and consumptive uses in Conowingo Reservoir, and the lower Susquehanna River in Maryland to Havre de Grace.

Applicable Maryland state law is summarized on the following Internet website: http://www.dsd.state.md.us/comar/subtitle_chapters/26_Chapters.aspx#Subtitle03. Maryland state law requires a water appropriation and use permit be obtained for most activities that withdraw from the state's surface and underground waters. Exceptions involve individual domestic well uses, fire-fighting, low-volume agricultural uses, low-volume groundwater uses, and low-volume, temporary dewatering during construction.

Applicable Pennsylvania state law is summarized in its state water plan which is located at: http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-76835/3010-BK-DEP4222.pdf. The Pennsylvania Water Rights Act (2002) gives public water supply agencies the right to acquire water rights to surface water and prohibits water suppliers from acquiring or taking surface water without a permit. The permitting process requires proof of the need for the water and balances other water needs. As part of its permit approval, PADEP, the Pennsylvania agency overseeing water actions, may require minimum flow releases from dams and reservoirs and pass-by flows that establish minimum instream flows that will not be allocated to any water supplier. Since public water supply agencies are estimated to account for approximately 10 percent of the surface water uses in Pennsylvania, the Water Rights Act allocation provisions cover only a small portion of Pennsylvania's water resources.

The Pennsylvania Water Resources Planning Act (2008) authorized the preparation of a state water plan, and requires the registration with PADEP of all withdrawals exceeding 10,000 gpd, and prohibits political subdivisions from allocating water resources. The law is summarized here: http://www.pacode.com/secure/data/025/chapter110/chap110toc.html.

2.5 CONOWINGO POND MANAGEMENT PLAN

In 2002, SRBC convened the Conowingo Pond Workgroup to develop a management plan for Conowingo Reservoir (SRBC, 2006c). The membership was comprised of representatives from federal and state agencies, local jurisdictions, operators of the lower Susquehanna hydroelectric facilities and Peach Bottom Atomic Power Station, local water utilities, and SRBC. The primary purpose of this 4-year planning effort was to evaluate operational alternatives for the reservoir and to recommend a management plan to SRBC that best meets the management needs. The workgroup completed their report in March 2006, and it served as the basis for the SRBC's *Conowingo Pond Management Plan* (SRBC, 2006c).

There is a wide range of interests, problems, and potential conflicts related to the resources, uses, and operation of Conowingo Reservoir. Effective management of the reservoir, particularly during low-flow conditions, is critical for economic, environmental, and human welfare. Operation of Conowingo Dam by Exelon is subject to FERC requirements, including provisions related to minimum flow releases and maintenance of recreational pond levels. By virtue of being a reservoir, the stored water has a variety of purposes including public water supply, power generation, recreation, and fish and wildlife habitat.

Using the SRBC's OASIS hydrologic model, the management plan established baseline conditions and evaluated a series of alternatives to manage multiple uses and needs of the water. Modeled simulation runs and evaluations developed a recommended plan that demonstrated the most favorable balance for preserving adequate levels in the pond, ensuring reliable multipurpose use of the pond, and meeting the requirements for the quantity of water released to the downstream reaches of the Susquehanna River and Chesapeake Bay.

2.6 ECOLOGICAL FLOW MANAGEMENT STUDY

The Susquehanna River Basin Ecological Flow Management Study was a partnership between USACE and SRBC. Under contract to SRBC, TNC provided technical expertise related to ecological flows. The reconnaissance phase of the study began in 2003 and a cost-sharing agreement was signed in 2008 by the two study partners. TNC conducted the technical analysis and facilitated three expert workshops. Federal, state, and local agencies, in concert with non-governmental organizations and academic institutions, participated in the effort. The overarching goal of the study was to clearly establish the volume and timing of flows required to support aquatic species, and to minimize and avoid deleterious ecosystem impacts in the Susquehanna River basin (SRBC and USACE, 2012).

The study process generally followed the Ecological Limits of Hydrologic Alteration framework (Poff et al., 2010). Using stream and river classifications to establish ecosystem response relationships to flow alterations across a broad geographic area, the approach enabled environmental flow needs to be assessed when in-depth studies were not possible for an entire watershed. The result was a set of streamflows that support ecosystem health; the study results are documented in *Ecosystem Flow Recommendations for the Susquehanna River Basin* (TNC, 2010) and *Susquehanna River Basin Ecological Flow Management Study Phase I Report* (SRBC and USACE, 2012).

Significant low flows, combined with water withdrawals and consumptive water use, may create critical low-flow conditions, impacting natural functions of the ecosystem and the species that depend on these functions and attributes. The complexity of the Susquehanna River system and the potential for changing conditions in the basin call for a better understanding of how to manage ecosystem flows. It is critical to maintain the current range of unaltered flow variability to sustain the full range of species and ecological processes throughout the basin.

The Phase I report identified strategies by USACE and SRBC to preserve and restore flows necessary to support ecosystem health and resilience. The variable flows may be supported with reservoir operations by USACE and water resource management actions by SRBC including consumptive use regulation, pass-by flows, water availability studies, and other related actions. Management and regulatory actions can help maintain and restore a flow regime that supports the natural habitats and characteristic species of the Susquehanna River basin and also provide benefits for all of the basin's inhabitants. The study is continuing with SRBC as the non-federal sponsor. This will allow for the examination of a number of options to protect aquatic ecosystems and augment low flows.

Chapter 3. Modeling Tools and Applications

The LSRWA team determined that application of a series of mathematical environmental models would be necessary in order to properly examine the physical processes of the study area. The models were selected because they were well developed, widely accepted, and have had wide use and application. More than one model was required because of the complex physical processes of the study area being evaluated (i.e., there was no "one" model that could accurately estimate all of the physical processes). Since more than one model was used certain parameters (e.g., hydrologic periods) were varied and required careful consideration when developing and interpreting modeling scenarios. Because of their importance to the LSRWA analyses, this section summarizes each of the modeling tools, their development, and application in the LSRWA effort, as well as sources of uncertainty.

In regards to uncertainty, 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 which is what was done for this LSRWA effort.

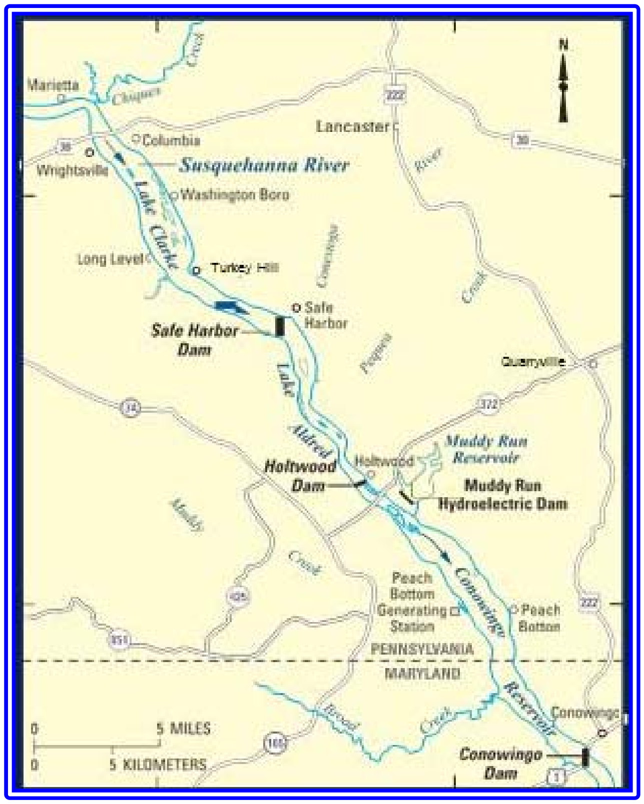
Extensive details on each modeling effort are provided in the technical appendices (see Appendices A, B, C, and D).

3.1 <u>HEC-RAS MODEL</u>

The first modeling tool used as part of this assessment was HEC-RAS (Hydrologic Engineering Center's River Analysis System). HEC-RAS is a model developed by USACE, which is a 1D movable boundary open-channel flow model designed to simulate and estimate changes in river profiles resulting from scour and/or deposition over moderate time periods (years). HEC-RAS was selected for this study because of its wide use and applicability in riverine systems and a previous application of a 1D HEC model in the lower Susquehanna River system (Hainly et al., 1995). Specifically, this study used HEC-RAS 4.2 beta 2012-07-19. The application area for HEC-RAS included Lake Clarke, Lake Aldred, and Conowingo Reservoir and was run by USGS; Figure 3-1 displays the HEC-RAS model area.

Ultimately, boundary condition files from HEC-RAS estimated conditions for daily flow, sediment transport, and particle size fractions from the upper two reservoirs, Lake Clarke and Lake Aldred, along with Conowingo Reservoir. These files were then provided to USACE for input into the 2D

Figure 3-1. Location Map of HEC-RAS Model Area



AdH model[5]. The hydrologic period used for these scenarios was 2008-11. This 4-year time period was utilized because it included low (less than 30,000 cfs), moderate (30,000 to 150,000 cfs) and high (greater than 150,000 cfs) flows, as well as two major flood events (above 400,000 cfs). Each HEC-RAS simulation provided a range of probable conditions and also provided a range of uncertainty in the boundary condition files (see Appendix A for more details on the HEC-RAS analyses and model).

For the LSRWA effort, the HEC-RAS model outputs provided a relative understanding of the reservoir sediment dynamics, indicating all three reservoirs are active with respect to scour and deposition even in a dynamic equilibrium state (the upper two reservoirs have been considered to be in dynamic equilibrium for decades). Additionally the boundary condition data from the HEC-RAS model were helpful in the calibration of the AdH model, especially by improving information on the inputs into Conowingo Reservoir.

HEC-RAS is designed primarily for non-cohesive sediment transport (sands and coarse silts) with additional, but limited, capability to simulate processes of cohesive sediment transport (generally

[5] HEC-RAS also simulated Conowingo Reservoir but given the AdH model would be simulating this area as well so these files were only used for informational purposes.

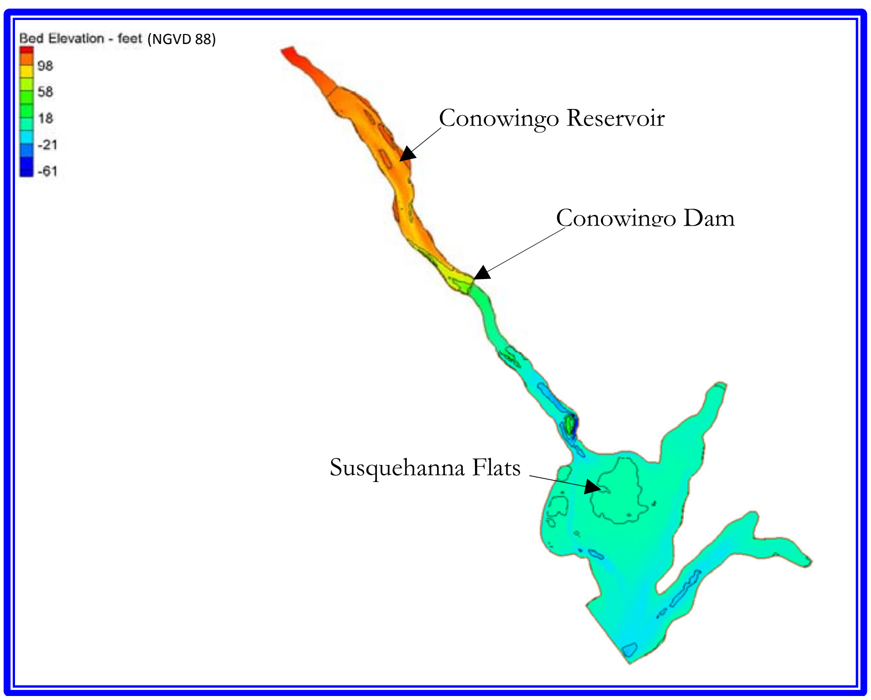
medium silts to fine clays). Thus, the model may not be suitable for all reservoir simulations, especially in areas of highly variable bed shear stress (the force of water required to move bed sediment) and active scour and deposition. Limitations of the model most likely resulted in: (1) less than expected deposition for the 2008-2011 simulation, and (2) less than expected erosion (scour) for the Tropical Storm Lee 7-day event simulation, when compared to other approaches and estimates. If a more detailed evaluation of the upper two reservoirs is required in the future, AdH would be a more appropriate model.

3.2 ADH MODEL

The second modeling tool utilized for this LSRWA effort was the AdH (Adaptive Hydraulics) model. The AdH model was developed at the USACE's ERDC, located in Vicksburg, MS, and has been applied in riverine systems around the country and world. For this assessment, the AdH model was constructed and applied from Conowingo Reservoir to the Susquehanna Flats just below the Conowingo Dam, as shown in Figure 3-2. Modeling scenarios were run by ERDC team members. Additional details about the AdH model and analyses are available in Appendix B.

The AdH model was selected for the LSRWA effort and for use in the Conowingo Reservoir/Susquehanna Flats area (versus HEC-RAS) because of the higher uncertainty of conditions and processes in this area, particularly in comparison to the upper two reservoirs which were understood to be in dynamic equilibrium for several decades.

Figure 3-2. Location Map of AdH Model Area



AdH simulates hydrodynamics and sediment transport. The AdH modeling results describe the transport of sediment solids and do not imply a relationship exists between solids transport and fate with nutrient loads. The sediment transport model is capable of simulating coarse sediment transport (sand size or greater), fine sediment transport (silt and clay sizes), and mixed sediment transport. Multiple bed layers can be simulated, with sorting of a mixed load due to variable erosion and deposition processes. The model contains sediment transport capacity functions for the coarse sediment transport. However, silt and clay deposits in reservoirs will most likely display cohesive behavior due to consolidation. Functions that describe the prototype sediment behavior can be directly input into AdH to describe the erosion and deposition characteristics.

For this assessment, the bed sediment in the reservoirs were sampled and analyzed in the laboratory to develop erosion rate functions specific to the sediment in the reservoir. The AdH model utilized these data to compute the erosion rate and critical shear stress for erosion of the cohesive fine sediment bed.

The AdH mesh density for the entire Conowingo Reservoir is depicted in Figure 3-3. Figure 3-4 provides the AdH mesh density for the Susquehanna Flats. The model mesh was designed to provide an adequate number of computational elements and associated nodes to capture details of the reservoir bathymetry and to provide highly resolved model results. For this study, a number of reservoir surveys (provided by USGS and Exelon) were mapped to the mesh for analysis.

All AdH simulations run for the LSRWA effort were conducted with the same Susquehanna River flow and inflowing sediment boundary conditions. Using the HEC-RAS input, the 4-year flow period from 2008 to 2011 was simulated in the model. As noted earlier, this time period was utilized because it included low, moderate, and high flows as well as two major high-flow events (above 400,000 cfs).

For the LSRWA effort, the AdH model was utilized to:

- Evaluate the uncertainty associated with applying a 2D model to Conowingo Reservoir;
- Measure the critical shear stress and erosion rate of bed sediments in Conowingo Reservoir for input into the 2D model;
- Evaluate how Conowingo Reservoir sediment transport responds to low, moderate, and flood flows for three different reservoir bathymetries representing temporal changes in sediment storage capacity (1996, 2008, and 2011);
- Determine how Conowingo Reservoir sediment transport responds to low, moderate, and flood flows for a full reservoir capacity scenarios;
- Evaluate how effective some sediment management techniques would be for reducing sediment loads passing through Conowingo Dam into the Chesapeake Bay; and
- Provide model output to the CBEMP for evaluating the impact of the 2D AdH output on water quality in the Chesapeake Bay.

The years 1996, 2008, and 2011 were selected for bathymetry input, because in these years, bathymetric surveys had been conducted and data were available. The bathymetric surveys were conducted by USGS, with the exception of the 2011 survey, which was accomplished by Exelon

Figure 3-3. Numerical Mesh of Conowingo Reservoir for AdH

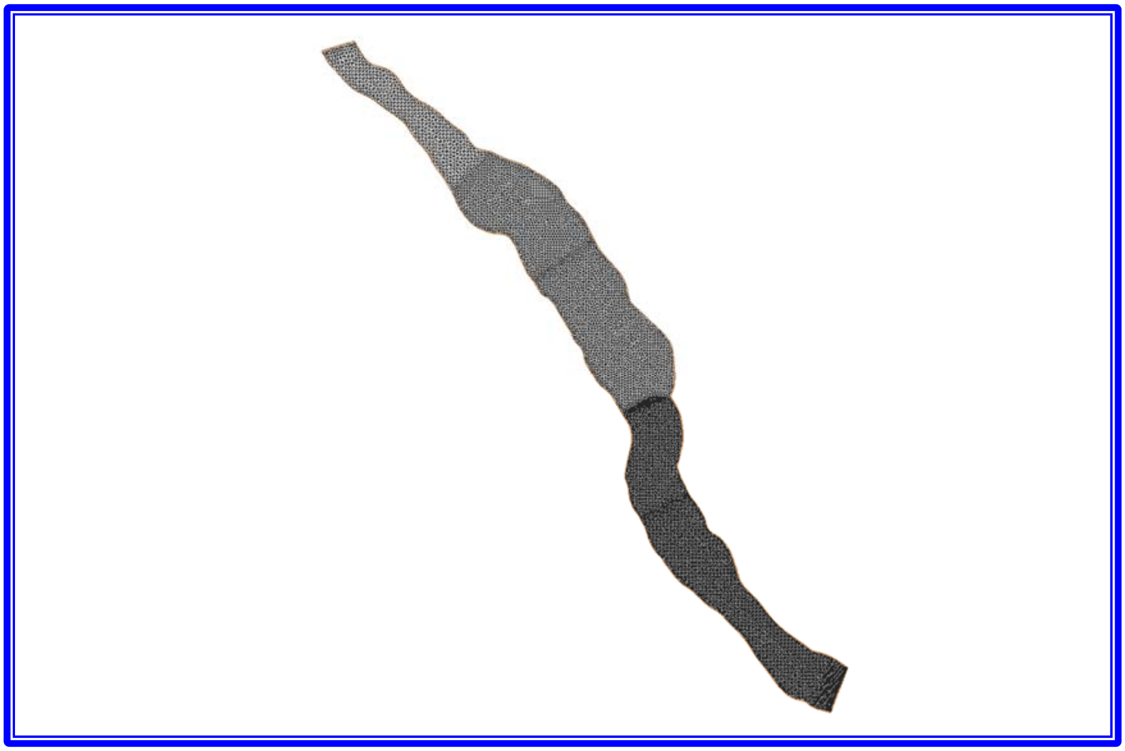
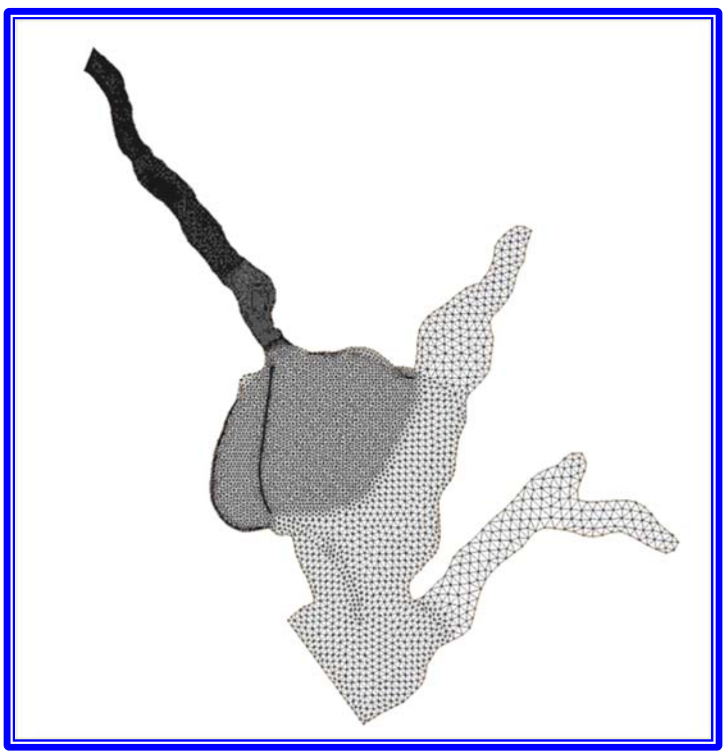


Figure 3-4. Numerical Mesh of Lower Susquehanna River and Flats for AdH



using USGS' survey methodology. USGS reviewed the Exelon survey methodology and data, confirming its appropriateness for use in the LSRWA effort. Appendix G includes results of the 2011 bathymetric survey by Exelon.

The AdH model was also utilized to estimate the effectiveness of selected sediment management strategies to reduce sediment loads transported through Conowingo Reservoir and Susquehanna Flats. Ultimately, the AdH model output was sediment transport, scouring loads, or erosion from the reservoirs which were utilized in CBEMP to compute the impact of the sediment management strategies on water quality in Chesapeake Bay.

Through a validation process, the application of the AdH 2D model to the Conowingo Reservoir and Susquehanna Flats system was determined to be adequate for simulating general reservoir sediment scour and deposition modeling scenarios for the LSRWA. However, there is some uncertainty that remains with the estimates provided by the AdH model that were considered in results, as described below.

One source of uncertainty was that the AdH model was not capable of simulating sediment passing through the flood gates of Conowingo Dam. Therefore, dam operations are not simulated in detail in the model; these include flood gate operation and Peach Bottom Atomic Power Station sequences (Appendix K provides a description of dam operations). For this study, Conowingo Dam was modeled as an open boundary with downstream control represented by the water surface elevation at the dam. This limitation impacted how sediment was spatially distributed in the lower reach of Conowingo Reservoir near the dam. To minimize this uncertainty, more sophisticated methods would need to be developed to incorporate dam operations in Conowingo Reservoir.

Another source of uncertainty concerned fine sediment flocculation and consolidation. Sediment transport models in general do not have a sophisticated approach to simulating fine sediment flocculation. Suspended fine sediment can either exist as primary silt and clay particles, or in low energy systems such as reservoirs, can form larger particles in the water column due to flocculation. Particles that flocculate are larger and have higher settling velocities, thus their fate in the reservoir can be quite different than the lighter primary particles (Ziegler, 1995).

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

The AdH model has the capability to relate flocculation to concentration, but not to other variables, such as shear stress which determines flock particle size and the overall fate of the sediment. The ability to predict flocculation dynamics is important to track the fate of sediment in a reservoir. To quantify this uncertainty, numerous model simulations were conducted to determine a potential range of values. To reduce uncertainty, more sophisticated methods would need to be developed to predict the flocculation dynamics.

The last major source of uncertainty was the limited data of suspended loads during storms and bed sediment erosion characteristics. Currently, the suspended sediment samples are collected from one location in Conowingo Reservoir. Because of the danger of sampling during large storms, samples are not currently collected at the peak of the largest storms. To verify the estimations of bed scour during large storms, improved field methods are required for sampling storm concentrations or turbidity over the entire storm hydrograph. Additionally, more samples of the reservoir bed would provide more data on the erosional characteristics of the sediment which would reduce uncertainty.

Uncertainties in the total sediment load entering Conowingo Reservoir will affect scour and deposition, and thus affect the total load output to the Bay. Consequently, to provide more information on reservoir mass balance, future sampling programs should extend both upstream and downstream of Conowingo Dam. To quantify the uncertainty of the limited data available to the LSRWA effort, numerous model simulations were conducted to determine a potential range of values.

In summary, of all the modeling uncertainties that exist, three are most critical for interpreting the Conowingo Reservoir modeling results. These include the potential for flocculation of sediment flowing into the reservoir, the potential for large sediment aggregates to erode from cohesive beds, and dam operations. Because of these uncertainties, the AdH model may potentially over-predict to some degree the transport of scoured bed sediment through the dam to the Chesapeake Bay. Appendix B provides further detail on the uncertainty associated with the AdH modeling, as well as documentation of the model inputs, outputs, and calculations.

3.3 CBEMP MODEL

The final modeling tool utilized for this LSRWA effort was CBEMP (Chesapeake Bay Environmental Model Package). CBEMP is an umbrella term used to describe a series of models that are applied to the Chesapeake Bay and its watershed. CBEMP was developed by the Chesapeake Bay Program (CBP), the state-federal partnership responsible for coordinating the Chesapeake Bay and watershed restoration efforts. CBEMP has had almost three decades of management applications, supporting collaborative, shared decision-making among the partners (USEPA, 2010b).

This suite of environmental models has an unrivaled capacity to translate loadings in the watershed to water quality in Chesapeake Bay (Linker et al., 2013). CBEMP includes the same models and was applied using the same scenario development and simulation methods for this LSRWA effort, as were used in the development of the 2010 Chesapeake Bay TMDL (USEPA, 2010a, Appendix D). In addition, the full suite of Chesapeake Bay models has been regularly updated and calibrated based on the most recently available monitoring data, about every 5 to 7 years over the past three decades; Linker et al. (2013) provides a complete description of the different phases and versions of the Chesapeake Bay models. Used properly, CBEMP provides the best estimates of water quality and habitat quality responses of the Chesapeake Bay ecosystem to future changes in the loads of nutrient and sediment pollutants.

For this LSRWA effort, CBEMP had two major applications. The first application was a series of modeling runs conducted by USACE ERDC, documented within Appendix C. These CBEMP application scenarios were utilized to estimate water quality impacts of selected watershed and land use conditions, reservoir bathymetries, a major storm (scour) event (January 1996) at different times of year, and selected sediment management strategies. Sediment erosion or scour from the bed of Conowingo Reservoir estimated from AdH was utilized as input for selected CBEMP scenarios. The second CBEMP application was a series of modeling runs conducted by EPA CBPO, as described in more detail in Appendix D. These model runs, which will be discussed later in this section, assessed attainment of the states' Chesapeake Bay water quality standards in terms of time and space for each of the 92 Chesapeake Bay segments.

3.3.1 Chesapeake Bay Estuarine Models

The suite of interfacing Chesapeake Bay estuarine models, applied collectively, have the ability to compute the impacts of sediment and nutrient loads to the estuary on light attenuation, SAV, chlorophyll, and DO concentrations in Chesapeake Bay tidal waters. The Chesapeake Bay Water Quality Model combines a three-dimensional (3D) hydrodynamic transport model (CH3D) with a eutrophication model (CE-QUAL-ICM). This model combination has the ability to predict water quality conditions in the Bay resulting from changes in loads from the contributing watershed, airshed, and ocean interface.

The hydrodynamic model computes intra-tidal transport using a 3D grid framework of 57,000 cells (Cerco et al., 2010). The hydrodynamic transport model computes continuous 3D velocities, surface elevation, vertical viscosity and diffusivity, temperature, salinity, and density using time increments of 5 minutes. The hydrodynamic model was calibrated for the period 1991–2000 and verified against the large amount of observed tidal elevations, currents, and densities available for the Chesapeake Bay. Computed flows and surface elevations from the hydrodynamic model were output at 2-hour intervals for use in the water quality model. Boundary conditions were specified at all river inflows, lateral flows, and at the mouth of the Chesapeake Bay.

The eutrophication model, referred to as the Chesapeake Bay Water Quality/Sediment Transport Model[6], computes algal biomass, nutrient cycling, and DO, as well as numerous additional constituents and processes using a 15-minute time step (Cerco and Cole, 1993; Cerco, 2000; Cerco et al., 2002; Cerco and Noel, 2004). In addition, the Chesapeake Bay Water Quality/Sediment Transport Model incorporates a predictive sediment diagenesis[7] component, which simulates the chemical and biological processes which take place at the bottom sediment-water interface after sediment is deposited (Di Toro, 2001; Cerco and Cole, 1994).

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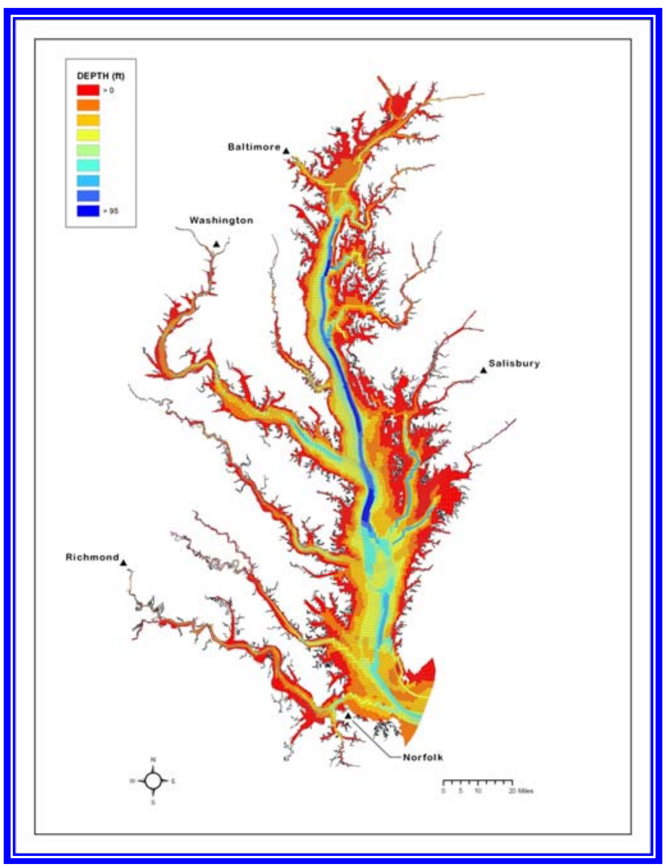
[6] Detailed documentation on the Chesapeake Bay Water Quality and Sediment Transport Model (Cerco and Noel, 2004; Cerco et al. 2010) is at http://www.chesapeakebay.net/content/publications/cbp_26167.pdf.

[7] Predictive sediment diagenesis is a predictive model of how organic material and nutrients in sediment on the Bay floor are processed.

Loads to the system include distributed or nonpoint source loads, point source loads, atmospheric loads, bank loads, and wetlands loads. Nonpoint source loads enter the tidal system at tributary fall lines and as runoff below the fall lines. Point source loads are from permitted industrial wastewater discharging facilities and municipal wastewater treatment plants. Atmospheric loads are deposited directly to Chesapeake Bay tidal surface waters. Atmospheric loads to the Chesapeake Bay watershed are incorporated in the distributed loads. Bank loads originate with shoreline erosion. Wetlands loads are materials created in and exported from wetlands, and include exported wetland oxygen demand.

The Chesapeake Bay Water Quality/Sediment Transport Model simulates water quality, sediment, and living resources in 3D in 57,000 discrete cells, which extend from the mouth of the Bay to the heads of tide of the Bay and its tidal tributaries and embayments, as depicted in Figure 3-5. The primary application period for the combined hydrodynamic model and eutrophication model covers the decade from 1991 to 2000. For LSRWA applications, the 1991-2000 hydrologic record was retained as this is the hydrologic period that CBEMP is based upon. Additionally, this is the same hydrologic period employed by the CBP partners in development of the 2010 TMDL (USEPA, 2010a).

Figure 3-5. Chesapeake Bay Water Quality and Sediment Transport Model



Source: Cerco et al., 2010.

At each time step, the CBEMP estimates the states' water quality variables of DO, chlorophyll, water clarity, and SAV area. These variables from each CBEMP model cell in each Chesapeake Bay designated use (e.g., shallow-water, deep-water, etc.) are used as spatially and temporally detailed inputs to determine the percent of time and space that the modeled results exceed allowable water quality criteria. Water quality criteria were set to protect designated uses of Chesapeake Bay, which include aquatic communities and habitats (USEPA, 2003a). Exceedance of water quality criteria results in harmful impacts to living resources. For details on the CBEMP assessment of water quality standards attainment, see Section 3.3.7 and Figure 3-10 later in this report.

3.3.2 Chesapeake Bay Watershed Model

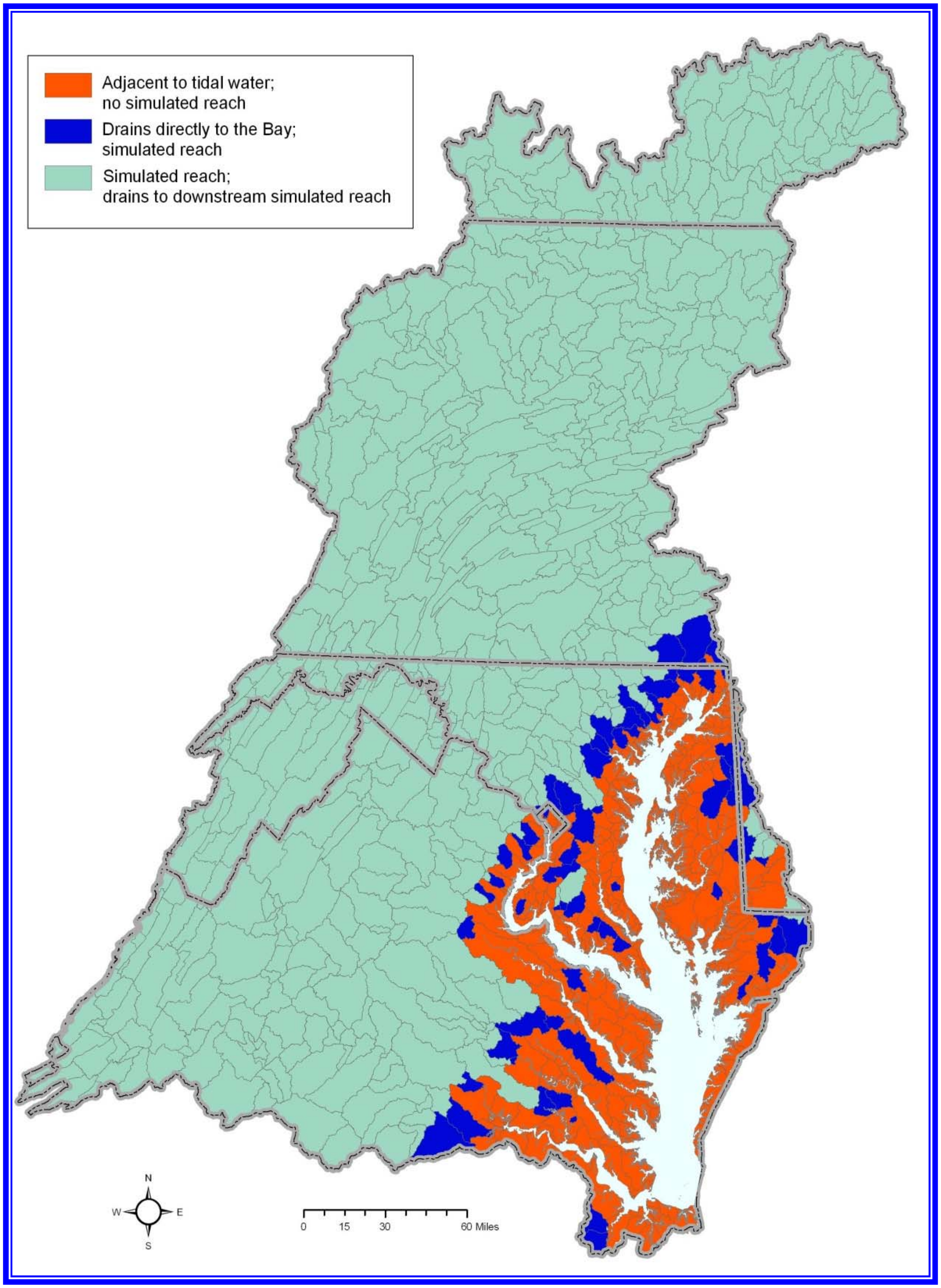
CBEMP also includes a Chesapeake Bay Watershed Model (WSM) which computes daily loads of sediment and nutrients from the heads of all tributaries and runoff from the adjacent watershed directly to the Bay within the 64,000-square mile watershed. Phase 5.3.2 of the Chesapeake Bay WSM provided daily sediment and nutrient loads from the watershed for application in the LSRWA effort.

The Phase 5.3.2 Chesapeake Bay WSM is an application of the Hydrologic Simulation Program-Fortran or HSPF (Bicknell et al., 2005). The segmentation scheme divides the Chesapeake Bay watershed into approximately 1,000 segments or subbasins, with the average size about 64 square miles. About 280 monitoring stations throughout the Chesapeake Bay watershed were used for calibration of hydrology, while approximately 200 monitoring stations were used to calibrate water quality, depending on the constituent being calibrated. There are 530 river segments with simulated reaches that drain to a simulated downstream reach. There are 62 river segments with simulated reaches that drain directly to the Chesapeake Bay, and 379 river segments adjacent to tidal waters that are without a simulated reach. These latter segments are segments that do not have streams with annual average flow of greater than 100 cfs; thus, they were too small to simulate effectively with the Chesapeake Bay WSM. The various segments are illustrated in Figure 3-6.

The Phase 5.3.2 Chesapeake Bay WSM simulation period covers 21 years, from 1985 to 2005, to take advantage of more recent and expanded monitoring data and information. The expansion of the model period to a 21-year period resulted in a more representative and improved land use inventory for use in model calibration. While the Phase 4.3 Chesapeake Bay WSM and all previous Chesapeake Bay WSM versions had a constant land use, the Phase 5.3.2 Chesapeake Bay WSM allows a time series of land use input data to change annually over the 1984-2005 simulation period (USEPA, 2010c). As a community model, the Phase 5.3.2 Chesapeake Bay WSM has open-source model code, pre-processors, post-processors, and input data that are freely available to the public (USEPA, 2010c)[8] . Input data include precipitation information, municipal and industrial wastewater treatment and discharging facilities, atmospheric deposition, and land use (USEPA, 2010c).

[8] The Phase 5.3.2 Chesapeake Bay Watershed Model can be downloaded from the ftp site: ftp://ftp.chesapeakebay.net/Modeling/phase5/community/ or the Chesapeake Community Modeling Program's website at http://ches.communitymodeling.org/models/CBPhase5/datalibrary.php.

Figure 3-6. Segmentation and Reach Simulation of the Phase 5.3.2 Chesapeake Bay WSM



Source: USEPA, 2010c.

The Chesapeake Bay WSM simulates the 21-year period (1985–2005) on a 1-hour time step (USEPA, 2010b). Nutrient inputs from manure, fertilizers, and atmospheric deposition are based on an annual time series using a mass balance of U.S. Census of Agriculture animal populations and crops, records of fertilizer sales, and other data sources. Best management practices (BMPs) are incorporated on an annual time step; nutrient and sediment reduction efficiencies are varied by the size of storms. Municipal and industrial wastewater treatment and discharging facilities and on-site wastewater treatment systems' nitrogen, phosphorus, and sediment contributions are also included in the Chesapeake Bay WSM.

3.3.3 WSM Scenarios

Outputs from two Chesapeake Bay WSM scenarios were utilized for this LSRWA effort. The first, the "2010 Progress Run," was based on land use, management practices, wastewater treatment facility loads, and atmospheric deposition from the year 2010. This run is considered to represent existing conditions. The second, the "TMDL" run, employed projected land use, management practices, waste loads, and atmospheric deposition upon which the 2010 Chesapeake Bay TMDL was based. As such, these parameters are based on full implementation by the seven Chesapeake Bay watershed jurisdictions' WIPs, leading to controlling the nutrient and sediment loads as mandated to meet the 2010 Chesapeake Bay TMDL.

In order to determine the nutrient and sediment loads from the lower Susquehanna River watershed, the Chesapeake Bay WSM routes watershed loads computed above the three reservoirs through Lake Clarke, Lake Aldred, and Conowingo Reservoir. The routing process includes calculation of the effects of settling, erosion, and biological transformations within the reservoirs. The loads at the head of each reservoir are supplemented by inputs from the local watersheds immediately adjacent to the reservoirs.

3.3.4 1996 January High-Flow Event Scenario

The January high-flow event in 1996 was selected as the event to observe water quality impacts for LSRWA scenarios requiring a storm event because it is the highest observed flow within CBEMP's 1991-2000 hydrologic period. High-flow events wash in loads (sediment and nutrients) from the watershed; if there is high enough flow, these events scour additional loads from the reservoir beds behind the three dams on the lower Susquehanna River.

The Chesapeake Bay WSM incorporates algorithms to calculate sediment and nutrient deposition, scour, and erosion in Conowingo Reservoir. The algorithms are parameterized empirically to optimize agreement between computed and observed (observations from monitoring data) sediment and nutrient concentrations flowing over Conowingo Dam. During the course of this LSRWA effort, it was determined that little or no scouring of reservoir bed material was calculated during the January 1996 flood event by the Chesapeake Bay WSM[9]. As a consequence, computed solids

[9] The Phase 5.3.2 Chesapeake Bay WSM calculates deposition and scour. These processes are parameterized to improve agreement between computed and observed concentrations at the Conowingo Dam outfall. However, there are no independent observations of deposition and scour. All that can really be calculated is the net difference between the

concentrations, and potentially particulate nutrient concentrations, were less than observed. Solids and nutrient loads from scour were calculated independently, based on computations from the AdH model for Conowingo Reservoir, and added to the Chesapeake Bay WSM loads for the 1996 event.

Since the AdH application period was 2008 to 2011 while the CBEMP application period was 1991 to 2000, a procedure was employed to adjust estimated loads of scour from AdH for use in the CBEMP. A procedure to apply AdH calculations to the 1996 storm was developed based on the volumetric flow in excess of the threshold (400,000 cfs) for mass erosion (scour which penetrates the deeper layers and occurs at higher flows with higher bed shear stresses [greater than 0.02 pounds per square inch]). The year 2011 contained two erosion events, an unnamed event in March and Tropical Storm Lee, in September. The excess volume for each event was computed by integrating flow over time for the period during which flow exceeded 400,000 cfs. The amount of sediment eroded during each event was taken as the difference between computed loads entering and leaving Conowingo Reservoir. Sediment loads leaving the reservoir in excess of loads entering were taken as evidence of net erosion from the Conowingo Reservoir 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 (see Appendix C for more details).

3.3.5 <u>Simulation of Sediment and Nutrient Loads to Chesapeake Bay</u>

A critical component of CBEMP is its ability to calculate nutrient loads and their influence on Chesapeake Bay water quality, habitat quality, and aquatic resources. The fraction of total nutrient load represented by bottom scour is highly variable and depends, among other factors, on the nature and timing of the storm event. 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 of these forms. Neither is there a universal suite of model variables for the particulate nutrients.

In order to compute water quality impacts with CBEMP, nutrient loads associated with sediment (in particular, nutrient loads carried over Conowingo Dam as a result of sediment scour from the reservoir bottom) were calculated by assigning a fractional nitrogen and phosphorus composition to the scoured sediment (solids). The initial fractions assigned for nitrogen and phosphorus were based on analyses of sediment cores removed from the reservoir (Appendix C, Attachment C-1). However, further analysis was done to ensure the most appropriate nutrient composition of loads was being utilized.

Data (sediment and nutrient concentrations) collected from the Conowingo Dam outfall during the January 1996 and September 2011 storm events were compared. The nutrients associated with suspended solids differed in the two events, with the 1996 event being lower. Both data sets represented a mixture of solids from the watershed and solids scoured from the reservoir bed so neither exactly represented the composition of scoured reservoir bed material alone. The 2011 observations are consistent with samples collected in recent reservoir bed samples, and represent a

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two. The problem of correctly evaluating deposition and scour is acute during the rare erosion events that take place during the WSM application period. The WSM can perform well for the majority of events but still miss rare and unusual events like the January 1996 storm. Apparently, the calculated scour during this event simply was not adequate.

typical tropical storm event rather than the anomalous circumstances of January 1996 (this event was a combined rain and snowmelt episode, which caused a rapid rise in river level and breakup of ice cover in the Susquehanna River and its tributaries). For these reasons, nutrient composition observed at Conowingo Dam in 2011 was considered the better data set; as such, it was utilized to characterize the nutrient composition of loads for LSRWA scenarios. Use of the 2011 nutrient composition provides a worst-case analysis. Consequently, several key scenarios were repeated with the 1996 composition to quantify the uncertainty inherent in the composition of solids scoured from the reservoir bottom.

Additionally, using nutrient concentrations observed at Conowingo Dam and USGS flow data, the modeling team estimated the component of nutrients associated with scoured sediments. First, the total nitrogen (TN), total dissolved nitrogen (TDN), total phosphorus (TP), and total dissolved phosphorus (TDP) concentrations observed at Conowingo Dam from the Chesapeake Bay Program database (CBP, 2015) were paired with daily mean flows at Conowingo Dam (for the given sample collection time), reported by USGS. More than 90 percent of samples were collected at flows less than 100,000 cfs, although some were collected at flows as high as 590,000 cfs (i.e., during Tropical Storm Lee). Then, a flow-weighted mean for TDN/TN was computed as 0.86, while a flow-weighted mean for TDP/TP was 0.37. This indicates that dissolved nitrogen represents 86 percent of the total nitrogen while dissolved phosphorus represents 37 percent of the total. In other words, during average flow conditions more than 60 percent of phosphorus is in particulate form while less than 15 percent of the nitrogen is particulate.

Plots of total dissolved nutrients versus flow indicate that the dissolved fraction declines as flow increases. At the highest observed flows, the dissolved nitrogen fraction declines to 60 percent or less. For example, during Tropical Storm Lee, 40 percent or more of the nitrogen was in particulate form, while 90 percent of the phosphorus was in particulate form. Major flood events are often responsible for a large fraction of the annual nutrient load, despite their short duration. For example, the Tropical Storm Lee event contributed more than 30 percent of the total nitrogen load and more than 60 percent of the total phosphorus load at Conowingo for the water year 2011 (Hirsch, 2012). Consequently, nutrient loads associated with the sediments cannot be ignored.

There are two reasons for the increased fraction of particulate nutrients flowing over the dam as flow increases. Firstly, high runoff from the watershed carries particulate nutrients from the land surface. Secondly, high runoff scours particulate nutrients from the bottom of inflowing streams and, potentially, from the bottom of Conowingo Reservoir itself. In contrast, during periods of low runoff, little or no particulate nutrients are washed from the land surface and particles tend to settle out in quiescent streams and reservoirs.

3.3.6 Assessment of Chesapeake Bay Water and Habitat Quality Responses

The second major application of CBEMP for this LSRWA effort was an assessment of whether Maryland, Virginia, Delaware, and the District of Columbia's Chesapeake Bay water quality standards, developed and promulgated into state regulation to protect Chesapeake Bay aquatic resources, were estimated to be met in terms of time and space for each Chesapeake Bay segment. This determination was based on estimated water quality impacts under various watershed and land use conditions, reservoir bathymetries, and flows conducted for this LSRWA effort. This procedure was conducted by EPA and is discussed in Chapter 2 and Appendix D.

This analysis of Chesapeake Bay water quality standards attainment was not part of the original LSRWA scope. It was added to the LSRWA effort after the study commenced to provide context to the magnitude of water quality changes that were estimated from selected LSRWA scenarios to help understand the potential effects to Chesapeake Bay aquatic resources.

The output from CBEMP scenarios run by USACE ERDC, which included estimates of water quality impacts from scenarios altering watershed and land use conditions, reservoir bathymetries, flow events, and selected sediment management strategies were utilized as input for the assessment of attainment of the states' Chesapeake Bay water quality standards in terms of time and space for each of the 92 Chesapeake Bay segments. These segments are shown in Figure 3-7 (USEPA, 2010a).

EPA established five designated uses for Bay waters to reflect the habitats of an array of recreationally, commercially, and ecologically important species (USEPA, 2003a). Use designations also considered supporting prey communities along with the target species. Sets of species utilize habitats within each designated use during particular life stages. Figure 3-8 shows the designated uses, which reflect the variety of habitat regions in the Chesapeake Bay. The Chesapeake Bay's aquatic resources have different water quality requirements for these different habitat regions. Figures showing these regions are in Appendix K. The following text describes each designated use and important species utilizing those habitats (USEPA, 2003a):

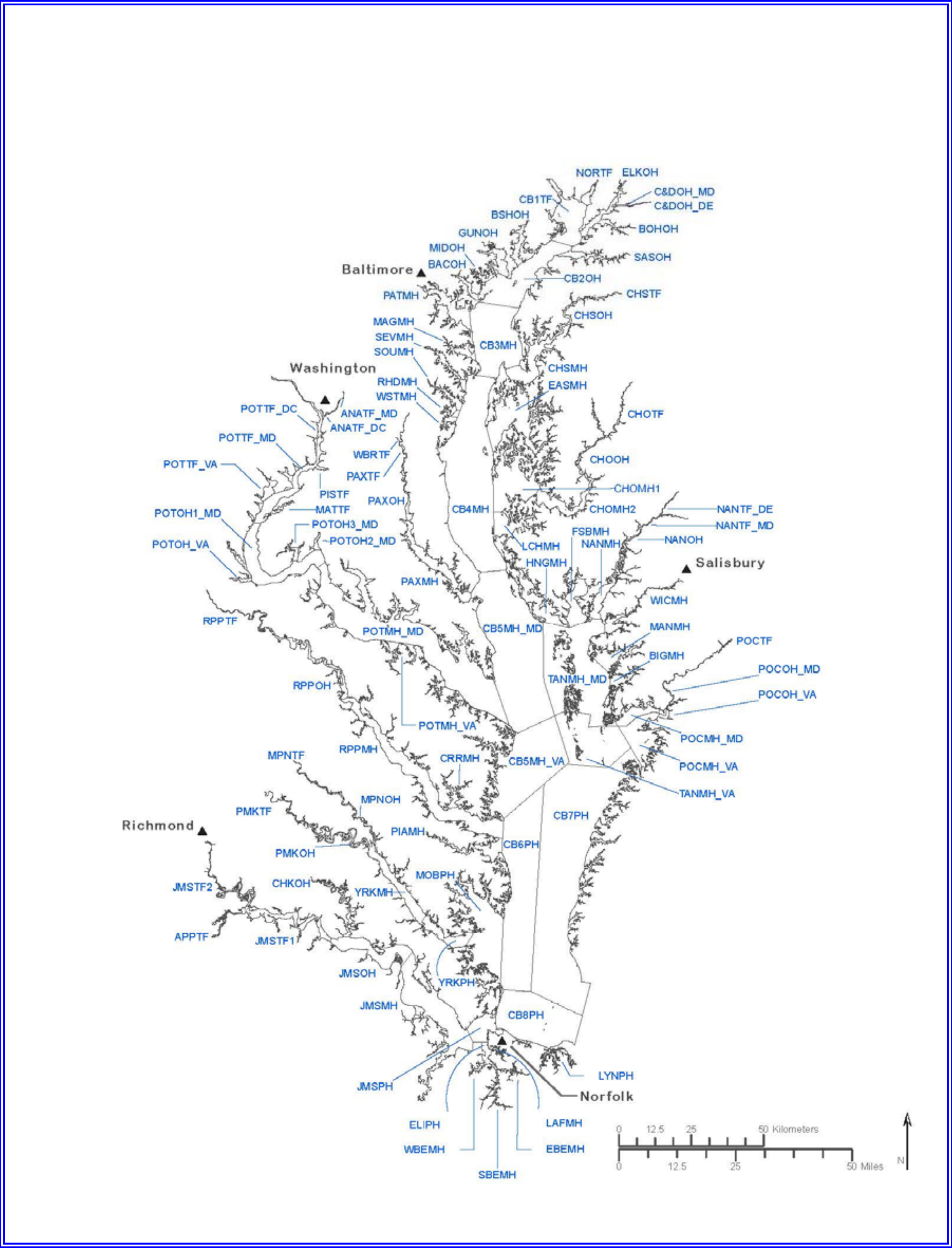
- The *migratory fish spawning and nursery designated use* protects migratory and resident tidal freshwater fish during the late winter to late spring spawning and nursery season in tidal freshwater to low-salinity habitats. Located primarily in the upper reaches of many Bay tidal rivers and creeks and the upper mainstem Chesapeake Bay, this designated use provides habitat for striped bass, perch, shad, herring, sturgeon, and largemouth bass.

- The *shallow-water bay grass designated use* protects underwater bay grasses and the many fish and crab species that depend on the vegetated shallow-water habitat provided by underwater grass beds. The shallow-water bay grass designated use provides habitat for a wide variety of species. Largemouth bass and pickerel inhabit vegetated tidal-fresh and low-salinity habitats; juvenile speckled sea trout occurs in vegetated higher salinity areas; and blue crabs inhabit vegetated shallow water over the full range of salinities in the Chesapeake Bay and its tidal tributaries.

- The *open-water fish and shellfish designated use* focuses on surface water habitats in tidal creeks, rivers, embayments, and the mainstem Chesapeake Bay. This provides habitat for diverse populations of sport fish, including striped bass, bluefish, mackerel, and sea trout, as well as important bait fish such as menhaden and silversides. This also provides habitat for federally-endangered Atlantic and shortnose sturgeons.

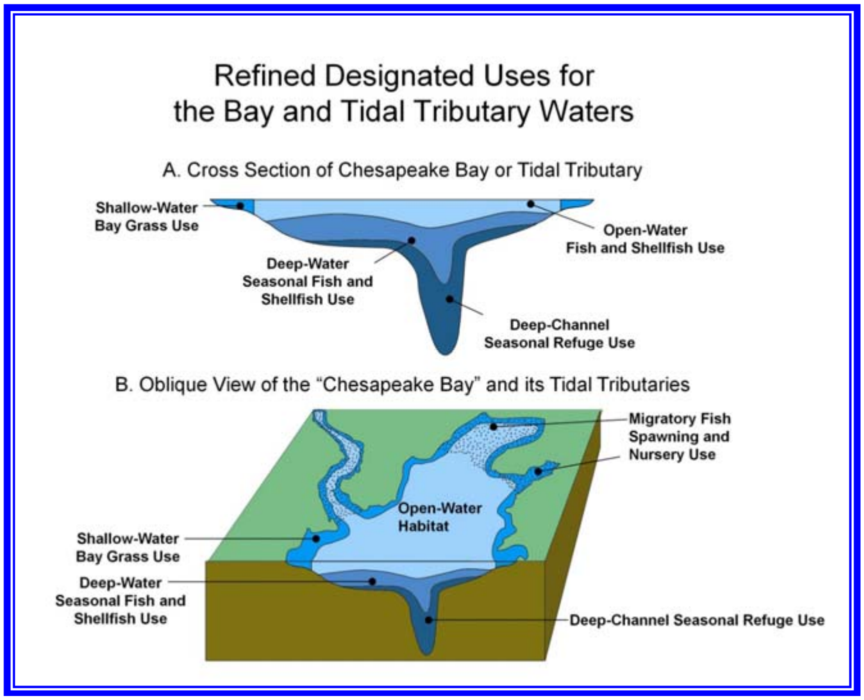
- The *deep-water seasonal fish and shellfish designated use* protects animals inhabiting the deeper transitional water-column and bottom habitats between the well-mixed surface waters and the very deep channels. This use provides habitat for many bottom-feeding fish, crabs, and oysters, and other important species such as the bay anchovy.

Figure 3-7. Chesapeake Bay Segments



Source: USEPA, 2010a.

Figure 3-8. Chesapeake Bay Tidal Water Designated Use Zones



Source: USEPA, 2003b.

- The *deep-channel seasonal refuge designated use* protects bottom sediment-dwelling worms and small clams that bottom-feeding fish and crabs consume. Low to occasional no DO conditions occur in this habitat zone during the summer. In the deep channel of the Chesapeake Bay, communities of mud-burrowing worms and clams have a broad tolerance to a wide range of sediment types, salinities, dissolved oxygen concentrations and organic loadings.

Maryland, Virginia, Delaware and District of Columbia's water quality standards are based on requirements to support and protect the Bay's designated uses, allowing living resources to thrive. Attainment of criteria for DO, chlorophyll *a*, and water clarity is necessary to protect these resources. For example, DO in deep-water habitats and good water clarity in the shallow waters are necessary for growth of SAV which provide habitat for juvenile fish and crabs (USEPA, 2010a). These water quality parameters and their relationship to the designated uses are described below.

Dissolved Oxygen

Aquatic creatures, other than some microbes, need oxygen to survive. DO concentrations of 5 mg/L (milligrams per liter) or greater allow Bay aquatic life to thrive. At DO levels below 2 mg/L, the water is considered hypoxic; and when DO drops below 0.2 mg/L, it is considered anoxic (CBP, 2013). Minimum oxygen survival requirements for aquatic life are shown in Figure 3-9. DO water quality 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 (USEPA, 2003a).

Figure 3-9. Minimum Oxygen Survival Requirements (mg/L)

Bay Habitat Type/Designated Use | **Associated Charismatic Species**

Source: Batiuk et al., 2009.

Non-mobile and poorly mobile organisms, such as oysters, clams, and worms, are unable to relocate when low DO conditions occur. Mobile organisms, such as fish and crabs, can avoid low DO waters. Chronically low levels of DO in the Chesapeake Bay reduce availability of inhabitable deep-channel and deep open-water habitat on a large scale (CBP, 2013). Availability of associated forage food for bottom-dwelling fish species is also consequently reduced substantially, reducing the capability of the Bay to support these fish species (Buchheister et al., 2013).

DO concentrations vary depending on location and time of year, based on temperature, salinity, nutrient levels, and biological uptake. Many factors interact to determine the DO content of Chesapeake Bay tidal waters. Nutrient loading, water column stratification, wind and tidal mixing, and water temperatures are important factors (CBP, 2013). These topics are covered in Appendix K. Each Chesapeake Bay segment may have multiple habitat regions and thus, different water quality criteria to meet (i.e., to be in "attainment").

Water Clarity (Light Attenuation)

Underwater grasses or SAV are an essential component of the Bay's living resources habitat. The water clarity criteria involve SAV restoration goals of "acres of standing SAV crop" (MDE, 2015). SAV can grow in shallow water to minimum depths where water clarity is adequate for the plants to grow. SAV occurs in both tidal and nontidal waters of the Chesapeake Bay watershed. They provide food for waterfowl and are critical habitat for juvenile fish and crabs (USEPA, 2010a). Underwater grasses also positively affect nutrient cycling, sediment stability, and water turbidity (Tango and Batiuk, 2013).

Water quality criteria for water clarity were derived to provide "light through water" requirements to support the propagation and growth of a wide variety of SAV species (Tango and Batiuk, 2013). Decreased water clarity (increased light attenuation) inhibits the growth of underwater Bay grasses. Increased sediment loads and algal biomass, spurred by excess nutrients to the Bay, impact water clarity. Bay water conditions should have high water clarity (low light attenuation) to allow sunlight to penetrate and support SAV throughout the Bay's shallow-water habitats (MDE, 2015).

Chlorophyll a

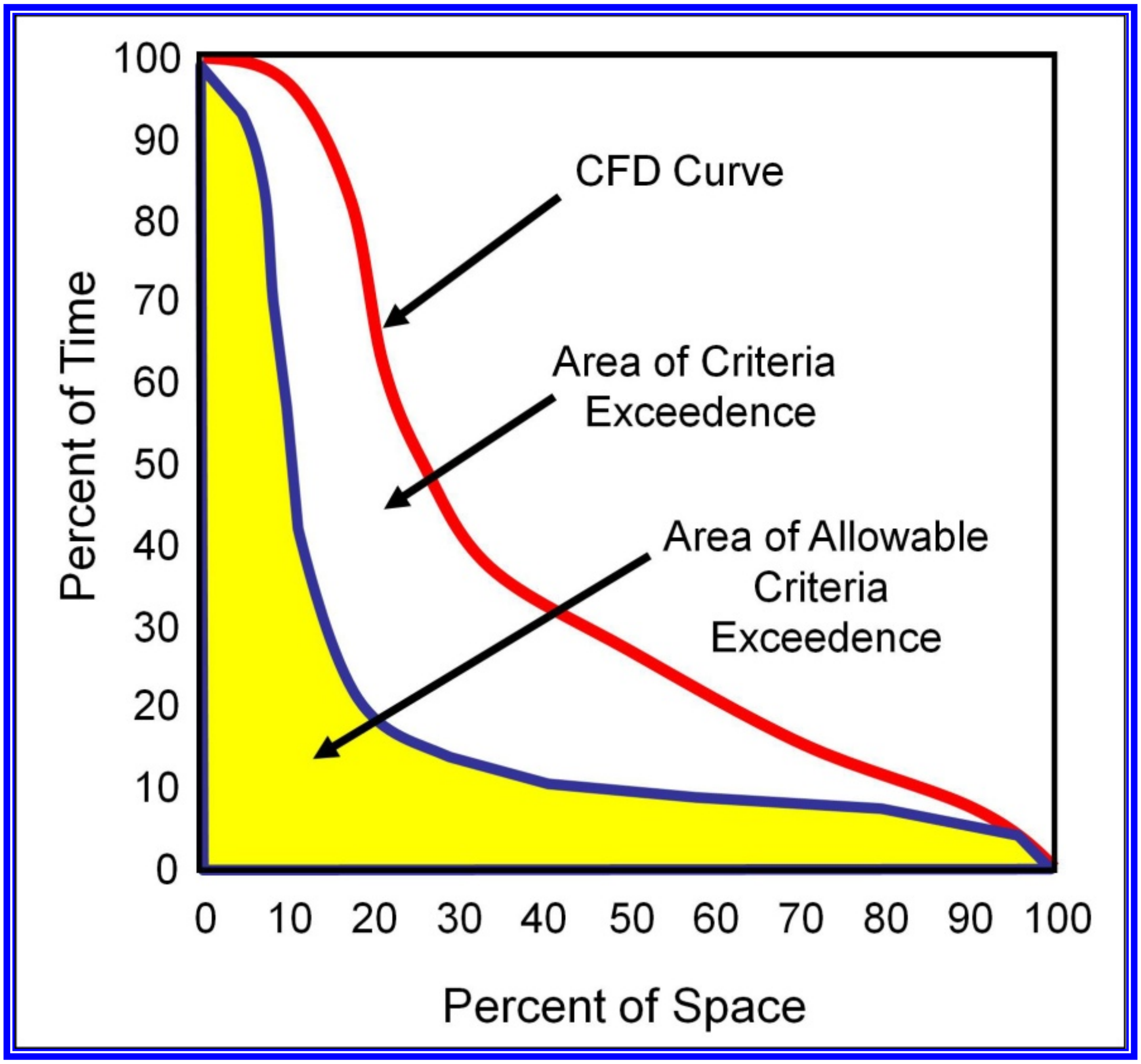
Attaining Chesapeake Bay DO and water clarity criteria requires reductions in chlorophyll *a* concentrations (Tango and Batiuk, 2013). Measures of chlorophyll *a* indicate levels of phytoplankton or algal biomass in the water column. When uneaten by zooplankton and filter-feeding fish or shellfish, excess dead algae are consumed by bacteria. This process removes oxygen from the water column, resulting in low dissolved oxygen conditions when the algae die off and sink to the bottom (MDE, 2015). Additionally, chlorophyll *a* plays a direct role in light attenuation, reducing light penetration in shallow-water habitats, which directly impacts SAV (EPA, 2003a).

The Chesapeake Bay water quality criteria that Maryland, Virginia, Delaware and the District of Columbia adopted into their respective water quality regulations provide for allowable exceedances of each set of DO, water clarity, SAV, and chlorophyll *a* criteria defined through application of a biological or default reference curve (USEPA, 2003a). Figure 3-10 depicts this concept, with the section in yellow being the area with an allowable exceedance of the criterion concentration.

3.3.7 Chesapeake Bay Water Quality Standards Attainment Assessments

To compare model results with the states' Chesapeake Bay water quality standards, EPA analyzed the Chesapeake Bay Water Quality/Sediment Transport Model results for each scenario and for each modeled segment to determine the percent of time and space that the modeled water quality results exceed the allowable concentration. For any modeled result where the exceedance in space and time (shown in Figure 3-10 as the area below the cumulative function distribution [CFD] reference curve, the red line) exceeds the allowable exceedance (the area below the blue line that is shaded yellow), that segment is considered in nonattainment (USEPA, 2003a). The amount of nonattainment is shown in the figure as the area in white between the red line and the blue line and is displayed in model results as percent of nonattainment for that segment. The amount of nonattainment is reported as a whole number percentage. The CFD reference curve is based on

Figure 3-10. Attainment Assessment of the Chesapeake Bay Water Quality Standards



Notes: CFD = cumulative function distribution. The CFD reference curve is based on observations of healthy ecosystem habitats for the assessed criterion.

Source: USEPA, 2003a.

observations of healthy ecosystem habitats for the assessed criterion where those observations exist with a default reference curve used in other areas (see Appendix D for more detail).

The criteria assessment procedure was used to evaluate attainment of the Chesapeake Bay DO, SAV, and water clarity water quality criteria adopted by the four jurisdictions into their water quality standards regulations. The third set of Chesapeake Bay water quality criteria, chlorophyll *a* concentrations, was not evaluated because as numeric chlorophyll *a* water quality standards are only present in areas in the District of Columbia's tidal waters and in the tidal James River in Virginia. Both of these estuarine systems are too far removed from the lower Susquehanna River to be influenced by its resultant nutrient and sediment pollutant loads.

3.3.8 Water Quality Standards Assessment Period

As stated previously, the CBEMP utilizes the 1991-2000 hydrologic period. For the criteria assessment procedure, a 3-year critical period (1993-95) was used as the period for assessing attainment of the water quality standards for several LSRWA model scenarios. The 1993–1995 critical period was chosen based on key environmental factors, principally rainfall and streamflow, which influenced attainment of the DO water quality standards for the deep-water and deep-channel habitats (USEPA, 2010a). Since the January 1996 high flow event was outside the 1993-95 critical period, the 1996-98 hydrologic period was used as the assessment period for LSRWA modeling scenarios that included an evaluation of a storm event.

3.3.9 CBEMP Uncertainty

CBEMP produce estimates, not perfect forecasts. Hence, it reduces, but does not eliminate, uncertainty in environmental decision-making. There are several sources of uncertainty summarized here and discussed in more detail in Appendix C.

One source of uncertainty is the exact composition of nutrients associated with sediment scoured from the reservoir bed. Two alternative sets of observations are presented in Appendix C, one based on observations at the Conowingo Dam outfall in January 1996, and one based on observations collected at Conowingo Dam during Tropical Storm Lee in September 2011. 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 (Appendix C, Attachment C-1), 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 Dam in 2011 is preferred and was utilized 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.

Another source of uncertainty is the availability (i.e., bioavailability) and reactivity of the nutrients scoured from the reservoir bottom. The majority of analyses of collected data at the Conowingo Dam outfall and from within the reservoir bed sediment quantify particulate nitrogen and particulate phosphorus without further defining the nature of the nitrogen or phosphorus. For the LSRWA effort, modelers opted to maintain the accepted, consistent particle composition that has been employed throughout the application of CBEMP. Uncertainty in the particle composition, and consequently, the processes by which particulate nutrients are transformed into biologically available forms, still exists.

Some uncertainty in computed storm effects on Chesapeake Bay would result from considering solely a January storm. Bay response to storms in other seasons might vary. To reduce this uncertainty, the January storm was moved to June and to October. The June storm coincides with the occurrence of the notorious Tropical Storm Agnes, which resulted in the worst recorded incidence of storm damage to the Bay. The October storm corresponds to the occurrence of Tropical Storm Lee, and is in the typical period of tropical storm events.

Finally, CBEMP evaluated water quality impacts from a single large flow event (January 1996). Lower flow, more frequent events may also have a cumulative impact over time in the future. Future modeling work could investigate the potential effects of smaller more frequent events to reduce uncertainty and expand understanding of how various flows influence Chesapeake Bay water quality.

3.4 MODELING SCENARIOS

Based on the study goals of the study, the LSRWA team developed a series of hydrologic and management scenarios representative of existing and anticipated future conditions for evaluation. Many iterations of scenarios were employed for this effort, with the major scenarios laid out in Tables 3-1 and 3-2. These scenarios applied different loading conditions from the Susquehanna watershed, the Susquehanna River, and Chesapeake Bay, as well as a number of reservoir bathymetries and various broad sediment management strategies. Depending on the scenario, some required all modeling tools (HEC-RAS, AdH, and CBEMP), some used desktop analyses (calculations performed outside of the modeling tools), while some included a combination of both. Tables 3-1 and 3-2 describe the major scenarios and provide descriptive details. Appendices A-D and J provide further description on scenarios evaluated for this effort.

Scenarios were broadly divided into two categories. The first category, LSRWA major baseline and future conditions scenarios, is outlined in Table 3-1. This category involves estimates of the current and future conditions of the watershed. These scenario modeling runs describe the environmental effects under a range of conditions. However, there were no modeling runs formulated for forecasted climate change conditions; a general discussion of global climate change impacts can be found in Section 4.1.4. All of the Table 3-1 scenarios contain no additional sediment and nutrient management activities above what is currently planned or ongoing, in the lower Susquehanna River and Chesapeake Bay watershed. Section 4.2 provides further detail and discussion of the results from these scenarios.

The second category addresses major sediment management scenarios, which are listed in Table 3-2. These scenarios provided estimates of Chesapeake Bay water quality conditions under selected sediment management strategies. The sediment management scenarios are identified and detailed in Chapter 5, including a description of the strategy concept, estimates of any changes to the system's sediment and nutrient loading due to the strategies, and the strategies' environmental effects.

As mentioned earlier, Tables 3-1 and 3-2 represent the major scenarios investigated and compared for the LSRWA effort. These scenarios have been numbered sequentially to reflect the questions and evaluations being addressed by the entire team. However, there were many more CBEMP modeling scenarios, outside of these numbered scenarios; these modeling scenarios are documented in Appendices C and D, and are summarized in Attachment J-5. In those appendices, the modeling scenarios are labeled "LSRWA" plus a number (e.g., LSRWA-21). To allow the reader to match up the appendices to the main report, the modeling scenario number is listed in the last row of each table. For the rest of this report, the scenarios will be referred by the number shown in the heading description (e.g., Scenario 1, Scenario 2, etc.).

Table 3-1. LSRWA Major Baseline and Future Conditions Scenarios

Characteristics	SCENARIO 1 What is the system's current (existing) condition?	SCENARIO 2 What is the system's condition with WIPs in full effect and reservoirs have not all reached dynamic equilibrium?	SCENARIO 3 What is the system's condition when WIPs are in full effect, reservoirs are trapping at current conditions and there is a winter scour event?	SCENARIO 4 What is the system's condition when WIPs are not in effect, reservoirs have all reached dynamic equilibrium and there is a winter scour event?	SCENARIO 5 What is the system's condition when WIPs are in full effect, the reservoirs have all reached dynamic equilibrium and there is a winter scour event?	SCENARIO 6 What is the system's condition if WIPs are in full effect, reservoirs are trapping at current conditions and a scour event occurs during summer, fall, or winter?
Modeling Tools Used	CBEMP	CBEMP	HEC-RAS/AdH+CBEMP	HEC-RAS/AdH+CBEMP	HEC-RAS/AdH+CBEMP	HEC-RAS/AdH+CBEMP
Land Use (Watershed Condition)	2010 land use	WIPs in place	WIPs in place	2010 land use	WIPs in place	WIPs in place
Hydrology	1991-2000 CBEMP	1991- 2000 CBEMP	2008-11 HEC-RAS/AdH; 1991-2000 CBEMP	2008-11 HEC-RAS/AdH; 1991-2000 CBEMP	2008-11 HEC-RAS/AdH; 1991-2000 CBEMP	2008-11 HEC-RAS/AdH; 1991-2000 CBEMP; January 1996 event moved to June and October
Reservoir Bathymetry/ Trapping Efficiency	1991-2000 levels	1991-2000 levels	2011 levels	Computed "full" Conowingo levels	Computed "full" Conowingo levels	2011 levels
Scouring	No <u>net</u> scouring of reservoirs accounted for during this period	No <u>net</u> scouring of reservoirs accounted for during this period	January 1996 (scour) event flow and solids adapted from AdH/HEC-RAS 2011 event nutrient composition	January 1996 (scour) event flow and solids adapted from AdH/HEC-RAS 2011 event nutrient composition	January 1996 (scour) event flow and solids adapted from AdH/HEC-RAS 2011 event nutrient composition	January 1996 (scour) event flow and solids adapted from AdH/HEC-RAS 2011 event nutrient composition occurring in January, June and October
Criteria Assessment Procedure Attainment Period	1993-95	1993-95	1996-98	1996-98	1996-98	1996-98
CBEMP Modeling Run Number [1]	LSRWA-4	LSRWA-3 Base	LSRWA-21	LSRWA-18	LSRWA-30	Summer = LSRWA-24 Fall = LSRWA-25 Winter = LSRWA-21

<u>Notes:</u> [1] USACE ERDC and EPA-CBPO ran roughly 30 modeling runs utilizing CBEMP. Modeling runs were denoted by "LSRWA-number." Only major modeling runs are reported and summarized in this main report. Appendices C and D provide further detail on the other modeling runs.

Table 3-2. LSRWA Major Sediment Management Modeling Scenarios

Characteristics	SCENARIO 7 What are the flows required for agitation dredging to be possible?	SCENARIO 8 What are the effects of strategic dredging?	SCENARIO 9 What are the effects of passing sediment downstream for three winter months, one time?	SCENARIO 10 What are the effects of passing sediment downstream for 3 winter months, over-time for a period of 10 years?	SCENARIO 11 What are the effects of passing sediment downstream for 9 months, one time?	SCENARIO 12 What are the effects of extreme dredging (restoring the system to 1996 bathymetry)?	SCENARIO 13 What are the effects of long-term strategic dredging over time for a period of 10 years?	SCENARIO 14 What are the effects of increasing BMPs in the watershed above that required to meet TMDL?
Modeling Tools Used	AdH.	HEC-RAS/AdH and CBEMP	None; Google Earth and GIS desktop analysis	CBEMP	None; Google Earth and GIS desktop analysis	HEC-RAS/AdH and CBEMP	None; Google Earth and GIS desktop analysis	None; Google Earth and GIS desktop analysis
Land Use	Not determined/not applicable	WIPs in place	Not determined/not applicable	WIPs in place	Not determined/not applicable	WIPs in place	Not determined/not applicable	Above TMDL/WIP requirements
Hydrology	Five runs varying between 30,000-400,000 cfs on AdH	2008-11 (AdH); 1991-2000 (CBEMP)	Not determined; this was a desktop calculation	1991-2000	Not determined; this was a desktop calculation	2008-11 (AdH); 1991-2000 (CBEMP)	Not determined; this was a desktop calculation	Not determined; this was a desktop analysis
Reservoir Bathymetry/ Trapping Capacity	Not determined	2011 – 3 mcy (2.4 million tons) removed	Not determined; this was a desktop calculation.	2011 – 3 mcy (2.4 million tons) removed	Not determined; this was a desktop calculation	1996	Not determined; this was a desktop calculation	Not determined; this was a desktop calculation
Scouring	Not determined	January 1996 event flow and solids 2011 event nutrient composition	Not determined, this was a desktop calculation	January 1996 event flow and solids 2011 event nutrient composition	Not determined, this was a desktop calculation	January 1996 event flow and solids 2011 event nutrient composition	Not determined, this was a desktop calculation	Not determined, this was a desktop calculation
Concept	Re-suspending reservoir bed sediment into the water column by mechanical means through the outlet structures of the dam Goal was to determine minimum flow required to maintain the resuspended sediment in suspension to allow transport through outlet structures.	One time removal of 3 mcy (2.4 million tons) from reservoir system An area behind Conowingo was selected, 1 to 1.5 miles above the dam. Dredging area selected based on the highest deposition rate.	3 mcy (2.4 million tons) bypassed over 3 months 90 days), one year December-February time period	3 mcy (2.4 million tons) bypassed over 3 months 90 days), every year for 10 years December-February time period	3 mcy (2.4 million tons) bypassed over 9 months time, one year (270 days) September-April time period.	The 1996 bathymetry was modeled. This bathymetry has 31 mcy (25 million tons) less sediment than the 2011 bathymetry.	Removing 3 mcy on an annual basis for 10 years	Implementing BMPs above PA and MD WIPs Reduction of 95,000 tons (117,000 cy) of sediment annually from entire lower Susquehanna Watershed
Criteria Assessment Procedure Attainment Period	Not determined	1996-98	Not determined	1996-98	Not determined	1996-98	1996-98	Not determined
CBEMP Modeling Run Number[1]		LSRWA-28		LSRWA-29		LSRWA-31		

Notes: [1] USACE ERDC and EPA-CBPO ran roughly 30 modeling runs utilizing CBEMP. Modeling runs were denoted by "LSRWA-number." Only major modeling runs are reported and summarized in this main report. Appendices C and D provide further detail on the other modeling runs.

Chapter 4. Problem Identification

Historically, sediment from erosion in the Susquehanna River watershed, and nutrients associated with these sediments, were transported in the Susquehanna River and discharged directly into the Chesapeake Bay (Langland, 2001). Following dam construction, the dams acted to trap sediment and associated nutrients, thus reducing the net amount of sediment and nutrients reaching the Bay. There is concern from scientists, government agencies, and the public that the filling of these reservoirs will negatively impact water quality and the living resources and habitat of the upper Chesapeake Bay, as well as undo the efforts of the states to meet Clean Water Act requirements to restore Chesapeake Bay.

Hydrodynamic interactions and sedimentation processes within the lower Susquehanna River watershed (including the series of hydroelectric dams) are not well defined. Additionally, the impacts on the ecological resources of Chesapeake Bay from sediment and the associated nutrients from the watershed and dams are poorly understood. This assessment was needed to understand how to better protect the designated uses of Chesapeake Bay (see Section 3.3.6), which includes living resources and their habitats. The assessment focused on two periods of time: (1) the current condition, including the current trapping capacity of the Conowingo Dam and Reservoir, and the impact of this on water quality and aquatic resources; and (2) a longer time frame that includes the life of the dam, during which a dynamic equilibrium exists and regulatory requirements to address water quality and protect the designated uses of Chesapeake Bay are in place.

As identified in Chapter 1, the purposes of this assessment were to estimate and evaluate sediment and associated nutrient loads from the series of hydroelectric dams and reservoirs located on the lower Susquehanna River, analyze hydrodynamic and sedimentation processes and interactions within the lower Susquehanna River watershed, consider structural and nonstructural strategies for sediment management, and assess cumulative impacts of future conditions and sediment management strategies on the upper Chesapeake Bay.

As noted in Chapter 3, the LSRWA team developed a series of hydrologic scenarios that are representative of the existing and anticipated future conditions in the lower Susquehanna River. These scenarios are described in detail in Table 3-1. The scenarios are comprised of varying reservoir bathymetries, flow events, and loading conditions in the Susquehanna watershed, river and Chesapeake Bay. Appendices A-D provide further description on the problem identification scenarios evaluated for this effort. This chapter provides the background on how these scenarios were developed and evaluated.

4.1 FUTURE CONDITIONS OF THE CHESAPEAKE BAY WATERSHED

This section describes the anticipated future condition of the Chesapeake Bay watershed in general terms based on existing information and trend data. For forecasts of the future condition of the watershed, sources were used with different forecasting time frames. To provide some consistency over which to evaluate future conditions within the watershed, conditions for population and land use, consumptive water use, public water supply, global climate change, and sea-level change were projected to 2030. Some conditions (e.g., global climate change) also include longer forecasts. Accordingly, this information provides context for any management actions (or no action) taken in the watershed. It is important to note that the system seen in the past and today could change in the future.

As discussed in Chapter 2, EPA, working with its seven watershed jurisdictional partners established the 2010 Chesapeake Bay TMDL, which sets nitrogen, phosphorus, and sediment regulatory pollutant limits. These limits help to support and protect Chesapeake Bay designated uses (described in Section 3.3.6) for aquatic life and habitats. The TMDL process includes accountability measures, so that actions to restore clean water in the Chesapeake Bay and the watershed's streams and rivers can be monitored. The TMDL is mandatory, and is designed to ensure that pollution control measures needed to fully restore the Bay and its tidal rivers are in place by 2025, while meeting 60 percent of the overall nitrogen, phosphorus and sediment reductions by 2017 (USEPA, 2010a).

In response to the Chesapeake Bay TMDL process, the District of Columbia, Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia prepared watershed implementation plans (WIPs), that contain detailed information on a wide array of restorative measures and actions to be undertaken to meet the states' assigned load reduction responsibilities under the Chesapeake Bay TMDL; examples of restorative measures and actions are found in Table 4-1. The implementation of these WIPs is a key factor in assessing future conditions in the watershed. More information on the seven watershed jurisdictions' Phase II WIPs can be found on the Internet at the following URL links:

1. Delaware: http://www.dnrec.delaware.gov/swc/wa/Documents/ChesapeakePhaseIIWIP/Final_Phase2_CBWIP_03302012A.pdf
2. District of Columbia: http://ddoe.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/FINAL%20DC%20WIP%20March%2030%202012.pdf
3. Maryland: http://www.mde.state.md.us/programs/Water/TMDL/TMDLImplementation/Pages/FINAL_PhaseII_WIPDocument_Main.aspx
4. New York: http://www.dec.ny.gov/docs/water_pdf/finalphaseiiwip.pdf
5. Pennsylvania: http://files.dep.state.pa.us/Water/Chesapeake%20Bay%20Program/ChesapeakePortalFiles/4-2-2012/Clean%20FINAL%20Phase%202%20WIP%203-30-2012%20%282%29.pdf
6. Virginia: http://www.deq.virginia.gov/Portals/0/DEQ/Water/TMDL/Baywip/vatmdlwipphase2.pdf
7. West Virginia: http://www.wvca.us/bay/files/bay_documents/253_WV_WIP_Final-Phase_II_03292012.pdf

Table 4-1. Potential Measures to be Undertaken to Meet TMDLs

Activity-Generating Nutrient and Sediment Loads	Examples of Measures and Actions to Prevent or Reduce Nutrient and Sediment Loads
Human and Industrial Waste	Wastewater treatment plant upgrade
	Septic system upgrade
Crop Production	Improve soil conservation practices
	Improve nutrient management
	Increase cover crops
Animal Production	Improve animal waste management
	Improve animal wastewater management
Rural Land Runoff / Polluted Groundwater Seepage [1]	Riparian wetland restoration
	Riparian and upland reforestation
Urban Land Runoff / Polluted Groundwater Seepage[1]	Stormwater management retrofits
	Sanitary sewer infrastructure maintenance/improvement
	Stream geomorphic restoration
Air Pollution	Power plant, auto, and other emission reductions

Notes: [1] Nutrients generated from historic and recent activities.

4.1.1 Population and Land Use Changes

While governments and citizens are striving to meet the Chesapeake Bay TMDL, many other changes will likely be underway. The human population of the Bay watershed was 17.7 million people in 2012. It is expected that this number will continue to rise, reaching 20 million by 2030 (CBP, 2013). A growing population means that pollutant loads in the watershed will increase. Changes in land use that disrupt the natural flow of water in the Chesapeake Bay watershed, including increases in impermeable surfaces, will increase as population grows.

4.1.2 Consumptive Water Use in Susquehanna Basin

There may be increases in consumptive use of water in the Susquehanna River basin. Consumptive use is water that is withdrawn and not returned to the basin. These demands for water by people include water for public water supply, electrical generation, manufacturing, mining, and recreational purposes. Managing future increases in consumptive use in the Susquehanna River watershed is an important objective of SRBC's water resource management and regulatory programs (SRBC, 2013b). A review of water appropriation and use permits issued by MDE for water withdrawals downstream of the Conowingo Dam, indicate the major consumptive use to be for water supply (MDE, 2015).

Consumptive use in the Susquehanna River basin was estimated in 2008 at 882.5 million gallons per day (mgd). Projected consumptive water use in 2025 is expected to increase by an additional 319.7 mgd or 36 percent (SRBC, 2008). SRBC is currently in the process of developing updated consumptive use projections; however, it is reasonable to expect that uses will not decrease by 2030 or beyond. Water availability is generally not a concern during most flow conditions, but becomes an issue during certain low-flow periods. However, the increase in human water consumption would not be expected to affect large storm flows or scour in the future that are of particular concern to this study.

4.1.3 Public Water Supply – Withdrawals Downstream of Conowingo Dam

Cecil County, MD, is potentially interested in increasing water drawn from the Susquehanna River to meet its growth objectives for its municipalities and growth corridor along U.S. Route 40 (Cecil County, 2008). Currently, two public water systems in Cecil County, Perryville and Port Deposit, withdraw water from the Susquehanna River; although Port Deposit's wastewater is returned to the river. Demand projected in 2008 to 2030 for these systems includes increases of 31 percent and 10 percent, respectively (Cecil County, 2010). Additionally, without new water sources, several other public water systems in Cecil County will be unable to support projected growth through 2030. To serve the projected growth, additional water withdrawal from the Susquehanna River has been identified as a potential option (Cecil County, 2010).

Harford County, MD, including the City of Havre De Grace, also has existing permits for water use from the Susquehanna River downstream of Conowingo Dam (MDE, 2015). While the population of the City of Havre De Grace is expected to grow, current supplies are expected to meet future needs to at least 2025 (Harford County, 2009).

4.1.4 Global Climate Change

For forecasted global climate change, simulations for the Chesapeake Bay watershed out to the year 2100 predict increased precipitation amounts in winter and spring, as well as increased intensities of precipitation, northeasters (though their frequency may decrease), and tropical storms (Najjar et al., 2010)[10]. Precipitation volume and intensity has increased in the mid-Atlantic region of the Chesapeake watershed over the last century, and these trends are projected to continue to the end of the 21st century (Karl and Knight, 1998; Markstrom et al., 2012; Melillo et al., 2014; Najjar et al., 2010). By 2030, annual mean precipitation may increase by up to 4 percent, with increases of up to 15 percent by 2095 (Najjar, 2010). River flows may increase in winter but be reduced in summer, on average.

Because streamflow changes are uncertain, the overall direction of salinity change in the Bay is uncertain; however, salinity variability is expected to increase. Chesapeake Bay water temperatures are expected to continue to warm. Warming water temperatures would likely cause a reduction of

[10] The text contained in much of this section is from Najjar, 2010. Information contained in Najjar, 2010, is a review and synthesis of the scientific literature on climate change impacts to the Chesapeake Bay. The synthesis builds on a number of reviews discussing the impact of climate change on ecosystems, coastal areas, and marine resources of the mid-Atlantic region.

eelgrass which is at about its southern limit. Ultimately, aquatic life characteristics of warmer regions to the south along the Atlantic Coast would be favored in Chesapeake Bay (Najjar et al., 2010).

Warming of the Bay could have large negative implications on DO as continued warming of the Bay causes low DO conditions to occur substantially earlier, or end substantially later in the year. Forecasts of winter and spring streamflow increases as a result of climate change, in turn support forecasts that nutrient and sediment loading during winter and spring will likewise increase (Najjar, 2010). Given climate change predictions for increased precipitation of 4 percent by 2030 and 15 percent by 2095, and assuming no changes in net anthropogenic nitrogen inputs or land use, nitrogen flux down the Susquehanna River is predicted to increase by 17 percent by 2030 and 65 percent by 2095 (Howorth et al., 2006). It is also likely that phosphorus and sediment loading will increase as a result of the more intense and potentially less frequent rain events. Specific studies of how the changes in precipitation and future land use will alter flow (as well as the future scour of Conowingo sediments) are underway and will continue through 2015 and 2016. The final estimates of the impacts of climate change will be available for the Chesapeake TMDL 2017 midpoint assessment.

4.1.5 Sea-Level Change

Starting from the year 2015, sea level is expected to rise 0.15 feet to almost half a foot by 2030 in the upper Chesapeake Bay, as tabulated in Table 4-2 (USACE, 2013). Sea level is predicted to rise 0.5 to 2.28 feet in 50 years. This determination was based on the sea-level change scenarios contained in USACE engineering circular 1165-2-212. This circular was developed in accordance with the National Research Council's 1987 report *Responding to Changes in Sea Level: Engineering Implications*. The sea-level determination accounted for factors affecting divergence of local sea-level rise rates from global sea-level rise and land subsidence. Ongoing sea-level rise is anticipated to increase the rate of conversion of Bay tidal wetlands to open water, and lead to a substantial net loss of tidal wetlands over the next century (Titus and Strange, 2008; USCCSP, 2009).

Table 4-2. Projected Sea-Level Rise for Baltimore, MD

Year	Sea-Level Rise by Scenario (feet)		
	Low	Intermediate	High
2015	0	0	0
2030	0.15	0.23	0.49
2065	0.50	0.92	2.28

Source: Determined per USACE engineering circular 1165-2-212, with a base year of 2015.

The rate of sea-level rise appears to be accelerating, as has been forecast for some time in accompaniment with ongoing global change (e.g., Calafat and Chambers, 2013). Implications of sea-level rise at historic and accelerated rates to current resource management via regulation and restoration are beginning to be addressed by society. For Maryland, a 2012 executive order dictates how the state will invest funds to address this issue; the executive order is at: http://www.governor.maryland.gov/executiveorders/01.01.2012.29.pdf.

4.1.6 <u>Chesapeake Bay Ecosystem Improvements</u>

It is expected that ongoing watershed management efforts will produce a suite of positive ecological consequences to water quality and aquatic life in the rivers and Chesapeake Bay. Of particular note, as nutrient loading is reduced, habitable oxygenated deep-water habitat will increase in area, and water clarity will improve. Aquatic life dependent upon these habitats would benefit, including SAV and demersal fish.

At this time, there is some uncertainty over the rate at which these positive ecological improvements would occur. Lag-time is the time gap between BMP implementation and delivery of the full water quality effect to the Bay (CBP STAC, 2013). The lag time between implementation of management actions and resultant improvement in Chesapeake Bay ecological condition will vary for different pollutants and modes of transport. Lag times will also vary within a watershed with areas near streams having shorter lag times than areas farther from streams. BMP effects will be noticed more quickly at the local scale versus the watershed scale due to fewer in-system storages and shorter travel time from source to water body (CBP STAC, 2013).

Lag times for dissolved nutrients (e.g., nitrate) that are transported through groundwater will be longer, on the order of decades. Lag times for sparingly soluble nutrients (e.g., phosphorus), which are primarily transported through runoff, will be moderate (i.e., years to decades). Transport of sediment involves suspension of particles followed by deposition and re-suspension, therefore lag times for sediment will be longer than for nitrogen or phosphorus (CBP STAC, 2013). Full implementation of the WIPs will occur by 2025. Prior to 2030, improvements in water quality for constituents with short lag times (e.g., nitrogen) may be seen in the Bay. By 2030, water quality improvements through reductions of phosphorus and sediment could become evident.

4.2 <u>RIVER AND RESERVOIR CONDITIONS AND IMPLICATIONS TO THE BAY</u>

This section describes estimated current and future conditions of the lower Susquehanna River, including the reservoirs, based on recent data collected and LSRWA model simulations. These conditions will be described in terms of the watershed, the dynamics of the reservoirs, and downstream receiving water body (i.e., the Chesapeake Bay). This information provides context for understanding the impacts of any management actions (or no action) taken in the watershed.

For the LSRWA effort, a series of modeling scenarios was run with the linked modeling tools (detailed in Chapter 3), to help address questions pertaining to both existing and estimated future conditions. The models were used to define the current trapping capacity of Conowingo Dam and Reservoir, and the impact of the current trapping capacity on water quality and aquatic resources. Additionally, a longer time frame was evaluated to assess conditions during which a dynamic equilibrium for sediment transport from the dam exists, and regulatory requirements to address water quality and protect the designated uses of Chesapeake Bay are in place. The reservoir is expected to remain in a condition of dynamic equilibrium into the future, unless sediment management measures are undertaken.

Full implementation of the WIPs is expected by 2025, with immediate and continued improvements in water quality (see Section 4.1.6). Specific studies of how the changes in precipitation and future land use will alter flow (as well as the future scour of Conowingo sediments) are underway and will continue through 2015 and 2016. Final estimates of the impacts of climate change will be available for the Chesapeake TMDL 2017 midpoint assessment.

The specific questions that were addressed by this LSRWA effort include:

1. What is the system's current (existing) condition?
2. What is the system's condition if the WIPs are in full effect and reservoirs are still trapping?
3. What is the system's condition when WIPs are in full effect, reservoirs are still trapping sediment, and there is a winter scour event?
4. What is the system's condition when WIPs are not in effect, reservoirs are in dynamic equilibrium, and there is a winter scour event?
5. What is the system's condition when WIPs are in full effect, the reservoirs are in dynamic equilibrium, and there is a winter scour event?
6. What is the system's condition if WIPs are in full effect, reservoirs are in dynamic equilibrium, and a scour event occurs during the summer, fall or winter?

Appendices A-D and J provide details on modeling scenarios and results. This section will provide an overview of the modeling results along with other recent research and data pertinent to this issue.

4.2.1 Sediment Transport and Scouring Dynamics

Sections 4.2.1 and 4.2.2 broadly summarize the lower Susquehanna River reservoir sediment transport and scouring dynamics, as well as linking these dynamics to watershed-loading dynamics. HEC-RAS and AdH were the primary tools utilized to estimate sediment-loading conditions and scouring. Sections 3.1 and 3.2 summarized these tools and their application for use in this LSRWA effort. Appendices A and B provide full details on these modeling efforts.

In the lower Susquehanna River system, as flow increases (i.e., during a storm event), sediment loads increase from the watershed and more sediment is scoured from the reservoir bed; details will be presented later in this section. Hirsch (2012) concluded that the frequency of high-flow events is not changing, but the behavior of the reservoir system has changed in response to these high-flow events. In particular, there is less sediment settling in the reservoirs from the water column, combined with a lower scour threshold as the reservoirs fill up. Scour threshold is the flow on average when scouring occurs transporting sediment out of the reservoir system to Chesapeake Bay. As the lower Susquehanna River reservoirs fill, water depths decrease and the water velocity increases, increasing the forces on the bed surface (which can result in more scour) and decreasing the amount of time for sediment to settle out of the water column. These actions subsequently reduce deposition within the reservoir (see Appendix A for more detail).

Generally in a reservoir, sediment transport dynamics are dependent on flow. For lower to moderate flows, sand-sized sediment will tend to deposit, along with the larger, silt-sized fine sediment. Clays are generally considered wash load in that they have the potential to transport through the reservoir as suspended load without interacting with the bed. Wash load is the part of a stream's sediment load that consists of grain sizes finer than those of the stream bed. All sediment sizes have the potential to transport through the dam, provided flow, and resulting turbulence, is high enough to maintain the sediment in suspension. Determining whether bed sediment is scoured from the reservoir bed during a storm event depends on the sediment size, how long the bed has been consolidating, and the length of time since the last scour event. In addition, a portion of the sediment that is scoured from within the reservoir may redeposit within the reservoir itself and not transport through Conowingo Dam into the Chesapeake Bay (see Appendices A and B for more detail).

Sediment transport is directly related to particle size. Storms can potentially scour the silts and clays, which are easier to transport, while frequently leaving behind the coarser, sand-sized sediment. For example, in the lower portion of Conowingo Reservoir in 1990, particle size analysis from 5-foot-deep sediment cores indicated the area had about 5 percent sand; in 2012, it was projected to have 20 percent sand based on all previous cores. The reservoir sediment data collected show that generally there is more sand in the bed upstream, and silts and clays are more prevalent closer to the dam for all three reservoirs. Silt is the dominate particle size transported from the reservoir system, with little sand (less than 5 percent) transported to the upper Chesapeake Bay (see Appendix A for further discussion).

There are circumstances where fines could require higher flows to scour from the bed. Suspended fine sediment can either exist as primary silt and clay particles, or in low energy systems, such as reservoirs, form larger particles in the water column due to flocculation. Particles that flocculate consolidate, are larger, and have higher settling velocities; thus, their fate in the reservoir can be quite different than the lighter primary particles (Ziegler and Nisbit, 1995).

Generally, over time, reservoir bed fine sediment (silts and clays) tend to consolidate, become denser, and develop cohesive properties. Generally, the more consolidated the bed, the higher the flow required to initiate erosion. For example, a recently deposited bed may have a bulk density of 1200 kilograms/cubic meter (high water content) and be easily scoured. If a flood occurs over this bed, it may readily erode at lower discharges. If this same bed were to remain for a year or more and consolidate to 1600 kilograms/cubic meter, the critical bed shear stress (the force on the bed required to start eroding sediment) could be 3 to 5 times higher (see Appendix B for more detail). In Conowingo Reservoir, the silts and clays that undergo flocculation may also redeposit in low-energy areas of the reservoir, particularly in the area approximately 1 mile upstream of the dam on the eastern side of the reservoir (see Appendix B for further discussion).

It is not known precisely when scour occurs. Hirsch (2012) estimates sediment concentrations (along with phosphorus) discharged from the reservoir system to the upper Chesapeake Bay are increasing at flows as low as 175,000 cfs, a 1-year return flow event. Hirsch (2012) attributes this increase to a change in the reservoir settling rates (i.e., sediment and associated nutrients settling from the water column), resulting from higher flow velocities and potential for increased scour due to the reservoir filling in.

The LSRWA modeling efforts indicate that the scour threshold for the current reservoir condition ranges from about 300,000 cfs to 400,000 cfs, with the threshold for mass scouring occurring at about 400,000 cfs, which represents a 4- to 5-year return flow event. The term mass scouring refers to the flow magnitude that results in very high erosion rates where significant high mass transport from the bed occurs. A close inspection of the LSRWA model simulation results performed for this assessment indicates that trace erosion (erosion of the unconsolidated material of the mixing layer in the reservoir, which occurs at low shear rates) does occur at lower flows (150,000 to 300,000 cfs). This will be discussed in more detail later in this chapter. While a reservoir can scour with deposition of material occurring in the reservoir, for this assessment, the main concern was the net scour – that is, the material scoured from the bottom of Conowingo Reservoir and carried over the Conowingo outfall.

While the focus for many of the LSRWA analyses is the Conowingo Reservoir, there most certainly is scour in the upper two reservoirs that supply Conowingo. However, without field data to quantify this scour, it is very uncertain how much of the scour enters Conowingo. More field data measurements would be needed below the two dams (Safe Harbor and Holtwood Dams) for this level of detail; efforts to collect this type of data are currently underway.

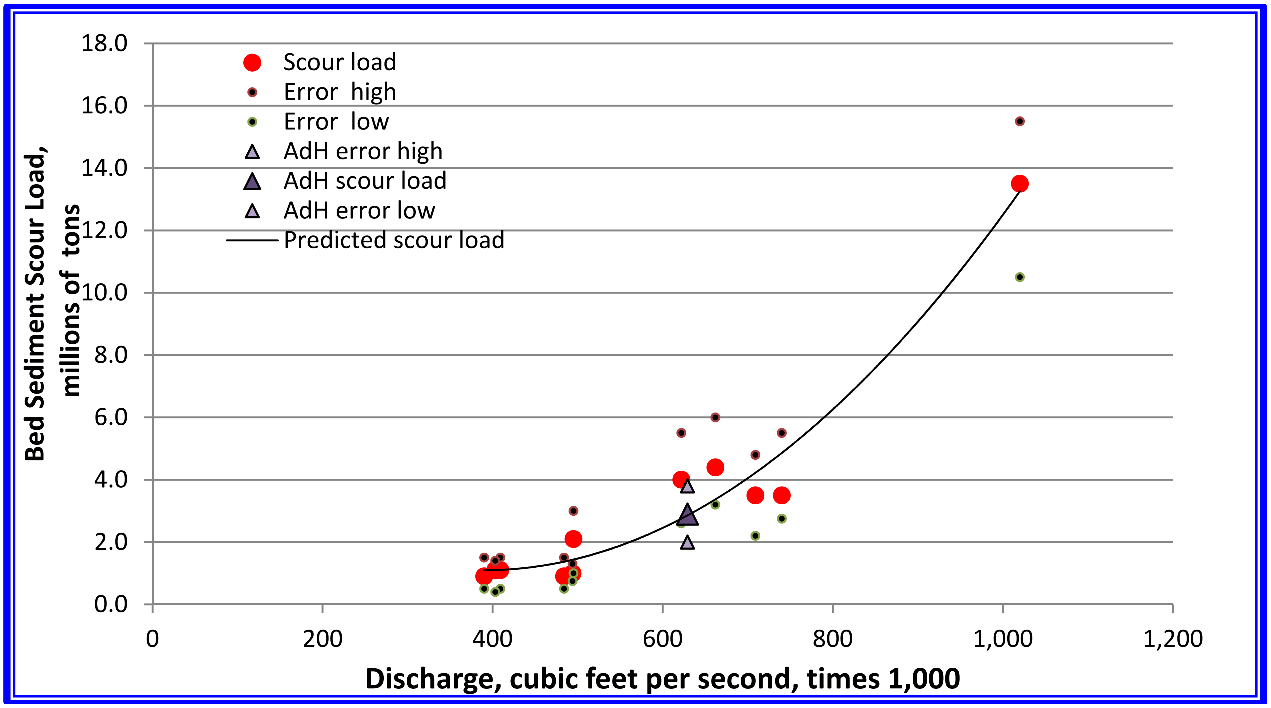
Reservoir Bed Scour Predictions

The USGS developed a regression equation to predict the bed sediment scour load for the mean daily discharge at Conowingo. The equation is based primarily on flow and loads from six storm events during 2006-11, with bathymetry (bed-elevation change) data in the reservoirs using the Reed and Hoffman (1997), Langland and Hainly (1997), Langland (2009), and URS and GSE (2012b) studies, and on a comparison of estimates of sediment inflow and outflow from the reservoirs. While not exact as a "scour predicting" tool, the equation is updated with each flood event resulting in a new slightly different equation. This equation predicts mass scour from flows generally exceeding 400,000 cfs in the lower Susquehanna River. The range of AdH modeling simulations results are included for the Tropical Storm Lee event in Figure 4-1, along with USGS scour load predictions (see Appendix A, Attachment A-2, for further details on this analysis).

The timing and frequency of flood events are generally unpredictable. Recurrence intervals (RIs) are used to help determine the frequency of a flow event over a long period of time. To provide context for the frequency of flows in Susquehanna River, expected flows for various RIs are presented in Table 4-3. The recurrence interval is a statistical estimate of the likelihood of a given flow to occur based on historic data. The annual exceedance probability is the chance of a given flow event to occur in a year. Table 4-3 illustrates the difference between RI and flow at two USGS Susquehanna River gages – Susquehanna River at Marietta, PA, and the Susquehanna River at Conowingo, MD – for 1968-2012. These gages represent the inflow and outflow from the reservoir system, respectively. There is a general coincidence of RI in flow up until about 1.5 years, then an increasing divergence in RI between the two sites as discharge increases. This is most likely due to the increase in drainage area and flow regulation of three hydroelectric facilities between the gages.

Since 1972, there have been 11 storms with daily mean streamflows greater than 400,000 cfs, the LSRWA-estimated scour threshold. This threshold has a 4- to 5-year recurrence interval. Flow hydrographs for the 11 high-flow events are depicted in Figure 4-2. These hydrographs reveal that the number of days with flows above 400,000 cfs, ranged from 1 to 5 days with an average of about 3 days.

Figure 4-1. USGS Scour Load Predictions with AdH Model Results



Notes: Since the reservoir system is dynamic and sediment type, time consolidating and previous scour events vary, it is not known precisely when scour occurs.

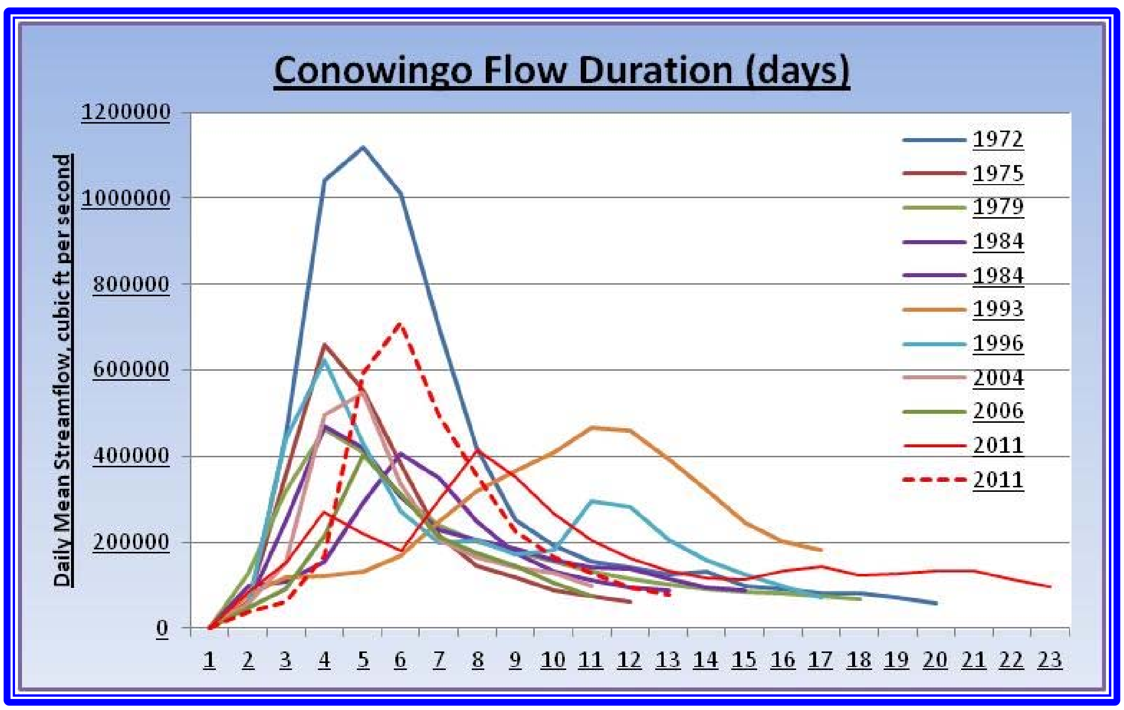
The LSRWA modeling efforts indicate that the scour threshold (flow on average when scouring occurs, transporting sediment out of the reservoir system to the Chesapeake Bay) for the current reservoir condition ranges from about 300,000 cfs to 400,000 cfs, with the threshold for mass scouring occurring at about 400,000 cfs, which represents a 4-5-year return flow event.

The term mass scouring refers to the flow magnitude that results in very high erosion rates where significant high mass transport from the bed occurs.

Table 4-3. Hydrologic Parameters for the Marietta and Conowingo Gages

Recurrence Interval (years)	Annual Exceedance Probability	Expected Flow Estimate (cfs)	
		Station 01576000 Susquehanna River at Marietta, PA (1932-2012)	Station 01578310 Susquehanna River at Conowingo, MD (1968-2012)
1	0.995	113,000	131,000
1.01	0.99	121,000	138,000
1.05	0.95	144,300	164,000
1.11	0.9	162,000	182,000
1.25	0.8	188,000	212,000
1.5	0.667	221,000	248,000
2	0.5	265,000	298,200
2.33	0.429	287,000	323,000
5	0.2	402,000	436,000
10	0.1	514,000	590,000
25	0.04	685,000	798,000
50	0.02	835,000	984,000
100	0.01	1,009,000	1,202,000
200	0.005	1,206,000	1,455,000
500	0.002	1,514,000	1,857,000

Figure 4-2. Flow Hydrographs for 11 Recent High-flow Events at Conowingo, MD



Source: USGS, Appendix A.

Dynamic Equilibrium

Previous studies (Langland, 2009; Reed and Hoffman, 1997) have documented important information on the lower Susquehanna River reservoirs, including the reservoirs' bottom-sediment profiles, reduced storage capacity, and trapping efficiency. These studies indicated that the capacity for Conowingo Reservoir to store sediment and associated nutrients has declined with time. The studies also presented an estimate of remaining time to reach a "full" capacity (or dynamic equilibrium) ranging from 10 to 20 years.

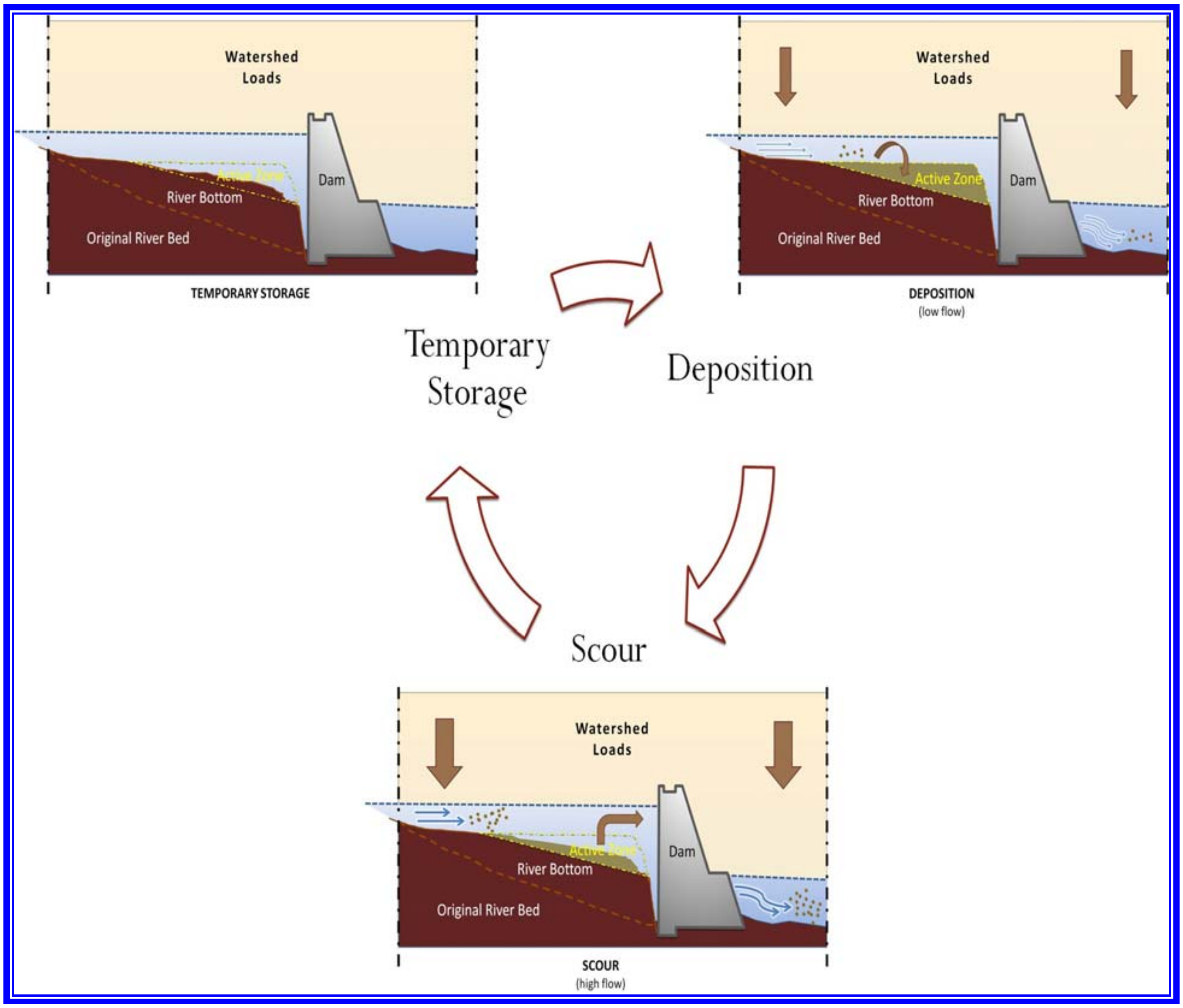
Langland (2009) and Reed (1996 et al., 1997) estimated the number of years until Conowingo Reservoir would reach long term sediment storage capacity and effects on sediment transport, based on limited suspended sediment data taken at Safe Harbor in the mid- to late 1950's and early 1960's. The Safe Harbor data indicated a linear trend of increasing sediment discharge through the 1950's and 1960's. However, later measurements indicated a relatively constant sediment discharge that may be the result of Safe Harbor's reservoir reaching long-term sediment storage capacity. A similar linear approach was used in Conowingo Reservoir (Langland, 2009; Reed and Hoffman 1997).

LSRWA modeling efforts have indicated that the relationship between time and capacity is non-linear in Conowingo Reservoir. Conowingo Reservoir has twice the storage capacity of Safe Harbor's reservoir and five times the capacity of Holtwood's reservoir, thus filling rates and time estimates are not transferrable to Conowingo Reservoir (see Appendix A for more details).

The LSRWA efforts described in this report assumed that Safe Harbor and Holtwood have already reached a dynamic equilibrium state with no long-term changes in storage capacity based on these earlier studies. In this state, these two reservoirs are still scouring in the short term under high flows and depositing in the short term under lower flows. As such, they still play a role in sediment and associated nutrient transport to Chesapeake Bay (see Appendix A for further discussion). A recent study by Hirsch (2012) concluded that the entire series of reservoirs appear very close to a dynamic equilibrium state, with the nutrient and sediment loads discharged from Conowingo Dam increasing over the past 10 to 15 years.

Based on these studies, it appears each reservoir has reached an end state of sediment storage capacity which is defined in this report as "dynamic equilibrium." Figure 4-3 provides a graphic representation of dynamic equilibrium. In the dynamic equilibrium state, episodic flood (scouring) events will temporarily increase sediment storage capacity, allowing for more deposition in the short term. This state is a periodic "cycle" with an increase in sediment and associated nutrient load to the Bay from scour also resulting in an increase in storage volume, followed by reduced loads transported to the Chesapeake Bay due to reservoir deposition. The lower Susquehanna River reservoirs have reached a maximum sediment storage capacity that may temporarily decrease based on the frequency of large storms through the system. However, sediment will continue to accumulate until an erosion event occurs. That is, there is no absolute capacity or point at which the reservoir is "full" and will no longer trap sediment. As the reservoir fills, however, the scour threshold to initiate an erosion event decreases until the next scour event occurs, whereby the scour threshold increases once again (see Appendices A and B for further explanation).

Figure 4-3. LSRWA Dynamic Equilibrium Concept



Dynamic equilibrium does not imply equality of sediment inflow and outflow on a daily, monthly, or even annual basis, or similar time scale. It implies a balance between sediment inflow and outflow over a long time period (years or decades) defined by the frequency and timing of scouring events. Sediment and associated nutrients that accumulate between high-flow events are scoured away during storm events, whereby accumulation begins again. Over time, there is no net storage or filling occurring in the reservoirs.

Each reservoir bed consists of a number of layers. The lowermost layer is considered an inactive layer that will rarely, if ever, scour to any degree. Above that, there is an "active" scour and depositional zone. The surface of the active layer consists of a relatively thin mixing layer that is unconsolidated and may have a high potential for scour at flows less than the scour threshold. For modeling purposes, the active layer is estimated to have a depth of approximately of 2 to 3 feet; however, it is spatially variable due to bed composition and consolidation. The thin unconsolidated mixing layer dimensions are uncertain, but are likely less than an inch (see Appendices A and B further discussion); this very thin layer at the surface where sediment sorting takes place was modeled as part of the active layer. The Holtwood and Safe Harbor reservoirs are not as large as Conowingo, but their bed composition is similar.

Model Simulations of Reservoir Sediment Transport

A number of model simulations were conducted to evaluate the sediment transport characteristics of Conowingo Reservoir. As described earlier, two models were used for this analysis: HEC-RAS and AdH. HEC-RAS incorporated all three lower Susquehanna River dams and reservoirs. It routed flows and sediment through the reservoir system and evaluated the scour potential of Conowingo Reservoir (HEC-RAS modeling details are in Appendix A). AdH was utilized to evaluate only Conowingo Reservoir sediment transport. The 2D AdH model utilized the HEC-RAS model results (sediment load and flow) from Holtwood Dam as the inflowing sediment load boundary condition (see Appendix B for AdH modeling details). The 2D AdH model was utilized to evaluate the following:

1. Change in scour and deposition potential from 1996 to 2011 reservoir bathymetry;
2. Change in scour and deposition potential from 2011 to "full" reservoir bathymetry; and
3. Change in scour threshold for Susquehanna River flows through Conowingo Reservoir.

A series of simulations was conducted varying only Conowingo Reservoir bathymetry to understand sediment transport implications and determine if Conowingo was also in a dynamic equilibrium state. A 4-year flow record was simulated in the models, representing 2008 to 2011. Since Tropical Storm Lee occurred in September of 2011, it was included in the model simulations; the Lee event had a peak instantaneous discharge of 778,000 cfs and a peak daily discharge of 709,000 cfs, both measured at the Conowingo gage. Reservoir bathymetries for 1996, 2008, 2011 and "full" were analyzed.

Because of the relatively small data set describing bed properties of Conowingo Reservoir, multiple parametric model simulations were conducted, varying key bed properties such as critical bed shear stress for erosion, erosion rate, and bed sediment depth. Model results were compared to the recent bathymetric surveys, sediment size gradations measured below Conowingo Dam, and empirical studies conducted by the USGS. The key validation parameters were net deposition and bed scour. The change in survey data indicated that the reservoir was net depositional. The AdH model validation exercise indicated that the Tropical Storm Lee flood event potentially had a bed scour load range of 2.0 to 4.0 million tons. These results are discussed in more detail in the following sections.

Bathymetry Comparisons

Model simulations were conducted to evaluate the change in sediment transport characteristics as a function of historical bathymetry. The 1996 bathymetry was the earliest survey recorded in digital form. It was compared to the 2008, 2011, and the "full" bathymetries. The full bathymetry was created by adding the estimated additional sediment storage capacity to the 2011 bathymetry. The 4-

year flow record (2008-11) was simulated for these comparisons. The summary data are found in Table 4-4. The "full" condition is a term used to describe the storage capacity of a given reservoir. A reservoir is full when it can no longer effectively trap sediment and associated nutrients in the long term (decades) as described previously.

The model results indicated that the bed scour load that passes through the dam during a recurrence of the Tropical Storm Lee event, increases by about 67 percent (1.8 to 3.0 million tons) due to the increased transport capacity of the 2011 bathymetry over the 1996 bathymetry. Although the scour load change is 67 percent, this scour load is a relatively small percentage (9 to 13 percent) of the total load delivered to the Bay. The net reservoir deposition, over the 4 years of analysis, decreases by about 33 percent between the 1996 and 2011 bathymetries (6.0 million tons to 4.0 million tons). These findings are directly related to the reduction of storage and subsequent increase in transport capacity of the 2011 bathymetry. The total outflow load through the dam which consists of the Conowingo scour load, the scour load of the upper two reservoirs, and the pass-through watershed load, increases by about 10 percent from 1996 to the 2011 for the 4-year simulation (2008-11).

A comparison of the present-day (2011 bathymetry) AdH model results with the projected full bathymetry model scenario results shows that sediment transport through Conowingo Reservoir does not appreciably change, indicating that the reservoir may currently be in a state of dynamic equilibrium. In this state, the reservoir will experience a periodic "cycle" with an increase in sediment and associated nutrient loads to the Bay from scour also resulting in an increase in storage volume (capacity) behind the dam, followed by reduced sediment and associated nutrient loads transported to the Chesapeake Bay due to reservoir deposition within that increased capacity.

Table 4-4. Calculated Sediment Transport under Various Bathymetries [1]

Bathymetry[2]	Outflow Load[3] (million tons)	Bed Scour Load[4] (million tons)	Net Deposition[5] (million tons)
1996	20.3	1.8	6.0
2008	21.9	2.9	4.4
2011	22.3	3.0	4.0
"Full" Condition	22.2	3.0	4.1

Notes: [1] These scenarios utilized flows from the 2008-11 hydrologic period which includes the Tropical Storm Lee scour event.
[2] Bathymetry data collected from each of these years were utilized as input parameters to the AdH model. Full condition was calculated utilizing USGS bathymetry data from 2008 (Langland, 2009) and Gomez and Sullivan Engineers bathymetry data from 2011 (URS and GSE, 2012b). This calculation is described in Appendix A.
[3] Outflow load is what flowed over Conowingo into Chesapeake Bay (includes bed scour load).
[4] Bed scour load is the load from the Conowingo Reservoir bed to the Chesapeake Bay, as estimated by AdH.
[5] Net deposition is what sediment remained in the Conowingo Reservoir during the 4-year simulation period.

Scour Load Model Simulations

As indicated in Table 4-4, the AdH model simulations indicate an increase of 1.2 million tons of bed sediment scour due to the increase in transportable sediment of the 2011 bathymetry over the 1996 bathymetry for a Tropical Storm Lee magnitude event. The bathymetry comparison simulations also indicate that the scour threshold for the current reservoir condition ranges from about 300,000 cfs to 400,000 cfs, with the threshold for mass scouring occurring at about 400,000 cfs, as discussed previously. The term mass scouring refers to the flow magnitude that results in very high erosion rates where significant high mass transport from the bed occurs.

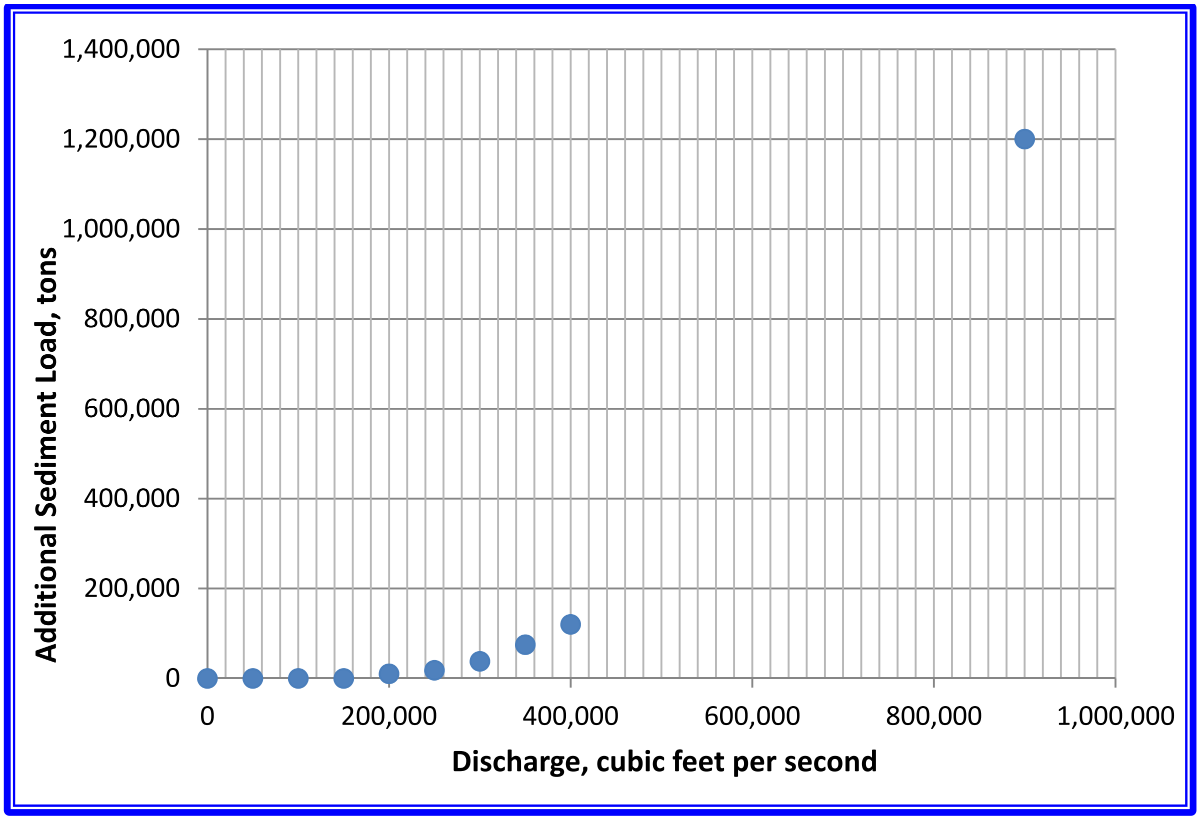
The majority of bed scour load occurs above this scour threshold flow. However, laboratory tests performed at USACE ERDC indicate that during depositional periods, a low density unconsolidated bed surface layer with a relatively low critical bed shear stress for erosion, will build as a top layer in Conowingo Reservoir and that this layer may mobilize at flows lower than the 400,000 cfs threshold. A close inspection of the model simulation results indicates that trace erosion does occur at lower flows (150,000 to 300,000 cfs). To investigate this, the AdH model was simulated with both the 1996 and 2011 bathymetries utilizing a flow hydrograph with a peak flow of 400,000 cfs.

The sediment flux through the model (that is, through Conowingo Dam) was computed for both the 1996 and 2011 simulations and compared. The results are presented in Table 4-5 and Figure 4-4. The data in Table 4-5 represent the additional bed scour load that will potentially be passed through the dam due to the increased transport capacity of the 2011 bathymetry when compared to the 1996 bathymetry. The Tropical Storm Lee data (a differential of 1.2 million tons) were plotted on Figure 4-4 along with the data from this series of simulations. It should be noted that after the scour threshold is reached, the load increase has an exponential trend, indicating the mass scour range, as illustrated in Figure 4-4.

Table 4-5. Additional Calculated Sediment Load Due to Increased Transport Capacity, 2011 vs. 1996

Discharge (cfs)	Increased Sediment Load 2011 vs. 1996 Bathymetry (tons)
50,000	0
100,000	0
150,000	74
200,000	3,000
250,000	22,000
300,000	34,800
350,000	79,200
400,000	234,000
700,000	1,200,000

Figure 4-4. Additional Calculated Sediment Load Due to Increased Transport Capacity, 2011 vs. 1996



USGS Analysis of Measured Sediment Loads

The USGS analyzed suspended sediment concentration data sampled below Conowingo Dam to quantify sediment transport and reservoir dynamics. For this evaluation, historical streamflow and sediment transport data from the Susquehanna River were analyzed to estimate sediment loads from 1928 to 2012. Data from the Marietta, PA gage represented the input to the reservoirs (see Appendix A, Attachment A-1 for further detail on these computations).

This analysis indicated that sediment loads were greater in the early to mid-1900s and have decreased over time, due to watershed management measures and other social and economic factors. As the reservoirs have filled with sediment over time, the sediment trapping efficiency has decreased as well. The loads and trapping efficiencies for five historical time periods are listed in Table 4-6.

By approximately 1959, the two uppermost reservoirs had become less efficient in trapping sediment, while the inflowing sediment load to Conowingo Reservoir from the watershed continued to be reduced. As the reservoirs have filled over time, the trapping efficiency has decreased from around 70 to 80 percent in the 1930s to the current 45 to 55 percent, resulting in a decrease in the amount of trapped sediment. Although the data indicate that on average, the trapping efficiency of

Table 4-6. Trapping Efficiency and Load Transport for Multiple Time Periods, 1928-2012

Time Period	Average Annual Load to Reservoirs (million tons/year)	Reservoir Trapping (percent)	Average Annual Load Trapped (million tons/year)	Average Annual Load to Bay (million tons/year)
1928-40	8.7	70-80	6.3	2.4
1941-50	8.5	65-70	5.8	2.7
1951-71	5.1	55-65	3.1	2.0
1973-92	4.9	50-65	2.6	2.3
1993-2012	3.5	45-55	1.3	2.2

Source: Calculated by USGS based on current and historical streamflow and sediment data; these numbers represent the total for all three reservoirs (Lake Clarke, Lake Aldred, and Conowingo Reservoir). Hurricane Agnes (1972) data not included. See Appendix A for more details.

Conowingo Reservoir is decreasing, large flow events can temporarily increase trapping efficiency by scouring existing bed sediment out of the reservoir into the Chesapeake Bay.

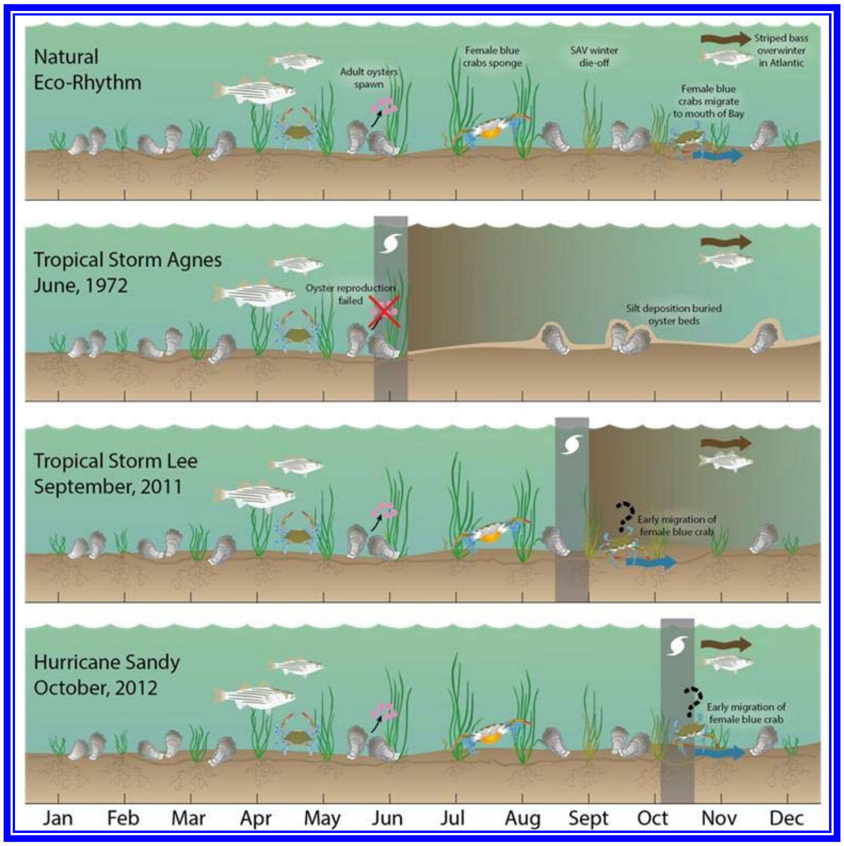
The USGS estimates that the average inflow for the last 20 years (1993-2012 evaluation period) of sediment was about 3.5 million tons per year into Conowingo Reservoir, with deposition around 1.3 million tons per year. Transport to the upper Chesapeake Bay has been relatively constant at about 2.2 million tons per year over the last 30 years, as illustrated in Table 4-6.

4.2.2 <u>Storm Effects and Implications</u>

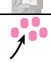
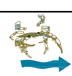
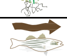
Storms are an influential factor to the watershed and reservoir system. Storms vary with respect to duration, timing, and severity; all of these factors play a role in the impacts to aquatic life and water quality. In addition, the storm track affects relative wind speeds, storm surge, and rainfall amounts across the Chesapeake Bay watershed (UMCES, 2012). Given the variables involved for each specific storm event, uncertainties exist regarding ecological impacts of major events; however, much has been learned by studying and comparing these events and evaluating the subsequent impacts to ecosystems.

Storm events can disrupt the normal eco-rhythm of species within Chesapeake Bay, as illustrated in Figure 4-5. For example, increased freshwater inputs can trigger early migration of female crabs to more saline waters at the mouth of the Chesapeake Bay (UMCES, 2012). More severe, large storm

Figure 4-5. Timing of Storm Events Affects Ecological Impacts



Source: UMCES, 2012.

Key to Symbols in Figure 4-5	
	The timing of storm events can have major impacts of the life histories of Chesapeake Bay flora and fauna.
	While the life histories of many Chesapeake Bay flora and fauna are well understood, many uncertainties remain about the impacts of major storm events. Many of the potential impacts are not observed until the next growing season.
	Oyster reefs provide habitat for many aquatic species.
	Adult oysters spawn during the summer months, typically June through August.
	Female blue crabs spawn two to nine months after mating, carrying fertilized eggs in a mass, or "sponge" on abdomen.
	After mating, female blue crabs migrate to high-salinity waters to over-winter before spawning.
	The peak growth period for aquatic grasses occurs during summer months. In the winter, plants senesce but reappear the following spring when temperatures increase.
	Striped bass are anadromous—they spend their adult life in the ocean but return to fresh water to spawn.

events can deliver large inputs of freshwater that can cause oyster mortality in the upper Bay, while increased sediment can cause widespread sea grass die-off and bury oyster beds (MDNR, 2012).

Runoff events with flows sufficient to scour reservoir sediment occur at various times of the year. Late winter and early spring floods occur in the Susquehanna River due to precipitation and snowmelt. Floods from tropical storms are more common during late summer and early fall, although Tropical Storm Agnes, the high-flow event of record in the Susquehanna River occurred in June 1972 (CRC, 1974).

Four storms will be characterized in this section to provide insights into storm variations and their associated impacts. They are Hurricane Sandy (October 2012), Tropical Storm Lee (September 2011), the January 1996 "Big Melt," and Tropical Storm Agnes (June 1972).

Hurricane Sandy

UMCES and MDNR conducted a rapid assessment of the impacts of Hurricane Sandy in November 2012 on the Chesapeake and Delmarva coastal bays. A report was developed and finalized and can be found here: http://www.mdcoastalbays.org/files/pdfs_pdf/HurricaneSandyAssessment-Final-1.pdf

Hurricane Sandy, unlike Tropical Storm Lee, had a relatively small impact on the Chesapeake Bay and lower Susquehanna River watershed due to the track, duration, and timing of the storm. In particular, Hurricane Sandy occurred later in the "eco-calendar," so there were less ecological impacts as illustrated in Figure 4-5. In addition, its peak daily discharge over Conowingo Dam on November 1, 2012, was 109,000 cfs.

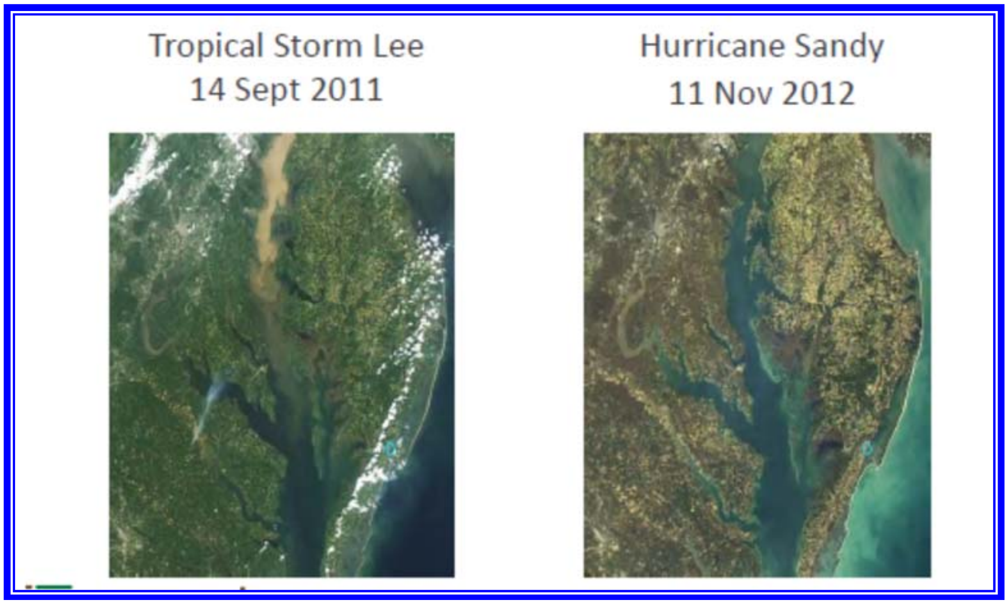
Hurricane Sandy had some minimal observed physical effects on the northwestern and northern side of the Susquehanna River basin in terms of higher flow and wind damage. However, more substantial physical effects were observed on the southeastern and eastern side of the basin within Pennsylvania, including flash floods, road closures, wind damage, and power outages.

Tropical Storm Lee

Intense rainfall occurred in the Susquehanna River watershed during Tropical Storm Lee (September 2011). Precipitation centered on the upper western shore, north to New York. Freshwater flow from Tropical Storm Lee ranks second all-time in recorded freshwater flow behind Tropical Storm Agnes in 1972 (USGS, 2013). The peak daily Conowingo discharge during Lee was measured at 709,000 cfs. When Tropical Storm Lee occurred, the Chesapeake Bay region was still recovering from an earlier storm, Tropical Storm Irene (August 2011), which had passed through just over two weeks prior, making it a wet season for the Bay (MD Sea Grant, 2011). Irene did not bring much rain to the Susquehanna River thus it is not one of the storms focused on in this section.

During Hurricane Sandy, the most intense precipitation was limited to the Maryland portion of the Susquehanna watershed, while nearly the entire Susquehanna watershed experienced high levels of rainfall during the Lee event. As a result, sediment runoff from Tropical Storm Lee was quite extensive compared to that of Hurricane Sandy and produced a large sediment plume in Bay waters,

Figure 4-6. Tropical Storm Lee vs. Hurricane Sandy Plumes in Upper Bay



Source: NASA/GSFC image.

as depicted in Figure 4-6. Where sediment transported into the Bay would be deposited is controlled by waves and currents, thus mainstem Bay deep waters and protected headwater tributary settings would likely retain sediment from this storm, whereas higher energy shallow waters of the mainstem Bay would be expected to show negligible deposition.

SAV species in the upper Bay were strongly affected by Hurricane Irene and Tropical Storm Lee which increased river flow and sediment loads in this region for almost two months (Gurbisz and Kemp, 2013). However, the dense SAV bed on the Susquehanna Flats persisted through the storms demonstrating how resilient SAV beds can be to water quality disturbances (CBP, 2013). Appendix K provides further discussion on SAV trends.

Regarding oysters, Maryland's 2011 oyster survey conducted after Tropical Storm Lee indicated that those high freshwater flows from heavy rains in the spring and two tropical storms in late summer impacted oysters in the upper Bay, although ultimately representing a relatively small proportion of the total oyster population. The lower salinities proved to be beneficial to the majority of oysters in Maryland by reducing disease impacts to allow the yearling oysters to thrive (MDNR, 2012).

January 1996

The "Big Melt" event occurred in January 1996. The daily peak flow for this event was 622,000 cfs at the Conowingo gage. This event was brought about by a warm rain event on an existing snow pack and frozen ground. The event led to high flows and pollutant loads. The event was further exacerbated by the breaching of an ice dam in Lake Clarke behind Safe Harbor Dam (SRBC, 2006b; Langland, 1997). No substantial effects from nutrients or sediment on SAV or dissolved oxygen were reported from the "Big Melt" event, likely because it occurred in late winter (USEPA, 2010a).

Hurricane Agnes

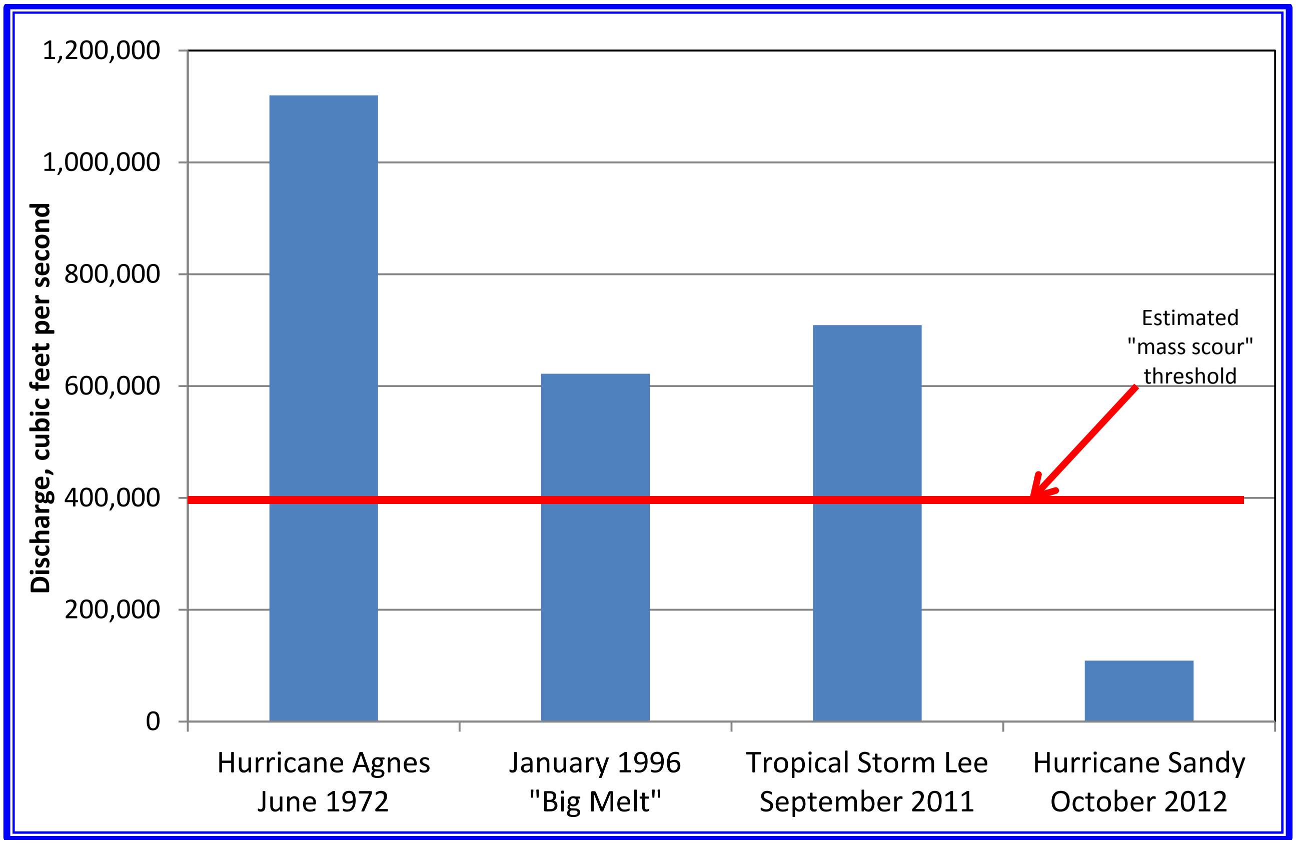
Hurricane Agnes occurred in June 1972, at a sensitive time of the "eco-calendar," as shown in Figure 4-5. Hurricane Agnes had extremely large flows and pollutant loads; this event is considered to have produced the most detrimental impacts observed in recent history to the Chesapeake Bay. The timing of the storm was particularly devastating, as it occurred during important reproductive stages for oysters and crabs, and the early growing season for aquatic grasses. Hurricane Agnes was the largest flood in the Susquehanna River basin since 1896, when recording of flow began at Harrisburg, PA. During the Agnes event, the daily flow over Conowingo Dam peaked at 1,120,000 cfs. After Hurricane Agnes, the second largest recorded flood event (for daily mean flow) in the lower Susquehanna River was Tropical Storm Lee in 2011 (UMCES, 2012). Figure 4-7 provides a comparison of the storm flows for all four high-flow events.

SAV populations had been decreasing Bay-wide during the 1960s from reduced water clarity, but underwent a dramatic decline in 1972 when massive quantities of sediments and nutrients were conveyed into the Bay by Hurricane Agnes runoff. The Susquehanna Flats remained sparsely vegetated by SAV until the late 1990s (Orth et al., 2010; see Appendix K). In the early 2000s, plant abundance rapidly increased. Gurbisz and Kemp (2013) found that the interplay of episodic drought and long-term underlying water quality improvements caused a resurgence of SAV levels even beyond historical abundance. Other factors identified in the SAV recovery were positive water quality feedbacks because of the presence of the SAV beds. The SAV beds had better water clarity and more beneficial nitrogen concentrations inside the SAV bed versus outside the bed, due to enhanced particle settling and nutrient processing within the SAV bed.

Hurricane Agnes caused widespread algal blooms and low dissolved oxygen conditions in the Bay in 1972, but not enough to cause major die-offs of organisms from these impacts. Effects of the storm on hard clams, blue crab, and finfish were temporary and minor. Soft-shell clam were substantially affected during summer 1972, but began recovering that fall. The massive volumes of freshwater introduced and consequent extended low-salinity conditions were lethal to oysters. Oyster suffered substantial population declines and bed failure in the upper and middle Bay. However, Bay-wide harvests were not substantially affected because the lack of harvestable oysters in the upper and middle Bay were offset by oyster harvests from the lower Bay (CRC, 1974).

As discussed in Chapter 3, the LSRWA modeling efforts included Tropical Storm Lee and the January 1996 high-flow event because these storms were included in the hydrologic period of the modeling tools utilized for this effort, and because there was existing collected data available for these storms. Bathymetry data and incoming loads to Conowingo Reservoir and watershed data are limited or nonexistent for the Agnes-event time period, so uncertainty would be high if this event were modeled. To model an Agnes-sized event, additional data collection would be required. That said, an Agnes-type run would provide a broader range of hydrologic conditions, thus shedding light on the storm of record in the Chesapeake Bay (worst-case scenario). Documentation including details of a running a modeling scenario like this are included in Appendix I, Attachment I-7.

Figure 4-7. Comparison of Major Historical Flow Events



Notes: All values are the peak daily flows as measured at the USGS Conowingo gage.
Since the reservoir system is dynamic and sediment type, time consolidating and previous scour events vary, it is not known precisely when scour occurs.
The LSRWA modeling efforts indicate that the storm scour threshold, which is defined here as the flow, on average, when mass bed erosion begins, transporting sediment out of the reservoir system to Chesapeake Bay, is 400,000 cfs which represents a 4- to 5-year return flow event.

Storms and the Reservoir in a Watershed Context

When a large storm event occurs (flows exceeding the 400,000-cfs scour threshold), the sediment load entering Chesapeake Bay potentially originates from two sources: the Susquehanna River watershed (including scour from the two upstream reservoirs) and scour from Conowingo Reservoir. It is estimated that bed scour from the upstream reservoirs may range from one-fourth to one-half of the total scour load. Table 4-7 provides USGS calculations (conducted as part of the LSRWA effort) of total sediment transported through the lower Susquehanna River system along with the sediment load contribution of each source (see Appendix A, Attachment A-1, for more details on this computation). This methodology allowed the team to look at a variety of flows to compare scour to watershed loads.

Table 4-7. Scour and Load Predictions for Various Flows in Conowingo Reservoir

Streamflow (cfs)	Recurrence Interval (years)	Percent Chance of Flow Event per Year	Predicted Sediment Scour Range (million tons)[1]	Predicted Total Sediment Load Range (million tons)[2]	Percent Scour to Total Load Range
1,000,000	60	1.7	10.5 - 15.5	27.1 - 31.1	39 - 49
900,000	40	2.5	6.6 - 11	21.8 - 26.2	30 - 42
800,000	25	4	4.5 -7.5	17.2 - 20.2	26 - 37
700,000	17	5 .9	3.5 - 6	13.1 - 15.6	27 - 38
600,000	10	10	1.8 - 4	7.9 - 10.1	22 - 40
500,000	5.7	17.5	1 - 3	4.9 - 6.9	20 - 42
400,000	4.8	21	0.5- 1.5	2.4 - 3.4	21 - 44
300,000	1.9	52	0 – 0.5	0.5 – 1.5	0 - 33

Notes: [1] Predicted scour from USGS scour equation, bathymetry results, and literature estimates.
[2] Predicted total load based on regression equation, bathymetry results, and literature estimates.

The results of this study indicate that bed scour from Conowingo Reservoir and the upper two reservoirs comprised an average of approximately 30 percent (average of the mean of the ranges for each selected flow) of the total loads entering the Bay during an event up to 800,000 cfs (recurrence interval of less than 40 years). The remaining load was estimated to be from the watershed. The study data indicate that as flow increases the bed sediment scour load becomes an increasingly higher proportion of the total sediment load. On average, flows above 800,000 cfs produced a scour load that comprised about 30 to 49 percent of the total load entering the Bay. Flows of this magnitude are rare with a recurrence interval of 40 years or more.

It is important to note that there will be a point where the sediment transported into the reservoirs will have a limited ability to scour based on the transport capacity and the ability of the reservoir bed to erode. As the bed scours, the reservoir becomes deeper and the bed shear becomes less. Also, the deeper bed layers will have a higher critical bed shear stress for erosion. So at some point, the bed will either not erode, or the erosion rate will be very low (further explanation on this can be found in Appendix B). More data collection and sediment transport modeling would be required to further understand this concept and when this maximum capacity for reservoir bed scour would occur.

The LSRWA AdH modeling effort also evaluated the contribution of reservoir bed scour to the total load. This methodology allowed the team to have a more detailed look at one scour event that was recent (Tropical Storm Lee) under various bathymetries (1996, 2008, 2011, and "full"). The AdH model estimated the impact of Tropical Storm Lee (approximately a 709,000-cfs event for the Conowingo peak daily discharge) on the total load passing through the Conowingo Dam. This evaluation used the model simulation period of 2008-11 hydrology. Results are summarized in Table 4-8.

For all four reservoir bathymetry simulations, Tropical Storm Lee provided about 65 to 66 percent of the total sediment outflow load (Conowingo reservoir bed scour and watershed loads) for the 4-year (2008-11) simulation. As an example, for the 2011 bathymetry, the Tropical Storm Lee load was about 14.5 million tons of the total sediment outflow load of 22.3 million tons.

Regarding the contribution of Conowingo Reservoir bed scour to the total load to the Chesapeake Bay during a storm event, under 2011 bathymetry conditions, the sediment scour load (from the reservoir behind Conowingo Dam) during Tropical Storm Lee comprises about 20 percent of the Tropical Storm Lee total sediment load (about 3.0 million tons of the 14.5 million tons). This includes scour from the upper two reservoirs and loads from the rest of the Susquehanna River watershed. Similar results were calculated for the "full" Conowingo Reservoir bathymetry. These results imply that the Susquehanna River watershed located above the Conowingo Dam (including the two upstream reservoirs) provided 80 percent of the load during Tropical Storm Lee, with the remaining 20 percent scoured from the sediment trapped behind Conowingo Reservoir.

Table 4-8. Summary of Modeling Simulations of Various Conowingo Bathymetries [1]

Bathymetry [2]	Sediment Outflow Load [3] (million tons)	Total Lee Sediment Outflow Load [4] (million tons)	Lee Percent of Sediment Outflow Load	Conowingo Sediment Scour Load [5] (million tons)	Conowingo Sediment Scour Percent of Lee
1996	20.3	13.1	65	1.8	14
2008	21.9	14.4	66	2.9	20
2011	22.3	14.5	65	3.0	21
Full Condition	22.2	14.6	66	3.0	21

Notes: [1] These scenarios utilized the 2008-11 hydrologic period which includes the Tropical Storm Lee event.

[2] Bathymetry data collected from each of these years were utilized as input parameters to AdH model. Full condition was calculated utilizing USGS bathymetry data from 2008 (Langland, 2009) and Gomez and Sullivan Engineers bathymetry data from 2011 (URS and GSE, 2012b). This calculation is described in Appendix A.

[3] Total sediment outflow loads that flowed over Conowingo Dam into Chesapeake Bay (includes bed scour load from each of the three reservoirs and loads from the watershed over 2008-11 hydrologic period.

[4] Includes watershed and Conowingo Reservoir scoured sediment load to Chesapeake Bay during Tropical Storm Lee

[5] Scour load from Conowingo Reservoir bed to Chesapeake Bay.

As for the contribution of reservoir bed scour to the total load during a longer hydrologic period (including flows large enough to scour and low flows), during the hydrologic period of 2008-11 under 2011 bathymetry, scour from Conowingo Reservoir was estimated to be 3.0 million tons comprising 13 percent of the total load to the Chesapeake Bay (estimated at 22.3 million tons), with 87 percent of the load originating from the watershed (includes scour from upper two reservoirs), as shown in Table 4-8. The inflowing sediment rating curve for the AdH simulations was increased to a maximum scour potential for the upper two reservoirs during Tropical Storm Lee of approximately 4 million tons (thus, the total amount of scour from all three reservoirs).

The transport capacity of Conowingo Reservoir during a large flow event is strongly influenced by the sediment load entering into the system which could impact the transport capacity and bed scour and subsequent sediment transport through the reservoirs to the upper Chesapeake Bay. The data in Table 4-8 reflect this estimated maximum inflow. It is estimated from additional AdH simulations that the percentage of Conowingo Reservoir bed scour load to the total Tropical Storm Lee load can potentially vary from 20 to 30 percent based on the assumption of inflow load.

Sediment Transport, Storm Effects, and Scour Summary

In summary, all three lower Susquehanna River reservoirs have reached dynamic equilibrium. Long-term sediment trapping in the reservoir system is much reduced compared to historical trapping. Nonetheless, the reservoirs still have sediment storage capacity under lower flow conditions and will continue to change the timing and the characteristics of the sediment and associated nutrient loads discharged to the Chesapeake Bay. Periodic, large storms will continue to scour and transport large quantities of reservoir bed sediment to Chesapeake Bay.

Sediment and nutrient loads from the Susquehanna River watershed are being reduced and will continue to be reduced as the WIPs are fully implemented (see Table 4-6 for the historical trends in sediment loads; USEPA, 2010a). Storms are the main driver of sediment transport loads to the Chesapeake Bay. About 27 days of the 47-year record (1967-2013), or 0.2 percent of the time, had average daily flows of 400,000 cfs or more. The 400,000-cfs flow represents the flow on average when mass scouring occurs, transporting sediment out of the reservoir system to the Chesapeake Bay. However, 36 to 56 percent of the total sediment load (includes watershed inflow and reservoir bed scour) is estimated to have come from these storm events during the period of record (Appendix B).

When a significant storm occurs within the Susquehanna River basin, the majority of the sediment load discharged from Conowingo Reservoir originates from the watershed (watershed drainage and scour from upstream reservoirs) versus scour of watershed sediments stored in the Conowingo Reservoir. It must be noted that the track, duration, and timing of the storm varies the amount of loads from the watershed and scour from behind the reservoirs, including Conowingo. More detailed discussions on storm scouring, dynamic equilibrium, and sediment transport are provided in Appendices A and B.

4.2.3 Environmental Implications

This section broadly summarizes the environmental implications of the reservoirs in a dynamic equilibrium state, including storm scour, as well as the effects of currently planned watershed management measures in the Bay. The CBEMP model was the primary tool utilized to estimate these impacts and was linked to AdH/HEC-RAS outputs for various scenarios. The model suite is based on a hydrologic record of 1991-2000 which includes one storm event that had a flow that exceeded the LSRWA calculated storm scour threshold of 400,000 cfs (the 1996 winter storm "Big Melt" event). Section 3.3 summarized the model suite and its application for use in the LSRWA effort. Appendices C and D provide additional details on the modeling efforts conducted to estimate environmental implications of the reservoirs in a dynamic equilibrium state, including storm scour, as well as the effects of currently planned watershed management measures in the Chesapeake Bay.

Table 4-9, which expands on Table 3-1, is a summary table of the major baseline and future conditions scenarios and the modeling results associated with these scenarios. The scenarios' estimated environmental effects represent conditions of no additional management activities in the Bay watershed above what is currently planned or ongoing sediment and associated nutrient load management activities. Timing of the scour event has varied effects on water quality and designated uses, as shown in Scenario 6. Scenario 6 includes several model runs evaluating scour events occurring in the summer, fall, and winter. These model scenarios were combined into one column to aid with comparison of the environmental effects of the timing of scour events.

For each scenario, Table 4-9 includes water quality characteristics and the designated uses that are most closely aligned with these characteristics. The rows presented in the "characteristics" column of Table 4-9 (and subsequent Table 5-7) provide a means to evaluate modeled environmental impacts of the scenarios upon the five designated uses of Bay waters (Habitats and species associated with the five designated uses are described in Section 3.3.6.); in particular, estimates of the impacts of sediment and nutrients on light attenuation, SAV, chlorophyll, and DO are highlighted. Table 4-9 also includes results of the water quality criteria assessment procedure and provides estimated changes in attainment of water quality standards developed and adopted to protect Bay living resources. Results for the scenarios will be discussed in detail in the following sections.

Potential impacts of excess sediment from the lower Susquehanna River to SAV beds and oyster beds are of particular concern because these both occur on the Bay bottom and comprise highly valued Bay habitats. The Chesapeake Bay Environmental Model Package (CBEMP) utilized for this assessment has state-of-the-art capability to predict a variety of Bay water quality parameters under varying environmental scenarios; however, the CBEMP is not refined enough to accurately predict the response of SAV, oysters, and other living resources. Numerous interacting living and non-living variables not incorporated into the CBEMP at this time limit use of the CBEMP for this purpose.

Accordingly, in order to provide consideration of effects of various baseline and future conditions upon SAV and oysters, it was necessary to review the historical record and findings of previous studies to supplement water quality modeling output from this assessment. This information is included below. Additionally, substantial background on environmental history, status, trends, and important stressors controlling Bay SAV beds and oyster beds is presented in Appendix K.

Table 4-9. LSRWA Major Baseline and Future Conditions Scenarios and Result Summary

Characteristics (Applicable Designated Use)	**SCENARIO 1** What is the system's current (existing) condition?	**SCENARIO 2** What is the system's condition with WIPs in full effect and reservoirs are trapping at current conditions?	**SCENARIO 3** What is the system's condition when WIPs are in full effect, reservoirs are trapping at current conditions and there is a winter scour event?	**SCENARIO 4** What is the system's condition when WIPs are not in effect, reservoirs have all reached dynamic equilibrium and there is a winter scour event?	**SCENARIO 5** What is the system's condition when WIPs are in full effect, the reservoirs have all reached dynamic equilibrium and there is a winter scour event?	**SCENARIO 6** What is the system's condition if WIPs are in full effect, reservoirs are trapping at current conditions and a scour event occurs during summer, fall, or winter?
General Water Quality Effects (All designated uses)	Conditions are usually worst during wet periods of high loading and stratification. Results emphasize summer average (June-August) during wet year (1996).	Predicted WQ improvements over Scenario 1 with WIPs in place. Hypoxia reduced, less anoxic conditions, DO levels increase, and chlorophyll *a* concentrations and light attenuation decrease.	DO would be depressed in comparison to WIPs in place with no scouring event (Scenario 2). Storm timing is important. Winter scour has minimal impacts to WQ by summer.	Scour under "full" conditions was similar to scour with current conditions (2008 bathymetry) indicating that the reservoirs were essentially "full" by 2008. When flow is below scour threshold, full-reservoir conditions are similar to non-full conditions. Sediment settles within Conowingo, and loads from the reservoir and Bay water quality are the same, as long as there is no scour event. When a scour event takes place, more material is scoured under reservoir-full conditions than not full.	When flow is below scour threshold, water quality conditions are similar to those predicted for the WIPs in full effect and reservoir trapping (Scenario 2). With scour, conditions are similar to #3 scenario since current conditions in the reservoir are not far from dynamic equilibrium.	June storm has the most deleterious effect on summer water quality. October storm has the least deleterious effect, followed by the January storm.
Dissolved Oxygen (DO) (Migratory fish and spawning nursery; open-water fish and shellfish; deep-water seasonal fish and shellfish; deep-channel seasonal refuge)	Bottom-water hypoxia (DO < 1 mg/L) for a 37-mile reach extending 50 to 87 miles below Conowingo Dam Bottom waters in this reach exhibit complete anoxia on occasion.	Bottom-water hypoxia (DO < 1 mg/L) in a 12-mile reach extending 50 to 87 miles below Conowingo Minimum summer-average DO is ~0.5 mg/L. Occasional excursions to 0 mg/L (anoxia) are still predicted.	The additional loads from the scour event depress summer-average, bottom-water DO by 0.05 mg/L for roughly 37 miles along the channel centerline in the summer following the storm, in comparison to Scenario 2. DO values vary. The effect is diminished in shallow areas relative to deeper areas. There are freshwater flow pulses and meteorological events which cause the effects on DO to vary over the course of a season.	Summer-average DO is depressed by 0.04 mg/L along a 62-mile reach of Bay bottom, in comparison to Scenario 1 Examination of the marginal effects on DO can be deceptive: in the region of the worst hypoxia, at the worst location, under existing conditions, average DO is almost 0 mg/L and it can't go much lower. Therefore, DO isn't depressed much because there is nowhere to go. Elsewhere, DO might average 0.5 mg/L so it can go down by 0.5. The greatest magnitude of depression is not where DO is worst, on average.	If a scour event occurs, average bottom DO concentration is depressed by 0.05 mg/L for 37 to 50 miles along the channel centerline, in comparison to Scenario 2. With WIPs in place, summer-average DO is higher than under 2010 conditions. Since summer-average DO is higher, it can go lower before hitting 0 mg/L, so the magnitude of depression can be worse for the WIPs than for 2010.	DO response to a storm is two-phased – an initial sharp decrease as the storm passes and then a secondary DO depression following the storm. Following a June storm, the two phases are difficult to separate. Summer-average bottom-water DO depression at the head of the trench is 0.4 mg/L or more. January storm DO depression (same location as June storm) is 0.2 mg/L. October storm depression is 0.1 mg/L. Spatial extent of the storm influence is large and DO depression is readily detected in the lower portion of the Potomac River which joins Chesapeake Bay roughly 120 miles below Conowingo Dam.

Characteristics (Applicable Designated Use)	**SCENARIO 1** **What is the system's current (existing) condition?**	**SCENARIO 2** **What is the system's condition with WIPs in full effect and reservoirs are trapping at current conditions?**	**SCENARIO 3** **What is the system's condition when WIPs are in full effect, reservoirs are trapping at current conditions and there is a winter scour event?**	**SCENARIO 4** **What is the system's condition when WIPs are not in effect, reservoirs have all reached dynamic equilibrium and there is a winter scour event?**	**SCENARIO 5** **What is the system's condition when WIPs are in full effect, the reservoirs have all reached dynamic equilibrium and there is a winter scour event?**	**SCENARIO 6** **What is the system's condition if WIPs are in full effect, reservoirs are trapping at current conditions and a scour event occurs during summer, fall, or winter?**
Chlorophyll Concentration (CHL) (Shallow-water bay grasses; open-water fish and shellfish)	Greatest average CHL concentrations (more than 10 µg/L) occur in surface waters of 37-mile reach extending 50 to 87 miles below Conowingo Dam.	Surface CHL concentration in this reach declines by 3 µg/L, relative to the current condition, to ~7 µg/L.	CHL (summer average) increases by 0.3 µg/L in the worst areas, over Scenario 2. The effect on CHL is spatially extensive. An increase of 0.2 µg/L or more extends 93 miles along the Bay channel centerline in the summer following the storm.	CHL (summer average) increases by 0.2 µg/L for a 62-mile reach of the Bay axis.	CHL increases by 0.3 µg/L in the 12-mile reach where CHL is maximum. CHL increases by 0.2 µg/L for 75 miles or more along the Bay channel centerline. It is possible for CHL to increase (worsen) with WIPs in place due to the fact that with WIPs in place the nutrient limitation of algae is more stringent; therefore, the added nutrients from the scour event can stimulate more chlorophyll.	CHL response to a storm is two-phased – an initial decline as the storm passes and then an increase, stimulated by the nutrients introduced by the storm. January storm, spring bloom, CHL increases as much as 5 µg/L, although the bloom largely precedes the critical SAV-growing season. In the summer, subsequent to the storm, the increase in CHL concentration is between 0.5 and 1 µg/L over a large reach of the Bay (to Potomac River). October storm – CHL increases by 0.5 µg/L. June storm introduces nutrients at the beginning of the seasonal peak in primary production; summer-average CHL concentration increases as much as 3 µg/L.
Light Attenuation (KE) (Shallow-water bay grasses)	Greatest computed KE, ~1.9/m, occurs immediately downstream of the Conowingo outfall and declines rapidly with distance away from the dam. A secondary peak, 1.2/m, occurs downstream, in the turbidity maximum located 25 miles below Conowingo Dam. Guidelines indicate KE should not exceed 1.5/m for survival of SAV at the 1-meter depth.	KE just below Conowingo declines by 0.5/m, relative to the current condition (Scenario 1), to 1.4/m and by 0.4/m to 0.8/m within turbidity maximum	Summer-average KE increases by 0.01/m over Scenario 2. Additional sediment disperses and settles before SAV-growing season (April-October.); KE increase is attributed to phytoplankton stimulated by scoured nutrient load. Sediment may be subject to resuspension; the January scour effect on summer KE is negligible. Nutrients associated with the storm event are persistent into summer, while sediment effects are short-lived. Effects of scoured nutrients diminish with time but are visible five summers following the scour event.	Impact of the winter scour event on summer KE is minimal (less than 0.02/m increase).	KE increase is ~0.01/m or less since additional sediment disperses and settles before summer. The minimal KE effects are almost identical to predictions with reservoirs still trapping. KE impacts are about the same if there is a winter storm whether the reservoir is "full" or at dynamic equilibrium, which is expected since the sediment scoured has ample time to settle before the critical SAV growth period.	Sediment loads from the June storm remain in suspension during the subsequent summer months resulting in KE increase of 2/m to 4/m (from Scenario 2) for a reach extending 37 miles downstream of the dam. Sediment loads from the January and October storms are dispersed and settle long before the subsequent SAV-growing season and have negligible effect on KE during this period.

Characteristics (Applicable Designated Use)	**SCENARIO 1** **What is the system's current (existing) condition?**	**SCENARIO 2** **What is the system's condition with WIPs in full effect and reservoirs are trapping at current conditions?**	**SCENARIO 3** **What is the system's condition when WIPs are in full effect, reservoirs are trapping at current conditions and there is a winter scour event?**	**SCENARIO 4** **What is the system's condition when WIPs are not in effect, reservoirs have all reached dynamic equilibrium and there is a winter scour event?**	**SCENARIO 5** **What is the system's condition when WIPs are in full effect, the reservoirs have all reached dynamic equilibrium and there is a winter scour event?**	**SCENARIO 6** **What is the system's condition if WIPs are in full effect, reservoirs are trapping at current conditions and a scour event occurs during summer, fall, or winter?**
Sediment Loads (Shallow-water bay grasses; migratory fish spawning and nursery; open-water fish and shellfish)	CBEMP calculated average sediment load over the 10-year period at 3,370 tons/day. Maximum daily load is 200,000 tons/day.	CBEMP calculated average sediment load over the 10-year period) at 2,540 tons/day. Maximum daily load is 149,000 tons/day.	CBEMP calculated - Scour event adds 2.6 million tons of sediment in addition to watershed loads over a 4-day period.	CBEMP calculated -Scour event adds 2.6 million tons of sediment in addition to watershed loads, over a 4-day period.	CBEMP calculated- Scour event adds 2.6 million tons of sediment in addition to watershed loads, over a 4-day period.	CBEMP calculated 3.1 million tons sediment over 7 days. This includes watershed and scour loads.
Nutrient Loads (All designated uses)	Nitrogen: The average TN load is 163 tons/day. Of this, 69.3 tons/day are particulate (organic) nitrogen associated with sediment. Phosphorus: The average TP load is 6.9 tons/day. Of this, 5.7 tons/day are particulate phosphorus associated with sediment.	Nitrogen: The average TN load is 115 tons/day. Of this, 50.8 tons/day are particulate (organic) nitrogen associated with sediment. Phosphorus: The average TP load is 5.2 tons/day. Of this, 4.2 tons/day are particulate phosphorus associated with sediment.	Nitrogen: Scour event adds 7,800 tons of particulate (organic) nitrogen in addition to watershed loads over a 4-day period. Phosphorus: Scour event adds 2,600 tons of particulate phosphorus in addition to watershed loads over a 4-day period.	Nitrogen: Scour event adds 7,800 tons of particulate (organic) nitrogen, in addition to watershed loads over a 4-day period. Phosphorus: Scour event adds 2,600 tons of particulate phosphorus, in addition to watershed loads over a 4-day period. The amount scoured is virtually equal to the amount scoured under existing bathymetry, indicating dynamic equilibrium.	Nitrogen: Scour event adds 7,800 tons of particulate (organic) nitrogen in addition to watershed loads, over a 4-day period. Phosphorus: Scour event adds 2,600 tons of particulate phosphorus in addition to watershed loads over a 4-day period. The amount scoured is not affected by WIPs.	Nitrogen: Over 7 days, the simulated storm event adds 14,300 tons TN, including watershed and scour loads. Phosphorus: Over 7 days, the simulated storm event adds 3,180 tons, including watershed and scour loads.

Characteristics (Applicable Designated Use)	**SCENARIO 1** What is the system's current (existing) condition?	**SCENARIO 2** What is the system's condition with WIPs in full effect and reservoirs are trapping at current conditions?	**SCENARIO 3** What is the system's condition when WIPs are in full effect, reservoirs are trapping at current conditions and there is a winter scour event?	**SCENARIO 4** What is the system's condition when WIPs are not in effect, reservoirs have all reached dynamic equilibrium and there is a winter scour event?	**SCENARIO 5** What is the system's condition when WIPs are in full effect, the reservoirs have all reached dynamic equilibrium and there is a winter scour event?	**SCENARIO 6** What is the system's condition if WIPs are in full effect, reservoirs are trapping at current conditions and a scour event occurs during summer, fall, or winter?
Deep-Channel DO (Dissolved Oxygen) Water Quality Standard Achievement for TMDL (Deep-channel seasonal refuge)	There is 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. This and other areas of nonattainment in the deep channel amounted to more than half of the deep-channel habitat in the Bay.	Complete attainment of the deep-channel DO standard was estimated.	An estimated increase of 1% nonattainment in segments CB4MH, EASMH and CHSMH over Scenario 2.	An increase of 1% nonattainment above Scenario 1 in segments CB4MH and PATMH.	An increase of 1% nonattainment over Scenario 2 was estimated in segments CB4MH, EASMH, and CHSMH.	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. The June event scenario had an estimated increase in deep-channel DO nonattainment of 1%, 4%, 8%, and 3% in segments CB3MH, CB4MH, CHSMH, and EASMH, respectively when compared to the No Storm Scenario. The January storm condition had an estimated increase in deep-channel DO nonattainment of 1%, 1%, 2%, and 2% in segments CB3MH, CB4MH, CHSMH, and EASMH, respectively, when compared to the No Storm Scenario. For the October high-flow event, the estimated deep-channel DO saw increased nonattainment of 2% and 1% in CHSMH and SEVMH (Severn River), respectively, compared to the No Storm Scenario.

Characteristics (Applicable Designated Use)	SCENARIO 1 What is the system's current (existing) condition?	SCENARIO 2 What is the system's condition with WIPs in full effect and reservoirs are trapping at current conditions?	SCENARIO 3 What is the system's condition when WIPs are in full effect, reservoirs are trapping at current conditions and there is a winter scour event?	SCENARIO 4 What is the system's condition when WIPs are not in effect, reservoirs have all reached dynamic equilibrium and there is a winter scour event?	SCENARIO 5 What is the system's condition when WIPs are in full effect, the reservoirs have all reached dynamic equilibrium and there is a winter scour event?	SCENARIO 6 What is the system's condition if WIPs are in full effect, reservoirs are trapping at current conditions and a scour event occurs during summer, fall, or winter?
Deep-Water DO (Dissolved Oxygen) Water Quality Standard Achievement for TMDL (Deep-water seasonal fish and shellfish)	There is widespread nonattainment of TMDL of deep-water DO. Estimated nonattainment of 11% in CB4 mainstem, 2% in Eastern Bay, and 11% in lower Chester River.	Complete attainment of the deep-water DO standard was estimated.	An estimated increase of 1% nonattainment over Scenario 2 was estimated in segments CB4MH and CB5MH.	An estimated increase of 1% nonattainment over Scenario 2 was estimated in segments CB3MH and PAXMH.	An estimated increase of 1% nonattainment over Scenario 2 was estimated in segments CB4MH and CB5MH.	Generally, a June high-flow event has the most detrimental influence on deep-water DO followed by a storm of the same magnitude in January, and then October. A "no large scour event" has the highest levels of deep-water DO attainment. The June event had an estimated increase in deep-water DO nonattainment of 1% in segments CB4MH, CB5MH, and SEVMH, when compared to the No Storm Scenario. Nonattainment levels of the January storm were estimated to be 1% in segments CB4MH, CB5MH, and SEVMH, when compared to the No Storm Scenario. The October high-flow event saw increased nonattainment of 1% in segment SEVMH, compared to the No Storm Scenario.
Open-Water DO Water Quality Standard Achievement for TMDL (Open-water fish and shellfish)	Widespread, but not complete attainment of the open-water DO standard was estimated.	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.
SAV Clarity Water Quality Achievement for TMDL (Shallow-water bay grass)	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.	Complete attainment was estimated.
CBEMP Modeling Run Number [1]	LSRWA-4	LSRWA-3	LSRWA-21	LSRWA-18	LSRWA-30	Summer = LSRWA-24 Fall = LSRWA-25 Winter = LSRWA-21

Notes: [1] ERDC/EPA-CBPO ran roughly 30 modeling runs utilizing CBEMP. Modeling runs were denoted by "LSRWA-number." Only major modeling runs are reported and summarized in this main report. Appendices C and D provide further detail on other runs. Values in Appendix C utilize units of metric tons; these values have been converted to U.S. tons for consistency with other parameters. The conversion is 1 ton = 0.9072 metric tons.

SAV Implications

The CBEMP does not capture several physical and biological factors affecting SAV populations at this time. Sandy sediments, even if only a thin layer on top, have an important effect on SAV bed success. Bottom sediment is not mapped at a scale adequate to assess this at a Bay-scale (Palinkas and Koch, 2012). Bottom disturbance by cownose rays and grazing by mute swan, an exotic waterfowl species, affects SAV beds (Orth et al., 2010). Populations of these organisms and their affects upon SAV are not included in the CBEMP.

Effects of future storms on SAV would produce different SAV responses as a function of storm character (timing, strength, duration, wet year versus dry year). This presents challenges beyond even predicting SAV response under non-storm conditions as described above. The CBEMP models water clarity impacts produced by storms over time, and consequent indirect effects of that on SAV beds can be considered. However, the CBEMP does not model direct storm wave damage to above or below ground SAV tissue, nor direct impacts of excess storm bottom erosion and deposition upon SAV.

Direct effects of storms could differ among the alternative scenarios if altered wave energy, currents, or water levels in the vicinity of SAV beds occurred; these conditions are discussed in Table 4-10. Additionally, direct effects on SAV beds from storms could differ among alternative scenarios during the SAV-growing season if SAV differentially resist erosion or promote deposition at the bed and vicinity.

Extreme storms cause significant indirect damage to SAV from extended reduced water clarity from suspended sediments if they occur during times of year when SAV has substantial shoot biomass. Conversely, storms in the winter or outside of the SAV-growing season when SAV lacks or has minimal aboveground shoot biomass have minimal impact on SAV (Wang and Linker, 2005). Storms produce long-term turbidity indirectly via delivery of excess nutrients from watershed

Table 4-10. Conditions Controlling Storm Effects on SAV Beds

Conditions at SAV Bed	Specific Factors	Differences Among Scenarios?	Cause of Difference
Wave Energy	Water levels, depths, channel alignment, fetch	No	Not Applicable
Currents	Volume of water passing through, channel/shoal position	No	Not Applicable
Bottom Resistance to Erosion	Sediment grain-size, shoal positions	Yes	Deposition of sediment released from Conowingo
Vegetation Extent and Density	Wave dampening, inducing sediment deposition, resiliency following storm	Yes	Pre- and post-storm Bay water clarity produced by nutrient releases from Conowingo

sources, as well as recycling nutrients from in-Bay sources, that stimulate phytoplankton production and promote eutrophication. Indirect impacts upon water clarity from storms can last for months to years (CBP STAC, 2007, as well as the results of this study). Indirect effects of storms could also differ based on SAV bed health, size, and density. Healthier, larger, and denser beds would have greater capacity for resiliency following storms by virtue of greater SAV biomass and numbers of propagules facilitating more rapid recovery.

Any alternative management scenario which would purposefully release substantial quantities of sediment from Conowingo Dam before or during storms could potentially alter patterns of erosion and deposition and affect the character of the Susquehanna Flats and adjacent areas of the upper Bay.

Oyster Implications

The CBEMP has the capability to forecast water quality (including salinity) changes within potential oyster habitat, but doesn't model oyster population responses to water quality changes. Accordingly, it is not possible to forecast oyster population changes or accompanying bed area changes utilizing the CBEMP alone.

Today, the mean depth of existing oyster habitat in Maryland is about 14 feet, with a range of 5 to 32 feet (USACE et al., 2009). Seasonal hypoxia/anoxia caused by anthropogenic nutrient loading has reduced quality of deeper waters as oyster habitat. In an effort to prevent exposure to anoxic waters, the Chesapeake Bay Oyster Management Plan suggests that reefs be constructed at depths less than 20 feet (CBP, 2004). Oysters are harvested commercially in Maryland, but regulations limit the harvests and are designed to maintain oyster populations.

Generally, oysters need salinities greater than 5 ppt to grow. Low-salinity conditions restrict oyster beds from occurring within about 20 miles of the Susquehanna River, and limit their occurrence in headwater tributaries throughout the Bay where low-salinity conditions occur. Oysters in the lowermost section of the upper Chesapeake Bay are vulnerable to the effects of freshets (influx of fresh water typically from rain events). Large volumes of fresh water from Hurricane Agnes in 1972 and Tropical Storms Lee and Irene in 2011 caused substantial oyster mortality in this region (CRC, 1974; MDNR, 2012).

Oyster larvae require hard surfaces on which to settle and grow. On healthy oyster beds, oysters can produce new shell substrate at a rate that matches Bay sedimentation rates. In stressed oyster communities, sediment can cover oyster reefs and other hard-bottom substrates, limiting oyster recruitment. Due to current stresses, oysters fail to produce substantial shell material, therefore natural sedimentation has dramatically reduced the amount of hard-bottom habitat available to oysters in the Bay (Smith et al., 2003). While the volumes of sediment entering the Bay from anthropogenic causes is greater today than under pre-European settlement conditions, this excess sediment tends to settle out in the Susquehanna Flats, headwater tributary, and deepwater settings (Colman et al., 2002; Colman and Bratton, 2003; and USGS, 2003) where oysters are largely absent. Tropical Storms Lee and Irene deposited substantial sediment in the Susquehanna Flats (Palinkas et al., 2014). However, the storms appear to have deposited minimal sediment on oysters in the upper Bay, and excess sediment was not identified as a cause of oyster mortality (MDNR, 2012).

Current Conditions and Conditions with WIPs Implemented

This section summarizes the results of Scenario 1 and Scenario 2 from Table 4-9. Scenario 2 represents conditions when all management actions called for in the seven Chesapeake Bay watershed jurisdictions' WIPs are fully implemented (USEPA, 2010a), there is no net scouring of the Conowingo Reservoir, and the reservoir is at 1991-2000 trapping levels. The only difference between Scenario 1 and Scenario 2 is that Scenario 2 is simulated with WIPs fully implemented while Scenario 1 simulates the nonpoint and point source controls estimated to be operational in 2010.

As such, Scenario 2 estimates the water quality improvements due to full WIP implementation, as compared to the 2010 conditions simulated by Scenario 1. Under Scenario 2 conditions, all the living resource-based water quality standards in the tidal Chesapeake water are met. Nevertheless, under the simulated conditions of Scenario 2, the Chesapeake Bay still experiences periods of anoxia in some places (as allowed by the water quality standards), phytoplankton "blooms" in the spring and summer, and places and times when light attenuation exceeds water quality criteria (see Appendix C for more details).

Regarding episodic anoxia (defined here as a DO concentration < 1 g/m^3), Scenario 2 shows that there are times and places in the Bay where these conditions currently exist. The magnitude and duration of anoxia varies due to changing loads from the watershed throughout the year, salinity, and a variety of other factors (see Appendix C for additional details).

Phytoplankton have a key influence, on Bay DO and water clarity. Oxygen consumption associated with the decay of organic carbon fixed by phytoplankton is the primary mechanism for the occurrence of bottom-water hypoxia. In addition, light attenuated by the chlorophyll pigment in phytoplankton and by particulate organic matter contributes to poor water clarity (see Appendix C for more information on this topic).

In Chesapeake Bay, phytoplankton exhibit two recurrent annual phenomena of high biomass, i.e., blooms. The first is the spring diatom bloom which occurs roughly from January through May. This bloom is characterized by high chlorophyll concentration, but low primary productivity. The second bloom period occurs during the period of maximum productivity which takes place in summer. A third smaller bloom often occurs in the autumn as well. Although the warmer, summer months are more biologically productive than spring, the summer bloom chlorophyll concentration may actually be lower than during the spring diatom bloom. In the summer, biological production is high, but loss from predation and respiration is high as well. The two phytoplankton intervals in spring and summer coincide with the SAV-growing season (April-October) for species that occupy the upper Chesapeake Bay (see Appendix C for more details).

Light attenuation by chlorophyll pigment, fixed (mineral) solids, volatile (organic, which are living or previously living) solids, and colored dissolved organic matter all contribute to light attenuation in Chesapeake Bay. Fixed (mineral) solids originate primarily in the watershed or from shoreline erosion. The major source of volatile solids, however, is primary production in the water column rather than external loading (loads from the shoreline or watershed). The period of greatest light attenuation in the upper Chesapeake Bay coincides with the period of greatest runoff, usually during winter and spring (see Appendix C for additional details).

Chesapeake Bay Dissolved Oxygen Water Quality Standards

To illustrate how the Bay's water quality responds to changes in nutrient and sediment loads, attainment results for Scenarios 1 and 2 (from Table 4-9) are tabulated in Tables 4-11 and 4-12. These tables illustrate the percent nonattainment of the deep-channel DO water quality standard (Table 4-11) and deep-water DO water quality standard (Table 4-12) for the two scenarios. The assessments of Chesapeake Bay DO water quality standard attainment in Tables 4-11 and 4-12 provide background and context for the LSRWA scenarios presented in Table 4-9. Figure 3-7 depicts the 92 delineated Bay segments.

The deep-channel DO has a criterion of at least 1 mg/L DO concentration which is required to be met at all times (USEPA, 2003a). All of the Chesapeake Bay segments that have a deep-channel designated use are listed in Table 4-11, along with the attainment results for the two scenarios (see Appendix D for more explanation of this analysis).

Deep water is defined as the region of the water column within the pycnocline and above the deep-channel designated use (see Figure 3-8 for an illustration of these designated use zones). The deep-water DO criterion is a 30-day mean of 3 mg/L (EPA, 2003a). All of the Chesapeake Bay segments that have a deep-water designated use are listed in Table 4-12, along with the attainment results for the two scenarios (see Appendix D for additional details).

When the seven watershed jurisdictions' WIPs are fully implemented, nutrient and sediment loads will decrease, and the level of estimated nonattainment of the Chesapeake Bay water quality standards, quantified in red font, is expected to decrease as illustrated in Tables 4-11 and 4-12. Attainment of the deep-channel and deep-water DO criteria is highlighted in green in the two tables. An entry of 0 indicates complete attainment of the applicable criterion. Deep-channel and deep-water DO criteria are estimated to reach full attainment under Scenario 2 (full WIP implementation) for all deep-channel and deep-water Bay segments, as shown in Tables 4-11 and 4-12. Appendix D provides further detail on the attainment analyses.

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 modeling scenarios. Deep-channel DO and deep-water DO were the most sensitive water quality standards, that is, the standards most likely to go into nonattainment with increases in sediment and the associated nutrient loads (see Appendix D for further explanation of this topic).

Table 4-11. Estimated Deep-Channel Dissolved Oxygen Nonattainment for Key Scenarios

Chesapeake Bay Segment	State	Estimated Percent Nonattainment for Dissolved Oxygen in the Deep-Channel Segments[1]	
		Scenario 1 WIPs Not Implemented [2]	Scenario 2 WIPs Fully Implemented [3]
CB3MH	Maryland	5%	0%
CB4MH	Maryland	23%	1.5%
CB5MH	Both	0%	0%
CBSMH	Maryland	28%	15%
EASMH	Maryland	14%	1.1%
PATMH	Maryland	18%	0%
POTMH	Both	0%	0%
RPPMH	Virginia	0%	0%

Notes: [1] The scenarios were run on the Chesapeake Bay WSM (Phase 5.3.2) and utilized the 1991-2000 hydrologic period; the 2010 Chesapeake Bay TMDL critical period of 1993-95 was used (see USEPA, 2010a, and Appendix D of this report).

[2] Scenario 1 included a 10-year annual average load of 132,000 tons (263 million pounds) of TN, 9,700 tons (19.4 million pounds) of TP, and 4.18 million tons (8,360 million pounds) of total suspended solids; CBEMP model scenario was LSRWA4.

[3] Scenario 2 included a 10-year annual average load of 95,500 tons (191 million pounds) of TN, 7,500 tons (15 million pounds) of TP, and 3.34 million tons (6,675 million pounds) of total suspended solids; CBEMP model scenario was LRSWA3.

[4] The green-highlighted cells indicate values that meet the four jurisdictions' Chesapeake Bay water quality standards, while the red-highlighted cells show exceedance in space and/or time such that a segment is considered to be in nonattainment status.

Table 4-12. Estimated Deep-Water Dissolved Oxygen Nonattainment for Key Scenarios

Chesapeake Bay Segment	State	Estimated Percent Nonattainment for Dissolved Oxygen in the Deep-Water Segments [1]	
		Scenario 1 WIPs Not Implemented [2]	Scenario 2 WIPs Fully Implemented [3]
CB3MH	Maryland	1%	0%
CB4MH	Maryland	11%	4.7%
CB5MH	Both	2%	0%
CB6PH	Virginia	0%	0%
CHSMH	Maryland	11%	0%
EASMH	Maryland	2%	0.9%
PATMH	Maryland	6%	0%
PAXMH	Maryland	0%	0%
POTMH	Both	0%	0%
RPPMH	Virginia	0%	0%
SBEMH	Virginia	0%	0%
YRKPH	Virginia	0%	0%

Notes: [1] The scenarios were run on the Chesapeake Bay WSM (Phase 5.3.2) and utilized the 1991-2000 hydrologic period; the 2010 Chesapeake Bay TMDL critical period of 1993-95 was used (see USEPA, 2010a, and Appendix D of this report).

[2] Scenario 1 included a 10-year annual average load of 132,000 tons (263 million pounds) of TN, 9,700 tons (19.4 million pounds) of TP, and 4.18 million tons (8,360 million pounds) of total suspended solids; CBEMP model scenario was LSRWA4.

[3] Scenario 2 included a 10-year annual average load of 95,500 tons (191 million pounds) of TN, 7,500 tons (15 million pounds) of TP, and 3.34 million tons (6,675 million pounds) of total suspended solids; CBEMP model scenario was LRSWA3.

[4] The green-highlighted cells indicate values that meet the four jurisdictions' Chesapeake Bay water quality standards, while the red-highlighted cells show exceedance in space and/or time such that a segment is considered to be in nonattainment status.

The open-water DO standard has a designated use for all tidal waters of the Chesapeake above the pycnocline (zone of rapid vertical change in salinity where less dense, fresher surface water layers are seasonally separated from saltier and denser water) (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 DO designated use is in contact with the atmosphere and reaeration is rapid. Under all LSRWA modeling scenarios, the open-water DO standard was achieved for all Chesapeake Bay segments, as noted in Table 4-9.

In summary, when the WIPs are not implemented (Scenario 1, Table 4-9), nutrient and sediment loads are high relative to Scenario 2, and the estimated level of deep-channel and deep-water DO attainment is low (Tables 4-11 and 4-12). When WIPs are fully implemented (Scenario 2, Table 4-9), nutrient and sediment loads decrease due to the widespread implementation of BMPs in the watershed, and the deep-channel and deep-water DO criteria are estimated to be attained for the entire Chesapeake Bay (Tables 4-11 and 4-12). As a graphical representation of deep-channel DO nonattainment, Figure 4-8 shows the estimated extent of nonattainment for deep-channel DO water quality standards when WIPs are not implemented (Scenario 1).

Scour Impacts

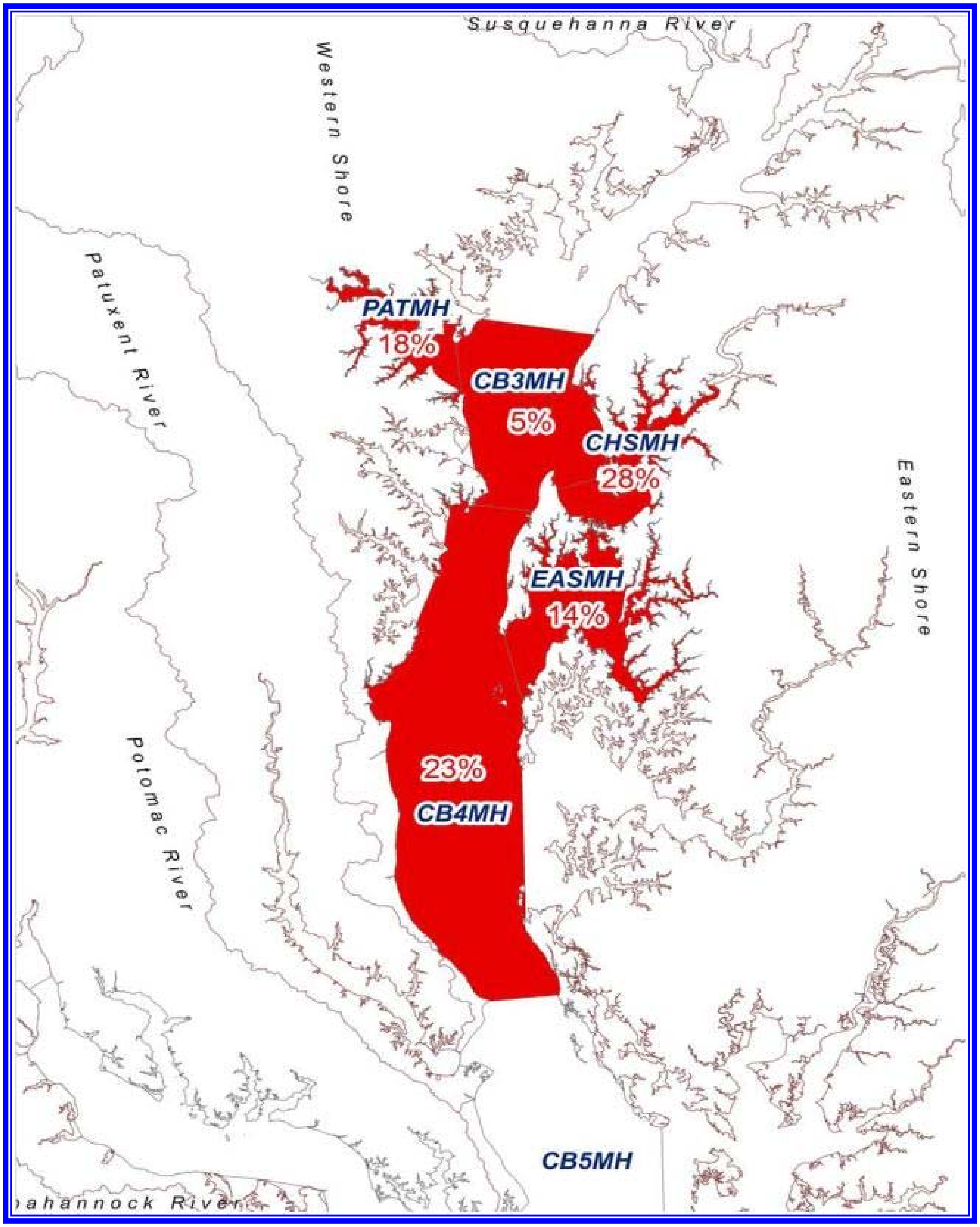
CBEMP was utilized to assess scour impacts by comparing Scenarios 2 to Scenario 3. The difference between the scenarios is that the January 1996 high-flow event was simulated for Scenario 3 using the HEC-RAS/AdH model, while Scenario 2 did not have this scour event. The estimates of particulate nutrients scoured by the January 1996 storm were based on observations made during Tropical Storm Lee in 2011. These updated nutrient and sediment loads augmented the nutrient and sediment loads estimated by the Phase 5.3.2 Chesapeake Bay WSM, which is what Scenario 2 utilized. This augmentation was performed because the Chesapeake Bay WSM did not calculate sufficient scour for the January 1996 high-flow event.

CBEMP estimated that the storm event produced a tremendous increase in computed light attenuation during the January storm. However, during the 1996 SAV-growing season (April-October) and in later years, 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/meter (m) compared to median base light attenuation of approximately 0.8/m. By the time growing season arrives, most of the sediment associated with the storm has settled out (see Appendix C).

Estimated surface chlorophyll decreases during the scour event, most likely due to increased light attenuation from scoured sediment resulting in lower phytoplankton production 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 (milligrams per cubic meter) extending into the lower Potomac River and below the mouth of the Potomac in the mainstem Bay. 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 the bottom sediment. Particulate nutrients associated with scoured sediment settle to the bottom. During the warmer months, diagenesis in the bottom sediment releases the

nutrients to the water Figure 4-8. Estimated Nonattainment of the Deep-Channel DO under Current Conditions



Notes: Current conditions assume that no WIPs are in place; this is Scenario 1.

column where they stimulate phytoplankton production. Over time, processes including burial and washout remove the sediment-associated nutrients from the active surface sediment layer and the stimulus provided by additional sediment nutrient release diminishes (see Appendix C for more details).

Bottom-water DO declines up to 0.2 g/m^3 (grams per cubic meter) although the decline is 0.1 g/m^3 or less when averaged over the summer season (see Appendix C for additional details). Although this decline is small in magnitude, the implications could be significant in regions of the Bay such as the deep-water and deep-channel habitat where the projected DO concentration, in the absence of scour, just meets the states' applicable DO water quality standards.

Chesapeake Bay Dissolved Oxygen Water Quality Standards

In Scenario 3, the high-flow event occurs in January 1996 making the TMDL's 1993-95 critical period impractical for comparison purposes because the January 1996 event is outside the 1993-95 simulation period. Therefore, the 1996-98 period of Scenario 2 was used for comparison. The estimated response in the deep-channel DO standards under Scenario 3 was an increase of 1 percent nonattainment over Scenario 2 in segments CB4MH, EASMH, and CHSMH, as shown in Figure 4-9 (see Appendix D for more details).

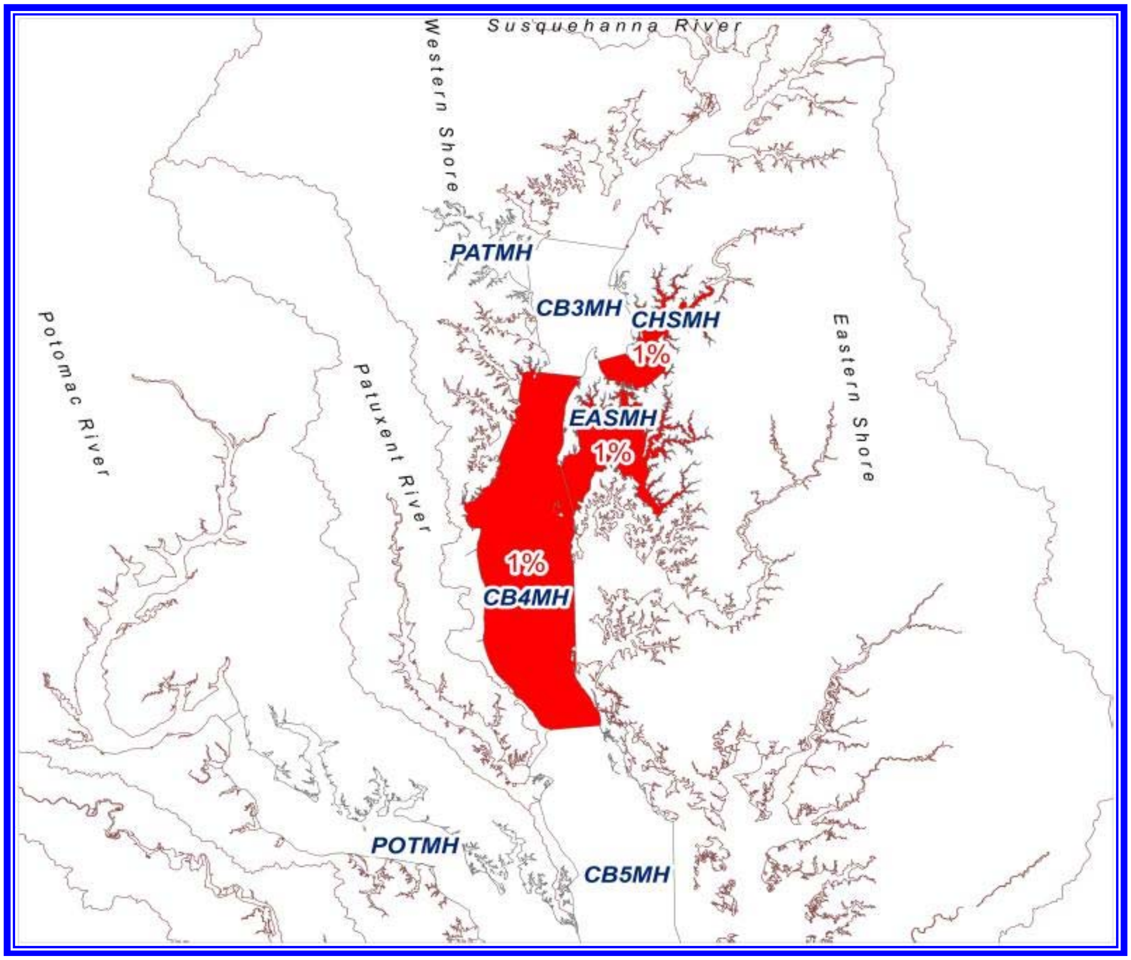
In summary, there does appear to be significant DO impacts from a January scour event. These impacts are observed when the CBEMP uses scouring adapted from AdH for the January 1996 storm and updated nutrient composition (from Tropical Storm Lee) to impact water quality standards attainment in the deep-channel and deep-water habitats of the upper Chesapeake Bay segments (1 percent nonattainment estimated). However, scour impacts on meeting DO water quality standards are much lower than those from not implementing the WIPs; the Scenario 3 scour event has limited increases of 1 percent nonattainment (Figure 4-9), while Scenario 1 (no WIP implementation) is estimated to have 5- to 28-percent nonattainment in a larger portion of the Chesapeake Bay.

EPA provided a first order estimate of the degree of Susquehanna River watershed nutrient pollutant load reduction needed to avoid estimated increases in DO nonattainment of 1 percent in the deep-water and deep-channel habitats; this analysis is described further in Appendix D. A rough estimate of the load reduction needed Bay-wide is about 2,200 tons of TN (4.4 million pounds) and 205 tons of TP (0.41 million pounds) to offset the 1 percent of DO criteria nonattainment in the deep-channel and deep-water habitats. Estimates of the nitrogen and phosphorus pollutant load reductions from the Susquehanna River watershed needed to offset the 1-percent increase in DO nonattainment are about 1,200 tons of nitrogen (2.4 million pounds) and 135 tons of phosphorus (0.27 million pounds).

Storms and Seasonality

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 (Scenario 6 from Table 4-9, with three CBEMP model runs).

These were compared to Figure 4-9. Estimated Deep-Channel DO Nonattainment for Scenario 3



conditions with the storm removed (both watershed and storm scour). The scenarios with the storm included both watershed loads and scour. Effects are discussed in terms of light attenuation, chlorophyll, and DO (see Appendix C for additional information on this topic).

All three storm events (January, June, and October) demonstrate a large, immediate response in light attenuation due to sediment loads. The January storm response is shortest-lived, on the order of ten days. In this instance, the high flows which prevail during this season, in addition to the storm flows, flush sediment downstream and out of the system. The influence of the sediment load on attenuation persists for approximately 90 days for the June and October storms. For both the January and October storms, sediment is virtually gone from the water column 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. The seasonal-average results indicate the spatial extent of increased attenuation is greater for the June storm, than for the January or October storms (see Appendix C for additional details).

Estimated surface chlorophyll concentration decreases immediately as the storm flows pass. 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. The region of increased chlorophyll concentration is also most extensive for the June storm. This effect is promoted by the introduction of nutrients at the beginning of the season of maximum production. For the January storm, roughly 5 months pass between the storm loading and the summer production season. For the October storm, 8 months pass, allowing time for the added nutrients to be flushed from the system or buried to deep, inactive bottom sediment (see Appendix C for more details).

As with chlorophyll, the initial effect of the storm on DO is a decrease as the storm passes. For the January and October storms, DO rebounds, then decreases due to oxygen demand associated with additional production and the decay of organic matter stimulated by storm-generated nutrient loads. For the June storm, the decrease associated with storm flow nearly coincides with the naturally occurring spring and summer phytoplankton "blooms." As a result, the decrease during the summer following the storm is of larger magnitude than for a January or October storm. 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 that accompanies the enhanced algal primary production (see Appendix C for more details).

Chesapeake Bay Dissolved Oxygen Water Quality Standards

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. For further analysis, the modeling team performed a "No Storm Scenario" with the 1996-98 hydrology. This No Storm Scenario is not specifically tabulated in Table 4-9, but rather was used as a point of comparison with the three seasonal storms. The No Storm Scenario had the January storm removed and was developed solely with the Chesapeake Bay WSM Phase 5.3.2 model. Additional details can be found about the No Storm Scenario, which has a CBEMP model designation of LSRWA23, in Appendix D.

The June scour event had an estimated increase in deep-channel DO water quality standard nonattainment (negative impact) of 1 percent, 4 percent, 8 percent, and 3 percent in segments CB3MH, CB4MH, CHSMH, and EASMH, respectively, when compared to the No Storm Scenario in the 1996-98 hydrologic period. The June event had an estimated increase in deep-water DO water quality standard nonattainment of 1 percent in segments CB4MH, CB5MH, and SEVMH, when compared to the No Storm Scenario in the 1996-98 hydrologic period, resulting in higher estimated levels of deep-water and deep-channel DO criteria nonattainment than for other LSRWA scenarios (see Appendix D for further details).

Using the 1996-98 hydrologic period, the estimated deep-channel DO water quality conditions from the October high-flow event compared to the No Storm Scenario was increased nonattainment of 2 percent and 1 percent in the Chester River segment CHSMH and the Severn River segment SEVMH, respectively. The estimated Chesapeake Bay deep-water DO water quality standard achievement for the October high-flow event was increased nonattainment of 1 percent in SEVMH, compared to the No Storm Scenario (see Appendix D for further details).

The January storm event 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 No Storm Scenario in the 1996-98 hydrologic period. The deep-water DO water quality standard attainment levels for the January storm were estimated to be 1 percent in segments CB4MH, CB5MH, and SEVMH, when compared to the No Storm Scenario in the 1996-98 hydrologic period (see Appendix D for further details).

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 June storm, October storm, and 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 contributes directly to ongoing primary production as the nutrients 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 generates 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 sediment (see Appendix D for further details).

Dynamic Equilibrium

Scenario 5, as noted in Table 4-9, utilized a "Full" or "Equilibrium Bathymetry" representing the Conowingo Reservoir in a dynamic equilibrium condition. The scour computed for the dynamic equilibrium bathymetry is virtually identical to the scour computed for the 2008-11 bathymetry (Scenario 3). This estimate implies that effectively, the lower Susquehanna reservoirs, including Conowingo Reservoir, had already achieved equilibrium by the 2008-11 period. Owing to the nearly identical sediment and nutrient loads, the chlorophyll, DO and light attenuation impacts are virtually identical to the results for the Scenario 3 (see Appendix C for more details).

Chesapeake Bay Dissolved Oxygen Water Quality Standards

Under "full" or "equilibrium" conditions (Scenario 5), the estimated response in the Chesapeake Bay deep-channel DO water quality standards was an increase of 1 percent nonattainment over Scenario 2 for Chesapeake Bay segments CB4MH, EASMH, and CHSMH. There is little difference in Chesapeake hypoxia response between Scenarios 3 and Scenario 5. As discussed earlier, the calculated "full" bathymetry scenario loads compared to the 2008-11 bathymetry scenario loads are virtually identical.

Chesapeake Bay SAV and Water Clarity Water Quality Standards

CBEMP estimates water clarity impacts produced by storms over time, and consequent indirect effects of that on SAV beds. All LSRWA modeling scenarios listed in Table 4-9 resulted in estimates of full attainment of the SAV and water clarity water quality standards for all Chesapeake Bay segments. During the 2010 TMDL allocation development, widespread attainment of the jurisdictions' Chesapeake Bay SAV and water clarity water quality standards was found. In this sense, the SAV and water clarity water quality standards were not the drivers behind the TMDL allocations like the DO deep-channel and deep-water 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 and water clarity water quality standards (USEPA, 2010a).

Though all LSRWA modeling scenarios listed in Table 4-9 resulted in estimates of full attainment of the SAV-clarity standards for all Bay segments, there were estimated detrimental impacts from sediment. When the January 1996 "Big Melt" event storm was moved to the June time period, light attenuation was estimated to be greater than 2/m for 10 days, a level of light attenuation that does not support long-term SAV growth and survival (1.5/m is required).

CBEMP does not model direct storm wave damage to aboveground or belowground SAV tissue, nor direct impacts of excess storm bottom erosion and deposition upon SAV. Accordingly, to consider these other effects of major storms on SAV, it was appropriate to consider the CBEMP model outputs as well as other recent and historical information in this study. Effects of storms can differ based on SAV bed health, size, and density. Healthier, larger, and denser beds would have greater capability for resiliency following storms by virtue of greater SAV biomass and numbers of propagules facilitating more rapid recovery. Wang and Linker (2005) found that the influence of suspended sediments mobilized during extreme storms cause significant damage to SAV if they occur during times of year when SAV has substantial shoot biomass. Conversely, storms in the winter or outside of the SAV-growing season, when SAV lacks or has minimal aboveground shoot biomass, have minimal impact on SAV.

Environmental Implications Summary

Generally speaking, when flow is above the scour threshold, material is scoured, thus impacting water quality. Over a long period of time, now that Conowingo Reservoir is in dynamic equilibrium, the quantity of material scoured will approximately equal the amount of material that settles in the reservoir. Prior to equilibrium, over a long period of time, more material settled than was scoured, and less sediment came out than went into the reservoir.

CBEMP modeling estimates showed that the sediment load (not including the nutrients that they contain) from Conowingo Reservoir scour events are not the major threat to Bay water quality. For most conditions examined, sediment from bottom scour settle out of the Bay water column before the period of the year during which light attenuation is critical. Although the sediment is subject to some resuspension, once it is deposited on the bottom, the effect of sediment on the Chesapeake Bay essentially cease (Appendix C).

The nutrients associated with the sediment are more damaging. After deposition, biological processes transform particulate organic nutrients, and inorganic nutrients adsorbed to sediment, into dissolved forms which diffuse into the overlying water and are bioavailable and affect Bay water quality. Dissolved nutrients are recycled to the water column and stimulate algal production. Algal organic matter decays and consumes oxygen in the classic eutrophication cycle. As a consequence, DO levels are diminished by Conowingo Reservoir scour events. Nutrients take years to undergo burial to a depth where they are no longer an influence on surface waters. CBEMP modeling predicts that as the years go by, the impacts to water quality decrease after a scouring event (Appendix C).

Nitrogen loads associated with the scoured sediment exceed the phosphorus loads, as noted in Table 4-9. The excess of nitrogen over phosphorus in Conowingo Reservoir bed sediment indicates that the scoured nitrogen load will exceed the scoured phosphorus load any time bottom material is scoured (eroded), regardless of the quantity of bottom material. Virtually all scoured nutrients are in particulate form. Since dissolved nitrogen is a large fraction of the watershed load (particulate and dissolved), particulate nitrogen is a small fraction of the total nitrogen load (watershed load plus scour load), compared to the fraction of particulate phosphorus in the total phosphorus load (watershed plus scour load) (Appendix C).

The magnitude of nitrogen scour load has not been emphasized in preceding studies. Since dissolved nitrogen loads from the watershed are much greater than phosphorus loads, the relative contribution of scour to the total phosphorus load is greater than the relative contribution of scour to the total nitrogen load. Increased loads of one or both nutrients should be viewed as detrimental to Bay water quality (Appendix C).

Scour events can occur at various times of the year, depending on the mechanism behind the high-flow event. The timing and duration of high-flow events affect their eventual impacts. Modeling estimates that a fall event has the least detrimental impact on the Bay water quality parameters investigated. A late spring storm has the greatest impact to these water quality parameters estimated (Appendix C).

A scouring event in June has greater adverse impacts to water quality, habitat, and living resources than October and January events. A storm event at any time creates an enormous, immediate response in light attenuation due to the solids loads. For the January and October storms, the solids settle out prior to the subsequent SAV-growing season. A June storm occurs during the SAV-growing season and has a negative effect on light attenuation and plant production. Nutrients introduced by a storm stimulate chlorophyll production in each subsequent SAV-growing season.

While numeric Chesapeake TMDL limits for chlorophyll are set only in the District of Columbia tidal waters and in the James River, high chlorophyll levels are a concern throughout the Chesapeake Bay region. Not only are chlorophyll levels too high ecologically but the resulting algal biomass is the primary cause of hypoxia. The resulting chlorophyll concentration is highest for the June storm, and least for the October storm. The amplified effect of the June storm is promoted by the introduction of nutrients at the beginning of the season of maximum algal production.

The initial effect of a storm on DO is a decrease as the storm passes. For the January and October storms, DO rebounds quickly, then decreases during summer 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. In addition, the nutrients in the storm flow are immediately available at the season of maximum algal production. As a result, the DO decrease during the summer following a June storm is of larger magnitude than for a January or October storm (Appendix C).

The estimated impact of storm scour associated with the January 1996 flood event on conditions with WIPs in place to meet Bay TMDL is small in magnitude for the water quality parameters observed. Although this impact is small in magnitude, the implications could be significant in regions of the Bay such as the deep-water and deep-channel habitat where the projected DO concentration, in the absence of scour, just meets the standards of the TMDL.

The 2010 Chesapeake Bay TMDL sets watershed-wide loads limits of 93,000 tons of TN (186 million pounds), 6,250 tons of TP (12.5 million pounds), and 3.23 million tons of total suspended solids (6.46 billion pounds) per year (USEPA, 2010a). These limits equate to a 25-percent reduction in nitrogen, a 24-percent reduction in phosphorus, and a 20-percent reduction in sediment from the 2010 estimated loads; similarly, these limits are a 46-percent reduction in nitrogen, a 48-percent reduction in phosphorus, and a 33-percent reduction in sediment from estimated 1985 loads. In the development of the 2010 Chesapeake Bay TMDL, 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 the Conowingo Reservoir (USEPA, 2010a).

The LSRWA study AdH model results of current conditions compared to conditions in the mid-1990s indicate that the scour load that passes through the Conowingo Reservoir during a storm increases by about 67 percent (from 1.8 to 3.0 million tons), due to the increased transport capacity of the 2011 bathymetry over the 1996 bathymetry. The reservoir deposition decreased by about 33 percent between 1996 and 2011 (6.0 million tons to 4.0 million tons). These findings are directly related to the reduction of storage and subsequent increase in transport capacity of the 2011 bathymetry. This means that more sediment and associated nutrients are being transported during storms, and less sediment and nutrients are depositing during lower flows now than compared to the 1990's. As a consequence, more of the bottom sediment and associated nutrient loads from Conowingo Reservoir are estimated to be available for transport to the Chesapeake Bay.

Of these increased pollutant loads, nutrients are most important from a Chesapeake Bay water quality perspective. Sediment loads from Conowingo Reservoir are estimated to have relatively little influence on attainment of the jurisdictions' Chesapeake Bay SAV and water clarity water quality standards. 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 Segment CB1TF (the Susquehanna Flats) which has often exceeded Maryland's SAV and water clarity water quality standards in recent years (Appendix D).

Nutrient loads are another matter. Consistent with the 2010 Chesapeake Bay TMDL findings, water quality impairments estimated to be caused by the gradual filling of Conowingo Reservoir are the increased nutrient loads associated with increased sediment scour. The Chesapeake Bay water quality standards that are 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).

In the TMDL process, any increase in pollutant loads that result in a failure to achieve water quality standards must be addressed and offset so as to ensure full attainment of the applicable water quality standards. Thus, from the perspective of the Chesapeake Bay TMDL, the estimated increase in nutrient releases from the Conowingo Reservoir in its most current condition of dynamic equilibrium compared to the 1990s (the reservoir condition which is what the 2010 Chesapeake Bay TMDL loads were based on) should be investigated further and a determination should be made by CBP partners as to how these additional nutrient pollutant loads will be offset.

Chapter 5. Development of Sediment Management Strategies

As mentioned in Chapter 3, the LSRWA team went through a process of developing sediment management strategies based on the problems, needs, existing conditions, and anticipated future conditions of the lower Susquehanna River watershed. The following determinations of existing and anticipated future conditions were the foundation for the strategy development process.

Existing Conditions

The lower Susquehanna River reservoirs, including Conowingo Reservoir, have entered into an end state of trapping capacity termed dynamic equilibrium. In this dynamic equilibrium state, sediment and associated nutrients will continue to accumulate until an episodic flood (scouring) event occurs. That is, there is no absolute capacity or point at which the reservoir is "full" and will no longer trap sediment. Storage capacity will increase after a scouring event, allowing for more deposition within the reservoir in the short term. This state is a periodic "cycle" with an increase in load to the Bay from scour also resulting in an increase in storage volume (capacity) behind the dam, followed by reduced sediment and associated nutrient loads transported to the Chesapeake Bay due to reservoir deposition.

Dynamic equilibrium does not imply equality of sediment inflow and outflow on a daily, monthly, or even annual basis, or similar time scale. It implies a balance between sediment inflow and outflow over a long time period (years to decades) defined by the frequency and timing of scouring events. Sediment and associated nutrients that accumulate between high-flow events are scoured away during storm events, whereby accumulation begins again. Over time, there is no net storage or filling occurring in the reservoirs behind the dams.

Storm characteristics are highly variable, and variations in track, timing, and duration can alter the amount of sediment and associated nutrients entering the system from both the watershed and from scouring in the reservoirs.

Susquehanna River watershed loads (sediment, nitrogen, and phosphorus) continue to decrease compared to historic loads due to implementation of watershed management measures by various entities throughout the watershed.

Anticipated Future Conditions

The lower Susquehanna River dams and reservoirs will continue trapping and scouring sediment and associated nutrient loads in their dynamic equilibrium state in a similar manner as seen today. Storms will continue to occur and will vary in track, timing and duration. Due to global climate change, it is predicted that there will be increased intensity of precipitation in spring and winter potentially causing more frequent scour events. Watershed loads of sediment, nitrogen, and phosphorus will continue to decrease compared to today due to the continued implementation of Pennsylvania, New York, and Maryland WIPs to meet the 2010 Chesapeake Bay TMDL allocations. Predicted higher temperatures and continued warming of Chesapeake Bay's tidal waters could have negative implications on DO, causing intense hypoxia to occur substantially earlier, or end substantially later in the year making it more difficult to meet Chesapeake Bay water quality standards, potentially increasing costs to achieve the Bay TMDL.

5.1 SEDIMENT STRATEGY DEVELOPMENT PROCESS

This assessment included a survey-level screening of sediment management strategies to address the additional loads to Chesapeake Bay from the reservoirs' bed sediment scour. The focus was on managing and evaluating sediment loads with the understanding that there are nutrients associated with those sediment loads (see Section 4.2.3 Environmental Implications). The reason for this is that particulate nutrients are contained within the reservoir bed sediment. A substantial portion of phosphorus delivered to the Bay is adsorbed to sediment. Some nitrogen is also delivered to the Bay with sediment. By virtue of their great volume, the reservoir bed sediment contains a great quantity of nutrients. Thus, by managing the reservoir bed sediment, one would also be managing the nutrients they contain. However, it must be noted that the primary importance of nutrients compared with the sediment trapped behind the dams was not well understood until late in the assessment process. For that reason, management measures focused primarily or solely on nutrients were not considered in this assessment.

Reducing impacts from storm scour of sediment is where attention was focused due to the fact that without storms, the reservoirs will continue to trap sediment in the short term at rates consistent with today. There was recognition that the team could not manage storm events (i.e., it is impossible to reduce all impacts from all storm events and it is unknown exactly when the next storm will occur as well as the magnitude of that storm); however, the team could investigate strategies to reduce the amount of sediment available in the reservoirs for a future storm (scour) event. In reducing the amount of sediment available for a scour event, water quality could be improved and impacts to aquatic life could be reduced.

Figure 5-1 displays the process that the LSRWA team followed to develop the sediment management strategies. The remainder of this section will provide a brief description of the various kinds of sediment management strategies that were identified, screened, evaluated and compared along with results.

The first step taken to develop sediment management strategies was to brainstorm and identify potential management options. For this identification process, the SRBC Sediment Task Force's 2002 findings were reviewed (SRBC, 2002), stakeholder input was requested (see Chapter 6, with detailed documentation in Appendix H), and a literature search was conducted on managing watershed and reservoir sedimentation. The full literature search and findings are included as Appendix H.

According to literature in general, sediment management strategies fall into three categories, as shown in Figure 5-2:

1. Reducing sediment yield from the upstream watershed;
2. Minimizing sediment deposition (within the reservoir); and
3. Increasing or recovering volume (of the reservoir).

Figure 5-1. LSRWA Sediment Strategy Development Process

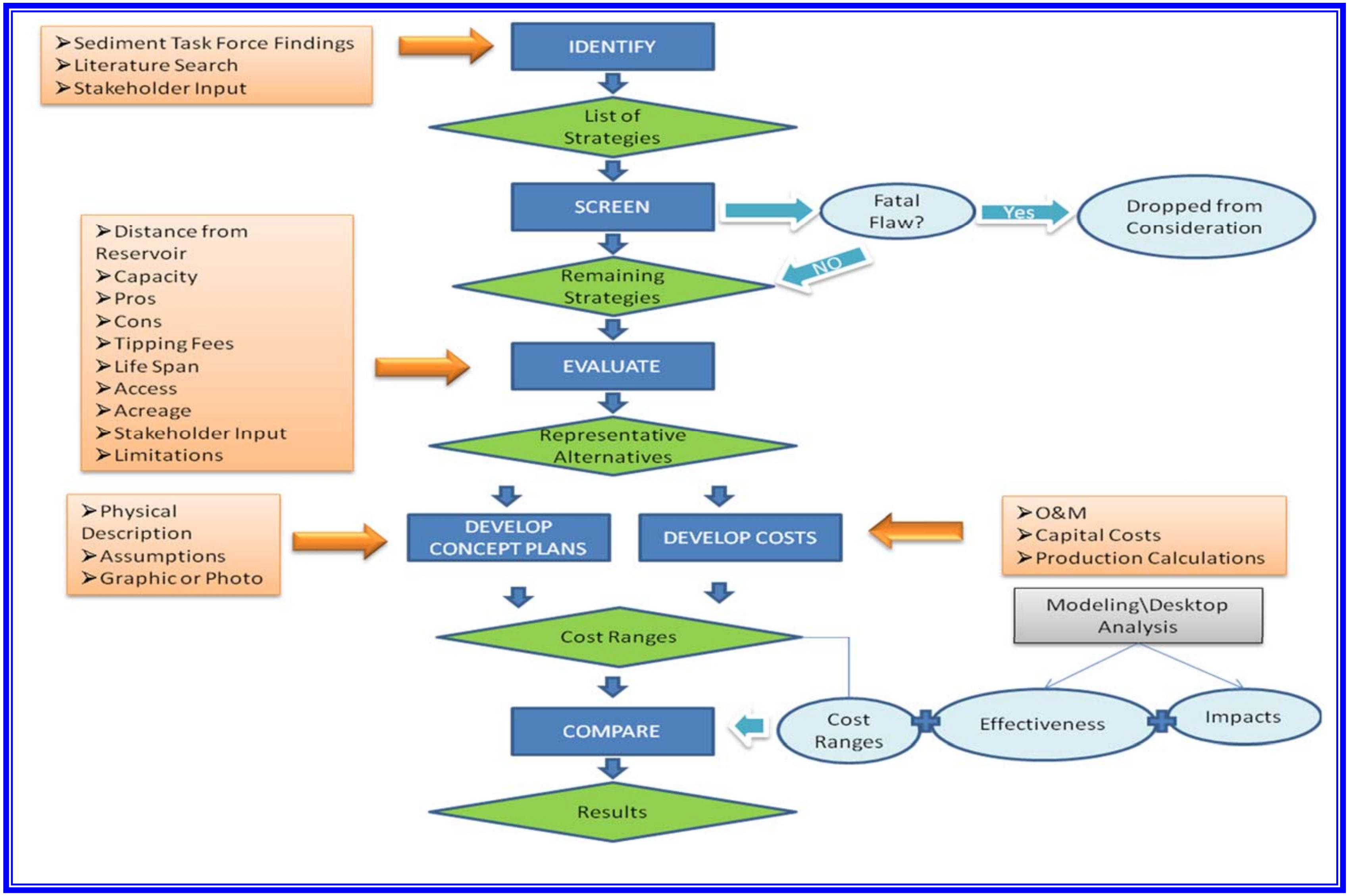
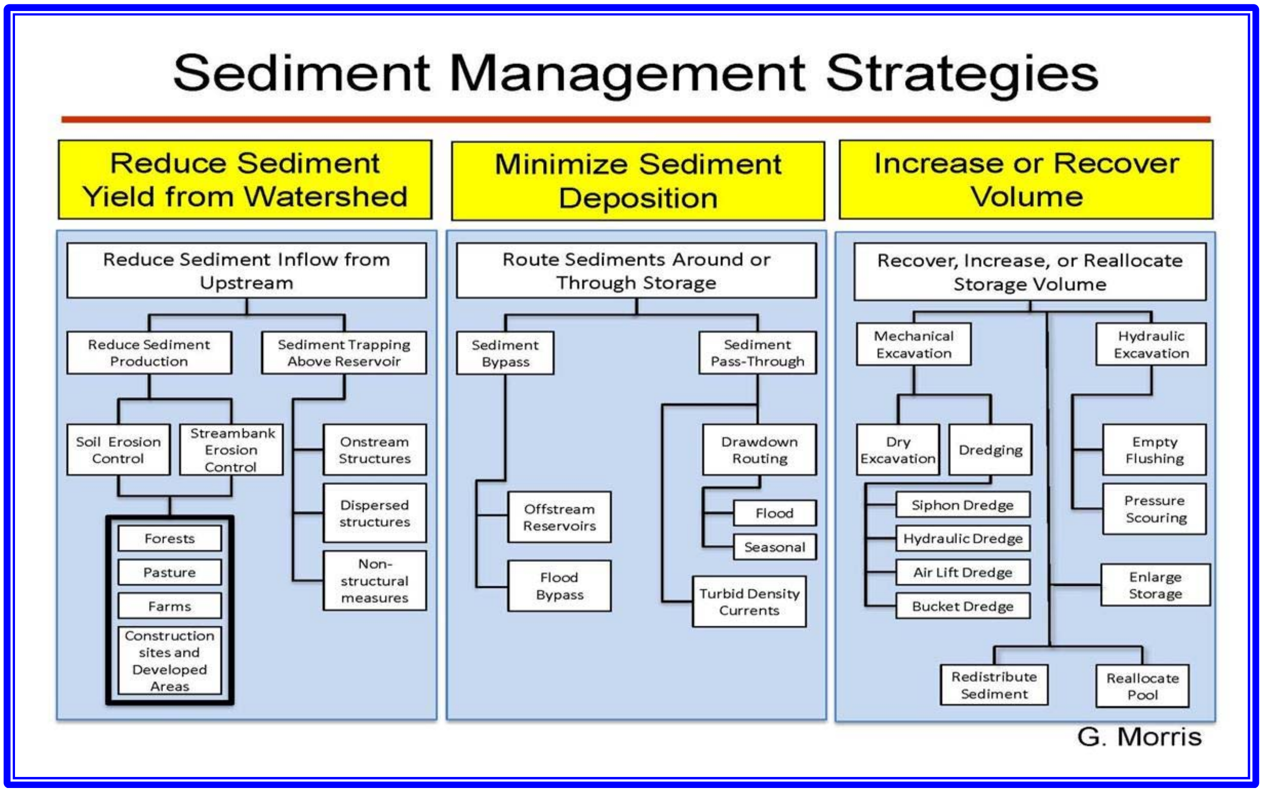


Figure 5-2. Sediment Management Strategies



Source: Morris, 2014.

According to literature, common factors that sediment managers consider are: goals, effectiveness of strategies, costs, optimization of effectiveness of strategies, environmental impacts, implementation sequence, and benefits.

5.2 REDUCING SEDIMENT YIELD FROM THE WATERSHED

The first category of sediment management strategies is those that reduce sediment yield from the upstream watershed. The LSRWA team depended heavily on the Chesapeake Bay TMDL work done by the watershed jurisdictional partners to develop their WIPs. The LSRWA team did not need to identify, screen, or evaluate these strategies since CBP's jurisdictional partners had already done this work. More specifically, the LSRWA team examined how implementation of the BMPs related to the jurisdictions' WIPs could potentially reduce sediment loads from the Susquehanna River watershed.

In December 2010, EPA and its CBP watershed partners agreed to a Chesapeake Bay-wide TMDL or "pollution diet," which set limits of 93,000 tons of nitrogen (185.9 million pounds), 6,250 tons of phosphorus (12.5 million pounds), and 3.2 million tons of sediment (6.45 billion pounds) per year. The 3.2-million-ton sediment load represents a 20-percent reduction over current basin-wide loads. The Chesapeake Bay Watershed model estimated sediment loads to the Susquehanna River from New York, Pennsylvania, and Maryland along each state's respective Susquehanna River watershed

Table 5-1. 2012 Estimated State Sediment Loads and 2010 Chesapeake Bay TMDL State Allocations for the Susquehanna River Watershed

State	Estimated 2010 Annual Load for the Susquehanna Watershed		Allocated Susquehanna River Sediment Annual Load	
	Tons per Year	Million Pounds per Year	Tons per Year	Million Pounds per Year
New York	158,000	317	146,000	293
Pennsylvania	1,100,000	2,200	870,000	1,741
Maryland	34,000	68	32,000	63
Total	**1,292,000**	**2,585**	**1,048,000**	**2,097**

Notes: Allocated load is the amount allowed to be discharged.
Source: USEPA, 2010a, from the Chesapeake Bay Program Phase 5.3.2 WSM scenario run for the 2012 estimated sediment loads to Chesapeake Bay from the Susquehanna River basin.

sediment Chesapeake Bay TMDL allocations are provided in Table 5-1. According to the Phase II WIPs for New York, Pennsylvania, and Maryland, BMP implementation levels outlined in the plans to meet their nutrient allocations are estimated to surpass the sediment planning targets (i.e., be lower than the target loads) by approximately 31,000 tons (62 million pounds) per year.

Additional load reductions can theoretically be achieved by implementing the "E3" (everything, everywhere, by everyone) scenario, which calls for jurisdictions to implement every feasible practice everywhere regardless of cost or feasibility. The CBP Partnership has determined that the E3 scenario is not achievable due to financial, physical, and engineering constraints, limitations, and realities (USEPA, 2010a). However, strictly for purposes of comparison and evaluation, if the E3 scenario were implemented, in the Susquehanna River basin, it is estimated that a total of 95,000 tons (which is equivalent to 117,000 cubic yards)[11] of sediment per year would be reduced from the Susquehanna River system beyond the sediment loads associated with full WIP implementation within the Susquehanna River watershed.

It is important to note that the E3 scenario is a "what-if" scenario of watershed conditions with theoretical maximum levels of pollution control. There were no cost and few physical limitations in

[11] For the sediment management strategies, the major units for description of mass and volume used are tons and cubic yards. Conversion factors of interest are: (1) 2,000 pounds = 1 ton; and (2) 1 cubic yard = 0.81 tons, based on an average bulk density of 1600 kilograms/cubic meter. Thus, 95,000 tons is equivalent to 117,000 cubic yards, as well as 190 million pounds. For ease of reading, tons and cubic yards will be reported in this section.

determining the full array of BMPs to be implemented in the E3 scenario. Generally, E3 implementation levels and their associated reductions in nutrients and sediment could not be achieved for many practices, programs, and control technologies when considering physical limitations and levels of participation by the jurisdictions. Therefore, the estimated sediment load reductions and BMP implementation levels beyond the WIPs should be considered theoretical boundaries of maximum implementation and load reductions.

5.2.1 Concept-Level Plan and Costs for Watershed Alternatives

The CBP partners developed the E3 scenario from a list of approved agriculture, urban, and suburban BMPs using output from the Phase 5.3.2 Chesapeake Bay WSM (see Appendix J in USEPA, 2010b). The list of BMPs and applicable acreages used in the E3 scenario was developed by consensus among the seven jurisdictions in the Chesapeake Bay partnership at a series of workgroup and subcommittee meetings (Kevin DeBell, personal communication, 2013). The technologies, practices, and programs selected by the partnership have been previously reported by the jurisdictions as part of annual model assessments, milestones, tributary strategies, and WIPs. The E3 scenario does not include the full suite of practices due to its goal of achieving maximum load reductions. The BMPs that are fully implemented under the E3 scenario were estimated to produce greater reductions than alternative practices that could be applied to the same land base (Jeff Sweeney, personal communication, 2013).

When implemented across the Susquehanna River watershed, these practices would, in theory, achieve significant reductions of sediment delivered to the lower Susquehanna River. The model scenario practices for New York, Pennsylvania, and Maryland, and with the area of land treated, in either acres or feet, were identified. There were 12 agricultural practices applied in New York, 13 in Pennsylvania, and 11 in Maryland (Jeff Sweeney, personal communication, 2013). Examples include planting cover crops on more than 1 million acres of farm land across the three states, improving pasture management on 591,000 acres, and developing and implementing conservation plans for approximately 3 million acres.

There were 9 urban and suburban practices applied in New York, 15 in Pennsylvania, and 18 in Maryland. Examples include installing a variety of stormwater management actions on 1.1 million acres of land, controlling sediment on 171,000 acres, and restoring 77,000 feet of urban streams. Resource practices, including forest harvesting and improving dirt and gravel roads were also included; however, these were considered a subset of agriculture practices.

Most, though not all, of the CBP Partnership-approved BMPs used in the E3 scenario have associated unit costs in either acres or feet. In order to have as complete a cost estimate as possible and in the absence BMP-specific unit costs from the CBP Partnership, costs from MDE (Greg Busch, personal communication, 2013), and costs from the Maryland Department of Agriculture (MDA, John Rhoderick, personal communication, 2013) were obtained. In cases where costs for a jurisdiction were not available, a cost that was available for one jurisdiction was used for all three.

Agriculture unit costs were available for all three states. For New York, nine costs were obtained from the CBP Partnership-approved list, two were from MDE, and one from MDA. Costs for 10 of the 13 agriculture BMPs for Pennsylvania were obtained from the CBP Partnership, two were from MDE, and one was from MDA. For Maryland, nine unit costs came from the CBP Partnership, two were obtained from MDE, and one from MDA. Agriculture unit costs ranged from $2 per acre to develop conservation management plans to $1,950 per acre for "loafing lot management" (stabilizing areas frequently and intensively used by animals, people, or equipment).

Eight of the nine unit costs for New York urban and suburban BMPs were obtained from the CBP Partnership-approved list, and one was obtained from MDE. Twelve unit costs were available from the CBP Partnership list for Pennsylvania, one from MDE, and no unit costs were available for the remaining two practices. Sixteen unit costs for Maryland were from the CBP Partnership list, and two were obtained from MDE. There were two resource practices for New York and Pennsylvania, and one for Maryland. In the absence of unit costs from the CBP Partnership, costs from MDE were used for all three states. No costs were available for urban growth reduction, mine reclamation, and erosion and sediment control on dirt and gravel roads in Pennsylvania, and erosion and sediment control on dirt and gravel roads in New York. These missing data represent an area of uncertainty in this analysis.

Five of the unit costs for urban and suburban BMPs were divided by the CBP Partnership into new construction and redevelopment, and retrofits of existing infrastructure. The total cost estimate for this project assumed that 10 percent of the urban and suburban practices would be implemented as new construction or redevelopment, and that 90 percent would be retrofits of existing infrastructure (retrofits are more costly than new construction or redevelopment). Some examples of urban and suburban unit costs are provided in Table 5-2.

The output from the CBP Partnership's Phase 5.3.2 Chesapeake Bay WSM, which was used to develop the practices in terms of the units of acres or feet of BMP needed to implement the E3 scenario, was combined with the unit cost estimates from the CBP Partnership and other sources to develop a range in the cost of achieving the theoretical maximum amount of watershed-based sediment load reductions to the lower Susquehanna River.

One example of a BMP used in the Phase 5.3.2 WSM run for the E3 scenario was wetland restoration. The number of acres in each state was multiplied by the respective unit cost in each state in dollars per acre to derive the cost for that BMP. The model used restoration of 133,000 acres of wetlands in Pennsylvania, 192 acres in Maryland, and 143,000 acres in New York at a combined cost of approximately $132 million. The cost of restoring wetlands for each state was combined with the cost of implementing the remaining agriculture, urban, and suburban BMPs to derive the estimated costs by jurisdiction and the totals that appear in Table 5-3.

The concept-level costs to implement the E3 scenario are detailed in Appendix J, Attachment J-1. Unit costs and a description of the agriculture, urban, and suburban BMPs are provided in Appendix J, Attachment J-1 of this report.

The cost of implementing the E3 scenario in Pennsylvania is considerably higher than in New York and Maryland because most (76.2 percent) of the Susquehanna River watershed is in Pennsylvania. Maryland has the smallest part of the watershed (1 percent), and consequently, the smallest cost. New York's share of the Susquehanna River watershed is 22 percent.

Table 5-2. Examples of Units Costs for Urban/Suburban BMPs

Practice		New/Redevelopment ($/acre)			Retrofits ($/acre)		
		NY	PA	MD	NY	PA	MD
Bio-swales	Low High	$400 $1,500	$400 $1,500	$400 $1,500	$600 $2,400	$600 $2,300	$600 $2,300
Impervious Surface Reduction	Low High	$11,400 $17,200	$11,400 $17,200	$11,400 $17,200	$11,400 $17,200	$11,400 $17,200	$11,400 $17,200
Urban Forest Buffers	Low High	$100 $100	$150 $150	$100 $100	$100 $100	$200 $200	$100 $100
Urban Infiltration	Low High	$700 $1,600	$600 $1,500	$600 $1,500	$1,000 $2,500	$1,000 $2,400	$1,000 $2,400

Notes: See Appendix J, Attachment J-1 for more details on unit cost development.

Table 5-3. Estimated Costs to Implement the E3 Scenario

State	Low Cost Estimate	High Cost Estimate
Maryland	$8,430,000	$15,700,000
New York	$108,700,000	$139,700,000
Pennsylvania	$1,399,000,000	$3,357,000,000
Total	**$1,516,000,000**	**$3,512,000,000**

As stated earlier, the maximum available load of sediment per year that could be reduced by additional BMP implementation above and beyond Pennsylvania, New York, and Maryland's WIPs fully implemented throughout the Susquehanna River watershed is approximately 95,000 tons (117,000 cubic yards) at a cost of $1.5 to $3.5 billion. This volumetric saving is an order of magnitude less than what is estimated to flow over Conowingo Dam into Chesapeake Bay on an average annual basis (about 1.8 million tons for the period of 1993-2012). Given the relatively small reduction in watershed-based sediment load reaching the lower Susquehanna River and the physical and engineering constraints, limitations, and realities as well as the high cost of implementing the E3 scenario, this strategy does not appear economically or practically feasible.

5.3 MINIMIZING SEDIMENT DEPOSITION

The second category of sediment management strategies involve minimizing sediment deposition, more specifically, passively routing suspended sediment through the dams (versus actively transporting deposited sediment around the dam, i.e., bypassing) so as to reduce large influxes of sediment to the Chesapeake Bay during storm events at ecosystem-sensitive times of year. These strategies would require some method of altering the way the dams operate. Appendix K describes the existing dam infrastructure and operations for the Safe Harbor, Holtwood, and Conowingo Hydroelectric Stations. The sections below present typical operational alternatives for sediment management, implementation considerations and constraints, and conclusions regarding the utilization of reservoir operations to minimize sediment deposition in the reservoirs to manage sediment in the lower Susquehanna River.

It is important to note that if suspended sediment was passively transported (e.g., via modification of reservoir operations, flushing, sluicing or agitation) as discussed in this section, a permit may not be required. However, if sediment transport were done actively through dredging or a pipeline, a permit would be required (Elder Ghigiarelli, MDE, Deputy Program Administrator, Wetlands and Waterways Program, Water Management Administration, personal communication, 2013).

5.3.1 Sluicing

Sediment sluicing is the removal of sediment from a reservoir by passing water and sediment through outlets located at a low level of the dam. The objective of sluicing is to minimize sediment deposition and maximize sediment movement through flow. Sediment sluicing also removes sediment by either completely scouring deposited sediment in the vicinity of the sluice gates or lowering the general level of deposits upstream. Sluicing requires timing of the release to periods of high-volume, high-sediment concentration inflows to the reservoir.

5.3.2 Density Current Venting

Density current venting is defined as a gravity flow of turbid water under water of different (i.e., less dense) density. The density difference is a function of the differences in temperature, salt content, or silt content of the two fluids. Density currents occur when sediment-laden (heavier) water enters an impoundment, plunges beneath the clear water, and travels downstream to the face of the dam. When the density current is strong enough and lasts long enough, the sediment-laden water can be discharged through low-level outlets. The venting of density currents has long been considered an effective means of reducing the rate of reservoir silting, especially in impounding reservoirs. This method is applicable only in reservoirs where, and when, such density currents occur, and their high-carrying capacity can be used to pass sediment through reservoirs. However, density currents may not make it all the way downstream to the face of the dam, depending on specific reservoir geometry and distance to the dam structure.

5.3.3 Flushing

Flushing takes advantage of the flow itself without using external energy to remove sediment from the reservoir. Flushing remobilizes sediment previously deposited in a reservoir by drawing down the water level and letting the water flow out through low-level outlets in the dam. Water flowing through the reservoir scours sediment and passes them through the dam. To effectively remove sediment with flushing, the water level in the reservoir needs to be kept low for some time while the flow rate is high. Flushing can take place when conditions are relatively convenient to reservoir operations. This cannot be done with a hydroelectric dam or a dam with water supply intakes, where the level of the lake must remain above a set minimum to allow for power generation and water supply operations.

The potential for flushing of the lower Susquehanna River reservoirs is complicated by both structural and operational constraints. With the reservoirs located in series, flushing operations would need to be coordinated to avoid depositing upstream sediment in downstream reservoirs. A hypothetical scenario might involve drawing down Conowingo Reservoir to minimum pool elevation ahead of a high-flow event in an attempt to mobilize additional sediment stored in the reservoir, thus creating a void for future deposition. Drawdown of the pool would significantly impact power generation and water supply operations.

Assuming drawdown of water within the Conowingo Reservoir was deemed feasible (which is not likely given the competing water use demands and associated public health and safety concerns), the reservoir bed sediment mobilized during a potential flushing event, coupled with the sediment-laden flood water yielded from the watershed, could pose a sediment surge to Chesapeake Bay negatively impacting downstream aquatic life and habitat.

5.3.4 Agitation Dredging

Agitation dredging is generally defined as the removal of bottom sediment from a selected area by using equipment to resuspend sediment into the water column where currents can transport sediment away. There are a number of different methodologies that can be employed to provide the bottom agitation and are selected based on site considerations. Typical methodologies include hopper overflow, air bubblers, rakes, and drag beams. Once the sediment is suspended in the water column, it can be transported downstream via streamflow and passed through the dam by way of release operations.

This particular operation would focus on fine sediment typically concentrated in downstream portions of each of the lower Susquehanna River reservoirs. The bulk of agitated suspended bed sediment would be in the lower half of the water column. To transport the suspended material, hydropower intakes would need to be open at the highest flow possible at Conowingo Dam.

AdH modeling results presented in Appendix B, Attachment B-3, indicate that to transport most of the suspended sediment, a flow of approximately 120,000 to 150,000 cfs would be needed. Flows only naturally exceed this range approximately 12 days out the year in the lower Susquehanna River, significantly limiting the window for implementing this operation. Furthermore, the modeling analysis indicates that only fine silts and clays (0.1 millimeter or smaller in diameter) would be transported in suspension through the dam and that larger sediment would likely redeposit within Conowingo Reservoir. Thus, the overall effect of agitation dredging would be extremely limited in terms of grain size impacted, locations targeted, area affected, and total volume transported. These limitations and the objectionable transport of only fine sediment render this strategy impractical.

5.3.5 Screening Conclusions for Minimizing Sediment Deposition Alternatives

In certain settings, strategies that minimize sediment deposition by altering reservoir operations can be implemented to meet sediment management objectives. However, the lower Susquehanna River reservoir system is complex in terms of hydrologic conditions and water resource demands.

The infrastructure and operational constraints associated with implementing strategies to minimize sediment deposition in the lower Susquehanna River reservoirs are not insignificant. Structurally, none of the three hydroelectric dams contain outlet works that would permit sediment releases for any of the strategies presented (sluicing, density current venting, flushing, and agitation dredging).

Existing gates at the Safe Harbor and Conowingo Dams are designed for flood operations, and as such, provide little opportunity for sediment management. Retrofitting the existing dam structures with sluice gates or other bottom outlet works would be difficult, at best, without compromising the dams' structural integrity. Release of sediment through the turbines, in excess of what is transported normally during generation operations at higher streamflows, could cause significant damage. Furthermore, post-construction addition of low-level outlets would be extremely expensive, and thus, not cost-effective.

The three reservoirs of the lower Susquehanna River are unique from an operational perspective. Each of the three hydroelectric dams has a limited amount of streamflow that can be passed through the turbines, ranging from 61,460 cfs to 110,000 cfs. The regulatory requirements memorialized in their FERC licenses take into consideration the needs of other water users in the lower Susquehanna River, including public water supply (Chester Water Authority, City of Baltimore, etc.), power generation (Peach Bottom Atomic Power Station, York Energy Center, etc.), recreation (boating, fishing, etc.), and others. The combination of FERC-licensed reservoir water-level ranges, intake locations serving water supply and nuclear plant cooling, and recreational water-level requirements result in limited storage capacity at the three reservoirs.

Deviating from FERC-licensed operating requirements could have significant public health and safety implications considering the multitude of users sharing the water resources of the lower Susquehanna River. These implications could include compromising public water supply sources by exposing intakes, requiring power generation facilities to shut down during peak demand periods, and impacting cooling systems at nuclear or fossil fuel-fired power plants. Basically, the reservoirs cannot just be drawn down to flush, dredge, or other activities, without having public health and safety implications.

Modifying FERC-licensed dam operations may unduly impact hydroelectricity, existing water supply and power generation projects, with only limited potential benefits to sediment management. The cumulative effect of competing water uses, operational limitations, structural constraints, and health and safety considerations are considered to be fatal flaws for these four sediment management strategies: sluicing, density current venting, flushing, and agitation dredging. Subsequently, these four strategies were dropped from further consideration in this assessment.

5.4 INCREASING OR RECOVERING STORAGE VOLUME

The third category of sediment management strategies involve those strategies that could increase or recover storage volume in the reservoir. This section will discuss the identification, screening, and evaluation of these strategies.

The first strategy in this category is dredging. There are hundreds of combinations of ways to dredge, manage, and place material. However, there are two main types of dredging – hydraulic dredging and mechanical dredging.

5.4.1 Hydraulic Dredging

Hydraulic dredging is essentially vacuuming the riverbed, by adding water to the material (i.e., making slurry) and pumping the slurry to a location outside of the reservoir. The slurry material is typically 80 percent water and 20 percent sediment through this process. Two dredge types can be used in hydraulic dredging – a hopper dredge or a cutter head dredge.

A hopper dredge is self-propelled and collects sediment by a drag arm and discharges the sediment into a bin on the dredge called the hopper. The dredge then delivers the sediment to a site where the material is deposited using a split hull (opening the hopper part of the dredge and letting the material fall out), or removing the material from the hopper, by re-slurring the material and pumping it to another location (i.e., a beach or into a nearby placement site). The use of a pipeline to transport the material is illustrated in Figure 5-3. The capacity of hopper dredges varies from 500 to 5,000 cubic yards.

Figure 5-3. Pipeline to Transport Dredged Material

A cutter head dredge uses the same concept as a hopper dredge, but has a cutter head in lieu of a drag arm. The cutter head is basically round and has teeth on the outside perimeter to loosen the sediment as it is rotating. A pump connected to the cutter head then draws in the sediment and water, sends it to a large pump on the dredge; from there, the material is pumped out through a pipeline to its final placement position. The typical cutter head dredge is not self-propelled like a hopper but moves slowly via a series of spuds, which are anchor-like objects that hold the dredge in place. The dredge is usually identified by the size of the pump discharge diameter (i.e., 16-inch, 20-inch, etc.). The pipeline is usually plastic but can be made of metal. The pipeline comes in certain lengths and are fused or connected to form longer lengths. These additional lengths must be added as the dredge moves farther from the placement site.

A typical hydraulic dredge can pump for about 14,000 feet; for longer distances, it would have to use a booster to pump. When a booster is used, the productivity is normally reduced. It is easier to pump silt than to pump sand. Both cutter head and hopper dredges can be delivered by truck and placed or assembled in a water body.

For hydraulically dredged material, a dike would need to be constructed to adequately contain the material due to the amount of water (80 percent water to 20 percent sediment). Such a dike would typically be 10 feet high with 8 feet used for the sediment material and 2 feet of freeboard to insure the integrity of the structure. After the slurry is pumped into the site, the excess water must be drained from the containment dike; this effluent can only be discharged after meeting the pertinent water quality standards. The effluent discharge is usually done by a gravity-fed pipeline to a nearby water body for eventual conveyance to the Bay. In some circumstances, it could be pumped back to the source.

While material is drying, it would also be subject to atmospheric conditions and in situ precipitation meaning more water to manage. To get the material to dry quicker, it would need to be actively managed. This could involve turning the material over to expose wet sediment to the atmosphere, digging trenches along the sides to encourage water to drain, or a combination of both. If water is ponding on the site, it may need to be removed to promote faster drying. Once dry, the material then could be rehandled and sent to its final destination. However, every time the material is handled, it would add costs.

5.4.2 <u>Mechanical Dredging</u>

Mechanical dredging consists of some type of excavator that could be located on shore or on a barge. The barge would be pushed with tugs to wherever dredging needed to occur. An advantage of mechanical dredging is one can access "tight spots" (e.g., shallower, narrower areas) in comparison to hydraulic dredging. The mechanism for removal is via a clamshell bucket, which has two sides and comes together to grab sediment. The capacity of a small bucket may be as small as 1 to 3 cubic yards, but they can be as large as 50 cubic yards. A typical clamshell operation is shown in Figure 5-4. Once the material is excavated, it must be placed somewhere. The material will be somewhat cohesive and will have water dripping from the bucket. Some buckets may have holes in it to allow more water to be released, and some buckets can be environmentally tight so as to not allow any water to be released.

Figure 5-4. Clamshell Dredging Operations

Material is typically loaded onto a transporting vehicle (e.g., a barge, scow, or truck) and then taken to another location for offloading and placement. From the offloading site, the material would then be placed in another container for transport to the final placement site. This could be directly into a truck or rail. At the offloading site, an excavator is required to clean out the barge or scow, and either place the material in a site for further drying (the site must be within the excavator's reach) or into a truck or railroad car for delivery. A typical truck will hold about 10 to 15 cubic yards of material. The truck will have to be watertight to avoid spillage onto roads. Once the truck reaches its destination, it would have to be unloaded (typically just dumped) and then the truck would return for another load. Transport by rail would have a similar cycle of material processing.

Mechanically dredged material does not contain the amount of water that hydraulically dredged material does. However, it would still need to dry following methods similar to the hydraulic dredging process, but it would take less time. The final placement site may require the material to be somewhat dryer than initial excavation and therefore would need to be dried. The pros of mechanical dredging are lessening the need for dewatering and the ability to access tight spots. The cons are double-handling of material, that is excavation and then transportation, which would incur extra costs.

An important aspect of dredging is determining the appropriate placement options. The placement site most often determines the method of dredging, and how it is managed once the material is dredged. The LSRWA team conducted an investigation to identify sediment placement options for sediment behind the three dams on the lower Susquehanna River. During this investigation, the LSRWA team conducted a desktop analysis of the study area (approximately a 100-mile radius), utilizing Google Earth and conducted an Internet search for new placement sites, as well as reviewing previous placement sites. Phone calls were made to potential placement site operators and site visits were made to investigate the sites with the greatest potential. Figures 5-5 through 5-7 show locations of potential placement sites.

When dredging is performed (hydraulically or mechanically), any contaminant attached to the sediment could be released during placement. To predict the release of contaminants, elutriate tests can be performed. The standard elutriate test is used to predict the release of contaminants to the water column resulting from open water placement. The modified elutriate test is used to evaluate the release from a confined disposal facility. The results will vary depending on the grain size of the material being dredged. Since the LSRWA was a broad assessment of alternatives, elutriate tests were not performed on the potential dredged material. If specific dredging and placement sites are investigated in the future, then it is recommended that these tests be done at that time.

Figure 5-5. Potential Placement Sites, Susquehanna River Watershed

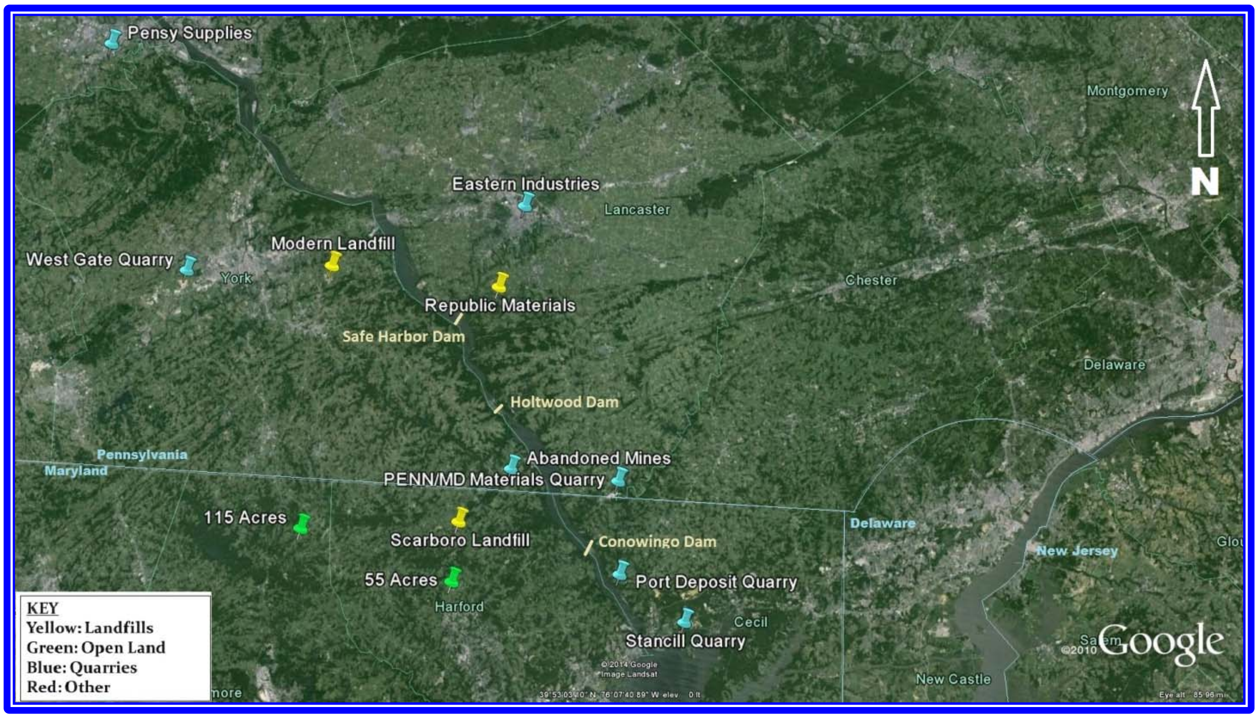


Figure 5-6. Potential Placement Sites, Upper Chesapeake Bay

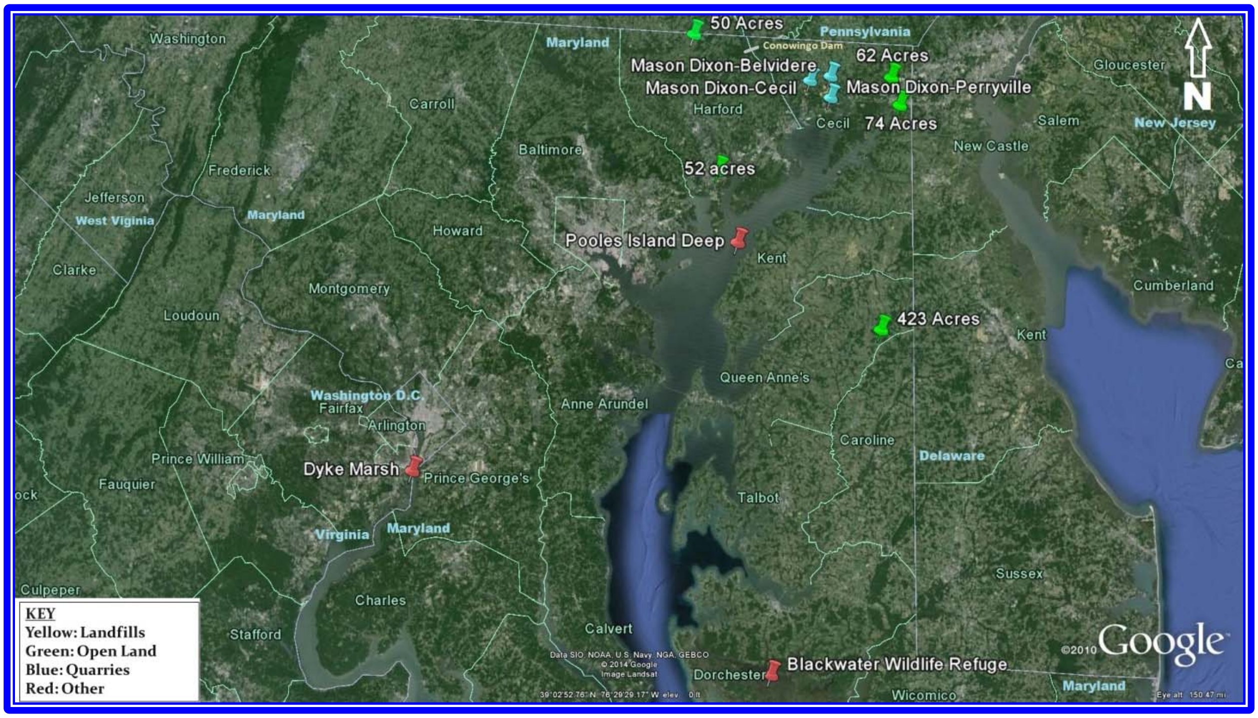
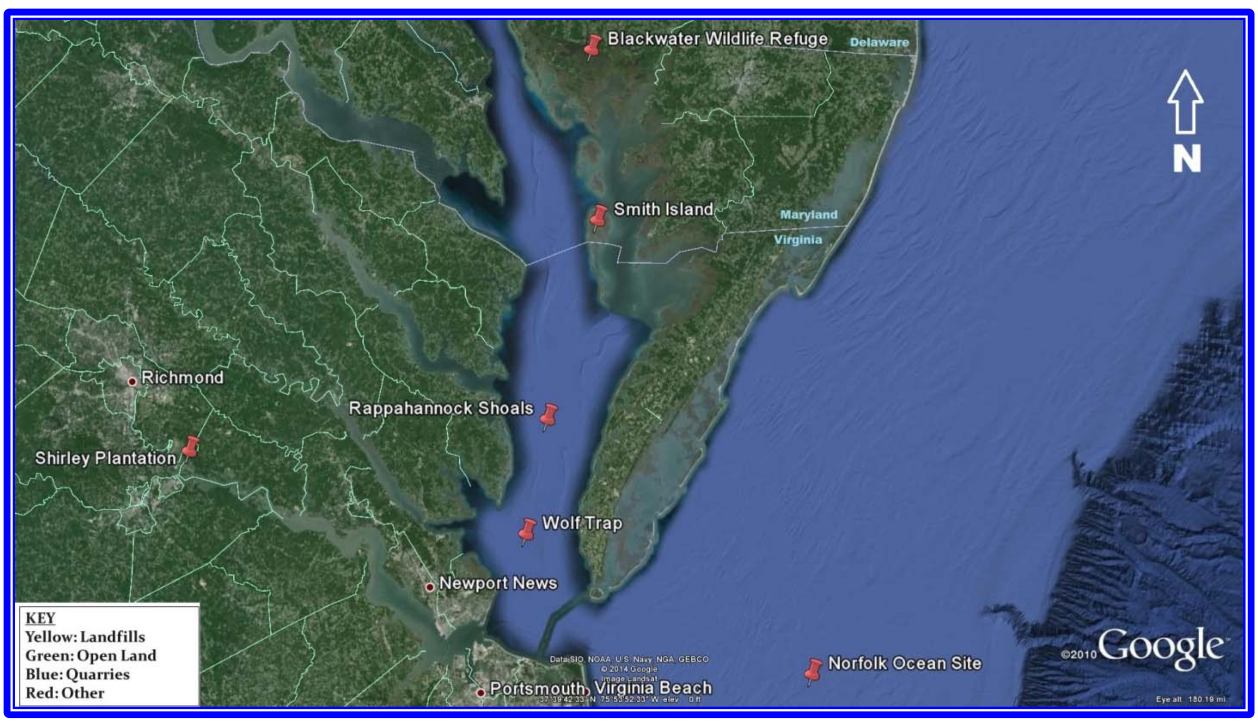


Figure 5-7. Potential Placement Sites, Lower Chesapeake Bay

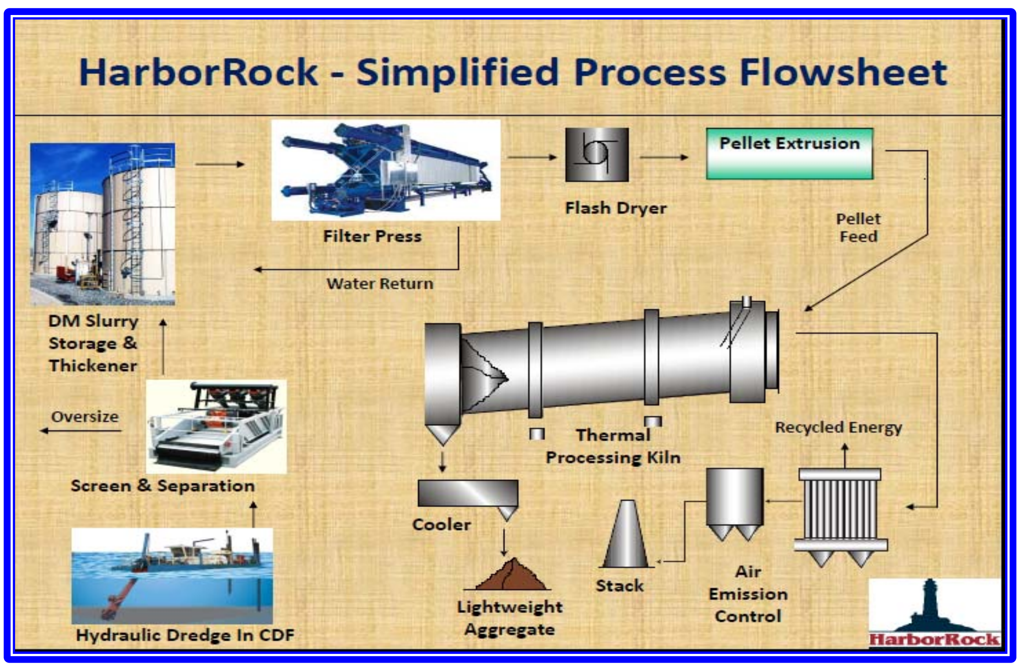


5.4.3 Beneficial Reuse

If material is dredged it could be used beneficially for habitat restoration, soil amendments for agricultural use, mining, landfill capping, or construction materials. One example of beneficial use is a company called HarborRock which uses dried dredged material to create lightweight aggregate (LWA) that could be sold commercially for construction use. This process is currently being evaluated as a beneficial reuse option for the Baltimore Harbor shipping channels. The HarborRock process takes dredged material and fires it in a kiln at high temperatures, as shown in Figure 5-8, yielding LWA.

The LSRWA team compared the results from the analysis of sediment cores taken from behind the Conowingo Dam (SRBC, 2006a) to the decision framework criteria laid out in the 2007 report, *Sediment in Baltimore Harbor: Quality and Suitability for Innovative Reuse.* These criteria helped the team better understand the suitability of the sediment in the lower Susquehanna River watershed for beneficial reuse options. It was determined that most metals in the sediment cores were below Maryland residential reuse thresholds, which include uses such as upland reclamation and manufactured topsoil for landscaping. There were some instances where the coring levels of arsenic, chromium, and cadmium were above Maryland residential reuse thresholds, indicating potential concerns. Site-specific assessments would be needed to address these regulatory issues if residential reuse were pursued.

Figure 5-8. Innovative Reuse Process for LWA



Notes: During this processing, the organic content of the sediment is vaporized while the metal remains bound to the aggregate (below amounts deemed harmful to the environment); about 10 percent of the material is lost during this process, while 90 percent is converted to LWA.
See Appendix J for additional details.

National Marine Fisheries Services (NMFS) has determined that appropriate substrate for any habitat restoration needs be around 70 percent sand (minimum) in composition (see Appendix H). While sediment coring data in the upper Conowingo Reservoir show about 80 percent sand, the lower portion of the reservoir only has about 20 percent sand. For a large volume of sediment, the ideal locations for habitat restoration are near the mouth of the Susquehanna River or in the Bay. Pumping long distances is costly. In addition, current Maryland law prohibits making new islands or land, so the only option at this time is to restore previously existing land, thus limiting the potential locations for habitat restoration.

In the upper portion of Conowingo Reservoir alone, there is an estimated 9.6 million tons of sediment. Consequently, it would be difficult to identify enough locations that could be restored back to what they were with this amount of sediment. Since the ecological damage is really being done by silts and clays during storm events due to the associated nutrients, removing sand would still leave behind the silts and clays making them available for transport during a storm.

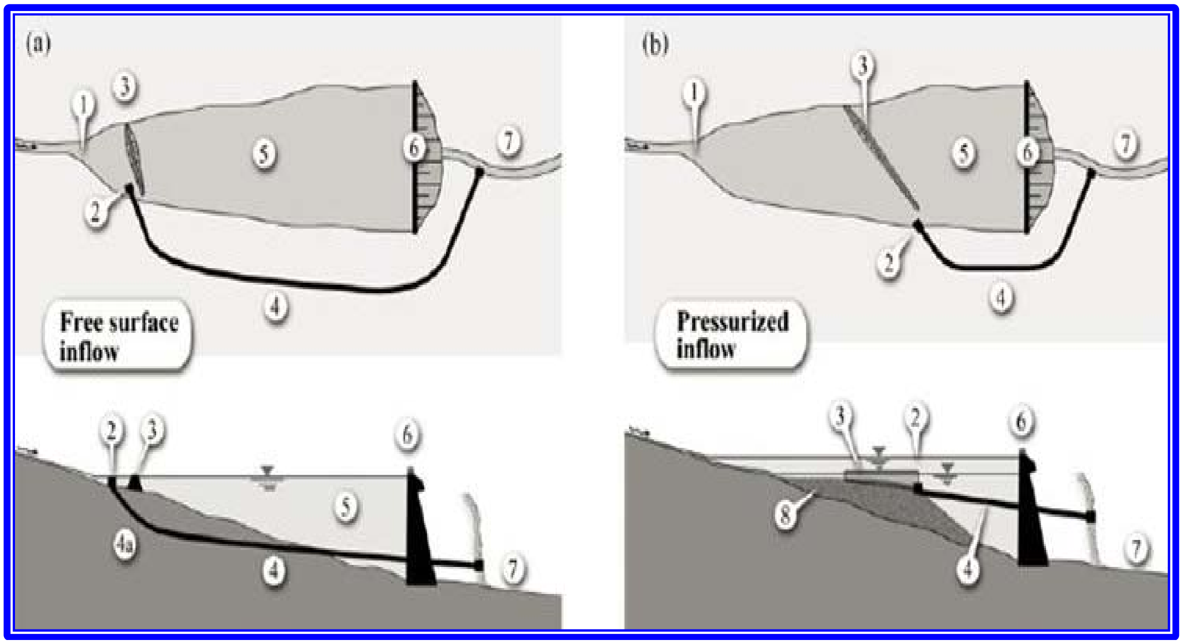
5.4.4 Sediment Bypassing

For this study, the concept of sediment bypassing is defined as routing sediment around the dam(s) downstream. The technology to bypass and transport sediment has been developed and used outside of the Chesapeake Bay. This concept could provide a mechanism to supply coarse-grained sediment to downstream reaches and replenish eroding river and shoreline habitats (Sumi *et al.*, 2004). One method of bypassing is utilizing a tunnel, as depicted in Figure 5-9.

Another method is bypassing via a submerged or floating pipeline. Pipeline diameter selection, and head size will vary depending on how much sediment is moved and how frequently. A permanent pipeline to bypass sediment is one possible method. Typically a pipeline can move 2,000 cubic yards per day with a 16- to 18-inch pipe. Factors like the size of the pump, time of year restrictions, and type of sediment being pumped affect how much sediment can be removed and how quickly. There are no permanent pipelines anywhere in Chesapeake Bay; however, permanent pipelines have been implemented elsewhere. One example is in Louisiana where a state-funded dredging project is pumping sand long distance (22 miles) to Scofield Island, west of the Mississippi River's mouth. The project is estimated to cost $100 million. Based on the fact that such a pipeline has been constructed and is in operation in the United States, it can be deduced that this approach is technically possible.

That said, based on the LSRWA analyses and coordination, it was determined that there are very limited times of year that are not critical to some species. For example, fish spawning occurs as early as February-March and the SAV-growing season is as late as October-November. This leaves the December-January as the only remaining ecologically benign period. Habitat restoration concerns identified in Section 5.4.3 (Beneficial Reuse) regarding the location of sandy sediment within Conowingo Reservoir, potentially suitable sites for active habitat restoration, and leaving behind fine-grained sediments that could be subsequently transported by a storm also apply to sediment bypassing.

Figure 5-9. Schemes of Two Different Sediment Bypass Tunnel Systems



Notes: Scheme (a) = free surface inflow, location of tunnel intake at reservoir head.
Scheme (b) = pressurized inflow, location of the tunnel intake downstream of reservoir head.
System features include (1) reservoir head; (2) intake; (3) guiding structure; (4) sediment bypass tunnel; (4a) acceleration section; (5) reservoir; (6) dam; and (7) tailwater.
The size and orientation of the intake structure primarily control the volume and composition of the sediment-enriched flow diverted past a reservoir.
Source: Sumi, 2004.

5.4.5 Biological Dredging (Floating Wetlands)

A company called Brinjac has developed a technology of floating wetlands which they term "biological dredging." The technology utilizes an artificial wetland matrix made of inert recycled plastic. This biological dredging system compacts sediment, potentially making sediment less likely to scour. Under normal flow conditions, the system would uptake nutrients from the water column. The floating wetlands could be constructed in the river as islands and anchored to the river bed. The wetlands would require regular harvesting and annual maintenance, incurring an annual operation and maintenance cost. Unfortunately, floating wetlands would not withstand very high flow events, like Tropical Storm Lee, and would likely be ripped up.

5.4.6 Upland Placement

Dredged material can also be placed in upland sites such as landfills, quarries, and mines. Distance and requirements of the site will determine how the material is dredged (hydraulic or mechanical), transported (direct pump, truck, rail), and placed (whether it needs to be dried, treated, etc).

5.4.7 Evaluation of Increasing and Recovering Volume Strategies

First, all of the potential strategies were reviewed for fatal flaws. Three strategies were deemed to have fatal flaws and thus were not evaluated any further by the LSRWA team – dam removal, new or enlarged dams to add storage volume, and sediment fixing. Sediment fixing, a strategy to cap sediments, was eliminated immediately as it would not appreciably mitigate scouring or add reservoir capacity. The fatal flaws for the other two strategies are detailed in Table 5-4.

Table 5-4. Increasing or Recovering Storage Volume: Strategies with Fatal Flaws

Strategy	Description	Fatal Flaw Description
Dam removal	Remove one or all three dams	Deemed impractical and infeasible, with little benefit due to multiple uses of dams to Chesapeake Bay population.
Enlarge existing dams or construct new dams	Increase the size of existing dams or construct new dams in the watershed.	Deemed impractical and infeasible, with little benefit to sediment management and would have environmental impacts.

Next, sediment management strategies that increase or recover volume, identified by the team, which did not have fatal flaws, were then evaluated. This initial evaluation did not include costs, effectiveness, or impacts. The purpose of this initial evaluation was to help determine which strategies seemed practical enough to determine costs, effectiveness and impacts.

This initial evaluation of storage volume strategies included the following factors:

1. Required acreage;
2. Expected lifespan in years;
3. Capacity in cubic yards (total and per year);
4. Access;
5. Site tipping fees (payment to allow material to be placed in a placement site);
6. Distance from reservoirs;
7. Pros (advantages, stakeholder input); and
8. Cons (disadvantages, limitations, stakeholder input).

Conclusions of this initial evaluation are that quarries appear to be the best option for material placement due to: (1) they can accept wet or dry material; (2) large volumes could be placed; and (3) there are several quarries nearby that can have material pumped in directly from Conowingo Reservoir, without the need for costly rehandling or trucking. Landfills have many qualifiers including cost, transportation, quantity limitations, and environmental regulations. Habitat restoration has many environmental regulations, logistical challenges, and far distances. Innovative re-use appears promising but hasn't be done on a large scale; this would be true of floating wetlands and bypassing as well.

Before any of these concepts are considered further for implementation, the following would need to be considered:

1. Additional analyses characterizing sediment to be dredged (grain size, plasticity and percent moisture, metals, non-metals, pesticides, PCB's and PAH's, paint filter, elutriate tests)[12] ;
2. Local, state, and federal environmental standards and laws;
3. Accessibility and distance to placement sites;
4. Tipping fees;
5. Logistics (what kind of dredge, how material will be dredged, how the material will be transported, where it will be placed, and how it will be managed once it is placed); and
6. Additional modeling to maximize dredging efficiency by selecting strategic areas.

Table 5-5 includes results of this evaluation; further details are included in Appendix J, Attachment J-3.

5.5 DEVELOPMENT OF CONCEPT-LEVEL PLANS AND COSTS

The LSRWA team identified, screened (fatal flaw analysis), and evaluated 38 "broad" sediment management strategies, as described in Sections 5.2 through 5.4. Broad means one strategy could have many different measures within that one strategy. For example, one strategy was "agricultural BMPs" which has 37 CBP-approved measures, while another was placing material dredged from behind the reservoirs at Blackwater Wildlife Refuge on the Eastern Shore of Maryland (any combination of ways). Figure 5-10 is a graphic schematic of the sediment management strategies investigated.

The next step in the LSRWA sediment strategy development process was to develop concept-level plans and costs. The team utilized a "representative alternative" approach to provide a range of unit costs to implement a management strategy and allow the team to compare costs. The alternatives were selected to offer a realistic range of costs for potential solutions. Whereas the representative

[12] Year 2000 sediment sampling data (averages) (SRBC, 2006a) were compared to the concentration limits that PADEP uses for clean fill standards; the sampled sediment met the clean fill limits for all organic and inorganic constituents. However, there were a few parameters required by PADEP that were not tested during 2000 sampling. For planning purposes, this effort assumed that the sediment behind the dams can be considered "clean fill" appropriate for landfill placement; however, sampling would most likely be required in the future if this option were to be implemented.

Table 5-5. Evaluation of Increasing and Recovering Storage Volume Strategies

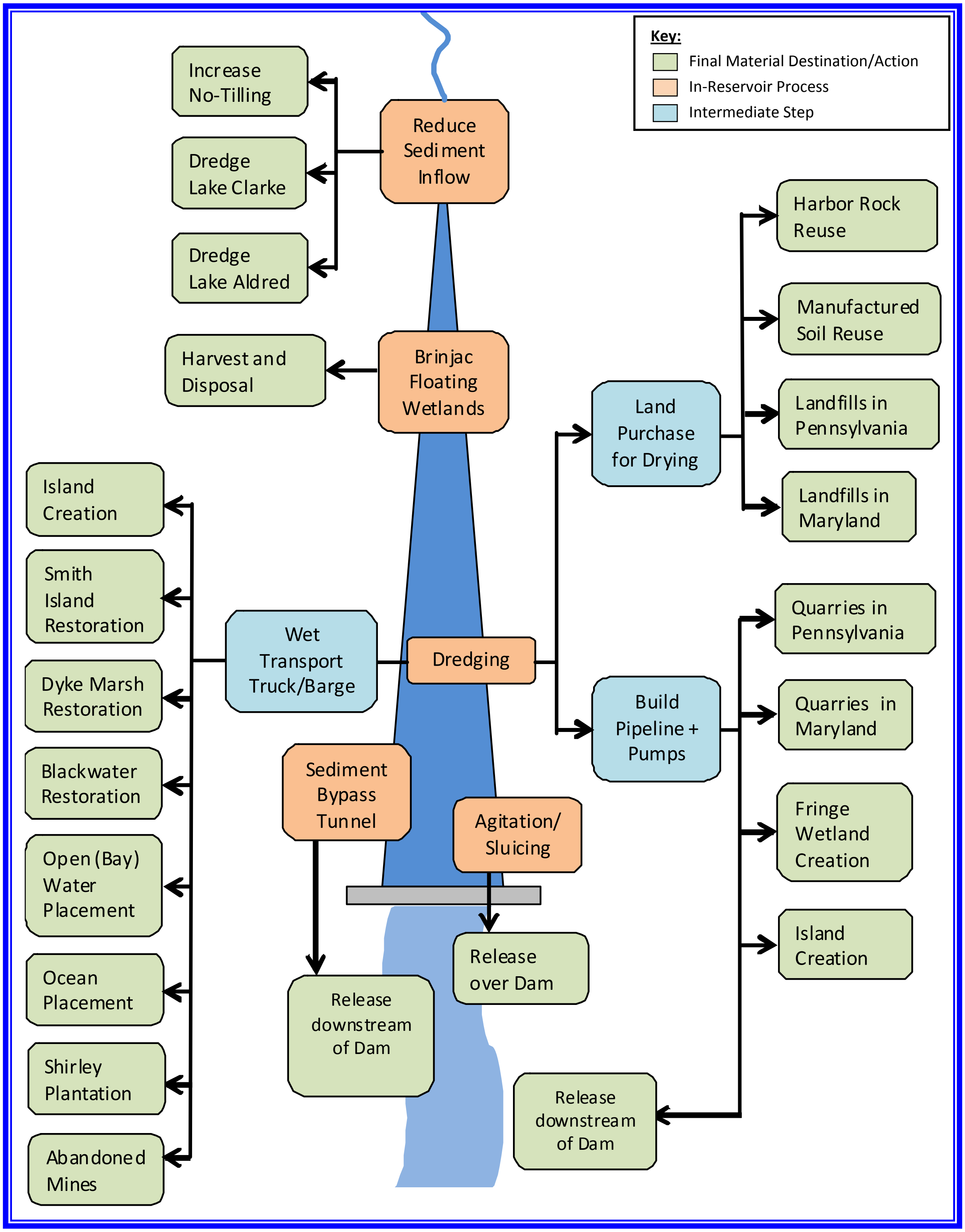
	Sediment Management Strategy	Description	Area Involved (acres)	Lifespan (years)	Lifespan and Yearly Capacities (cubic yards, cy)	Access	Tipping Fee ($/cy)	Distance from Reservoirs (miles)	Pros	Cons
1	**Tunnel Bypass**	Pass coarse sediment around the dam by tunnel	N/A	N/A	Lifespan = variable Yearly = variable	N/A	N/A	Variable	Potential for long-term management Supply of course, medium, and fine-grained sediment to replenish downstream habitats Could deliver sediment at less ecologically critical times of year, i.e., winter.	Tunnel abrasion, incurring maintenance High cost (from literature) for installation ($80-160 million) High annual maintenance ($1 million)
2	**Beneficial Reuse for Lightweight Aggregate (LWA)**	LWA can be sold commercially for construction use. Other commercial uses for dredged material include landfill capping, and cement blocks.	50-100	Greater than 40 years	Lifespan = N/A Yearly: 1 kiln handles 1 million tons per year Can have multiple kilns	Road, barge	$20-25/cy	10 to 15	40-year plant lifespan Beneficial use of material Relatively short transport distance	Material must be dried High cost Have to build plant Limited by amount of dredged material The unit cost for the operation would benefit from economies of scale; however, the ability of the LWA market to absorb increased production may reduce the viability of large operations.
3	**Biological Dredging/Floating Wetlands (Brinjac)**	Artificial wetland matrix made of inert recycled plastic Compacts sediment potentially making sediment less likely to move during high flows Could be constructed in the river as islands	Variable	Indefinite	Lifespan = variable Requires annual maintenance and harvesting of plants	N/A	0	N/A, technology is mobile	No tipping fee Low environmental impact Potential to offset dredging impacts	Annual maintenance Strategy doesn't reduce sediment, so it is not a stand-alone; it would need to be implemented with another strategy to have benefits. Would not withstand extreme storm events
4	**Island Creation in Susquehanna River or Upper Bay**	Placement site "Tear drop" islands in Susquehanna River and upper Bay	Variable	Indefinite	Lifespan = variable until islands are filled Yearly = depends on island size and volume dredged per year.	Pipeline, barge	0	Maximum of 75	Material can be wet No tipping fee Beneficial use More flexibility in amount of material that can go to this site Moderate transport distance	Environmental hurdles Maryland state law forbids island creation in the Bay Material must be sandy or contained Requires use of barges with associated load and unload fees; may not be enough barges to do job Erosion potential
5	**Smith Island Creation**	Placement site	Variable	Indefinite	Lifespan = variable until island is filled Yearly = depends on island size and volume dredged per year	Barge	0	128	Material can be wet No tipping fee Beneficial use More flexibility in amount of material that can go to this site	Possible erosion Environmental hurdles Material must be pure sand Requires use of barges with associated load and unload fees; may not may be enough barges to do job Confinement necessary Long transport distance Potential issues in obtaining water quality certificate; tidal wetlands permit/ authorization required
6	**Fringe Wetland Creation**	Placement site	Variable	Indefinite	Lifespan = variable until wetland is filled Yearly = small, volume depends on the wetland size	Road, pipeline, barge	0	Maximum of 75	Material can be piped Material can be wet No tipping fee Beneficial use More flexibility in amount of material that can go to this site Moderate transport distance	Possible erosion of material Material must be sandy or contained by hay bales or coir logs Requires use of barges with associated load and unload fees; may not be enough barges to do job Confinement necessary Smaller amounts of material can be placed vs. island creation Potential issues in obtaining water quality certificate; tidal wetlands permit/ authorization required

	Sediment Management Strategy	Description	Area Involved (acres)	Lifespan (years)	Lifespan and Yearly Capacities (cubic yards, cy)	Access	Tipping Fee ($/cy)	Distance from Reservoirs (miles)	Pros	Cons
7	**Manufactured Soil**	Dredged material for use as soil or for solid amendments in agriculture, mining, etc.	Variable	Indefinite	Lifespan = N/A Yearly = variable	Road, pipeline, barge	0	Variable	No tipping fee Volume depends on demand for material Beneficial use	Material must be dried High cost Must have other material to mix dredge material with, such as compost Confinement necessary
8	**Dyke Marsh (Potomac, MD)**	Placement site	245	Indefinite	Lifespan = unknown Yearly = 2,000 cy/day, about 700,000 cy/year Dependent on whether a placement cell is available at needed time.	Pipeline, barge	0	230	Most likely no tipping fee Beneficial use of material	Requires use of barges with associated load and unload fees; may not be enough barges to do job Environmental hurdles Long transport distance Erosion Confinement necessary Potential issues in obtaining water quality certificate; tidal wetlands permit/ authorization required
9	**Blackwater**	Placement site	Variable	Indefinite	Lifespan = variable Yearly = depends on size of wetland creation and volume dredged per year	Barge, Road	0	100-125	Wetland creation Beneficial use Flood protection for refuge	Requires use of barges with associated load and unload fees; may not be enough barges to do job Environmental hurdles Long transport distance Potential issues in obtaining water quality certificate; tidal wetlands permit/ authorization required
10	**Pump Downstream (Active Bypassing)**	Pass sediment around dams via a bypass during less critical (non-storm, non-high-flow) periods This will allow the reservoirs to maintain storage capacity for high-sediment transport storm events which would in turn, reduce the amount of sediment passed during storm events.	N/A	N/A	Lifespan = variable Yearly = variable	N/A	0	N/A	Lower costs Potential for long-term management Supply of course, medium, and fine-grained sediment to replenish downstream habitats Could deliver sediment at less ecologically critical times of year, i.e., winter.	Increased turbidity levels downstream Changes in water chemistry Impacts of sediment-removal upstream Consultation with regulatory agencies to develop an upper limit of sediment concentration to minimize impacts Outflowing sediment concentration has to be regularly monitored and controlled Regulatory/permitting issues Outflow must be in an area of the river where velocities are sufficient to continue to move the material. Benthic organisms and/or SAV may be covered by release of sediment downstream.
11	**Pooles Island Placement**	Placement site	1,700	Indefinite	Lifespan = unknown Yearly = 5,000,000 cy/year	Barge	0	32	Material can be wet No tipping fee Moderate transport distance	Currently cannot place material here legally Requires use of barges with associated load and unload fees; may not be enough barges to do job Environmental hurdles
12	**Ocean Placement**	Placement site	N/A	Indefinite	Lifespan = unlimited Yearly = depends on volume dredged per year	Barge	0	240	Material can be wet No tipping fee Most likely larger volumes could be acceptable.	Very long transport distance Environmental hurdles Requires use of barges with associated load and unload fees; may not be enough barges to do job Must pass bioassay tests

	Sediment Management Strategy	Description	Area Involved (acres)	Lifespan (years)	Lifespan and Yearly Capacities (cubic yards, cy)	Access	Tipping Fee ($/cy)	Distance from Reservoirs (miles)	Pros	Cons
13	**Wolf Trap and Rappahannock, VA**	Placement site	N/A	Indefinite	Lifespan = unknown Yearly = 500,000 cy/year to 1,000,000+ cy/year	Barge	0	155	Larger volumes could be accepted No tipping fee	Need Virginia approval Long transport distance Environmental hurdles Requires use of barges with associated load and unload fees; may not be enough barges to do job Material must be dewatered. Site is currently used by Maryland Port Administration. Potential issues in obtaining water quality certificate; tidal wetlands permit/ authorization required
14	**Purchase Land**	Placement site/staging area for processing dredged material for final placement	Variable (100+)	Indefinite	Lifespan = variable, until land is filled. Yearly = volume depends on land size and volume dredged per year	Road, pipeline, barge	N/A	Variable	Potentially large capacity Could help as a place to dry material for other sites	Cost Must meet state regulations (PADEP for PA and MDE for MD) Transport containers must be watertight. Potential long transport distance Purchase of land would be needed. Potential for zoning hurdles or contamination/ groundwater issues Water may need to be decanted, requiring another pipeline to return the effluent to the river.
15	**Shirley Plantation**	Placement site	1,800	Indefinite	Lifespan = unknown Yearly = 500,000 cy/year to 1,000,000 cy/year An additional 40-60 million cy could be available through mine reclamation.	Road, barge	$50/cy	270	Large capacity Potential to help with mine reclamation Beneficial use	Must meet VA chemical criteria and regulations Transport containers must be watertight. Long transport distance Water may need to be decanted, requiring another pipeline to return the effluent to the river Potential issues in obtaining water quality certificate; tidal wetlands permit/ authorization required
16	**Mines**	Placement site	Variable	Indefinite	Lifespan = variable, until mine is filled Yearly = volume depends on mine size and volume dredged per year	Road, pipeline, barge	Unknown	Variable	Large capacity Reclamation potential	Must meet state regulations (PADEP for PA and MDE for MD) Transport containers must be watertight. Long transport distance Water may need to be decanted, requiring another pipeline to return the effluent to the river. Mine owners contacted had no interest in sediment because of limitations on their mining permits.
17	**Modern Landfill (York, PA)**	Placement site	80	8	Lifespan = 240,000 cy Yearly = TBD	Road, rail	$24/cy (equivalent to $30/ton)	37	Some capacity Moderate transport distance	Tipping fees Dry material High cost Water may need to be decanted, requiring another pipeline to return the effluent to the river. Regulations – PADEP and MDE have limits on what sediment can be placed; sediment is either classified as clean or waste based on certain criteria. If material is considered waste, special handling is required, which adds more cost.
18	**Republic Materials Landfill (Conestoga, PA)**	Placement site	80	26	Lifespan = 240,000 cy Yearly = TBD	Road, rail	$24/cy (equivalent to $30/ton)	46	Some capacity Moderate transport distance	
19	**Scarboro Landfill (Aberdeen, MD)**	Placement site	106	Unknown	Lifespan = 318,000 cy Yearly = TBD	Road, pipeline	To be determined	13	Some capacity Within acceptable pumping distance, potential to be pumped directly	

	Sediment Management Strategy	Description	Area Involved (acres)	Lifespan (years)	Lifespan and Yearly Capacities (cubic yards, cy)	Access	Tipping Fee ($/cy)	Distance from Reservoirs (miles)	Pros	Cons
20	**Stancills Quarry (Perryville, MD)**	Placement site	70	Unknown	Lifespan = 9,000,000 cy Yearly = TBD	Road, pipeline	$4/cy	13	Large capacity Within acceptable pumping distance, potential to be pumped directly	Must meet state regulations Tipping fees May only take dry material Drying Water may need to be decanted, requiring another pipeline to return the effluent to the river High cost Watertight transport Potential long transport distance This alternative may require groundwater protections actions. Further testing to characterize the sediment (e.g., TCLP) would need to be done before placement. Potential groundwater protection actions could include: (1) ensuring 4 feet of unsaturated soil to groundwater table; (2) 12 inches of impermeable cover material on the top; (3) a venting system for the gas byproducts of the decomposed organics; (4) a leachate collection system for the residual liquid in the sediment and water from decomposed organics ; and (5) a liner to prevent migration of contaminants (worst case).
21	**Port Deposit Quarry (MD)**	Placement site	68	Indefinite	Lifespan = 3,250,000 cy Yearly = TBD	Road, rail, pipeline	0	3.5	Large capacity Within acceptable pumping distance, potential to be pumped directly	
22	**Penn/MD Materials Quarry (Peach Bottom, PA)**	Placement site	60	25-30	Lifespan = 9,000,000 cy Yearly = TBD	Road, pipeline	To be determined	5	Large capacity Within acceptable pumping distance, potential to be pumped directly	
23	**Penn/MD Materials Quarry (Skippack, PA)**	Placement site	100	Unknown	Lifespan = 300,000 cy Yearly = TBD	Road	To be determined	72	Some capacity Moderate transport distance	
24	**Mason Dixon Quarry (Belvidere Plant, MD)**	Placement site	565	40	Lifespan = 35,000,000 cy Yearly = TBD	Road, pipeline	To be determined	12.5	Large capacity Within acceptable pumping distance, potential to be pumped directly	
25	**Mason Dixon Quarry (Perryville Plant, Perryville, MD)**	Placement site	107	40	Lifespan = 21,400,000 cy Yearly = TBD	Road, pipeline	To be determined	12.3	Large capacity Within acceptable pumping distance, potential to be pumped directly	
26	**Mason Dixon Quarry (Cecil Plant, Cecil County MD)**	Placement site	150	40	Lifespan = 16,050,000 cy Yearly = TBD	Road, pipeline	To be determined	10	Large capacity Within acceptable pumping distance, potential to be pumped directly	
27	**Mason Dixon Quarry (Westgate Plant, York County, PA)**	Placement site	21	Indefinite	Lifespan = 3,060,000 cy Yearly = TBD	Road, rail	To be determined	38	Large capacity Moderate transport distance	
28	**Pennsy Supply Quarry Sites (PA)**	Placement site	--	Unknown	Initial indication is that the sites do not have the ability to assist in the disposal of material	Road, rail	--	Up to 100 miles	Large capacity One company with multiple sites	
29	**Eastern Industries Quarry Sites (PA)**	Placement site	--	Unknown	Company has not replied to multiple inquiries	Road, rail	--	Up to 100 miles	Large capacity One company with multiple sites	

Figure 5-10. Schematic of Sediment Management Strategies



alternatives were chosen due to their apparent viability relative to other similar strategies, no rigorous comparisons were conducted nor were the alternatives optimized (e.g., to be more effective) through a detailed design process. Furthermore, more complex alternatives were not developed (e.g., combining additional BMP's in conjunction with dredging).

A number of factors could be varied to develop conceptual plans and corresponding concept costs. For example:

- How material is dredged – mechanically or hydraulically;
- Where material is dredged: behind any of the three of the reservoirs;
- How material is transported to dewatering site and/or placement site – truck, rail, barge, direct pump;
- How material is dewatered – rotationally via cells, via construction equipment;
- Final placement site – distance, topography, on-site needs, permitting;
- How much material is removed, how often, and what time of year; and
- Strategic evaluations: varying/combining any of the factors above.

Concept-level plans and costs were developed for four groups of representative alternatives. These groups were: (1) innovative (beneficial) reuse, (2) open-water placement, (3) upland placement, and (4) watershed management. The first three groups fall under the third strategy category, increasing or recovering storage volume, while the fourth group was in the first category of reducing sediment from the watershed.

As discussed in Section 5.3, all four strategies that fall under the second category of minimizing sediment deposition (passively routing suspended sediment through the dams) were deemed to have fatal flaws and were dropped from consideration; therefore, no concept-level plans or costs were developed for the second category of sediment management strategies.

For each representative alternative, the LSRWA team developed a factsheet to lay out a conceptual plan and range of costs. These factsheets are included in Appendix J, Attachment J-2. Items contained in each factsheet include a physical description, assumptions, and a graphic (photograph or map). These factsheets lay out the operational assumptions, major limitations, investment costs, and annual/removal costs for each representative alternative, as applicable.

For the open-water, innovative (beneficial) reuse, and upland placement representative alternatives, the team compiled available information collected during the management strategy identification, screening, and evaluation process. The team then laid out possible logistics and infrastructure investments for three levels of one-time removal: 1 million cubic yards (mcy), 3 mcy, and 5 mcy to get a sense of unit costs. This methodology was not applicable for the watershed management representative alternative since management strategies (e.g., BMPs) once implemented, continue to remove or reduce sediment (although many BMPs will need to be cleaned out and maintained to continue to be effective).

Cost values are presented as a range. The limitations presented in the factsheets are not all encompassing and could be expanded. For example, tipping fees were based on recently collected data, but may be able to be negotiated. The costs developed are concept-level only; a feasibility study would be required to determine more detailed design and cost analyses if an entity was looking to implement any of these alternatives.

As described in Section 5.2, the LSRWA team relied heavily on the work done by the jurisdictional partners in development of their WIPs for the watershed management strategies. As such, the LSRWA team adopted the CBP methodology and unit costs as the representative alternative for a watershed management strategy; additional cost and design analyses were not undertaken. [13]

The information detailed for each representative alternative was compiled into a summary spreadsheet, with one worksheet for each removal volume considered (1 mcy, 3 mcy, and 5 mcy) to allow for easy comparisons. These worksheets are also provided in Appendix J, Attachment J-2.

The representative alternatives are summarized in Table 5-6.

[13] For alternatives that are increasing/recovering storage volume, the annualized, one-time investment costs are based on a 50-year project life and the fiscal year 2014 federal interest rate of 3.5 percent while CBP methodology utilized a 5% discount rate.

Table 5-6. Summary of Representative Alternatives

Representative Alternative	Description of Alternative	Estimated Unit Cost for Annual Removal ($/cy)		
		1 mcy	3 mcy	5 mcy
1 – Innovative Reuse	Sediment hydraulically dredged and turned into LWA for use as construction material.	$39-50	$29-39	$26-39
2A – Open-Water Placement, Placement Site at Pooles Island	Hydraulically dredge material and pump downstream to a temporary placement site that is available near Port Deposit. At this location, material can be dewatered and loaded into barges, and then transported to Pooles Island, MD.	$16-23	$16-21	$16-21
2B – Open-Water Placement, Winter Sediment Bypassing	Hydraulically dredge sediment, utilizing a pipeline from the dredge to pump past Conowingo Dam downstream to a release point, during the winter months (December-February).	$11-17	$10-16	$10-16
2C – Open-Water Placement, 9 Months of Sediment Bypassing	Hydraulically dredge sediment; utilizing a pipeline from the dredge, to pump past Conowingo Dam downstream to a release point over 9 months (September-April).	$6-12	$5-11	$5-11
3A – Upland Placement, Stancills Quarry	Hydraulically dredge material and pump downstream to a dewatering site at Stancills Quarry, prior to permanent placement at Stancills Quarry.	$23-35	$22-34	$22-33
3B – Upland Placement, Mason-Dixon (Cecil) Quarry, Mechanical Dredging	Mechanically dredge material and place into barges. Barges will be offloaded via excavators, using staging areas on the shoreline. Material will be transferred from each barge to trucks, which can haul 12 cy of material; the assumed rate of filling is one truck every 10 minutes; the trucks will then proceed to the Mason-Dixon Quarry for unloading and then return.	$53-90	$52-89	$52-88
3C – Upland Placement, Mason-Dixon Quarry (Cecil), Hydraulic Dredging	Hydraulically dredge material and pump downstream to a dewatering site that is across the Susquehanna River from Port Deposit. At this location, material can be dewatered and then placed onto the trucks via excavators to be moved to a final placement site at Mason-Dixon Quarry.	$36-55	$36-54	$36-53
3D – Upland Placement, MD Belvidere Quarry, Hydraulic Dredging,	Hydraulically dredge material and pump downstream directly to the Belvidere Quarry (Mason-Dixon owned) where it can be dewatered and permanently placed at the site.	$36-50	$36-49	$36-48
4 – Watershed Management, Sediment Management Beyond the WIPs	Based on CBP E3 Scenario, this includes additional BMPs in the Susquehanna watershed above the planned WIPs. Scenario estimates a reduction of 117,000 cubic yards (95,000 tons) of sediment annually for a one-time total investment of $1.5-3.5 billion.	$256-$597		

<u>Notes</u>: For Alternative 3D, removing 1 mcy annually equates to a total removal of 50 mcy over a 50-year project life; with a unit cost of $36-50/mcy, the total investment would be $1.8 to $2.5 billion.

For Alternative 4, the annual reduction of 117,000 cubic yards equates to a total removal of 5.86 mcy over a 50-year project life; with a unit cost of $256-597mcy, the total investment would be $1.5 to $3.5 billion.

5.6 EFFECTIVENESS AND IMPACTS OF MANAGEMENT STRATEGIES

The next step in the management strategy development process was to determine the effectiveness and impacts of the sediment management strategies. Modeling scenarios (and in some cases desktop analyses) were run to shed insight on the effectiveness of alternatives and impacts. Effectiveness can be described in terms of increasing deposition (reservoir sedimentation) or by decreasing the amount of sediment available for scour during a storm (especially during ecologically critical times of year).

Impacts are described in terms of the effects of sediment (and associated nutrients) on light attenuation, SAV, chlorophyll, and DO in the Bay. Also, results of the criteria assessment procedure shed further light on the impacts and provided estimated changes in attainment of water quality standards developed to protect Chesapeake Bay living resources. The CBEMP model was the primary tool utilized to estimate impacts and is linked to the AdH/HEC-RAS outputs (which determined effectiveness) for various scenarios as described in Chapter 3. The text in Section 3.3.6 describes aquatic ecosystems and the Bay's designated uses with respect to the water quality parameters shown in Table 5-7.

The modeling runs were not set up to match each of the representative alternatives. The representative alternative approach was important for determining costs but, in some cases, effectiveness and impacts could be evaluated without corresponding model runs. When model runs were necessary, required information included: (1) the quantity of sediment removed or managed; (2) whether material is removed out of system (dredging, BMP's) or placed elsewhere within the Bay (bypassing); and (3) in some cases, the time of year.

Appendix J, Attachment J-4, provides details on all of the modeling scenarios performed for the sediment management scenarios. Table 5-7, which builds on the earlier Table 3-2, is a summary table of the major sediment management scenarios showing estimates of their effectiveness and environmental effects.

An agitation dredging scenario (Scenario 7) is presented in Table 5-7. However as discussed in Section 5.3, this type of strategy was deemed to have a fatal flaw and was dropped from further consideration. Modeling was required in order to make this determination; thus, it is presented in Table 5-7, but will not be discussed any further in this section.

A watershed management scenario (Scenario 14) is presented in Table 5-7. This strategy was not modeled. As discussed in Section 5.2, this LSRWA effort relied heavily on the work of CBP to develop this strategy, the E3 scenario was used as an example, and a desktop analysis was performed by the team (Section 5.2) to determine sediment quantities available to be managed. Based on the CBP E3 scenario, Scenario 14 includes additional BMPs in the Susquehanna River watershed above the planned WIPs. Scenario 14 estimates a reduction of 117, 000 cubic yards (95,000 tons) which is an order of magnitude less than what is estimated to flow over Conowingo Dam into Chesapeake Bay on an average annual basis (approximately 1.8 million tons for the 1993-2012 average). This strategy/scenario will not be discussed any further in this section. Results of the remaining scenarios are discussed below.

Table 5-7. LSRWA Sediment Management Scenarios and Results

Characteristic (Applicable Designated Use)	**SCENARIO 7** What are the effects of agitation dredging?	**SCENARIO 8** What are the effects of strategic dredging?	**SCENARIO 9** What are the effects of passing sediment downstream for 3 winter months, one time?	**SCENARIO 10** What are the effects of passing sediment downstream for 3 winter months each year for a period of 10 years?	**SCENARIO 11** What are the effects of passing sediment downstream for 9 months?	**SCENARIO 12** What are the effects of extreme dredging (restoring the system to 1996 bathymetry)?	**SCENARIO 13** What are the effects of long-term strategic dredging over time for a period of 10 years?	**SCENARIO 14** What are the effects of increasing BMPs in the watershed above that required to meet TMDL?
Concept	Re-suspending reservoir bed sediment into the water column by mechanical means through the outlet structures of the dam Goal was to determine minimum flow required to maintain resuspended sediment in suspension to allow transport through outlet structures.	One time removal of 3 mcy (2.4 million tons) from reservoir system An area behind Conowingo was selected, 1.0 to 1.5 miles above the dam. Dredging area selected based on the highest deposition rate	3 mcy (2.4 million tons) bypassed over 3 months (90 days) in 1 year December-February time period	3 mcy (2.4 million tons) bypassed over 3 months every year for 10 years December-February time period	3 mcy (2.4 million tons) bypassed over 9 months (270 days) in one year September-April time period	The 1996 bathymetry was modeled. This bathymetry has 31 mcy (25 million tons) less sediment than the 2011 bathymetry.	Removing 3 mcy (2.4 million tons) on an annual basis for 10 years	Implementing BMP's Based on CBP E3 scenario Includes additional BMPs in Susquehanna watershed above planned WIPs Scenario estimates a reduction of 117,000 cubic yards (95,000 tons) annually.
Sediment Loads (Migratory fish spawning and nursery; shallow-water bay grasses; open-water fish and shellfish)	A minimum flow of 150,000 cfs is required to ensure transport of sediment through dam. This flow occurs on average 12 days per year, usually in the spring which is a critical time of year for living resources. During this flow, conditions could be unsafe for operations.	AdH load to Bay (2008-11) was reduced by 1.4 % (22.3 to 22.0 million tons). The scour load decreased by 10% (3.0 to 2.7 million tons). Net reservoir sedimentation increased by 7.5% (4.0-4.3 million tons). Scour load decreased by 3.3% for every mcy removed. CBEMP - 1996 scour load was reduced by 32% compared to same scour event with existing bathymetry (2.61 to 1.77 million tons).	Calculated that daily load to Bay increased from 1,940 to 28,600 tons per day for 90 days assuming a base flow of 60,000 cfs out of Conowingo Dam.	CBEMP calculated an additional sediment load of 2.40 million tons annually.	Calculated that daily load to Bay increasing from 1,940 to 10,800 tons per day for 270 days The impact to daily load concentrations is more severe over 3 months of bypass operations and less concentrated over 9 months of bypass operations. The 9-month bypass approach will have the effect of discharging loads during the SAV-growing season.	AdH (2008-11) calculated 1.8 million tons of scour for TS Lee (1996 bathymetry) vs. 3.0 million tons of scour (2011 bathymetry) – a 67% scour load increase. Total sediment load to the Bay (1996 bathymetry) was 20.3 million tons; with 2011 bathymetry, it was 22.3 million tons, a 10% increase in total load to the Bay. Reservoir sedimentation was 6.0 million tons (1996 bathymetry) and 4.0 million tons in 2011, a 33% decrease in deposition. CBEMP calculated a reduced scour of the 1996 storm of 44% compared to existing bathymetry (2.61 to 1.44 million tons).	Total removal of 31 mcy 1.5 million tons of sediment is estimated to accumulate annually in Conowingo. If 3 mcy per year (2.4 million tons per year) were removed for 10 years, the system does not go back to the 1996 bathymetry. Assuming an average system deposition of 1.5 million tons a year, 15 million tons would be deposited over 10 years; removal of 24 million tons (3 mcy) over the decade yields a net removal of 9 million tons in 10 years. This would be an average net removal of 0.9 million tons per year. Benefits are likely to be less than Scenario 12 since deposition will occur over 10 years.	Maximum available sediment per year that could be reduced by additional BMP implementation is approximately a reduction of 117,000 cubic yards (95,000 tons) annually. This is an order of magnitude of what is estimated to flow over the Conowingo into Bay on an average annual basis (Conowingo overflow = approximately 1.8 million tons/year, 1993-2012).

Characteristic (Applicable Designated Use)	**SCENARIO 7** What are the effects of agitation dredging?	**SCENARIO 8** What are the effects of strategic dredging?	**SCENARIO 9** What are the effects of passing sediment downstream for 3 winter months, one time?	**SCENARIO 10** What are the effects of passing sediment downstream for 3 winter months each year for a period of 10 years?	**SCENARIO 11** What are the effects of passing sediment downstream for 9 months?	**SCENARIO 12** What are the effects of extreme dredging (restoring the system to 1996 bathymetry)?	**SCENARIO 13** What are the effects of long-term strategic dredging over time for a period of 10 years?	**SCENARIO 14** What are the effects of increasing BMPs in the watershed above that required to meet TMDL?
Nutrient Loads (All designated uses)	Not determined	The nitrogen scour load estimated by CBEMP for the January 1996 storm with strategic dredging is 5,310 tons organic nitrogen. The phosphorus scour load estimated by CBEMP is 1,770 tons particulate phosphorus. These represent 32% reductions from the 1996 scour load calculated with 2011 bathymetry.	The one-time additional nutrient load estimated by CBEMP is 7, 210 tons organic nitrogen and 2,400 tons particulate phosphorus.	The additional organic nitrogen and particulate phosphorus loads associated with bypassing estimated by CBEMP are 7,210 tons/year and 2,400 tons/year, respectively.	Not determined	The nitrogen scour load estimated by CBEMP for the January 1996 storm with extreme long-term removal is 4,340 tons organic (particulate) nitrogen. The phosphorus scour is 1,450 tons particulate phosphorus. These represent 45% reductions from the scour load calculated with 2011 bathymetry by CBEMP.	Under ideal circumstances, the benefits from this scenario would be the same as Scenario 12. These are the benefits realized from net removal of 3 mcy/year for 10 years. In reality, the benefits are likely to be less since deposition will occur during the 10-year interval. Results for Scenario 12 should be regarded as the "best case" results from long-term strategic dredging.	No projections for nutrient loads reductions to accompany the solids load reductions
General Water Quality Effects (All designated uses)	Not determined	Effects are most obvious in the summer following the scour event. DO improvements extend along the trench of the Bay from Baltimore Harbor to the mouth of Potomac and into the Potomac trench. Reductions in chlorophyll are roughly the same extent. Limited benefits are seen in light attenuation, because scoured sediment settles out or is dispersed before SAV-growing season.	Dredging and bypassing for solely 1 year is an unlikely management strategy. Projecting the effects of 1 year of bypassing would be no worse in magnitude than Scenario 10. The temporal extent would be limited primarily to the summer season following the bypassing. Detrimental effects would diminish with time thereafter.	Water quality deteriorates as a result of sediment bypassing. The effects are widespread, ranging from near the head of the Bay to the mouth of the Potomac River and beyond. The lower Potomac River is affected as well. Diminished water quality is seen in all years of our simulation since the bypassing takes place in all years.	Not determined	The benefits from dredging back to 1996 conditions extend from above Baltimore Harbor to the mouth of the Potomac River and, in some years, into the Potomac River. Since the benefit comes from a one-time storm event, the extent and magnitude of the benefits generally diminish with time following the storm.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12 as a best case, although this is unlikely.	The water quality effects will vary from year to year depending on hydrology and annual loading. Experience with other scenarios indicates the benefits from solids reductions are limited since the loads largely occur during non-critical periods for SAV.

Characteristic (Applicable Designated Use)	**SCENARIO 7** What are the effects of agitation dredging?	**SCENARIO 8** What are the effects of strategic dredging?	**SCENARIO 9** What are the effects of passing sediment downstream for 3 winter months, one time?	**SCENARIO 10** What are the effects of passing sediment downstream for 3 winter months each year for a period of 10 years?	**SCENARIO 11** What are the effects of passing sediment downstream for 9 months?	**SCENARIO 12** What are the effects of extreme dredging (restoring the system to 1996 bathymetry)?	**SCENARIO 13** What are the effects of long-term strategic dredging over time for a period of 10 years?	**SCENARIO 14** What are the effects of increasing BMPs in the watershed above that required to meet TMDL?
Dissolved Oxygen (Migratory fish and spawning nursery; open-water fish and shellfish; deep-water seasonal fish and shellfish; deep-channel seasonal refuge)	Not determined	Summer-average DO improvements are largely 0.01 to 0.02 mg/L. Occasional improvements of up to 0.04 mg/L are seen in limited areas.	Potential declines of 0.2 to 0.3 mg/L estimated for the summer immediately following the bypassing. This estimate is based on results of the model run completed with sediment bypassing for 10 years.	Summer average declines of 0.2 to 0.3 mg/L are widespread. DO declines more than 0.3 mg/L in portions of the deep trench at the head of the Bay.	Not determined	The improvement in summer-average DO is 0.02 to 0.04 mg/L in widespread regions of the Bay and lower Potomac. Occasional improvements in excess of 0.04 mg/L are noted. The benefits are noted primarily in the one or two summers following the storm event.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined
Chlorophyll Concentration (Shallow-water bay grasses; open-water fish and shellfish)	Not determined	Chlorophyll reductions are largely in the range 0.02 to 0.05 µg/L, with limited regions showing improvements greater than 0.05 µg/L. The improvements are spatially-extensive in the summer following the scour event but diminish in successive years.	Potential increases of 0.5 to 1.5 µg/L for the SAV-growing season following the bypassing.	Chlorophyll increases, during the SAV-growing season, from 0.5 to 1.5 µg/L over large portions of the upper Bay. Excursions greater than 2 µg/L are seen in limited areas.	Not determined	Summer average chlorophyll declines by 0.02 to 0.05 µg/L in a large expanse of the Bay and lower Potomac River. The spatial extent of the benefits diminishes with time following the storm event	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined
Light Attenuation (KE) (Shallow-water bay grasses)	Not determined	Little change occurs in light attenuation, approximately 0.01/m. The improvement is minimal because the SAV-growing season is months after the scour event.	Minimal effects on light attenuation The solids from bypassing will settle out of the system before the SAV-growing season.	Light extinction increases by 0.01 to 0.025/m in the reach of the Bay from head to the Potomac River. The increases are attributed to increased chlorophyll rather than suspended sediment.	Not determined	Improvements in light attenuation during the SAV-growing season are minimal, 0.01/m or less. As with other scenarios, the solids effects from a winter storm do not extend into the prime growing season.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined

Characteristic (Applicable Designated Use)	SCENARIO 7 What are the effects of agitation dredging?	SCENARIO 8 What are the effects of strategic dredging?	SCENARIO 9 What are the effects of passing sediment downstream for 3 winter months, one time?	SCENARIO 10 What are the effects of passing sediment downstream for 3 winter months each year for a period of 10 years?	SCENARIO 11 What are the effects of passing sediment downstream for 9 months?	SCENARIO 12 What are the effects of extreme dredging (restoring the system to 1996 bathymetry)?	SCENARIO 13 What are the effects of long-term strategic dredging over time for a period of 10 years?	SCENARIO 14 What are the effects of increasing BMPs in the watershed above that required to meet TMDL?
Deep-Channel DO Water Quality Standard Achievement for TMDL (Deep-channel seasonal refuge)	Not determined	A decrease of 0.2% nonattainment over Scenario 3 (future conditions with WIPs in effect, existing bathymetry, scour event in winter) was estimated for CB3MH and CB4MH, and a 0.1% decrease in nonattainment in EASMH. These represent positive improvements.	Not determined	An estimated increase of nonattainment of 4% at CB3MH, 5% at CB4MH, 3% at CHSMH, 4% at EASMH, and 2% at PATMH over Scenario 3 (future conditions with WIPs in effect, existing bathymetry, scour event in winter). These represent negative impacts.	Not determined	A decrease of nonattainment over Scenario 3 (future conditions with WIPs in effect, existing bathymetry, scour event in winter) of 0.3% at CB3MH, 0.5% at CB4MH, and 0.2% at EASMH was estimated. These represent positive improvements.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined
Deep-Water DO Water Quality Standard Achievement for TMDL (Deep-water seasonal fish and shellfish)	Not determined	A decrease of 0.1% nonattainment over Scenario 3 (future conditions with WIPs in effect, existing bathymetry, scour event in winter) was estimated for CB4MH. This is a positive improvement.	Not determined	Estimated increases of 2% nonattainment at CB4MH, and 1% nonattainment at CSHMH, EASMH, MD5MH and PATMH over Scenario 3 (future conditions with WIPs in effect, existing bathymetry, scour event in winter). These represent negative impacts.	Not determined	A decrease of nonattainment over Scenario 3 (future conditions with WIPs in effect, existing bathymetry, scour event in winter) was estimated to be 0.3% at CB3MH, 0.5% at CB4MH, and 0.2% at EASMH. These represent positive improvements.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined
Open-Water DO Water Quality Standard Achievement for TMDL (Open-water fish and shellfish)	Not determined	Complete attainment of open-water DO standard was estimated.	Not determined	Complete attainment of open-water DO standard was estimated.	Not determined	Complete attainment of open-water DO standard was estimated.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined.
SAV Clarity Water Quality Achievement for TMDL (Shallow-water bay grass)	Not determined	Complete attainment was estimated.	Not determined	Complete attainment was estimated.	Not determined	Complete attainment was estimated.	The benefits from this scenario, when dredging is completed, are the same as Scenario 12.	Not determined.
CBEMP Modeling Run Number [1]		LSRWA-28		LSRWA-29		LSRWA-31		

Notes: [1] ERDC/EPA-CBPO ran roughly 30 modeling runs utilizing CBEMP. Modeling runs were denoted by "LSRWA-number." Only major modeling runs are reported and summarized in this main report. Appendices C and D provide further detail on other runs. Values in Appendix C utilize units of metric tons; these values have been converted to U.S. tons for consistency with other parameters. The conversion is 1 ton = 0.9072 metric tons.

5.6.1 Strategic Dredging

Effectiveness

The sediment management strategy for strategic dredging is depicted in Table 5-7 as Scenario 8. In this scenario, it was assumed that 3 mcy (2.4 million tons) were removed by dredging from an area above the Conowingo Dam on the eastern side of the reservoir approximately 1 to 1.5 miles north of the dam. This dredging area was selected because large amounts of sediment still naturally deposit at this location. Although changing the dredging area location will likely influence results, removing such a relatively small quantity of sediment will have a minimal impact on total load delivered to the Bay when large flood events occur, as detailed in Appendix B.

Utilizing the AdH model, the 2011 bathymetry was lowered approximately 5.0 feet in this area to simulate a post-dredging bed elevation. The altered 2011 bathymetry was simulated over the same 4-year flow record (2008-11 hydrology; Tropical Storm Lee scour event) and compared back to the unaltered 2011 Conowingo Reservoir bathymetry simulation. The total load to the Chesapeake Bay (watershed and scour) was reduced by about 1.4 percent, from 22.3 to 22.0 million tons; the scour load decreased by 10 percent (from 3.0 to 2.7 million tons); and the net reservoir sedimentation increased by 7.5 percent (4.0 to 4.3 million tons) for the 4-year simulation period (2008-11). For this simulation, the scour load decreased approximately 3.3 percent for every million cubic yards removed. Details on these modeling runs and calculations can be found in Appendix B.

Although the bed scour load is reduced, it is a relatively small contribution to the overall total load dominated by watershed and upstream reservoir sources. Dredging limited quantities from depositional areas in the reservoir has a minimal impact on total sediment load transported to the Bay. Large periodic flood flows dominate sediment transport dynamics in Conowingo Reservoir. The amount of sediment passed through the dam during floods is significantly higher than the estimated bed sediment scour load, thus small reductions in bed sediment scour due to dredging operations provide minimal benefits in terms of sediment load reductions to the Bay over time.

Impacts

Results of the strategic dredging scenario are depicted in Table 5-7 under the Scenario 8 column. As a result of dredging 3 mcy (2.4 million tons), the estimated scouring of sediment and nutrients was reduced by 32 percent in comparison to scour with a 2011 bathymetry (all other parameters the same). Dredging had little effect on model simulated water quality conditions in Chesapeake Bay. In the first summer following the storm event, surface chlorophyll is reduced a maximum of 0.1 mg/m^3 with the effect diminishing over time. The influence of the dredging on computed light attenuation during the SAV-growing season is negligible. Changes in chlorophyll and light attenuation induced by the dredging are much less than 1 percent. Bottom DO improves by 0.01 to 0.04 g/m^3. The reduction in anoxia in the summer following the storm event ranged from effectively 0 to 12 percent in various Chesapeake Bay segments; overall reduction in anoxia was 1.7 percent. The model calculations and results of this scenario analysis are found in Appendix C.

CBEMP estimated a decrease (a positive improvement) of 0.2 percent nonattainment in the deep-channel DO water quality standard for segments CB3MH and CB4MH, while a decrease of 0.1 percent nonattainment in segment EASMH was estimated. CBEMP also estimated a decrease of 0.1 percent in the deep-water DO water quality standard in CB4MH. The nonattainment calculations and analyses for this scenario are detailed in Appendix D.

Nutrient loads were estimated to have decreased somewhat under conditions of strategic dredging of 3 mcy, and as a consequence, the levels of deep-channel and deep-water DO standard attainment were estimated to be slightly improved under this condition.

5.6.2 Extreme Dredging

Effectiveness

The next sediment management strategy of extreme dredging is documented in Table 5-7 under Scenario 12. This modeling scenario looked at effects of dredging back to the bathymetry measured after the 1996 storm. Comparison of bathymetries between 1996 and 2011 indicate approximately 25 million tons of sediment have deposited in Conowingo Reservoir between 1996 and 2011 (approximately 31 million cubic yards, assuming a consolidated bulk density of 1600 kilograms per cubic meter). AdH model results for the 2011 and 1996 bathymetries indicate that the decrease in reservoir capacity between 1996 and 2011 has resulted in a 10-percent increase in total sediment load to the Bay (from 20.3 to 22.3 million tons), a 67-percent increase in bed scour (from 1.8 to 3.0 million tons), and a 33-percent decrease in reservoir sedimentation (from 6.0 to 4.0 million tons) for the 4-year simulation period (2008-11).

The results imply that if 31 mcy (25 million tons) of sediment were removed, there would be a 9-percent decrease in total load to the Bay (from 22.3 to 20.3 million tons), a 40-percent decrease in bed scour (from 3.0 to 1.8 million tons) and a 50-percent increase in reservoir sedimentation or deposition (from 4.0 to 6.0 million tons). These results are displayed in Table 5-8, and the modeling details can be found in Appendix B.

Although the scour increase from 1996 to 2011 appears significant, it only represents a relatively small fraction of the total load resulting from Tropical Storm Lee, as shown in Table 5-9. The modeling calculations to support these analyses are documented in Appendix B.

Impacts

Results of the extreme dredging scenario are shown in Table 5-7 under the Scenario 12 column. The nature of the response to removal of 31 mcy is similar to the response to the removal of 3 mcy although the magnitude of the effects is greater, especially for chlorophyll and DO. Similar to dredging 3 mcy, there is an initial increase in computed surface chlorophyll due to a reduction in sediment load and an improvement in computed water clarity. By summer, the improvement in water clarity is nearly indistinguishable as the scoured sediment from the storm 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. The modeling calculations to support these impacts are documented in Appendix C.

Table 5-8. Comparison of Sediment Transport in Conowingo Reservoir: 1996 to 2011 [1]

Bathymetry[2]	Outflow Load[3] (million tons)	Bed Scour Load[4] (million tons)	Net Deposition[5]
1996	20.3	1.8	6.0
2011	22.3	3.0	4.0

Notes: [1] These scenarios utilized the 2008-11 hydrologic period, which includes the Tropical Storm Lee scour event.
[2] Bathymetry data collected from each of these years were utilized as input parameters to AdH model.
[3] Outflow load is what flowed over Conowingo Dam into the Chesapeake Bay (includes bed scour load).
[4] Bed scour load is load from the Conowingo Reservoir bed to the Chesapeake Bay as estimated by AdH.
[5] Net deposition is what sediment remained behind Conowingo Dam in the reservoir.

Table 5-9. Comparison of Sediment Transport in Conowingo Reservoir with Tropical Storm Lee Percentage: 1996 to 2011[1]

Bathymetry[2]	Sediment Outflow Load[3] (million tons)	Total Lee Sediment Load[4] (million tons)	Lee Percent of Sediment Outflow Load	Conowingo Sediment Scour Load[5] (million tons)	Conowingo Sediment Scour Percent of Lee
1996	20.3	13.1	65%	1.8	14%
2011	22.3	14.5	65%	3.0	21%

Notes: [1] These scenarios utilized the 2008-11 hydrologic period which includes the Tropical Storm Lee scour event.
[2] Bathymetry data collected from each of these years were utilized as input parameters to AdH model.
[3] Sediment loads that flowed over Conowingo Dam and into the Chesapeake Bay (includes bed scour load from each of the reservoirs and loads from the watershed over 2008-11 hydrologic period).
[4] Includes watershed and Conowingo scoured sediment load to Chesapeake Bay during Tropical Storm Lee
[5] Scour load from Conowingo Reservoir bed to Chesapeake Bay

Averaged over the 1996 growing season, the improvements in chlorophyll are roughly 0.05 mg/m^3 Improvements in seasonal-average surface chlorophyll approach 1 percent in some Bay segments while improvements in light attenuation are limited to less than 0.5 percent. 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 percent in some Bay segments and by 2.8 percent overall. Appendix C contains the supporting documentation for these results.

In comparison to the scour with a 2011 bathymetry (and all other parameters the same), CBEMP estimated that removal of 31 mcy sediment from Conowingo Reservoir decreased Chesapeake Bay deep-channel DO water quality nonattainment by 0.3 percent, 0.5 percent, and 0.2 percent for segments CB3MH, CB4MH, and EASMH, respectively, as noted in Table 5-7. Nonattainment of the Chesapeake Bay deep-water DO water quality standard was also estimated decrease by 0.2 percent in segment CB4MH. Nutrient loads are estimated to decrease somewhat under conditions of extreme dredging, and as a consequence the deep-channel and deep-water DO standard were estimated to be slightly improved under this condition over no dredging and dredging 3 mcy. Supporting details for these results are provided in Appendix D.

5.6.3 Long-Term Strategic Dredging

The third sediment management strategy evaluated was long-term strategic dredging. This scenario is presented in Table 5-7 as Scenario 13. For this analysis, no models were used instead it was a desktop analysis utilizing information from other modeling runs.

Extreme dredging (restoring back to 1996 bathymetry) requires the removal of 31 mcy. It is unlikely that this could be done in one occurrence, due to the large volume involved; therefore, it would need to be done over time.

The 31-mcy (25 million tons) removal strategy would result in a 9-percent decrease in total sediment load to the Bay, a 40-percent decrease in bed scour, and a 50-percent increase in reservoir sedimentation at the end of a 10-year period of long-term strategic dredging.

However, 1.8 mcy (1.5 million tons) of sediment is estimated to accumulate every year in Conowingo Reservoir from the incoming watershed load (2008-2011 hydrology). If 3 mcy per year (2.4 million tons per year) were removed every year for 10 years, the net result would not be the 1996 bathymetry, because of this incoming load. Assuming the deposition is 1.5 million tons a year (based on 2008-2011 hydrology), 15 million tons would deposit in the 10-year period and 24 million tons (2.4 million tons annually) are removed in the same period, with a net removal of 9 million tons by the end of the decade. Thus, in the 10-year period, there is an average net removal of 0.9 million tons or 1.1 mcy per year.

This removal rate is about 37 percent of that associated with the strategic dredging scenario (Scenario 8, 3 mcy removed per year). However, these calculations do not take into account that the storage capacity would be increasing and thus more incoming sediment could be depositing. Even still, the benefits of long-term strategic dredging are likely to be much less than projected for the extreme dredging alternative (Scenario 12, net removal of 31 mcy at one time).

5.6.4 Sediment Bypassing

Effectiveness

The next sediment management strategy investigated was a set of scenarios for sediment bypassing. These scenarios are noted in Table 5-7 as Scenarios 9, 10, and 11. These scenarios combine desktop analyses and computations from CBEMP. Desktop analyses were used to estimate the effects of bypassing on sediment loads and concentrations under 2008-11 conditions.

For Scenario 9 and 10, it was assumed that 3 mcy (2.4 million tons) of sediment was transported below the dam and discharged into the Bay over a 90-day period. For Scenario 9, this volume was discharge one-time in winter, and for Scenario 10, the volume was discharged annually in winter for 10 years. CBEMP was run for Scenario 10 only. Results from Scenario 10 were extended to Scenario 9 via a desktop analysis. For Scenario 11, a desktop analysis was done assuming 3 mcy (2.4 million tons) of sediment was transported below the dam and discharged into the Bay over a 270-day period (fall, winter, early spring).

One goal of these scenarios was to determine the impact to suspended sediment concentrations below the dam. The total suspended sediment load for the sediment bypassing strategy consisted of the total Susquehanna River load passing through the dam plus the bypassed sediment load from the bypassing operation. It was assumed that the average Susquehanna River flow during the winter months was 60,000 cfs, approximately twice that of the median flow of about 30,000 cfs. At 60,000 cfs, the average suspended sediment measurement below the dam was assumed to be about 12 mg/L, which equates to a daily load of about 1,940 tons of sediment passing through the dam.

The bypassed load discharged below the dam for the 90-day period was 26,700 tons per day with a bypassing discharge of about 61 cfs. The dredging load discharged below the dam for the 270-day period was 8,900 tons per day. Thus, the total solids loading per day below the dam for the 90- and 270-day scenarios was 28,600 and 10,800 tons, respectively. Details about the modeling of the sediment bypassing strategy are located in Appendix B.

Analysis indicates that the 90-day loading resulted in an increase in total solids concentration from 12 to 177 mg/L, whereas the 270-day loading resulted in an increase in concentration from 12 to 67 mg/L. Bypassing sediment around Conowingo Dam will increase suspended sediment loading to the lower channel and Susquehanna Flats, with the 90-day bypassing scenario increasing suspended sediment concentrations by a factor of 15 (12 to 177 mg/L) and the 270-day bypass scenario increasing concentrations by a factor of 6 (12 to 67 mg/L). Specifics on these modeling results are in Appendix B.

These numbers should not be considered "benefits." The sediment bypassing alternative involves removing deposited bed sediment from some location within the reservoirs and pumping material to the upper Bay. The original intent of considering sediment bypassing was: (1) there were some sand-starved areas in the upper Bay that could benefit from bypassed sediment; and (2) the team hypothesized that sediment influx in winter would be less harmful than other times of year, thus reducing the amount of sediment available for scouring at more critical ecological periods (i.e., spring and summer).

Based on this analysis, these strategies would have similar effectiveness as the strategic dredging scenario since the same amount of sediment is removed. These effects include: (1) the scour load decreased by 10 percent (from 3.0 to 2.7 million tons); (2) the net reservoir sedimentation increased by 7.5 percent (from 4.0 to 4.3 million tons); and (3) scour load decreased approximately 3.3 percent for every million cubic yards removed. The difference, however is, unlike, the strategic dredging scenario (Scenario 8) which reduced the total load to the Chesapeake Bay (watershed and scour) by about 1.4 percent from 22.3 to 22.0 million tons, the sediment bypassing scenarios would not decrease loads to the Bay, but simply pass sediment loads that would have potentially scoured at other times of year.

Impacts

CBEMP was utilized to examine impacts of Scenario 10 (bypassing during the three winter months, annually for 10 years). Sediment was bypassed during the period of December through February of each simulation year (1991-2000). Using the CBEMP results, Scenario 10 scenario was compared to the strategic dredging scenario (one-time removal of 3 mcy from the reservoir), Scenario 8.

As expected, sediment bypassing results in increased suspended solids computed in the Bay during the bypassing period. The bypassed sediment settles quickly after bypassing stops. A secondary suspended sediment increase occurs during the summer when nutrients that accompany the bypassed sediment 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 Bay segment (CB2OH) averages approximately $0.1/m^1$ and the typical increase is approximately $0.025/m^1$, as noted in Appendix C.

As a result of the continuous discharge of nutrients associated with the bypassed sediment, computed increases in surface chlorophyll are extensive 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 Bay segments and increases of approximately 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. Decreases of 0.2 to 0.3 g/m^3 in summer average DO are widespread and an overall increase of 30 percent is estimated for anoxia. Modeling details to support these impact conclusions can be found in Appendix C.

CBEMP estimated that deep-channel DO and deep-water DO water quality standards were seriously degraded as a result of nutrients associated with the bypassed sediment. CBEMP calculated that sediment bypassing had the effect of increasing nutrient loads delivered to Chesapeake Bay by 7,210 tons/year of TN and 2,400 tons/year of TP. This scenario was estimated to increase Chesapeake Bay deep-channel DO nonattainment by an estimated 4 percent, 5 percent, 3 percent, 4 percent, and 2 percent (in comparison to the simulation with 2011 bathymetry, with all other parameters the same) for segments CB3MH, CB4MH, CHSMH, EASMH, and PATMH, respectively. These results are documented further in Appendix D.

CBEMP modeling indicates that the environmental costs of bypassing (diminished DO, increased chlorophyll) are roughly 10 times greater than the benefits gained from reducing scour in the reservoir (Appendix C).

5.7 SEDIMENT MANAGEMENT STRATEGY RESULTS

The final step in the development of sediment management strategies was to compare the cost ranges, effectiveness, and impacts of the strategies that were developed via modeling and desktop analyses. The full matrix of sediment strategies, cost ranges, effectiveness, impacts, and evaluation factors is included in Appendix J, Attachment J-3.

Strategic dredging reduces bed sediment scour load. However, it is a relatively small contribution to the overall total sediment load dominated by watershed and upstream of Conowingo Dam sources. Dredging limited quantities from depositional areas in the reservoir has a minimal impact on total sediment load transported to the Bay. Large periodic flood flows dominate sediment transport dynamics in Conowingo Reservoir. The amount of sediment passed through the dam during high flows, is significantly higher than the estimated bed scour load; thus, small reductions in bed sediment scour due to dredging operations provide minimal benefits in terms of sediment load reduction to the Bay over time. Strategic dredging had little effect on estimated water quality conditions in the Chesapeake Bay.

Extreme dredging produces a reduction of total sediment load discharged to the Bay, a reduction of in bed sediment scour, and an increase in net sedimentation. However, the net reduction in sediment discharge represents a small fraction of the total sediment load resulting from an event such as Tropical Storm Lee. The nature of the response to extreme dredging is similar to the response to a one-time removal of 3 mcy of sediment, although the magnitude of the effects is greater.

Different volumes of sediment could have been selected to evaluate benefits, but results would have only fallen between these two values of extreme (31 mcy) and strategic (3 mcy) dredging. Any dredging alternative comes with very high costs with relatively small benefits observed. The long-term reality of dredging is that large volumes of sediment are depositing annually. Therefore, the net removal of sediment out of the system is minimal because part of the dredging operation would simply be "keeping up" with sediment deposition; therefore, apparent benefits would also be reduced.

Bypassing costs are still high but not as high as dredging. Bypassing is just as effective as dredging at increasing sediment deposition and reducing available sediment for scour events. However, this method increases total sediment loads to the Bay. The environmental costs (diminished DO, increased chlorophyll) are roughly 10 times greater than the benefits gained from reducing bed sediment scour in Conowingo reservoir.

Among the alternative management scenarios formulated, agitation dredging and sediment bypassing could provide additional sediments that would be deposited in the upper Bay and impact bottom conditions. The other alternative scenarios would have essentially no effect on the upper Bay bottom.

As discussed in Appendix K, the bottom sediments of the Susquehanna Flats are substantially anthropogenic (Gottschalk, 1945), and SAV thrives at this location because of the large expanse of shallow water within the photic zone. As sea level rises, natural reworking of sediments of the flats by waves and currents would continue to maintain shallow-water habitat within the photic zone; however, the available area within the photic zone would presumably decrease over time. Consequently, maintenance of the flats' geomorphic character and the vast SAV beds there over decades to centuries would likely be dependent on continued receipt of excess sand above natural levels from the Susquehanna River. Alternative scenarios releasing substantial quantities of sand could tend to have detrimental impacts to SAV over the short term, but could be beneficial to SAV over the long term by maintaining shallow water in the photic zone.

While storms have substantial effects on SAV (Gurbisz and Kemp, 2013; Wang and Linker, 2005), the principal difference among alternatives over the long term with respect to SAV (other than maintenance of geomorphic character and shallow water of the flats) would be a function of how the alternatives affect nutrient releases to Chesapeake Bay, and thus water clarity, within the Bay. Alternatives that improve Bay water clarity more greatly than others would generate healthier, denser SAV beds that would be more resilient to storm damage, and recover more rapidly than would less healthy beds. Alternatives that serve to impair water clarity during the SAV-growing season would induce less healthy beds that would be more vulnerable to future storm damage.

The substantial distance from the mouth of the Susquehanna River to extant oyster beds limits sediment that can be delivered to these beds from the river. Thus, differences among alternatives in quantities of sediment delivered are probably not of substantial importance with regard to oyster health in this region, since oysters in the upper Bay are overall more affected by freshets than by sediment. Any alternative reducing dissolved oxygen levels in deeper waters of the oysters' range could detrimentally impact oyster populations in affected waters.

Additional opportunities (e.g., implementation of BMPs) to reduce sediment in the watershed (above levels already committed to with the states' WIPs) are high cost and sediment load reductions are small in comparison to other strategies. Therefore, benefits would be small. However, a long-term advantage of this type of strategy is lower maintenance costs, whereas any dredging or bypassing would have high annual costs as it would need to be implemented each year to incur benefits. When strategies developed for this effort to reduce sediment available for a storm event are compared to the implementation of WIPs, benefits are significantly higher for WIP implementation.

CBEMP modeling estimates showed that the sediment load (not including nutrients they contain) from scour events are not the major threat to Bay water quality. Although the sediment is subject to some resuspension, once deposited on the bottom, the effect of sediment on Chesapeake Bay water quality essentially ceases (Appendix C). Thus, sediment management strategies that focus solely on sediment (even very large volumes) and moving it out of the river/reservoir system entirely or downstream do not incur significant benefits (i.e., water quality improvements) for aquatic life.

The nutrients associated with the sediment are more damaging to the Chesapeake Bay ecosystem. After deposition, biogeochemical processes transform particulate organic nutrients and inorganic nutrients adsorbed to sediment into dissolved forms which diffuse into the overlying water, are bioavailable, and adversely affect Bay water quality. Dissolved nutrients are recycled to the water column and stimulate algal production. Algal organic matter decays and consumes oxygen in the classic eutrophication cycle. As a consequence, DO is diminished by Conowingo scour events. Nutrients take years to undergo sediment burial to a depth where they are no longer an influence on the overlying (surface) tidal waters. CBEMP modeling predicts that as the years go by, the impacts to Chesapeake Bay water quality decrease after a scouring event (Appendix C).

The relative importance of nutrient load impacts from the lower Susquehanna River system indicates that nutrient load management and mitigation options could be more cost-effective and provide more management flexibility than solely relying on management options focused on sediment only (Appendix D).

It should be noted that the LSRWA effort was a watershed assessment and not a detailed investigation of a specific project alternative(s) proposed for implementation. That latter would likely require preparation of a NEPA document. The evaluation of sediment management strategies in the assessment focused on water quality impacts, with some consideration of impacts to SAV. Other environmental and social impacts were only minimally evaluated or not evaluated at all. A full investigation of environmental impacts would be performed in any future, project-specific NEPA effort.

Sediment management strategies could also impact issues of navigation. Large storm events can transport and deposit substantial quantities of sediment from the Susquehanna River into the Susquehanna Flats region, and thus impact the USACE Susquehanna/Havre de Grace navigation project and other small USACE navigation projects in the upper Bay.

Reduced sediment from the Susquehanna River via any of the scenarios analyzed would provide for some reduction in need for maintenance dredging of these small projects. USACE also maintains deep-draft navigation channels in open waters of the upper Bay (the approach channels to the C&D Canal and the Baltimore Harbor), portions of which are geographically positioned to potentially receive substantial sediment from the Susquehanna River watershed. However, substantial portions of these channels lie within the upper Bay estuarine turbidity maxima (ETM; described in Appendix K, Section 5.1) and are thus located in areas of natural chronic high bottom sedimentation rates, independent of large storms. ETM sediments derive both from the Bay and the watershed. Benefits of reduced dredging to these deep-draft navigation channels in any of the scenarios would likely be limited (see Appendix K, Section 5.1 and Figure K-7).

Table 5-10 is a matrix summarizing the modeling results of effectiveness for the sediment management strategies along with the computed cost ranges.

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Table 5-10. Sediment Management Strategy Summary Matrix

		Effectiveness			Sediment Loads	Nutrient Loads		Impacts		Cost Range			
Sediment Management Alternative	**Concept**	**Load to Bay (2008-11) Hydrology**	**Scour Load (TS Lee)**	**Reservoir Sedimentation (2008-11) Hydrology**	**1996 Scour Event Only, OR 1991-2000 Average Loads to Bay from Susquehanna River**	**Organic Nitrogen (tons)**	**Particulate Phosphorus (tons)**	**Deep-Channel DO Water Quality Standards**	**Deep-Water DO Water Quality Standards**	**Unit Cost (per cy)**	**Total Cost**	**Representative Alternative**	**Study Scenario and Analysis Method**
No Action	2010 land use 1991-2000 hydrology and reservoir trapping levels	N/A	N/A	N/A	3,370 tons/day on average over 10-year period Maximum load of 201,000 tons/day from Susquehanna River to Bay	69.3 tons/day on average over 10-year period	5.7 tons/day on average over 10-year period	Widespread nonattainment 23% in the CB4 mainstem, 14% in Eastern Bay, and 28% in the lower Chester River More than half of the deep-channel habitat in the Bay impacted	Widespread nonattainment, 11% in CB4 mainstem, 2% in Eastern Bay, and 11% in lower Chester River	N/A	N/A	N/A	Scenario 1 CBEMP LSRWA 4
WIPs in Place	WIPs in place 1991-2000 hydrology and trapping levels	N/A	N/A	N/A	2,540 tons/day on average over 10-year period Maximum load of 149,000 tons/day	50.8 tons/day on average over 10-year period	4.2 tons/day on average over 10-year period	Complete attainment	Complete attainment	N/A	N/A	N/A	Scenario 2 CBEMP LSRWA 3
WIPs in Place with a Scour Event	WIPs in place 1991-2000 hydrology and trapping levels Scour event	N/A	N/A	N/A	2.6 million tons over a 4-day period of scour event	7,800 tons over a 4-day period of scour event	2,600 tons over a 4-day period of scour event	Increase of 1% nonattainment at CB4MH, EASMH, and CHSMH over Scenario 2 (future conditions with WIPs in effect, but no scour event)	Increase of 1% nonattainment at CB4MH and CB5MH over Scenario 2 (future conditions with WIPs in effect, but no scour event)	N/A	N/A	N/A	Scenario 3 CBEMP LSRWA 21
Strategic Dredging	One-time removal of 3 mcy	Reduced from 22.3 to 22.0 million tons 1.4% reduction from existing bathymetry	Reduced from 3.0 to 2.7 million tons 10% reduction from existing bathymetry	Increased from 4.0 to 4.3 million tons 7.5% increase from existing bathymetry	Reduced from 2.61 to 1.77 million tons scour 32% reduction from existing bathymetry	5,310 tons during scour event 32% reduction over Scenario 3 (future conditions with WIPs in effect)	1,770 tons during scour event 32% reduction over Scenario 3 (future conditions with WIPs in effect)	Nonattainment decreases of 0.2% at CB3MH and CB4MH, and 0.1% at EASMH over Scenario 3 (future conditions with WIPs in effect) These represent positive improvements.	A decrease of nonattainment of 0.1% at CB4MH over Scenario 3 (future conditions with WIPs in effect) This represents a positive improvement.	$16-89	$48-267 million	1, 2A, 3A, 3B, 3C, 3D	Scenario 8 CBEMP LSRWA 28
Extreme Dredging	Removal of 31 mcy to restore reservoir back to 1996 bathymetry	Reduced from 22.3 to 20.3 million tons 9% reduction from existing bathymetry	Reduced from 3.0 to 1.8 million tons 40% reduction from existing bathymetry	Increased from 4.0 to 6.0 million tons 50% increase from existing bathymetry	Reduced from 2.61 to 1.44 million tons scour 44% reduction from existing bathymetry	4,340 tons during scour event 45% reduction	1,450 tons during scour event 45% reduction	Nonattainment decreases of 0.3% at CB3MH, 0.5% at CB4MH, and 0.2% at EASMH over Scenario 3 (future conditions with WIPs in effect) These represent positive improvements.	A decrease of nonattainment of 0.3% at CB3MH, 0.5% at CB4MH, and 0.2% at EASMH over Scenario 3 (future conditions with WIPs in effect) These represent positive improvements.	$16-89	$496 million to $2.8 billion	1, 2A, 3A, 3B, 3C, 3D	Scenario 12 LSRWA 31

Sediment Management Alternative	Concept	Effectiveness			Sediment Loads	Nutrient Loads		Impacts		Cost Range		Representative Alternative	Study Scenario and Analysis Method
		Load to Bay (2008-11) Hydrology	Scour Load (TS Lee)	Reservoir Sedimentation (2008-11) Hydrology	1996 Scour Event Only, OR 1991-2000 Average Loads to Bay from Susquehanna River	Organic Nitrogen (tons)	Particulate Phosphorus (tons)	Deep-Channel DO Water Quality Standards	Deep-Water DO Water Quality Standards	Unit Cost (per cy)	Total Cost		
Strategic Long-Term Dredging	Removal of 3 mcy (2.4 million tons) annually for 10 years. 1.5 million tons estimated to deposit annually (2008-11 hydrology) such that 15 million tons deposit in 10 years while 24 million tons is removed over 10 years. Net removal of 9 million tons (0.9 million tons or 1.1 mcy per year) This is about 37% of removal volume from one-time strategic dredging (Scenario 8).	Not determined	Not determined	Not determined	Not determined	Not determined	Not determined	Benefits are likely to be less than strategic dredging since deposition will occur during the 10-year interval.	Benefits are likely to be less than strategic dredging since deposition will occur during the 10-year interval.	$16-89	$480 million to $2.7 billion	1, 2A, 3A, 3B, 3C, 3D	Scenario 13 Desktop analysis
Bypassing, One-Time 3 Months	3 mcy passed downstream one time over 3 winter months	Daily load increased from 1,490 to 28,600 tons for 90 days	Reduced from 3.0 to 2.7 million tons 10% reduction from existing bathymetry	Increased from 4.0 to 4.3 million tons 7.5% increase from existing bathymetry	2.40 million tons, one time	7,210 tons added one time over Scenario 3 (future conditions with WIPs in effect)	2,400 tons added one time over Scenario 3 (future conditions with WIPs in effect)	Not determined But would be no worse than 10-year scenario	Not determined But would be no worse than 10-year scenario	$10-16	$150-480 million	2B	Scenario 9 CBEMP LSRWA 29
Bypassing, One Time 9 Months	3 mcy passed downstream one time over 9 months	1,940 to 10,800 tons per day for 270 days	Not determined	Not determined	Not determined	Not determined	Not determined	Not determined	Not determined	$5-11	$15-33 million	2C	Scenario 11 Desktop analysis
Bypassing, 3 Months Every Year for 10 Years	3 mcy passed downstream during 3 winter months for 10 years	Daily load increased from 1,490 to 28,600 for 90 days every year for 10 years	Reduced from 3.0 to 2.7 million tons 10% reduction from existing bathymetry	Increased from 4.0 to 4.3 million tons 7.5% increase annually from existing bathymetry	2.40 million tons annually	7,210 tons added annually over Scenario 3 (future conditions with WIPs in effect)	2,400 tons added annually over Scenario 3 (future conditions with WIPs in effect)	Increase of nonattainment of 4% at CB3MH, 5% at CB4MH , 3% at CHSMH, 4% at EASMH, and 2% at PATMH over Scenario 3 (future conditions with WIPs in effect)	Increase of nonattainment of 2% at CB4MH, and 1% at CSHMH, EASMH, MD5MH, and PATMH over Scenario 3 (future conditions with WIPs in effect) These represent negative impacts.	$10-16	$150-480 million	2B	Scenario 10 CBEMP LSRWA 29
Watershed Sediment Management Beyond the WIPs	Based on CBP E3 Scenario Additional BMPs in the Susquehanna watershed above and beyond the planned WIPs	Reduction of 95,000 tons (117,000 cy) annually	Not determined. Approximately 4% removal compared to strategic dredging	Not determined	Reduction of 95,000 tons (117,000 cy) annually	Not determined	Not determined	Not determined	Not determined	$256-597	$1.5-3.5 billion	4	Scenario 14 Desktop analysis

Chapter 6. Stakeholder Involvement

Because the LSRWA effort will not directly lead to implementation of specific actions to manage sediment and associated nutrients in the lower Susquehanna River, no formal National Environmental Policy Act (NEPA) compliance was required. Though no formal NEPA compliance was required, the LSRWA team recognized that it was imperative to involve stakeholders in order for the LSRWA to be a useful tool to the Chesapeake Bay community. Stakeholders were defined as all interested state, regional, and federal agencies, local governments, non-governmental organizations, business groups, and the general public; many of these were engaged throughout the LSRWA effort.

The Stakeholder Involvement Appendix (Appendix I) includes all documentation of stakeholder involvement including:

- Stakeholder outreach plan (Attachment I-1);
- Stakeholder coordination tracking sheet (summarizes date, audience, type of coordination, comment received, and team response follow-up to comments; Attachment I-2);
- Press releases (Attachment I-3);
- Study initiation notice (Attachment I-4);
- Resource agency mailing list, coordination letters, and responses (Attachment I-5);
- Quarterly meeting summaries[14] (Attachment I-6);
- Stakeholder review comments, including comments received prior to public release of the assessment (Attachment I-7); and
- Public review comments, including comments and response to comments received during the public comment period from November 13, 2014, to January 9, 2015 (Attachment I-8).

It was the consensus of the LSRWA team that getting input early and often from all stakeholders was very important in order to have a good understanding of stakeholder concerns of proposed strategies to manage sediment in the lower Susquehanna River, and to have an open, fully accessible process.

Key goals for stakeholder involvement included:

- Transferring knowledge gained during this assessment to all stakeholders;
- Incorporating the management efforts and activities of others in the watershed;

[14] Enclosures to the quarterly meeting summaries, such as handouts and presentations, are located on the project website at: http://bit.ly/LowerSusquehannaRiver.

- Receiving feedback on the sediment and nutrient management strategies that were developed; and
- Creating, facilitating, and maintaining open channels of communication with stakeholders to allow for full consideration of stakeholder views and information.

To accomplish these goals, the LSRWA team developed a stakeholder outreach plan. The team developed a public website where all study products (factsheets, meeting summaries, reports, and related studies) could be posted. The LSRWA website is: http://bit.ly/LowerSusquehannaRiver.

The team sent out study coordination letters to various federal and state resource agencies in February 2012 to inform agencies of the initiation of the study and to determine the level of involvement each agency would like to have with the study. Two response letters were received requesting involvement in the study as well as various emails from agencies confirming their willingness to participate in study. A study initiation notice was distributed via email in February 2012 as well.

The team held quarterly meetings to discuss, coordinate, and review technical components of the assessment, as well as management activities. These meetings were open to attendance by all stakeholders. Agendas and handouts were provided to stakeholders via email prior to the meeting and the meeting summary with items presented at quarterly meetings was posted to the public website after quarterly meetings. A total of 10 quarterly meetings were held from November 2011 to January 2014, with attendance ranging from 30 to 50 participants. These participants represented 19 different stakeholder groups.

Throughout the duration of the assessment, the LSRWA team coordinated with other pertinent and interested Chesapeake Bay groups, so as to be included on their agendas to provide updates and get feedback on the LSRWA. Feedback received from these other Chesapeake Bay groups was reported back to the rest of the LSRWA team and was incorporated into this LSRWA report.

Throughout the duration of the assessment, email updates were sent out periodically to interested stakeholders on study progress and news. This email distribution list was started by the original Sediment Task Force (included interested stakeholders) that SRBC led in 1999 and 2000. The team has been updating this list since 2009 with people interested in this effort.

Prior to public release, the draft LSRWA report was reviewed by the agencies involved in quarterly meetings. Additionally, the Chesapeake Bay Program Partnership's Scientific and Technical Advisory Committee (STAC) sponsored an independent scientific peer review of the draft LSRWA report in June-August of 2014. STAC provides scientific and technical guidance to the Chesapeake Bay Program Partnership on measures to restore and protect the Chesapeake Bay. More information about STAC, is located here: www.chesapeake.org/stac. Appendix I, Attachment I-7 contains the comments and LSRWA team responses to the LSRWA quarterly group's reviews and the STAC sponsored independent scientific peer review.

On December 9, 2014, a public meeting was held at Harford Community College in Bel Air, MD. The meeting consisted of a presentation of the study findings and recommendations, and a panel question and answer period. The presenters of the findings and recommendations included Dan

Bierly (USACE), Bruce Michael (MDNR), and Mark Bryer (TNC). Panelists included the presenters as well as Rich Batiuk (EPA), Mike Langland (USGS), and Matthew Rowe (MDE). A total of 67 attendees were present at the public meeting, while 20 persons participated via webinar.

Attendees at the public meeting were provided with index cards in order to ask questions of the panelists. Webinar participants were able to submit their questions as well. Telephone access to the meeting was also available. The panel tried to address as many questions as possible during the allotted time. All questions and comments, including those not addressed during the meeting, were addressed during the public comment period and are now included in Appendix I, Attachment I-8. The meeting agenda and the webinar (including slide presentation and audio) for the full meeting are available for download at the LSRWA website.

The draft report (dated October 10, 2014) was released on November 13, 2014. The public comment period for the draft report ran from November 13, 2014, to January 9, 2015. During this time, over 2,000 downloads of materials from the study website occurred. The most downloaded material included the executive summary (431 downloads) and full report (262 downloads). Over 300 comment were submitted by stakeholders, including agencies, non-profits, and the public. Comments were received by mail, email, and via hand delivery. All comments were addressed individually by the study team.

To protect the privacy of the individual members of the general public who submitted comments, comment codes (rather than individual's names) were used to identify and number comments. In addition to the general public, a number of agencies, businesses, and non-profit organizations also submitted comments. These include the Chesapeake Bay Foundation, the Soil and Water Conservation Society, the State Water Quality Advisory Committee, Support Conowingo Dam, Exelon, the Clean Chesapeake Coalition, and the U.S. Fish and Wildlife Service. A list of comment codes and all public comments and team responses can be found in Appendix I, Attachment I-8.

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Chapter 7. Recommendations for Modeling Tool Enhancements

During the course of the LSRWA effort and in response to the CBP STAC-sponsored independent scientific peer review, it became evident that future sediment transport and impact analyses could be improved with enhancements to the suite of modeling tools. In the interest of potential future studies, recommended enhancements to the specific models are detailed in the section.

7.1 HEC-RAS MODEL

HEC-RAS is designed primarily for non-cohesive (sands and coarse silts) sediment transport with additional but limited capability to simulate processes of cohesive (generally medium silts to fine clays) sediment transport. The model may not be suitable for all reservoir simulations, especially in areas of highly variable bed shear stress, active scour and deposition, and particle size. For the LSRWA effort, the HEC-RAS model outputs were deemed acceptable because they provided relative understanding of the physical process of the upper two reservoirs which had been considered to be in dynamic equilibrium for decades. If a more detailed evaluation of the upper two reservoirs is required in the future, AdH would be the more appropriate model to apply.

7.2 ADH MODEL

Overall, AdH was an excellent tool to estimate sediment transport in the lower Susquehanna River system. However, there are two specific recommendations to improve this tool.

The first recommendation is to improve methods to predict fine sediment flocculation in the reservoir system. Deposition in reservoirs is highly dependent on flocculation of the inflowing fine silts and clays. The fine sediment adhere to each other and form larger particles with higher settling velocities, thus they are more likely to settle in the reservoir than pass through. The AdH model has the capability to relate flocculation to concentration, but not to other variables, such as shear stress, which determine flock particle size and overall fate. The AdH model must reliably predict the critical bed shear stress of consolidated bed sediment, as well as compute associated erosion rates of the bed. The ability to predict flocculation dynamics is critical to tracking the fate of sediment in a reservoir system. More sophisticated methods need to be developed to provide this capability.

Currently, the AdH model relies on laboratory experiments to develop the critical shear and erosion rate of bed materials. Improvements are needed within AdH for computing a grain bed shear stress comparable to that used in the laboratory experiments, so the laboratory input data are better utilized in the model calculations. Currently, the AdH model approximates fine sediment flocculation by increasing the fall velocity of the fine sediment sizes to increase deposition. A more robust method for assigning flocculation potential needs to be determined from either laboratory studies or literature, and incorporated into AdH. It is recommended that the capability of the AdH model be enhanced by including a more robust method of computing grain bed shear stress for fine sediment beds as well as an improved method for predicting flocculation potential of inflowing fine sediment. The model would be enhanced through code changes, with test simulations conducted on Conowingo Reservoir.

The second recommendation is to develop more sophisticated methods to incorporate dam operations in Conowingo Reservoir. The AdH model was not capable of passing sediment through the flood gates of Conowingo Dam; therefore, dam operations are not incorporated into the model which includes flood gate operation and Peach Bottom Atomic Power Station sequences. For this study, the Conowingo Dam was modeled as an open boundary with downstream control represented by the water surface elevation at the dam. This limitation impacted how sediment was spatially distributed in the lower reach of Conowingo Reservoir near the dam.

7.3 CBEMP MODEL

Overall, CBEMP was an excellent suite of linked modeling tools to compute Chesapeake Bay and Susquehanna River watershed loads, and to estimate impacts of sediment and associated nutrient loads on light attenuation, SAV, chlorophyll, and DO in the Chesapeake Bay. However, there is one specific recommendation to improve this tool.

Particulate phosphorus eroded from the Conowingo Reservoir bed sediment comes in two forms: organic and inorganic. These forms are further subdivided into compounds and fractions of varying composition and reactivity. The particulate phosphorus passed over the dam settles to the bottom of Chesapeake Bay where it undergoes diagenesis (decay). Dissolved phosphorus is one end product of this diagenesis. Under particular combinations of temperature, salinity, and DO, the dissolved phosphorus can find its way into the water column where it can fuel the eutrophication process. CBEMP includes a predictive model of sediment diagenesis which was utilized for the LSRWA effort. However, extensive experiments into the nature and availability of sediment associated nutrients in Conowingo Reservoir are recommended. The present diagenesis model may require revisions and improvements based on the results of these recommended investigations. Improving the diagenesis model will further our understanding of the bioavailability of nutrients in the sediment, and those nutrient impacts to water quality and Chesapeake Bay aquatic life.

Chapter 8. Assessment Findings

The LSRWA was developed to better understand the ecosystem effects of sediment and associated nutrient loads from the lower Susquehanna River watershed, which are then delivered to Chesapeake Bay. This included analyses of the hydrodynamic and sedimentation processes and interactions within the lower Susquehanna River watershed (including the series of hydroelectric dams), consideration of strategies for sediment management, and assessments of cumulative impacts of future conditions and sediment management strategies on the upper Chesapeake Bay ecosystem.

Over the past three decades, concerted actions have been taken to better manage and reduce sediment and nutrient pollution in the Susquehanna River basin and throughout the Chesapeake Bay watershed. These efforts have been spurred by a better understanding of the impacts of these pollutants on rivers, streams, lakes, and estuaries, and have been further encouraged by the series of Chesapeake Bay agreements that have sought to reduce nitrogen, phosphorus, and sediment input to the Bay. More recently, Presidential Executive Order 13508 and the Chesapeake Bay TMDL have added urgency to the efforts. In response to the Chesapeake Bay TMDL, the seven watershed jurisdictions have developed and are implementing WIPs, with a goal of full implementation by 2025. These efforts are likely to show great success based on the investigations that preceded their development, and this has been confirmed during the LSRWA study. In addition, the series of hydroelectric dams in the lower Susquehanna River have been trapping sediment and associated nutrients for approximately 85 years, and have acted as an "end of the pipe" BMP since their construction. Concerns have been raised that the filling of these reservoirs will mean the end of the sediment and associated nutrient retention BMP benefit of the dams and their reservoirs will undo the efforts of the states to implement their WIPs.

In this chapter, the major findings from the assessment are presented.

Finding #1: Conditions in the Lower Susquehanna reservoir system are different than previously understood.

- ✓ **Conowingo Reservoir is essentially at full capacity; a state of dynamic equilibrium now exists.**
- ✓ **Previously, it was thought that Conowingo still had long-term net trapping capacity for decades to come.**

Recent attention has been focused on the largest and farthest downstream reservoir, Conowingo. The other two upstream reservoirs have been considered full for many years, and it has been assumed that they no longer trap sediment nor act as BMPs. Previous studies (Langland et al., 2009; Reed et al., 1997) had indicated that the sediment storage capacity of Conowingo Reservoir was declining with time, and estimated 10-20 years of remaining time before it reached full capacity.

Results from this study and others improved on this knowledge through additional sampling and state-of-the-art analyses; these now indicate that Conowingo Dam and Reservoir have essentially already reached full capacity. Modeling simulations revealed that when a present day (2011

Conowingo) bathymetry is compared to a projected "full" Conowingo bathymetry, the sediment transport through Conowingo Reservoir does not appreciably change, indicating that the reservoir is in a state of dynamic equilibrium in which long-term sediment storage capacity is minimal or non-existent (Appendix B).

In this state of dynamic equilibrium, episodic high-flow events (i.e., arising from major storms) will scour out sediment and associated nutrients from the Conowingo reservoir into Chesapeake Bay. The storage capacity will temporarily increase, allowing for more deposition within the reservoir in the short term. As the reservoir fills, however, the scour threshold to initiate an erosion event decreases until the next scour event occurs, whereby the scour threshold increases once again. On average, in this dynamic equilibrium state, a major scour event will occur once every 4 to 5 years. Minor scour events with trace amounts of erosion will occur every 1 to 2 years (150,000 to 300,000 cfs); while at lower flows, sediment and associated nutrients will accumulate until an erosion event occurs again. In the flow range of 150,000 to 300,000 cfs, it is not fully understood if this increase in sediment load to the Bay is due to an increase in scour or due to a decrease in deposition in the reservoir itself; it very likely could be a combination of both and warrants further study.

The deposition-scour cycle will repeat over and over again, resulting in no long-term storage of sediment and associated nutrients behind the series of three dams and reservoirs on the lower Susquehanna River. With no long-term net storage of the watershed's sediment and associated nutrients, this study indicates a new status for how the river system is operating, and the amount of sediment and associated nutrient loads now being passed through the lower Susquehanna River's three dams and reservoirs and into Chesapeake Bay (Appendices A and B).

Model simulations were conducted to evaluate the change in sediment transport characteristics as a function of historical bathymetry. The 1996 bathymetry was compared to the 2011 bathymetry. The 4-year flow record of 2008-2011 was simulated for these comparisons. The model results indicated that the bed sediment scour load that passes through the dam increases by about 67 percent (from 1.8 to 3 million tons) due to the increased transport capacity of the 2011 bathymetry over the 1996 bathymetry. It should be noted that although the scour load change is 67 percent, this scour load is a relatively small percentage (9 to 13 percent) of the total load delivered to the Bay. The reservoir sediment deposition decreases by about 33 percent between 1996 and 2011 (from 6.0 million tons to 4.0 million tons).

These findings are directly related to the reduction of sediment storage and subsequent increase in sediment transport capacity of the 2011 bathymetry. It is estimated that approximately 25 million tons of sediment deposited in Conowingo Reservoir between 1996 and 2011 (about 1.7 million tons per year). The total sediment outflow load through the dam, which consists of the Conowingo Reservoir bed sediment scour load, the bed sediment scour load of the upper two reservoirs, and the pass-through Susquehanna River watershed load, increased by about 10 percent from the 1996 bathymetry to the 2011 bathymetry for the 4-year simulation (2008-2011) (Appendix B).

- ✓ **Effective management actions in the Susquehanna River watershed have delayed the loss of sediment and associated nutrient trapping capacity.**
- ✓ **Previously, it was not fully understood how management activities in the watershed impacted the filling of and scouring and trapping dynamics of the reservoirs.**

Over the past 30 years, due to widespread implementation of regulatory and voluntary nutrient and sediment reduction strategies, nutrient and sediment loads to the lower Susquehanna River are significantly lower than what was delivered in the mid-1980s. Flow-adjusted concentrations of total nitrogen (TN), total phosphorus (TP), and suspended sediment concentration declined by 30, 40, and 45 percent, respectively between 1985 and 2012 at Marietta, PA (see http://cbrim.er.usgs.gov/). These actions have improved the health of the Chesapeake Bay and effectively delayed the Conowingo Reservoir from reaching dynamic equilibrium earlier; if not for the large decreases in sediment from the upstream Susquehanna River watershed, Conowingo Dam and Reservoir may have reached this dynamic equilibrium many years ago, resulting in increased sediment and associated nutrient loads to Chesapeake Bay over a much longer time frame.

- ✓ **Storm event-based scour of Conowingo Reservoir has increased.**
- ✓ **Previously, it was not fully understood how scouring was changing as the reservoirs filled.**

As the lower Susquehanna River reservoirs have filled, water depths have decreased and water velocity has increased. This has led to increasing the bed shear (which can result in more scour) and to decreasing the amount of time sediments spend in the reservoir, which thereby, reduces sediment deposition within the reservoir (Appendix A).

Since the reservoir system is dynamic and sediment type, consolidation time, and previous scour events vary, it is not known precisely when scour occurs. The LSRWA modeling efforts indicate that the scour threshold for the current Conowingo Reservoir condition ranges from about 300,000 cfs to 400,000 cfs, with the threshold for mass scouring occurring at about 400,000 cfs. The term mass scouring refers to the flow magnitude that results in very high erosion rates where significant high mass sediment transport from the reservoir bed sediment to Chesapeake Bay occurs. This flow represents a 4- to 5-year flow event (Appendix B).

The majority of bed sediment scour load occurs above this threshold flow. However, laboratory tests performed for this effort indicate that unconsolidated reservoir bed surface layers have a relatively low critical bed shear stress for erosion. A close inspection of the model simulation results indicate that trace erosion does occur at lower flows (150,000 cfs to 300,000 cfs), which is a 1- to 2-year flow event. However, the load increase has an exponential trend, with a sharp turn in the data set indicating when the mass scour threshold is reached. Additionally, modeling simulations comparing current conditions of the Conowingo Reservoir to the mid-1990s indicate that a higher volume of sediment is scoured currently at flows above 150,000 cfs in comparison to the mid-1990s (Appendix B).

- ✓ **Not all sediment is the same; most sand remains in the reservoir system.**
- ✓ **Previously, the variances in sediment scouring as it relates to grain size in the reservoir were not fully understood.**

Sediment transport is related to particle size. Storms can potentially scour the silts and clays (easier to transport) leaving behind the coarser sand-sized sediment. For example, in the lower portion of the Conowingo Reservoir in 1990, particle size analysis from sediment cores indicated the area had about 5 percent sand; in 2012, it had 20 percent sand. Reservoir sediment data show that generally there is more sand in the bed upstream; silts and clays are more prevalent closer to the dam for all three reservoirs. Silt is the dominant particle size transported from the reservoir system, with little sand (less than 5 percent) transported to the upper Chesapeake Bay (Appendix A).

Sand provides important benefits to fish and their habitats in Chesapeake Bay, while silt and clay can carry attached nutrients and have deleterious effects on water quality (e.g. reduced water clarity) and habitat (e.g. smothering oyster beds).

Finding #2: Sources upstream of Conowingo Dam deliver more sediment and nutrients and, therefore, have more impact on the upper Chesapeake Bay ecosystem, than do the scoured sediment and associated nutrients from the reservoir behind Conowingo Dam.

- ✓ **The Susquehanna River watershed, not the Conowingo Dam and its reservoir, is the principal source of adverse pollutant impacts on the upper Chesapeake Bay water quality and aquatic life.**

Impacts to the upper Chesapeake Bay ecosystem from all three reservoirs, now in a dynamic equilibrium state, are important. Yet, this assessment finds that the majority of sediment and nutrients, and their impacts on the upper Chesapeake Bay ecosystem during storm events, originate from the upstream Susquehanna River watershed rather than from being scoured from the reservoirs behind the dams.

The results of this study indicate that Conowingo Reservoir and the two upstream reservoirs' bed sediment scour comprised an average of approximately 30 percent (average of the mean of the ranges for each selected flow) with a range of 20 to 35 percent of the total sediment loads entering Chesapeake Bay during an event up to 800,000 cfs (recurrence interval of less than 40 years at the Marietta, PA gage); the remaining load was estimated to be from the Susquehanna River watershed. The range of scour to watershed loads is due to variations in sediment-loading conditions from the bed and the watershed. The study data indicate that as flow increases the bed scour load becomes an increasingly higher proportion of the total sediment load. On average, flows above 800,000 cfs at the Marietta, PA gage produced scour load that comprised about 30 to 50 percent of the total load entering the Bay; however, an event of this magnitude has a recurrence interval of 40 years or more.

There will be a point where the sediment transported into the reservoirs will have a limited ability to scour based on the transport capacity and the ability of the reservoir bed to erode. As the bed scours, the reservoir becomes deeper and the bed shear becomes less. Also, the deeper bed layers will have a higher critical bed shear stress for erosion. So at some point, the bed will either not erode, or the erosion rate will be very low (Appendix B). More data collection and sediment transport modeling would be required to further understand this concept and when this maximum capacity for reservoir bed scour would occur.

This effort evaluated the recent scour event, Tropical Storm Lee, in closer detail. Modeling estimated the impact of Tropical Storm Lee (approximately a 709,000-cfs event for the Conowingo peak daily discharge) on total sediment load passing through the Conowingo Dam. The model used the 2008-11 hydrology as the period of simulation. Runs were conducted at 1996, 2008, 2011, and "full" bathymetries. For all four reservoir bathymetry simulations, Tropical Storm Lee provided about 65 to 66 percent of the total outflow load for the 4-year simulation period, roughly 14.5 million tons of the 22.3 million tons.

Under 2011 bathymetry conditions, the bed sediment scour load from Conowingo Reservoir during Tropical Storm Lee comprised about 20 percent of the Tropical Storm Lee total sediment load (about 3.0 million tons of the 14.5 million tons); this load included scour from the two upstream reservoirs and loads from the rest of the Susquehanna River watershed. Similar results were calculated for the "full" Conowingo Reservoir bathymetry. These results imply that the Susquehanna River watershed located above the Conowingo Dam (including the two upstream reservoirs) provided 80 percent of the load during Tropical Storm Lee, with the remaining 20 percent from scoured bed sediment trapped in Conowingo Reservoir behind the dam.

Storm characteristics are highly variable and variations in track, timing, and duration can alter the amount of sediment entering the system from both the watershed and from the reservoirs behind the dams. Consequently, this percentage of scour and watershed contributions can vary as well, so this concept is not universal to all storms, but it does give a good sense of magnitude. For the entire time period of 2008-2011 under 2011 bathymetry, scour from the Conowingo Reservoir (estimated 3.0 million tons) comprised 13 percent of the total sediment load to the Chesapeake Bay (estimated 22.3 million tons), with 87 percent of the load originating from the upstream Susquehanna River watershed, including any scour from the two upstream reservoirs (Appendix B).

The sediment transport capacity of Conowingo Reservoir during a large flow event is strongly influenced by the sediment load entering into the system. Generally, the higher the inflowing sediment load, the lower the sediment transport capacity and subsequent bed sediment erosion in the reservoir. It is estimated from modeling simulations that the percentage of Conowingo Reservoir scour load to the total Tropical Storm Lee load can potentially vary from 20 to 30 percent based on the assumption of inflow load (Appendix B).

- ✓ **With or without the Susquehanna River dams, large storm events will continue to contribute sediment to the Chesapeake Bay and impact its health.**

With or without a Conowingo Dam and Reservoir that is essentially full of sediment, the study indicates that Susquehanna River watershed contributions of sediment and nutrients during large storm events will have significant effects on the Bay's living resources. Analyses also indicate that full implementation of the jurisdictions' WIPs exerts a tremendous positive impact on water quality, eliminating the current nonattainment of water quality standards absent the effects of scour events (Appendix D). There will, however, continue to be periodic, large storms that will continue to transport large quantities of sediment and nutrients downstream impacting the Chesapeake Bay ecosystem. These events and the levels of sediment and nutrients they bring are enormous and unpredictable, thus their impacts are difficult to manage.

Finding #3: The loss of long-term sediment trapping capacity is causing impacts to the health of the Chesapeake Bay ecosystem.

- ✓ **Nutrients associated with sediment scoured from the Conowingo Reservoir cause impacts to the upper Chesapeake Bay ecosystem.**

The assessment indicates that the ecosystem impacts to Chesapeake Bay result from the changed conditions, and are due primarily to extra nutrients associated with the scoured sediment, as opposed to the sediment itself. After a major scour event, which now includes higher volumes of sediment, modeling estimates showed that the sediment load (not including nutrients they contain) from Conowingo Reservoir scour events are not the major threat to Bay water quality. For most conditions examined, sediment from bottom scour settles out of the Bay water column before the period of the year during which light attenuation is critical. Although the sediment is subject to some resuspension, once deposited on the bottom, the adverse effects of sediment on the Chesapeake Bay ecosystem essentially cease (Appendix C).

The nutrients associated with the sediment are more damaging to the upper Chesapeake Bay ecosystem. After deposition, biological processes transform particulate organic nutrients, and inorganic nutrients adsorbed to sediment, into dissolved forms which diffuse into the overlying water column. This process makes the nutrients bioavailable and adversely affects Bay water quality and aquatic life. Dissolved nutrients are recycled into the water column and stimulate algal production. Algal organic matter decays and consumes oxygen in the classic eutrophication cycle. As a consequence, the concentration of dissolved oxygen (DO) available to the Bay's aquatic life is diminished by Conowingo Reservoir scour events. Nutrients take years to undergo permanent sediment burial to a depth where they are no longer an influence on the overlying (surface) tidal waters. Modeling predicts that the water quality impacts to the Chesapeake Bay associated with a given scour event will diminish over time as associated nutrients are cycled through the ecosystem (Appendix C).

Low DO was estimated to persist in the deeper waters of northern Chesapeake Bay for multiple seasons due to nutrient storage in the Bay's bed sediment and recycling between the bed sediment and overlying water column (Appendix D).

The impact to habitat and living resources is also tied to the timing of the scour event. That is, a scouring event in June has greater adverse impacts to Chesapeake Bay water quality and living resources than October and January events (Appendices C and D).

All three storm events (January, June, and October) demonstrate a large, immediate response in light attenuation due to sediment loads. For both the January and October storm events, however, sediment is virtually gone (flushed downstream out of the system) from the water column prior to the subsequent SAV-growing season, whereas the June storm occurs during the SAV-growing season (Appendix C). The Chesapeake Bay water quality effects in the October and January storm event periods are diminished because of colder temperatures and decreased primary productivity, resulting in less interception of the nutrient loads by algae. In the fall and winter, a greater portion of the storm-pulsed nutrient load is transported down the Chesapeake Bay to be discharged at the ocean boundary, or is lost through denitrification or deep burial in sediment along the way. In the June storm event the pulse of delivered nutrient loads contributes directly to ongoing primary production as the nutrients are taken up to produce more algae. As a consequence, these loads contribute to deep-water water quality and aquatic life impacts when the increased June production of algal biomass sinks to the bottom and generates sediment and water column oxygen demand (Appendix D).

- ✓ **Full WIP implementation won't fully restore Chesapeake Bay given changes to the Conowingo Reservoir sediment and associated nutrient trapping capacity.**

Under the Chesapeake Bay TDML, the seven Chesapeake Bay watershed jurisdictions are implementing their respective WIPs through the year 2025 in order to meet their water quality standards that were established to protect the Bay's aquatic life. Modeling done for this assessment estimated that under current conditions (no WIP implementation), more than half of the deep-channel habitat in the Chesapeake Bay is frequently unsuitable for healthy aquatic life. This study estimates that in 2025, with WIPs fully implemented, DO levels required to protect aquatic life in the Bay's deeper northern waters will still not be achieved in 3 of the 92 Chesapeake Bay segments. An increased frequency of scour and the amount of scoured sediment from behind the dams on the lower Susquehanna River is a major contributor to these results. To achieve the required water quality conditions under the Chesapeake Bay TDML, full attainment of the states' Chesapeake Bay water quality standards, the extra nutrient loads associated with sediment scoured from the three lower Susquehanna reservoirs must be offset by equivalent nutrient load reductions. The exact amount of reductions is not known at this time; such analyses were beyond the scope of this assessment.

Finding #4: Managing sediment via large-scale dredging, bypassing and dam operational changes, by itself does not provide sufficient benefits to offset the upper Chesapeake Bay water quality impacts from the loss of long-term sediment trapping capacity.

- ✓ **Strategies to reduce sediment in the Susquehanna River watershed beyond what is required in the jurisdictions' WIPs are likely limited in their ability to improve upper Chesapeake Bay water quality.**

There are a variety of sediment reduction strategies for the watershed in addition to what is mandated under the Chesapeake Bay TMDL and the jurisdictions' WIPs that were identified through this assessment. Additional sediment management above and beyond the levels committed to within the jurisdictions' WIPs is limited in relation to the total amount of sediment coming down the Susquehanna River and through Conowingo Dam and, therefore, will have little additional effect on achieving the jurisdictions' Chesapeake Bay water quality standards.

The maximum available load of sediment per year that could be reduced by additional BMP implementation throughout the Susquehanna River watershed, beyond the levels contained within the jurisdictions' WIPs, is approximately 95,000 tons (or about 117,000 cubic yards), at a cost of $1.5

to $3.5 billion. This an order of magnitude less than the sediment load that is estimated to flow over Conowingo Dam into Chesapeake Bay on an average annual basis; the annual sediment loading from the Susquehanna River to the Bay averaged approximately 1.8 million tons for the period 1993-2012 (Appendix A and Appendix J).

Although they will not add significant water quality benefit to the Bay, strategies to limit erosion from the Susquehanna River watershed may have significant local benefit, such as streambank stability and limiting soil erosion on farms, construction sites, and residential neighborhoods and should continue to be pursued.

- ✓ **Minimizing sediment deposition via structural and operational changes to Conowingo Dam does not address the water quality impacts to the upper Chesapeake Bay.**

In certain settings, reservoir operational alternatives can be implemented to meet sediment management objectives. However, the lower Susquehanna River system is complex in terms of hydrologic conditions and water resource demands. The cumulative effect of competing water uses, operational limitations, structural constraints, and health and safety considerations related to the placement and operation of flood gates render traditional reservoir operational alternatives impractical and are unlikely to mitigate the impacts of degraded water quality associated with bed sediment scour. Depending on the sediment type and time of year, it is possible that changes in reservoir operations might cause additional adverse impacts to the upper Chesapeake Bay's water quality and aquatic life (Appendix J).

- ✓ **Increasing reservoir sediment storage volume yields minimal, short-lived benefits at high costs.**

Evaluation of a range of dredging alternatives did not yield any management strategies that could approach fully offsetting sediment and associated nutrient loads from the Conowingo reservoir due to scour events and provide meaningful, long-term Chesapeake Bay water quality benefits. Increasing or recovering sediment storage volume of the reservoirs via dredging or other methods is possible, and in some cases can effectively reduce sediment and associated nutrient scour. But analyses in the study indicate upper Chesapeake Bay water quality benefits are minimal and short-lived, and the costs are high (Appendices C and J).

When sediment is strategically removed from the Conowingo reservoir, there was an observed minor influence on bed sediment scour load (reduction) and sediment deposition (increase) and an observed minor reduction in impacts to Chesapeake Bay health for a future similar storm event. Scour events would still occur, but lower amounts of material were estimated to be mobilized during the events (Appendices B, C, and D).

Dredging limited quantities from depositional areas in the Conowingo reservoir result in minimal impact on the total sediment load transported to the Chesapeake Bay. Large periodic flood flows dominate sediment transport dynamics in Conowingo Reservoir. The amount of sediment passed through the Conowingo dam during floods is significantly higher than the estimated bed sediment scour load, thus small reductions in bed sediment scour due to dredging provide minimal benefit to sediment load reductions to the Chesapeake Bay over time (Appendix B).

Strategic dredging had little effect on estimated water quality conditions in the Chesapeake Bay. Results from extreme dredging regarding reduction of total sediment discharged to the Bay, reduction in bed sediment scour and increase in net sedimentation appear significant; however, these reductions represent a relatively small fraction of the total sediment load resulting from a storm with the same flow magnitude of a Tropical Storm Lee (Appendix B).

Long term, the reality of dredging is that large volumes of sediment are depositing annually. Therefore, the net removal of sediment out of the Conowingo Reservoir is reduced, because part of the dredging operation would simply be "keeping up" with deposition, and subsequently, benefits are reduced.

Removal would be required annually, or on some regular cycle, to achieve any sustained improvement to the health of Chesapeake Bay. It was determined that the annual cost of such a program would likely be on the order of $48 to $267 million, with costs likely increasing in future years as placement sites become less convenient. Further, this positive influence on the Chesapeake Bay ecosystem is significantly minimized due to the majority of sediment loads coming from the Susquehanna River watershed during a scour event. The lower end of the cost range encompasses cheaper methods of dredging to closer placement sites (e.g. direct pump and placement) while the higher end of the cost range encompassing more expensive methods of dredging with further placement sites (e.g. mechanical, dewatering required, etc).

Sediment bypassing is defined here as routing sediment around the reservoirs and downstream. It has been used in other river systems to extend the life of storage capacity in a reservoir, protect turbines, or restore sediment supply for downstream habitat value. Ideally, such a system could introduce sediment to Chesapeake Bay during periods of the year when impacts would be minimal. It is also possible that the system could be fashioned to deliver a more desired sediment composition (i.e., sandier material) to the downstream tidal areas for habitat improvement. Bypassing at the scale required for the Susquehanna River has never been attempted, and the cost for such a strategy is estimated to be high (albeit less costly than dredging), ranging from $15 to $48 million annually.

Bypassing is just as effective as dredging at increasing sediment deposition and reducing available sediment for scour events; however, this methodology increases total sediment loads to the Chesapeake Bay. The environmental costs (lower DO concentrations, increased algae growth) are roughly 10 times greater than the benefits gained from reducing sediment scour from the Conowingo reservoir (Appendix C).

- ✓ **Strategies focused on reducing nutrients, as opposed to sediment, are likely more effective at addressing impacts to Chesapeake Bay water quality and aquatic life.**

Modeling estimates showed that the sediment load (not including the nutrients they contain) from scour events are not the major threat to upper Chesapeake Bay water quality. Although the sediment is subject to some resuspension, once deposited on the Bay bottom, the adverse effect of sediment on the Chesapeake Bay ecosystem essentially ceases (Appendix C). Thus, sediment management strategies that focus solely on sediment (even very large volumes) and moving it out of the Susquehanna river-reservoir system entirely or downstream to the Chesapeake Bay do not incur significant benefits (i.e., water quality improvement) for aquatic life.

Analyses completed for this assessment indicate that the implementation of jurisdictions' WIPs results in significantly more improvement to Chesapeake Bay water quality and benefits to aquatic life than management options designed to increase sediment storage capacity and reduce scour in the reservoirs. Since this watershed assessment was designed to study the issue of sediment movement in the lower Susquehanna watershed and delivery to the Chesapeake Bay, management strategies developed for the LSRWA were primarily targeted at sediment removal or bypass.

The nutrients associated with the sediment are more damaging to Chesapeake Bay water quality. After deposition, biological processes transform particulate organic nutrients, and inorganic nutrients adsorbed to sediment, into dissolved forms which diffuse into the overlying water column. These nutrients are then bioavailable and adversely affect Bay water quality. Dissolved nutrients are recycled to the water column and stimulate algal production. Algal organic matter decays and consumes oxygen in the classic eutrophication cycle. As a consequence, DO levels are reduced by Conowingo Reservoir bed scour events. Nutrients take years to undergo permanent sediment burial to a depth where they are no longer an influence on overlying (surface) tidal waters. CBEMP modeling predicts that as the years go by, the impacts to water quality decrease after a scouring event (Appendix C).

The conclusion that the primary impact to living resources in Chesapeake Bay from reservoir scour was from nutrients associated with the sediment and not the sediment itself, was not determined until late in the study process. Further study on this is warranted, and opportunities in the watershed above the three dams and reservoirs to reduce nutrient delivery are likely more available than sediment reduction opportunities. The relative importance of nutrient load impacts from the lower Susquehanna River reservoirs is a finding that indicates that nutrient management and mitigation options could be more cost-effective and provide more management flexibility than solely relying on sediment management options.

8.1 FUTURE NEEDS AND OPPORTUNITIES IN THE WATERSHED

Based on the LSRWA findings, four specific recommendations were identified to provide state, federal, and local decision makers with the additional information needed to take further actions to protect water and living resources of the lower Susquehanna River watershed and Chesapeake Bay.

Recommendation #1: **Before 2017, quantify the full impact on Chesapeake Bay aquatic resources and water quality from the changed conditions in the lower Susquehanna River's dams and reservoirs.**

The assessment indicates that there are water quality impacts resulting from changed conditions in the lower Susquehanna River. The study was not able, however, to fully quantify those impacts.

There are three specific and important areas in which to build upon existing knowledge and more effectively manage the Bay:

1. Determine the detailed characteristics and bioavailability of sediment and associated nutrients likely to be scoured within Conowingo Reservoir. The emphasis in the future should shift from the relative vague impact of additional "sediment and associated nutrients" to the differential impact of specific particulate and dissolved nutrients.
2. Determine the quantity and nature of the sediment-associated nutrients transported downstream under current conditions (dynamic equilibrium) versus conditions that prevailed in previous times when the reservoirs had substantial trapping ability.
3. Determine impacts on shallow water habitats from reduced light availability and physical burial in the upper Chesapeake Bay due to delivery of scoured sediment from flood events.

Field and laboratory investigations as well as modeling would be needed to address these information needs. Investigations would involve taking sediment core samples from behind the dam and collecting multiple storm event water quality samples above and below all Susquehanna River dams. To generate information adequate for management, a 2-year period would be required. From these samples, the characteristics, fate, and bioavailability of sediment and associated nutrients likely to be scoured within Conowingo Reservoir should be determined. Additional modeling coupled with new data on sediment and nutrient fate and bioavailability, should be conducted. It is critical to answer these questions prior to 2017, to adequately inform ongoing and planned policy decisions by the Chesapeake Bay Program Partnership as part of Chesapeake Bay TMDL 2017 midpoint assessment process.

Since this report was drafted, Exelon, MDNR, MDE, UMCES, USGS, and EPA finalized the "Lower Susquehanna River Integrated Sediment and Nutrient Monitoring Program." This plan identifies the data collection and analysis to supplement the findings of the LSRWA and includes two 3years of field study. Data collection is currently underway. The monitoring plan can be found at http://mddnr.chesapeakebay.net/lsrwa/Docs/LSR_int_sed_nut_mon_final.pdf. Agencies are confident work can be completed in time for the midpoint assessment process.

Recommendation #2:	**EPA and the Bay watershed jurisdictional partners should integrate findings from the LSRWA into their ongoing analyses and development of the seven watershed jurisdictions' Phase III WIPs as part of Chesapeake Bay TMDL 2017 midpoint assessment.**

This assessment indicates that additional nutrient loadings associated with changed conditions in the lower Susquehanna River system may result in nonattainment of jurisdictions' Chesapeake Bay water quality standards, even with full implementation of the jurisdictions' WIPs. This information, along with additional knowledge gained from Recommendation 1 above, should be incorporated into ongoing analyses integrated into the Chesapeake Bay TMDL to reflect new loadings, and allocate the additional offset reductions needed to fully attain the jurisdictions' water quality standards. Fortunately, the Chesapeake Bay TMDL was designed by the CBP Partnership to collect and integrate new information through a planned 2017 midpoint assessment. By using the knowledge gained through the LSRWA, this assessment should serve as the vehicle through which to adapt the strategies to meet the Chesapeake Bay TMDL by 2025.

Currently, EPA and its seven watershed jurisdictional partners are collaborating on how to integrate knowledge gained through the LSRWA effort and integrate findings into the Chesapeake Bay 2017 midpoint assessment and the jurisdictions' Phase III WIPs.

Recommendation #3: **Develop and implement management options that offset impacts to the upper Chesapeake Bay ecosystem from increased sediment-associated nutrient loads.**

Management strategies developed for the LSRWA were targeted primarily at reservoir bed sediment reducing scour and increasing deposition in the lower Susquehanna River reservoirs. These strategies were shown to be costly and not very effective at improving Chesapeake Bay water quality, as they were not designed to address the nutrient loads identified as a significant problem in the study.

Nutrient load reduction management and mitigation options are likely to be more effective and provide more management flexibility when compared to relying solely on sediment management options. As such, it is likely more appropriate and cost-effective to increase management actions targeted toward nutrients above and beyond WIP implementation in the Susquehanna River watershed. It is therefore recommended to conduct further analysis and modeling to understand costs and water quality influence of controllable nutrient mitigation measures beyond the watershed jurisdictions' Phase II WIPs. For example, as technologies improve, there may be opportunities available from increased efficiency of wastewater treatment, expanded stormwater management in urban/suburban areas, and restoration of riparian areas along streams and rivers, particularly wetlands. These practices should be focused in priority watersheds from which concentrated loads originate to provide long-term ecosystem benefits.

In addition, information collected as a result of Recommendation #1 should lead to a better understanding of the role that dredging and beneficial use could potentially play in an overall suite of management strategies. For example, strategic dredging in targeted locations might be appropriate if certain areas of the reservoir contain high amounts of nutrients that are subject to erosion, or if the cost-effectiveness of moving coarse sediment (i.e., sands) downstream to improve habitat conditions can be increased.

It is important to restate that if not for sediment management practices implemented in the past several decades across the Susquehanna River watershed, Conowingo Dam and Reservoir may have reached sediment storage capacity decades ago. Therefore, it is strongly recommended to continue the ongoing and planned actions described in the jurisdictions' WIPs that have demonstrated critical progress in sediment and nutrient load reductions thus far. Opportunities to implement additional management activities that provide long-term storage of sediment and nutrients should also be explored for their permanence and cost-effectiveness.

Management actions can significantly help control sediment and nutrients in the Susquehanna River and its watershed, and attain the jurisdictions' Chesapeake Bay habitat-based water quality standards. However, severe storm impacts cannot be fully reduced and large flood events will occur that detrimentally impact the Bay's health by delivery of large pollutant loads from the Bay watershed. Risk and cost are important factors that stakeholders should consider when planning to manage the impacts from large storm events in the lower Susquehanna River and Chesapeake Bay. Additionally comprehensive, long-term sediment and nutrient management solutions is a shared responsibility. The use of public-private partnerships to fund and implement management actions to move forward in the future will be important.

In 2013, a "Conowingo Policy Work Group" was convened by the State of Maryland Governor's office "to develop strategies for addressing the Susquehanna River sediment accumulation behind the dam and formulate a funding plan to put those strategies in place." This group included the following agencies: USFWS, USGS, EPA, CBC, SRBC, NOAA, USACE, PADEP, and the Maryland Governor's Office. The agencies determined that once the LSRWA report findings were finalized the group would reconvene. This group will collaborate to address this recommendation.

Recommendation #4: **Commit to enhanced long-term monitoring and analysis of sediment and nutrient processes in the lower Susquehanna River system and upper Chesapeake Bay to promote adaptive management.**

As the LSRWA demonstrates, the lower Susquehanna River system is complex, and sediment and nutrient transport is dynamic. In order to enhance understanding of these changes in the future, including evaluating the effectiveness of management actions, the existing shared monitoring network must be expanded and/or adjusted. The importance of this long term monitoring is that it allows managers to track and ensure effectiveness of implemented management strategies; observe and account for any future changed conditions in the Susquehanna River and Chesapeake Bay; and refine and further improve management strategies that are planned and implemented in the future.

Currently, MDNR, MDE, PADEP, SRBC, USGS, EPA, and the larger CBP Partnership fund, participate, and coordinate the existing Chesapeake Bay watershed and Chesapeake Bay tidal monitoring networks. These agencies are currently collaborating to leverage the financial and staffing resources necessary to implement this recommendation.

Specific monitoring network expansions or adjustment should include:

1. Currently suspended sediment samples are collected above the series of reservoirs (Susquehanna River at Marietta, Pennsylvania; 01576000) and below the series of dam and reservoirs (Susquehanna River at Conowingo, Maryland; 01578310). To continue to improve understanding of sediment and nutrient storage and transport dynamics, long-term sediment and nutrient monitoring stations should be established upstream and downstream of the Safe Harbor, Holtwood and Conowingo dams. Sample analysis should include improved size fractionation of particle sizes and measurements of nutrients in their various forms in

suspended sediment. This monitoring data would enhance model sensitivity in quantifying sediment and nutrient impacts.

2. Currently, there are limited data on suspended sediment loads during storms. Due to the danger of sampling during large storms, samples are not currently collected at the peak of the largest storms. Improved field methods are required for sampling storm suspended sediment concentrations or turbidity over the entire storm hydrograph to verify estimations of bed sediment scour during large storms.
3. Currently, there are limited data of bed sediment erosion characteristics. Additional and deeper sediment core samples of the reservoir bed(s) would provide more data on the erosional characteristics of the sediment at greater depths, the amount of unconsolidated material at the surface that may have a higher potential for scour at lower flows, longitudinal differences in sediment composition/shear stress, and nutrient concentrations associated with sediment, to enhance model sensitivity in quantifying sediment and nutrient impacts.
4. Increased monitoring and data collection should occur at the mouth of the river (Susquehanna Flats) to better model and predict the ecosystem impacts due to sediment moving through the lower Susquehanna watershed including the deposition to and scour from Conowingo Reservoir.
5. Collecting and characterizing the sediment and nutrient contributions during moderate flow events (greater than 80,000 cfs, but less that 400,000 cfs) upstream and downstream of the Safe Harbor, Holtwood and Conowingo dams should be established to enhance understanding of the contribution and impacts to Chesapeake Bay from stored sediment and nutrients behind the reservoirs.
6. Continue conducting regularly scheduled and event-triggered bathymetric surveys (events greater than 400,000 cfs) in all three reservoirs to continue to monitor sediment and nutrient storage at dams.
7. Continue monthly sampling for nutrients and suspended sediment at the CBP Partenrship's Chesapeake Bay watershed water quality and streamflow monitoring network stations located throughout the Susquehanna basin. These data provide a continuous record of transport trends throughout the basin.

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Chapter 10. List of Acronyms and Abbreviations

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AdH	Adaptive Hydraulics Model
BMP	Best management practice
CBC	Chesapeake Bay Commission
CBEMP	Chesapeake Bay Environmental Model Package
CBP	Chesapeake Bay Program
CFD	Cumulative Function Distribution
CRC	Chesapeake Research Consortium
CWA	Clean Water Act
DO	Dissolved oxygen
EIS	Environmental impact statement
EPA	Environmental Protection Agency
EPA-CBPO	Environmental Protection Agency – Chesapeake Bay Program Office
ERDC	USACE Engineer Research and Development Center
ETM	Estuarine turbidity maxima
FERC	Federal Energy Regulatory Commission
g	Gram
gpd	Gallons per day
HEC-RAS	Hydrologic Engineering Center's River Analysis System
L	Liter
LA	Load allocation
LSRWA	Lower Susquehanna River Watershed Assessment
LWA	Lightweight aggregate
m	Meter
m^3	Cubic meter
mcy	Million cubic yards
MDA	Maryland Department of Agriculture
MDE	Maryland Department of the Environment
MDNR	Maryland Department of Natural Resources
µg	Microgram
mg	Milligram
MGS	Maryland Geological Survey
MLLW	Mean lower low water
MOS	Margin of safety
MW	Megawatts
NEPA	National Environmental Policy Act
NGVD29	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Services
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Survey

NPDES	National Pollutant Discharge Elimination System
NWR	National Wildlife Refuge
PADEP	Pennsylvania Department of Environmental Protection
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PFBC	Pennsylvania Fish and Boat Commission
PPL	PPL Holtwood, LLC
ppt	Parts per thousand
RI	Recurrence intervals
SAV	Submerged aquatic vegetation
SRBC	Susquehanna River Basin Commission
STAC	Scientific and Technical Advisory Committee
TMDL	Total maximum daily load
TN	Total nitrogen
TNC	The Nature Conservancy
TP	Total phosphorus
TS	Tropical Storm
UMCES	University of Maryland Center for Environmental Science
USACE	U.S. Army Corps of Engineers
USCCSP	U.S. Climate Change Science Program
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VIMS	Virginia Institute of Marine Science
WIP	Watershed implementation plan
WLA	Waste load allocation
WQC	Water quality certification
WQSTM	Water Quality Sediment Transport Model
WRDA	Water Resources Development Act
WSM	Watershed model

Chapter 11. Glossary of Terms

Term	Definition
Adsorb	To gather (a gas, liquid, or dissolved substance) on a surface in condensed layer.
Afforestation	The act or process of creating a new forest where none had existed before, or reforestation of areas long deforested.
Algal	Any of numerous groups of chlorophyll-containing, mainly aquatic eukaryotic organisms ranging from microscopic single-celled forms to multicellular forms 100 feet (30 meters) or more long, distinguished from plants by the absence of true roots, stems, and leaves and by a lack of no reproductive cells in the reproductive structures: classified into the six phyla – Euglenophyta, Crysophyta, Pyrrophyta, Chlorophyta, Phaeophyta, and Rhodophyta.
Alluvial deposits	Detrital material which is transported by a river and deposited – usually temporarily – at points along the flood plain of a river. Commonly composed of sands and gravels.
Anadromous	The migration of fish from salt water to spawn in fresh water
Anoxic	Refers to an environment that contains little or no dissolved oxygen and hence little or no benthic marine life. These conditions arise in some basins or fjords where physical circulation of seawater is limited.
Anthropogenic	Related to the influence of human beings or their ancestors on natural objects. Wastewater is any water that has been adversely affected in quality by anthropogenic influence.
Atmospheric deposition	The wet or dry deposition on land of a wide variety of pollutants, including mercury, nitrates, organochlorines, and others. Acid deposition is one type of atmospheric deposition.
Attenuation	(1) A lessening of the amplitude of a wave with distance from the origin. (2) The decrease of water-particle motion with increasing depth. Particle motion resulting from surface oscillatory waves attenuates rapidly with depth, and practically disappears at a depth equal to a surface wavelength.
Azoic	Without higher life forms.
Base flow	Normally refers to the stream levels associated primarily with groundwater or subsurface contributions, as opposed to storm flow which corresponds to stream levels associated with recent precipitation and surface runoff.
Basin	A depressed area with no surface outlet, such as a lake basin or an enclosed sea.
Bathymetry/ bathymetric	The measurement of water depths in oceans, seas, and lakes; also information derived from such measurements.

Term	Definition
Bedrock	The solid rock that underlies gravel, soil, and other superficial material. Bedrock may be exposed at the surface (an outcrop) or it may be buried under a few centimeters to thousands of meters of unconsolidated material.
Bed shear stress	The force of water required to move bed sediment, expressed in terms of force per unit area (e.g., pounds per square inch)
Benthic	Pertaining to the sub-aquatic bottom.
Benthic invertebrates	Aquatic animals without backbones that dwell on or in the bottom sediment of fresh or salt water. Examples: clams, crayfish, and a wide variety of worms.
Benthos	Those animals that live on the sediment of the sea floor, including both mobile and non-mobile forms.
Biomass	In ecology, organic material that makes up living organisms; the collective mass of living matter in a given place and time. In energy, organic material derived from living or recent living organisms, containing chemical energy that originated with photosynthesis.
Brackish	Having a somewhat salty taste, especially from containing a mixture of seawater and fresh water.
Buffer (area)	A parcel or strip of land that is designed and designated to permanently remain vegetated in an undisturbed and natural condition to protect an adjacent aquatic or wetland site from upland impacts, to provide habitat for wildlife and to afford limited public access.
Clay	A fine grained, plastic, sediment with a typical grain size less than 0.004 mm. Possesses electromagnetic properties which bind the grains together to give a bulk strength or cohesion; - Substrate particles that are smaller than silt and generally less than 0.003 mm in diameter.
Confluence	The junction of two or more river reaches or channels (the opposite of a bifurcation).
Consumptive use	Use of fresh water whereby water is removed from a particular aquifer or surface water body and is not returned to it. Irrigation for agriculture is an example of consumptive use.
Critical shear stress	The shear stress required to mobilize and transport sediment. In general, when the shear exceeds the critical shear stress, sediment is mobilized. Conversely, when the shear is less than the critical shear, sediment will deposit. The critical shear varies by particle size, bed imbeddedness, and other factors.
D modeling	Assumes all water flows in the longitudinal direction only. One-dimensional models represent the terrain as a sequence of cross-sections and simulate flow to estimate the average velocity and water depth at each cross-section.

Term	Definition
D modeling – 2-dimensional models	Water is allowed to move both in the longitudinal and lateral directions, while velocity is assumed to be negligible in the vertical direction. Unlike one-dimensional models, two-dimensional models represent the terrain as a continuous surface through a finite element mesh.
Dam	Structure built in rivers or estuaries, basically to separate water at both sides and/or to retain water at one side.
Dead zone	An area in a body of water, especially an ocean, having oxygen levels that are notadequate to support life:
Deforestation	The clearing and loss of forests.
Degradation	The geologic process by means of which various parts of the surface of the earth are worn away and their general level lowered, by the action of wind and water.
Delta	(1) An alluvial deposit, usually triangular or semi-circular, at the mouth of a river or stream. The delta is normally built up only where there is no tidal or current action capable of removing the sediment at the same rate as it is deposited, and hence the delta builds forward from the coastline. (2) A tidal delta is a similar deposit at the mouth of a tidal inlet, the result of tidal currents that flow in and out of the inlet.
Demersal	Bottom-dwelling.
Denudation	The exposing or laying bare of rock by erosive processes.
Deposition	The arrival of eroded soil at a new location.
Desorbed	To change from an adsorbed state on a surface to a gaseous or liquid state.
Discharge(s)	The volume of water per unit of time flowing along a pipe or channel.
Dredging	The practice of excavating or displacing the bottom or shoreline of a water body. Dredging can be accomplished with mechanical or hydraulic machines. Most is done to maintain channel depths or berths for navigational purposes; other dredging is for shellfish harvesting, for cleanup of polluted sediment, and for placement of sand on beaches.
Dynamic equilibrium	Used in this report to describe the reservoir sediment storage condition. In this condition, little to no sediment storage remains; however, scour events will increase sediment storage for a short period of time, resulting in a reduction in sediment load in the upper Chesapeake Bay for a short time. In the long-term, sediment will continue to deposit in the reservoirs and be removed with scour-producing flow events.
Elevation	The vertical distance from mean sea level or other established datum plane to a point on the earth's surface; height above sea level. Although sea floor elevation below mean sea level should be marked as a negative value, many charts show positive numerals for water depth.
Emergent/emergent coast	A coast in which land formerly under water has recently been exposed above sea level, either by uplift of the land or by a drop in sea level.

Term	Definition
Erosion	The wearing a way of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.
Estuary	(1) The part of a river that is affected by tides. (2) The region near a river mouth in which the fresh water of the river mixes with the salt water of the sea and which received both fluvial and littoral sediment influx.
Eutrophic	Usually refers to a nutrient-enriched, highly productive body of water.
Eutrophication	The process of enrichment of water bodies by nutrients.
Evapotranspiration	The quantity of water transpired (given off), retained in plant tissues, and evaporated from plant tissues and surrounding soil surfaces. Quantitatively, it is usually expressed in terms of depth of water per unit area during a specified period of time.
GIS	Database of information which is geographically referenced, usually with an associated visualization system.
Gorge	1) The deepest portion of an inlet; (2) A narrow, deep valley with nearly vertical rock walls.
Herbaceous	Non-woody.
Hydrograph	A curve showing stream discharge over time.
Hydrography	(1) The description and study of seas, lakes, rivers and other waters. (2) The science of locating aids and dangers to navigation. (3) The description of physical properties of the waters of a region.
Hydraulic dredge	Floating or (occasionally) truck-based plant which lifts the material through a suction pipe. It requires dilution water for material pickup, lift, and transportation. Often used to renourish beaches when material is pumped onto the shore from an offshore sand source.
Hydrology	The scientific study of the water of the earth, its occurrence, circulation and distribution, its chemical and physical properties, and its interaction with its environment, including its relationship to living things.
Hydropower	The generation of electricity using the kinetic energy of moving water.
Hypoxia	Deficiency in the amount of oxygen reaching body tissues.
Indurated sediment	Turned to rock.
Macroinvertebrate	Invertebrates visible to the naked eye, such as insect larvae and crayfish.
Mass erosion	Scour which penetrates the deeper layers and occurs at higher flows with higher bed shear stresses (greater than 0.02 pounds per square inch).
Mixing layer	A very thin layer at the surface where sediment sorting takes place.
Morphology	River/estuary/lake/seabed form and its change with time.
Mouth	Entrance to an inland water body (e.g., river).
Nutrient	An element or compound that organisms consume and require for survival.
Outcrop	A surface exposure of bare rock, not covered by soil or vegetation.

Term	Definition
Photic zone	The zone extending downward from the ocean surface within which the light is sufficient to sustain photosynthesis. The depth of this layer varies with water clarity, time of year and cloud cover, but is about 100 meters in the open ocean. It may be considered the Depth to which all light is filtered out except for about one percent and may be calculated as about two and one-half times the depth of a Secchi disk reading.
Phytoplankton	Minute plants, usually algae, that live suspended in bodies of water and that drift about because they cannot move by themselves or because they are too small or too weak to swim effectively against a current.
Reservoir	An artificial lake, basin or tank in which a large quantity of water can be stored.
Riverine	Relating to, formed by, or resembling a river including tributaries, streams, brooks, etc.
Runoff	Water that flows over the ground and reaches a stream as a result of rainfall or snowmelt.
Salinity	Number of grams of salt per thousand grams of sea water, usually expressed in parts per thousand (symbol: ‰).
Scour/scouring	Removal of underwater material by waves and/or currents, especially at the base or toe of a shore structure.
Scour threshold	The flow on average when scouring occurs transporting sediment out of the reservoir system to Chesapeake Bay.
Sea level rise	The long-term trend in mean sea level.
Sediment	(1) Loose, fragments of rocks, minerals or organic material which are transported from their source for varying distances and deposited by air, wind, ice and water. Other sediment is precipitated from the overlying water or form chemically, in place. Sediment includes all the unconsolidated materials on the sea floor. (2) The fine grained material deposited by water or wind.
Sedimentation	(1) The combined processes of soil erosion, entrainment, transport, deposition, and consolidation. (2) Deposition of sediment.
Shear stress	The force exerted by water on the sediment in the banks and bottom surface, usually expressed in pascals (standard unit of stress, English units - pounds per square inch).
Shoal	(1) (noun) A detached area of any material except rock or coral. The depths over it are a danger to surface navigation. Similar continental or insular shelf features of greater depths are usually termed banks. (2) (verb) To become shallow gradually. (3) To cause to become shallow. (4) To proceed from a greater to a lesser depth of water.
Shoaling/shoaled	Decrease in water depth. The transformation of wave profile as they propagate inshore.
Silt	Sediment particles with a grain size between 0.004 mm and 0.062 mm, i.e., coarser than clay particles but finer than sand.

Term	Definition
Sluicing/sluice	A structure containing a gate to control the flow of water from one area to another.
Spawning	To produce or lay eggs in water.
Storm surge	A temporary and localized rise in sea level brought on by the high tides and winds associated with storms.
Stratification	Formation or deposition of layers, as of rock or sediment.
Submerged aquatic vegetation	Grasses that grow to the surface of—but do not emerge from—shallow water are called submerged aquatic vegetation (SAV).
Substrate	(1) The composition of a streambed, including either mineral or organic materials. (2) Material that forms an attachment medium for organisms.
Topography	The configuration of a surface, including its relief and the positions of its streams, roads, building, etc.
Total load	Total load is including all material in transport; bed load plus wash load for the total sediment load.
Toxins	Poisonous chemicals that react with specific cellular components to kill cells or to alter growth or development in undesirable ways; often harmful, even in dilute concentrations.
Trace erosion	Erosion of the unconsolidated material of the mixing layer in the reservoir, which occurs at low shear rates.
Tributary	A stream that flows into a larger stream or river or into a lake.
Turbidity	Not clear or transparent because of stirred-up sediment or the like; clouded; opaque; obscured.
Urbanization	The process by which towns and cities are formed and become larger as more and more people begin living and working in central areas.
Vertical mixing	In the atmosphere or oceans, an upward and downward movement of air or water that occurs as a result of the temperature gradients (temperature differences between layers of the fluid). In the atmosphere vertical mixing is sometimes discernible as a form of atmospheric turbulence.
Wash load	The part of stream's sediment load that consists of grain sizes finer than those of the stream bed. This part of the stream's suspended sediment load is not derived from the bed but is supplied to the stream by bank erosion, sheet wash, and mass wasting.
Waterfowl	A water bird, especially a swimming bird.
Watersheds	The area of land that includes a particular river or lake and all the rivers, streams, etc. that flow into it.
Wetlands	Land that has a wet and spongy soil, as a marsh, swamp, or bog.

Chapter 12. List of Participants

This collaborative effort included participants from several local, state, federal and non-governmental organizations (NGOs). Key study participants are listed below.

Interagency Study Team Membership

Name	Role	Agency
Non-Federal Team Members		
Herb Sachs	Special Projects Coordinator	MDE
Matt Rowe	Project Manager	MDE
Tim Fox	Project Manager	MDE
Bruce Michael	Director	MDNR
Shawn Seaman	Project Manager	MDNR
Richard Ortt	Director	MGS
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Dave Ladd	Project Manager	SRBC
Kathy Boomer	Project Manager	TNC
Mark Bryer	Project Manager	TNC
Federal Team Members		
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Lewis Linker	Modeler/Modeling Team Leader	EPA-CBPO
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Name	Role	Agency
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