Section 4: Nutrient Flux and Sediment Transport Modeling Results

Background & Objectives (4.1)

In 2010, the Chesapeake Bay Total Maximum Daily Load (TMDL) defined numerical reduction targets for sediment, phosphorus, and nitrogen with the goal of meeting these targets by 2025 (EPA, 2010). The TMDL, and the associated modeling that informed the sediment and nutrient reduction targets, assumed that the Conowingo Reservoir would continue to trap sediment and nutrients through 2025. Since that time, and due in large part to ongoing monitoring, considerable advancements have taken place in our understanding of the water quality of the Bay, its connection to various upstream sources of sediment and nutrients, and the delivery of sediment and nutrients throughout the 64,000 square mile watershed. The Chesapeake Bay TMDL included a progress review known as the Mid-Point Assessment that provided an opportunity to review the targeted load reductions and account for new understandings. A preponderance of evidence including bathymetric surveys, mass balance using upstream and downstream monitoring data, and modeling analyses resulted in general agreement among stakeholders that the Conowingo Reservoir is currently in dynamic equilibrium (Zhang et al., 2016). This has been defined as a state associated with equal input and output of materials averaged over long time-periods which has been exhibited in the Conowingo Reservoir since approximately the late 1990s. These findings were integrated into the 2017 Mid-Point Assessment and resulted in the annual addition of 0.26 million pounds per year (0.26-Mlb/yr.) of phosphorus and 6 million pounds of nitrogen (6-Mlb/yr.). This precipitated the development of a Conowingo Watershed Implementation Plan (CWIP), which was finalized July 31, 2021, and outlines the best management practices and strategies to address the increased reductions required to meet the TMDL targets. While the CWIP does not specifically include dredging as a management strategy, it notes that sediment removal needed to be explored further.

Strategic dredging of infill sediments in the Conowingo Reservoir has been considered as a potential sediment and nutrient management strategy since at least 2015 when it was evaluated within the Lower Susquehanna River Watershed Assessment (LSRWA, 2016). Dredging and other Reservoir sediment management strategies are targeted because of the large contribution of sediment and associated nutrients that are delivered to Bay during high-flow events. This has motivated researchers and others to understand the specific contribution that infill sediments play in non-attainment of water quality standards in the upper Bay.

While much of the early research focused on the sediment and nutrient contribution associated with scour events, typically defined as flows that exceed approximately 400,000 cubic feet per second (cfs), recent research has concluded that these large flow events are not necessarily *directly* responsible for degraded water quality in the Bay. These scour events tend to be relatively infrequent and when they do occur the nutrient and sediment dynamics in the upper Bay tend to trap scoured suspended sediment (Palinkas, 2019 and USACE, 2015). However, if viewed holistically, infill sediments likely influence the timing of both scour-derived and watershed-derived loading to the Bay. As pointed out in Palinkas et al. (2019), a decrease in deposition of watershed sediments within the Reservoir, due to diminished trapping efficiency related to available sediment capacity and particularly with higher energy during flow events, would allow the sediments to remain in suspension and transport downstream to the Bay. The Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC) identified a similar finding that "net sediment and particulate nutrient deposition behind the Dam are decreasing over a wide range of flows – including flows well below levels typically viewed as scour events" (Linker, 2016). Ongoing research will help determine whether infill- or scour-derived load is contributing to non-attainment of water quality standards in the Bay and at what timescale these impacts take place; however, the conclusion remains that management of infill sediment is an opportunity for intervention.

The objective of this section of the Pilot Project is to develop a planning-level framework to inform decision making for strategic dredging management. The approach includes reviewing and synthesizing available publications and modeling results to identify best practices that can be applied to any strategic dredging management scenario and the development of a planning-level screening tool to approximate the effect of different sediment removal quantities on sediment and nutrient loading and impact towards the needed TMDL reductions. It should be noted that development of novel numerical models or research is beyond the scope of this Pilot Project. There are many well established models and a growing body of research investigating specific aspects of sediment and nutrient dynamics within the Lower Susquehanna River, Conowingo Reservoir, and Chesapeake Bay. Instead, this Pilot Project seeks to understand the implications of this research and current regulatory requirements on potential scenarios for strategic dredge management.

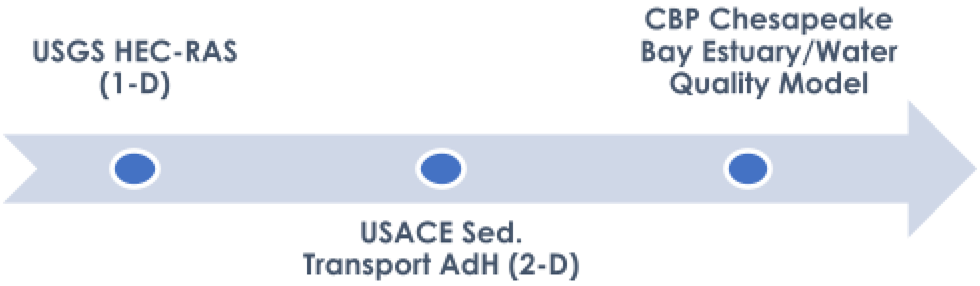
History and Current State of Conowingo Sediment and Nutrient Modeling (4.2)

The establishment of numerical TMDLs and sound planning for implementation of sediment and nutrient reduction measures requires that models are used to predict water quality conditions. As mentioned above, the 2010 TMDL relied upon modeling to develop the required reductions. The model used is referred to as the Chesapeake Bay Environmental Modeling Package (CBEMP). It consists of an Airshed Model, Land Use Change Model, Watershed Model (currently in Phase 7), and Estuary Model. These models are informed by decades of monitoring data resulting in improvements to our understanding of the mechanisms and dynamics associated with sediment and nutrient processes.

In May of 2015, the U.S. Army Corps of Engineers, Baltimore District (USACE) and the Maryland Department of the Environment (MDE) published the Lower Susquehanna River Watershed Assessment (LSRWA). The LSRWA advanced our understanding of the lower Susquehanna River sediment and nutrient dynamics and their consequences. This work included development of two new models: a hydraulic and sediment transport model of the river corridor from Lake Clarke to the Conowingo Reservoir using HEC-RAS and an Adaptive Hydraulics (AdH) model to simulate hydrodynamics and sediment transport of the Conowingo Reservoir to the Susquehanna Flats, the area below the Conowingo Dam. The AdH model scenarios included 1996, 2008, and 2011 Reservoir bathymetries to evaluate different infill conditions and their effect on transport. Both models used the flow period from 2008 to 2011.

The HEC-RAS model is a 1-dimensional model that is effective at simulating scour and deposition within a river corridor over time. This model provided input information for the AdH model including flow and sediment inflows. The AdH model is a more complex 2-dimensional model that can simulate scour and deposition of bed sediment layers where these patterns may not be uniform across the flow path. The AdH model in turn provided inputs to the CBEMP to understand the downstream impacts of different conditions (Figure 1).

Figure 1. Modeling Process



The LSRWA states that the HEC-RAS model uncertainty is primarily associated with its limited capability to simulate transport of cohesive silt and clay soils. The potential outcome of this could be underestimation of both deposition and scour under some circumstances. Stated uncertainties associated with the AdH model include simulating flocculated sediment coming into the Reservoir, simulating scour of larger compacted sediment aggregates, and the ability to simulate dam operations (USACE, 2015).

To address some of the uncertainties associated with the USACE produced HEC-RAS model documented in the LSRWA, in 2016 a new HEC-RAS model was developed by WEST Consultants and funded by Exelon, Inc. This model utilized gage data from 2008 to 2015 and also provided particle size class inputs to the Conowingo Reservoir.

In June 2017, Exelon published the Conowingo Pond Mass Balance Model (CPMBM) documentation. This work sought to answer questions related to the reactivity of scoured and deposited sediment, their chemical changes, and their transport. The CPMBM includes a hydrodynamic and sediment transport model known as ECOMSED and a water quality model developed by HDR, known as RCA. These models improved upon the previous modeling framework by addressing previous model uncertainties associated with diagenesis, hydrodynamics, transport, and dam operations.

The HEC-RAS model of the lower Susquehanna River and the CPMBM were subsequently reviewed and incorporated into the 2017 Mid-Point Assessment and represented enhancements to the CBEMP that were used to inform the Conowingo Watershed Implementation Plan (CWIP).

Strategic Dredge Water Quality Impact Calculator (4.3)

Strategic dredging is the most direct method to regain the trapping efficiency and associated transport reduction benefits associated with less Reservoir sediment infill. The assumption inherent in the additional reduction requirements identified in the TMDL Mid-Point Assessment is that if infill volume were returned to quantities associated with a state of non-dynamic equilibrium – e.g., with remaining trapping capacity – then the required reductions or a portion thereof would be accomplished. While the reality of achieving water quality standards and the conditions that bring them about are more complicated, and thus have greater associated uncertainty, the underlying relationship between lower infill volume and improved downstream water quality is built in to the TMDL, planning, and modeling framework.

The relationship between infill and nutrient loading is utilized for evaluating the relative impact of different dredging scenarios on water quality. To understand the infill condition of the Reservoir, the bathymetry or capacity at different points in time must be known or calculated. The Conowingo Reservoir bottom-surface profile was surveyed in 1959/60, 1990, 1993, 1996/7, 2008, 2011, and 2014 (Langland, 2009; and Langland, 2015). This record provides a robust understanding of infill conditions and patterns. This information in combination with depositional rates from long-term monitoring provides the potential for approximating infill conditions for intervening years to be interpolated while understanding that scour/depositional processes are highly variable depending on flow events.

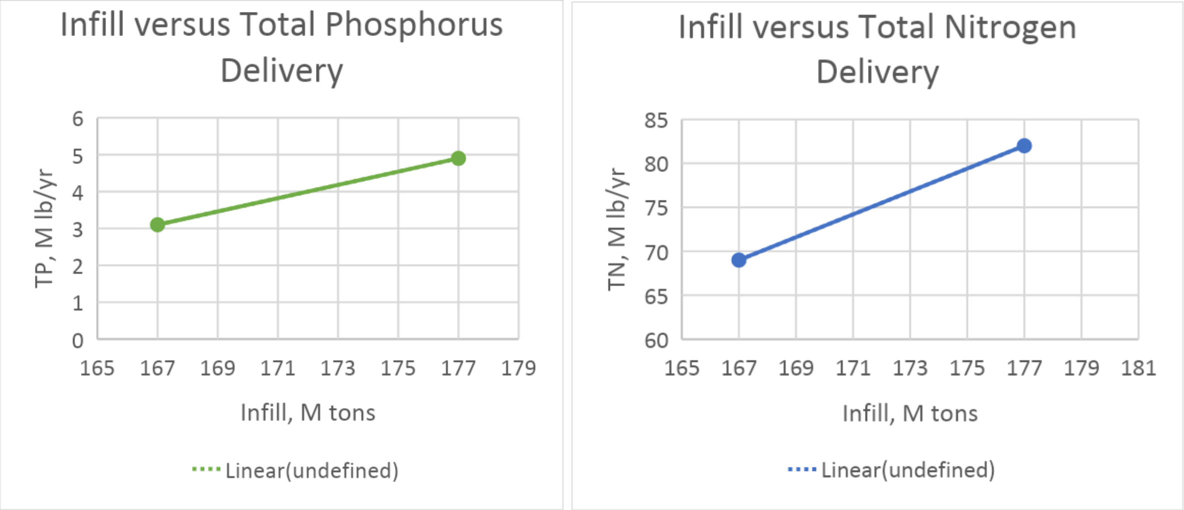
During the Mid-Point Assessment, the Modeling Workgroup (MWG) used the CBEMP to run two scenarios to determine the effect of infill conditions on nutrient loading to the Bay. They used 1995 conditions to represent infill volume that held the previous assumption of remaining capacity and 2010 conditions to represent infill volume at dynamic equilibrium (MWG, 2017). The difference between these two scenarios represents the loading contribution due to infill volume at dynamic equilibrium. It was noted that although scour increases the delivery of particulate nutrients, many of these nutrients are not bioavailable and only reach the Bay during high, infrequent flow events. For this reason, only a portion of these nutrients, those more associated with watershed derived sediments, were assumed to impact water quality and to be relevant to the TMDL.

With the bathymetric and depositional information and the delivered nutrient rates calculated through the MWG efforts, a linear regression can be developed to approximate the effect of different infill volumes on downstream water quality (Table 1). While it is not certain that this relationship is linear, given the nonlinearity of sediment concentrations to flow-events among other uncertainties inherent in a stochastic system, the connection to the CWIP TMDL reductions given the two points of analysis makes this relationship a useful planning level tool to evaluate how infill volume relates to downstream water quality. This relationship is defined in Figure 2 for nutrient delivery rates for the portion of that delivered load that impacts nonattainment of water quality standards and has been incorporated into the TMDL calculations.

Table 1. Infill volume and associated loading for infill states

		Delivered Load			***TMDL***	
Year	***Infill (M tons)***	***TP (M Lb/yr)***	***TN (M Lb/yr)***	***TSS (M Lb/yr)***	***TP (M Lb/yr)***	***TN (M Lb/yr)***
1995	167	3.1	69	1863	0	0
2010	177	4.9	82	3217	0.26	6

Figure 2. Phosphorus and Nitrogen Loading vs. Infill Volume



(TP = Total Phosphorous; TN = Total Nitrogen; M = million)

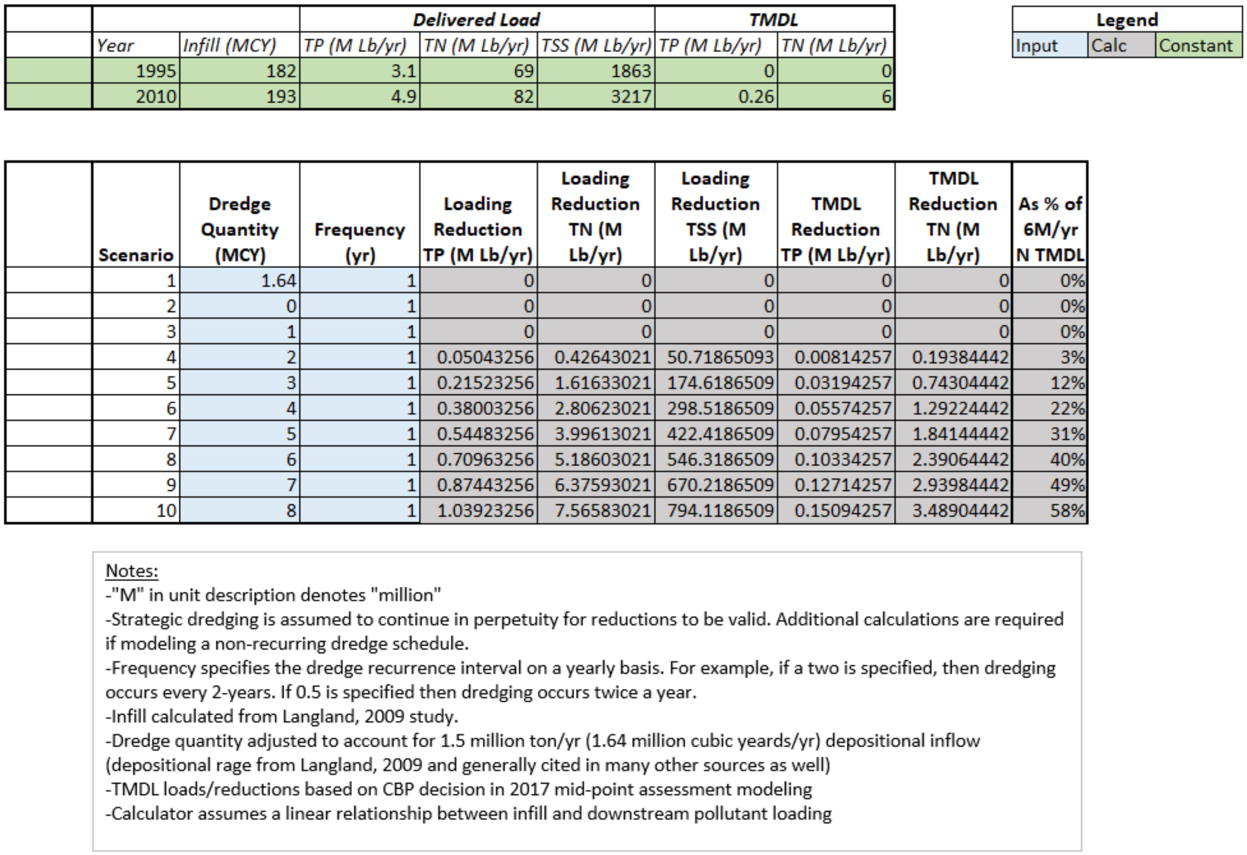
The linear regression above was used to develop a tool that can be used to estimate the impact of infill volume changes such as dredging on yearly nutrient and sediment export and TMDL allocations (Calculator). The Calculator also considers the 1.5 MT/yr of sediment estimated to deposit in the Conowingo Reservoir. Estimates produced by the Calculator are intended as a planning or screening level assessment to understand the potential relative impact of sediment removal. The Calculator does not take into consideration resuspension during dredging or the hydrodynamic impacts of altered bed bathymetry among other characteristics that affect fate and transport of sediment and nutrients within the Reservoir. More sophisticated modeling will be necessary to produce more accurate estimates of the effect of dredging.

The Calculator is designed with tabs that allow dredge quantities to be input in either million cubic yards (MCY) or million tons (MT). This work relied on infill densities as reported and used in previous studies (Langland, 2009) for consistency; however, actual soil densities may vary.

Scenario Results and Considerations (4.4)

Table 2 below is from the Calculator and shows results of different dredging quantities and their impact on downstream water quality and specifically their impact on the TMDL allocations outlined in the CWIP.

Table 2. Sample Calculator Results and Annotation



			Delivered Load			*TMDL*	
	Year	*Infill (MCY)*	*TP (M Lb/yr)*	*TN (M Lb/yr)*	*TSS (M Lb/yr)*	*TP (M Lb/yr)*	*TN (M Lb/yr)*
	1995	182	3.1	69	1863	0	0
	2010	193	4.9	82	3217	0.26	6

Legend		
Input	Calc	Constant

	Scenario	**Dredge Quantity (MCY)**	**Frequency (yr)**	**Loading Reduction TP (M Lb/yr)**	**Loading Reduction TN (M Lb/yr)**	**Loading Reduction TSS (M Lb/yr)**	**TMDL Reduction TP (M Lb/yr)**	**TMDL Reduction TN (M Lb/yr)**	**As % of 6M/yr N TMDL**
	1	1.64	1	0	0	0	0	0	0%
	2	0	1	0	0	0	0	0	0%
	3	1	1	0	0	0	0	0	0%
	4	2	1	0.05043256	0.42643021	50.71865093	0.00814257	0.19384442	3%
	5	3	1	0.21523256	1.61633021	174.6186509	0.03194257	0.74304442	12%
	6	4	1	0.38003256	2.80623021	298.5186509	0.05574257	1.29224442	22%
	7	5	1	0.54483256	3.99613021	422.4186509	0.07954257	1.84144442	31%
	8	6	1	0.70963256	5.18603021	546.3186509	0.10334257	2.39064442	40%
	9	7	1	0.87443256	6.37593021	670.2186509	0.12714257	2.93984442	49%
	10	8	1	1.03923256	7.56583021	794.1186509	0.15094257	3.48904442	58%

Notes:
-"M" in unit description denotes "million"
-Strategic dredging is assumed to continue in perpetuity for reductions to be valid. Additional calculations are required if modeling a non-recurring dredge schedule.
-Frequency specifies the dredge recurrence interval on a yearly basis. For example, if a two is specified, then dredging occurs every 2-years. If 0.5 is specified then dredging occurs twice a year.
-Infill calculated from Langland, 2009 study.
-Dredge quantity adjusted to account for 1.5 million ton/yr (1.64 million cubic yards/yr) depositional inflow (depositional rage from Langland, 2009 and generally cited in many other sources as well)
-TMDL loads/reductions based on CBP decision in 2017 mid-point assessment modeling
-Calculator assumes a linear relationship between infill and downstream pollutant loading

Dredging of the Reservoir has been described in the LSRWA and the CWIP as a potential solution to be paired with watershed BMPs that will reduce pollutant inflow to the Conowingo Reservoir. These results support that conclusion by showing that increased dredging of the Reservoir above the rate of depositional inflow is expected to reduce downstream sediment and nutrient loading.

Strategic Dredge Management Best Practices (4.5)

Strategic dredging has many potential benefits that will help reduce sediment nutrient flux to the upper Chesapeake Bay including:

- Physical removal of sediment and attendant nutrients
- Increase in Reservoir storage-capacity
- Decrease in flow velocity
- Increase in particle settling rates
- Increase in sediment deposition
- Decrease of shear stress
- Increase in scour threshold
- Decrease of scour induced transport of sediment and nutrients downstream
- Decrease of suspended load transport of sediment and nutrients downstream
- Increase of sediment trap efficiency

A dredging management strategy should consider the conditions needed to achieve these benefits to derive the greatest reduction in nutrient and sediment flux. Key elements of a dredging management strategy include:

Location

Locations within the Reservoir where dredging is to occur and the sequence of multi-year dredging locations could focus areas where deposition has occurred in recent decades (Figures 3 and 4). They could also focus on recent depositional areas (Figure 5). Areas identified as A and B in Figure 4 represent areas of consistent deposition and in the case of Area B, scour during high-flow events. Area A is likely also susceptible to high and moderate flow events due to the narrowing of the Reservoir in this location, which increases velocity and lowers the scour threshold.

Figure 3. Change in depth to bottom surface by transect in Conowingo Reservoir, 1993 to 2008 (Langland, 2009)

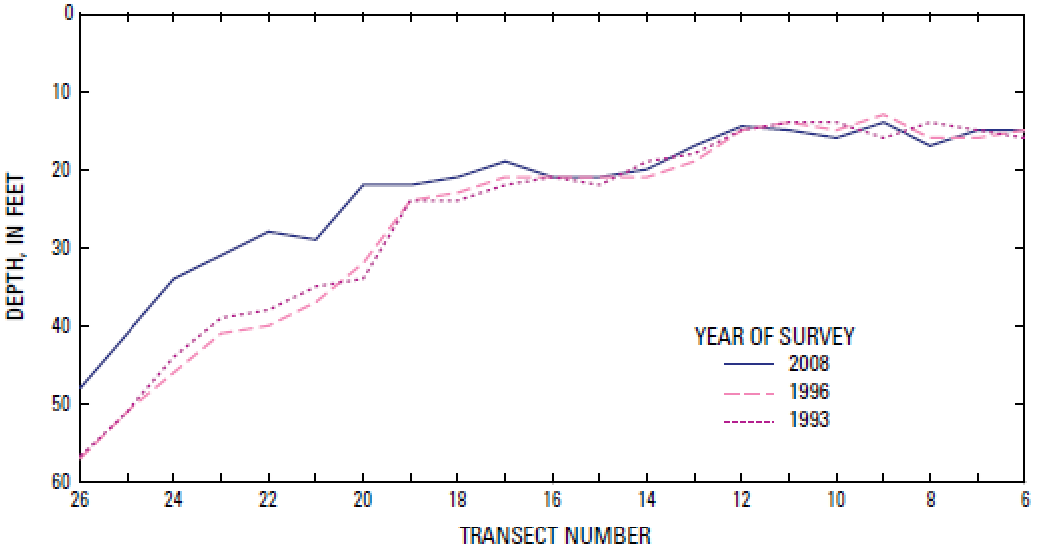
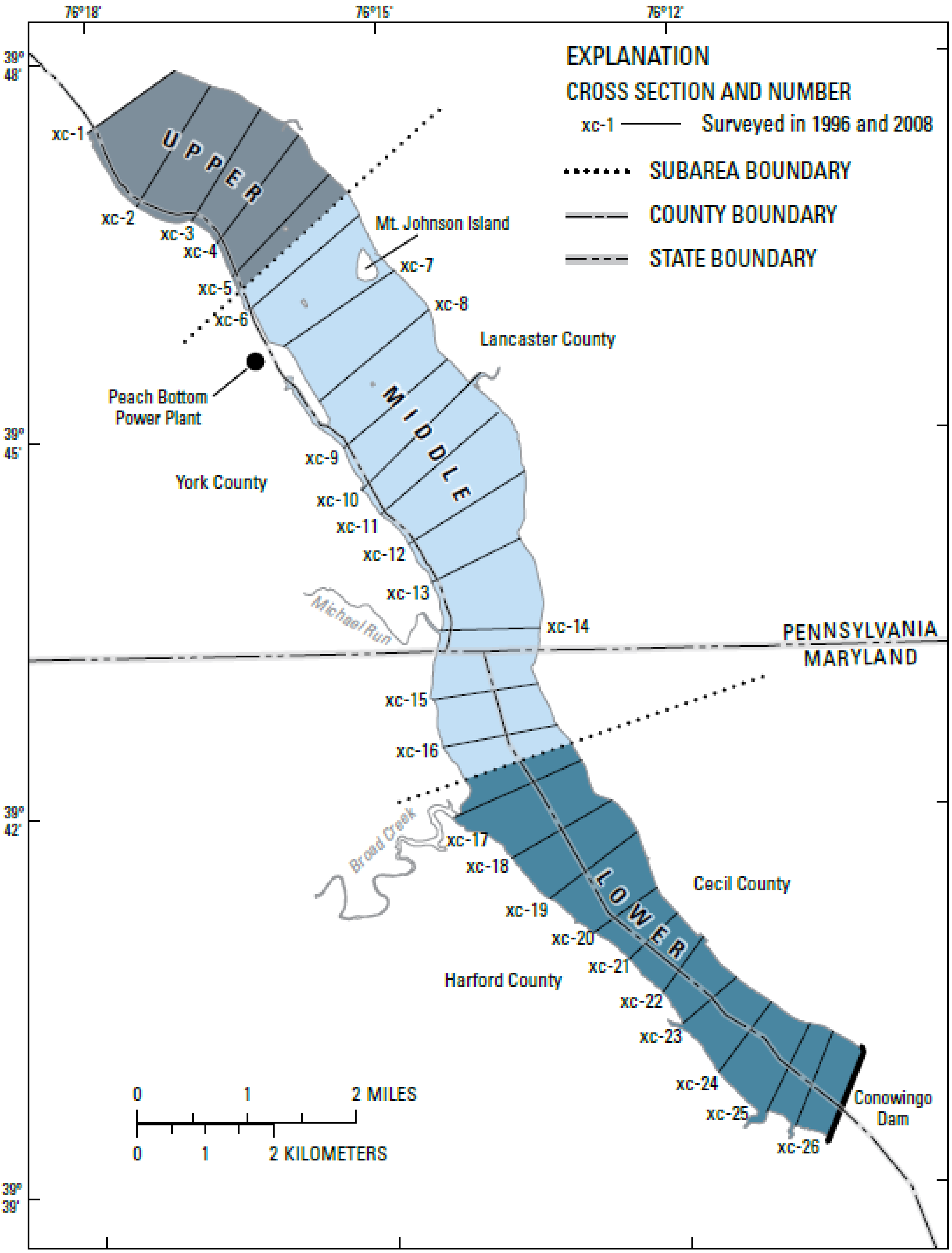


Figure 4. Bathymetric survey transects surveyed in Conowingo Reservoir (Langland, 2009)

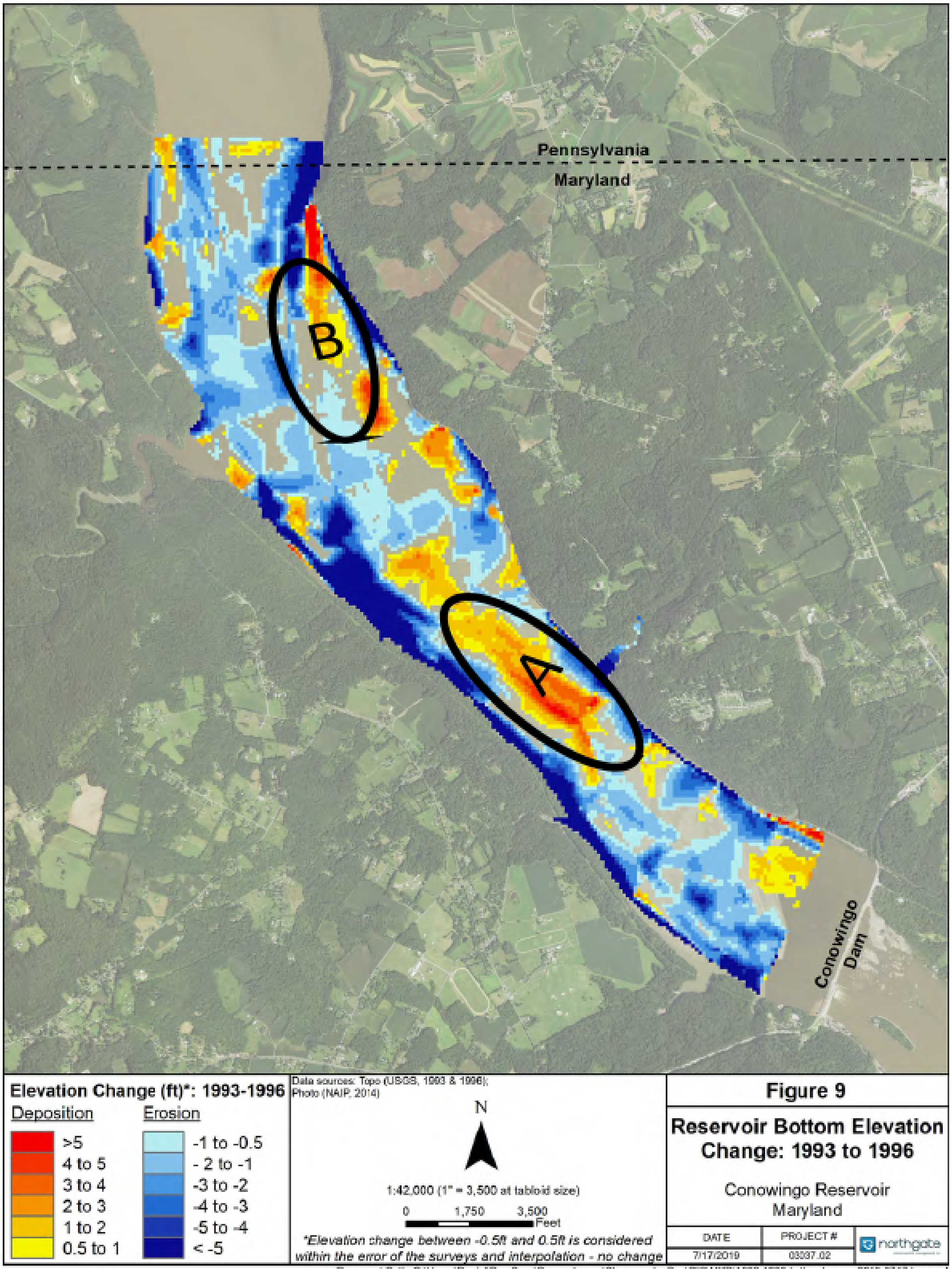


State and County Boundaries: USGS 1:100,000-scale data,
Universal Transverse Mercator Projection: Zone 18, NAD 1983

Hydrography data: USGS, 1:24,000-scale National Hydrography Dataset

Figure 9. Bathymetric survey transects surveyed in Conowingo Reservoir, lower Susquehanna River.

Figure 5. Areas of consistent deposition in the Conowingo Reservoir.



Time of Year

Moderate flow-events, those capable of moving suspended sediment downstream of the dam, occur most frequently during the Spring due to snow melt and moderate to heavy rains associated with the freshet. Higher flow-events occur in the late summer or early fall associated with the Mid-Atlantic hurricane season. Aligning dredge scenarios prior to these events would increase the depositional opportunities resulting from these events and potentially reduce the susceptibility of newly deposited sediments to scour.

Volume

To achieve the goal of providing trapping capacity that can capture net volumes of sediment and nutrients that flow downstream, dredge volumes in any year need to be greater than the annual sediment deposition rate of 1.5 MT (1.64 MCY). Results from the regression calculator above indicate that if 3 MCY/yr are dredged in a given year, total Nitrogen delivered to the Bay (TN) will be reduced by 1.616 M lb/yr. Note though that this TN estimate is not the same as the TMDL reduction that would be observed for TN (0.743 M lb/yr). This TMDL reduction would be 12.4% of the EPA's 6 M lb/yr target.[1] Because of the annual deposition rate, doubling sediment removal to 6 MCY/yr would more than double this percentage; the percentage would jump to 40%. Volumes removed annually could be structured in reference to nutrient reductions from a more refined version of the calculator presented here, recognizing practical limitations on maximum potential volume based on a six month window.

Depth and Spatial Extent

The profile of Conowingo Reservoir bed sediments is commonly organized by reactivity and referred to as G1, labile; G1, refractory; and G3, inert. The layer of sediment closer to the surface has the greatest bioavailability and thus the greatest impact on downstream water quality. Strategic dredging that focuses on removing a wide rather than deep cross-section of sediment would thereby likely have the

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[1] This is because "delivered load" reflects nutrients that reach the Bay, whereas TMDL reductions are calculated based on amounts of nutrients considered to be bioavailable after passing through tidal regimes, SAV beds, and biogeochemical conversions that render some nutrients unavailable.

greatest impact by removing the most reactive (labile) layer. Further modeling should take these parameters into account.

Time Interval

Given the time of year of the two higher flow conditions, dredging prior to the Spring will reduce the impact of transport during moderate storms in the Spring and potentially reduce the downstream impact of scour events in the late summer.

Conclusions and Implications for Further Investigation

This work provides planning or screening level estimates of the potential impact of a dredging management strategy. For example, screening level results include that dredging 3 MCY/yr is expected to provide a TMDL reduction for TN of 12% (vs. the EPA-stated annual need to reduce 6 M lb/yr), and dredging 6 MCY/yr is expected to raise this contribution to 40% TMDL reduction. However, it is expected that more precise measurements of pollutant reduction would be needed prior to implementation of a full dredging approach. Currently, and as described in Section 4.2, the Chesapeake Bay Program has used the CPMBM developed by HDR and funded by Exelon, Inc. to produce input into the CBEMP. It is recommended that a modified modeling approach be used to generate more precise pollutant reduction quantities. It is also expected that more focused modeling may show a greater TMDL reduction than calculated in this study, because dredge activities would be tailored to 1) locations where deposition is most likely to occur and 2) times of year when resuspension would be minimized. To model changes that dredging would cause, Conowingo Reservoir bathymetry would need to be modified in the dredging locations and updated at the frequency outlined in the dredging scenario. G-fraction reactivity differences should also be incorporated as described above. Such a modeling effort should be conducted in a manner consistent with CPMBM and able to be incorporated into forecasting models using CBEMP.

Also, because the CPMBM model has no feedback between changes in bathymetry resulting from sediment deposition/erosion and Reservoir hydrodynamics, it would be unable to represent the process by which dredged areas of different dimensions fill with sediment over multi-year simulations, during which the depth of the dredged area is decreased and sediment trapping efficiency is gradually reduced. Further, the HDR model has no windwave resuspension, which is important because sediment seasonally deposited at the upper end of the Reservoir is redistributed into deeper parts of the Reservoir during high flow events. Future comparisons of Reservoir dynamics under different dredging scenarios should take this resuspension into account. A strategic dredging modeling effort that addresses these issues could produce more refined results than this project; results may include slightly different TMDL implications from those found here.