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FEATURED COLLECTION INTRODUCTION: CHESAPEAKE BAY TOTAL MAXIMUM DAILY LOAD DEVELOPMENT AND APPLICATION[1]

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BACKGROUND

The Chesapeake Bay Program (CBP), a state-federal partnership, is an ongoing experiment in how to restore the national treasure which is the United States' (U.S.) largest estuary. The Chesapeake Bay experiment has now been running for three decades, but in 2010 a new tool was added to the restoration effort when the nation's most extensive Total Maximum Daily Load (TMDL) program was established for the Chesapeake Bay watershed.

The Chesapeake Bay TMDL marked a change in direction for the CBP partnership from a voluntary restoration program to one based on a regulatory form of allocations. The reasons for this pivot are outlined in the Executive Summary of the 2010 Chesapeake TMDL (USEPA, 2010). The Chesapeake Bay TMDL is based on the achievement of a suite of living resource-based water quality standards for dissolved oxygen, chlorophyll *a*, and water clarity, which support fish, shellfish, underwater grasses, and other important aquatic life communities.

The Chesapeake Bay TMDL incorporates several key elements. Scientifically based, publically understandable, water quality standards are the most important of these. The Chesapeake Bay water quality standards are based on requirements for the Bay's living resources to thrive, including adequate dissolved oxygen in deep water habitats and good water clarity in the shallow waters necessary for growth of underwater grasses which provide habitat for juvenile fish and crabs.

The partnership of state and federal agencies, which provides resource management governance and collaborative decision making for the entire watershed, is the second key element. This year the CBP marks its 30th anniversary. The CBP partnership was formed 30 years ago when the first Chesapeake Bay agreement was signed in 1983, recognizing the "historical decline of living resources" in the Chesapeake Bay and committing to a cooperative approach to "fully address the extent, complexity, and sources of pollutants entering the Bay." It laid the foundation for a cooperative program that now includes all the Chesapeake Bay watershed jurisdictions.

Finally, there is the long history of ever-increasing scientific understanding of the Bay ecosystem and the surrounding watershed. The underlying science enables the state and federal partners to agree on an equitable allocation of pollutant load reduction responsibilities. The JAWRA Featured Collection on the Chesapeake Bay TMDL tells the story of the

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Chesapeake Bay TMDL from developing water quality standards through to establishing allocations — an up-to-date picture of the result of 30 years of restoration effort.

The Chesapeake Bay restoration experiment is still running, and substantial activity is required to implement the management actions needed by 2025. A major midpoint assessment of the TMDL process is planned in 2017 when the management practices necessary to achieve 60% of the pollutant load reductions required under the Bay TMDL will be in place.

THE CHESAPEAKE BAY TMDL

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

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

The 2010 Chesapeake Bay TMDL sets watershed-wide limits of 84.3 million kilograms of nitrogen, 5.67 million kilograms of phosphorus, and 2.93 billion kilograms of sediment per year. Implementation of the nutrient and sediment limits is through the seven watershed jurisdictions' Watershed Implementation Plans, which detail how and when the six Bay watershed states and the District of Columbia will meet their assigned pollution allocations.

OVERVIEW OF THE FEATURED COLLECTION

The collaborative work and decision making of hundreds of state, federal, regional, and local agencies, universities, and nongovernmental organizations were required for the development of the Chesapeake TMDL. Decisions were supported by decades of scientific discovery as well as the application of a suite of integrated environmental models. The science, model development and application, and development of water quality standards, which supported this unprecedented shared decision-making process across a six-state watershed, are described here.

The Featured Collection begins with a summary by Linker *et al*. (this issue (a)) of the multidecadal history of establishing pollutant load reduction targets and allocations. Nutrient load allocations and subsequent reductions of total nitrogen and phosphorus have been applied in the Chesapeake Bay watershed since 1992 to reduce hypoxia and restore living resources. After more than two decades of evolution of the load reduction process, the 2010 Chesapeake Bay TMDL follows a more quantitative allocation process than previous versions. The process ensures achievement of all tidal water quality standards while assessing equitable levels-of-effort in reducing nutrients and sediments across all seven watershed jurisdictions. The equitable levels-of-effort are determined through application of two key watershed scenarios; a scenario where no action is taken in nutrient control and a scenario where maximum nutrient control efforts are applied. Once the needed level-of-effort is determined for each of the different jurisdictions, the overall load reductions are set watershed wide to achieve water quality standards.

A good TMDL is based on scientifically sound and publically understandable water quality standards, based on quantifiable water quality criteria (Tango and Batiuk, this issue). In 2003, the CBP partners worked with the U.S. Environmental Protection Agency to develop and publish ambient water quality criteria protective of specific Chesapeake Bay tidal water designated uses along with assessment procedures for dissolved oxygen, water clarity, and chlorophyll *a* (USEPA, 2003). The adoption of these criteria, designated uses, and assessment procedures into Delaware, District of Columbia, Maryland, and Virginia water quality standards ultimately provided the basis for developing the Chesapeake Bay TMDL.

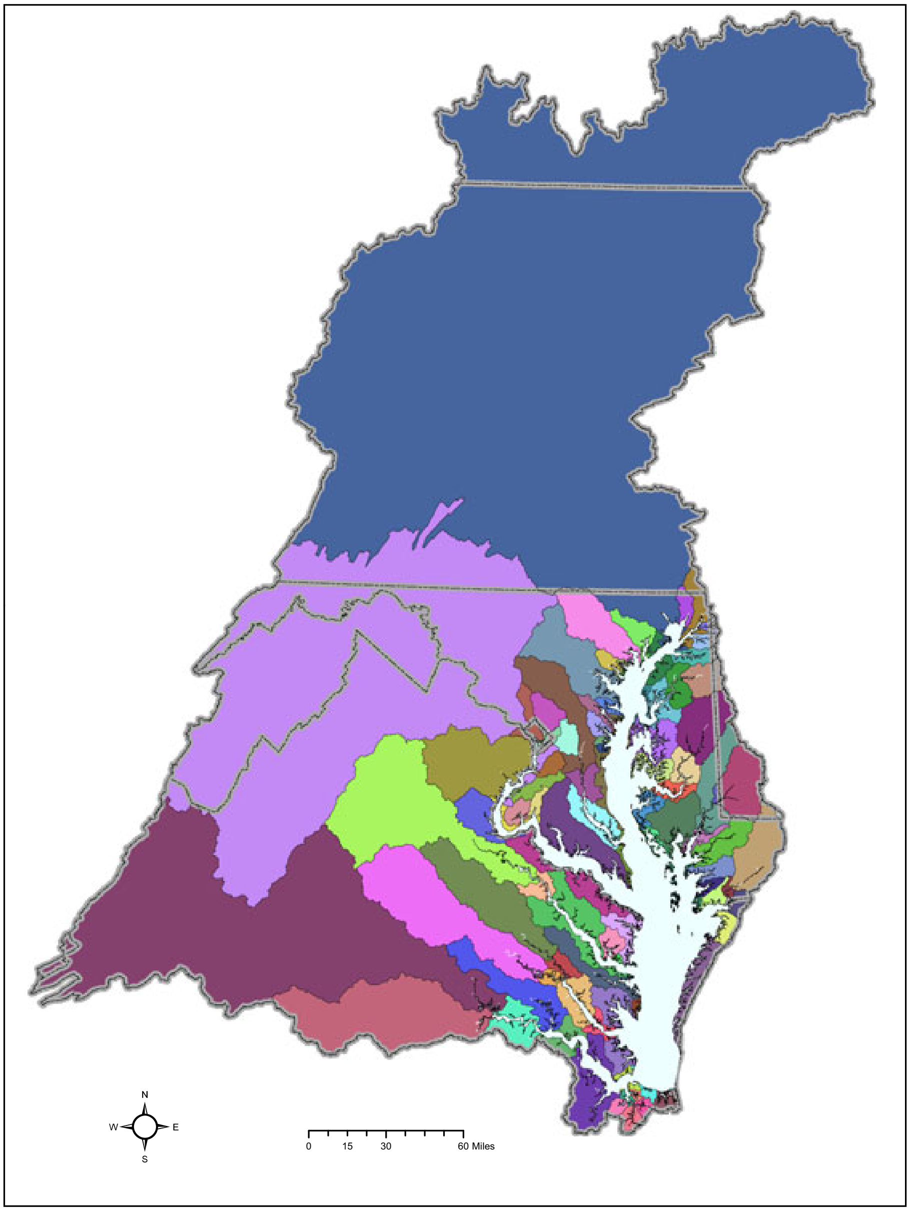

FIGURE 1. The 92 Chesapeake Bay Segment Watersheds for Which Separate Nitrogen, Phosphorus, and Sediment Total Maximum Daily Load Were Developed (USEPA, 2010).

The Featured Collection next includes a series of articles describing the development and application of integrated models of the Chesapeake Bay airshed, watershed, and estuary. The CBP partners recognized the importance of atmospheric nutrient deposition in the 1980s and quantified the first estimates of atmospheric loads delivered to the Chesapeake Bay and its watershed in 1992. Currently, the linkage between national NO_x emission reductions, brought about to address human health concerns, and reduced nitrogen loads delivered to the Chesapeake Bay ecosystem is recognized by including atmospheric deposition reductions to the tidal waters of the Bay as part of the Chesapeake Bay TMDL allocations (Linker *et al.*, this issue (b)).

The Phase 5.3 Chesapeake Bay Watershed Model is the most recent of a series of increasingly refined versions of a model that has been operational for more than three decades (Shenk and Linker, this issue). A "community model" approach was taken in development and application of the Phase 5.3 version. The model community encompassed a broad coalition of practitioners including environmental engineers, scientists, and environmental managers. The Watershed Model incorporates comprehensive information including meteorology, land use and surface characteristics, fertilizer and manure application data, and management practices. Following calibration to observed flow and water quality data, the Phase 5.3 Chesapeake Bay Watershed Model provides daily computations of flow, sediment load, and nutrient loads delivered to Chesapeake Bay.

Reliable land use data is a key determinant of the accuracy of the Chesapeake Bay Watershed Model. But assessment of the extent of impervious and pervious areas using land-cover data derived from satellite imagery is limited due to the resolution of the data and systematic discrepancies between land-cover classes. To overcome these limitations, Claggett *et al.* (this issue) introduced a new method to consistently estimate the areas of impervious surface and turf grass across the Chesapeake Bay watershed over a 22-year time frame.

The CH3D Hydrodynamic Model has been applied to represent the hydrodynamics of Chesapeake Bay tidal waters since 1992. The current version, described by Kim (this issue), incorporates improved grid resolution, expanded spatial coverage, and realistic bathymetry to enhance model performance both in open water and shoreline regions. Hydrodynamic computations are based on a comprehensive suite of forcing functions including high-frequency astronomical tides, lower frequency meteorological forcing, freshwater inflows from the upland watershed, and distributed sources along the shoreline.

The Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM) incorporates a shallow water component which focuses on the regions of the estuarine system inside the 2-m depth contour (Cerco *et al.*, this issue). The shallow water component is an integral part of the larger system-wide water quality model, but emphasizes simulation of the locally significant variables and processes, notably submerged aquatic vegetation (SAV), sediment resuspension, and light attenuation.

Wang *et al.* (this issue) analyzed the correlations of the observed and modeled light attenuation coefficient, Kd, with total suspended solids (TSS) and chlorophyll *a* concentrations in Chesapeake Bay tidal waters. Although light attenuation is closely related to TSS and chlorophyll *a* concentrations, the strength and nature of the relationship differ among the Chesapeake Bay segments. This article expands on the work of Gallegos (2001) and analyzes the relationship of watershed nutrient and sediment loads to Kd, TSS, and chlorophyll *a* in the estuarine water column. TMDL development and management implementation benefit from the additional options provided by this investigation.

Cerco and Noel (this issue) report on application of the Chesapeake Bay WQSTM in a 21-year, 1985-2005, simulation of Chesapeake Bay water quality. The WQSTM computes, in three dimensions, physical properties, algal production, and key elements of the aquatic carbon, nitrogen, phosphorus, silica, and oxygen cycles. The model incorporates multiple submodels including sediment diagenesis (DiToro, 2001), SAV (Cerco and Moore, 2001), benthic invertebrates (Cerco and Meyers, 2000), light attenuation based on inherent optical properties (Gallegos *et al.*, 2011), and suspended solids (Cerco *et al.*, 2013). The WQSTM is the fourth generation of tidal water quality models that have been applied by the CBP partnership over the past three decades. The present application emphasizes the role of physical processes, as well as nutrient loads, in determining the volume of anoxic water in the main stem bay.

The Featured Collection concludes with work described by Keisman and Shenk (this issue) on water quality criteria assessments using a combination of monitoring data and model outputs. For complex estuarine systems like the Chesapeake Bay, TMDL determination has been limited by difficulty in estimating precisely how changes in input loads will impact ambient water quality. An innovative method to deal with this limitation combines the strengths of the Chesapeake Bay WQSTM, which simulates load response, and the Chesapeake Bay Program's robust historical monitoring dataset. The method uses linear regression to relate modeled responses from load reductions to historical observations of water quality. The method quantifies responses of dissolved oxygen and chlorophyll to load reductions on a monthly time basis and at a spatial scale comparable to model cell dimensions.

LITERATURE CITED

Cerco, C. and M. Meyers, 2000. Tributary Refinements to the Chesapeake Bay Model. Journal of Environmental Engineering 126(2): 164-174.

Cerco, C. and K. Moore, 2001. System-Wide Submerged Aquatic Vegetation Model for Chesapeake Bay. Estuaries 24(4):522-534.

Cerco, C.F. and M.R. Noel, this issue. Twenty-One-Year Simulation of Chesapeake Bay Water Quality Using the CE-QUAL-ICM Eutrophication Model. Journal of the American Water Resources Association, doi: 10.1111/jawr.12107. EPA-903-R-13-011, CBP/TRS-317-13-10.

Cerco, C.F., M.R. Noel, and S.-C. Kim, 2013. Management Modelling of Suspended Solids in the Chesapeake Bay, USA. Estuarine, Coastal and Shelf Science 116:87-98.

Cerco, C.F., M.R. Noel, and P. Wang, this issue. The Shallow-Water Component of the Chesapeake Bay Environmental Model Package. Journal of the American Water Resources Association, doi: 10.1111/jawr.12106. EPA-903-R-13-009, CBP/TRS-315-13-8.

Claggett, P.R., F.M. Irani, and R.L. Thompson, this issue. Estimating the Extent of Impervious Surfaces and Turf Grass Across Large Regions. Journal of the American Water Resources Association, doi: 10.1111/jawr.12110. EPA-903-R-13-007, CBP/TRS-313-13-6.

DiToro, D., 2001. Sediment Flux Modeling. John Wiley and Sons, New York City, New York, ISBN 0-471-13535-6.

Gallegos, C., 2001. Calculating Optical Water Quality Targets to Restore and Protect Submerged Aquatic Vegetation: Overcoming Problems in Partitioning the Diffuse Attenuation Coefficient for Photosynthetically Active Radiation. Estuaries 24(3):381-397.

Gallegos, C.L., P.J. Werdell, and C.R. McClain, 2011. Long-Term Changes in Light Scattering in Chesapeake Bay Inferred from Secchi Depth, Light Attenuation, and Remote Sensing Measurements. Journal of Geophysical Research 117:1-19, doi: 10.1029/JC2011007160.

Keisman, J. and G. Shenk, this issue. Total Maximum Daily Load Criteria Assessment Using Monitoring and Modeling Data. Journal of the American Water Resources Association, doi: 10.1111/jawr.12111. EPA-903-R-13-012, CBP/TRS-318-13-11.

Kim, S.-C., this issue. Evaluation of a Three-Dimensional Hydrodynamic Model Applied to Chesapeake Bay Through Long-Term Simulation of Transport Processes. Journal of the American Water Resources Association, doi: 10.1111/jawr.12113. EPA-903-R-13-006, CBP/TRS-312-13-5.

Linker, L.C., R.A. Batiuk, G.W. Shenk, and C.F. Cerco, this issue (a). Development of the Chesapeake Bay Watershed Total Maximum Daily Load Allocation. Journal of the American Water Resources Association, doi: 10.1111/jawr.12105. EPA-903-R-13-003, CBP/TRS-309-13-2.

Linker, L.C., R. Dennis, G.W. Shenk, R.A. Batiuk, J. Grimm, and P. Wang, this issue (b). Computing Atmospheric Nutrient Loads to the Chesapeake Bay Watershed and Tidal Waters. Journal of the American Water Resources Association, doi: 10.1111/jawr.12112. EPA-903-R-13-008, CBP/TRS-314-13-7.

Shenk, G.W. and L.C. Linker, this issue. Development and Application of the 2010 Chesapeake Bay Watershed Total Maximum Daily Load Model. Journal of the American Water Resources Association, doi: 10.1111/jawr.12109. EPA-903-R-13-004, CBP/TRS-310-13-3.

Tango, P.J. and R.A. Batiuk, this issue. Deriving Chesapeake Bay Water Quality Standards. Journal of the American Water Resources Association, doi: 10.1111/jawr.12108. EPA-903-R-13-005, CBP/TRS-311-13-4.

USEPA (U.S. Environmental Protection Agency), 2003. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries. EPA 903-R-03-002. U.S. Environmental Protection Agency, Region 3, Chesapeake Bay Program Office, Annapolis, Maryland.

USEPA (U.S. Environmental Protection Agency), 2010. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. U.S. Environmental Protection Agency Chesapeake Bay Program Office, Annapolis, Maryland.

Wang, P., L.C. Linker, and R.A. Batiuk, this issue. Monitored and Modeled Correlations of Sediment and Nutrients with Chesapeake Bay Water Clarity. Journal of the American Water Resources Association, doi: 10.1111/jawr.12104. EPA-903-R-13-010, CBP/TRS-316-13-9.