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DEVELOPMENT OF THE CHESAPEAKE BAY WATERSHED TOTAL MAXIMUM DAILY LOAD ALLOCATION[1]

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ABSTRACT: Nutrient load allocations and subsequent reductions in total nitrogen and phosphorus have been applied in the Chesapeake watershed since 1992 to reduce hypoxia and to restore living resources. In 2010, sediment allocations were established to augment nutrient allocations supporting the submerged aquatic vegetation resource. From the initial introduction of nutrient allocations in 1992 to the present, the allocations have become more completely applied to all areas and loads in the watershed and have also become more rigorously assessed and tracked. The latest 2010 application of nutrient and sediment allocations were made as part of the Chesapeake Bay total maximum daily load and covered all six states of the Chesapeake watershed. A quantitative allocation process was developed that applied principles of equity and efficiency in the watershed, while achieving all tidal water quality standards through an assessment of equitable levels of effort in reducing nutrients and sediments. The level of effort was determined through application of two key watershed scenarios: one where no action was taken in nutrient control and one where maximum nutrient control efforts were applied. Once the level of effort was determined for different jurisdictions, the overall load reduction was set watershed-wide to achieve dissolved oxygen water quality standards. Further adjustments were made to the allocation to achieve the James River chlorophyll-*a* standard.

(KEY TERMS: Chesapeake Bay; Chesapeake Bay Program; TMDLs; integrated environmental models; water quality standards; dissolved oxygen; chlorophyll; water clarity; watershed management; nitrogen; phosphorus; sediment.)

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INTRODUCTION

The 2010 Chesapeake Bay total maximum daily load (TMDL) is the largest, most complex TMDL in the country, covering a 166,000 km^2 area across seven jurisdictions. The Bay TMDL allocates loadings of nitrogen, phosphorus, and sediment to sources and areas of the watershed contributing those pollutants to remove impairments for aquatic life uses in the Bay's tidal tributaries and embayments. Nutrient and sediment loads were allocated from sources in Delaware, the District of Columbia, Maryland, New York, Pennsylvania, Virginia, and West Virginia (USEPA, 2010a, b).

The Chesapeake Bay TMDL allocations for nutrients and sediment are the basis of comprehensive watershed restoration plans, which include rigorous

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accountability measures, to restore water quality and living resources in the Chesapeake Bay. The 2010 allocations were based on more than two decades of allocation experience by the state, federal, academic, and public partners within the Chesapeake Bay Program (CBP) partnership (USEPA, 2010a, b, c, d, e, f, g, h). Over this period, the allocations have become progressively more comprehensive in their spatial resolution and more rigorous in their accounting for all nutrient and sediment loads in the watershed, airshed, and tidal Bay.

The first allocation, or reduction in nutrients, in the Chesapeake Bay was directed by the 1987 Chesapeake Bay Agreement (Chesapeake Executive Council, 1987), which called for "at least a 40% reduction in the overall nutrient loads entering the mainstem of the Chesapeake Bay." Key research in Chesapeake Bay eutrophication (Gillelan *et al.*, 1983; Kemp *et al.*, 1992, 2004, 2005; Boynton *et al.*, 1995; Madden and Kemp, 1996; Boynton and Kemp, 2008) provided backing for the management directive of the 1987 Chesapeake Bay Agreement and its 1992 Amendments for reducing watershed nutrient loads.

The generalized, nonspecific 40% reduction goal of the 1987 Chesapeake Bay Agreement was quantified in 1992 with the first major river basin-jurisdiction allocations of nitrogen and phosphorus (Perciasepe, 1992). Basin jurisdictions are formed by the intersection of the eight major basins of the Susquehanna, Potomac, James, Patuxent, Rappahannock, and York Rivers, the Western Shore tributaries, and the Eastern Shore tributaries with the seven jurisdictions in the Bay watershed — Delaware, the District of Columbia, Maryland, New York, Pennsylvania, Virginia, and West Virginia (Figure 1). There are 19 major basin jurisdictions from this intersection of basins and jurisdictions, but many more minor ones are generated in the process such as one example of the a portion of the East Shore divided into the Upper East Shore-Maryland, Upper East Shore-Delaware, and Upper East Shore-Pennsylvania. In all, the major and minor basin jurisdictions total 30.

The 1992 quantitative allocation of nutrients to Chesapeake basin jurisdictions were applied to only the basin jurisdictions of the three states signatory to the Chesapeake Bay Agreement — Maryland, Pennsylvania, and Virginia — along with the District of Columbia. Furthermore, the 40% reduction was applied only to controllable loads, and the definition of controllable loads was restrictive, limiting the impact of a full 40% reduction in nutrients. The controllable load definition effectively excluded air deposition loads and loads from forested lands, which are the predominant (>60%) land use in the watershed. In addition, any nutrient loads from Delaware, New York, and West Virginia, which were jurisdictions not signatory to the 1987 Chesapeake Bay Agreement, were also considered uncontrollable by the Agreement (Perciasepe, 1992). With the limited scope of the controllable load definition, the application of the 40% nutrient reduction in the watershed, resulted in an overall reduction in nutrient loads that were less than 40% and were actually only a 22% reduction in nitrogen, and a 33% reduction for phosphorus as compared to the benchmark of estimated 1985 loads. The benchmark 1985 loads, assumed to be the high load zenith in Chesapeake loading, were estimated to be 155 million kilograms nitrogen and 11.7 million kilograms phosphorus per annum (Cerco and Cole, 1993, 1994; Thomann *et al.*, 1994; Linker *et al.*, 1996; Shenk and Linker, this issue).

In 1997, the specificity of the basin-jurisdiction nutrient allocations was tightened by removing interim allocation loads for the Rappahannock, York, and James River basins and replacing them with specific basin-jurisdiction nutrient allocations (Butt *et al.*, 2000). The interim nutrient allocations were initially done for these three tributaries because the lower Virginia tributaries had less influence on hypoxia than the tributaries north of, and including, the Potomac due to their closer proximity to the ocean mouth of the Chesapeake and the relatively lower residence times of waters and associated nutrient loads from these tributaries (Shen and Wang, 2007). Accordingly, the allocations given to the lower tributary basins of the Rappahannock, York, and James Rivers were based on an assessment of the water quality and living resource needs in those tidal tributaries instead of a percentage of a controllable load aimed at controlling mainstem hypoxia as they were for the basins in the 1992 allocation (Cerco *et al.*, 2002). The nutrient load allocations to the lower tributaries were based on the load reduction necessary to achieve tributary specific submerged aquatic vegetation (SAV) restoration goals, an assessment of target chlorophyll *a* levels in the James, and dissolved oxygen (DO) habitat requirements in the lower Rappahannock and York River estuaries (Butt *et al.*, 2000; Cerco *et al.*, 2002; USEPA, 2003c).

The next milestone was the Chesapeake 2000 Agreement, a landmark agreement that included commitments for the adoption of living resource-based water quality standards, determining sediment load reductions that would be protective of SAV and other living resources, improving air deposition accounting in the Chesapeake watershed and tidal Bay, and encouraging tighter partnerships with the headwater jurisdictions of Delaware, New York, and West Virginia (Chesapeake Executive Council, 2000). The 2003 allocations associated with the Chesapeake 2000 Agreement reflected the expanded partnership. The 2003 allocations were based on DO, chlorophyll *a*,

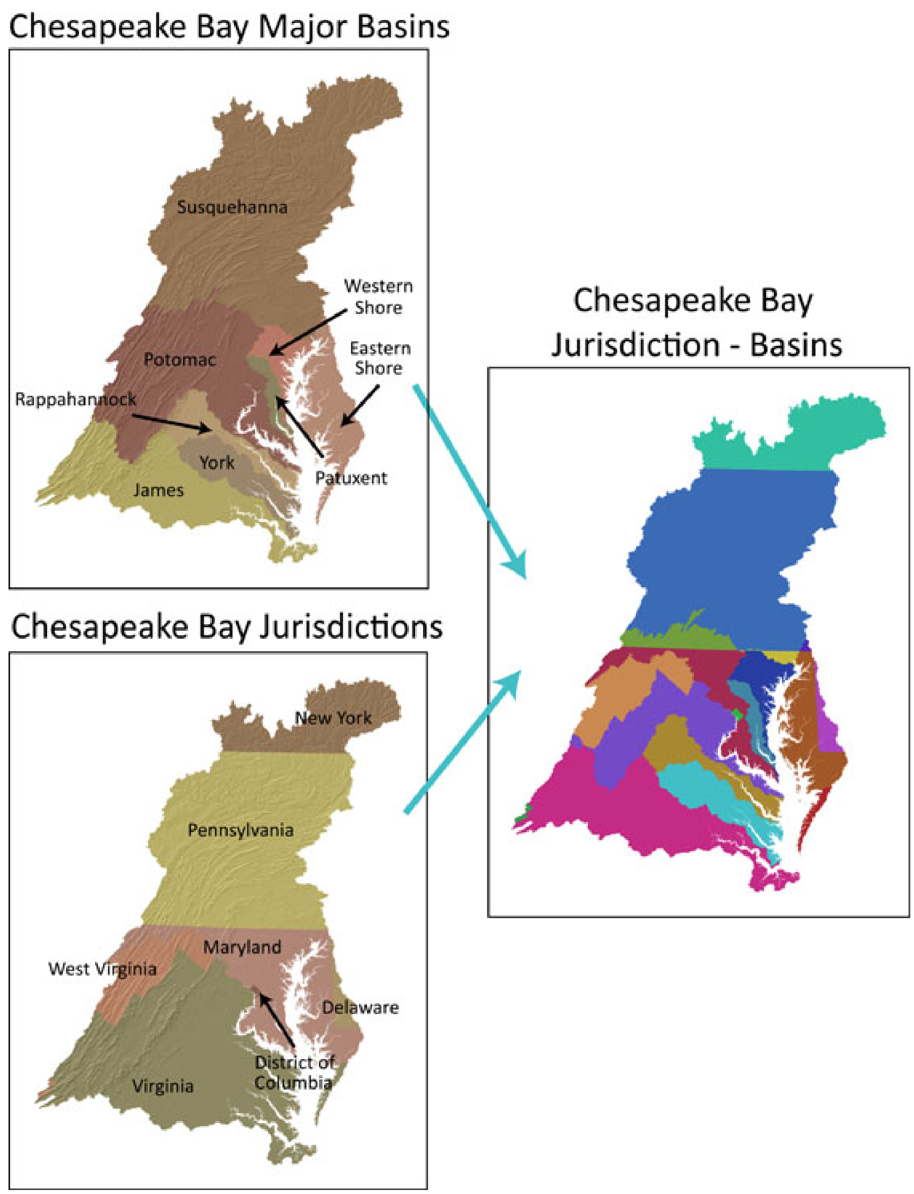

FIGURE 1. The Chesapeake Basin Jurisdictions Are Formed by the Combination of the Eight Major Basins of the Susquehanna, Western Shore, Patuxent, Potomac, Rappahannock, York, and James with the State Boundaries of New York, Pennsylvania, West Virginia, Maryland, Delaware, and Virginia and the District of Columbia.

and water clarity and water quality criteria that were protective of Chesapeake living resources (USEPA, 2003a, b, c, 2004, 2007, 2010a; Tango and Batiuk, this issue) and included all six Chesapeake Bay watershed states of New York, Pennsylvania, West Virginia, Maryland, Delaware, and Virginia and the District of Columbia. For the first time, the 2003 allocations included an allocation for sediment loads along with refined allocations for nitrogen and phosphorus loads (Murphy, 2003; USEPA, 2003c). With a more inclusive and accurate accounting for nutrient loads than that of the 1992 allocation, the relative amount of nutrient load reductions, as compared to the estimated 1985 benchmark of loads (Shenk and Linker, this issue), was a 48% reduction in total nitrogen (TN) and a 53% reduction in total phosphorus (TP) (USEPA, 2003c). Also included in the 2003 allocation was a 29% reduction in total suspended sediment loads delivered to the Bay.

Despite the extensive restoration efforts of the Chesapeake 2000 Agreement and associated 2003 allocations, the TMDL was prompted by insufficient progress and continued poor water quality in the Chesapeake Bay and its tidal tributaries. The TMDL was required under the federal Clean Water Act and responded to consent decrees in Virginia and the District of Columbia from the late 1990s. By 2007, an assessment of nutrient loads found that estimated nutrient and sediment load reductions by 2010 would be insufficient to avoid a Chesapeake TMDL, and work began in 2008 to ensure completion of the TMDL allocation by 2010 (USEPA, 2008a).

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

To set the allocations in the watershed, a quantitative approach was used that was based on a metric of an equitable relative level of effort in reducing nutrient and sediment loads. Equitability was based on the principle that basin jurisdictions that contributed relatively more to the water quality problems in the Chesapeake should do relatively more in nutrient and sediment reductions, a variant on the *polluter pays* principle, but perhaps in this application better characterized as *the greater polluter pays more* principle.

Allocations were originally developed on the basin-jurisdiction scale and then the seven-state and District of Columbia watershed jurisdictions developed watershed implementation plans (WIPs) that were designed to achieve the allocations by the year 2025 (USEPA, 2010h). Each jurisdiction decided on more spatially explicit allocations as well as allocations to the major pollutant source sectors and even individual permitted wastewater discharge facilities. Generally, the finest scale of WIP application was at the county scale, which is on average equivalent to about 550 km^2. Assessment of the nutrient and sediment reduction progress laid out in the WIPs will be facilitated by ongoing two-year quantitative assessments as well as a major assessment of progress at the 2017 half-way mark to the 2025 deadline.

The 2010 allocation provided flexibility and efficiency in achieving the allocations through decision rules that allowed exchanges of nutrient loads between major basins, exchanges between nitrogen and phosphorus reductions, and exchanges between air and water program reductions in nitrogen. The decision rules were set up conservatively so that the water quality standards would be achieved while flexible solutions to achieving the Chesapeake Bay water quality standards were also provided. An additional feature of the 2010 allocation is the first allocation of atmospheric deposition of nitrogen loads in a TMDL (Linker *et al.*, this issue). Also, allocations to federal lands and facilities in the Chesapeake Bay watershed, lands which cover 6.2% of the watershed area, were applied for the first time. For example, the District of Columbia has 7.4% of its impervious area and 6.3% of its pervious area in federal lands, which are now included in the accounting of the Chesapeake TMDL allocation.

METHODS

Models of the airshed (Community Multiscale Air Quality Model — CMAQ and a regression model of wet fall nitrogen deposition), watershed (Watershed Model Phase 5.1), and tidal Bay water quality (Water Quality and Sediment Transport Model — WQSTM) were applied to develop the 2010 allocation (Cerco, 2000; Grimm and Lynch, 2000, 2005; Linker *et al.*, 2000, 2008, this issue; Cerco *et al.*, 2002, 2010; Cerco and Noel, 2004, this issue; Shenk and Linker, this issue).

The CBP airshed, watershed, and Bay models were used to predict water quality conditions for the various loading scenarios explored. It was necessary to compare these model results with the applicable water quality standards to determine compliance with the standards. In general, to determine management scenarios that achieved water quality standards, model scenarios were run representing different nitrogen, phosphorus, and sediment loading conditions using the CBP models (Cerco *et al.*, this issue; Linker *et al.*, this issue; Shenk and Linker, this issue). The resultant model-simulated nitrogen, phosphorus, and sediment loadings were used as input into the Bay WQSTM to evaluate the response of critical water quality parameters, specifically DO, SAV, water clarity, and chlorophyll *a*.

To determine whether the different loading scenarios (USEPA, 2010d) met the Bay DO and chlorophyll *a* water quality standards, the Bay WQSTM's simulated tidal water quality responses for DO, SAV, water clarity, and chlorophyll *a* were compared to the corresponding observed monitoring values collected during the same 1991-2000 hydrological period as described in Keisman and Shenk (this issue). In other words, the Bay WQSTM was primarily used to estimate the *change* in water quality that would result from various loading scenarios. Once the water quality standards were predicted by the WQSTM to be met, the allocations were developed by the Watershed Model Phase 5.1 in conjunction with the airshed model for the TMDL. Figure 2 provides an overall representation of the allocation process.

Hydrologic Periods

The simulation period of the key airshed, watershed, and estuary models used in the TMDL allocation analysis were from 1985 to 2005 and the hydrologic period chosen to represent the long-term hydrologic conditions for the Chesapeake watershed, 1991-2000 (USEPA, 2010c) was within the calibrated simulation period. This provided average long-term simulation conditions for each area of the Bay watershed and the Bay's tidal waters so that all areas had a representative mix of point and nonpoint loads under a wide range of high to low river flows. The selection of a representative hydrologic averaging period was determined by examining the statistics of long-term flow relative to each 10-year period at nine key U.S. Geological Survey gauging stations, which measure the discharge of the major rivers flowing to the Bay (USEPA, 2010c). The 10-year average period was used to set 10-year average loads in the 2010 allocation.

Within the 10-year hydrologic period a 3-year critical period was chosen, which was used as the assessment period of the water quality standards in the tidal Bay. The critical period was based on key environmental factors, principally rainfall and streamflow, which influenced the DO water quality standard in the deep water and deep channel of the Chesapeake. The critical period and conditions determined major design conditions of the TMDL [40 CFR 130.7(c)(1)] (CFR, 2011), in particular the period of loads, flows, and other environmental conditions during which the water quality standards were assessed in the tidal waters. The three-year period selected as the critical period was 1993-1995, which was the second highest flow period of all the eight three-year contiguous periods contained in the 1991-2000 record. In the Chesapeake, high flows bring high levels of nutrient and sediment loads, resulting in more DO and SAV-clarity impairments.

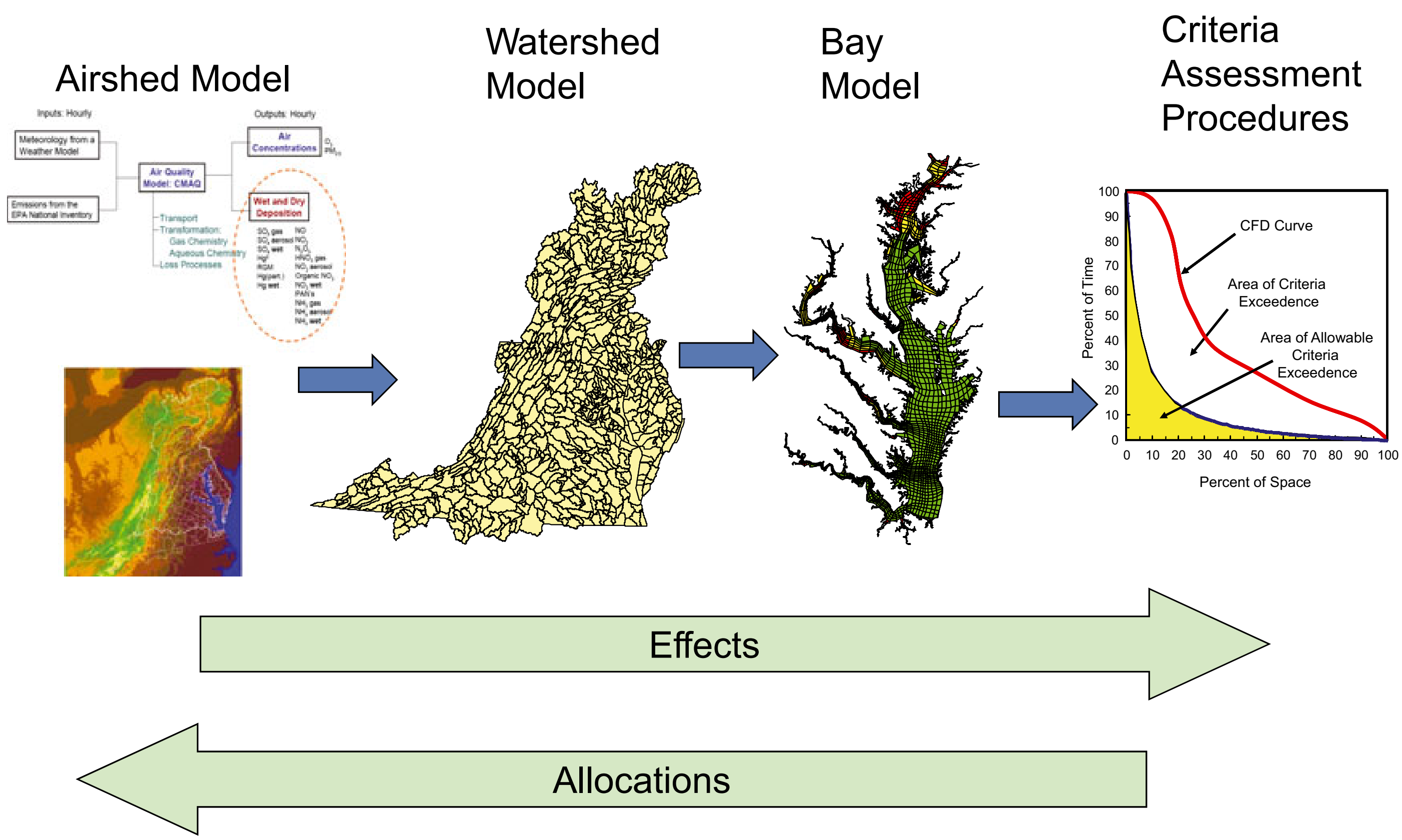

FIGURE 2. An Overall Representation of the Allocation Process.

The 1993-1995 critical period was chosen because it experienced streamflows that historically occurred about once every 10 years, which is typical of the return frequency for hydrologic conditions employed in developing TMDLs in the Chesapeake region (USEPA, 2010g). While the modeling for the Bay TMDL consisted of an assessment of the entire hydrologic period of 1991-2000 for many aspects of the allocation, including the 10-year average loads of the basin jurisdictions, the water quality conditions during the 1993-1995 critical period was specifically used to assess attainment of the Chesapeake water quality standards.

Chesapeake Bay Water Quality Standards

A good TMDL is based on a foundation of solid water quality standards. In the case of the Chesapeake Bay TMDL, the water quality standards were biologically based and designed to be protective of Chesapeake living resources, including full consideration of their unique seasonal-based conditions across different habitats (USEPA, 2003a, b, c, d, 2004, 2007, 2010a; Batiuk *et al.*, 2009; Tango and Batiuk, this issue). Table 1 lists the Chesapeake Bay DO criteria. The chlorophyll *a* and SAV-clarity criteria can be found in USEPA (2010a, b).

Water criteria are numerical, though sometimes narrative, values of environmental parameters (chemical, biological, and physical) which reflect concentrations, levels, or conditions protective of desired aquatic life species and communities. Water quality standards, on the other hand, are the combination of criteria, designated uses (defining the desired human and/or aquatic life uses of the subject water body), and antidegradation statements (commitments not to degrade the current water quality conditions) promulgated and adopted into states' water quality standard regulations through a public process and final approval by the U.S. Environmental Protection Agency. In the case of the four Chesapeake Bay jurisdictions, their water quality standards also include descriptions of, and references to, more detailed criteria attainment assessment procedures.

The DO criteria were designed to be protective of living resources in all major habitat regions of the Chesapeake including regions of open surface waters, migratory fish spawning areas, deep-water habitats, and deep-channel areas (Batiuk *et al.*, 2009; USEPA, 2003a, b, c, d, 2004, 2007, 2010a; Tango and Batiuk, this issue). Similarly, the chlorophyll *a* criteria was designed to be protective of growth, reproduction, behavior, and survival of key species in the James River and the tidal waters of the District of Columbia where the chlorophyll *a* standards were in effect. The

TABLE 1. Chesapeake Bay Dissolved Oxygen Criteria.

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

SAV-clarity criteria were protective of the shallow-water regions of the Chesapeake (USEPA, 2003a, b, c, d, 2004, 2007, 2010a; Kemp *et al.*, 2004; Tango and Batiuk, this issue).

The DO, chlorophyll-*a*, and SAV-clarity criteria were adopted into water quality standards by all of the tidewater CBP jurisdictions of Virginia, Maryland, Delaware, and the District of Columbia (USEPA, 2003a, b, c, d, 2004, 2007, 2010a). The water quality standard violations of open surface water, deep-water, and deep-cannel DO, and chlorophyll *a* spring and summer were estimated by the WQSTM to be widespread, particularly in the deep water and deep channel of the mainstem, with 110 violations estimated under conditions of the 1985 nutrient and sediment loads. Under the 2009 estimated load condition, which has nutrient loads reduced about half way toward the TMDL load condition, the number of total DO and chlorophyll *a* water quality violations decreased to 34, and by the time the estimated loads of the TMDL were achieved the number of violations was estimated to be zero.

Time and Space Assessment of Standards Attainment

The degree of achievement of the Chesapeake Bay water quality standards was assessed through quantitative analyses of the WQSTM results for each scenario and for each Chesapeake Bay TMDL segment (Figure 3) to determine the percent of time and space that the modeled water quality results exceeded the allowable criteria concentration as described in USEPA (2003a, b, c, 2004, 2007, 2008b, 2010a, b) and Keisman and Shenk (this issue). For any modeled result where the exceedance in space and time, shown in Figure 4 as the area below the dashed curve, was more than the allowable exceedance, shown in Figure 4 as the area below the solid shaded curve, that segment is considered in nonattainment. The dashed curve is also the cumulative distribution function (CDF) of criteria exceedance for the TMDL segment. The solid curve above the shaded allowable exceedance area is the reference curve representing a healthy biological system. The amount of nonattainment is shown in the figure as the area in white between the dashed line and the solid line and is displayed in model results as percent of nonattainment for that segment.

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

Allocation Principles Applied and Overall Allocation Process

An early step in the process of developing the Bay TMDL, especially for nitrogen and phosphorus, was to determine the allowable loading from jurisdictions and major river basins draining to the Bay that was needed to attain the most difficult to achieve water quality standards — DO in the deep-water and deep-channel habitats of the mainstem Bay and lower Potomac. Nitrogen and phosphorus from all sources within the Chesapeake watershed, including atmospheric deposition, affect the DO concentrations in the Bay's mainstem deep-water and deep-channel habitats. A key objective of the nitrogen and phosphorus allocation methodology was to first find a process, based on an equitable distribution of loads for which the basinwide load for nitrogen and phosphorus could be distributed among the basin jurisdictions while achieving the deep-water and deep-channel DO water quality standards and then to achieve the more locally influenced water quality standards of chlorophyll *a* and SAV-clarity.

To this end, principles and guidelines were established so that the allocated loads would be protective of the living resources of the Bay and its tidal tributaries and result in all segments of the Bay mainstem, tidal tributaries, and embayments meeting water quality standards for DO, chlorophyll *a*, and water clarity (USEPA, 2010b, c). In addition, major river basins that contributed the most to the Bay water quality problems were given the most responsibility in resolving those problems. All tracked and reported reductions in nitrogen and phosphorus loads were credited toward achieving final assigned loads.

The specific critical concepts employed in developing the nitrogen and phosphorus allocations included the following: (1) accounting for the geographic and source loading influence of individual major river basins on tidal water quality, i.e., relative effectiveness, (2) determining the controllable load through the difference of the No Action Scenario and the E3 Scenario, and (3) relating the controllable load with relative effectiveness to determine the allocations of the basinwide loads to the basin jurisdictions (USEPA, 2010b, c).

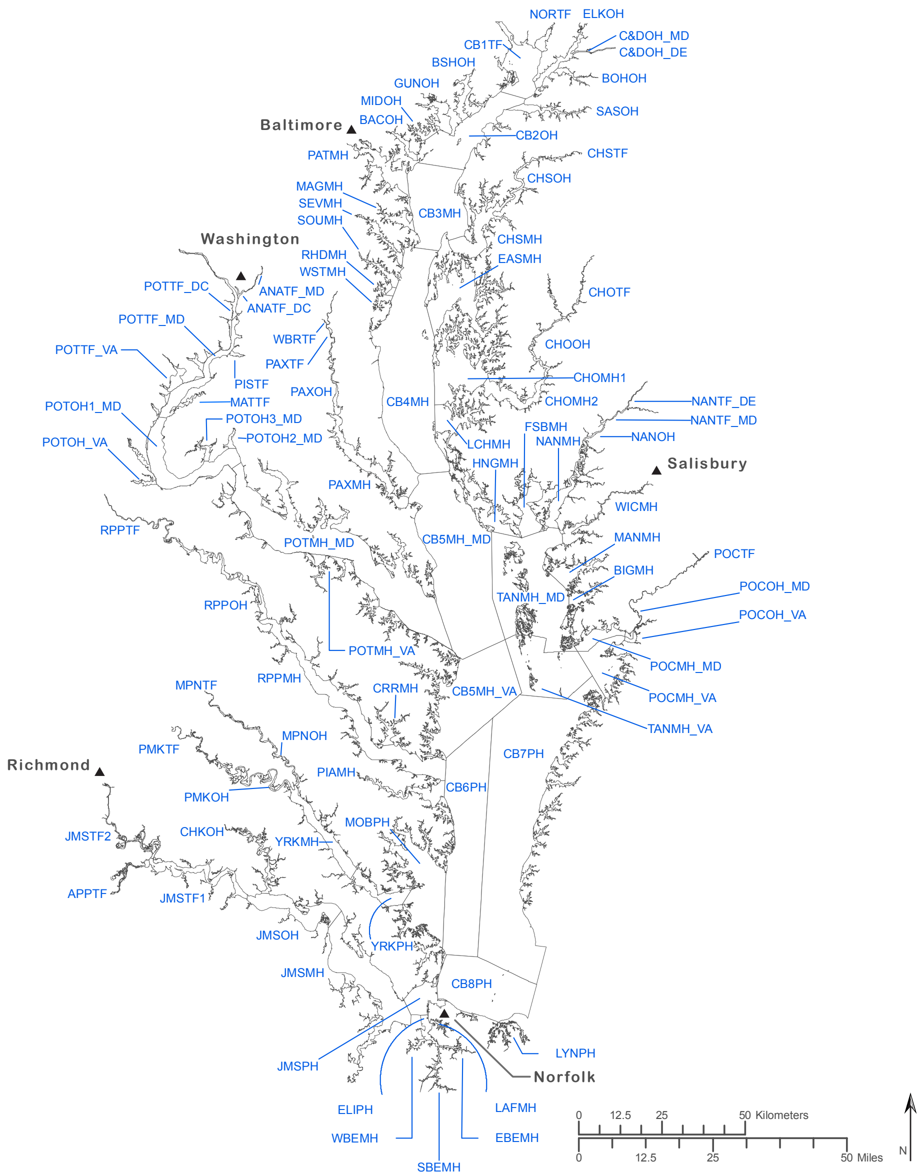

FIGURE 3. The 92 Chesapeake Bay Segments that Were Assessed for Water Quality Standard Exceedance in Time and Space, i.e., a Water Quality Violation (USEPA, 2010b).

Relative Effectiveness of Basin-Jurisdiction Loads for Hypoxia Reduction

A key factor in the allocation process was determining the relative effectiveness of nutrient load reductions in different river basins in the watershed on improving DO concentrations in the deep waters and deep channel of the tidal Chesapeake (Figures 5a and 6a). Relative effectiveness accounts for the role of geography on nitrogen and phosphorus transport and fate, and in turn, on Bay water quality (USEPA, 2010f). Instream transport factors, including denitrification, settling, and loss particularly in reservoirs, play a role in watershed so that the same control applied in the headwaters of the watershed, will generally have less of an effect on Bay DO than one applied adjacent to tidal waters. In the tidal Bay the potential residence time (Shen and Wang, 2007), as well as localized nutrient limitation in regions of the Bay, cause differences in relative effects of nutrient loads on bottom water DO (USEPA, 2003b). Consequently, nutrient loads at the head of the estuary have more influence than nutrient loads discharged closer to the Bay's mouth (Kuo *et al.*, 1991; Kemp *et al.*, 1992; Thomann *et al.*, 1994; Cerco, 1995; Shen and Wang, 2007).

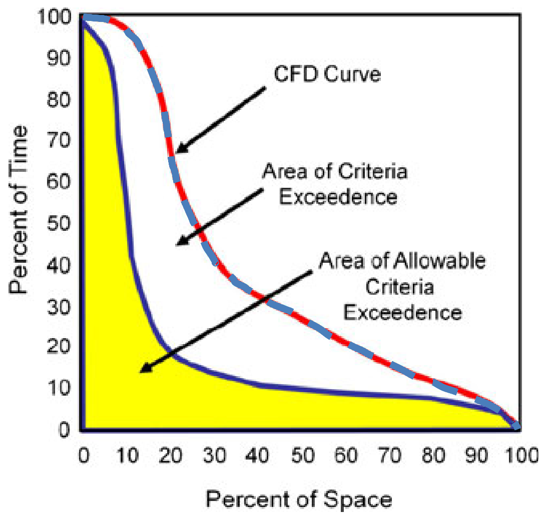

FIGURE 4. The Analysis Applied for Each TMDL Chesapeake Bay Segment to Determine the Percent of Time and Space that the Simulated Chesapeake Bay Water Quality Results Exceed the Allowable Concentration (USEPA, 2003a, b, c, d, 2008b, 2010a).

The relative estuarine effectiveness assessment evaluates the effects of both riverine transport (location of the discharge/runoff loading in the watershed) and estuarine transport (the location of the discharge/runoff loading to the tidal Bay) (USEPA, 2010f). The relative estuarine effectiveness was quantified for each contributing basin jurisdiction in the Bay watershed influence on DO concentrations within the deep-water and deep-channel habitats in the deepest contiguous region in the mainstem and lower tidal Potomac River. The contiguous deep-water and deep-channel region covered the Chesapeake Bay segments CB3MH, CB4MH, CB5MH, and POTMH (Figure 3). The WQSTM was used to run a series of isolation runs of loads from different parts of the watershed to examine the relative effect of those loads on the deep-water DO. In addition, the Watershed Model was used to estimate attenuation of nitrogen and phosphorus loads through the watershed. The riverine transport efficiency, or delivery factor, which accounts for nutrient and sediment attenuation in the watershed attenuation was calculated as the fraction of load produced in the watershed that is delivered to the estuary by the Watershed Model, i.e., the fraction of edge-of-stream loads that are delivered to tidal waters in units of delivered kilogram per edge-of-stream kilogram of nitrogen or phosphorus (USEPA, 2010f).

The absolute estuarine effectiveness was estimated by running a series of WQSTM scenarios, which held one major river basin at a time at a high-nutrient load reduction level and all other major river basins at base calibration levels to assess each basin's influence on Chesapeake hypoxia (USEPA, 2010f). After considering several metrics to assess the DO benefit from progressive reductions in nitrogen and phosphorus loadings, the 25th percentile was selected as the appropriate metric that would be indicative of a change in low DO (USEPA, 2010f). The 25th percentile was chosen as an appropriate metric for seasonal average DO because at low DOs there is an absolute cutoff at 0 mg/l DO even though oxygen demand can still be expressed through sediment oxygen demand. On the other hand, at higher DO levels problems with supersaturation can occur. To avoid these problems at either end of the range of DO the model-estimated 25th percentile was used. For each scenario, the increase in the 25th percentile DO concentration was recorded for the summer criteria assessment period (June 1 through September 30) in the critical segments of CB3MH, CB4MH, and CB5MH for deep-channel DO and CB3MH, CB4MH, CB5MH, and POTMH for deep-water DO (Tango and Batiuk, this issue).

Relative estuarine effectiveness is defined as the absolute estuarine effectiveness divided by the total load reduction delivered to tidal waters necessary to gain that water quality response. Units for the relative estuarine effectiveness for nitrogen are the change in μg/l DO per 454,000 kg nitrogen load (as N), and the equivalent units for phosphorus are the change in μg/l DO per 45,400 kg phosphorus load (as P). For example, if the load reduction in the Potomac basin above fall line was 15 million kilograms of nutrients to change the annual average DO concentration 0.15 mg/l., the relative estuarine effectiveness is 0.01 mg/l per million kilograms. The higher the relative estuarine effectiveness, the less reduction required to achieve the change in status. The relative estuarine effectiveness calculation is an attempt to isolate the effect of geography by normalizing the load on a per-pound basis. Comparing the relative estuarine effectiveness among the major river basins shows the resulting gain in attainment from performing equal mass reductions among the major river basins. The relative estuarine effectiveness also allows basin-to-basin trades of nitrogen or phosphorus, which is a feature provided for in the Chesapeake TMDL that allows the possibility of greater watershed management efficiency while still attaining all Chesapeake water quality standards.

Multiplying the estuarine relative effectiveness (measured as DO increase per delivered pound reduction) by the riverine effectiveness factor (measured as delivered kilogram per edge-of-stream kilogram) gives the overall relative effectiveness in DO concentration increase per edge-of-stream pound (USEPA, 2010f). The relative estuarine effectiveness is the same for nitrogen and phosphorus, while the riverine delivery varies for nitrogen and phosphorus, so the overall

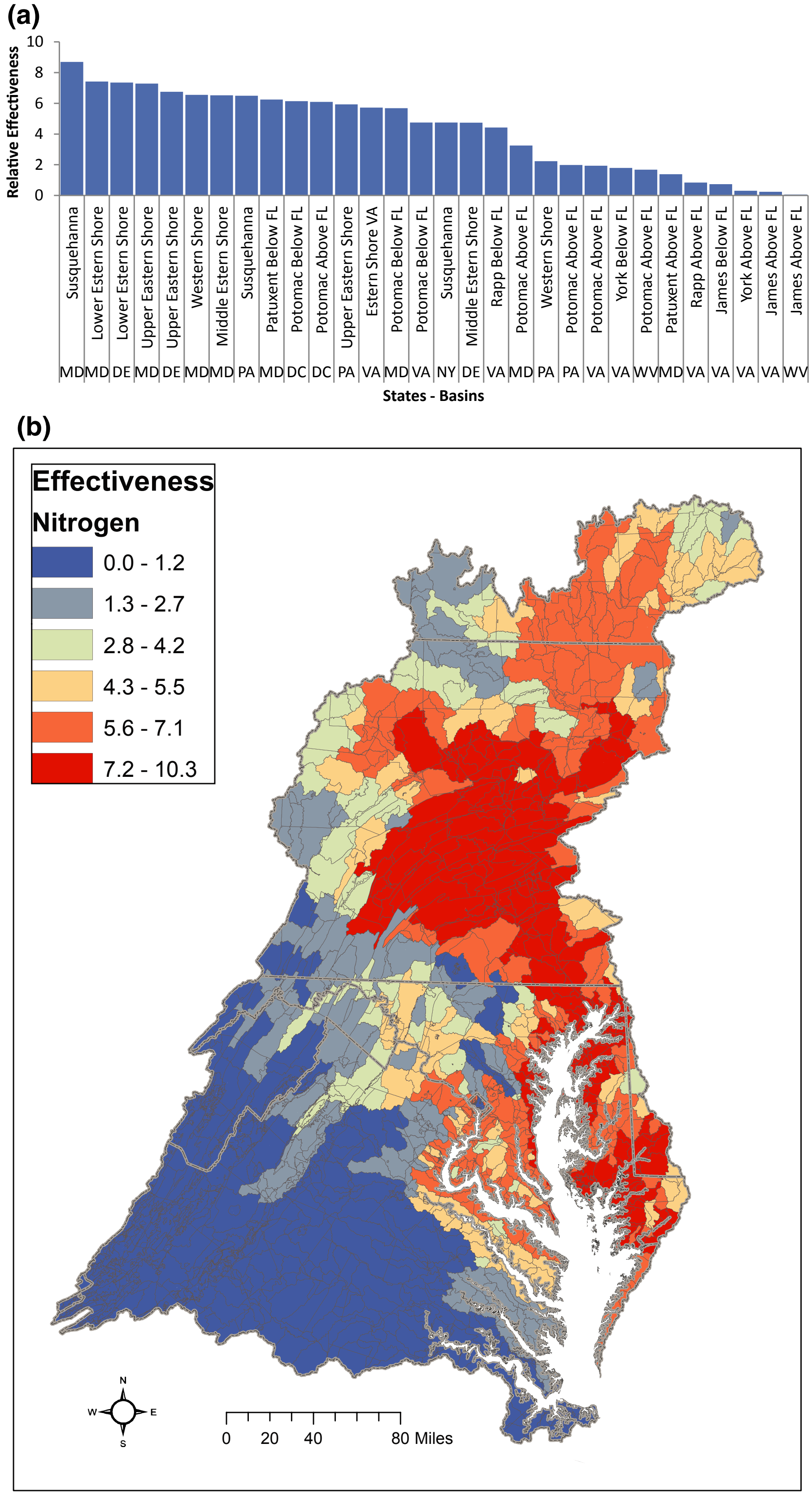

FIGURE 5. (a) Relative Effectiveness for Nitrogen Aggregated up to the Level of the Major Jurisdiction Basins in Descending Order and (b) Relative Effectiveness for All the Land-River-Segments (Shenk and Linker, this issue) to Nitrogen Loading. Units are the change in μg/l DO per 454,000 kg nitrogen load (as N).

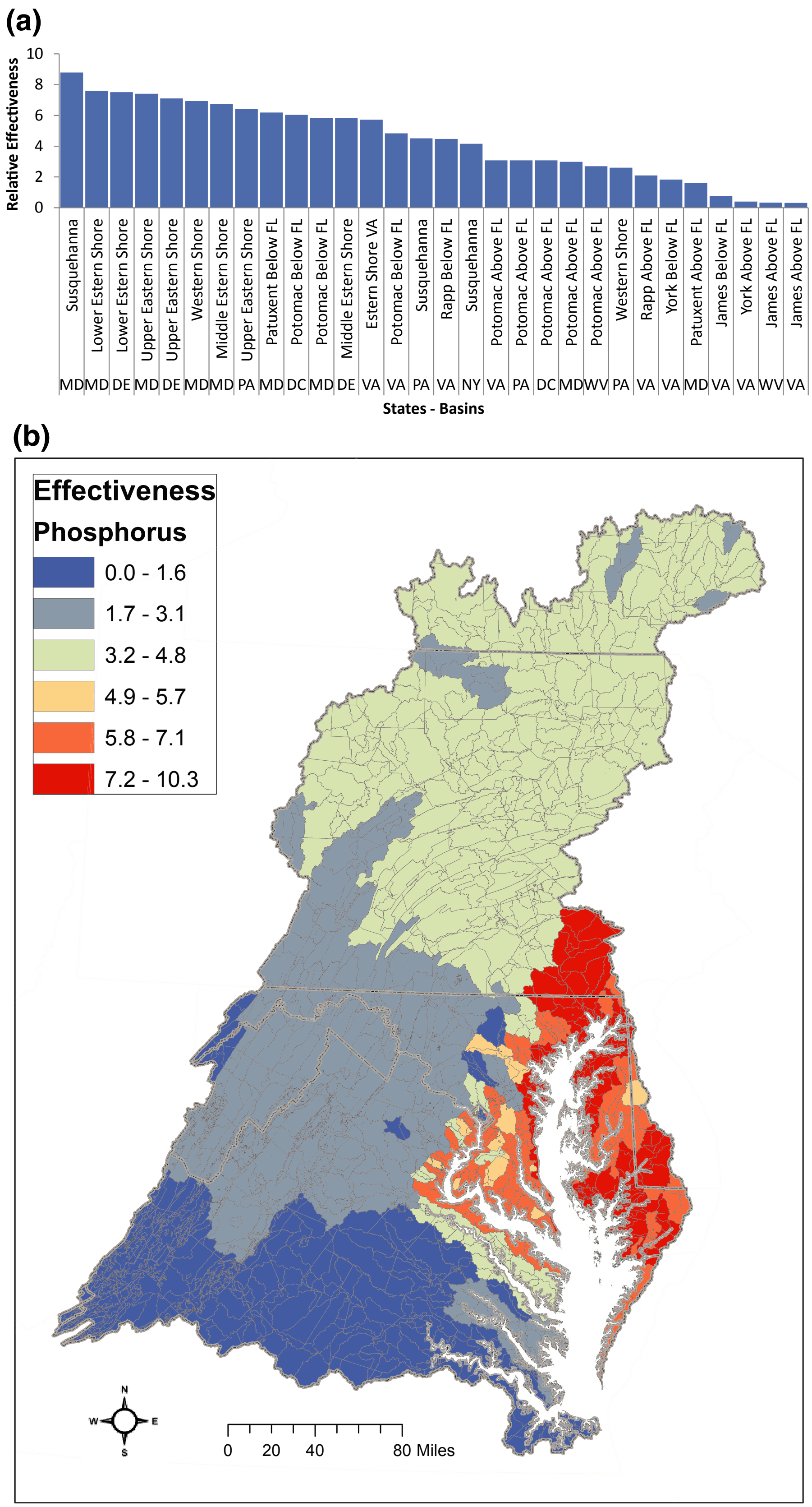

FIGURE 6. (a) Relative Effectiveness (Estuarine and Watershed Combined) for Phosphorus Aggregated up to the Level of the Major Jurisdiction Basins in Descending Order and (b) Relative Effectiveness for All the Land-River-Segments (Shenk and Linker, this issue) to Phosphorus Loading. Units are the change in μg/l DO per 45,400 kg phosphorus load (as P).

relative effectiveness is calculated separately for each. Figure 5a illustrates the relative effectiveness for nitrogen of the major basin jurisdictions in descending order. Figure 5b provides graphical illustration of the relative effectiveness for nitrogen at the finer scale of river segments (Shenk and Linker, this issue) in the watershed. Figure 6b represents the same relative effectiveness at the river-segment scale for phosphorus.

From the relative estuarine effectiveness analysis, several things are apparent. Northern major river basins have a greater relative influence than southern major river basins on the central Bay and the lower Potomac River DO levels because of the longer potential residence time and cycling of nutrients from northern basin nutrients. Nitrogen and phosphorus from the southern river basins, such as the James and York rivers, have relatively less influence on mainstem Bay water quality because of their proximity to the mouth of the Bay. Because these southern river basins are on the western shore, the counterclockwise circulation of the lower Bay also tends to transport nitrogen and phosphorus loads from those larger southern river basins out of the Bay mouth. That same counterclockwise circulation tends to sweep loads from the lower Eastern Shore northward increasing the relative influence of the Eastern Shore (USEPA, 2003c; Shen and Wang, 2007). Transport in the watershed plays a role too, with greater attenuation of nutrient and sediment loads with longer travel times.

Quantitative Allocation Approach of Assessing an Equitable Level of Effort

Developing the TMDL allocations employed two theoretical scenarios that quantified controllable load reductions. The two scenarios were the no nutrient and sediment reduction scenario, called the No Action Scenario, and the high load reduction scenario of the reductions by everyone, everywhere, doing everything, or the E3 Scenario (USEPA, 2010d).

The No Action Scenario estimated a theoretical worst case situation of no controls to reduce or prevent nitrogen, phosphorus, and sediment loads from any sources in the watershed. Specifically, all levels of control technologies, best management practices (BMPs), and program implementation were completely removed from the No Action Scenario (USEPA (2010d, k) and wastewater discharging facilities' loads controlled by National Pollutant Discharge Elimination System permits were assumed at levels of secondary treatment (TN effluent = 18 mg/l, and TP effluent = 3 mg/l). Atmospheric deposition loads were at levels of their historical high in 1985 (Linker *et al.*, this issue).

In contrast, the E3 Scenario represented everything being done by everyone, everywhere in the watershed, and estimated a best-case nutrient and sediment control situation, where all practicable BMPs and available control technologies were applied to the land, given the human and animal populations extent in 2010 (USEPA, 2010d). Wastewater treatment facilities were represented at highest technologically achievable levels of treatment (TN effluent = 3 mg/l; TP effluent = 0.1 mg/l.) and atmospheric deposition levels of nitrogen were controlled at high levels (Linker *et al.*, this issue).

The gap between the No Action Scenario and the E3 Scenario represented the maximum theoretical controllable load reduction that could be achieved. The year 2010 was selected as the base year for the No Action and E3 Scenarios because it represented conditions at the time the Bay TMDL was developed. The anthropogenic controllable loads were determined by subtracting each basin-jurisdiction's E3 load from their No Action load. The calculated *percentage of E3* — from 0% at the No Action Scenario load up to 100% at the E3 Scenario load — is used as the quantitative assessment of the relative level of effort between various loading reduction scenarios in different basin jurisdictions.

To apply the allocation methodology, loads from each major river basin were divided into two categories — wastewater and all other sources (Figure 7). Wastewater loads included all major and minor municipal, industrial, and permitted combined sewer overflow (CSO) discharges (USEPA, 2010a, c, d, e, f, g, h, i, j, k). The category of "all other" sources included nonpoint source and stormwater loads. The rationale

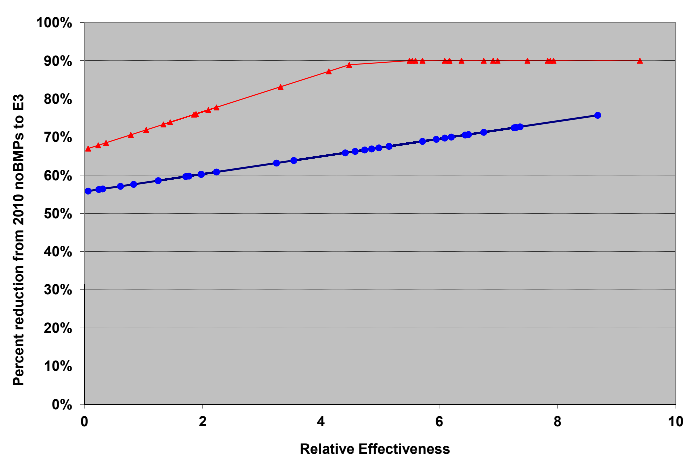

FIGURE 7. Allocation Methodology Example Showing the Straight Line Reduction Approaches to All Loads other than Point Sources (Bottom Line with Circle Symbols) and the Two-Piece Linear Approach, to Point Source Nitrogen (Top Line with Triangle Symbols). Each of the circles or triangles represents a particular basin jurisdiction.

for the separate accounting is the higher likelihood of achieving greater load reductions for the wastewater sector than for other source sectors (USEPA, 2010f). In addition, there was a wide disparity between major river basins and watershed jurisdictions on the fraction of the load coming from the wastewater sector as opposed to other sectors. Therefore, that disparity is addressed by separate accounting for the wastewater sector from the other sectors in the allocation methodology. Then, as described below, lines developed for each of the two source categories so that the addition of the two lines would equal the basinwide nitrogen and phosphorus loading targets for nitrogen and phosphorus.

To account for atmospheric deposition loads of nitrogen, the estimated national reductions brought about through all Clean Air Act rules and reductions by the year 2020 (Linker *et al.*, this issue) were applied as a reduction to the nonpoint source loads early in the allocation methodology. This allowed the Bay jurisdictions to develop targets that guided and focused their WIPs on the remaining nonpoint source load reductions that were needed.

For any given level of water quality, an infinite number of lines can be drawn on the allocation plots (Figure 7). To calculate an equivalent line to an existing line, it is necessary to meet the condition of the following:

$$\sum(\text{Delivered Load}) \times (\text{Estuarine Delivery}) = C \tag{1}$$

or the sum of all delivered loads for each state/basin/fall-line combination multiplied by its estuarine delivery factor must equal a constant for the family of lines that meets the same water quality.

Expanding the delivered load term to create an equation between relative effectiveness and delivered load gives the following:

$$\sum(E3_i + (\text{NoBMP}_i - E3_i)(1 - mX_i - b))\ \mathit{EstuarineDelivery}_i = C, \tag{2}$$

where X_i is the relative effectiveness; $E3_i$ and NoBMP_i are the loads for that state/basin/fall-line/sector for the E3 and No Action Scenarios, respectively; m and b are the slope and intercept of the line and the only unknowns; and C is the loading condition, based on annual average loads during the three-year critical period, where the Bay water quality standards are achieved.

Given a slope or an intercept, the above equation can be solved numerically for the other parameter of the line. This method generates in effect a "level-of-effort" line that quantifies the degree that a particular basin jurisdiction needs to move toward an E3 level of nutrient reduction. In the case of a basin-jurisdiction point source load that has a high level of effectiveness in generating hypoxia in the deep waters and deep channels of the Bay, that can be quite a lot — 90% of the maximum controllable load in fact. Basin jurisdictions with less effective loads in generating Chesapeake hypoxia have a decreased level of effort.

Using the methodology described above, the Chesapeake Bay watershed jurisdictions had the option of considering different allocation approaches among the different combinations of wastewater and other source controls and slopes of the lines on the allocation graph (USEPA, 2010f). After extensive discussions, the following graph specifications were generally accepted by the watershed jurisdictions.

The wastewater line was set first and was piecewise linear in two sections as shown in Figure 7 with load reductions increasing with relative effectiveness (the positive linear slope portion) until a maximum percent controllable load was reached and maintained (zero slope linear portion). For wastewater nitrogen, the maximum percent controllable load was 90%, corresponding to an effluent concentration of 4.5 mg/l (Figure 7). This set the high point of the linear positive slope portion of the curve and the height of the horizontal portion of the curve. The lowest portion of the positive slope curve for wastewater was set at a minimum percent controllable load of 67%, corresponding to an effluent concentration of 8 mg/l, which would also represent the maximum allowable discharge concentration for wastewater nitrogen in the watershed.

For example, each of the points on the level-of-effort lines in Figure 7 corresponds to a particular basin jurisdiction. The most effective basin jurisdiction would be one like the Maryland portion of the Susquehanna that is located adjacent to the tidal Chesapeake and has little watershed losses in transport to the Bay, and is also at the head of the Chesapeake where its nutrient loads can be expressed most effectively as deep-water hypoxia. In this case, the Maryland portion of the Susquehanna would be one of the points on the far right of the graph with one of the greatest relative effectiveness and because of this the maximum percent controllable load for wastewater nitrogen required would correspond to an effluent concentration of 4.5 mg/l (Figure 7). On the other hand a basin jurisdiction like the West Virginia portion of the James River would be far removed from tidal waters, have a loss of its loads due to watershed transport, and also have a discharge point low in the tidal Chesapeake that would be relatively less effective in generating Chesapeake deep-water hypoxia. In this case, the West Virginia portion of the James would have one of the highest allowable discharge concentrations of wastewater nitrogen.

For wastewater phosphorus, the maximum percent controllable load was 96%, corresponding to an effluent concentration of 0.22 mg/l and the minimum percent controllable load was 85%, corresponding to an effluent concentration of 0.54 mg/l.

The next step was to determine what level of control for wastewater nitrogen and phosphorus to set relative to each basin-jurisdiction's watershed and estuarine effectiveness. For nitrogen and phosphorus wastewater any overall relative watershed and estuarine effectiveness that was within the top two quartiles of the maximum relative effectiveness value was given maximum percent controllable. That is, if the basin-jurisdiction's relative watershed and estuarine effectiveness was greater than the median value of all the basin-jurisdictions' watershed and estuarine effectiveness, then that basin's control level for nitrogen would be 4.5 and 0.22 mg/l for phosphorus. The minimum controllable load value for nitrogen and phosphorus was assigned to the basin jurisdiction with the minimum relative effectiveness, and all values of relative effectiveness between the minimum and the top two quartile values were assigned interpolated percentages (Figure 7).

The "other nitrogen and phosphorus sources" line was set at a level that was necessary to achieve the basinwide load needed for achieving the DO standards in the middle mainstem Bay and lower tidal Potomac River segments. That line was set at a slope such that there was a 20% overall difference from highest to lowest, controllable load ranging from 56% of controllable loads for basins with low relative effectiveness to 76% of controllable loads for basins with high relative effectiveness for nitrogen (Figure 7). The slope provides a balance of enough relief of controls for the less effective basins and yet still requires significant controls for all basins.

Setting the Chlorophyll a and SAV-Water Clarity Criteria Allocations

Process of Assessing the Chlorophyll *a* Criteria. The tidal James River was the principal area of chlorophyll *a* water quality standard nonattainment in the Chesapeake. Assessment of attainment of the chlorophyll *a* monitoring data found significant nonattainment of Virginia's chlorophyll *a* water quality standard for most of the tidal James River segments over the past two decades. In addition, the WQSTM estimated that the nutrient load reductions applied to meet DO criteria in the mainstem Chesapeake failed to simultaneously satisfy chlorophyll *a* criteria in the James, requiring further James River basin nutrient reductions than would be required for the mainstem DO standard alone (USEPA, 2010i).

The WQSTM was well calibrated to the tidal James River chlorophyll *a* and effectively simulated average seasonal conditions in the five tidal segments of the river (Cerco *et al.*, 2010). The WQSTM also consistently estimated improved chlorophyll *a* conditions with increasing nitrogen and phosphorus load reductions. At the same time, however, the model did not simulate individual algal bloom events, which are highly variable and caused by numerous factors, some of which are poorly understood (Cerco and Noel, this issue). The chlorophyll *a* water quality standards adopted in Virginia's regulation to protect the tidal James River were set at numerical limits for spring and summer seasonal averaged conditions, not for addressing individual algal bloom events lasting hours to days. Therefore, nitrogen and phosphorus loadings required to attain chlorophyll *a* water quality standards in the tidal James River were based on those years and James River segments for which the WQSTM reliably simulated the water quality monitoring-based chlorophyll *a* calibration data (USEPA, 2010i).

Process of Assessing the Water Clarity-SAV Criteria. The WQSTM used in setting the 2003 Chesapeake Bay nutrient and sediment allocations (Linker *et al.*, 2000; Cerco and Noel, 2004; Cerco *et al.*, 2010) was refined to include full sediment transport of four classes of inert particulates approximating the settling and transport behavior of sand, silt, clay, and a sediment fraction of slowly settling clay (Cerco *et al.*, 2013). The resulting Chesapeake Bay WQSTM was capable of resolving turbidity maximum zones in the Bay and appropriately setting the boundary conditions for the shallow-water region of the SAV/water clarity criteria. Resuspension of sediment was generated by currents, both tidal and residual, and by waves. Additional refinements included additional depth resolution in the shallow-water SAV growth areas (Cerco and Noel, this issue), an advanced optical model of underwater light attenuation (Gallegos *et al.*, 2011), improvements to the SAV simulation, and refinements to sediment loads from shoreline erosion (Cerco *et al.*, 2010).

The methodology used for allocating sediment loads to major river basins and jurisdictions for sediment was different from the methodology used for nitrogen and phosphorus because sediment has a localized water quality effect and the immediate subbasin discharging sediment loads is the dominant controlling influence on water clarity and SAV growth in tidal waters adjacent to the subbasin (USEPA, 2010e). Exceptions to this rule are major storms which transport sediment loads widely throughout the Bay and are discussed in Wang and Linker (2005).

Both the simulated SAV areas and the areas where water clarity meet the water quality criteria acres were estimated in the load-reduction scenarios. The light extinction coefficient, *Ke*, was the metric used to measure water clarity (Cerco *et al.*, this issue; USEPA, 2010e). The simulated Ke in the WQSTM is based on the amounts of simulated clay, silt, sand, organic particulates, and dissolved organic material in a model cell. Because the simulated Ke is an imperfect representation of the observed Ke, a data correction method similar to the one described for DO in Keisman and Shenk (this issue) was used to obtain an adjusted scenario Ke in each shallow cell for the target loading scenario. While several sophisticated data correction methods were tried, a simple proportional adjustment of the shallow-water Ke to the nearest observed water quality monitoring station was found to provide the best shallow-water data correction as determined by independent, shallow-water monitoring sites (USEPA, 2010e).

To adjust for limitations in the simulation of SAV area by the WQSTM (STAC, 2010), observed SAV was used for each Chesapeake Bay segment and adjusted by the factor of SAV biomass change in the WQSTM. The factor was calculated from the relative difference between nutrient and sediment management scenarios and the base calibration of the WQSTM (USEPA, 2010e).

Basin-Jurisdiction Scale of Allocations

Allocations were made to the basin jurisdictions (Figure 1). Subsequently, each of the seven watershed jurisdictions developed a WIP that described how it would achieve the basin-jurisdiction allocations for nitrogen, phosphorus, and sediment assigned to it (USEPA, 2010b, c).

RESULTS

DO Water Quality Standard Results

The process used for determining the load that achieved the DO water quality standards in the Bay's deep-water and deep-channel habitats was to progressively lower the nitrogen and phosphorus loadings simulated in the WQSTM and to assess DO water quality standard attainment in all tidal Bay segments for each loading scenario. Numerous iterations of different load scenarios were run until the appropriate nitrogen and phosphorus loadings to achieve water quality standards were determined as shown in Figure 8. The water quality measure on the vertical axis is the number of Bay segments that were not attaining the applicable Bay DO water quality standards, which are monthly criteria for Open-Water and Deep-Water DO and instantaneous DO, i.e., a violation for any DO observed sample point found to be less than the criteria of 1.0 mg/l for Deep-Channel DO (USEPA, 2010a, b). As can be expected, as loadings are lowered throughout the Bay watershed, the number of DO water quality standards nonattaining segments was reduced. At the loading of 86.2 million kilograms per year of nitrogen and 5.8 million kilogram per year of phosphorus, all Bay segments were in attainment. The segments of CB3MH, CB4MH, and CB5MH for deep channel and CB3MH, CB4MH, CB5MH, and POTMH for deep water were among the last segments to come into water quality standard attainment.

Allocating Nitrogen and Phosphorus Loads to Jurisdictions within the Bay Watershed

To allocate allowable loads to each of the jurisdictions and the major river basins, the method of allocating loadings based on equity was applied, and this was agreed upon by most of the jurisdictions. Using that method, the relative effectiveness of each of the major river basins in the Bay watershed were plotted as points (Figure 7) to determine the basin-jurisdiction allocation. On the vertical axis is the percent of controllable load (represented in the graph as No Action load — E3 load) that would correspond to the allocated load for each basin jurisdiction. For exam-

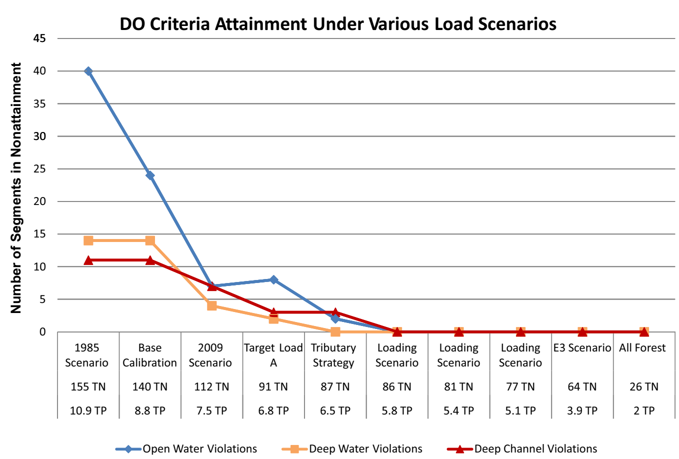

FIGURE 8. Chesapeake Bay Water Quality Model Simulated DO Criteria Attainment under Various TN and TP Loading Scenarios. Loads in millions of kilograms. Units are the counts of Chesapeake Bay segments that are in violation of the DO water quality standards.

ple, 100% represents a loading such that all sources would have all control technologies and practices installed as defined in the E3 Scenario. The horizontal axis represents the relative effectiveness of each of the basin jurisdictions, a measure of the impact that a kilogram of nitrogen and phosphorus has on the DO concentrations in the middle Chesapeake Bay mainstem. The wastewater line (line with triangles in Figure 7) was set on the basis of the removal efficiencies of established treatment technologies as previously described.

Then the allocation for all sources other than wastewater was constructed (line with circles in Figure 7) by setting it at a level that would achieve the basinwide load needed for the DO standards in the deep waters and deep channel of the mainstem Chesapeake. That line was set with a slope providing for a 20% overall difference from the highest controllable load to the lowest. This ranged from 56% of controllable loads for basins with low relative estuarine effectiveness to 76% of controllable loads for basins with high relative estuarine effectiveness for nitrogen (Figure 7). The slope was chosen as the most supported by the jurisdiction partners after exploring many options. The various options had different tradeoffs of: (1) providing enough relief from controls for basin jurisdictions with low relative estuarine effectiveness, (2) requiring significant controls for all basins to achieve water quality standards, and (3) avoiding inefficiently high levels of nonpoint source controls for basin jurisdictions that had high relative estuarine effectiveness.

Finally, the allocated load for wastewater and the allocated load for all other sources were added to determine the total allocated load for each basin jurisdiction. Although the graph separates wastewater and other sources, this did not require the jurisdictions to use that separate wastewater or other sources loading in their WIPs for suballocating the loads. The jurisdictions had complete flexibility and discretion in achieving their basin-jurisdiction allocations by further allocating by the source sectors and geography.

Chlorophyll a Water Quality Results for James River

After determining the target basinwide nitrogen and phosphorus allocations and distributing those loads to the major basins and jurisdictions for achieving the deep-water and deep-channel water quality standards for DO, the WQSTM scenario results and monitoring data indicated nonattainment for numeric chlorophyll *a* in the tidal James River in Virginia. On the basis of WQSTM runs at the basinwide nitrogen and phosphorus loadings of 86.2 million kilograms per year nitrogen and 5.8 million kilograms per year phosphorus allocated by basin jurisdiction to attain mainstem Bay DO standards, the WQSTM predicted the seven segments of the James River (Figure 3) (Tango and Batiuk, this issue) to be in nonattainment of Virginia's respective numeric chlorophyll *a* water quality standards.

To bring the James River chlorophyll *a* standard into attainment, the James River basin allocation was determined to be 10.7 million kilograms per year TN and 1.1 million kilograms per year TP (USEPA, 2010b, c). Figure 9 shows the number of James River Chesapeake Bay segments and three-year periods (segment-periods) in nonattainment of Virginia's James River chlorophyll *a* water quality standards (out of the simulation period of 1991-2000) for the various load scenarios simulated. Only those model results where the model is reliably simulating the calibration data were used in the assessment.

The James chlorophyll *a* standard required a greater level of James nutrient reductions than the reductions required to meet the deep-water and deep-channel mainstem DO standards. The reduced nutrient loading in the James River basin to 10.7 million kilograms per year of nitrogen and 1.1 million kilograms per year of phosphorus achieved the James chlorophyll standard and contributed to the reduction in the mainstem hypoxia as well. Therefore, the allocations for nitrogen and phosphorus loads were set at those levels and the overall Bay-wide TMDL allocation was set as shown in Table 2.

SAV-Clarity Water Quality Standard Results

In general, widespread attainment of the SAV-clarity water quality criteria was found at allocation

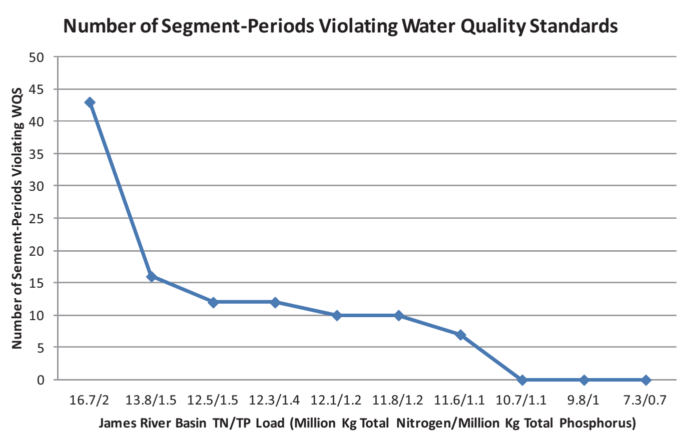

FIGURE 9. James River Nonattainment of the Chlorophyll *a* Water Quality Standard (WQS) at Various Load Scenarios. James River watershed loads shown on the *x* axis as millions of kilograms nitrogen and phosphorus. Units are the counts of James River Chesapeake Bay segments that are in violation of the spring and summer chlorophyll *a* water quality standards (USEPA, 2010a).

TABLE 2. Chesapeake Bay Watershed Nitrogen and Phosphorus and Sediment Allocations by Major River Basin by Jurisdiction, or Jurisdiction-Basin, to Achieve the Chesapeake Bay Water Quality Standards.

Jurisdiction	Basin	Nitrogen Allocations (million kg/year)	Phosphorus Allocations (million kg/year)	Sediment Allocations (million kg/year)
Pennsylvania	Susquehanna	31.25	1.13	789.78
	Potomac	2.14	0.19	100.29
	Eastern Shore	0.13	0.00	9.59
	Western Shore	0.01	0.00	0.17
Maryland	Susquehanna	0.49	0.02	28.50
	Eastern Shore	4.40	0.46	76.59
	Western Shore	4.10	0.23	90.64
	Patuxent	1.30	0.11	48.22
	Potomac	7.43	0.41	308.57
Virginia	Eastern Shore	0.59	0.06	5.13
	Potomac	8.06	0.64	376.27
	Rappahannock	2.65	0.41	317.53
	York	2.45	0.24	53.43
	James	10.47	1.08	417.41
District of Columbia	Potomac	1.05	0.05	5.06
New York	Susquehanna	3.98	0.26	132.88
Delaware	Eastern Shore	1.34	0.12	26.23
West Virginia	Potomac	2.46	0.26	133.47
	James	0.01	0.00	7.55
Total basin/jurisdiction draft allocation		**84.34**	**5.69**	**2,927.31**
Atmospheric deposition draft allocation[1]		**7.12**	**N/A**	**N/A**
Total basinwide draft allocation		**91.46**	**5.69**	**2,927.31**

Notes: Values in bold indicate they represent the total allocation from the watershed, the total allocation to the tidal waters of the Chesapeake, and the combined total watershed plus tidal water allocation, respectively.
[1]Cap on atmospheric deposition loads direct to Chesapeake Bay and tidal tributary surface waters to be achieved by federal air regulations through 2020 (Linker *et al.*, this issue).

levels of nutrient and sediment loads sufficient to achieve the DO and chlorophyll *a* standards. In this sense, the SAV-clarity water quality standard's criteria were not driving the allocations. Generally, the nutrient reductions needed to achieve the DO and chlorophyll *a* standards were often accompanied by reductions in sediment in management practices, such as farm plans and conservation tillage. Together, these nutrient and sediment load reductions were sufficient to achieve the SAV-clarity water quality standard (USEPA, 2010b, c).

Development of WIPs by the Chesapeake Watershed States

The jurisdictions used the modeled basin-jurisdiction allocations to develop their WIPs, but had the flexibility to further suballocate and to adjust the nitrogen and phosphorus loadings to finer geographic scales and to individual sources or aggregate source sectors (USEPA, 2010b, c). Table 2 lists the nitrogen, phosphorous, and sediment allocations that jurisdictions used as the starting points to develop their WIPs. The allocations were calculated as annual delivered loads that reach the tidal Chesapeake waters. The allocations were further refined through the jurisdictions' WIPs by exchanges of loadings for some basins in Maryland and exchanges of nitrogen to phosphorus or phosphorus to nitrogen within a basin based on the effectiveness measures with respect to Chesapeake deep-water DO. The allocations included provisions for WIP implementation flexibility, which improved management efficiency through basin-to-basin exchanges of allocations based on the estuarine efficiencies, nitrogen to phosphorus exchanges, and air- water nitrogen exchanges (Linker *et al.*, this issue) while maintaining complete attainment of the water quality standards (USEPA, 2010b, c).

SUMMARY AND CONCLUSIONS

There are an infinite number of ways that nutrient and sediment loads can be allocated among the Bay Program's six states and the District of Columbia to achieve the Chesapeake tidal water quality standards. While the participants in the allocation development were aware of the contributions that decision theory, economics, and statistics could make in the Chesapeake TMDL allocation decisions, the application of these methods in practice was limited. In practice, the seven sovereign governments that had to decide how to allocate the responsibility and costs of the nutrient and sediment reductions based their decisions largely on discussion and consensus leading to the allocation process described in this article. While the application of operations research and decision theory can quantify and balance optimal solutions of equity, cost-effectiveness, and environmental protection, their application in the allocation was perhaps unrealized because the decision makers, through the more than two years of discussion and consensus building, felt closer to, and were ultimately able to adopt, a decision that they developed and evolved together.

Difficult, amorphous concepts like equity among states need to be grappled with in a multistate TMDL allocation like the Chesapeake's. In the end, *de facto* equity is what decision makers decide is equitable, and in this case, equity was defined and allocated through the level of effort on watershed management that was greatest for basin jurisdictions having the greatest influence on Chesapeake water quality.

Based on the decision-maker's direction, the allocation process was guided by the quantification of levels-of-effort set by the two key scenarios of a no reductions or "No Action" Scenario and a high level of reduction or "E3" Scenario. The living resource-based water quality standards of DO, chlorophyll *a*, and SAV-clarity, were fully protected by the Chesapeake Bay TMDL allocations, which were developed with the level of effort approach. A key point is that the level of effort approach applied a principle that regions of the watershed, which contributed the most to Chesapeake Bay deep-water and deep-channel hypoxia became responsible for a relatively greater level of effort in nutrient controls. These regions had a greater influence on Bay water quality because of low attenuation in transport through the watershed and estuarine tributaries and the geographic location of the discharged loads within the Chesapeake Bay watershed. In a separate process, nutrient controls for chlorophyll water quality standards were applied in the James River. Assessment of the degree of attainment of the water quality standards was through a time and space assessment of model-simulated water quality criteria as described by Keisman and Shenk (this issue).

After the nutrient reductions for DO and chlorophyll reduction were decided, a separate process was applied to determine additional nutrient and sediment reductions needed for achievement of the SAV-clarity water quality standards. It was found that the nutrient reductions needed for DO and chlorophyll *a* also reduced sediment loads by a considerable amount through nonpoint source controls such as conservation tillage, stormwater management, and other best management practices when applied in agriculture, developed urban land, and other land uses. The nutrient load reduction, along with the co-reduction in sediment loads through nonpoint source nutrient management, were found to be sufficient to achieve the SAV-clarity water quality standard.

The TMDL sets Bay watershed limits of 84.3 million kilograms of nitrogen, 5.69 million kilograms of phosphorus, and 2.93 billion kilograms of sediment per year — a 25% reduction in nitrogen, 24% reduction in phosphorus, and 20% reduction in sediment from 2010 estimated loads, and a 46% reduction in nitrogen and 48% reduction in phosphorus from estimated 1985 loads. These pollution limits were further divided by basin jurisdictions on the basis of the CBP model findings, extensive monitoring data, peer-reviewed science, and close interaction with the jurisdictional partners. The 2010 allocation included an allocation of nitrogen atmospheric deposition to the tidal Chesapeake Bay, a precedent in TMDL allocation development nationwide (Linker *et al.*, this issue).

The TMDL is designed to ensure that all pollution control measures needed to fully restore the Bay and its tidal rivers are in place by 2025. The TMDL is supported by rigorous accountability measures to ensure cleanup commitments are met, including two-year milestone checks of progress, a major assessment period planned for 2017, a tracking and accountability system for jurisdiction nutrient and sediment reduction activities, and three phases of WIPs, which detail how and when the six Bay states and the District of Columbia will meet their respective pollution allocations.

Going forward, the emerging science needed to support future assessments and adaptive management of the 2010 Chesapeake TMDL include the following: (1) a first-principal, fine-scale distributed watershed model to allow better assessments of nutrient and sediment loads at smaller scales; (2) an improved shallow-water simulation to better simulate the shallow-water clarity and SAV as well as to take further advantage of the recent extensive shallow-water monitoring data and research; (3) improved model simulation, monitoring, and research into Chesapeake chlorophyll *a*, primary productivity, and phytoplankton blooms particularly in the tidal James River; and (4) improved climate change global modeling, downscaling, and explicit simulation within the CBP partnership's watershed, airshed, and Chesapeake water quality models.

ACKNOWLEDGMENTS

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