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DERIVING CHESAPEAKE BAY WATER QUALITY STANDARDS[1]

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ABSTRACT: Achieving and maintaining the water quality conditions necessary to protect the aquatic living resources of the Chesapeake Bay and its tidal tributaries has required a foundation of quantifiable water quality criteria. Quantitative criteria serve as a critical basis for assessing the attainment of designated uses and measuring progress toward meeting water quality goals of the Chesapeake Bay Program partnership. In 1987, the Chesapeake Bay Program partnership committed to defining the water quality conditions necessary to protect aquatic living resources. Under section 303(c) of the Clean Water Act, States and authorized tribes have the primary responsibility for adopting water quality standards into law or regulation. The Chesapeake Bay Program partnership worked with U.S. Environmental Protection Agency to develop and publish a guidance framework of ambient water quality criteria with designated uses and assessment procedures for dissolved oxygen, water clarity, and chlorophyll *a* for Chesapeake Bay and its tidal tributaries in 2003. This article reviews the derivation of the water quality criteria, criteria assessment protocols, designated use boundaries, and their refinements published in six addendum documents since 2003 and successfully adopted into each jurisdiction's water quality standards used in developing the Chesapeake Bay Total Maximum Daily Load.

(KEY TERMS: Chesapeake Bay; water quality standards; dissolved oxygen; water clarity; chlorophyll *a*; water quality criteria.)

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INTRODUCTION

Quantitative water quality criteria contained within state or tribal water quality standards are essential to a water quality-based approach to pollution control. Chesapeake Bay suffers from a long history of eutrophication-based changes in the structure and function of the estuarine ecosystem stressed by nutrient and sediment pollution (Kemp *et al.*, 2005; NAS, 2011). There has been a corresponding decline in ecological health of the Bay and its tributaries expressed through a number of undesirable water quality conditions such as excessive algal growth, low dissolved oxygen (DO), and poor water clarity caused by excessive nutrient and sediment loading (Langland *et al.*, 2004; Kemp *et al.*, 2005; Brakebill *et al.*, 2010; USEPA, 2010a, b). Through the 1987 *Chesapeake Bay Agreement*, state and federal signatories — Pennsylvania, Maryland, Washington, D.C., and Virginia, the Chesapeake Bay Commission, and the United States Environmental Protection Agency (USEPA) — committed to "develop and adopt guidelines for the protection of water quality and habitat

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conditions necessary to support the living resources found in the Chesapeake Bay system, and to use the guidelines in the implementation of water quality and habitat quality programs" (CEC, 1987). These same signatories further agreed "to define the water quality conditions necessary to protect aquatic living resources" upon signing the Chesapeake 2000 Agreement (CEC, 2000). Through a six-state memorandum of understanding with USEPA, Delaware, New York, and West Virginia also signed onto this commitment (Chesapeake Bay Watershed Partners, 2000).

Water quality standards must contain scientifically defensible water quality criteria that are protective of designated uses of aquatic ecosystems. Therefore, USEPA used a multistakeholder, science-based approach to subsequently develop and publish *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay, and Its Tidal Tributaries* on behalf of the Chesapeake Bay Program partnership, thereby providing the jurisdictions with criteria protective of tidal designated uses for adoption into water quality standards (USEPA, 2003a). Based on those criteria and designated uses, Delaware, the District of Columbia, Maryland, and Virginia adopted jurisdiction-specific Chesapeake Bay water quality standards regulations consistent with the USEPA's published guidance between 2004 and 2005 (USEPA, 2010a). Subsequently, published technical addenda to the original criteria and designated uses factored in improved scientific understanding, particularly of how to best assess criteria attainment to ensure protection of the estuarine living resources (USEPA, 2004a, b, c, 2005, 2007a, b, 2008, 2010b). Since 2006, Delaware, the District of Columbia (hereafter "DC"), Maryland, and Virginia have each proposed and adopted very specific amendments to their jurisdiction's respective Chesapeake Bay water quality standards regulations.

Under USEPA regulations, criteria adopted into state's water quality standards are used to define which waters are impaired and require establishment of a total maximum daily load (TMDL). In 2010, the USEPA established a TMDL that accounts for maximum load limits of nitrogen, phosphorus, and sediment from all point sources (e.g., federally regulated wastewater discharge facilities, stormwater, and confined animal feeding operations discharges) and nonpoint sources (e.g., nonfederally regulated runoff from agricultural, developed, and forest lands) necessary to attain the four jurisdictions' Chesapeake Bay water quality standards (Linker *et al.*, 2012). The Chesapeake Bay TMDL was based on the 2008 USEPA-approved four tidal Bay jurisdictions' lists of impaired waters under section 303(d) of the Clean Water Act. These four combined section 303(d) lists identified 89 of 92 Chesapeake Bay Program segments as impaired (USEPA, 2010a). Individual TMDLs for nitrogen, phosphorus, and sediment have been prepared for each of the 92 Chesapeake Bay management segments encompassing the tidal waters of the Chesapeake Bay and its tributaries (Figure 1) (USEPA, 2010b).

Quantitative criteria within water quality standards serve as a critical basis for assessing the attainment of designated uses and measuring status and progress toward meeting the water quality goals of the Clean Water Act. When water quality criteria are met, water quality is expected to protect its designated use. Chesapeake Bay water quality criteria factored in the physiological needs and habitats of the Bay's living resources. The National Research Council (2001) and Batiuk *et al.* (2009) indicated that magnitude, duration, frequency, spatial extent, and temporal assessment period were important in determining water quality standards attainment. The USEPA (2003a) Chesapeake Bay criteria assessment approach effectively incorporated these five elements and allowable exceedances into a criteria attainment assessment procedure.

Management Applications of the Water Quality Criteria Guidance in Developing the Chesapeake Bay Total Maximum Daily Load

The nutrient and sediment allocations for the TMDL are based on modeled landscape management scenarios. However, measuring the progress of ecosystem restoration and recovery relies on the interpretation of water quality monitoring data. Water quality monitoring data are collected once a month most of the year and twice a month during summer at approximately 175 long-term water quality monitoring stations throughout the Bay and its tidal tributaries. The data are evaluated against the published set of season-relevant water quality standards applied to the established designated uses boundaries. The water quality criteria assessment guidance was developed in the USEPA published technical documents and addenda (USEPA, 2003a, b, c, 2004a, b, c, 2005, 2007a, b, 2008, 2010b) that support procedures for documenting the status of the Bay health through meeting water quality standards attainment.

To establish the TMDL, the time and space water quality attainment approach used to assess DO, submerged aquatic vegetation (SAV), and chlorophyll *a* monitoring data against water quality standards in the Bay was also used to assess water quality standards of model-based water quality output from a variety of management load reduction scenarios. It was necessary to compare model results with the applicable water quality standards to determine compliance with the standards (Linker *et al.*, 2012).

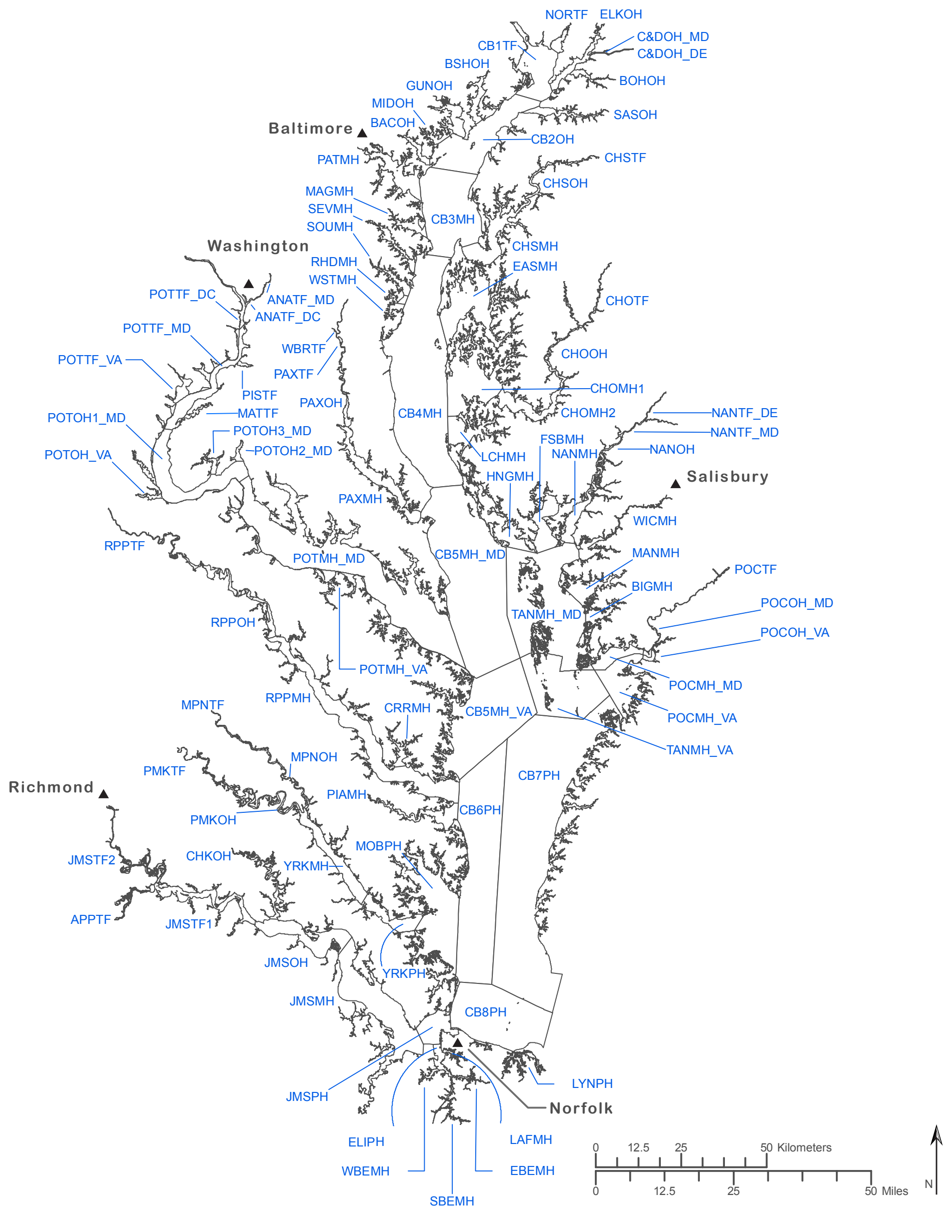

FIGURE 1. Chesapeake Bay Management Segmentation Scheme.

Key research in Chesapeake Bay eutrophication provided backing for the original 1987 management directive in the 1987 Chesapeake Bay Agreement and its 1992 Amendments for reducing watershed nutrient loads to restore water quality and living resources in Chesapeake Bay and its tidal tributaries (Linker *et al.*, 2012). The Chesapeake 2000 Agreement included commitments for adopting living resource-based water quality standards that would be protective of fish, shellfish, other invertebrates, and SAV. Specifically, DO, water clarity, and chlorophyll *a* criteria were determined and guidance published (USEPA, 2003a, b, c, 2004a, b, 2007a, b, 2008, 2010b) based on protection for Chesapeake Bay living resources. The application of numerical water quality criteria provided critical support for refining the Baywide, tributary-specific, and basin-jurisdiction-focused nutrient and sediment load reduction allocations creating the TMDL (Linker *et al.*, 2012).

The remainder of the article provides the methods supporting the decision-making process in deriving the water quality criteria thresholds. The results illustrate the criteria values adopted by the Chesapeake Bay tidal water jurisdictions of Maryland, Virginia, Delaware, and DC into water quality standards. Forthcoming challenges are highlighted for updating decisions that may be used to support modification in existing water quality standards or lead to adopting modified or new standards assessment protocols.

METHODS

The USEPA developed regional ambient water quality criteria guidance in accordance with section 117(b) of the Clean Water Act using a multistakeholder approach. The water quality criteria and tidal water designated uses are the product of a collaborative effort among Chesapeake Bay Program partners through a Chesapeake Bay Program-coordinated Water Quality Steering Committee. Various stakeholder groups were involved in the development process including staff of federal and state governments, scientific and academic institutions, citizen conservation groups, business and industry. Direct contributions of more than 100 individuals as well as over 40 additional contributors to various syntheses about Chesapeake Bay living resources habitat requirements (CBP, 1987; Funderburk *et al.*, 1991; Batiuk *et al.*, 1992, 2000; Jordan *et al.*, 1992) participated in the water quality criteria development (USEPA, 2003a). Twelve independent scientific reviewers, recognized for their national expertise and drawn from agencies and institutions across the country, conducted two rounds of independent peer reviews of the draft criteria prior to the Chesapeake Bay Program Partnership's approval and USEPA's publication.

The derivation of these regional criteria followed the methodologies outlined in the USEPA's *Guidelines for Deriving Numerical National Water Quality for the Protection of Aquatic Organisms and Their Uses* (USEPA, 1985), the risk-based approach used in developing the *Ambient Aquatic Life Water Quality Criteria for DO (Saltwater) Cape Cod to Cape Hatteras* (USEPA, 2000), and the *Biological Evaluation on the CWA 304 (a) Aquatic Life Criteria* as part of the National Consultations Methods Manual (USEPA, 2003b).

Designated Uses

Water quality standards are built upon a framework of aquatic habitats classified according to designated uses. Through a process run in parallel to criteria derivation, USEPA convened state, federal, academic, and multistakeholder representatives to develop a consistent set of tidal water designated uses across all of the Chesapeake Bay and its tidal tributaries. Representatives from the six bay states and Washington, D.C. considered five factors in refining existing Chesapeake Bay designated uses:

1. Habitats used in common by sets of species and particular life stages should be delineated as separate designated uses;
2. Natural variations in water quality should be accounted for to define separate designated uses;
3. Seasonal uses of different habitats should be accounted for in separating designated uses;
4. The Chesapeake Bay criteria for DO, water clarity, and chlorophyll *a* should be tailored to each designated use; and
5. The refined designated uses applied to Chesapeake Bay and its tidal tributary waters will support the Federal Clean Water Act goals and state goals for protecting uses attained in these waters since 1975.

The Chesapeake Bay Program partnership workgroup started with consideration of the four jurisdictions' existing designated uses and then factored in mapped and projected habitats of key commercially, recreationally, and ecologically important estuarine species and communities. Then development of vertical depth and horizontal breadth of designated use boundaries evolved to consider a combination of factors including natural water column stratification, bottom bathymetry, and circulation patterns within the context of historical and potential future living resource habitat distributions.

The most prominent bathymetric feature in the Bay is the midchannel, deep trench ranging in depth from 24 to 48 m. Such bathymetric features as the deep trench (hereinafter termed deep channel) were coupled with an understanding of seasonal, vertical water column stratification patterns coincident with flow and circulation patterns in the Bay. These water column features were taken together to determine boundaries for three of the five designated uses: open water, deep water, and a deep channel (Figure 2) (USEPA, 2003c). Observed and model-simulated characterizations of water quality dynamics were also factored into the boundary classifications. The deep channel designated use boundaries, for example, were further delineated using hypoxic volume maps based on nearly two decades of Chesapeake Bay Program long-term water quality monitoring program DO, temperature, and salinity data. Hypoxic volume maps identified areas where physical processes strongly influenced the persistence of chronically low DO considering a wide range of river flows and nutrient loads (USEPA, 2003c, 2008, 2010a, b).

The shallow water designated use reflected the desired restoration of underwater bay grass beds out to the 2-m depth contour (Figure 2). The open water designated use was inclusive of the shallow water, recognizing the critical support provided to communities of phytoplankton, zooplankton, bottom-dwelling worms, clams, and forage fish that rely on nearshore and shoal habitats in their life history (USEPA,

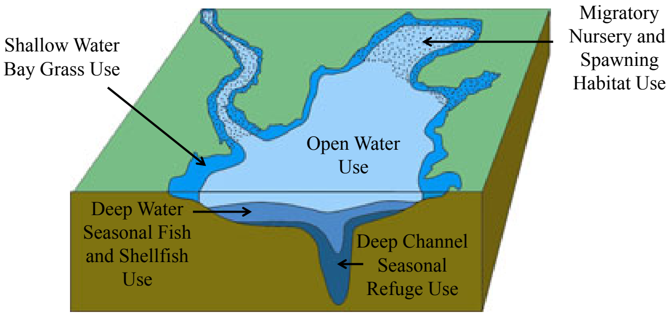

FIGURE 2. Chesapeake Bay Designated Use Zones.

2003a). Bay grasses further provide shelter for the variety of life stages of balanced and indigenous communities of fish and shellfish species (USEPA, 2004b).

Maps of the spawning and nursery habitat distributions of commercially, recreationally, and ecologically important anadromous and semianadromous fish species in Chesapeake Bay tidal waters were compiled and overlaid (Funderburk *et al.*, 1991). The resultant composite maps were used to delineate the migratory spawning and nursery designated use boundaries (Figure 2) (USEPA, 2003c).

Dissolved Oxygen

The goal in setting DO criteria was to establish a science-based approach to define habitat conditions that would sustain the suitability of Chesapeake Bay habitats for finfish and invertebrates. States, DC, and tribes could ultimately take into account designated use attainability in adopting the criteria into water quality standards (Batiuk *et al.*, 2009). Criteria derivation reflected: (1) the wide variety of Chesapeake Bay tidal water habitats, (2) seasonal movements of species across these habitats, (3) spatial and seasonal variations in DO, and (4) ensured protection of these species across an array of adverse effects (e.g., survival, growth, and larval recruitment). Durations of exposure leading to these effects were fully factored in (USEPA, 2003a).

The original Chesapeake Bay DO restoration goal and its supporting framework included spatial segregation of habitats vertically in the water column and horizontally across the Bay and its tributaries (Jordan *et al.*, 1992). DO averaging periods reflected short-term and long-term DO dynamics conditions tailored to each habitat. Assessment methodologies could be applied to monitoring and modeling output evaluating against applicable target DO concentrations. Building on the framework set up in developing the DO restoration goal, the DO criteria derivation process further resolved the separate accounting for seasonal and spatial habitat differences in natural DO dynamics as well as spatial and temporal variations in their living resource species use of different habitats well delineated by the five designated uses. The DO criteria were derived to ensure protection of the specific critical life stages — from egg through larvae, juvenile, and adult stages — present within the applicable designated uses.

Dissolved oxygen criteria were established based on matching temporal durations of exposure and concentrations protecting against adverse effects in exposure studies for dozens of commercially, recreationally, and ecologically valuable species, a representative subset of the approximately 350 fish species and hundreds of invertebrate species found in Chesapeake Bay. Exposure data provided support for: (1) acute, instantaneous minimum criteria for protecting against short-term lethal impacts on a variety of living resources and their critical life stages and (2) chronic, longer term exposure criteria that reduced adverse effects on routine metabolism, feeding, growth, and survival (USEPA, 2000, 2003a; Batiuk *et al.*, 2009). Tables of available laboratory-based adverse effects to exposure to low DO data for Chesapeake Bay species were synthesized and organized by information on the criteria protection component (e.g., growth, survival, life stages, threatened or endangered species protections), threshold DO concentrations, associated exposure durations, and source of the original exposure/effects data (USEPA, 2003a; Batiuk *et al.*, 2009). Behavioral response patterns of Chesapeake Bay benthic organisms to declining DO concentrations along with mortality information further helped set DO criteria protective of survival of infaunal organisms in the deep channel habitats (USEPA, 2003a).

Modeling tools enhanced the criteria derivation process, ensuring protection of endangered species and larval recruitment into the juvenile and adult populations. Niklitschek and Secor (2005) developed a spatially explicit bioenergetics model for Chesapeake Bay Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*). Model outputs demonstrated lost potential production to sturgeon due to summer-fall habitat squeezes. Instantaneous minima were set as protections against lethal effects from short-term exposures and highlighted critical temperature considerations for shortnose (*Acipenser brevirostrum*) and Atlantic sturgeon in Chesapeake Bay (NMFS, 2003; USEPA, 2003a, b). Criteria to protect bay anchovy eggs and larvae were derived using the larval recruitment model described in the USEPA's Virginia Province DO criteria document (USEPA, 2000) applying Chesapeake Bay anchovy-specific parameters (Batiuk *et al.*, 2009).

Water Clarity

Underwater bay grasses are submerged vascular plants (i.e., "seagrasses" or SAV). There are more than 20 freshwater and marine species of rooted submerged flowering plants in Chesapeake Bay tidal waters (Batiuk *et al.*, 1992, 2000). These underwater bay grasses provide food for waterfowl and provide critical habitat for fish and shellfish. Underwater bay grasses also positively affect nutrient cycling, sediment stability, and water turbidity. The health and survival of these plant communities in the Chesapeake Bay and its tidal tributaries depend on suitable environmental conditions, which define the quality of underwater bay grass habitat (Dennison *et al.*, 1993). The key to restoring these critical habitats and food sources is to provide the necessary levels of light penetration in shallow waters to support their survival, growth, and reproduction (USEPA, 2003a, b, c, d; Kemp *et al.*, 2004).

Two technical syntheses of information supported the development of quantitative habitat requirements for Chesapeake Bay underwater grasses (Batiuk *et al.*, 1992, 2000). These technical syntheses, along with Chesapeake Bay-specific research and field studies, model simulations, and data evaluation, formed a scientific foundation for water clarity criteria development (Kemp *et al.*, 2004). The water clarity criteria were derived to support the propagation and growth of a wide variety of species including meadow formers (e.g., *Vallisneria americana*), perennials (e.g., *Potamogeton perfoliatus*), canopy formers (e.g., *Myriophyllum spicatum*), and annuals (e.g., *Zanichellia palustris*) for tidal fresh and oligohaline habitats. Water clarity of mesohaline and polyhaline habitats call for light conditions necessary for the survival and growth of two primary species — wigeon grass (*Ruppia maritima*) and eelgrass (*Zostera marina*) (USEPA, 2003a).

The Chesapeake Bay-specific water clarity criteria provided percent light through water (PLW) necessary for supporting survival, growth, and continued propagation of bay grasses. The water clarity criteria were derived in four stages. First, water column-based light requirements for underwater bay grass survival and growth were determined based on extensive field studies and laboratory-based experimentations. Then, factors contributing to water column light attenuation were quantified through field studies, evaluation of long-term water quality monitoring and SAV aerial surveys and bed distribution mapping, laboratory experimentation, and model simulation. Third, contributions from epiphytes to light attenuation at the leaf surface were quantified and then factored into methods for estimating and diagnosing the components of total light attenuation. Finally, a set of salinity regime-based minimal requirements for light penetration through the water column and at the leaf surface were determined (USEPA, 2003a). Criteria development relied on the minimum light requirements for SAV survival and growth synthesized in Batiuk *et al.* (1992, 2000), photosynthesis-irradiance measurements, field observations of bay grass maximum depth and coincident available light (Batiuk *et al.*, 2000), light manipulation experiment findings, and light availability models (Canfield *et al.*, 1985; Chambers and Kalff, 1985).

The PLW requirements for each salinity regime reflect minimum light requirements for SAV and light attenuation according to Beer's Law:

$$I_z = I_o \exp(-K_d Z),$$

where I_o is light as photosynthetically active radiation measured just below the surface, I_z is light measured at depth Z (in meters), and K_d as a light attenuation coefficient.

The PLW uses the relationship as PLW = 100exp $(-K_d Z)$ and K_d is converted to Secchi depth (in meters) by conversion as K_d = 1.45/Secchi depth (USEPA, 2003a).

Chlorophyll a

Chlorophyll *a* concentrations serve as an especially useful and responsive indicator of water quality. Attaining the Chesapeake Bay DO and water clarity criteria requires reductions in chlorophyll *a* concentrations. The USEPA indicates developing and adopting quantitative chlorophyll *a* criteria in addition to water clarity and DO are necessary to protect the Chesapeake Bay (USEPA, 2007b). The absence of quantitative interpretation for the qualitative, narrative desired ecological conditions in water quality standards prevents states from fully and properly applying the narrative sections of their water quality standards regulations (USEPA, 2007b).

Derivation of chlorophyll *a* criteria relied on several different approaches to develop relationships between chlorophyll *a* and water quality impairments. Chesapeake Bay numerical chlorophyll *a* criteria were derived to address specific water quality, human and aquatic life endpoints when applied to specific seasons and salinity-based tidal habitats.

The reference conditions derivation approach began with the acquisition of historical (1950-2004) chlorophyll *a* data from archival sources (see USEPA, 2007b, table III-1) and more current Chesapeake Bay Water Quality Monitoring Program (1984-2004) data. The data consisted of surface chlorophyll *a* and vertical water column chlorophyll *a* profiles. Field collection and analytical laboratory methods were carefully evaluated for comparability between the historical and current data. The data were analyzed and modeled to develop reference chlorophyll *a* concentrations. General linear models of surface chlorophyll *a* were devised for the complete historical time series to generate predictions for specific periods and flow conditions. This process allowed selection of a time period (e.g., decade) to function as a reference restoration target (USEPA, 2007b). The approach followed the logic that chlorophyll *a* concentrations have increased significantly between the 1950s (i.e., reference) and the 1980s (i.e., impacted) (Harding and Perry, 1997; USEPA, 2007b). It also accounted for strong climate forcing of chlorophyll *a* concentrations by establishing regional seasonal reference chlorophyll *a* concentrations based on mean chlorophyll *a* and factoring in spatial and temporal variances for wet, dry, and average conditions (Harding and Perry, 1997; USEPA, 2007b). To complete the definition of chlorophyll *a* reference concentrations, establishing a criteria threshold for each salinity zone/season combination to use for criteria attainment assessment was necessary. The criteria threshold for chlorophyll *a* was developed as a concentration that should rarely be exceeded thus characterizing healthy water quality conditions. The 90th percentile of a distribution was adopted as such a criterion threshold to allow a relatively low level (10%) of naturally occurring high levels of chlorophyll inherent even in healthy populations (USEPA, 2003a, 2007b). A similar approach was followed using depth-weighted average chlorophyll *a* from the water quality profiles (USEPA, 2007b).

Summer average bottom DO (mg/l) has been related to average surface chlorophyll *a* (μg/l) at several time scales (USEPA, 2007b). Long-term Chesapeake Bay Water Quality Monitoring program data for the Choptank and Patuxent rivers were analyzed for relationships between chlorophyll *a* and DO. The Choptank River is considered representative of many rural tidal tributaries on the Eastern Shore Coastal Plain with low human populations and substantial agriculture. Similarly, the Patuxent River was considered representative of the more urbanized western shore tributaries that rest on Piedmont and Coastal Plain lands with high population densities and large wastewater treatment plant inputs. Combining chlorophyll *a* and DO data from the tidal Patuxent and Choptank rivers, an envelope of DO concentrations showed a declining relationship with increasing chlorophyll *a* concentrations at a rate of 0.15-1.1 mg O_2/μg chlorophyll *a* (USEPA, 2007b). A range of annual mean chlorophyll *a* criterion threshold concentrations was derived from the intersection of the envelope with a monthly mean DO criterion threshold of 5 mg/l.

Water clarity impairment-based chlorophyll *a* concentration thresholds were derived for tidal fresh, oligohaline, mesohaline, and polyhaline salinity zones to meet SAV minimum light requirements. Water quality target protection depths vary with location in Chesapeake Bay. Depending on SAV species light requirements and their historical abundance and distribution in shallow waters of Chesapeake Bay, the target depths have been established at 0.5, 1, and 2 m (USEPA, 2003a). Surface water chlorophyll *a* concentration thresholds were determined by inversion of a bio-optical model for the given colored dissolved organic matter (CDOM μg/l) and nonalgal suspended solids (μg/l) concentrations as being values protective of SAV minimum light requirements, averaged by salinity zone, and accounting for Chesapeake Bay water clarity application depths. The bio-optical modeling approach represents the absorption and scattering spectra as functions of water quality concentrations (Gallegos and Bergstrom, 2005). The absorption wavelengths can be expressed as the sum of contributions due to water, CDOM, chlorophyll *a*, and Total Suspended Solids (TSS) (Gallegos and Bergstrom, 2005; USEPA, 2007b). Recommended chlorophyll *a* criteria are based on averages calculated across all Chesapeake Bay management segments within each salinity zone containing sufficient data. Management segments were flagged with chlorophyll *a* concentration thresholds too high due to one of three identifiable reasons: (1) water clarity application depth too low or SAV distribution limited by factors other than water clarity, (2) suspect background TSS, and (3) suspect particulate optical properties were excluded from the salinity/application depth-based averages (USEPA, 2007b). The application of these numerical chlorophyll *a* criteria is proposed for the Chesapeake Bay SAV growing seasons by salinity zone (i.e., April-October for tidal fresh, oligohaline, and mesohaline; split season of March-June and August-November in polyhaline) and specific to application depth.

A literature review was used in deriving numerical chlorophyll *a* criteria related to harmful algal blooms (HABs) by first developing a gradient of management action thresholds that focused on human health risks, but also included living resource impacts and coincident chlorophyll *a* concentrations associated with the conditions (USEPA, 2007b). Toxic cyanobacteria events in the Chesapeake Bay basin date back to the 1930s (Tisdale, 1931a, b; Veldee, 1931) indicating human health impacts, and more recently waterbird deaths and protective beach closures and recreational activity alerts on tidal tributaries of Chesapeake Bay (USEPA, 2007b; Tango and Butler, 2008). Cyanobacteria toxins, principally the hepatotoxin microcystin, formed the basis of human health risk relationships for establishing chlorophyll *a* criteria thresholds. Next, conversions were developed between toxin concentrations, cell counts related to toxin levels, and chlorophyll *a* as a function of cell counts (USEPA, 2007b; Tango and Butler, 2008). These values were subsequently available to assess (1) the chlorophyll *a* levels expected based on literature-derived human health risks associated with harmful cyanobacteria blooms; (2) assessing risk categories based on cell counts to determine whether previously described management action thresholds in the literature were practical for Chesapeake Bay; and (3) for evaluating Chesapeake Bay-specific cyanotoxin data to gauge if the published risk levels applicable to Chesapeake Bay were being exceeded, the exceedance frequency, and the relationship with observed, ambient chlorophyll *a* concentrations (USEPA, 2007b). The management action threshold gradient showed that 25 μg/l chlorophyll *a* was the first level that generated waterway closures protective of human health (USEPA, 2007b). Classification and regression tree (CART) analyses were conducted on summer season surface or above pycnocline Chesapeake Bay long-term water quality monitoring program data for the combination of tidal fresh and oligohaline salinity zones. Analysis results provided average subestuary surface water chlorophyll *a* values associated with separating high and low human health risk. The CART-derived thresholds were averaged with the literature-derived value to provide a recommendation on a criterion threshold value. The criterion threshold value was recommended as a value such that less than 10% of ambient chlorophyll *a* concentrations should be observed above this value to limit human health and other living resource-related risks (USEPA, 2007b).

Criteria Assessment Procedures

Specific criteria assessment procedures were developed in tandem and published with the 2003 Chesapeake Bay criteria (USEPA, 2003a). These procedures were periodically refined as new scientific understanding became available and the jurisdictions and USEPA gained experience in the application to Chesapeake Bay monitoring data (USEPA, 2004c, 2005, 2007a, b, 2008, 2010b). Delaware, DC, Maryland, and Virginia have adopted by reference the original criteria assessment procedures and the full series of published addenda into their jurisdictions' water quality standards regulations.

The water quality criteria assessment methodology currently used by the USEPA and the Chesapeake Bay watershed jurisdictions evaluates observed violations of the criteria based on comparison of cumulative frequency distribution (CFD) curves developed using interpolated monitoring data compared against criterion-specific reference curves (USEPA, 2003a, 2007b). Spatial (water clarity, chlorophyll *a*) or volumetric (DO) assessment of criteria violations are developed from interpolation of Chesapeake Bay Program quality assured water quality monitoring data. In some instances, data were transformed (e.g., natural log or log base 10 for chlorophyll *a*) (USEPA, 2008, 2010b) before interpolation. Interpolation techniques include inverse distance weighting (DO, chlorophyll *a*) and ordinary kriging (water clarity) (USEPA, 2008). The CFD approach is considered the best science available for assessment of the Bay's water quality criteria (STAC, 2006).

Historically, USEPA has recommended a 10% allowable exceedance in temporal or spatial assessments against thresholds. The application of a two-dimensional CFD simultaneously accounting for exceedances in time and space is an innovative approach designed to better reflect the relative impact of varying degrees of exceedance (USEPA, 2003a). A reference curve is the curve of compliance, represented in a two-dimensional plane of percent space and percent time (Figure 3). The curve may be a mathematically derived 10% curve or a "bioreference curve." The bioreference curve is a reference CFD derived from observed criterion threshold exceedances tolerated by healthy communities of a relevant biological resource. The bioreference curve could allow more or less than the 10% allowable exceedance defined by the mathematically derived curve.

Chesapeake Bay Management Segmentation

Criteria assessments are conducted for the 92 Chesapeake Bay Program segments (Figure 1). Criteria attainment results are reported for each designated use segment combination (USEPA, 2007a). Since 1983, the Chesapeake Bay Program partnership has used some form of basic segmentation of the Chesapeake Bay and its tidal tributaries to organize the collection, analysis, and presentation of environmental data (USEPA, 2004b, 2005, 2008, 2010b). The 92-segment map is the most current Chesapeake Bay Program segmentation scheme for use in evaluating monitoring data and summarizing model-simulated outputs (Figure 1).

For diagnosing anthropogenic impacts, segmentation is a way to group regions with similar natural physical, chemical, and biological characteristics so that differences in water quality and biological communities among similar segments can be identified and stressor sources elucidated (USEPA, 2008). Natural characteristics (e.g., bathymetry, circulation patterns, salinity) as well as geographic and political boundaries provided boundary definitions for each

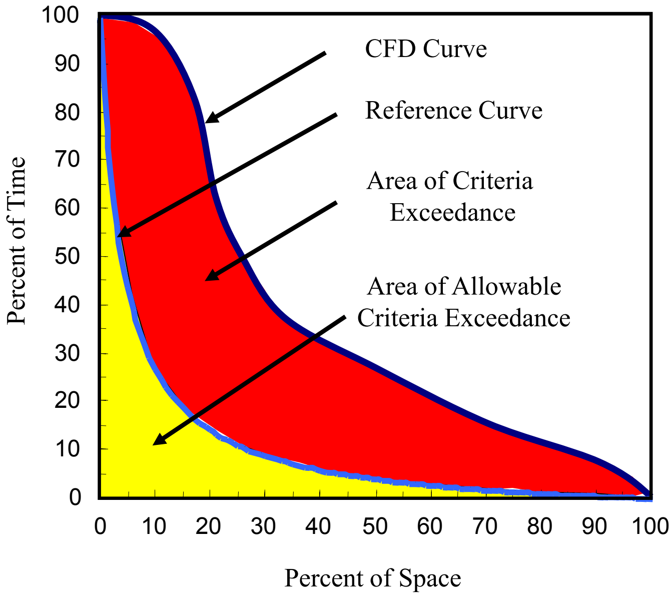

FIGURE 3. Cumulative Frequency Distribution (CFD) Approach to Chesapeake Bay Water Quality Criteria Attainment Assessments.

segment. For management purposes, segmentation has been used to group similar regions, target implementation actions, and monitor ecosystem responses. The general procedural outline from data collection through water quality standards compliance assessment is provided below (Box 1). This framework is currently applied to the assessment of the monthly DO criteria in the open water and deep water designated uses, and to the instantaneous minimum DO criterion in the deep channel designated use, as well as open water chlorophyll *a* in the James River, DC, and in bay-wide modeling scenario assessments for DO, water clarity, and chlorophyll *a* criteria attainment.

BOX 1. Process Outline for the Water Quality Criteria Assessments.

Step 1. Collect data at approximately 175 Chesapeake Bay Partnership long-term water quality monitoring locations (generally twice per month May-September and once per month at other times). Additional data within a segment may be included when meeting EPA QA/QC protocols (e.g., data coordinated by the Alliance for the Chesapeake in Virginia tidewaters).

1.1. Average data when more than one observation are collected in a given month.

Step 2. Spatially interpolate the monthly data across each segment using the following method.

2.1. Vertically interpolate for a sampling cruise (first or second) (grid resolution is 1 m).

2.2. Horizontal interpolation of a cruise (grid resolution is 1 km^2).

2.3. If there are two or more sampling cruises in a month, average interpolations within a month to get a monthly result.

2.4. Apportion results by designated uses.

Step 3. Determine the compliance status of each cell in the segment volume.

Step 4. Produce a percent compliance matrix with sample period and percent space in compliance.

Step 5. Rank the percent compliance in space from greatest to lowest values and assign percent of time associated with the compliance values.

Step 6. Plot ranked percent space (x-axis) against percent time (y-axis).

Step 7. Evaluate habitat compliance against the reference curve.

RESULTS

Designated Uses

The five tidal water designated uses (Box 2) provided the spatial and temporal context for deriving DO, water clarity, and chlorophyll *a* water quality criteria for Chesapeake Bay and its tidal tributaries.

BOX 2. Chesapeake Bay Designated Use Definitions (USEPA, 2003b).

1. *Migratory fish spawning and nursery designated use* protects migratory and resident tidal freshwater fish during the late winter to late spring spawning and nursery season in tidal freshwater to low-salinity habitats. Located primarily in the upper reaches of many bay tidal rivers and creeks and the upper main stem Chesapeake Bay, this use will benefit several species, including striped bass, perch, shad, herring, sturgeon, and largemouth bass.
2. *Shallow water bay grass designated use* protects underwater bay grasses and the many fish and crab species that depend on the vegetated shallow water habitat provided by underwater grass beds.
3. *Open water fish and shellfish designated use* focuses on surface water habitats in tidal creeks, rivers, embayments, and the main stem Chesapeake Bay and protects diverse populations of sport fish, including striped bass, bluefish, mackerel, and sea trout, as

well as important bait fish such as menhaden and silversides.

4. *Deep water seasonal fish and shellfish designated use* protects animals inhabiting the deeper transitional water column and bottom habitats between the well-mixed surface waters and the very deep channels. This use protects many bottom-feeding fish, crabs and oysters, and other important species such as the bay anchovy.
5. *Deep-channel seasonal refuge designated use* protects bottom sediment-dwelling worms and small clams that bottom-feeding fish and crabs consume naturally. Low to occasional no dissolved oxygen conditions occur in this habitat zone during the summer.

Dissolved Oxygen, Water Clarity/Underwater Grasses, and Chlorophyll a Criteria

Dissolved Oxygen Criteria. Habitat-specific DO criteria were developed that would support unimpaired growth and survival of estuarine organisms (Batiuk *et al.*, 2009). Exposure criteria were designed to protect finfish and shellfish species and epifaunal communities inhabiting Chesapeake Bay tidal waters at all life stages. Annual and seasonal applications were developed (Table 1).

Seasonal applications were particularly relevant to migratory fish spawning and nursery habitat (February 1-May 31) that protected tidal fresh resident fish, threatened and endangered species, and migratory fish life stages. Deep water criteria for June 1-September 30 protected summer season survival and recruitment of bay anchovy eggs and larvae as well as open water juvenile and adult fish. Deep channel seasonal refuge conditions for summer season (June 1-September 30) targeted survival of bottom-dwelling worms and clams. Shallow-water bay grass designated use merged with open-water fish and shellfish use for DO criteria applications. For designated uses with season-specific criteria, the remainder of the year applied open-water fish and shellfish year-round protections for growth across life stages, protections for threatened and endangered species, and survival level exposure protections. Open-water fish and shellfish use criteria has one caveat where temperatures >29°C are considered stressful to shortnose sturgeon.

TABLE 1. Chesapeake Bay Water Quality Criteria (from USEPA, 2003a).

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 salinity)	Survival/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 criteria apply		Year-round
Open water fish and shellfish use[1]	30-day mean ≥5.5 mg/l (tidal habitats with ≤0.5 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 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[1]	
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

[1]At temperatures considered stressful to shortnose sturgeon (*Acipenser brevirostrum*) (>29°C) dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg/l will protect survival of this list sturgeon species.

TABLE 2. Options for Measuring Attainment of the Chesapeake Bay Shallow Water Designated Use.

Measure of Attainment	Option
Submerged aquatic vegetation acres only	The single best year of SAV acreage mapped through the bay-wide aerial survey in the past three years passes attainment of water clarity standards if the acreage in a management segment is equal to or higher than the segment-specific SAV restoration goal target
Water clarity acres only	If a segment does not pass its SAV acreage goal with aerial survey data, and there are available water quality mapping data, achievement of a water clarity criteria acreage necessary to support the SAV acreage goal can be assessed. Water clarity acres can be assessed regardless of whether or not SAV is present. Water clarity acre goals are 2.5× the SAV goal acres in a Chesapeake Bay management segment
Integrated measure of submerged aquatic vegetation and water clarity acres	A combination assessment of mapped SAV and water clarity acreage that, taken together, meets acreage goals

Note: SAV, submerged aquatic vegetation.

TABLE 3. Chesapeake Bay Water Clarity Criteria.

Salinity Regime	Water Clarity as Percent Light Through Water (%)	Water Clarity Criteria as Secchi Depth: Water Clarity Criteria Application Depths 0.25	0.50	0.75	1.0	1.25	1.50	1.75	2.0	Temporal Application
		Secchi Depth (meters) for Above Criteria Application Depths								
Tidal fresh	13	0.2	0.4	0.5	0.7	0.9	1.1	1.2	1.4	April 1-October 31
Oligohaline	13	0.2	0.4	0.5	0.7	0.9	1.1	1.2	1.4	April 1-October 31
Mesohaline	22	0.2	0.5	0.7	1.0	1.2	1.4	1.7	1.9	April 1-October 31
Polyhaline	22	0.2	0.5	0.7	1.0	1.2	1.4	1.7	1.9	March 1-May 31, September 1-November 30

The instantaneous minimum protection value here is increased from 3.2 mg O_2/l to 4.3 mg O_2/l to account for interactions between DO saturation and hence availability with temperature relative to meet sturgeon physiological needs.

Addressing acute, short-term low DO protection exposure concerns provided support for instantaneous minimum criteria. Addressing chronic, long-term low DO exposure protection concerns provided support for longer duration criteria from published 1-day minima, 7-day, and 30-day means. Acute and chronic criteria are applicable in all five designated uses.

Water Clarity Criteria. The attainment of the shallow water designated use is assessed based on water clarity, SAV acreage, or a combination of the two measures (Table 2). The Chesapeake Bay water clarity criteria (Table 3) are expressed as PLW and Secchi depth equivalents for a range of depths from 0.25 to 2 m (USEPA, 2003a, b, c, d). The water clarity criteria reflect a set of minimum light requirements protecting underwater bay grass species with widely varying life histories (e.g., meadow formers, canopy formers, annuals, and perennials). Minimum light requirements differed for bay grasses in two sets of salinity regimes — a tidal fresh and oligohaline group which required less light (13% PLW) than the mesohaline-polyhaline group (22% PLW). These PLW requirements were consistent with scientific literature and model findings described in Batiuk *et al.* (2000) and validated through comprehensive analyses of 13 years (1985-1998) of Chesapeake Bay water quality monitoring data and corresponding annual mapping of the spatial distribution of SAV beds (USEPA, 2003a).

Submerged aquatic vegetation restoration acreage goals and water clarity application depths were developed based on historic and recent data on the distribution of SAV (USEPA, 2003d). Detailed analyses using that data — including historical aerial photographs — were undertaken to map the distribution and depth of historical SAV beds in the Chesapeake Bay and its tidal tributaries and embayments. The analyses led to the adoption of the single best year method that considers historical SAV distributions from the 1930s through the early 1970s and more recent distributions since 1978 to the present mapped through annual SAV aerial surveys of the Bay's shallow water habitats. Using that method, the EPA and its watershed jurisdictional partners established a bay-wide SAV restoration goal of 185,000 acres and bay segment-specific

TABLE 4. Recommended Chesapeake Bay Chlorophyll *a* Narrative Criteria (USEPA, 2003a).

Concentrations of chlorophyll *a* in free-floating microscopic aquatic plants (algae) shall not exceed levels that result in ecologically undesirable consequences such as reduced water clarity, low dissolved oxygen, food supply imbalances, proliferation of species deemed potentially harmful to aquatic life or humans or aesthetically objectionable conditions or otherwise render tidal waters unsuitable for designated uses

acreage goals. The water clarity goal is based on SAV light requirements, but if SAV is present in a designated use to an extent equal to or greater than what has ever been observed in the historical record, then the clarity standard is considered to be the de facto achieved standard regardless of the water clarity metrics. The dual nature of the water clarity/SAV water clarity standard is specifically codified in Maryland and Virginia state statutes so that either sufficient water clarity, or sufficient SAV area, or a combination of both will satisfy achievement of the standard. The use of SAV area as a standard allows an efficient and rapid annual assessment of the water clarity/SAV standard by aerial photography (USEPA, 2003a).

The temporal application periods were defined as critical periods when changes in water quality will have the greatest impact on long-term SAV community survival. Critical periods for the tidal fresh, oligohaline, and mesohaline regions of the Bay were characterized by the aboveground growing season for bay grasses which is spring through fall (Batiuk *et al.*, 1992). Critical period for the polyhaline region reflected the bimodal growth pattern of the dominant SAV, *Z. marina*, which expresses high growth in spring and fall and low growth in summer and winter (Batiuk *et al.*, 1992). Temporal application periods for water clarity criteria were, therefore, defined as April 1 to October 31 for tidal fresh, oligohaline, and mesohaline waters. A split temporal application period was applied to polyhaline habitats for March 1 to May 31 then September 1 to November 30, reflecting the bimodal growth pattern for *Z. marina* (Batiuk *et al.*, 1992).

Chlorophyll *a* Criteria. A qualitative, narrative chlorophyll *a* criterion was recommended for encompassing a full array of possible water quality impairments, all of which may not manifest themselves in one particular water body at any one time (Table 4). The site-specific nature of phytoplankton-based impairments has supported state or tribal adoption of the USEPA-recommended narrative criteria with development of locally specific quantitative criteria to address specific algal-related impairments. The scientific basis for bay-wide quantitative criteria have not been agreed upon and thus not published and adopted by the Chesapeake Bay tidal water jurisdictions into their water quality standards.

States, however, were encouraged to use the published information developed in deriving numerical translators for their qualitative criteria. From 2004 to 2006 Delaware, Maryland, Virginia, and DC promulgated narrative chlorophyll *a* criteria into their water quality standards. Virginia promulgated numeric and season-specific (spring and summer) mean chlorophyll *a* criteria for the James River's tidal fresh, oligohaline, and mesohaline habitats (USEPA, 2007b). DC promulgated numeric chlorophyll *a* criteria (i.e., summer season mean 25 μg/l chlorophyll *a*) for its reach of the tidal Potomac River and its remaining waters, having previously adopted numerical chlorophyll *a* criteria for the protection of the tidal Anacostia River (USEPA, 2008). Maryland has a quantitative interpretation of a qualitative chlorophyll *a* criterion for application in TMDLs based on Thomann and Mueller (1987). The Thomann and Mueller guidelines acknowledge protection against "undesirable" levels of phytoplankton (chlorophyll *a*) that can vary considerably depending on the water body. The State of Maryland has determined that as per Thomann and Mueller (1987) it is acceptable to ensure (1) instantaneous chlorophyll *a* concentration measures remain below 100 μg/l at all times and (2) minimize exceedances of 50 μg/l chlorophyll *a*, using a 30-day rolling average, to a frequency that will not result in ecologically undesirable conditions.

Further development of quantitative chlorophyll *a* criteria for Chesapeake Bay tidal waters documented the scientific basis for numerical criteria based on multiple lines of evidence using Chesapeake Bay monitoring data. Historical chlorophyll *a* reference concentrations, chlorophyll *a* relationships with DO impairments, chlorophyll *a* contributions to water clarity impairments, and characteristic chlorophyll *a* conditions associated with specific impairments related to HABs were all developed to converge upon a common criterion or range (USEPA, 2007b). Results of the analyses supported recommendations on Chesapeake Bay chlorophyll *a* criteria are summarized in Table 5.

Recommended Implementation and Criteria Assessment Procedures — Addressing Magnitude, Duration, Frequency, Space, and Time of Impairments

Total Exceedances. Criteria attainment for DO, water clarity, and chlorophyll *a* is assessed in terms

TABLE 5. Chesapeake Bay Chlorophyll *a* Derivations Toward Numerical Criteria (summarized from USEPA, 2007b).

Method	Season	Salinity Zone	Criteria	Application
Historical reference DO	Spring	OH	18	90th percentile of a log normal distribution
		MH	8	
		PH	4	
	Summer	OH	46	90th percentile of a log normal distribution
		MH	23	
		PH	5	
DO impairment	Annual	TF-OH-MH-PH	10-15	Mean, deep water
			30	Mean, shallow water
Water clarity reference condition	SAV growing season	TF-OH	43, 11, N/A	Seasonal means for restoration targets of clarity are 0.5-, 1.0-, and 2.0-m depths, respectively
		MH-PH	39, 16, 3	
HAB impairment	Summer	TF-OH	27.5	90th percentile of a log normal distribution

Note: TF, tidal fresh; OH, oligohaline; MH, mesohaline; PH, polyhaline; DO, dissolved oxygen; SAV, submerged aquatic vegetation; HAB, harmful algal bloom.

of the spatial and temporal extent of criterion threshold exceedances — what volume or surface area of the Bay segment exceeds a given criterion threshold and for how much time during the assessment period (USEPA, 2003a, 2004a). The allowable frequency with which criteria can be violated without a loss of the designated use is also considered. For each listing cycle, assessments are based on monitoring data collected over a three-year period in each spatial assessment unit. In the case of chlorophyll *a*, statistical treatment of chlorophyll *a* data from a review of non-Chesapeake Bay and Chesapeake Bay-specific peer reviewed scientific literature and USEPA Chesapeake Bay criteria documentation supported a common recognition of skewness with chlorophyll *a* datasets. Log transformation of chlorophyll *a* data during analysis was recommended to better reflect a normal distribution (USEPA, 2010b). Analyses conducted with data approximating a normal distribution through the calculations support the wide array of statistical inference procedures based on normal distributions. The assessment protocol modifications constituted a more consistent and technically sound calculation when working with chlorophyll *a* data than the previously published methods (USEPA, 2003a, 2007a, 2008). Specific sampling and assessment procedure recommendations directed toward a HAB-based chlorophyll *a* criterion that could be applied to the Chesapeake Bay tidal fresh and oligohaline waters were also detailed (USEPA, 2007b).

Spatial assessment units are defined by Chesapeake Bay segments and applicable designated uses. Such assessment of the criteria as further described below is designed to provide reliable protection for the associated refined aquatic life use. The spatial exceedances of criteria are determined using a grid cell-based data interpolation software application that enables estimation of water quality values for the entire Bay using monitored data at specific points (USEPA, 2003a, 2007a, 2008). The interpolated data are compared with water quality criteria on a cell by cell basis, and the percent of surface area or volume exceeding the criterion in each spatial assessment unit is calculated. The percent spatial exceedances for each assessment unit are then compiled for each monitoring event conducted during the three-year monitoring period.

The temporal extent of exceedances is determined by calculating the probability that an observed percent exceedance will be equaled or exceeded. To calculate that probability, the percent of spatial exceedances are sorted and ranked, and a cumulative probability is calculated for each spatial exceedance value (USEPA, 2003a). The spatial and temporal exceedances can be graphically illustrated by plotting the CFD curve, which is a plot of the temporal exceedance values on the *Y*-axis *vs.* the spatial exceedance values (in area or volume) on the *X*-axis (USEPA, 2003a, 2007a, 2008; STAC, 2006).

Allowable Exceedances. USEPA developed reference curves for each water quality criterion (DO, water clarity, and chlorophyll *a*) to provide a scientifically based, direct measure of the time and space during which a particular criterion can be allowably exceeded — i.e., without resulting in harm to the designated uses(s) (USEPA, 2003a). For assessment purposes, USEPA and its watershed jurisdictional partners developed two types of reference curves: a biological reference curve and a 10% default reference curve for use when a biological reference curve is unavailable.

Biological reference curves are CFDs developed for a given criterion in areas for which monitoring data are available and in which healthy aquatic communities exist (USEPA, 2003a). They represent the range of conditions that can reasonably be expected in a

TABLE 6. Summary of Published Water Quality Criteria Addenda and Their Guidance and Documentation Revising and Updating the Original USEPA (2003a) Water Quality Criteria.

Water Quality Criteria Addendum	Guidance and Documentation Revising and Updating the Original USEPA (2003a) Ambient Water Quality Criteria
USEPA (2004a)	• Temperature-based criteria to protect endangered short-nosed sturgeon • Site-specific DO criteria derivation guidance • Method for delineating upper and lower pycnocline boundaries • Water quality criteria attainment alternatives for the shallow water bay grass designated use • Numerical chlorophyll *a* criteria applications in Chesapeake Bay tidal waters
USEPA (2004b)	• Revisions, decisions, and rationales for Chesapeake Bay management segment schemes
USEPA (2007a)	• Refinements to spatial interpolation and statistical aspects of measuring water quality criteria attainment assessment • Recommendations for further development of spatial interpolation and statistical aspects of measuring water quality criteria attainment assessment • Refinement to procedures assessing DO, water clarity, and chlorophyll *a* criteria • Additions to procedures for assessing DO, water clarity, and chlorophyll *a* criteria • Recommended methods for using shallow water high-frequency continuous monitoring water quality data in criteria assessment • Document 303(d) list decision-making framework for water quality criteria attainment assessments
USEPA (2007b)	• Scientific bases to support numerical chlorophyll *a* criteria applicable to Chesapeake Bay and its tidal tributaries • Recommended procedures for assessing attainment of HAB-based numerical chlorophyll *a* criteria
USEPA (2008)	• Refinements to the Chesapeake Bay and tidal tributary management segment scheme • Refinements to previously published DO, water clarity, and chlorophyll *a* attainment assessment procedures • Additions to procedures for DO, water clarity, and chlorophyll *a* attainment assessment procedures • Chlorophyll *a* criteria assessment procedures
USEPA (2010a, b)	• Refinements to procedures for defining Chesapeake Bay designated uses • Refinements and additions to previously published procedures for deriving biologically based reference curves • Recommendations for applications of biologically based reference curves for DO criteria assessments • Refinements to procedures and recommendations for assessing chlorophyll *a* criteria

Note: DO, dissolved oxygen; HAB, harmful algal bloom.

healthy community. As a result, the biological reference curve can be used to provide an understanding of what level of criteria exceedances are allowable without losing support of the designated use. Given the Bay's nutrient-enriched status, however, appropriate reference sites are limited. Biological reference curves have been published for and are used to assess allowable exceedances for the deep water DO criteria (USEPA, 2010a) and the water clarity criteria (USEPA, 2003a).

In some cases, developing a biologically based reference curve is not possible because of a lack of data describing the health of the relevant species or biological communities and lack of appropriate reference sites. In those cases, EPA used a 10% default reference curve (USEPA, 2007a). The 10% default reference curve is defined as a hyperbolic curve that encompasses not more than 10% of the area of the CFD graph (percent of space multiplied by percent of time) (USEPA, 2007a, p. 13, figure II-4 and equation 1).

Once the CFD curve for a spatial assessment unit is developed from monitoring data (also referred to as the assessment curve), it is compared to the appropriate reference curve as in Figure 3. The area on the graph above the reference curve (blue line) and below the assessment curve (red line) is considered a region of nonallowable exceedance. The area below the reference curve (yellow) is considered as the region of allowable exceedances.

FORTHCOMING CHALLENGES

At the time of publishing the original regional criteria guidance, a number of technical issues still remained to be worked through, resolved, and documented. The application of the regional ambient water quality criteria guidance has allowed for consideration of reasonable and prudent alternatives. During the decade since the regional guidance was published, multiple interagency, interjurisdictional teams involving water quality standards program managers and coordinators, and water quality scientists, took on the responsibility of collectively working through the technical issues. Addenda and technical documents were supplemental to the original guidance; new or replacement chapters and appendices have been published to supersede elements of the original published guidance.

New addenda and documents are published when new scientific research and management applications reveal new insights and knowledge to be incorporated into revisions of state water quality standards regulations (Table 6). Examples of outstanding issues that have been resolved with science and management team efforts ranged from refinements of criteria to protect endangered species to documenting revisions or recommendations for protocols and procedures that support water quality criteria attainment assessment (Table 6). Evolving scientific and management insights may lead to further revisions of criteria, criteria assessment procedures, designated use boundaries that support state review, and successful adoption of the refinements to their regulations.

Opportunities for Applying an Umbrella Criterion

There are more criteria that have been adopted into States' water quality standards than are presently being assessed with the current monitoring and modeling tools available to the Chesapeake Bay Program jurisdictions. Data analyses based on Chesapeake Bay Program Water Quality model output suggested the summer season monthly mean for DO served as the most conservative DO criterion being assessed in open water and deep water designated uses. The monthly mean was said to be serving as an umbrella to the unassessed, shorter duration criteria. This finding therefore suggested that if the monthly DO criterion was being attained then all shorter duration criteria were also being met. Furthermore, meeting the summer season instantaneous minimum DO criterion in the deep channel designated use was an umbrella to all published criteria. However, USEPA (2004a) provided guidance on where and when attainment of the instantaneous minimum, 1-day mean and seven-day mean DO criteria can be assessed using monthly water quality monitoring data from the Chesapeake Bay long-term water quality monitoring program. The analyses supporting the guidance suggested that the monthly mean was not completely protective of all shorter duration criteria in the appropriate designated uses. An Umbrella Criteria Assessment Team analysis of historical and expanded high frequency water quality monitoring datasets (i.e., offshore vertical water quality profilers and nearshore, fixed-station continuous water quality sensor arrays) largely supported the 2004 findings where the target analyses overlapped in focus (STAC, 2012). The issue highlights, for example, the challenge to the jurisdictions for decisions on modifying their existing water quality standards or adopting new protocols to assess all standards.

Implications of Creating a New Shallow Water Dissolved Oxygen Designated Use Definition

The open water designated use has been defined in space as inclusive of shallow water (≤2 m) habitat. There was insufficient evidence that nearshore and offshore water DO behaved in a significantly different manner (USEPA, 2003a; Batiuk *et al.*, 2009). The Umbrella Criteria Assessment Team, however, showed that short time-scale (i.e., less than seven day mean) differences in DO variability were significantly different between nearshore and offshore habitats (STAC, 2012). With a potential basis in place to separate the offshore open water from a shallow water designated use for assessing DO attainment, new issues need to be resolved before adopting such changes in designated uses for DO criteria. Such new issues include identifying appropriate assessment and evaluation protocols in these separate habitats. In addition, the management implications of making this change in designated use need to be assessed to understand the level of impact it could have on our management approaches to the restoration of the Bay and its tributaries. If, for example, the open water designated use is further divided, and the summer season shallow water zone were to show that it required greater nutrient load reductions to achieve water quality standards than the deep channel of the Chesapeake Bay, then the foundation for allocations would need to change. Additional follow-up research will be necessary to understand and support management-relevant decisions regarding these water quality standards issues facing the jurisdictions based on the most recent findings of the Umbrella Criteria Assessment (STAC, 2012).

Challenges with Developing and Applying a Full Set of Quantitative Chlorophyll a Criteria

Chlorophyll *a* is a useful expression of phytoplankton biomass and is arguably the single most responsive indicator of nitrogen and phosphorus enrichment in the Chesapeake Bay (Harding and Perry, 1997). Yet, while DO and water clarity have a full set of seasonally and designated use-based numerical criteria for tidal waters of Chesapeake Bay and its tributaries (USEPA, 2003a, b, c, d), a set of numerical chlorophyll *a* criteria remains to be established. The four jurisdictions that include Chesapeake Bay tidal waters within their boundaries all have narrative water standards in their existing regulations that require achievement and maintenance of a balanced, nonnuisance phytoplankton community.

The absence of a complete bay-wide tidal water set of quantitative chlorophyll *a* criteria, however, prevents the jurisdictions from fully assessing whether their tidal waters are meeting their designated uses. Collectively the tidal Chesapeake Bay jurisdictions water quality standards regulations contain clear narrative requirements that address the adverse human health and aquatic life impairments caused by overabundant, nuisance algal production measured as chlorophyll *a*. Quantifying undesirable chlorophyll *a* levels in the water remains a challenge because concentrations that cause "ecologically undesirable consequences" in one tributary or in one region of Chesapeake Bay do not necessarily cause problems in other tidal tributaries or regions. From 2004 to 2006, Virginia and DC adopted locally relevant numerical chlorophyll *a* criteria for the tidal James River (Virginia) and across all the District's jurisdictional tidal waters. Maryland has a generally applied numerical translation of their narrative (USEPA, 2008).

The scientific bases for quantitative chlorophyll *a* criteria were further developed by a multiagency, multi-institutional team and published as USEPA guidance to the original criteria (USEPA, 2007b). The approaches used in the criteria derivations included evaluation of historical conditions for references, assessment of DO impairment thresholds, water clarity impairment threshold relationships, and HAB impairment thresholds relationships. However, the criteria derivations were not focused on the same season and have monitoring method dependencies. The DO impairment approach, for example, provided annual-based criteria whereas HABs-based impairment methods targeted the Chesapeake Bay regulatory definition of summer season (i.e., June-September). Furthermore, additional monitoring may be needed to refine HAB-toxin relationships because the original derivation was a two-step approach. Toxin data are not collected as part of the long-term Chesapeake Bay routine water quality monitoring program but have been obtained opportunistically with HAB event encounters (Tango and Butler, 2008). Coincident data collection on species composition, chlorophyll *a*, and algal or cyanobacteria toxins remains needed to strengthen the foundation of HAB-based chlorophyll *a* criteria in Chesapeake Bay.

Further challenges to be resolved before adopting a revised bay-wide set of chlorophyll *a* criteria involve the interpretation and application of the recommended values. The multiple approaches used by various authors generated criteria based on means, geometric means, or two-part statistically distribution-based criteria (e.g., mean and 90th percentile that serve as a reference to a desired distribution) (USEPA, 2007b). There are additional suggestions for supporting climate sensitive criteria as illustrated by wet season *vs.* dry season behavior of chlorophyll *a* in Chesapeake Bay (Harding and Perry, 1997; USEPA, 2007b). A program in Virginia is presently underway to reevaluate James River numerical chlorophyll *a* criteria.

SUMMARY

Water quality criteria guidance was developed for Chesapeake Bay providing a stable foundation for more than a decade for their adoption into water quality standards. The water quality standards are science-based support for a decision-making framework defining clear restoration goals, targeting of management actions, assessing progress in the water quality response of bay habitats and the adaptive management process involved in the Bay recovery effort. New science and management insights continue to be considered that may lead to revisions of criteria, criteria assessment protocols, and designated use boundaries supporting review and successful adoption of refinements into water quality standards regulations.

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