chapter vi

Recommended Implementation Procedures

This chapter presents implementation procedures as regional guidance to the Chesapeake Bay watershed states and other agencies, institutions, groups or individuals applying the criteria to determine the degree of attainment. In accordance with Section 117(b)(2)(B)(iii) of the Clean Water Act, these procedures accompany the regional criteria to promote their consistent, baywide application in common tidal-water designated uses across jurisdictional boundaries.

The Chesapeake Bay criteria, as presented in the previous three chapters, will protect designated uses if they are applied strictly following current EPA national guidelines. The regional implementation procedures described in this chapter are tailored to the Chesapeake Bay and its tidal tributaries, the refined tidal-water designated uses and the current and anticipated enhancements to the baywide coordinated monitoring program. Adoption and application of the Chesapeake Bay–specific implementation procedures across jurisdictions will give the states and other partners a greater degree of confidence in assessing the attainment of criteria and protection of designated uses. The extensive shared tidal waters should be assessed consistently across the four jurisdictions using these recommended procedures that account for natural conditions and processes, highlight the magnitude and extent of remaining impairments and provide up-front diagnostics of possible reasons for criteria nonattainment. The EPA strongly encourages states to adopt these implementation procedures into their water quality standards.

The chapter includes:

- A brief review of the criteria, defining the spatial and temporal boundaries within which criteria attainment will be measured;
- A method for quantifying and visualizing the degree of criteria attainment or exceedance that incorporates the amount of area or volume of a region that meets or exceeds a criterion and how often a criterion is met or exceeded;
- A description of successful criteria attainment recognizing that 100 percent attainment is not necessary to protect designated and existing uses;

- A practical description of how monitoring information may be used to assess attainment, including statistical estimation methods for addressing assessment of the short-interval criteria, such as the 7-day mean, 1-day mean and instantaneous minimum dissolved oxygen criteria; and
- A description of how mathematical model-simulated information may be used to assess the effect on future criteria attainment under various nutrient/sediment reduction scenarios, which support decisions on load reductions and caps on loadings to maximize the beneficial effect on attainment.

DEFINING CRITERIA ATTAINMENT

DISSOLVED OXYGEN CRITERIA

The Chesapeake Bay dissolved oxygen criteria were derived to protect species and communities in the five tidal-water designated uses during specific seasons (Table VI-1). See Chapter III for detailed information on the designated use-specific criteria and appropriate periods for applying them. Refer to Appendix A and the *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability* (U.S. EPA 2003) for details on the five designated uses and their boundaries. The Chesapeake Bay dissolved oxygen criteria should not be applied to a designated use or during a period of the year for which they were not specifically derived (see Chapter III).

The EPA expects the states to adopt the full set of dissolved oxygen criteria that will protect the refined tidal-water designated uses, presented in Table VI-1. Given recognized limitations in direct monitoring at the temporal scales required for assessing attainment of the instantaneous minimum, 1-day mean and 7-day mean criteria (see section titled "Monitoring to Support the Assessment of Criteria Attainment" for more details), states can waive attainment assessments for these criteria until monitoring at the required temporal scales is implemented or apply statistical methods to estimate probable attainment. Where sufficient data at these temporal scales exist for specific regions or local habitats, states should assess attainment of the full set of applicable dissolved oxygen criteria.

WATER CLARITY CRITERIA

The Chesapeake Bay water clarity criteria were derived based on the minimum percent light-through-water (PLW) requirements of underwater bay grasses (Table VI-2). These criteria apply only to shallow-water designated use habitats. The water clarity criteria are not intended to apply in areas where underwater bay grasses are precluded from growing by non-water clarity-related factors such as excessive wave action or at depths where natural and other physical habitat factors will prevent sufficient light penetration required by the plants. See Chapter IV for a discussion of the salinity regime-specific criteria and time periods for application. Refer to

Table VI-1. Chesapeake Bay dissolved oxygen criteria.

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use	7-day mean $\geq$ 6 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum $\geq$ 5 mg liter^{-1}	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 $\geq$ 5.5 mg liter^{-1} (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 $\geq$ 5 mg liter^{-1} (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean $\geq$ 4 mg liter^{-1}	Survival of open-water fish larvae.	
	Instantaneous minimum $\geq$ 3.2 mg liter^{-1}	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean $\geq$ 3 mg liter^{-1}	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean $\geq$ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum $\geq$ 1.7 mg liter^{-1}	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 $\geq$ 1 mg liter^{-1}	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 (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

Table VI-2. Summary of Chesapeake Bay water clarity criteria for application to shallow-water bay grass designated use habitats.

Salinity Regime	Water Clarity Criteria as Percent Light-through-Water	Water Clarity Criteria as Secchi Depth								Temporal Application
		Water Clarity Criteria Application Depths								
		0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0	
		Secchi Depth (meters) for above Criteria Application Depth								
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

[1]Based on application of Equation IV-1, PLW = 100exp($-K_dZ$), the appropriate PLW criterion value and the selected application depth are inserted and the equation is solved for K_d. The generated K_d value is then converted to Secchi depth (in meters) using the conversion factor K_d = 1.45/Secchi depth.

Appendix A and U.S. EPA (2003) for broad and detailed descriptions, respectively, of the shallow-water designated use and its boundaries.

The Chesapeake Bay water clarity criteria should not be applied to a designated use or in a period during the year for which they were not derived. The March 1 through May 31 and September 1 through November 30 temporal application for the polyhaline water clarity criteria was originally established for protection of eelgrass (*Zostera marina*) beds (Batiuk et al. 1992). Widgeon grass (*Ruppia maritima*) co-occurs with eelgrass in polyhaline habitats. In shallow-water habitats where both species currently or historically co-occur[1], states and other users should assess water clarity criteria attainment using a March 1 through November 30 or April 1 through October 31 temporal application period.

When the water clarity criteria were derived, there was an insufficient scientific basis for deriving a set of water clarity or related (e.g., total suspended solids) criteria for protection of open-water designated use habitats.

The EPA expects the states to adopt the salinity regime-specific water clarity criteria to protect their shallow-water designated uses, presented in Table VI-2. States are expected to measure the achievement of the shallow-water designated use at the Chesapeake Bay Program segment scale by achieving an established acreage of underwater bay grasses, attainment of the applicable water clarity criteria at an

[1]Maps of the potential and recent distributions of both species were published by Batiuk et al. (1992); see page 125 for eelgrass and page 128 for widgeon grass. Further information on underwater bay grass aerial survey findings on the distribution of these two species can also be found at the Virginia Institute of Marine Science's website at http://www.vims.edu/bio/sav.

established application depth or attainment of the applicable water clarity criteria throughout an established potential shallow-water habitat acreage. The available supporting technical information on segment-specific underwater bay grass acreages, application depths and potential shallow-water habitat acreages are described in the "Monitoring to Support the Assessment of Criteria Attainment," section of this chapter and published in detail in the *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability* (U.S. EPA 2003).

CHLOROPHYLL *A* CRITERIA

Because of the regional and site-specific nature of algal-related water quality impairments, only narrative chlorophyll *a* criteria have been published here. The chlorophyll *a* concentrations tabulated in Chapter V are not numerical EPA criteria. Along with the documented methodologies, they are provided as a synthesis of the best available technical information supporting the states' development and adoption of site-specific numerical chlorophyll *a* criteria or the derivation of numerical translators for their narrative chlorophyll *a* criteria.

The narrative Chesapeake Bay chlorophyll *a* criteria were derived to address the full array of possible impairments, all of which may not manifest themselves within a particular water body at a given time (Table VI-3). The site-specific nature of impairments caused by the overabundance of algal biomass supports the states' adoption of the EPA-recommended narrative criteria, with application of site-specific numeric criteria only for localized waters addressing local algal-related impairments.

The EPA expects states to adopt narrative chlorophyll *a* criteria into their water quality standards for all Chesapeake Bay and tidal tributary waters. The EPA strongly encourages states to develop and adopt site-specific numerical chlorophyll *a* criteria for tidal waters where algal-related impairments persist after the Chesapeake Bay dissolved oxygen and water clarity criteria have been attained.

The formulation and ultimately the assessment of numerical chlorophyll *a* criteria should be based upon seasonal dynamics and concentrations of chlorophyll *a* in the Chesapeake Bay and its tributaries. Spring and summer were chosen for these purposes. Any site-specific numerical impairment-based chlorophyll *a* criteria should be applied as salinity regime-based spring (March through May) and summer (July through September) seasonal mean concentrations.

Table VI-3. Recommended Chesapeake Bay chlorophyll *a* narrative criteria.

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.

ADDRESSING MAGNITUDE, DURATION, FREQUENCY, SPACE AND TIME

To define and measure criteria attainment, a number of factors are taken into account. According to a recent National Research Council (2001) review, establishing the "magnitude, duration and frequency" of a condition is crucial for successful development and application of state water quality standards. Equally important is the spatial extent of a condition, and the spatial and temporal dimensions of attainment assessment must be defined.

Magnitude refers to how much of the pollutant—or a given quantifiable measure of condition—can be allowed while still achieving the designated uses. Magnitude is assessed through a direct comparison of ambient concentrations with the appropriate Chesapeake Bay criterion value. The magnitude of nonattainment of a criterion value also provides information useful to making management decisions on taking corrective actions.

Attainment of all three Chesapeake Bay criteria should be assessed by Chesapeake Bay segment (Figure VI-1; Table VI-4), separately for each designated use habitat. Therefore, each designated use habitat in an individual Chesapeake Bay Program segment is considered a *spatial assessment unit*. This is consistent with the scale of data aggregation and reporting for Chesapeake Bay tidal-water quality monitoring and the physical scale of the designated use areas.

Criteria attainment should be presented in terms of *spatial extent*, i.e., the percentage of the volume (dissolved oxygen) or surface area (water clarity, chlorophyll *a*) of the particular designated use habitat in each Chesapeake Bay Program segment that meets or exceeds the applicable criteria. Measuring spatial extent will be enabled through the use of spatial interpolation methods, which are described later in this chapter. Such 'interpolators' work by dividing a water body into a three-dimensional grid, with cell size depending on data density and the application's resolution requirements, among other factors.

Duration is defined as the period over which exposure to the constituent of concern is to be averaged within the assessment period (see below) to prevent detrimental effects. Duration can also be thought of as the allowable time of exposure before effects occur. For example, the open-water dissolved oxygen criteria includes a criterion with a magnitude of 5 mg liter^{-1} evaluated as a 30-day mean; another criterion has a magnitude of 4 mg liter^{-1} evaluated as a 7-day mean.

The dissolved oxygen, water clarity and chlorophyll *a* criteria are *season-specific,* and attainment should be measured only over the applicable season. For example, attainment of the dissolved oxygen criteria for the migratory fish spawning and nursery designated use should be assessed and reported for the period of February 1 through May 31; attainment of the open-water fish and shellfish designated use criteria, as applied to both open- and shallow-water bay grass designated uses, should be assessed and reported seasonally, in winter (December, January and February), spring (March, April and May), summer (June, July, August and September) and fall (October and November). Tables VI-1 and VI-2 define 'seasons' and applicable criteria for dissolved oxygen and water clarity, respectively. Numerical chlorophyll *a* criteria should be applied to the spring and summer seasons defined previously.

The *assessment period* refers to the most recent three consecutive years for which relevant monitoring data are available. In circumstances where three consecutive years of data are not available, a minimum of three years within the most recent five years should be used.

A three-year period is consistent with the water quality status assessment period used for over a decade by the Chesapeake Bay Program partners (e.g., Alden and Perry 1997). A three-year period includes some natural year-to-year variability largely due to climatic events, and it also addresses residual effects of one year's conditions on succeeding years. Two years is not enough time to assess central tendency, and four or more years delay response to problems that may be detected. Longer periods are more appropriate for detecting trends than for characterizing current water quality conditions.

A comparison of criteria attainment across one-, three- and five-year assessment periods confirmed the selection of three years as the appropriate temporal averaging period. Attainment levels were highly variable using single-year periods. The five-year period smoothed much of the variability and resulted in little difference between one assessment period and the next.

The allowable *frequency* at which the criterion can be violated without a loss of the designated use also must be considered. Frequency is directly addressed through comparison of the generated cumulative frequency distribution with the applicable criterion reference curve. All values falling below the reference curve are considered biologically acceptable exceedances of the applicable Bay criteria. Through its derivation, the reference curve directly incorporates a biologically acceptable frequency of exceedances of the applicable Chesapeake Bay criteria.

By combining these factors to measure attainment, the spatial extent of violation or attainment of the criterion can be determined for each designated use within each Chesapeake Bay Program segment at temporal increments defined by the criterion. As the next section describes, the frequency of these occurrences is tallied for each season over the assessment period.

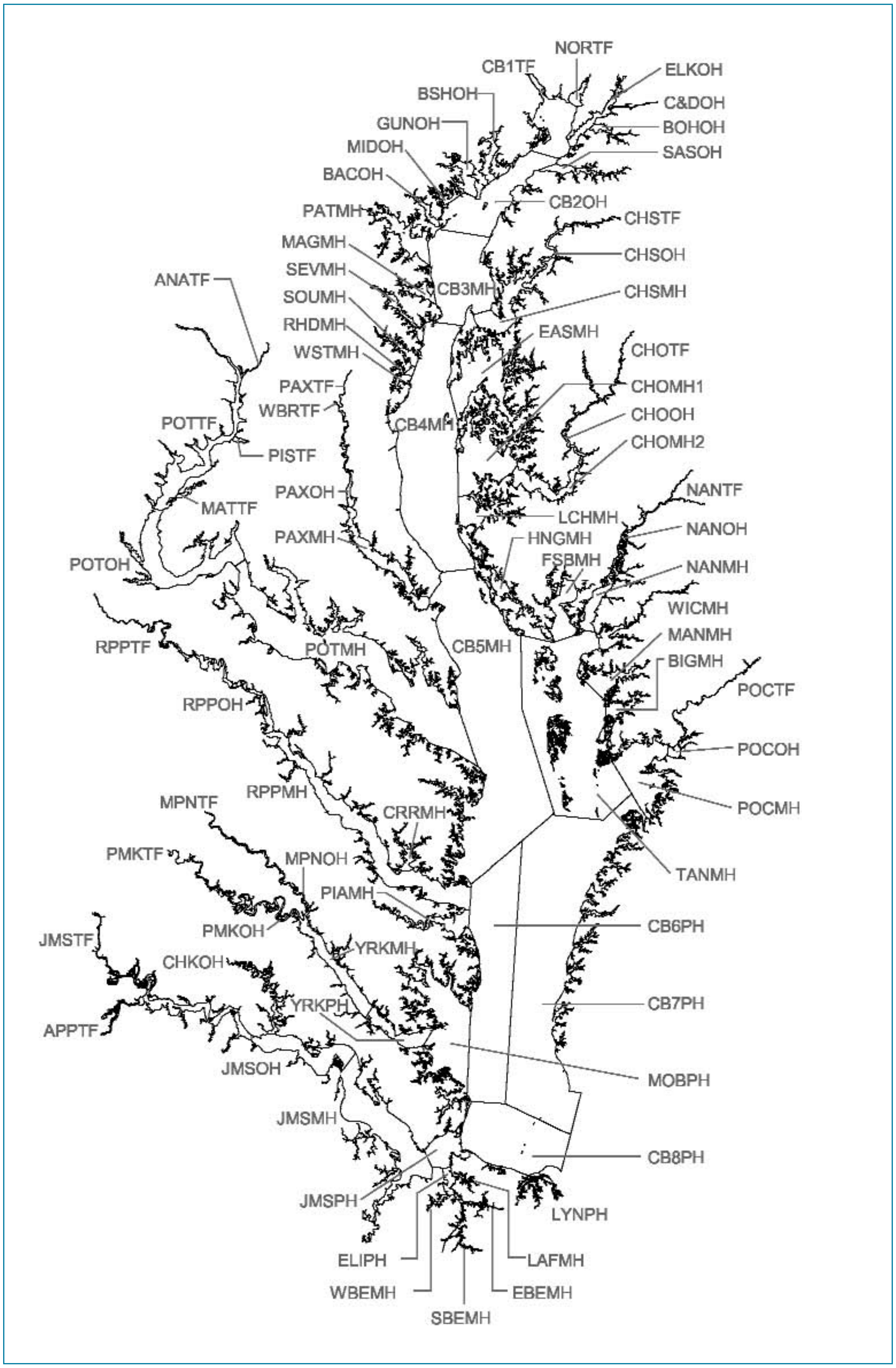

Figure VI-1. The geographical location of the 78 Chesapeake Bay Program segments.

Source: Chesapeake Bay Program 1999.

Table VI-4. Chesapeake Bay Program segmentation scheme segments.

Northern Chesapeake Bay	CB1TF	Mobjack Bay	MOBPH
Upper Chesapeake Bay	CB2OH	Upper James River	JMSTF
Upper Central Chesapeake Bay	CB3MH	Appomattox River	APPTF
Middle Central Chesapeake Bay	CB4MH	Middle James River	JMSOH
Lower Central Chesapeake Bay	CB5MH	Chickahominy River	CHKOH
Western Lower Chesapeake Bay	CB6PH	Lower James River	JMSMH
Eastern Lower Chesapeake Bay	CB7PH	Mouth of the James River	JMSPH
Mouth of Chesapeake Bay	CB8PH	Western Branch Elizabeth River	WBEMH
Bush River	BSHOH	Southern Branch Elizabeth River	SBEMH
Gunpowder River	GUNOH	Eastern Branch Elizabeth River	EBEMH
Middle River	MIDOH	Lafayette River	LAFMH
Back River	BACOH	Mouth to mid-Elizabeth River	ELIPH
Patapsco River	PATMH	Lynnhaven River	LYNPH
Magothy River	MAGMH	Northeast River	NORTF
Severn River	SEVMH	C&D Canal	C&DOH
South River	SOUMH	Bohemia River	BOHOH
Rhode River	RHDMH	Elk River	ELKOH
West River	WSTMH	Sassafras River	SASOH
Upper Patuxent River	PAXTF	Upper Chester River	CHSTF
Western Branch Patuxent River	WBRTF	Middle Chester River	CHSOH
Middle Patuxent River	PAXOH	Lower Chester River	CHSMH
Lower Patuxent River	PAXMH	Eastern Bay	EASMH
Upper Potomac River	POTTF	Upper Choptank River	CHOTF
Anacostia River	ANATF	Middle Choptank River	CHOOH
Piscataway Creek	PISTF	Lower Choptank River	CHOMH1
Mattawoman Creek	MATTF	Mouth of the Choptank River	CHOMH2
Middle Potomac	POTOH	Little Choptank River	LCHMH
Lower Potomac	POTMH	Honga River	HNGMH
Upper Rappahannock River	RPPTF	Fishing Bay	FSBMH
Middle Rappahannock River	RPPOH	Upper Nanticoke River	NANTF
Lower Rappahannock River	RPPMH	Middle Nanticoke River	NANOH
Corrotoman River	CRRMH	Lower Nanticoke River	NANMH
Piankatank River	PIAMH	Wicomico River	WICMH
Upper Mattaponi River	MPNTF	Manokin River	MANMH
Lower Mattaponi River	MPNOH	Big Annemessex River	BIGMH
Upper Pamunkey River	PMKTF	Upper Pocomoke River	POCTF
Lower Pamunkey River	PMKOH	Middle Pocomoke River	POCOH
Middle York River	YRKMH	Lower Pocomoke River	POCMH
Lower York River	YRKPH	Tangier Sound	TANMH

Source: Chesapeake Bay Program 1999.

DEVELOPING THE CUMULATIVE FREQUENCY DISTRIBUTION

The use of cumulative frequency distributions (CFDs) is recommended for assessing spatial and temporal water quality criteria exceedance in the Chesapeake Bay. CFDs offer a number of advantages over other techniques that are applied for this purpose. First, the use of CFDs is well established in both statistics and hydrologic science. CFDs have been used for much of the past century to describe variations in hydrologic assessments (Haan 1977). For example, the U.S. Geological Survey has traditionally used CFDs to describe patterns in historical streamflow data for the purpose of evaluating the potential for floods or droughts (Helsel and Hirsch 1992).

Second, the application of the CFD for evaluating water quality criteria attainment in the Chesapeake Bay allows for the evaluation of both spatial and temporal variations in criteria exceedance. Methods currently used for the assessment of criteria attainment are based only on temporal variations because measurements are usually evaluated only at individual monitoring station locations. One of the limitations of this approach is that it is often difficult to determine whether an individual sampling location is representative, and there is always potential for bias. In a water body the size of the Chesapeake Bay, accounting for spatial variation can be very important and in that respect, the CFD approach represents a significant improvement over methods used in the past.

A CFD is developed first by quantifying the spatial extent of criteria exceedance for every monitoring event during the assessment period. Compiling estimates of spatial exceedance through time accounts for both spatial and temporal variation in criteria exceedance. Assessments are performed within spatial units defined by the intersection of Chesapeake Bay Program segments (see Figure VI-1) and the refined tidal-water designated uses (see U.S. EPA 2003 for specific boundaries), and temporal units of three-year periods. Thus, individual CFDs will be developed for each spatial assessment unit over three-year assessment periods. Details on the steps involved in developing CFDs are described below.

STEP 1. INTERPOLATION OF WATER QUALITY MONITORING DATA

The Chesapeake Bay Program partners collect monitoring data over a range of spatial scales and frequencies. Much of the water quality monitoring data collected in the Chesapeake Bay and its tidal tributaries is drawn from a limited number of fixed stations that are visited on a monthly (or more frequent) basis. Other types of data are collected at different spatial frequencies. For example, some chlorophyll *a* data are collected in a spatially continuous in-situ manner along the cruise tracks of monitoring vessels. All of the different types of data are useful for assessing criteria attainment; however, they must be connected to a single spatial framework in order to provide a common basis for interpretation. Assessment of criteria attainment requires that conclusions be drawn for all locations within a spatial unit and not just the locations where data may have been collected. Thus, the data must be extrapolated in order to evaluate criteria attainment for the larger spatial unit that the data represent.

For the Chesapeake Bay and its tidal tributaries, using a grid-based spatial interpolation software provides a common spatial framework and spatial extrapolation. Spatial interpolation provides estimates of water-quality measures for all locations within a spatial assessment unit. This is accomplished at any single location by linear interpolation of the data of all its nearest neighbors. This approach provides an estimate of the water quality measure at all locations within the spatial unit being considered.

An example of the use of spatial interpolation is illustrated in Figure VI-2, which displays the monitoring segment boundaries and fixed-station locations in the area

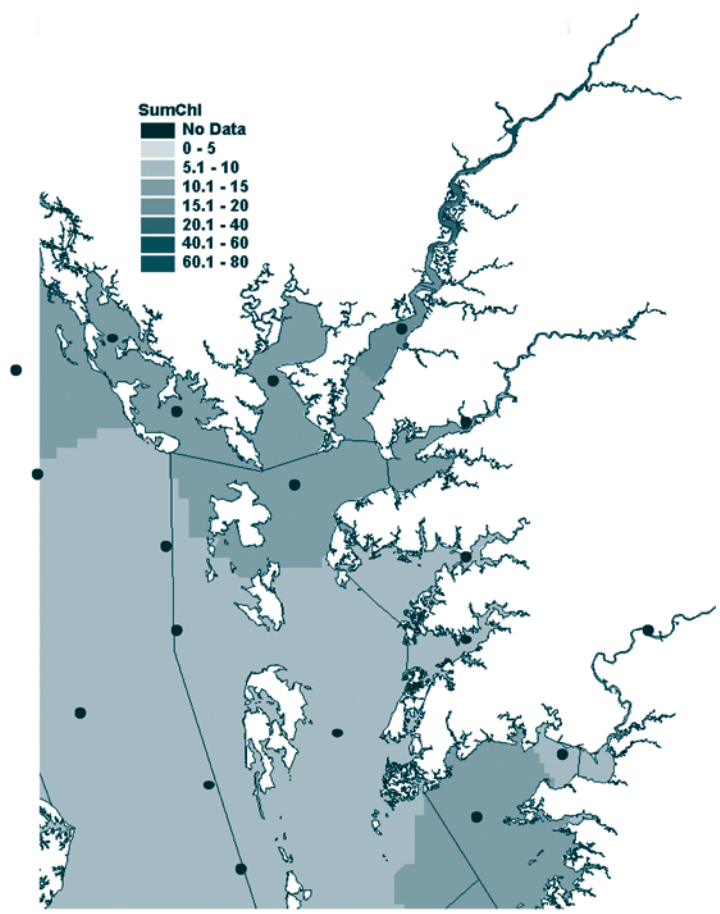

Figure VI-2. Chesapeake Bay Program segment boundaries, fixed monitoring station locations and summer chlorophyll *a* concentration (μg liter^{-1}) distribution in the Tangier Sound area of the Eastern Shore of Maryland and Virginia. Summer chlorophyll *a* concentration distribution is defined by spatial interpolation.

around Tangier Sound and the adjacent portion of the Eastern Shore of Maryland and Virginia. Using spatial interpolation, chlorophyll *a* concentrations were estimated for all locations in the Tangier Sound area. Based on those estimates, the spatial distribution of chlorophyll *a* is illustrated by shading the area according to the estimated concentration (darker shading represents higher chlorophyll *a* concentrations). The results illustrate the spatial gradients that tend to occur throughout an area of this size. Those gradients need to be accounted for in order to accurately assess the extent of criteria exceedance.

The Chesapeake Bay Program spatial-interpolation software (or 'CBP interpolator') computes water quality concentrations throughout the Chesapeake Bay and its tidal tributaries from measurements collected at point locations or along cruise tracks (Bahner 2001). It estimates water quality concentrations at all locations in a two-dimensional area or in a three-dimensional volume. The CBP interpolator is cell-based. Fixed cell locations are computed by interpolating the nearest number (*n*) of neighboring water quality measurements, where *n* is normally 4, but is adjustable. Typically an interpolation is performed for the entire Chesapeake Bay for a single monitoring event (e.g., a monthly cruise). In this way all monitoring stations are used to develop a baywide picture of the spatial variation of the parameter being considered. Segment and designated use boundaries can then be superimposed over the baywide interpolation to assess the spatial variation of the parameter in any one segment's designated use(s).

Cell size in the Chesapeake Bay was chosen to be 1 kilometer (east-west) by 1 kilometer (north-south) by 1 vertical meter, with columns of cells extending from the surface to the bottom of the water column, thus representing the three-dimensional volume as a group of equal-sized cells. The tidal tributaries are represented by various cell sizes, depending on the geometry of the tributary, since the narrow upstream portions of the tidal rivers require smaller cells to represent the river's dimensions accurately. This configuration results in a total of 51,839 cells for the mainstem Chesapeake Bay and a total of 238,669 cells for the Chesapeake Bay and its tidal tributaries.

The CBP interpolator is tailored for use in the Chesapeake Bay in that the code is optimized to compute concentration values that closely reflect the physics of stratification. The Chesapeake Bay is very shallow despite its width and length; hence water quality varies much more vertically than horizontally. The CBP interpolator uses a vertical filter to select the vertical range of data for each calculation. For instance, to compute a model cell value at 5-meters deep, monitoring data at 5 meters are preferred. If fewer than *n* (4) monitoring data values are found at the preferred depth, the depth window is widened to search up to *d* (normally ± 2 m) meters above and below the preferred depth, with the window being widened in 0.5-meter increments until *n* monitoring values have been found for the computation. The user is able to select the smallest *n* value that is acceptable. If fewer than *n* values are located, a missing value (normally a -9) is calculated for that cell.

A second search radius filter is used to limit the horizontal distance of monitoring data from the cell being computed. Data points outside the radius selected by the user (normally 25,000 meters) are excluded from calculation. This filter is included so that only data near a specific location are used for interpolation. In the current version of the CBP interpolator, segment and region filters have been added (Bahner 2001).

The Chesapeake Bay Program segments are geographic limits for interpolation. For instance, the mainstem Chesapeake Bay is composed of eight segments (see Figure VI-1 and Table VI-4). The tidal tributaries are composed of 70 additional segments, using the Chesapeake Bay Program 1998 segmentation scheme (CBP 1999). Each segment represents a geographic area that has somewhat homogeneous environmental conditions. Segmentation enables users to report findings on a segment-by-segment basis, which can reveal localized changes compared to the entire Chesapeake Bay ecosystem.

As stated above, the CBP interpolator uses monitoring data to fill in the three-dimensional space of the Chesapeake Bay. The CBP interpolator assumes a linear distribution of the data between points. Given the dynamic nature of estuaries, this is obviously a conservative assumption. However, the spatial limitations of the data make the simplest approach the most prudent. The strength of the CBP interpolator's output is directly related to the quality and spatial resolution of the input data. As sample size increases, interpolation error decreases. For more detailed documentation on the Chesapeake Bay Program interpolator and access to a downloadable version, refer to the Chesapeake Bay Program web site at http://www.chesapeakebay.net/tools.htm.

STEP 2. COMPARISON OF INTERPOLATED WATER QUALITY MONITORING DATA TO THE APPROPRIATE CRITERION VALUE

To quantify the spatial extent of criteria exceedance, the interpolated water quality monitoring data must be compared to the appropriate criteria value. In all cases, the water quality criteria are defined within specific spatial limits and with varying spatial values. In order to define the spatial extent of criteria exceedance, the appropriate criteria values must be aligned with the water quality measures throughout the spatial assessment unit. Accordingly, the spatial definition of each criterion is superimposed on the interpolator grid structure to assign a criteria value to each cell. Criteria assessments can then be made on a cell-by-cell basis using the water quality estimate from the interpolator and the criteria value defined for each cell. Figure VI-3 illustrates a schematic of the process for spatially defined criteria assessment. Chlorophyll *a* estimates generated from the interpolator (such as that for Tangier Sound, Figure VI-2) are combined with the grid-based definition of criteria values. The integration of those two layers allows the comparison of 'measured' chlorophyll *a* to the applicable criteria value in each cell to determine if that cell exceeds the criterion for the time period for which data were collected (Figure VI-3).

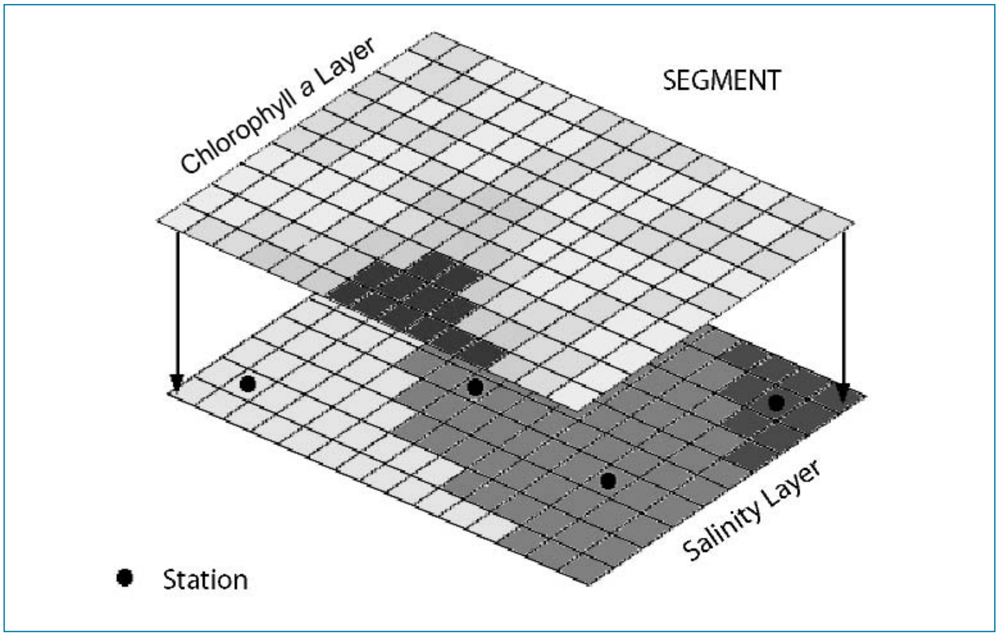

Figure VI-3. Chlorophyll *a* concentration values estimated for each interpolator cell are compared to the appropriate criterion value on a cell-by-cell basis to determine the spatial extent of exceedance.

STEP 3. IDENTIFICATION OF INTERPOLATOR CELLS THAT EXCEED THE CRITERION VALUE

When the appropriate criterion value has been assigned to each interpolator cell, comparisons can be made on a cell-by-cell basis to determine if the estimated water quality values met or exceeded the criteria at the time of the monitoring event. Evaluation of criteria exceedance is performed for each cell in a spatial unit (Figure VI-4a), enabling the entire spatial unit to be characterized. The percentage of cells that exceed the criteria represents the spatial extent of exceedance in that spatial unit and for that sampling event. The same process is repeated for every sampling event (Figure VI-4b) and the compilation of the estimates of the extent of spatial exceedance provides an indication of the frequency of exceedance.

STEP 4. CALCULATION OF THE CUMULATIVE PROBABILITY OF EACH SPATIAL EXTENT OF EXCEEDANCE

The spatial extent of exceedance (represented by the colored cells in Figure VI-4) is calculated as the percentage of area or volume exceeding the criteria. This is accomplished by simply dividing the area or volume of all the cells exceeding the criteria by the total area or volume of the spatial assessment unit and multiplying by 100.

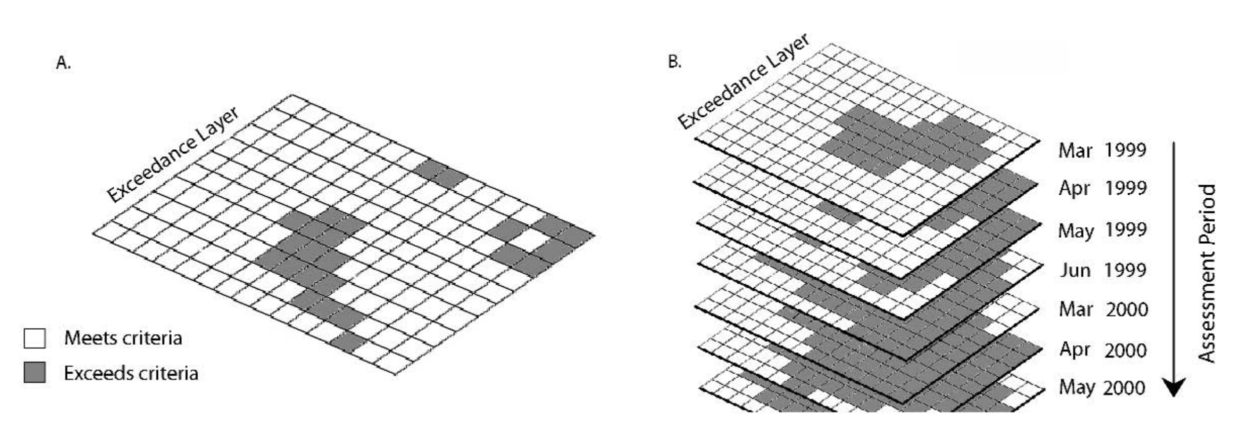

Figure VI-4. For a given sampling event, cells that exceed the criterion are determined by comparing the interpolator estimated water quality value in each cell (e.g., chlorophyll *a*) to the appropriate criterion value (a) as in Figure VI-3. The same process is repeated for each sampling event through the assessment period (b).

The development of CFD is based on the estimates of spatial exceedance percentages for all monitoring events conducted during the assessment period (Figure VI-5).

CFDs are based on the concept of 'cumulative frequency,' where each observed value is assigned a probability that represents the potential for observing a lower value. To calculate cumulative frequency, data are sorted in ascending order and then ranked. This approach is typically used for evaluating streamflow data (Helsel and Hirsch 1992). It is similar to that used in assessing water quality criteria except that the values are ranked in descending order (Figure VI-5), because the interest lies in the potential for observing a spatial exceedance rate greater, not less, than the one observed.

Once the data are sorted and ranked, the cumulative probability is calculated using a 'plotting position' formula (Helsel and Hirsch 1992). The Weibull formula, rank/(n+1), developed by Weibull (1939) was chosen as the simplest and most commonly used; there is a strong precedent for the use of this formula in the hydrologic literature (Helsel and Hirsch 1992).

Figure VI-6 summarizes the results of the calculations for the development of the CFD. Cumulative probability represents the frequency of occurrence of each value of spatial exceedance or a greater value. For example, more than 50 percent spatial exceedance was observed 46 percent of the time. At the lower end of the plot, the point (100, 0) is included because more than 100 percent of the area or volume will be in exceedance 0 percent of the time. At the upper end of the plot, the point (0, 100) was included because 0 percent of the area or volume will be in exceedance more that 100 percent of the time.

a.

Month	Percent Area/ Volume
March 1998	72
April 1998	55
May 1998	65
June 1998	75
March 1999	49
April 1999	34
May 1999	67
June 1999	25
March 2000	20
April 2000	39
May 2000	35
June 2000	50

b.

Month	Percent Area/ Volume	Rank
June 1998	75	1
March 1998	72	2
May 1999	67	3
May 1998	65	4
April 1998	55	5
June 2000	50	6
March 1999	49	7
April 2000	39	8
May 2000	35	9
April 1999	34	10
June 1999	25	11
March 2000	20	12

Figure VI-5. To develop a CFD for an area/volume, estimates of spatial extent of criteria exceedance for all of the sampling events conducted over a three-year assessment period (See Figure VI-4b) are compiled (a). To prepare for developing the CFD the estimates of spatial extend of exceedance are sorted in descending order (b) and ranked.

a.

Month	Percent Area/ Volume	Rank
June 1998	75	1
March 1998	72	2
May 1999	67	3
May 1998	65	4
April 1998	55	5
June 2000	50	6
March 1999	49	7
April 2000	39	8
May 2000	35	9
April 1999	34	10
June 1999	25	11
March 2000	20	12

b.

Month	Percent Area/ Volume	Rank	Cumulative Probability [Rank/(n+1)]
	100		0.00%
June 1998	75	1	7.69%
March 1998	72	2	15.38%
May 1999	67	3	23.08%
May 1998	65	4	30.77%
April 1998	55	5	38.46%
June 2000	50	6	46.15%
March 1999	49	7	53.85%
April 2000	39	8	61.54%
May 2000	35	9	69.23%
April 1999	34	10	76.92%
June 1999	25	11	84.62%
March 2000	20	12	92.31%
	0		100.00%

Figure VI-6. To develop a CFD, estimates of spatial extent of criteria exceedance for all of the sampling events conducted over a three-year assessment period (see Figure VI-4) are compiled, sorted in descending order and ranked (a). Cumulative probability is calculated using the formula 'rank/(n+1)' (b).

STEP 5. PLOT OF SPATIAL EXCEEDANCE VS. THE CUMULATIVE FREQUENCY

The CFD is a graphical illustration that summarizes criteria exceedance by plotting the temporal and spatial exceedance values listed in Figure VI-6. Temporal frequency of exceedance is plotted on the vertical axis and spatial extent of exceedance on the horizontal axis (Figure VI-7). The resulting figure can be used to draw conclusions about the extent and pattern of criteria exceedance. Each point on the curve represents the cumulative amount of space and time in which the criteria were exceeded. The potential for observing a spatial extent of exceedance greater than the one observed is indicated by the temporal frequency. The curve in Figure VI-7 shows two examples of the interpretations of individual points. In addition to the interpretation of individual point, the area beneath the curve represents a spatial and temporal composite index of criteria exceedance. This area is recommended as the basis for defining criteria attainment for all Chesapeake Bay segments and designated uses.

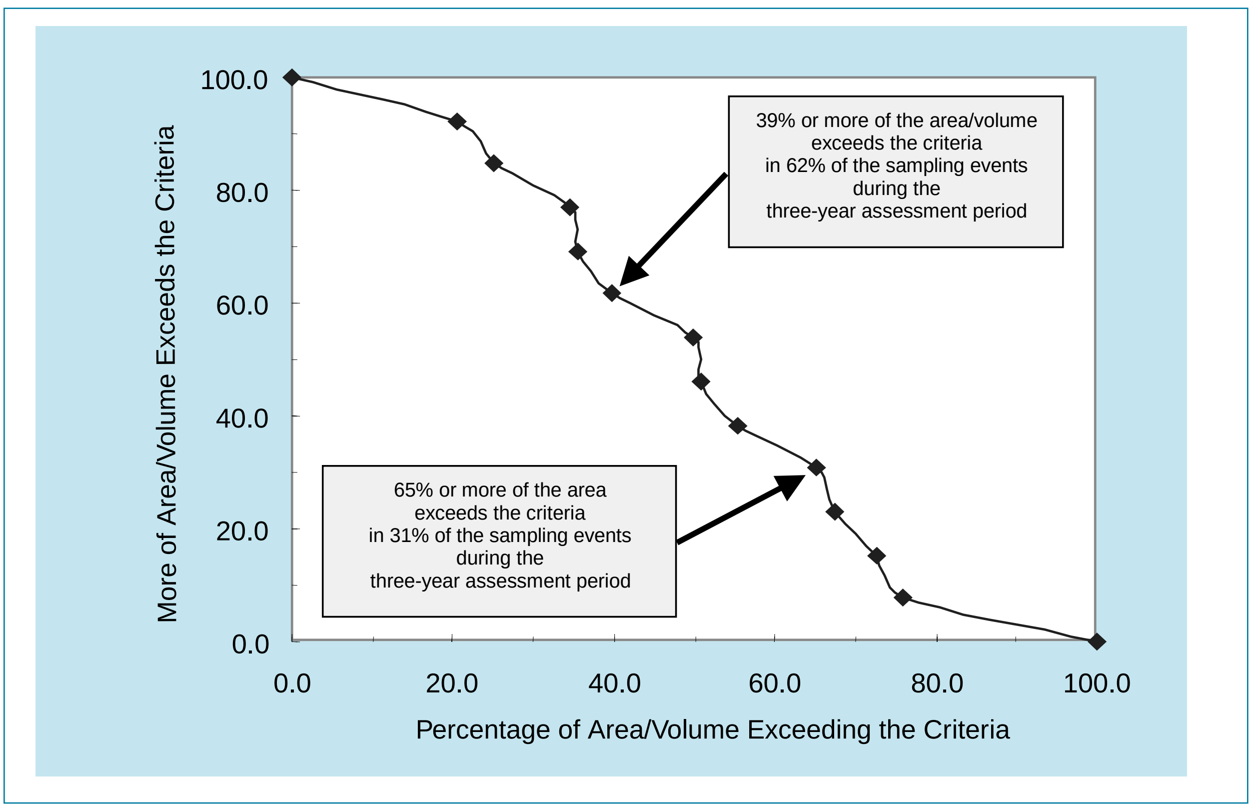

Figure VI-7. The horizontal axis is the spatial extent of criteria exceedance based on monitoring data extrapolated using spatial interpolation. The vertical axis is the cumulative frequency of criteria exceedance for the monitoring events conducted during the assessment period.

The shape of the curve also indicates the spatial and temporal pattern of criteria exceedance. Figure VI-8 illustrates three potentially observable CFD plots. Curve (a) indicates a situation in which the water quality criteria are chronically exceeded in a relatively small amount of a given segment. Managers could use this information to target segments for further monitoring and assessment and to identify chronic problems and tailor management plans to address them. Curve (b) illustrates a situation where criteria are exceeded on a broad spatial scale, but relatively infrequently. Such broad-scale acute problems should be evaluated individually. If the frequency and duration of broad-scale criteria exceedances were low enough, ecological impacts could be limited. On the other hand, some short-term exceedances can have significant ecological effects. Curves (a) and (b) reflect a similar degree of overall criteria exceedance; however, the exceedance of curve (a) is primarily temporal, and the exceedance of curve (b) is primarily spatial. Curve (c) reflects broad-scale criteria exceedance in both space and time. The shape of the curves should be used for diagnostic purposes only. Decisions regarding full attainment should be based on the overall amount of criteria exceedance indicated by the area under the curve.

As discussed above, it is possible that some spatial and temporal criteria exceedances could be observed, without necessarily having significant effects on ecological health or on the designated use of a portion of the Chesapeake Bay. Such exceedances are referred to as ‘allowable exceedances.’ Such exceedances have been

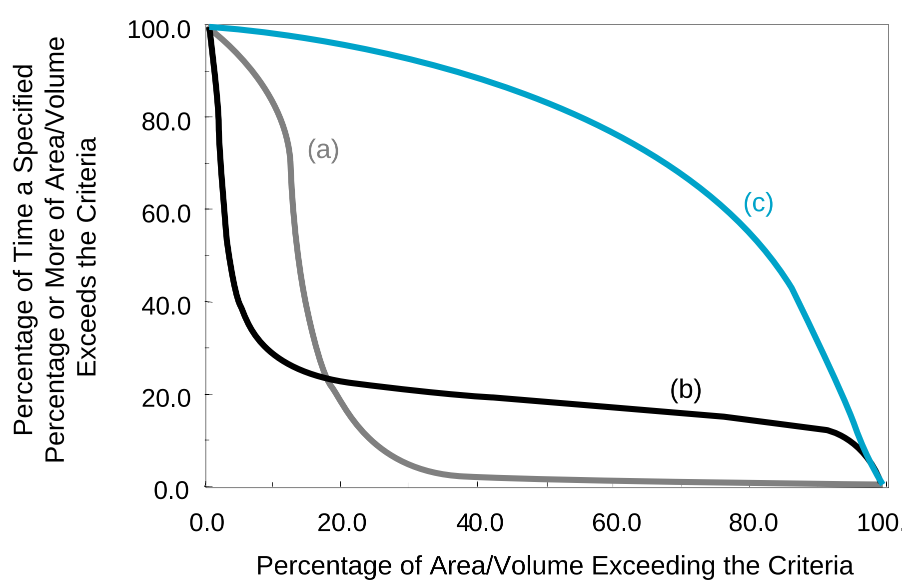

Figure VI-8. Use of cumulative frequency distribution to characterize patterns of water quality criteria exceedance. Curve (a) indicates that criteria are chronically exceeded in a relatively small portion of the spatial unit. Curve (b) indicates that criteria are exceeded over a large portion of the spatial unit on a relatively infrequent basis. Curve (c) indicates that criteria are exceeded over large portions of space and time.

provided for in EPA national guidance for assessing criteria attainment (U.S. EPA 1997). Ten percent of the samples collected at a point are allowed to reflect nonattainment of water quality criteria without indicating nonattainment of designated uses. These criteria exceedances are considered 'allowable exceedances' that had limited impact on the designated use. The 10-percent rule is not directly applicable in the context of the CFD methodology for defining criteria attainment because it was designed for samples collected at one location and, therefore, is only reflective of time.

A more appropriate approach for defining 'allowable exceedances' in the CFD context is to develop a reference curve (described below) that identifies the amount of spatial and temporal criteria exceedance that can occur without causing significant ecological degradation. Such curves can be based on biological indicators of ecological health that are separate from the criteria measures themselves. Biological indicators can be used to identify areas of the Chesapeake Bay and its tidal tributaries that have healthy ecological conditions and supportive water quality conditions. CFDs can be developed for those areas as well. Since healthy ecological conditions exist in the selected areas, CFDs developed for the area would reflect an extent and pattern of criteria exceedance that did not have significant ecological impact. Thus, the reference curve approach takes the development of criteria levels beyond those developed in a laboratory setting and provides actual environmental context. Small incidents of spatial and temporal criteria exceedance that do not have ecological impacts are identified and allowed in the assessment of criteria attainment. A description of the application of the reference curve is provided in this section, with more details on reference curves in the section titled "Defining the Reference Curve."

Figure VI-9 illustrates the use of the reference curve and the interpretation of criteria attainment using the CFD. The light blue line illustrates a possible reference curve, below which a certain amount of spatial or temporal exceedance is allowed. An actual reference curve could be asymmetrical, indicating that the system could withstand either short-term excursions in time or chronic exceedances in small portions of space, but not both.

Development of the reference curve is intended to identify such specifics to more accurately reflect what the ecological system needs to thrive. It also is intended to be developed as a benchmark that is not changed on a regular basis, recognizing the potential for updates as new information is gathered. By contrast, the attainment curve is developed over every assessment period during which monitoring data are collected.

The attainment curve is the assessment of the condition in the segment during the assessment period and is compared to the reference curve. The area above the reference curve and below the attainment curve reflects criteria attainment and is referred to as "non-allowable exceedances." It is recommended that separate attainment curves be developed for each criteria component, for subsequent application in every spatial assessment unit (Chesapeake Bay Program segment/designated use) and for at least one full assessment period of three years.

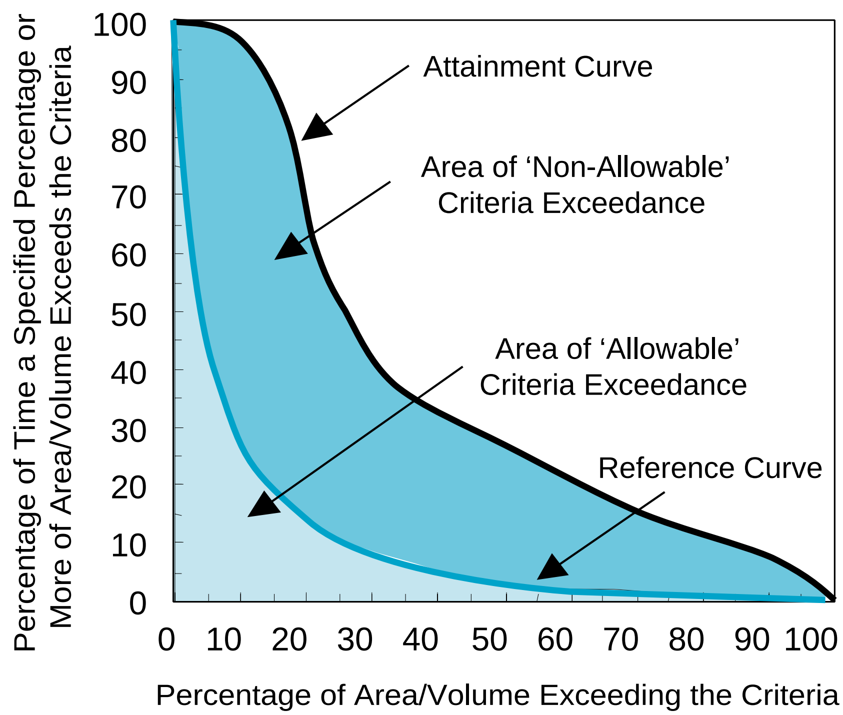

Figure VI-9. Light area reflects amount of 'allowable' criteria exceedance defined as the area under the reference curve (light line). Dark area reflects the amount of 'non-allowable' criteria exceedance defined as the area between the attainment curve (black line) and the reference curve.

In cases where the amount of 'non-allowable exceedances' is large (e.g., Figure VI-8, line c; Figure VI-9), decisions regarding the attainment of designated uses will be unequivocal. However, situations could arise where small amounts of non-allowable exceedance could render the decisions less clear. Figure VI-10 illustrates a situation in which a decision on nonattainment might be clear (a) and one in which the decision might be less clear (b). In the latter case, questions could arise about the certainty of the analysis and whether the data were adequate to unequivocally decide that the portion of the Chesapeake Bay was not attaining its designated use. In some cases, many data points could have contributed to the development of the CFD, whereas in other cases there may have been only a few. It is possible to define the decision rule that any non-allowable exceedance would indicate nonattainment of the established designated use. However, a decision rule based on a statistical test could help to address some of the uncertainty involved by accounting for differences in the number of observations on which the analysis is based.

Work is currently under way to devise a statistical test for the application of CFDs to assess water quality criteria attainment in the Chesapeake Bay. The test currently

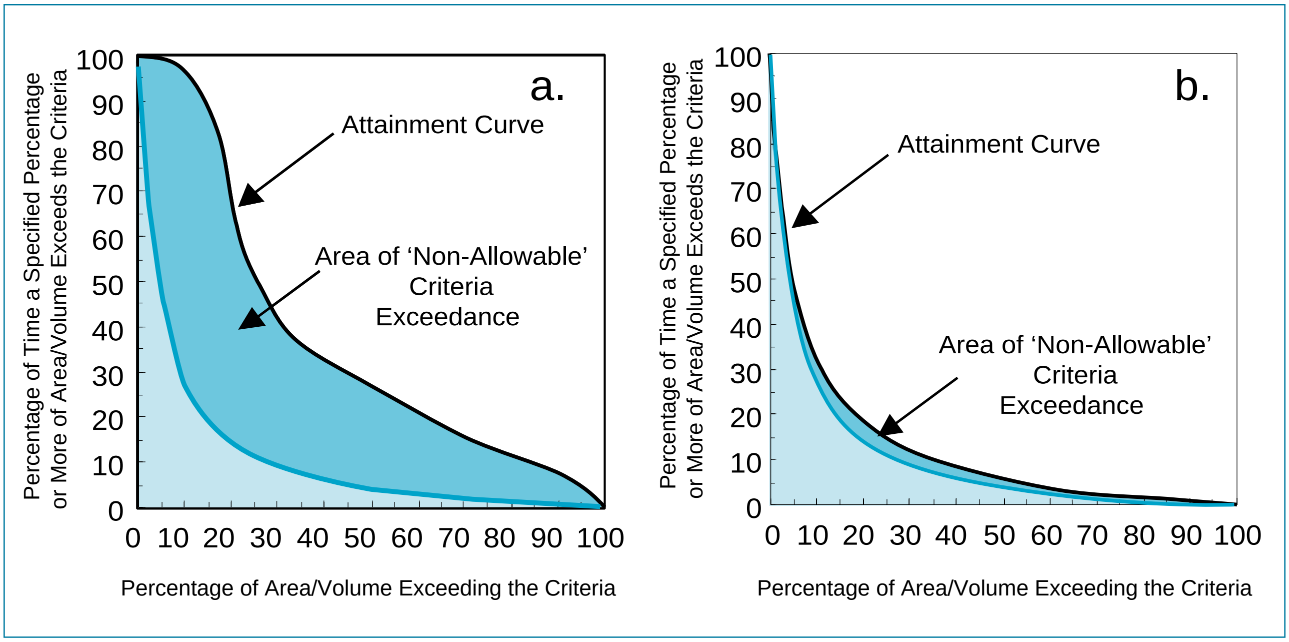

Figure VI-10. Light area reflects amount of 'allowable' criteria exceedance defined as the area under the reference curve (light line). Dark area reflects the amount of 'non-allowable' criteria exceedance defined as the area between the attainment curve (black line) and the reference curve.

being evaluated and refined is the Kolmogorov-Smirnov (KS) test, which was originally developed to test for significant differences between cumulative density functions (Haan 1977). The KS test is nonparametric and is based on the maximum difference between curves (Figure VI-11). The maximum difference is somewhat different than the area between the curves, which is the preferred indicator for assessing attainment. However, it can be shown that the maximum difference and the area between the curves are closely correlated and, therefore, evaluation of one will reflect an evaluation of the other.

The KS test is well-documented and accepted in the statistical literature. Some refinements that may be necessary are currently being evaluated. Overall, however, the KS test has a strong potential for evaluating water quality criteria attainment in the Chesapeake Bay.

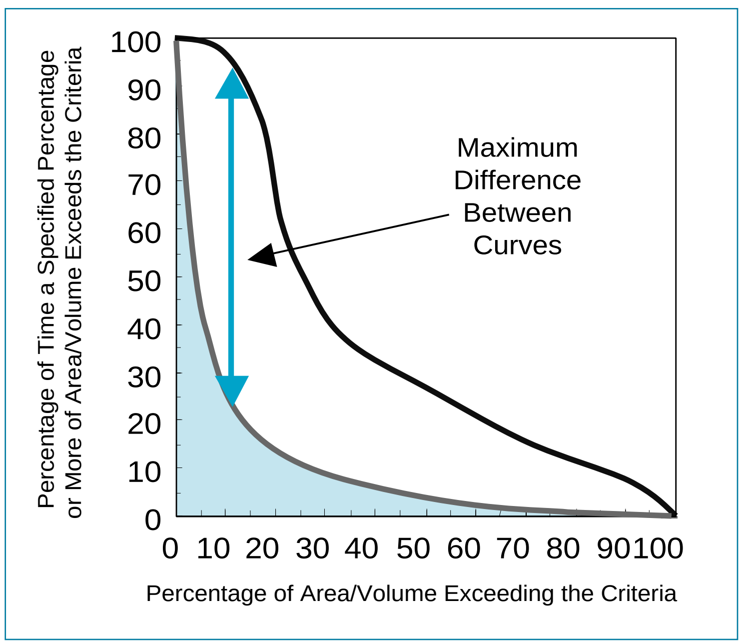

Figure VI-11. Illustration of the basis of the Kolmogorov-Smirnov statistical test for identifying statistically significant differences between cumulative density functions. In this case, the test is applied to identify statistically significant differences between the reference and attainment curves.

DIAGNOSING THE MAGNITUDE OF CRITERIA EXCEEDANCE

The CFD is a useful tool for evaluating water quality criteria attainment, but it is based on pass/fail principles and provides no information on the magnitude of criteria exceedance, which would interest managers, because it indicates how much effort is needed to correct any impairment. To fill this need and provide supporting information for the CFD, it is recommended that interpolator plots be generated for each monitoring event conducted during an assessment period. Viewed either individually or as a movie, interpolator plots will shed light on the magnitude of exceedance during the assessment period.

Two types of interpolator plots are useful for this purpose. The first is the basic interpolator plot of the criteria parameter (i.e., concentration for dissolved oxygen and chlorophyll *a*, and percent light-through-water for water clarity; Figure VI-12). Such

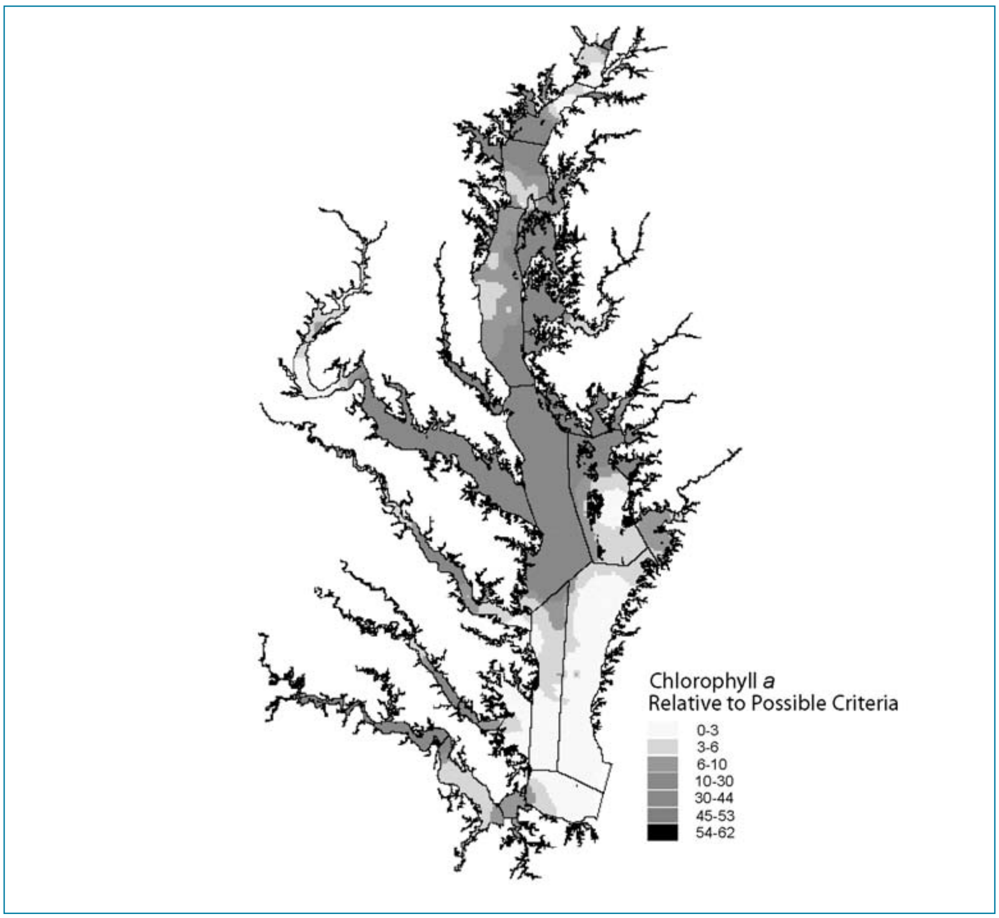

Figure VI-12. Example plot of chlorophyll *a* concentration (μg liter^{-1}) estimates generated through spatial interpolation for purposes of evaluating the magnitude of criteria exceedance.

plots show problem areas and indicate their distance from criteria attainment. However, they are limited in evaluating the overall picture of magnitude of criteria exceedance for the entire Chesapeake Bay. Criteria values vary spatially and thus the magnitude of exceedance will depend on both actual interpolator values and the criteria values themselves. To address this need, a second set of interpolator plots illustrating the magnitude of exceedance as a percentage of the criteria values themselves should be generated (Figure VI-13). Any estimated values below the criteria level will be less than one and bounded at zero, whereas estimated values above the criteria level will be in percentage of criteria level.

Other information is available to evaluate the significance of the criteria attainment assessment results and to place them in context. This includes the size of the designated use (as surface area or volume) and the percentage of the total habitat that is represented by the designated use. This particular data is especially useful for dissolved oxygen criteria attainment assessment. The information is used to understand the relative percentage of the total habitat that is accounted for by the

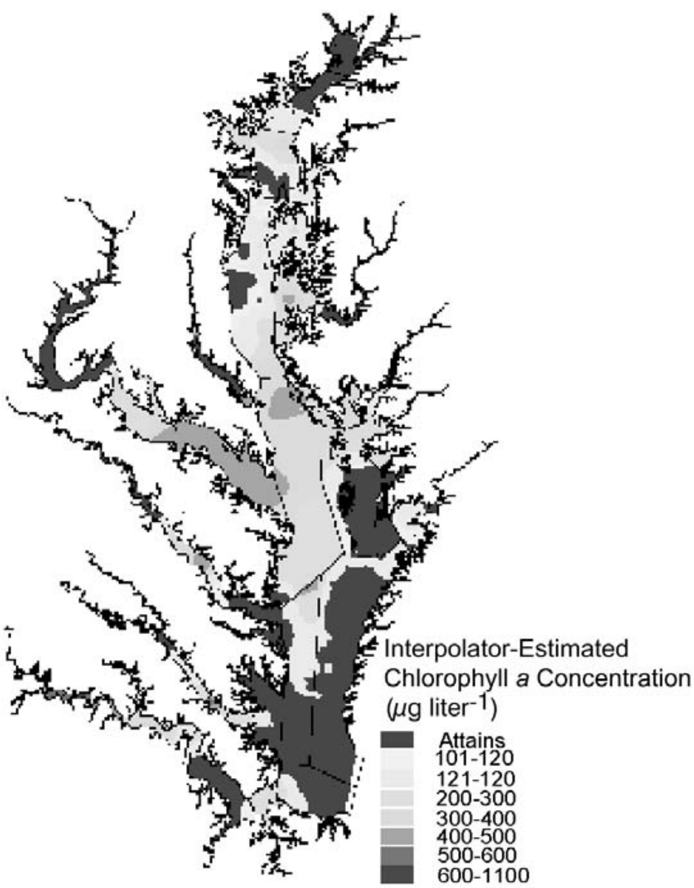

Figure VI-13. Example plot of chlorophyll *a* concentration (µg liter^{-1}) estimates generated through spatial interpolation, expressed as a percentage of a possible spring season criteria value, for purposes of evaluating the magnitude of criteria exceedance.

open-water, deep-water or deep-channel designated use habitats in the entire water column. For example, if the deep-water use was found in nonattainment at a rate of 50 percent but only accounted for 10 percent of the total habitat of the water column, the management actions taken in response would differ from those taken if the deep-water use accounted for 75 percent of the total habitat. This may prove to be a useful, additional source of data when difficult decisions must be made.

DEFINING THE REFERENCE CURVE

The recommended criteria attainment assessment approach is designed to protect the living resources as defined by the designated uses. The criteria levels themselves were largely based on scientific studies performed in laboratory settings or under controlled field conditions. The criteria establish the level of a given habitat condition that living resources need for survival. They do not account for many other environmental factors that could affect survival.

Reference curves were developed to provide a scientific-based, direct measure of the 'allowable' criteria exceedances. These exceedances are defined to be those that last a short enough time or cover a small enough area to have no adverse affects on the designated use. It is assumed that the designated uses can be attained even with some limited level of criteria exceedances and thus, the reference curves define those criteria exceedances deemed to be allowable—chronic in time but over small areas, or infrequent occurrences over large areas. Exceedances that occur over large areas of space and time would be expected to have significant detrimental effects on biological communities, which would imply nonattainment of designated uses.

STRENGTHS AND LIMITATIONS

Although the Chesapeake Bay and its tidal tributaries are listed as impaired water bodies, there are some places that have met or usually meet the Chesapeake Bay criteria and support healthy aquatic living resource communities. Reference curves derived from monitoring these areas reveal patterns of criteria attainment or exceedances that support the healthy community. That is, they show whether areas that support a relatively healthy target community: 1) never exceed the applicable criteria, 2) exceed the criteria frequently, but over a small area or volume, 3) exceed the criteria infrequently over a large area or volume or 4) exhibit some other pattern.

The EPA recognizes that there are currently a limited number of reference sites, given the Chesapeake Bay's nutrient-enriched status. In addition, there are limited data available—both for criteria parameters as well as measures of the biological health of target communities—with adequate spatial and temporal coverage from which to develop a full array of biological-based reference curves. However, where sufficient data exist, the reference curves appear to be stable. The reference curve for the deep-water designated use dissolved oxygen criteria is the most solidly grounded in data.

This biological reference curve (see below for details) is based on dissolved oxygen concentration distributions at sites associated with bottom sediment-dwelling benthic communities scoring 3 or higher on the Chesapeake Bay benthic index of biotic integrity (benthic-IBI). If several of the reference segments were randomly removed, the regenerated reference curves do not change much, suggesting that within designated uses, the attainment curves for reference segments appear to be very similar. Although less firmly grounded, the reference curves for other designated uses and other criteria also seem to be relatively stable.

APPROACHES TO DEFINING REFERENCE CURVES

At least three options exist for defining a reference curve (Figure VI-14). Fixed percentages could be selected based on a policy decision or other basis similar to the 10 percent level of acceptable exceedances allowed in 305(b) EPA national guidance (Figure VI-14a; U.S. EPA 1997). Alternatively, laboratory or empirical field data from areas known to be unimpaired by the stressor can be used to derive a biologically-based reference curve (Figure VI-14b). Even this second approach, however, requires technical or policy decisions regarding the acceptable level of biological effect. Finally, a reference curve could be established to reflect uncertainty based on the assumption of a normal distribution, and using observed or estimated error variance for both time and space (Figure VI-14c).

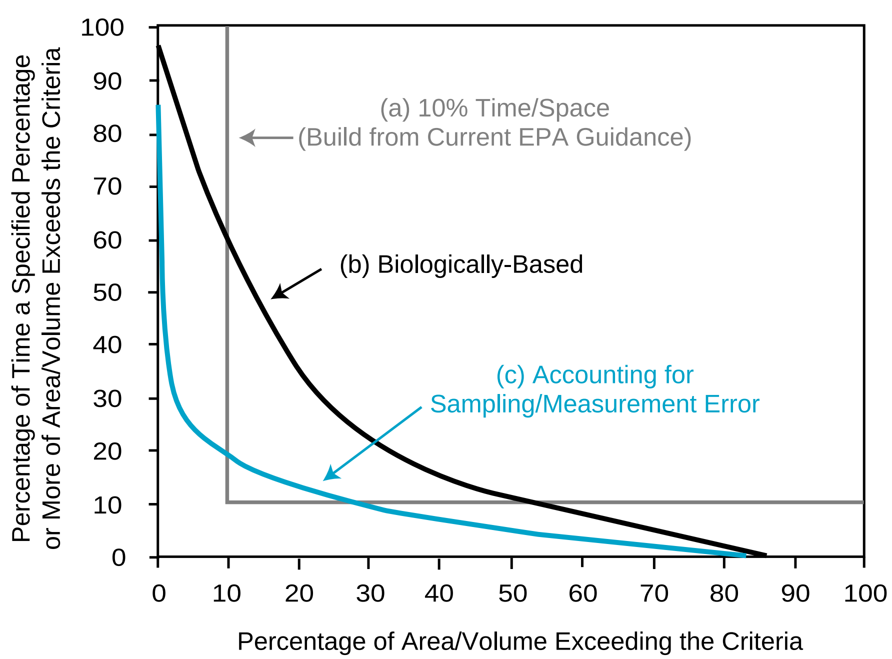

Figure VI-14. Three possible options for setting reference curves for application to the cumulative frequency distribution approach for defining criteria attainment: (a) fixed percentages based on policy decisions; (b) biological effects-based empirical field or laboratory data and; (c) observed or estimated uncertainty data.

The reference curves described below for the dissolved oxygen and water clarity criteria are based on empirical, biologically-based field data where possible. Where no corroborating field data exist, a normal distribution curve representing approximately 10 percent exceedance is used (see Figure VI-18). Appendix H contains supporting analyses and detailed descriptions of the methodologies used for defining these reference curves, as well as the list of reference locations.

REFERENCE CURVES FOR DISSOLVED OXYGEN CRITERIA

Reference curves for dissolved oxygen are intended to represent the spatial and temporal distribution of dissolved oxygen concentrations in areas supporting healthy species and communities the criteria were established to protect. The deep-water designated use, for example, contained the necessary water quality and biological source data collected over similar temporal and spatial scales. When such data were not available at the scales necessary to establish quantitative relationships between the criteria parameter and measured living resource community health, surrogate measures of biological and habitat conditions were explored. Ideally, each set of designated use-based dissolved oxygen criteria should have a separate, individually derived reference curve. However, satisfactory synoptic water quality and biological indices data or surrogate measures of habitat condition were found only for the open-water fish and shellfish and deep-water designated uses and were tested only against the 30-day mean criteria for those uses.

Migratory Fish Spawning and Nursery Dissolved Oxygen Criteria Reference Curve

Current Chesapeake Bay water quality monitoring in migratory fish spawning and nursery habitats is limited to midchannel stations. There also are insufficient spawning success fisheries-independent data available to identify biologically-based reference sites for these criteria. In addition, the criteria duration components for this designated use are an instantaneous minimum and 7-day mean, and methodologies to translate less frequently monitored dissolved oxygen measurements into these time steps have not been finalized.

An attainment curve for exploratory purposes was created for the February-May spawning period, using a 30-day criterion of 6 mg liter^{-1} and reference sites identified using nitrogen, phosphorus, chlorophyll *a* and total suspended solids as parameters (Figure VI-15). Attainment was very close to 100 percent. Until more data are collected to assess the attainment of the 7-day mean and instantaneous minimum criteria in the migratory fish spawning and nursery designated use, however, the open-water dissolved oxygen criteria reference curve should be applied (Figure VI-16).

Open-Water Dissolved Oxygen Criteria Reference Curve

In the absence of a Chesapeake Bay open-water fish community index of biotic integrity, reference Chesapeake Bay Program segments with ‘good’ water quality

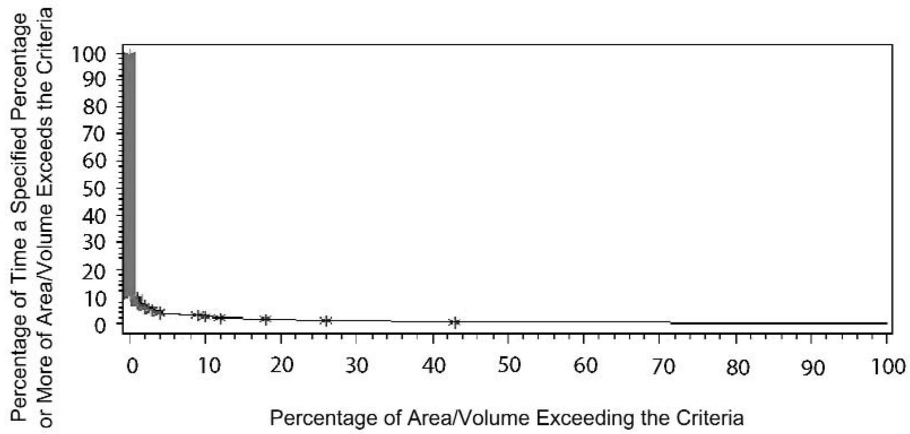

Figure VI-15. Initial attempt at developing a dissolved oxygen criteria reference curve for migratory, spawning and nursery habitat designated use areas using the 6 mg liter^{-1} 7-day mean criterion assessed as a 30-day mean.

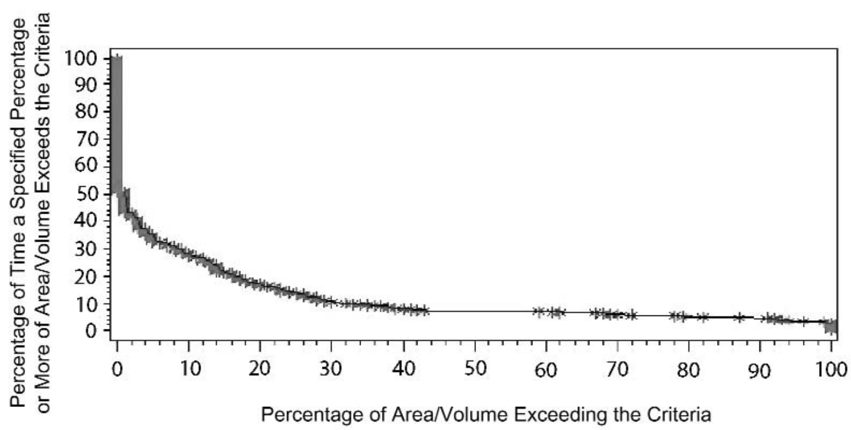

Figure VI-16. Dissolved oxygen criteria reference curve for defining criteria attainment in open-water designated use habitats.

were identified based on assessments of surface and above-pycnocline concentrations of four parameters: total nitrogen, total phosphorus, chlorophyll *a* and total suspended solids (see Appendix F for details). Cumulative frequency distribution reference curves for migratory spawning and nursery designated use habitats from February through May (Figure VI-15) and for open-water designated use habitats in summer (Figure VI-16) were derived using dissolved oxygen concentration data from these segments.

The Chesapeake Bay Program's Tidal Monitoring and Analysis Workgroup developed a procedure to assess relative status for cases in which an absolute point of reference for a water quality parameter is not available (Alden and Perry 1997). That procedure uses the logistic distribution of a parameter in a 'benchmark' data set as a standard against which individual data points are assessed. The individual data are thus scored between 1 and 100. The assessments are conducted separately in salinity classification and in depth layers corresponding to the designated uses. The median score of the individual data scores is then calculated. The benchmark distribution is divided roughly into thirds, which are defined as ‘good’, ‘fair’ and ‘poor’ (these terms relate only to each other, not necessarily to actual water quality requirements of living resources). Status of the parameter is assigned depending on where the median score falls among these divisions.

Using this procedure, open-water concentrations of the four parameters were assessed for each Chesapeake Bay Program segment, yielding for each parameter an assessment of ‘good,’ ‘fair’ or ‘poor’ for each segment, year and season (spring and summer). To qualify as a reference location, at least three out of four parameters had to be ‘good’ and only one parameter could be ‘fair’. Once the times and locations were selected, the corresponding monthly average dissolved oxygen concentration data were evaluated against the migratory fish spawning and nursery dissolved oxygen criterion value of 6 mg liter^{-1} (evaluated as a 30-day mean, not as a 7-day mean) and the open-water dissolved oxygen 30-day mean criterion of 5 mg liter^{-1} for spring and summer, respectively. The percent volume failing the criterion was calculated for each month of the season/year. The resulting cumulative frequency distribution curves are shown in figures VI-15 and VI-16, respectively. Figure VI-16 currently serves as the recommended reference curve for both the migratory fish spawning and nursery and open-water fish and shellfish designated uses for purposes of assessing dissolved oxygen criteria attainment.

Deep-Water Dissolved Oxygen Criteria Reference Curve

Reference areas were identified using a measure of benthic community health, the Chesapeake Bay Benthic Index of Biological Integrity (benthic-IBI; Weisberg et al. 1997). Sessile benthic communities are good indicators of water quality conditions of overlying waters. Although relatively tolerant of lower oxygen concentrations, a dissolved oxygen concentration of 2 mg liter^{-1} is considered the lower threshold below which benthic infaunal communities become severely stressed (see Chapter III). A healthy benthic community, therefore, could indicate that dissolved oxygen conditions meeting deep-water dissolved oxygen criteria were met. Benthic infaunal community samples are collected as part of a long-term Chesapeake Bay Benthic Monitoring Program. Samples are collected at fixed and random locations in the summer season, usually in August/September. If the benthic-IBI of that sample is ‘good’, in this case 3 or greater on a scale of 1 to 5, then it is likely that dissolved oxygen conditions have been adequate for the previous one to two months of the summer.

The benthic-IBI data from 1985 through 1994 were assessed and a list of deep-water reference locations identified by year and segment was compiled. Then, the summer (June through September) dissolved oxygen data that were collected as part of the Chesapeake Bay Water Quality Monitoring Program at the times and places on the list were evaluated relative to the deep-water criteria. Figure VI-17 shows the

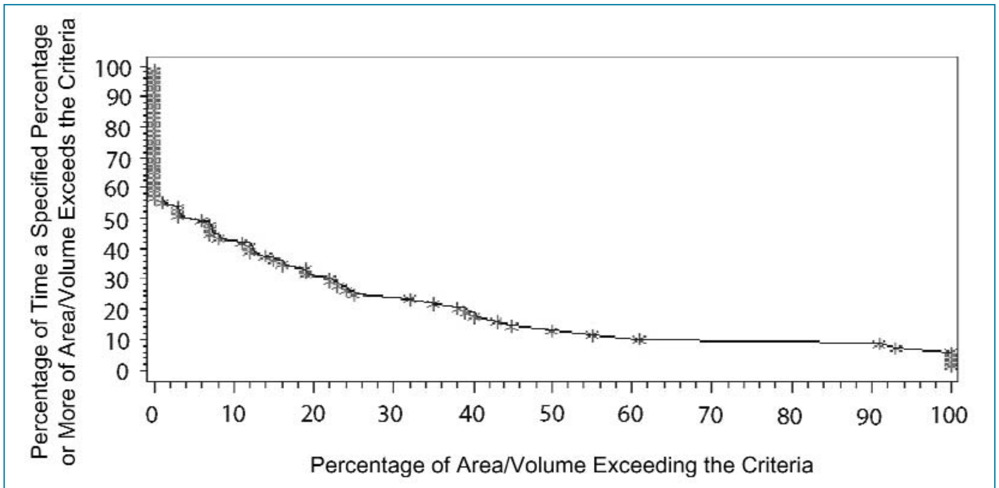

Figure VI-17. Dissolved oxygen criteria reference curve for defining criteria attainment in deep-water designated use habitats.

resulting cumulative frequency distribution curve, which serves as the recommended reference curve for the deep-water seasonal fish and shellfish designated use for assessing dissolved oxygen criteria attainment (see Appendix H for documentation of the validation curves used to confirm the reference curve).

Deep-Channel Dissolved Oxygen Criteria Reference Curve

The deep-channel seasonal refuge designated use contains dissolved oxygen concentrations that are inadequate to support most Chesapeake Bay species, and the criterion is set to protect the survival of benthic organisms. Unfortunately, a biologically-based reference curve could not be developed for the deep-channel use at this time. This area is assumed to be severely degraded and is not now sampled as part of the Chesapeake Bay Program long-term benthic monitoring program. No other appropriate biological data were available with which to identify reference sites.

While a biologically-based reference curve is recommended for the future, a default reference curve such as the normal distribution curve representing approximately 10 percent exceedance is appropriate in this case to account for anticipated natural criteria exceedances (Figure VI-18). States and other users must recognize that the deep-channel dissolved oxygen criterion is stated as an instantaneous minimum, thus *any* exceedance is assumed to have direct consequences to the survival of the bottom-dwelling community.

REFERENCE CURVES FOR WATER CLARITY CRITERIA

Reference areas for development of the water clarity criteria reference curve were identified as Chesapeake Bay Program segments or parts of segments where underwater bay grasses were abundant historically and thriving or increasing in coverage

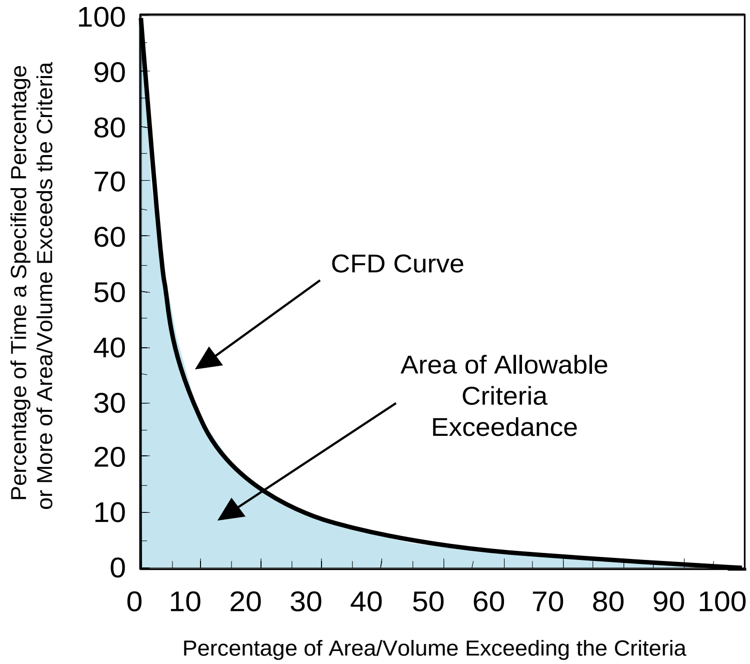

Figure VI-18. Cumulative frequency distribution curve in the shape of a hyperbolic curve that represents approximately 10 percent allowable exceedances equally distributed between time and space.

in recent years. Separate reference curves were developed for low salinity—tidal-fresh and oligohaline–and higher salinity–mesohaline and polyhaline–zones. The supporting analyses for deriving the water clarity criteria reference curves are provided in Appendix H.

Once the reference Chesapeake Bay Program segments were identified, the water clarity data (as measured by Secchi depth) for those segments were extracted from the Chesapeake Bay water quality monitoring program data base. Percent light-through-water (PLW) is the operational parameter used for assessing attainment of the water clarity criteria. PLW = 100exp(-K_dZ), where Z is the target restoration depth and K_d, the coefficient of extinction, is estimated as K_d= 1.45/Secchi depth (see Chapter III for details). K_d values calculated from the Secchi depth data were averaged by month for each station. The monthly data were then spatially interpolated baywide for each month in the underwater bay grass growing season from 1985 through 1994 to match the Chesapeake Bay water quality model hydrologic simulation period. PLW was calculated for each interpolation cell using the interpolated K_d value and the defined segment-specific restoration depth. The PLW values were compared to the criterion value appropriate to the Chesapeake Bay Program segment's salinity zone, and the percent of the shallow-water area (< 2 meters) failing the criterion in each segment was calculated for each month. The monthly attainment percentages for each reference Chesapeake Bay Program segment were pooled in their respective low and higher salinity groups and plotted as cumulative frequency distribution curves (figures VI-19 and VI-20). Appendix H contains the reference curves generated using the more recent 1995-2000 data. All these water clarity criteria reference curves were derived using data spanning decadal scales, capturing the full range of wet, dry and average hydrologic conditions.

The derived water clarity criteria reference curves reflect findings published in the scientific literature for Chesapeake Bay species that indicate that underwater plants can survive reduced light conditions for periods of days to weeks. Field and laboratory experiments indicated that lower salinity species were more tolerant of longer periods of reduced light conditions (Rybicki et al. 2002) compared with species inhabiting higher salinity waters (Goldsborough and Kemp 1988). These salinity regime differences also are reflected in the different shapes of the derived reference curves. The lower salinity reference curve allows for more exceedances over time and space than are allowed for by the higher salinity reference curve (figures VI-19 and VI-20, respectively).

It should be noted that the water clarity criteria were derived, in part, on the basis of underwater bay grass growing season medians (Batiuk et al. 1992, 2000), but attainment is measured on a monthly basis over the growing season (see “Developing the Cumulative Frequency Distribution,” p. 154, for details). Appendix H also shows water clarity reference curves based strictly on growing season median assessments.

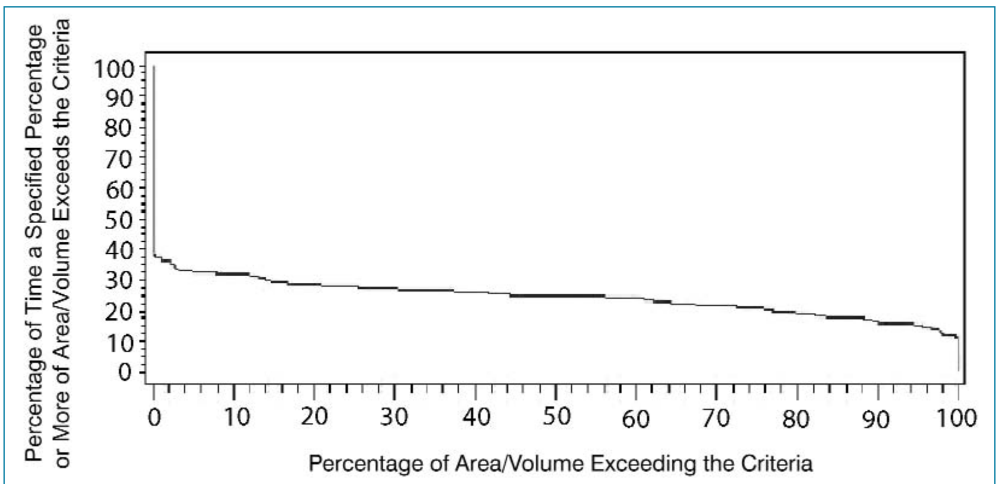

Figure VI-19. Water clarity criteria reference curve for defining criteria attainment in tidal-fresh/oligohaline shallow-water bay grass designated use habitats.

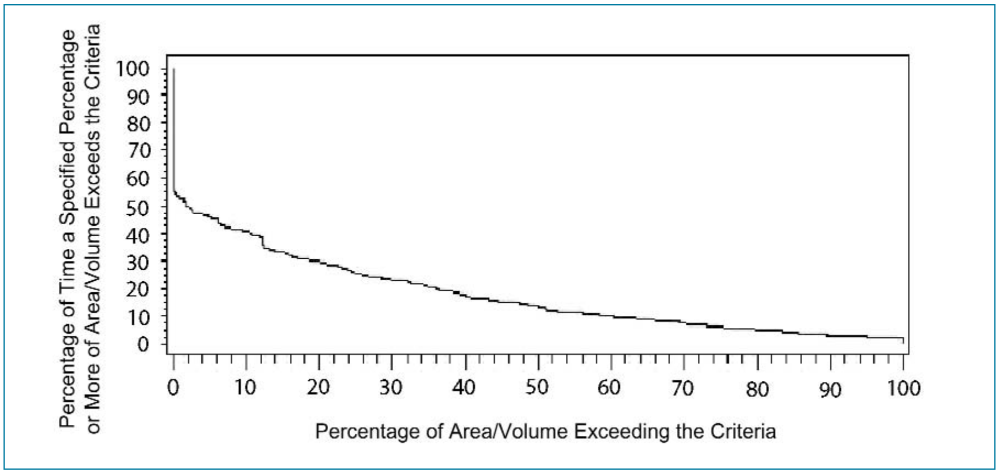

Figure VI-20. Water clarity criteria reference curve for defining criteria attainment in mesohaline/polyhaline shallow-water bay grass designated use habitats.

REFERENCE CURVES FOR CHLOROPHYLL *A* CRITERIA

As states derive numerical regional and local specific chlorophyll *a* criteria, they should either derive biologically-based reference curves that reflect the 'allowable' exceedances of local impairments or apply the normal distribution curve representing approximately 10 percent 'allowable' exceedance in time and space (see Figure VI-18).

The cumulative frequency distributions derived from the subset of Chesapeake Bay water quality monitoring program chlorophyll *a* data associated with the 'Better' and 'Best,' and sometimes 'Mixed_Better Light' water quality categories closely matched the normal distribution curve in both spring and summer (figures VI-21 and VI-22). These categories formed the basis for characterizing the Chesapeake Bay phytoplankton reference community (see Chapter V and Appendix F for details). The cumulative frequency distributions were derived from applying the 95th percentiles of chlorophyll *a* values occurring in these categories (see Table V-6). In figures VI-21 and VI-22, respectively, the cumulative frequency distributions of spring (March–May) and summer (July–September) chlorophyll *a* concentration exceeding the 95th percentile phytoplankton reference community values (a) are overlaid with the normal distribution curve (b). The normal distribution curve matches well with both seasonal biological-based cumulative frequency distributions, providing further justification for applying the normal distribution curve as a chlorophyll *a* criteria reference curve in the absence of a directly derived biological reference curve.

REFERENCE CURVE IMPLEMENTATION

As the states adopt the Chesapeake Bay criteria and concomitant procedures into their water quality standards, they may decide to: 1) allow for no criteria exceedance, 2) select the normal distribution curve representing approximately 10 percent allowable criteria exceedance or 3) apply a biological reference curve. The first two

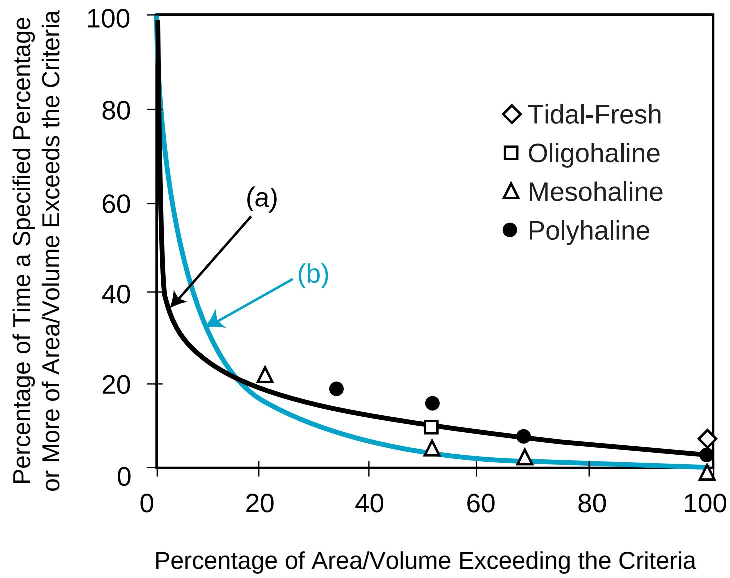

Figure VI-21. Cumulative frequency distribution of spring (March-May) chlorophyll *a* concentration exceeding the 95th percentile phytoplankton reference community values (a) compared with the normal distribution curve (b).

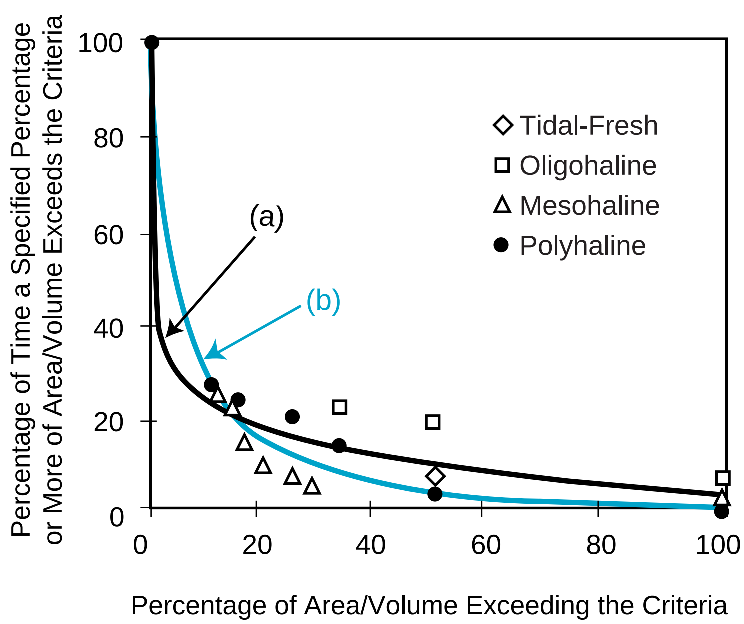

Figure VI-22. Cumulative frequency distribution of summer (July-September) chlorophyll *a* concentration exceeding the 95th percentile phytoplankton reference community values (a) compared with the normal distribution curve (b).

options are likely to be more restrictive than the biological reference curve approach. If states choose to apply the biological reference curve, then there should be a strong incentive to collect relevant data to strengthen the scientific basis of those reference curves in the future.

MONITORING TO SUPPORT THE ASSESSMENT OF CRITERIA ATTAINMENT

To support the development of cumulative frequency distributions for criteria attainment assessment purposes, additional monitoring will be required. The current fixed-station Chesapeake Bay Water Quality Monitoring Program will support many aspects of the effort to assess criteria attainment. However, some aspects will require new monitoring in areas of Chesapeake Bay tidal waters from which data have not yet been collected. Other aspects will require new types of monitoring based on new technologies that will better address the technical requirements of the criteria as they are currently defined. The Chesapeake Bay Program has developed a tidal monitoring network design that identifies the needs and proposes options for addressing those needs. Many of those options can feasibly be implemented, but additional monitoring will be expensive, and it is expected that available funds will limit what can be done.

The following describes options for conducting monitoring to support the assessment of criteria attainment. Given that funding may be limited, the monitoring options are divided into three categories based on funding level. The first category, 'recommended', assumes that funding will be available to conduct monitoring to fully support the assessment of criteria attainment. The 'recommended' level of monitoring is based on technological needs to provide a set of data that can be defended legally and scientifically in making decisions regarding the attainment of designated uses. The second category, 'adequate', assumes that funding will be somewhat limited, but will be sufficient to collect enough data to support the development of cumulative frequency distributions for most criteria components in most Chesapeake Bay Program segments and tidal-water designated uses. The third category, 'marginal', assumes that monitoring will be significantly limited by available funding and that it will not be possible to assess all criteria components in all segments of the Chesapeake Bay and its tidal tributaries.

Efforts are underway to develop the tools necessary to generate verifiable and quantitative estimates of error and the levels of monitoring required for given levels of accuracy acceptable to management agencies. The three general categories defined above were developed to give the reader some perspective on the range of options available and the adequacy of the options.

SHALLOW-WATER MONITORING

Resource managers rely upon habitat and water quality monitoring data to characterize problem areas in a watershed, such as areas of low dissolved oxygen, and to detect changes related to management strategies to reduce nutrients and sediments on a tributary to baywide level. Traditional monitoring programs have collected periodic data at a small number of fixed sampling locations, often in the deeper midchannel areas. These measurements provide a good baseline for watershed assessment and long-term trends, but may miss small-scale gradients in tidal water quality and neglect critical shallow-water habitats.

In the past, intensive water quality monitoring of these shallow-water habitats has been time-intensive and cost-prohibitive. The advent of a new suite of technologies known as the DATAFLOW water quality monitoring system, however, has brought intensive monitoring of shallow-water habitats into reach (http://mddnr.chesapeakebay.net/sim/index.html). DATAFLOW is a system of shipboard water quality probes that measure spatial position, water depth, water temperature, salinity, dissolved oxygen, turbidity (a measure of clarity of the water) and chlorophyll *a* from a flow-through stream of water collected near the water body's surface. The system allows data to be collected rapidly (approximately every four seconds) and while the boat is traveling at speeds up to 25 knots. Because the DATAFLOW system is compact, it can be housed on a small boat, enabling sampling in shallow water and the ability to map an entire small tributary in less than a day. Typical DATAFLOW research cruise sampling paths traverse shallow and channel areas to obtain a full characterization of a tributary's water quality.

The discussion below focuses on migratory spawning and nursery, open-water, deep-water and deep-channel designated uses. The DATAFLOW system is the only viable option for monitoring water quality conditions in the shallow-water designated use. The high temporal and spatial variability expected in shallow-water areas implies that intensive data collection would be required for any assessment to have credibility. A probability-based approach was considered as a less expensive approach for shallow-water monitoring, but the cost savings were not sufficient to justify the reduced amount of information that this approach would provide. The only option for reduced costs in shallow-water monitoring is to limit the amount that is conducted during any one year.

DISSOLVED OXYGEN CRITERIA ASSESSMENT

'Recommended' Level of Monitoring

Monitoring for dissolved oxygen criteria attainment should address all four frequencies of dissolved oxygen criteria: 30-day mean, 7-day mean, 1-day mean and instantaneous minimum. The current fixed-station monitoring program is designed to provide a long-term record of dissolved oxygen concentrations that reflect seasonal and interannual variation. For that reason, even though instantaneous measurements are collected, the current monitoring is best suited for assessing the 30-day mean dissolved oxygen criteria component and poorly suited for assessing the 7-day, 1-day mean and instantaneous minimum criteria components. To address the need for data that will address the 7-day, 1-day mean and instantaneous minimum criteria components, continuous monitors mounted to buoys or piers will be required. At least one continuous monitor should be located at each assessment location. The continuous record will then be combined with fixed-station data, used to calibrate the spectral-analysis model (described below), and all criteria components could be quantified using that model. Individual criteria component estimates would be assessed at all fixed locations and interpolated for incorporation in a cumulative frequency distribution.

'Adequate' Level of Monitoring

Assuming that funding will not be available for the 'recommended' monitoring approach, an alternative would be to place a limited number of continuous monitors at representative locations in the Chesapeake Bay and tidal tributaries. The number of continuous monitors would be relatively small, but the number would be established to characterize different types of settings in the Chesapeake Bay. Those representative temporal records would then be combined with fixed-station data in similar settings, and spectral models would be developed for each fixed-station location. Dissolved oxygen criteria components would be assessed based on the spectral models, interpolated and used to develop the cumulative frequency distributions. This approach would entail much greater uncertainty in the assessments. The absolute variation would be characterized well by regular monthly measurements at the fixed-stations. However, the higher frequency assessments would be based on data collected at only a few locations, which would then be extrapolated over large distances.

'Marginal' Level of Monitoring

Assuming that funding will not be available for even the 'adequate' level of monitoring, assessments would need to rely on the fixed-station data only. As stated above, this type of monitoring was designed for long-term assessments and would only be truly appropriate for the 30-day mean criteria component. If the 'marginal' level of monitoring was selected, it is likely that higher frequency criteria components would not be assessed in most designated use areas.

Assessing Dissolved Oxygen Criteria Attainment

Addressing Duration Issues. The dissolved oxygen criteria have several different durations: 30-day mean, 7-day mean, 1-day mean (deep-water only) and instantaneous minimum. A state's ability to assess these criteria and to have certainty in the results depends on the time scale of available data and on the capacity of models to estimate conditions at those time scales. At present, long-term, fixed-station, midchannel water quality monitoring in the Chesapeake Bay and its tidal tributaries provides dissolved oxygen measurements twice monthly at most or approximately every 15 days between April and August. Proposed enhancements to the tidal water quality monitoring program include shallow-water monitoring, as well as high-resolution spatial and temporal monitoring in selected locations. However, these new components are only in the planning and early implementation stages at this point, and because of financial constraints or limitations to current technology, direct monitoring at the scales of the criteria may not be possible in the foreseeable future. Therefore, the direct assessment of attainment for some geographic regions and for some short-term criteria elements (e.g., instantaneous minimum, 1-day mean and 7-day mean) must be waived for the time being or based on statistical methods that estimate probable attainment. Several approaches to addressing the duration issue are described below.

Thirty-Day Mean Attainment Procedure. This duration appears to be within the temporal scale of the current Chesapeake Bay water quality monitoring programs. The simplest assessment approach is to use the one value or average of two values collected within a month as the best estimate of the true 30-day mean. At present, this is the approach recommended for assessing attainment of criteria with this duration. However, it is debatable how well one or two samples per month represent what is intended as protective by the 30-day mean.

These procedures assume the existence of a baywide tidal-water monitoring program with a fixed-station sampling design and sampling frequency at least once per month during the seasons defined by the criteria. The procedures assume that horizontal and vertical measurements of dissolved oxygen will be sufficiently dense that the interpolator can create an accurate three-dimensional representation of dissolved oxygen in the defined designated uses. It also assumes that data are sufficient to define the boundaries of the designated uses where boundaries are variable, depending on pycnocline depth.

To simplify computations, if there is more than one observation per month, then the monthly average is calculated prior to input to the volumetric interpolator. Prior to averaging for the month, each station's dissolved oxygen profile is interpolated vertically to obtain a value at each half-meter interval from surface to bottom. The monthly average concentrations at each fixed station at each half-meter are then interpolated horizontally by the Chesapeake Bay interpolator to yield a basinwide grid of concentrations for each month. A comparable reference grid or a table of grid coordinates and depths can be used to relate the monthly cell concentrations to be evaluated with the correct designated use and corresponding criteria concentrations. The cell is scored as meeting or not meeting the criterion level and cell volume is accumulated in the pool of passing or failing totals for each designated use in each Chesapeake Bay Program segment. From this, the spatial extent of nonattainment, i.e., the percentage of the total volume exceeding the criterion in each designated use in each Chesapeake Bay Program segment is tallied for each month in the assessment period (most recent three years).

Dissolved oxygen criteria attainment is reported seasonally (see Table VI-1). To assess, for example, attainment of the summer season 30-day mean criterion for the deep-water seasonal fish and shellfish designated use, the percent exceedance data for the months of June through September for a three-year period for all Chesapeake Bay Program segments with deep-water designated use habitats would be extracted and evaluated individually using the cumulative frequency distribution approach. The cumulative frequency distribution attainment curve would be calculated (and plotted, if desired) and compared to the appropriate reference curve for the designated use and season using the statistical test described earlier. If the two curves are significantly different, then the segment/designated use is considered out of attainment, and failing by the amount defined by the area between the two curves.

Seven-Day Mean Attainment Procedure. The 7-day time frame is much shorter than the temporal scale of the current baywide water quality monitoring programs, and statistical forecasting models are necessary to assess criteria of this duration. The proposed approach, referred to as the *spectral analysis approach* in this chapter and discussed in more detail below, uses long-term, low-frequency data from the monitoring program and shorter-term, high-frequency data from in situ semi-continuous monitors to synthesize a data set that incorporates both long- and short-term patterns of variability. The synthetic data set is created at user-specified time intervals, e.g., weekly, daily and hourly. The minimum interval will depend on the interval length of the continuous data. The synthetic data set is then analyzed at the appropriate temporal scale, which in this case is seven days. At present there are insufficient high-frequency data and insufficient validation of the approach to recommend its implementation. For now, attainment of 7-day mean criteria should not be assessed unless data are available for a specific location/segment at a temporal scale consistent with the 7-day duration.

One-day Mean Attainment Procedure. The 1-day attainment procedure is the same as the 7-day mean procedure described above. For now, attainment of the 1-day mean criteria should not be assessed unless data are available for a specific location/segment at a temporal scale consistent with the 1-day duration.

Instantaneous Minimum Attainment Procedure. Again, the instantaneous minimum time frame is much shorter than is currently sampled. The spectral analysis approach presented above is one way to estimate attainment of these dissolved oxygen criteria. Another approach, referred to as the *logistic regression approach* in this chapter and described in more detail below, applies by restating the criterion in slightly different temporal terms. An instantaneous minimum implies that the criterion is not met if dissolved oxygen concentrations are below the criterion value at *any* time. The logistic regression approach estimates the relative frequency or percent of time that a region falls below a specified concentration based on the empirical relationship between seasonal or monthly mean values and the percent of dissolved oxygen concentrations above or below the specified level as observed in the historical data record (of the Chesapeake Bay water quality monitoring program). This method has been applied experimentally with reasonable results (Jordan et al. 1992) and can approximate criteria exceedance/attainment frequency. However, at this time the method has not been adequately validated to recommend implementation for formally assessing criteria attainment. Attainment of instantaneous minimum criteria should not be assessed unless data are available for a specific location/segment at a temporal scale consistent with the instantaneous minimum duration.

Spectral Analysis Approach. The foundation for this method was developed by Neerchal et al. (1992) in the context of implementing the Chesapeake Bay dissolved oxygen restoration goal (Jordan et al. 1992) and has been modified for criteria application. The method uses spectral analysis to extract the cyclical components of the long- and short-term time-series records and combines them to create a synthesized time-series data set with data synthesized at user-specified time steps. At present, the synthetic data are hourly, with cyclic components limited to two cycles per day. The synthetic data have the annual and seasonal cyclic and trend characteristics of the long-term record as well as the tidal, diurnal and any other periodic characteristics of the short-term, high-frequency record. The long-term record comes from fixed-station monitoring data collected at regular once or twice monthly intervals in the seasons of interest. The short-term data come from in-situ semicontinuous oxygen monitors deployed on buoys or other fixed structures at designated locations around the Chesapeake Bay and its tidal tributaries. These semicontinuous oxygen monitors are put in place for various lengths of time at many different locations and depths. Sites are chosen in order to best characterize the dissolved oxygen conditions in each designated use. The sampling interval of the semicontinuous monitors are commonly 5, 10 or 20 minutes. To be most useful, the interval should be no longer than one hour. More details are provided in Appendix I.

Application of the Spectral Analysis Approach. The spectral analysis application shown in Figure VI-23 uses long-term data from station CB4.2C, a monitoring station in the midregion of the Chesapeake Bay, and a two-month series of continuous dissolved oxygen measurements at a buoy deployment near that station at approximately 9 meters below the surface. Figure VI-23 shows the observed monthly dissolved oxygen concentrations (asterisks) at station CB4.2C (8- to 10-meter depth) and the long-term forecast (line) from the spectral equation.

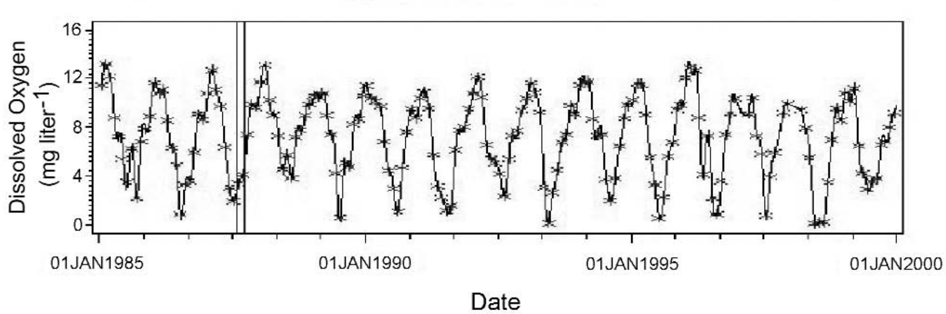

Figure VI-23. Observed monthly dissolved oxygen concentrations (*) at Chesapeake Bay Monitoring Program station CB4.2C (at the 8 to 10 meter depth) from January 1985 to January 2000 and the long-term 'forecast' (—) from application of the spectral equation.

The synthetic data record is obtained by combining the long- and short-term equations. A sample two-month period, August through September 1987 (indicated by the two, close-together vertical reference lines in Figure VI-23), is illustrated in Figure VI-24. This synthetic record can then be analyzed relative to the applicable criteria elements. In the example shown, the 9-meter depth at station CB4.2C is near or below the pycnocline and is, therefore, subject to criteria for the deep-water designated use. Summer dissolved oxygen criteria for the deep-water designated use is a 3 mg liter^{1} 30-day mean, 2.3 mg liter^{1} 1-day mean and 1.7 mg liter^{1} instantaneous minimum. For demonstration purposes, let a 7-day mean of 2.5 mg liter^{-1} also apply.

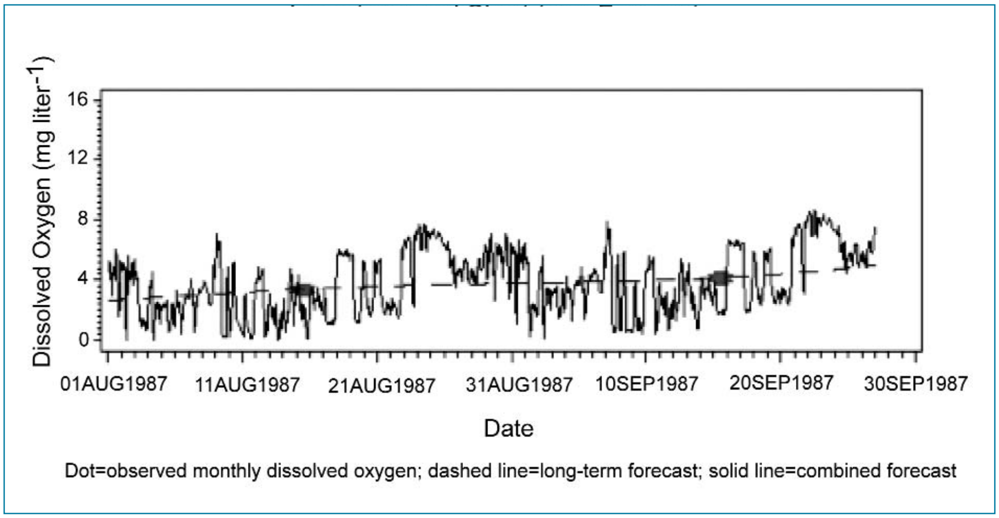

Figure VI-24. Expanded view from Figure VI-23 of the two-month period August–September 1987 synthetic data record obtained by combining the long- and short-term spectral equations.

Based on monitoring data alone (two observations each month), the August and September mean monthly values are 3.4 mg liter^{1} and 4.2 mg liter^{1}, respectively. Basing assessment on the synthetic data record, attainment can be measured either in sequential or rolling time windows, as described below. In some cases the results vary depending on which option is used (Table VI-5). For the 30-day duration, the sequential option results in two 30-day periods within the 61 days, between August 1 and September 30, 1987; the rolling time window option yields 31 periods. If there was a 7-day criterion for deep-water designated use, there would be 8 sequential versus 55 rolling-window periods in those 61 days. For the 1-day minimum duration, the question of sequential and rolling-window is moot.

Verifying the Spectral Analysis Approach. The number and distribution of high frequency semicontinuous dissolved oxygen data sets is small compared to the variety of habitats, times of year and layers of the water column that need to be characterized. There are gaps in critical seasons, geographic coverage and designated

Table VI-5. Sample attainment results when assessing with varying time windows

Dissolved Oxygen Criterion	Time Windows Meeting Criterion	Percent of Observations at or above Criterion
30-day Mean (3 mg liter $^{-1}$):		
Sequential	2 of 2	100%
Rolling window	31 of 31	100%
7-day Mean (2.5 mg liter $^{-1}$):		
Sequential	7 of 8	87.5%
Rolling window	46 of 55	83.6%
Instantaneous Minimum (1.7 mg liter $^{-1}$)		
Pool of hourly measurements	1,250 of 1,484	84.2%

uses. Nevertheless, the number of such data sets on hand is substantial and growing, relative to the number and location of fixed monitoring stations.

Developing and verifying the method will be an ongoing process. Short-term forecasts based on synthetic data are created and compared to actual semicontinuous records not used in the original forecasting process. There are some, but not many, instances in which semicontinuous data are available at the same site in different years. Also, in some instances, multiple semicontinuous records are available for the same region. In these cases, one record is used in the spectral analysis and equation development and the other is used to verify the results. With data recorders deployed for the specific purpose of validating and refining the forecasting models, better verification will be available in the future.

Even with these issues resolved, there are still questions concerning how synthetic time-series data sets should be adapted to enable an assessment of spatial extent and frequency of attainment in a manner consistent with criteria assessed by other analytical methods.

Logistic Regression Approach. This method modifies and significantly updates a method developed originally to measure attainment of the 1992 Chesapeake Bay dissolved oxygen restoration goal (Jordan et al. 1992). The early work demonstrated predictable relationships, on a segment-by-segment basis, between seasonal mean dissolved oxygen concentrations and the percent of observations above a target concentration. The relationships proved to be strong and applicable in areas where dissolved oxygen concentrations ranged above and below the goal target concentrations. Given the tidal water quality monitoring data record that spans more than 17 years with the measurements from multiple depths (the vertical dissolved oxygen profile is collected at 1- to 2-meter intervals), the regression models are now month- and depth-specific in many segments. Based on the monthly mean dissolved oxygen concentration measured at a specified depth, the models predict the percent of time that the dissolved oxygen concentration at that depth in a segment is at or above a user-specified concentration, e.g., an instantaneous minimum of 1.7 mg liter^{-1} (see Appendix I for more details).

Application of the Logistic Regression Approach. The method can be applied using the three-dimensional baywide interpolations of monthly average dissolved oxygen, as described for the determination of 30-day duration criteria. The monthly average concentrations at each fixed station at each half-meter are interpolated horizontally by the Chesapeake Bay interpolator to yield a basinwide grid of concentrations for each month. A comparable reference grid or a table of grid coordinates and depths relate the monthly cell concentrations to be evaluated with the correct designated use and corresponding criteria concentration (e.g, instantaneous minimum of 1.7 mg liter^{-1}). In the data processing step, a segment- and criterion level-specific prediction model uses the cell's monthly average concentration, depth and month as factors in predicting the percent of the time that particular cell is at or above the criterion. The cell is scored as passing or failing the criterion level depending on the model results. The cell volume is accumulated in the pool of passing or failing totals for each designated use in each segment. Like the method for assessing the 30-day mean, the spatial extent of nonattainment, i.e., the percentage of the total volume exceeding the criterion in each designated use in each segment, is tallied for each month in the assessment period (most recent three years). The cumulative frequency distribution attainment and reference curves can then be derived, and the same statistical test for determining attainment as described for the direct assessment method can be applied.

Strengths and Current Limitations. The logistic models are based on conditions represented by the fixed stations in the current monitoring program, which in most tributaries are sited in the main channel. Until more data are collected, the similarity of shallow areas to the midchannel in the same segment is not known. This approach would assume, in the absence of other data, that the main channel data are representative of similar depths in the shallows. If salinity or other physical data from the shallows indicate that all or part of the shallow water column is more similar to a different depth in the midchannel (as is sometimes the case for various reasons), then the more representative depth would be used to estimate percent attainment. For example, the pycnocline typically is deeper in the portion of the Chesapeake Bay than on the flanks, and the depth of the pycnocline on one flank is typically deeper than the other. Thus a 4-meter-deep, above-pycnocline water parcel on one flank may be most similar to the 4-meter-above-pycnocline depth in the midchannel profile, while the 4-meter-deep, subpycnocline parcel on the opposite flank is more similar to the 5-meter depth in the midchannel profile.

To date, dissolved oxygen concentrations have shown little significant trend in most areas of the Chesapeake Bay and its tidal tributaries and, therefore, history-based estimation models are reasonable. However, where significant trends are detected, it would be important to review the models and their basis in light of new, emerging empirical relationships at those locations. This approach provides an estimate of the amount of time a water parcel is above or below a particular concentration, but does not address the length of individual exposure, rate of re-exposure, or a specific event-duration such as daily or 7-day mean.

WATER CLARITY CRITERIA ASSESSMENT

'Recommended' Level of Monitoring

Because the DATAFLOW technology is the only viable approach for assessing water quality conditions in shallow-water designated use areas, there is only a 'recommended' level of monitoring for assessing the water clarity criteria. Significant spatial and temporal variability are expected in the shallow-water designated use area. The DATAFLOW is best suited to address the high level of variability and provide data for credible assessments of criteria attainment. The only option for reduced costs in shallow-water monitoring is to limit either the total number of tidal systems assessed and/or the frequency of monitoring events for each system that are conducted during a single year.

Assessing Attainment of the Shallow-Water Bay Grass Designated Use

Restoring underwater bay grasses to areas supporting "the propagation and growth of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish inhabiting vegetated shallow-water habitats" is ultimately the best measure of attainment of the shallow-water bay grass designated use. To determine the return of water clarity conditions necessary to support restoration of underwater grasses and, therefore, attainment of the shallow-water designated use, states may: 1) evaluate the number of acres of underwater bay grasses present in each respective Chesapeake Bay Program segment, comparing that acreage with the segment's bay grass restoration goal acreage; and/or 2) determine the attainment of the water clarity criteria within the area designated for shallow-water bay grass use. The shallow-water bay grass use designated use area may be defined by either: 1) applying the appropriate water clarity criteria application depth (i.e., 0.5, 1 or 2 meters) along the entire length of the segment's shoreline (with exception of those shoreline areas determined to be underwater bay grass no-grow zones; see U.S. EPA 2003 for details); or 2) determining the necessary total acreage of shallow-water habitat within which the water clarity criteria must be met using a salinity regime specific ratio of underwater bay grass acres to be restored within a segment to acres of shallow-water habitat that must meet the water clarity criteria within the same segment (regardless of specifically where and at what exact depth those shallow water habitat acreages reside within the segment). These approaches to assessing attainment of the shallow-water bay grass designated use are described below in more detail.

Assessing Underwater Bay Grasses Restoration. In response to a commitment in the *Chesapeake 2000* agreement, the Chesapeake Bay watershed partners adopted a baywide underwater bay grasses restoration goal of 185,000 acres. This baywide restoration goal was established "to reflect historic abundance, measured as acreage and density from the 1930s to present" (*Chesapeake 2000*, Chesapeake Executive Council 2000).

The single best year of underwater bay grasses growth observed in each Chesapeake Bay Program segment from the entire available record of aerial photographs (1938-2000) was determined by state and federal agency resource managers and Chesapeake Bay scientists as the best available data on underwater bay grasses occurrence over the long-term. The underwater bay grasses goal acreage was set using the single best year acreage out to a Chesapeake Bay Program segment-specific application depth determined as summarized in Table VI-6 and described in detail in the *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability* (U.S. EPA 2003). Based on the implementation

Table VI-6. Methodology for establishing the 185,000 Chesapeake Bay baywide underwater grasses restoration goal.

The baywide underwater bay grasses goal acreage was set using the single best year acreage out to an application depth determined as follows:

1. Bathymetry data and aerial photographs were used to divide the single best year underwater bay grasses acreage in each Chesapeake Bay Program segment into three depth zones: 0-0.5 meters, 0.5-1.0 meters and 1-2 meters.

2. The aerial photographs were then used to determine the maximum depth to which the underwater bay grass beds grew in each segment with either a minimum abundance or minimum persistence. The underwater bay grass goal for a Chesapeake Bay Program segment is the portion of the single best year acreage that falls within this determined depth range. The decision rules for this were as follows:

    In all segments, the 0-0.5 meter depth interval was designated for shallow-water bay grass use. In addition, the shallow-water bay grass use was designated for greater depths within a segment if either:

    A) The single best year of underwater bay grasses distribution covered at least 20 percent of the potential habitat in a deeper zone; or,

    B) The single best year of underwater bay grasses distribution covered at least 10 percent of the potential habitat in the segment-depth interval, and at least three of the four five-year periods of the more recent record (1978-2000) show at least 10 percent SAV coverage of potential habitat in the segment-depth interval.

3. The single best year underwater bay grasses distribution acreage of all Chesapeake Bay Program segments were clipped at the deeper depth of the segment-depth interval, determined above. The resulting underwater bay grass acreages for each segment were added, resulting in the total baywide underwater bay grass restoration goal of 185,000 acres.

Source: U.S. Environmental Protection Agency 2003 of this methodology, each Chesapeake Bay Program segment (see Figure VI-1 and Table VI-4) has an underwater bay grass restoration goal acreage, with the exception of those segments documented as underwater bay grass no-grow zones along their entire shoreline, with the total acreage summed up from all segments equaling 185,000 acres.

In adopting and implementing their water quality standards for protecting the shallow-water bay grass designated use, states may: 1) adopt the segment-specific underwater bay grass restoration goal acreages that make up the baywide 185,000 restoration goal; or 2) adopt a lower initial Chesapeake Bay Program segment-specific underwater bay grass acreage, below the established goal acreage for a segment, and use their upcoming triennial reviews of state water quality standards to continually evaluate and appropriately increase the segment-specific acreages towards the ultimate underwater bay grass restoration goal acreage. If states choose to adopt a lower initial segment-specific acreage, at a minimum they must adopt an underwater bay grass acreage for that Chesapeake Bay Program segment equal to or greater than the existing use underwater bay grasses acreage defined as either the single best year of composite acreage of underwater bay grasses mapped through the baywide underwater bay grasses aerial survey since 1975. The Chesapeake Bay Program segment-specific acreages that, added together, make up the baywide 185,000 restoration goal are documented in the *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability* along with the segment-specific existing use underwater bay grasses acreages (U.S. EPA 2003).

Achieving the Chesapeake Bay Program segment-specific underwater bay grass restoration acreages should be measured as the single best year of acreage as observed through the most recent three years of data from the Chesapeake Bay underwater bay grasses aerial survey. All mapped acreages of underwater bay grasses in a segment should be counted towards achievement of each segment-specific restoration goal regardless of the depth. Chesapeake Bay segment level acreages of underwater bay grasses are published annually and can be accessed through the Chesapeake Bay Program's web site at http://www.chesapeakebay.net/data, or directly through the Virginia Institute of Marine Science's "Bay Grass in Chesapeake Bay and Delmarva Peninsula Coastal Bays" web site at http://www.vims.edu/bio/sav/index.html.

Assessing Water Clarity Criteria Attainment at an Established Application Depth. The recommended method for assessing water clarity criteria attainment is, first, to interpolate monthly values of K_d to obtain a K_d value for each interpolator cell, then to calculate PLW for each cell using the interpolated value of K_d and the Chesapeake Bay Program segment-specific shallow-water bay grass designated use boundary depth (see U.S. EPA 2003 for a full listing of the recommended shallow-water bay grass designated use boundary depths). Note that for statistical reasons, the interpolations are performed using a log transformation of the light values ($\log[K_d]$). The resulting interpolated cell values are converted back to their untransformed status for the PLW calculation.

As described previously in this chapter, the interpolator cells can be associated with the proper Chesapeake Bay Program segment and salinity zone so that each cell's PLW value can be compared to the proper salinity regime-based water clarity criterion value. The cell area is then accumulated in the 'fail' or 'pass' tally for each Chesapeake Bay Program segment for each month. The cumulative frequency distribution curve resulting from the monthly percent attainment measures over the respective underwater bay grass growing season (see Table VI-2) and three-year attainment period is then compared statistically to the reference curve for the appropriate salinity zone to determine the degree of attainment or nonattainment. If the curves are differ significantly, then the segment/designated use is considered out of attainment and fails by the amount defined by the area between the two curves.

Assessing Water Clarity Criteria Attainment throughout a Defined Shallow-Water Habitat Acreage. Restoring underwater bay grasses within a segment requires that the particular shallow-water habitat meets the Chesapeake Bay water clarity criteria across acreages much greater than those actually covered by underwater bay grasses. The ratio of underwater bay grass acreage to the required shallow-water habitat acreage achieving the necessary level of water clarity to support return of those underwater bay grasses varies, based upon the different species of bay grasses inhabiting the Chesapeake Bay's four salinity regimes. The average baywide ratio of underwater bay grass acreage to suitable shallow-water habitat acreage is approximately one acre of underwater bay grasses for every three acres of shallow-water habitat achieving the Chesapeake Bay water clarity criteria (U.S. EPA 2003).

The salinity regime and, therefore, bay grass community-specific underwater bay grass acreage to shallow-water habitat acreage ratios have been derived through an evaluation of extensive underwater bay grass distribution data within tidal-fresh, oligohaline, mesohaline and polyhaline salinity regimes (reflecting different levels of coverage by different underwater bay grass communities). The *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability* documents the methodology followed and the resulting underwater bay grasses acreage to shallow-water habitat acreage ratios derived for each of the four salinity regimes (U.S. EPA 2003).

The same procedures as described above in "Assessing Water Clarity Criteria Attainment at an Established Application Depth" are followed for determining attainment of the water clarity criteria across the total required shallow-water habitat acreage for a specific Chesapeake Bay Program segment. The only difference is that a segment-specific water clarity criteria application depth is not applied. Instead, the depth of attainment of the water clarity criteria is determined for each interpolator cell. The area in each interpolator cell from the intertidal zone out to the water-column depth at which the water clarity criteria was attained is combined along with other similar areas determined for the other interpolator cells comprising the shallow-water areas in a specific segment.

Factoring in the Influence of Tidal Range on Water Clarity Attainment

Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat-Based Requirements and Restoration Targets: A Second Technical Synthesis specifies that half the diurnal tidal range for that Chesapeake Bay Program segment should be added to the restoration depth Z before calculating PLW or PLL (Batiuk et al. 2000, page 102). These half tidal-range values, taken from tidal-range tables and averaged by Chesapeake Bay Program segment, were listed on page 202 of that document in Table D-4. However, for the purposes of testing attainment of the water clarity criteria, the EPA recommends using the water clarity criteria application depths without adding half the diurnal tidal range to it (see U.S. EPA 2003). This recommendation is based on the biologically-based water clarity criteria reference curves. The methodology followed in the derivation of those reference curves did not include adding the half tidal range to the restoration depth, Z (see Appendix H). The EPA believes it is important to maintain consistency throughout the entire set of procedures for determining water clarity criteria attainment.

Using Midchannel Data to Estimate Shallow-water Conditions

The majority of baywide, regional and local tidal Bay water quality monitoring programs in the past have collected data only from fixed midchannel stations. Incorporating a rotational shallow-water monitoring into the tidal monitoring network is leading to the generation of shallow-water data for evaluating attainment for the water clarity criteria. However, given the rotational nature of this shallow-water monitoring network component, fixed midchannel stations are still going to be used in criteria assessment. It is relevant, in assessing water clarity criteria attainment, to note the extent to which water quality monitoring data collected from midchannel stations in the Chesapeake Bay and its tidal tributaries represent conditions at shallow-water sites where underwater bay grasses potentially occur and the water clarity criteria apply.

Evaluation of Midchannel and Nearshore Data Comparability. Several studies have addressed the shallow-water versus midchannel sampling issue in the Chesapeake Bay (Stevenson et al. 1991; Batiuk et al. 1992; Ruffin 1995; Bergstrom, unpublished data; Parham 1996; Karrh 1999; Hunley, unpublished data). While most studies indicate that midchannel data can be used to describe shallow-water conditions, several suggest the opposite. There is no doubt that demonstrable differences in water quality can occur between shallow-water and midchannel stations over varying temporal and spatial scales, especially when bay grasses are present (Ward et al. 1984; Moore 1996). Other possible causes of variability between shallow-water and midchannel environments include localized resuspension of sediments, algal patchiness, point source effluents or sediment chemistry variability (Goldsborough and Kemp 1988; Moore 1996).

Using Shallow-water Water Quality Data where Available. Because of these sources of variability, the use of midchannel data to evaluate the water-clarity criteria should be avoided whenever shallow-water data are available. Managers of tidal-water quality monitoring programs should consider the need for enhanced evaluation of the shallow-water environment in future monitoring efforts and requests for funding.

Guidance for Using Midchannel Data when Shallow-water Information Is Absent. When nearshore shallow-water monitoring data are not available, Karrh (1999) and Batiuk et al. (2000) provide guidance on the use of midchannel information. The findings published by Karrh (1999) and reported by Batiuk et al. (2000) were based on a comprehensive analysis of shallow-water and midchannel data in the Chesapeake Bay, which have been collected since 1983 to determine whether such data can be used to characterize shallow-water environments. Data for the Karrh (1999) study, obtained from state monitoring efforts, academic researchers and citizen monitors, were incorporated from the entire Chesapeake Bay and its tidal tributaries, including the upper Chesapeake Bay region; the Middle, Magothy, Rhode, Chester, Choptank, Patuxent, Potomac, Rappahannock, Poquoson, York and James rivers; and Mobjack Bay.

These reports indicated that underwater bay grass habitat quality conditions (relative to attainment or nonattainment of the 1992 bay grass habitat requirements published by Batiuk et al. in 1992 and Dennison et al. in 1993) were comparable between nearshore and adjacent midchannel stations 90 percent of the time, when station pairs were separated by less than two kilometers.

Midchannel and nearshore areas usually show similar attainment/nonattainment of the individual water quality parameters—K_d or Secchi depth, dissolved inorganic nitrogen, dissolved inorganic phosphorus, chlorophyll *a* and total suspended solids—published in 1992 as the original set of Chesapeake Bay underwater bay grass habitat requirements (Batiuk et al. 1992; 2000). These same water quality parameters are used in calculating percent light-at-the-leaf (PLL) and applying the supporting diagnostics tools (see Chapter VII).

The Karrh (1999) study results also indicated that individual water quality parameter concentrations at many of the comparison sites differed significantly between shallow-water and midchannel areas, from a statistical standpoint. These differences suggest that although the attainment/nonattainment status may have been comparable, the magnitude of attainment/nonattainment and the diagnosis of the water quality factors involved between the shallow-water and midchannel areas could be affected.

It should be noted that the comparisons made between shallow-water and midchannel areas may also have been affected by temporal factors, given that the pairs were not sampled on the same day. Water quality managers should also be aware that these reports were developed to support the application of nonregulatory bay grass habitat requirements and restoration goals, not regulatory aquatic life water quality criteria. Therefore, the report's recommendations for the allowable use of midchannel data should be used with appropriate caution only in the absence of shallow-water quality monitoring data.

Estimating Areas Characterized by Midchannel Stations. It is possible to determine a distance from a specific midchannel station for which it is appropriate to use the midchannel distance to characterize the shallow-water environment. Results revealed that the underwater bay grass habitat quality conditions are indistinguishable between shallow-water and adjacent midchannel stations 90 percent of the time, when station pairs were separated by less than two kilometers. This radius differs on a site-by-site basis (see Batiuk et al. 2000, Chapter IX, Table IX-3 and figures IX-4a through IX-4o). Decisions to use midchannel data to characterize shallow-water conditions should be made on a site-by-site, tributary-by-tributary basis. Karrh (1999) provides detailed illustrations of estimated distances from midchannel monitoring stations to the farthest point where the shallow-water/midchannel data are comparable.

River Input and Flow Considerations

States responsible for measuring water clarity/shallow-water bay grass designated use attainment near the fall-lines of where major free flowing rivers enter tidal waters should recognize the strong influences of intra- and interannual flows on conditions in the shallow-water habitats. The quality of the waters entering the tidal-fresh reaches of these rivers is greatly influenced by flow levels. The decadal scale record of underwater bay grasses distributions and concurrent water quality monitoring data provides the states and other users with a wealth of information from which to gather information on the relative influence of flow conditions on observed attainment. In the case of water clarity attainment and restoration of underwater grasses, the EPA recommends recognition within states' water quality standards of the influence of river flow conditions on water clarity and underwater bay grasses (through chlorophyll *a* and suspended solids contributions to reduced light penetration) particularly for the tidal reaches just below the major river fall lines. Management actions directed toward attaining the water clarity criteria and shallow-water bay grass designated use attainment in these tidal reaches should also reflect the long-term flow conditions and influences on local shallow-water habitat quality.

CHLOROPHYLL *A* CRITERIA ASSESSMENT

'Recommended' Level of Monitoring

Monitoring for chlorophyll *a* criteria assessment requires a significant amount of spatially and temporally intensive data. Algal blooms tend to occur sporadically and in patches throughout the Chesapeake Bay. The severe nature of blooms, associated dissolved oxygen extremes and associated releases of toxins are what cause ecological impacts.

To capture data that reflect those blooms, spatially and temporally intensive data are required. In the shallow-water designated use areas, the DATAFLOW system can adequately characterize the spatial variability in chlorophyll *a*.

A 'recommended' monitoring program for the open-water and migratory spawning and nursery designated use areas would include a combination of fixed-station, continuous track and remotely sensed data collection. Fixed-station data is usually considered the most reliable type of data collection because it includes ambient sample analysis in the laboratory. For that reason, it serves as the baseline for all other types of chlorophyll *a* measurement. Continuous-track ('flow-through') monitoring should be developed for all vessels used to conduct the fixed-station monitoring program. Like the DATAFLOW system, the continuous-track monitoring would provide intensively collected data that would significantly improve our assessment of the spatial variation in chlorophyll *a*. One of the limitations of continuous-track monitoring is that it does not cover the entire Chesapeake Bay. Thus, the third type of recommended monitoring is remote sensing, which can provide estimates of chlorophyll *a* for most locations in the Bay. It is not clear at this point that remote sensing is ready for the criteria assessment application, but it does offer great potential. All three types of monitoring (fixed-station, continuous track, remote sensing) are recommended because each provides complementary types of information that are useful for evaluating different parts of the Chesapeake Bay.

'Adequate' Level of Monitoring

Assuming that funding will not be available for the recommended monitoring approach, an alternative would be to collect only fixed-station data enhanced with continuous track monitoring. This provides spatially intensive data wherever cruises occur, including most tidal tributaries. Furthermore, it represents a relatively small cost, particularly when considered in proportion to the amount of information that could be generated. The improvement of this approach over current monitoring is that spatially intensive data collection would be collected on a regular basis in most large tidal tributaries. The limitation would be that data would only be collected along cruise tracks and not intensively throughout the Chesapeake Bay (i.e., as might be possible with remote sensing). For that reason, the uncertainty associated with the 'adequate' monitoring plan would be higher than the 'recommended' plan.

'Marginal' Level of Monitoring

If funding is not available for even the adequate level of monitoring, assessments would need to rely on fixed-station data only. This type of monitoring is limited in its ability to assess the spatial and temporal variability of chlorophyll *a* found in most of the Chesapeake Bay. The uncertainty associated with the assessment of chlorophyll *a* criteria attainment using only the fixed-station monitoring program would be expected to be quite high.

Assessing Chlorophyll *a* Criteria Attainment

Phytoplankton are actively growing and consuming nutrients throughout the surface mixed layer of the water column. The pycnocline region below the this layer, as well as other depth strata below the pycnocline, rarely contain sufficient light for active photosynthesis. Therefore, there is little or no autotrophic growth below the surface mixed layer, although phytoplankton accumulate within and below the pycnocline due to the physical processes of sinking and estuarine circulation. Given that the chlorophyll *a* concentrations throughout the water column will be expressed at the surface at some point during the natural cycling of phytoplankton and for the sampling reasons described above, the chlorophyll *a* criteria are applied to surface waters only.

Chlorophyll *a* samples used in determining attainment of numerical chlorophyll *a* criteria should be collected at 0.5 to 1 meter below the surface. The majority of historical and current chlorophyll *a* data are collected from a discrete surface depth. The potential for assessing broad areas of the estuary via high-speed vessels and flow-through technologies or remote sensing can only be tapped if the criteria apply only to surface chlorophyll *a* distributions. In general, chlorophyll *a* concentrations are highest in the surface layer of the water column.

The formulation and ultimately the assessment of numerical chlorophyll *a* criteria should be based upon seasonal dynamics and concentrations of chlorophyll *a* in the Chesapeake Bay and its tidal tributaries. Spring and summer were chosen for these purposes because chlorophyll *a* concentrations attain annual peaks during these months in the estuary's various salinity regimes. Any site-specific numerical impairment-based chlorophyll *a* criteria should be applied as salinity regime-based spring (March through May) and summer (July through September) seasonal mean concentrations.

In spring, river inputs with high dissolved inorganic nitrogen dominate, dissolved inorganic nitrogen is abundant, phytoplankton are primarily limited by the availability of phosphorus, and bottom waters are oxygenated. By contrast, under summer conditions, recycling of nitrogen and phosphorus is the dominant supply, both dissolved inorganic nitrogen and dissolved inorganic phosphorus are low, phytoplankton are primarily limited by the availability of nitrogen and deep bottom waters are anoxic. The ecological implications of chlorophyll *a* concentrations in spring and summer are vital to physical and chemical processes such as hypoxia and anoxia, nutrient recycling and light attenuation, and biological processes such as the availability of sufficient and appropriate food for filter and suspension-feeders.

After years of monitoring the Chesapeake Bay and its tidal tributaries, characterizing phytoplankton dynamics and analyzing these data, Bay scientists have found that June is indeed a 'transition' month from spring to summer. During certain years, June behaves more like spring in the types and quantity of phytoplankton that are present, while in other years, the flora reflect the summer patterns of composition and densities. This means that in attempts to measure 'spring' and 'summer' phytoplankton populations, June is either springlike, summerlike or uniquely different from either season.

At present, the recommended method for assessing numerical chlorophyll *a* criteria attainment is to interpolate monthly chlorophyll *a* concentrations for each surface interpolator cell from the available fixed stations. The interpolator cells can be associated with the proper segment and salinity zone, so that each cell's chlorophyll *a* concentration can be compared to the proper chlorophyll *a* criterion value. The cell area is then accumulated in the fail or pass tally for each Chesapeake Bay Program segment for each month. The cumulative frequency distribution curve resulting from the monthly percent attainment measures over the spring or summer seasons and the three-year attainment period is then compared statistically to the reference curve to determine the degree of attainment/nonattainment. If the curves are significantly different, then the segment/designated use is considered out of attainment, and failing by the amount defined by the area between the two curves.

River Input and Flow Considerations

States responsible for measuring chlorophyll *a* criteria attainment near the fall lines where major free-flowing rivers enter tidal waters should recognize the strong influences of intra- and interannual flows on conditions in the adjacent tidal-fresh habitats. In addition to their upstream contributions of chlorophyll *a*, the flow levels of waters directly entering the tidal-fresh reaches of these rivers greatly influence the resulting tidal habitat chlorophyll *a* concentrations. The decadal scale record of water quality monitoring data provides the states and other users with a wealth of information from which to understand the relative influence of flow conditions on observed chlorophyll *a* criteria attainment. The EPA recommends recognition within states' water quality standards of the influence of river flow conditions on chlorophyll *a* concentrations, particularly in the tidal reaches just below the major fall lines. Management actions directed toward chlorophyll *a* criteria attainment in these tidal reaches should also reflect the long-term flow conditions and influences on local water quality.

EVALUATION OF CHESAPEAKE BAY WATER QUALITY MODEL OUTPUT

The Chesapeake Bay Program has developed what have become standard estuarine modeling tools, including a watershed model (Donigian et al. 1994; Linker et al. 1996, 2000), airshed model (Shin and Carmichael 1992; Appleton 1995, 1996), estuarine hydrodynamic model (Wang and Johnson 2000), estuarine water quality model (Cerco 1993, 1995a, 1995b; Thomann et al. 1994; Cerco and Meyers 2000; Cerco 2000; Cerco and Moore 2001; Cerco et al. 2002) and estuarine sediment diagenesis model (Di Toro 2001). Together these linked simulations provide a system to estimate dissolved oxygen, water clarity and chlorophyll *a* in 35 major segments of the Chesapeake Bay and its tidal tributaries. The same criteria attainment assessment process applied to observed data is applied to integrated modeling/monitoring 'scenario' data to determine likely criteria attainment under management loading scenarios.

The watershed and airshed models are loading models. As such, they provide an estimate of management actions through air controls, agricultural best management practices, or point source controls which will reduce nutrient or sediment loads to the Chesapeake Bay tidal waters. The advantage of using loading models is that the full simulation through different hydrologies of wet, dry and average periods can be simulated on existing or hypothetical land use patterns. All of the Chesapeake Bay Program models used in this system simulate the 10-year period from 1985 to 1994 (Linker and Shenk 2000).

CHESAPEAKE BAY WATERSHED MODEL

The Chesapeake Bay Watershed Model is designed to simulate nutrient and sediment loads delivered to the Chesapeake Bay under different management scenarios (Donigian et al. 1994; Linker et al.1996; Linker 1996). The simulation is an overall mass balance of nitrogen and phosphorus in the basin, so the ultimate fate of the input nutrients is incorporation into crop or forest plant material, incorporation into soil, or loss through river runoff.

The Chesapeake Bay Watershed Model has been in continuous operation in the Chesapeake Bay Program since 1982 and has had many upgrades and refinements. The current version of the Watershed Model, Phase 4.3, is a comprehensive package for the simulation of watershed hydrology, nutrient and sediment export from pervious and impervious land uses and the transport of these loads in rivers and reservoirs. The model is based on a modular set of computer codes called Hydrologic Simulation Program—Fortran (HSPF). A slightly modified version of HSPF release 11.1 (Bicknell et al. 1996) is applied in the watershed simulation. Version 11 is a widely-used public-domain model supported by the U.S. EPA, U.S. Geological Survey and U.S. Army Corps of Engineers (Shenk et al. 1998).

The Watershed Model allows for the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The model takes into account watershed land uses and the application of fertilizers and animal manure; loads from point sources, atmospheric deposition and onsite wastewater management systems; and best management practice reduction factors and delivery factors. Land uses, including cropland, pasture, urban areas and forests, are simulated on an hourly time-step.

Fourteen calendar years (1984–1997) of varying hydrology are simulated by the Watershed Model, although only 10 of those years (1985–1994) are used in this study because of the more limited simulation period of the Chesapeake Bay water quality model. Scenarios are run on a 1-hour time step and results are often aggregated into 10-year-average annual loads for reporting and comparisons among scenarios. Watershed Model results, in the form of daily flows and nutrient and sediment loads, are used as input to the Chesapeake Bay water quality model.

CHESAPEAKE BAY WATER QUALITY MODEL

The complex movement of water within the Chesapeake Bay, particularly the density driven vertical estuarine stratification, is simulated with a Chesapeake Bay hydrodynamic model of more than 13,000 cells (Wang and Johnson 2000). Three-dimensional equations of the intertidal physical system, including equations of continuity, momentum, salt balance and heat balance, are employed to provide the correct simulation of the movement, or the barriers to movement, of the water quality constituents of dissolved oxygen, water clarity and chlorophyll *a*. Correct formulation of vertical mixing, including the simulation of vertical eddy diffusion coefficients in the hydrodynamic model is particularly important for the dissolved oxygen criteria as the principal barrier to vertical movement of dissolved oxygen from surface waters to the deep water is the pycnocline simulated by the hydrodynamic model.

The water quality model is linked to the hydrodynamic model and uses complex nonlinear equations describing 26 state variables relevant to the simulation of dissolved oxygen, water clarity and chlorophyll *a* (Cerco 1993, 1995a, 1995b, 2000; Thomann et al. 1994; Cerco and Meyers 2000). Dissolved oxygen is simulated as the mass balance calculation of reaeration at the surface, respiration of algae, benthos and underwater bay grasses; photosynthesis of algae, benthic algae and underwater bay grasses; and the diagenesis, or decay of organics, by microbial processes in the water column and sediment. This mass balance calculation is made for each model cell and for associated sediment cells at each hourly time step, providing an estimate of dissolved oxygen from nutrient loads from the watershed and airshed to the waters of the 35 major segments of the Chesapeake Bay and its tidal tributaries. Chlorophyll *a* is estimated based on Monod calculations of algal growth given resource constraints of light, nitrogen, phosphorous or silica. Water clarity is estimated from the daily input loads of sediment from the watershed and shoreline acted on by regionally-calibrated settling rates, as well as estimated advection due to hydrodynamics. Coupled with the water quality model are simulations of settling to the sediment of organic material and its subsequent decay and flux of inorganic nutrients from the sediment (Di Toro 2001) as well as a coupled simulation of underwater bay grasses in shallow waters (Cerco and Moore 2001).

INTEGRATION OF MONITORING AND MODELING FOR CRITERIA ASSESSMENT

The load allocation process requires that specific water quality conditions be met over critical time periods within designated use areas. These areas are given either a ‘pass’ or ‘fail’ status. While the Chesapeake Bay water quality model can estimate changes in water quality due to changes in input loads with reasonable accuracy, an exact match of the simulated and observed data is impossible. The following method was developed to make the best use of the strengths of the Chesapeake Bay water quality model and the Chesapeake Bay Water Quality Monitoring Program in assessing criteria attainment.

The observed data is used to assess criteria attainment during a 'base' period corresponding to the years of calibration for the Chesapeake Bay water quality model, 1985–1994. The Chesapeake Bay water quality model is used in scenario mode to determine the effect of changes in nutrient and sediment loads on water quality concentrations. A modified 1985–1994 observed data set is generated for each scenario using both the model and the observations. The same criteria attainment assessment process applied to the observed data is then applied to this scenario data to determine likely criteria attainment under modified loading scenarios.

To generate the modified data set for a particular scenario (e.g., 2010 Clean Air Act), the EPA compared the output of the scenario to the output of the calibration on a point-by-point and month-by-month basis. For each point in space and time where an observation exists during the 1985–1994 period, a mathematical relationship between the model scenario and the model calibration was established by regressing the 30 or so daily values for the month when the observation occurred in the water quality model cell that contains the observation. The regression generates a unique equation for each point and month that transforms a calibration value to a scenario value. This relationship is then applied to the monitored observation as an estimate of what would have been observed had the Chesapeake Bay watershed been under the scenario management rather than the management that existed during 1985–1994. This procedure is repeated for each monitored observation of dissolved oxygen, water clarity and chlorophyll *a* to generate an 'observed' data set for the scenario. For a full discussion of this procedure, see *A Comparison of Chesapeake Bay Estuary Model Calibration With 1985–1994 Observed Data and Method of Application to Water Quality Criteria* (Linker et al. 2002).

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