United States
Environmental Protection
Agency

Region III
Chesapeake Bay
Program Office

Region III
Water Protection
Division

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In coordination with the Office of Water/Office of Science and Technology, Washington, DC

# Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries

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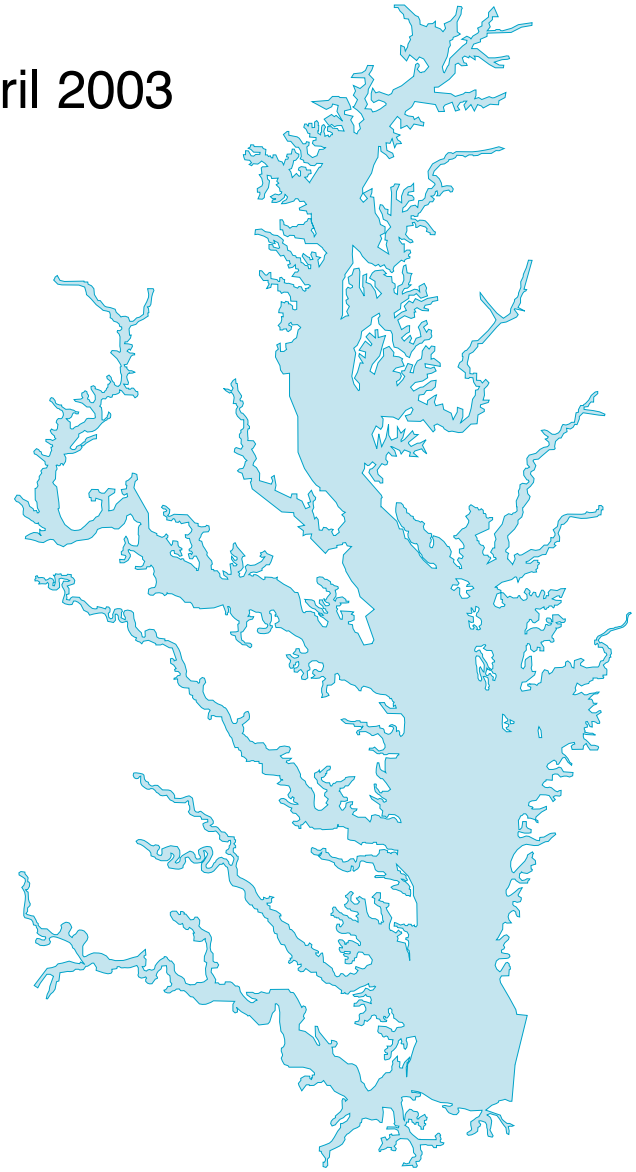

# Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries

April 2003

U.S. Environmental Protection Agency
Region III
Chesapeake Bay Program Office
Annapolis, Maryland

*and*

Region III
Water Protection Division
Philadelphia, Pennsylvania

*in coordination with*

Office of Water
Office of Science and Technology
Washington, D.C.

# Foreword

In order to achieve and maintain the water quality conditions necessary to protect the aquatic living resources of the Chesapeake Bay and its tidal tributaries, the U.S. Environmental Protection Agency (EPA) Region III has developed this guidance document, entitled *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll* a *for the Chesapeake Bay and Its Tidal Tributaries (Regional Criteria Guidance)*. This document presents the EPA's regionally-based nutrient and sediment enrichment criteria expressed as dissolved oxygen, water clarity and chlorophyll *a* criteria, applicable to the Chesapeake Bay and its tidal tributaries. EPA is issuing this guidance pursuant to Section 117(b) of the Clean Water Act and in accordance with the water quality standards regulations (40 CFR Part 131).

This *Regional Criteria Guidance* provides EPA's recommendations to the Chesapeake Bay states for use in establishing their water quality standards consistent with Section 303(c) of the Clean Water Act. Under Section 303(c), states and authorized tribes have the primary responsibility for adopting water quality standards as state or tribal law or regulation. The standards must contain scientifically defensible water quality criteria that are protective of designated and existing uses. EPA's water quality standards regulations suggest three possible sources for establishing protective criteria: 1) guidance for water quality criteria recommendations published under the authority of Section 304(a) of the Clean Water Act, 2) Section 304(a) guidance modified to reflect site-specific conditions, or 3) other scientifically defensible methods (see 40 CFR 131.11). Section 117 of the Clean Water Act authorizes a Chesapeake Bay programs office to publish information pertaining to the environmental quality of the Chesapeake Bay, as well as to coordinate Federal and state efforts to improve the quality of the Bay.

Quantified water quality criteria contained within state or tribal water quality standards are essential to a water quality-based approach to pollution control. Whether expressed as numeric criteria or quantified translations of narrative criteria within state or tribal water quality standards, quantified criteria serve as a critical basis for assessing the attainment of designated uses and measuring progress toward meeting

the water quality goals of the Clean Water Act and the *Chesapeake 2000* agreement. This *Regional Criteria Guidance* presents scientifically defensible methods and serves as guidance for the states to use in developing appropriate and protective Section 303 criteria and standards for the Chesapeake Bay. EPA's *Regional Criteria Guidance* is not law or regulation; it is guidance that states in the Chesapeake Bay watershed may consider in the development and/or modification of appropriate criteria for their water quality standards.

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# Executive Summary

In order to achieve and maintain water quality conditions necessary to protect aquatic living resources of the Chesapeake Bay and its tidal tributaries, the U.S. Environmental Protection Agency (EPA) Region III has developed guidance, entitled *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll* a *for the Chesapeake Bay and Its Tidal Tributaries (Regional Criteria Guidance)*. This final guidance is intended to assist the Chesapeake Bay states, Maryland, Virginia and Delaware, and the District of Columbia, in adopting revised water quality standards to address nutrient and sediment-based pollution in the Chesapeake Bay and its tidal tributaries.

EPA Region III developed this guidance to promote the overall goals of the Clean Water Act and specifically in accordance with the EPA *National Strategy for the Development of Regional Nutrient Criteria*, announced in June 1998. This national nutrient strategy laid out the EPA's intentions to develop technical guidance manuals for four types of waters (lakes and reservoirs, rivers and streams, estuaries and coastal waters and wetlands) and to produce criteria for specific nutrient eco-regions (www.epa.gov/ost/standards/nutrient.html). In addition, the EPA is committed to working with states and tribes to develop more refined and localized nutrient and nutrient enrichment-related criteria based on approaches described in the water body guidance manuals. The *Regional Criteria Guidance* provides the regional nutrient guidance applicable to the Chesapeake Bay and its tidal tributaries.

EPA Region III developed the *Regional Criteria Guidance* in accordance with Section 117(b) of the Clean Water Act using the multi-stakeholder approach to implementing the *Chesapeake 2000* agreement. *Chesapeake 2000* was signed on June 28, 2000, by the governors of Maryland, Pennsylvania and Virginia, the mayor of the District of Columbia, the chair of the Chesapeake Bay Commission and the Administrator of the U.S. EPA. Subsequently, the governors of Delaware, New York and West Virginia signed a Memorandum of Understanding committing to implement the Water Quality Protection and Restoration section of the agreement.

The water quality criteria and tidal-water designated uses presented in this document are the product of a collaborative effort among the Chesapeake Bay Program partners. They represent a scientific consensus based on the best available scientific

findings and technical information defining the water quality conditions necessary to protect Chesapeake Bay aquatic living resources from effects due to nutrient and sediment over-enrichment. Various stakeholder groups have been involved in their development, with contributions from staff of federal and state governments, local agencies, scientific institutions, citizen conservation groups, business and industry.

In the *Regional Criteria Guidance* the EPA recommends and expects that the numerical criteria and refined designated uses will be considered by and appropriately incorporated into the water quality standards of the Chesapeake Bay jurisdictions with tidal waters—Maryland, Virginia, Delaware and the District of Columbia. Using existing state authority and public process, each jurisdiction is expected to consider and propose criteria and appropriate designated uses, subject to review and approval by the EPA, that are consistent with the requirements of the Clean Water Act. The EPA will consider the *Regional Criteria Guidance* in reviewing any state submission regarding this issue. The guidance contained in this document is subject to change with the synthesis and interpretation of future scientific findings.

## REFINED DESIGNATED USES: ESSENTIAL AQUATIC LIFE COMMUNITIES

EPA Region III has identified and described five habitats (or designated uses) that, when adequately protected, will ensure the protection of the living resources of the Chesapeake Bay and its tidal tributaries. Those five uses (see Figure 1) provide the context in which EPA Region III derived adequately protective Chesapeake Bay water quality criteria for dissolved oxygen, water clarity and chlorophyll *a*, which are the subject of this *Regional Criteria Guidance*. Accurate delineation of where to apply these tidal-water designated uses is critical to the Chesapeake Bay water quality criteria. EPA Region III is publishing a *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability*, which provides further information on the development and geographical extent of the designated uses to which the criteria may apply.

The *migratory fish spawning and nursery designated use* protects migratory and resident tidal freshwater fish during the late winter to late spring spawning and nursery season in tidal freshwater to low-salinity habitats. Located primarily in the upper reaches of many Bay tidal rivers and creeks and the upper mainstem Chesapeake Bay, this use will benefit several species including striped bass, perch, shad, herring, sturgeon and largemouth bass.

The *shallow-water bay grass designated use* protects underwater bay grasses and the many fish and crab species that depend on the vegetated shallow-water habitat provided by underwater grass beds.

The *open-water fish and shellfish designated use* focuses on surface water habitats in tidal creeks, rivers, embayments and the mainstem Chesapeake Bay, and protects diverse populations of sport fish, including striped bass, bluefish, mackerel and sea trout, as well as important bait fish such as menhaden and silversides.

The *deep-water seasonal fish and shellfish designated use* protects animals inhabiting the deeper transitional water-column and bottom habitats between the well-mixed surface waters and the very deep channels. This use protects many bottom-feeding fish, crabs and oysters, and other important species such as the bay anchovy.

The *deep-channel seasonal refuge designated use* protects bottom sediment-dwelling worms and small clams that bottom-feeding fish and crabs consume naturally. Low to occasional no dissolved oxygen conditions occur in this habitat zone during the summer.

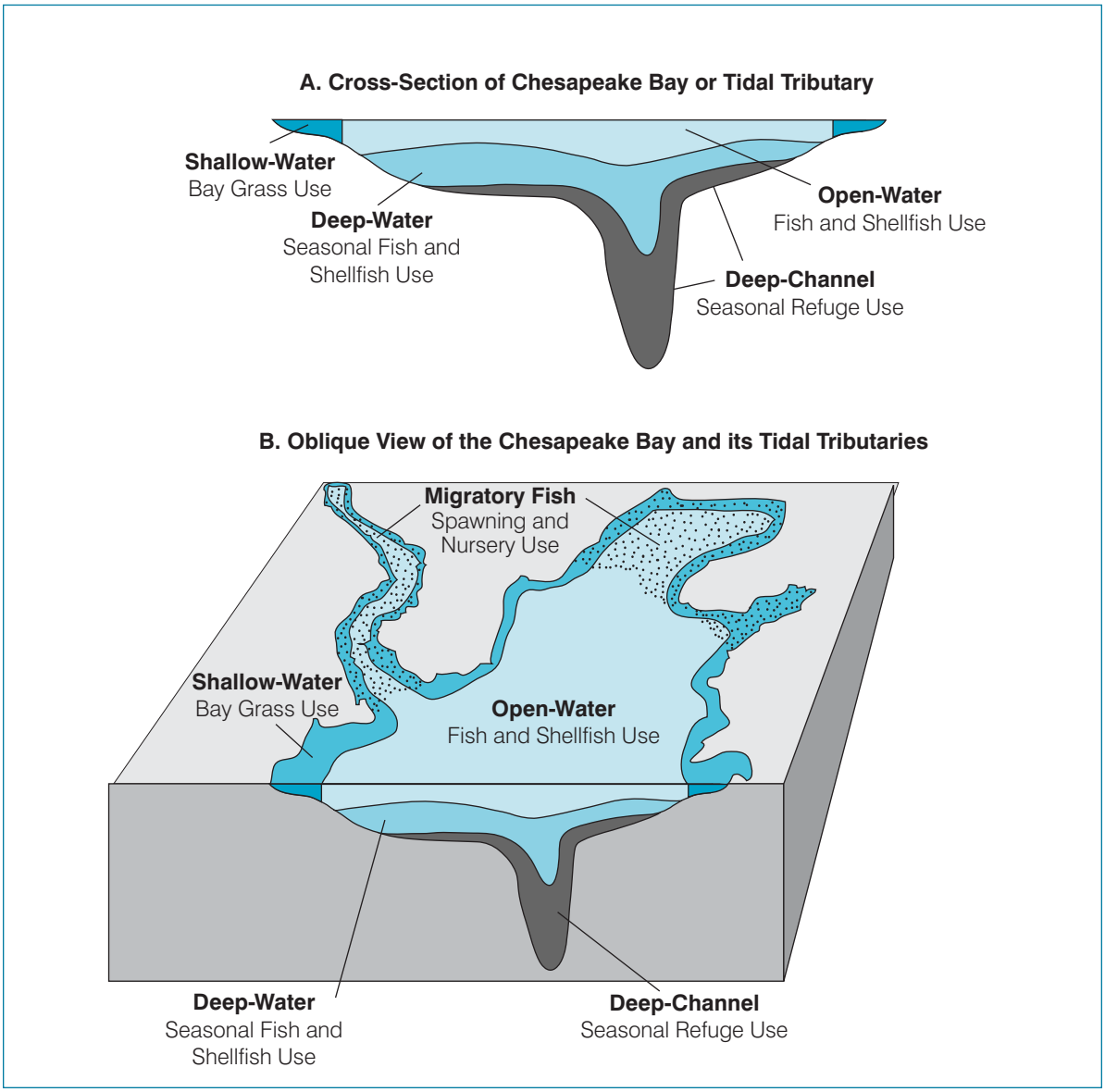


**Figure 1.** Conceptual illustration of the five Chesapeake Bay tidal water designated use zones.

The Chesapeake Bay watershed states with tidally influenced Bay waters—Maryland, Virginia, Delaware and the District of Columbia—are ultimately responsible for defining and formally adopting a refined set of designated uses into their respective water quality standards.

## DISSOLVED OXYGEN CRITERIA

Oxygen is one of the most essential environmental constituents supporting life. In the Chesapeake Bay's deeper waters, there is a natural tendency toward reduced dissolved oxygen conditions because of the Bay's physical morphology and estuarine circulation. The Chesapeake Bay's highly productive shallow waters, coupled with strong density stratification, long residence times (weeks to months), low tidal energy and its tendency to retain, recycle and regenerate nutrients from the surrounding watershed, all set the stage for low dissolved oxygen conditions. Against this backdrop, EPA Region III has derived a set of dissolved oxygen criteria to protect specific aquatic life communities (outlined above) and reflect the Chesapeake Bay's natural processes that define distinct habitats (Figure 1).

The derivation of these criteria followed the EPA's national guidelines; the EPA, National Marine Fisheries Science and U.S. Fish and Wildlife Service's joint national endangered species consultation guidelines; and the risk-based approach used in developing the EPA's Virginian Province saltwater dissolved oxygen criteria (for estuarine and coastal waters from Cape Cod, Massachusetts to Cape Hatteras, North Carolina). The resulting criteria reflect the needs and habitats of Chesapeake Bay estuarine living resources and are structured to protect five tidal-water designated uses (Figure 2).

Criteria for the migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated uses were set at levels to prevent impairment of growth, and to protect the reproduction and survival of all organisms (Table 1). Criteria for deep-water seasonal fish and shellfish designated use habitats during seasons when the water column is significantly stratified were set at levels to protect juvenile and adult fish, shellfish and the recruitment success of the bay anchovy. Criteria for deep-channel seasonal refuge designated use habitats in summer were set to protect the survival of bottom sediment-dwelling worms and clams.

## WATER CLARITY CRITERIA

Underwater bay grass beds in the Chesapeake Bay create rich animal habitats that support the growth of diverse fish and invertebrate populations. Underwater bay grasses, also referred to as submerged aquatic vegetation or SAV, help improve tidal water quality by retaining nutrients as plant material, stabilizing bottom sediments (preventing their resuspension) and reducing shoreline erosion. The health and survival of these underwater plant communities in the Chesapeake Bay and its tidal

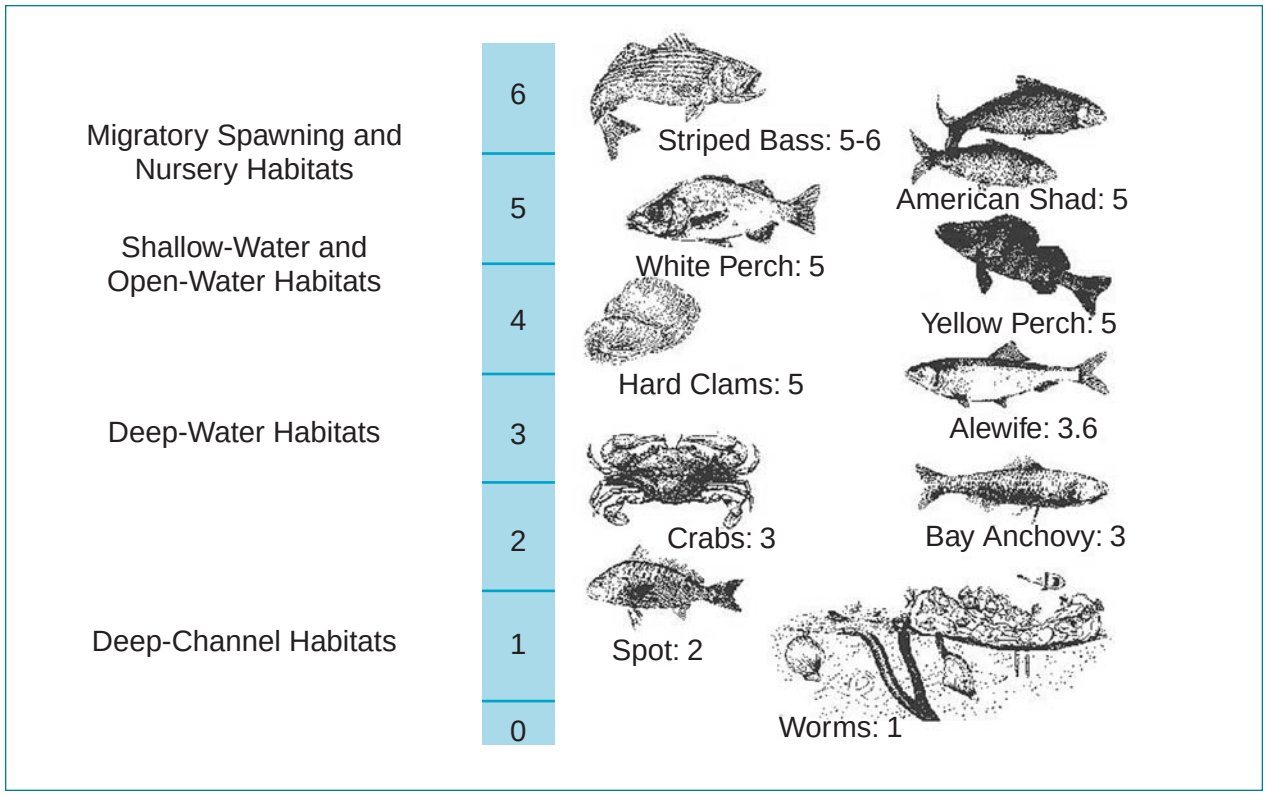


**Figure 2.** Dissolved oxygen (mg liter$^{-1}$) concentrations required by different Chesapeake Bay species and communities.

tributaries depend on suitable environmental conditions. The loss of underwater bay grasses from the shallow waters of the Chesapeake Bay, which was first noted in the early 1960s, is a widespread, well-documented problem. The primary causes of the decline of these underwater bay grasses are nutrient over-enrichment and increased suspended sediments in the water, and associated reductions in light availability (Figure 3). Other factors such as climatic events and herbicide toxicity may also have contributed to the loss of bay grasses. In order to restore these critical habitats and food sources, enough light must penetrate the shallow waters to support the survival, growth and repropagation of diverse, healthy underwater bay grass communities.

EPA Region III has identified Chesapeake Bay water clarity criteria to establish the minimum level of light penetration required to support the survival, growth and continued propagation of underwater bay grasses. Using a worldwide literature synthesis, an evaluation of Chesapeake Bay-specific field study findings, as well as model simulation and diagnostic tools, the EPA derived Chesapeake Bay-specific water clarity criteria for low and higher salinity habitats (Table 2).

The water clarity criteria, applied only during the bay grass growing seasons, are presented in terms of the percent ambient light at the water surface extending through the water column and the equivalent Secchi depth by application depth. The

**Table 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.

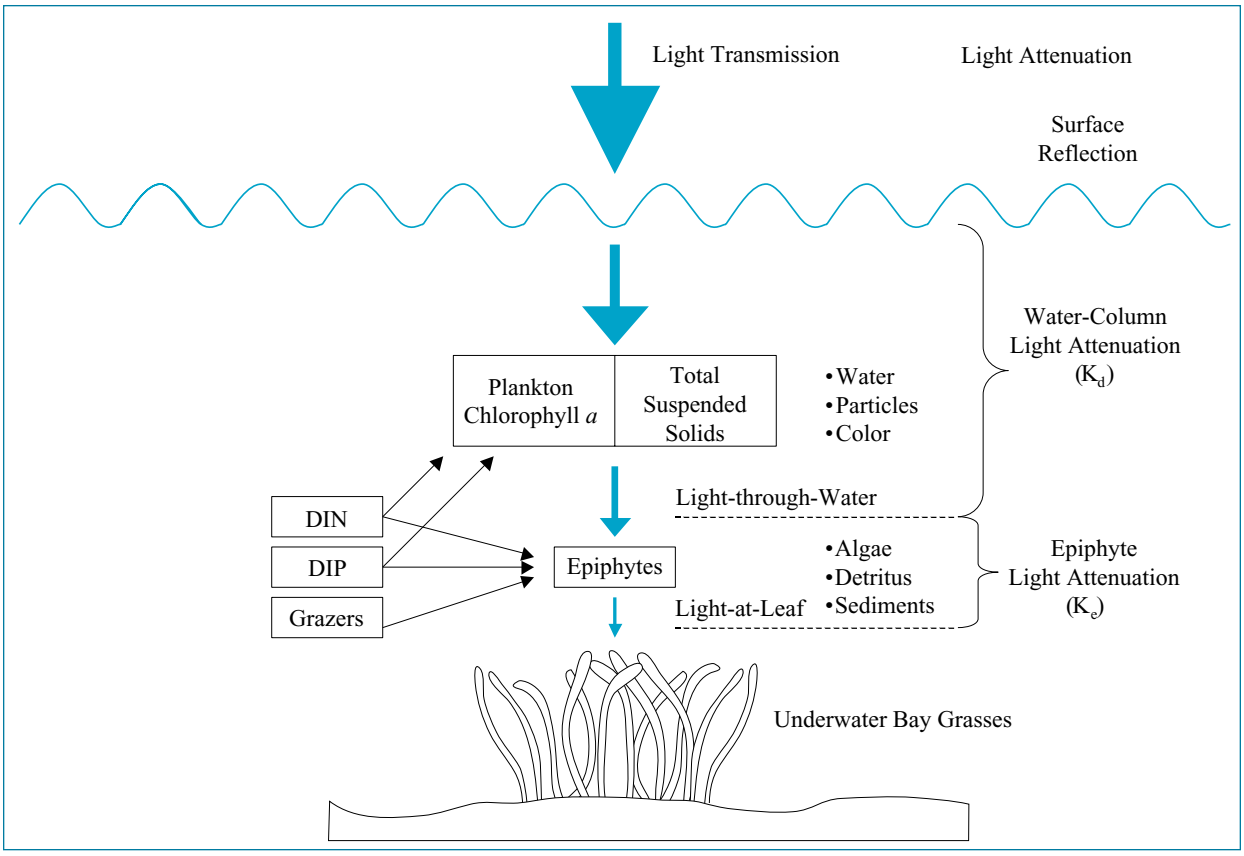


**Figure 3.** Availability of light for underwater bay grasses is influenced by water-column and at-the-leaf surface light attenuation processes. DIN = dissolved inorganic nitrogen and DIP = dissolved inorganic phosphorus.

**Table 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 |

recommended percent light-through-water criteria can be directly measured using a Secchi disk or a light meter. A specific application depth is required in order to apply and determine attainment of the water clarity criteria.

## CHLOROPHYLL *A* CRITERIA

Phytoplankton are small, often microscopic plants floating in the water. These organisms form the base of the Chesapeake Bay's food web, linking nutrients and sunlight energy with forage fish such as menhaden and bay anchovy, and with bottom-dwelling invertebrates such as oysters, clams and worms. The majority of the Bay's animals feed directly on phytoplankton or on organisms that consume the phytoplankton. Therefore, the Bay's "carrying capacity," or its ability to produce and maintain a diversity of species, depends in large part on how well phytoplankton meet the nutritional needs of their consumers.

A primary characteristic of algae is the presence of photosynthetic pigments. Chlorophyll *a* is the primary photosynthetic pigment in algae and cyanobacteria (blue-green algae). Since chlorophyll *a* is a measure of photosynthesis, it is thus also a measure of the primary food source of aquatic food webs.

Chlorophyll *a* also plays a direct role in reducing light penetration in shallow-water habitats, which has a direct impact on underwater bay grasses. Uneaten by zooplankton and filter-feeding fish or shellfish, excess dead algae are consumed by bacteria, and in the process, remove oxygen from the water column. Phytoplankton assemblages can become dominated by single species which represent poor food quality or even produce toxins that impair the animals that feed directly on them. From a water quality perspective, chlorophyll *a* is the best available, most direct measure of the amount and quality of phytoplankton and the potential to lead to reduced water clarity and low dissolved oxygen impairments.

The EPA is providing the states with a recommended narrative chlorophyll *a* criteria applicable to all Chesapeake Bay and tidal tributary waters (Table 3). The EPA encourages states to adopt numerical chlorophyll *a* criteria for application to tidal waters in which algal-related designated use impairments are likely to persist even after attainment of the applicable dissolved oxygen and water clarity criteria. The technical information supporting states' quantitative interpretation of the narrative chlorophyll *a* criteria is published in the body of the Chesapeake Bay water quality criteria document.

The three Chesapeake Bay criteria–dissolved oxygen, water clarity and chlorophyll *a*–should be viewed as an integrated set of criteria applied to their respective sets of designated use habitats and addressing similar and varied ecological conditions and water quality impairments. They provide the basis for defining the water quality conditions necessary to protect the five essential Chesapeake Bay tidal-water designated uses.

**Table 3.** Chesapeake Bay narrative chlorophyll *a* 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.

## CRITERIA IMPLEMENTATION

EPA Region III also is presenting Chesapeake Bay criteria implementation procedures as additional regional guidance in accordance with Section 117(b)(2) of the Clean Water Act to the Chesapeake Bay watershed states and other agencies, institutions, groups or individuals considering how to apply the criteria to determine the degree of attainment. The EPA expects that these procedures will promote consistent, baywide application of the criteria across jurisdictional boundaries.

The criteria were derived specifically to protect species and communities in the five tidal-water designated uses during specific time periods. For example, dissolved oxygen criteria have been derived for application to each of the five designated uses, whereas the chlorophyll *a* criteria apply only to open-water fish and shellfish designated use habitats and the water clarity criteria only to the shallow-water bay grass designated use habitats.

In defining what it means for the criteria to be attained, stressor magnitude, duration, return frequency, spatial extent and temporal assessment period must be accounted for. Stressor magnitude refers to how much of the pollutant or condition can be allowed (e.g., 5 mg liter$^{-1}$) while still achieving the designated uses. Duration refers to the period of time over which measurements of the pollutant or water quality parameter is to be averaged (e.g., the 30-day mean). The allowable return frequency at which the criterion can be violated without a loss of the designated use also must be considered. Attainment of all three Chesapeake Bay criteria within the respective designated use habitats should be assessed at the spatial scale of the 78 Chesapeake Bay segments (spatial extent) using the most recent three consecutive years of applicable tidal water quality monitoring data (temporal assessment period).

As the estuarine habitats gradually attain the three Chesapeake Bay criteria, not only will the concentrations and values increase (i.e., dissolved oxygen and water clarity) or decrease (chlorophyll *a*), but also occurrences of extreme changes in concentrations over a short period of time (e.g., dissolved oxygen concentration changes from 6 mg liter$^{-1}$ to 2 mg liter$^{-1}$ in a matter of hours) will be greatly reduced. Even if the Chesapeake Bay ecosystem is fully restored, it is unlikely that a circumstance of 'zero violation' of these criteria will ever be observed, given natural Bay processes and extreme weather events. As these criteria were developed with conservative (protective) assumptions, allowing a small percentage of circumstances in which the criteria may be exceeded will still fully protect the tidal-water designated uses.

The cumulative frequency distribution methodology for defining criteria attainment addresses the circumstances under which the criteria may be exceeded in a small percentage of instances, by integrating the five elements of criteria definition and attainment: magnitude, duration, return frequency, space and time. The methodology summarizes the frequency of instances in which the water quality threshold (e.g., dissolved oxygen concentration) is exceeded, as a function of the area or volume affected at a given place and over a defined period of time. Acceptable and protective combinations of the frequency and spatial extent of such instances are defined using a biologically based reference curve.

Using this approach to define criteria attainment, the EPA recommends a procedure to quantify the spatial extent (area or volume) to which the water quality criterion has been achieved or exceeded for each monitoring event. For example, under a monthly monitoring program, the spatial extent to which the criterion has been achieved or exceeded would be estimated for each month. This could be accomplished through interpolation of the available point, transect and remote-sensing data. The criteria measure could thus be estimated at all locations in a given spatial unit. The spatial extent to which a water quality criterion had been exceeded for a given monitoring event would be defined as the fraction of the total area or volume (expressed as a percent) that exceeds the criterion.

Through the integrated application of coupled airshed, watershed and tidal-water quality Chesapeake Bay models and long-term tidal water quality monitoring data records, the reductions in air, land and water-based loadings of nitrogen, phosphorus and sediments required to attain the criteria-defined ambient tidal-water concentrations of dissolved oxygen, water clarity and chlorophyll *a* can be directly determined. In effect, the conditions necessary for attaining the three sets of Chesapeake Bay water quality criteria can be translated into watershed-based caps on nutrient and sediment loadings and further allocated to specific sources and locations within those watersheds.

# Notices

This document has been developed by the U.S. Environmental Protection Agency (EPA) Region III Chesapeake Bay Program Office, with the assistance and support of the EPA Region III Water Protection Division, EPA Region II, EPA Headquarters Office of Water and Office of Research and Development, the states of Maryland, Virginia, Delaware, Pennsylvania, New York and West Virginia and the District of Columbia.

The goal of the Clean Water Act is to restore and maintain the chemical, physical and biological integrity of the nation's waters and, where attainable, to achieve water quality that provides for the protection and propagation of fish, shellfish and wildlife and recreation in and on the water. As a means of meeting this goal, the Clean Water Act requires states and authorized tribes to establish water quality criteria to protect designated uses. This document provides regional technical guidance and recommendations to states, authorized tribes and other authorized jurisdictions to develop water quality criteria and water quality standards under the Clean Water Act to protect against the adverse effects of nutrient and sediment over-enrichment in the Chesapeake Bay and its tidal tributary waters.

States and tribal decision-makers retain the discretion to adopt approaches that differ from this regional guidance on a case-by-case basis when appropriate and scientifically defensible, consistent with the Clean Water Act. While this document contains the EPA's scientific findings and policy recommendations regarding ambient concentrations of dissolved oxygen, water clarity and chlorophyll *a* that protect Chesapeake Bay estuarine aquatic resources, it is not a substitute for the Clean Water Act or EPA regulations; nor is it a regulation. Thus, it cannot impose legally binding requirements on the EPA, states, authorized tribes or the regulated community, and it may not apply to particular situations or circumstances. The EPA may change this regional guidance in the future.

This document is available to the public through the Internet at http://www.epa.gov/waterscience/standards/nutrient.html or www.chesapeakebay.net/baycriteria.htm. Requests for the document should be sent to the U.S. Environmental Protection Agency, National Service Center for Environmental Publications, 11029 Kenwood Road, Building 5, Cincinnati, Ohio 45242 (513-489-8190) or by email (waterpubs@epamail.epa.gov). Please refer to EPA document number EPA 903-R-03-002.

# Acknowledgments

These Chesapeake Bay-specific water quality criteria were derived through the collaborative efforts, collective knowledge and applied expertise of the following four Chesapeake Bay criteria and standards coordinator teams.

## Water Clarity Criteria Team

Richard Batiuk, U.S. EPA Chesapeake Bay Program Office; Peter Bergstrom, U.S. Fish and Wildlife Service; Arthur Butt, Virginia Department of Environmental Quality; Ifeyinwa Davis, U.S. EPA Office of Water; Frederick Hoffman, Virginia Department of Environmental Quality; Charles Gallegos, Smithsonian Environmental Research Center; Will Hunley, Hampton Roads Sanitation District; Michael Kemp, University of Maryland Horn Point Laboratory; Ken Moore, Virginia Institute of Marine Science; Michael Naylor, Maryland Department of Natural Resources; and Nancy Rybicki, U.S. Geological Survey.

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Laboratory; Mirta Teichberg, Woods Hole Oceanographic Institution; and David Wilcox, Virginia Institute of Marine Science.

## Dissolved Oxygen Criteria Team

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## Chlorophyll *a* Criteria Team

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# Contents

chapter i

# Introduction

Nutrients are essential to the health and diversity of our surface waters. However, excessive nutrients lead to low dissolved oxygen, fish kills, algal blooms and imbalances in the aquatic food web. They also pose potential risks to human health, such as those recently manifested in the harmful algal blooms of the Gulf and East coasts, including the tidal tributaries of the Chesapeake Bay.

National water quality inventories have repeatedly shown that nutrients are a major cause of ambient water quality impairments. The EPA's 1996 Section 305(b) report identified excessive nutrients as the leading cause of impairments to lakes and the second leading cause of impairments to rivers, after siltation. In addition, nutrients were the second leading cause of impairments reported by the states in their 1998 Section 303(d) lists. Nutrients, along with sediment, were the primary causes of impairments to the Chesapeake Bay and its tidal tributaries on the respective Maryland and Virginia Section 303(d) lists. To meet the objectives of the Clean Water Act, the EPA's implementing regulations specify that states must adopt criteria that contain sufficient parameters to protect existing and designated uses. Until 2000, the EPA had not published recommended quantitative water quality criteria for nutrients that states could adopt to protect uses.

In order to achieve and maintain water quality conditions necessary to protect the aquatic living resources of the Chesapeake Bay and its tidal tributaries from the effects of nutrient and sediment pollution, EPA Region III has developed *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll* a *for the Chesapeake Bay and Its Tidal Tributaries* (*Regional Criteria Guidance*). EPA Region III has also identified and described five habitats (or designated uses) that when adequately protected will ensure the protection of the living resources of the Bay and its tidal tributaries. Those five uses (described in Appendix A) provide the context in which EPA Region III derived protective Chesapeake Bay water quality criteria for dissolved oxygen, water clarity and chlorophyll *a* (see Figure 1 in the Executive Summary), which are the subject of the *Regional Criteria Guidance*. EPA Region III has also published the *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability*. This document provides

further information on the development and geographical extent of the designated uses to which the criteria may apply.

## NATIONAL CRITERIA

Under the Clean Water Act Section 304(a), the EPA issues national criteria recommendations to states and tribes to assist them in developing their water quality standards. When the EPA reviews a state or tribal water quality standard for approval under 303(c) of the Clean Water Act, the agency must determine whether the adopted designated uses are consistent with the Clean Water Act requirements and whether the adopted criteria protect the designated use. The EPA's regulations encourage states and tribes, when adopting water quality criteria as part of their water quality standards, to employ the EPA's Section 304(a) guidance, to modify the EPA's 304(a) guidance to reflect site-specific conditions or to use other scientifically defensible methods to derive criteria to protect the designated uses.

## REGIONAL NUTRIENT CRITERIA

In 1995 the EPA gathered a group of nationally recognized scientists and managers to address the national nutrient problem. They recommended that the agency avoid setting criteria for phosphorus or nitrogen that would apply to all water bodies and regions of the country. Instead they suggested that the EPA develop guidance (assessment tools and control measures) for specific bodies of water and ecological regions across the country and use reference conditions, which reflect pristine or minimally affected waters, as a basis for developing nutrient criteria.

Using these suggestions as starting points, the EPA published the *National Strategy for the Development of Regional Nutrient Criteria* in June 1998. The strategy articulated the EPA's intention to develop technical guidance manuals for four types of waters (lakes and reservoirs, rivers and streams, estuaries and coastal waters, and wetlands) and produce nutrient criteria for specific eco-regions. In addition, the EPA is committed to working with states and tribes to develop more refined and localized nutrient criteria based on approaches described in the water body guidance manuals. The *Regional Criteria Guidance* provides EPA's recommendations to the Chesapeake Bay states for use in establishing their water quality standards consistent with Section 303(c) of the Clean Water Act.

## CHESAPEAKE BAY CRITERIA

The EPA's current guidance for dissolved oxygen can be found in the 1986 freshwater dissolved oxygen criteria and 2000 Virginian Province saltwater criteria documents. EPA Region III developed the criteria presented in this document by integrating and supplementing the scientific findings and data to fully protect specific Chesapeake Bay tidal-water habitats. The revised criteria are based on and consistent with the existing EPA dissolved oxygen criteria.

There are no national 304(a) criteria specific to chlorophyll *a* or water clarity. In accordance with sections 117(b) and 303 of the Clean Water Act, EPA Region III derived the water quality criteria addressing these critical nutrient and sediment enrichment parameters specifically to protect Chesapeake Bay living resources and their tidal-water habitats.

The water quality criteria presented in this document are designed to apply to the Chesapeake Bay and its tidal tributaries and embayments within the tidally influenced waters of the states of Maryland, Virginia and Delaware and the District of Columbia (Figure I-1). These regional criteria may also apply to other estuarine and coastal systems, with appropriate modifications.

The regional criteria and designated uses presented in this document and the *Technical Support Document* are the product of a collaborative effort among the Chesapeake Bay Program partners. They represent a scientific consensus based on the best available scientific findings and technical defining water quality conditions necessary to protect Chesapeake Bay aquatic living resources from effects due to nutrient and sediment over-enrichment. Various stakeholder groups have been involved in their development, with contributions from the staffs of federal and state governments, local agencies, scientific institutions, citizen conservation groups, business and industry. In the *Regional Criteria Guidance* the EPA recommends and expects that the numerical criteria and refined designated uses will be considered by and appropriately incorporated into the water quality standards of the Chesapeake Bay jurisdictions with tidal waters—Maryland, Virginia, Delaware and the District of Columbia.

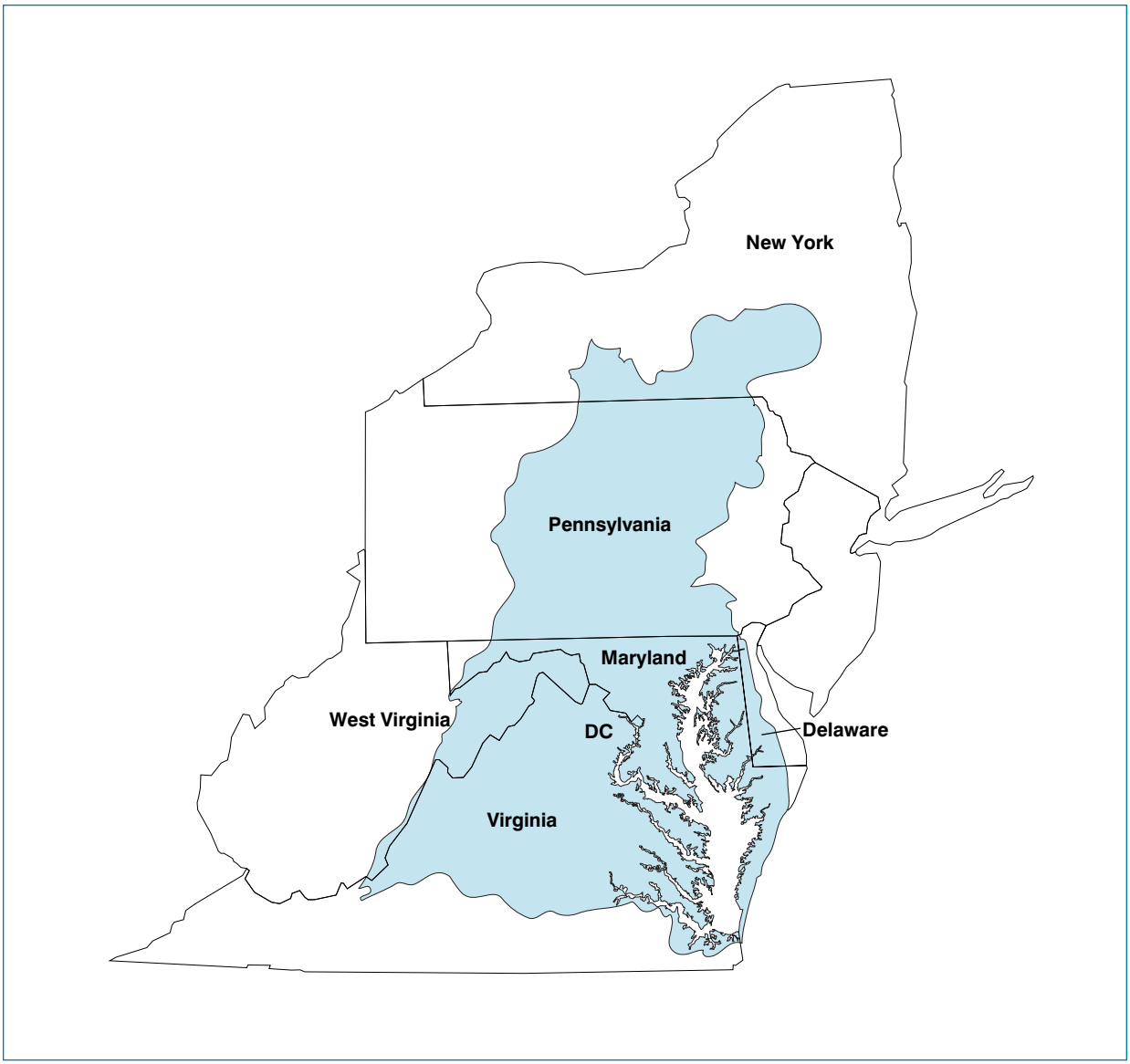



**Figure I-1.** The Chesapeake Bay watershed crosses the boundaries of six states—Maryland, Virginia, Delaware, Pennsylvania, New York and West Virginia—and the District of Columbia.

chapter ii

# Chesapeake Bay Nutrient and Sediment Enrichment Criteria

The *Chesapeake 2000* agreement committed its signatories (the states of Pennsylvania, Maryland and Virginia; the District of Columbia; the Chesapeake Bay Commission and the EPA) to "define the water quality conditions necessary to protect aquatic living resources" in the Chesapeake Bay and its tidal tributaries. New York, Delaware and West Virginia agreed to the same commitment through a separate six-state memorandum of understanding with the EPA.

EPA Region III has identified the water quality conditions that are necessary to protect living resources through the Chesapeake Bay-specific water quality criteria for dissolved oxygen, water clarity and chlorophyll *a* published in this document. The Chesapeake Bay criteria have been derived to protect a series of five *refined tidal-water designated uses* which, in turn, reflect important and unique habitats throughout the Chesapeake Bay and its tidal tributaries (Appendix A). More detailed descriptions of these refined subcategories of tidal-water designated uses and their recommended boundaries can be found in the EPA Region III publication, *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability*. Collectively, these three water quality conditions provide the best and most direct measures of the effects of too much nutrient and sediment pollution on the Chesapeake Bay's aquatic living resources–fish, crabs, oysters, their prey species and underwater bay grasses.

Fish and other aquatic life require specific levels of *dissolved oxygen* to survive. Seasonal algae blooms, when uneaten by fish and shellfish, deplete dissolved oxygen, potentially rendering the deep waters of the Bay uninhabitable to certain species during certain times of the year. The Chesapeake Bay dissolved oxygen criteria were based on the oxygen levels required by different aquatic communities inhabiting distinct habitats in the Bay's tidal waters during different times of the year (Chapter III).

Underwater bay grasses are an essential component of the Chesapeake Bay's habitat and an important food source for waterfowl. Decreased *water clarity* inhibits the growth of underwater bay grasses. Building on decades of scientific research, the

Chesapeake Bay water clarity criteria were derived to protect the minimum light required by both low and higher salinity underwater plant communities (Chapter IV).

Measurements of *chlorophyll* a indicate levels of phytoplankton or algal biomass in the water column. Levels that are too high indicate algal blooms, which lead to a proliferation of less desirable species, shade the light in shallow-water habitats and cause low dissolved oxygen conditions, as uneaten algae die off and sink to the bottom. Narrative Chesapeake Bay chlorophyll *a* criteria were derived to support desired ecological conditions and protect against an array of water quality impairments (Chapter V).

The EPA provides Chesapeake Bay criteria *implementation procedures* as additional regional guidance to the Chesapeake Bay watershed states and other agencies, institutions, groups or individuals for consideration of how to apply the criteria in order to determine the degree of attainment of those criteria (Chapter VI). These implementation procedures are published in this document to promote consistent, baywide application of the criteria across jurisdictional boundaries.

A series of *diagnostic procedures* and tools designed to explain the reasons for non-attainment of the water quality criteria are documented (Chapter VII). Approaches for addressing natural exceedances of the criteria not already accounted for in the implementation procedures are provided for consistent application across all tidal water habitats.

The EPA is publishing this *Regional Criteria Guidance* to further to goals of the Clean Water Act and, specifically, pursuant to Sections 117(b) and 303(c) of the the Act.

chapter iii

# Dissolved Oxygen Criteria

## BACKGROUND

Of all life-supporting environmental constituents, oxygen is one of the most essential. In cells, oxygen stores and liberates the energy that drives vital processes of fish, crabs and shellfish such as feeding, growth, swimming and reproduction. Low dissolved oxygen concentrations can increase mortality, reduce growth rates and alter the distribution and behavior of aquatic organisms, all of which can produce significant changes in the overall estuarine food web (Breitburg 2002).

The Chesapeake Bay and its tidal tributaries harbor diverse and productive communities of aquatic organisms that are supported by a complex array of food webs. To establish dissolved oxygen criteria for these living resources and the food webs they depend upon, we must characterize the dissolved oxygen conditions that lead to stressful conditions for the living resources of the Chesapeake Bay, ranging from copepods to sturgeon.

## CHESAPEAKE BAY SCIENCE

The development of the scientific underpinnings for Chesapeake Bay-specific criteria has been under way for decades. The first documentation of seasonal occurrence, low dissolved oxygen conditions in the Chesapeake Bay took place in the 1930s (Newcombe and Horne 1938; Newcombe et al. 1939), with low oxygen conditions documented in the lower Potomac River in the early 1900s (Sale and Skinner 1917). Chesapeake Bay dissolved oxygen dynamics, which are critical to deriving criteria that reflect the ecosystem process, first became understood during the research cruises of the Johns Hopkins Chesapeake Bay Institute during the 1950s through the late 1970s. A five-year, multidisciplinary research program established in the late 1980s, funded and coordinated by the Maryland and Virginia Sea Grant programs, yielded significant advances in the understanding of Chesapeake Bay oxygen dynamics, effects and ecosystem implications (Smith et al. 1992). The coordinated state-federal Chesapeake Bay Water Quality Monitoring Program, initiated

in 1984, provided decadal scale records of seasonal to interannual variability in dissolved oxygen conditions throughout the tidal waters. Building on the long-term baywide monitoring data record, a series of multi-investigator, multi-year National Science Foundation, NOAA and EPA-funded research programs provided new insights into Bay ecosystem processes and responses. These investigations laid the groundwork for management application of the resulting science.

## NATURAL DISSOLVED OXYGEN PROCESSES

Dissolved oxygen in any natural body of water is primarily a function of atmospheric oxygen (which diffuses into the water at the surface), oxygen produced by plants (microscopic free-floating plants or phytoplankton) during photosynthesis and aquatic animals, plants and bacteria that consume dissolved oxygen through respiration. Oxygen also is consumed by chemical processes such as sulfide oxidation and nitrification. The reduction of dissolved oxygen stimulates sulfate reduction and results in hydrogen sulfide, a more toxic form of sulfur. Oxygen depletion also can inhibit nitrogen removal via coupled nitrification and denitrification and enhance the recycling of ammonia and phosphates as well as the release of heavy metals from bottom sediments into the overlying water column.

The amount of oxygen dissolved in the water changes as a function of temperature, salinity, atmospheric pressure and biological and chemical processes. Gill and integumentary respiration, which most Chesapeake Bay aquatic species use, is accomplished by extracting dissolved oxygen across a pressure gradient (rather than a concentration gradient). As the partial pressure of dissolved oxygen increases in the water (e.g., increasing temperature and salinity), it can more readily be extracted by an organism. Cold-blooded organisms, however, have much higher metabolic rates and oxygen requirements at higher temperatures, which more than offsets the oxygen gained at the higher temperature. The interactions among metabolism, temperature and salinity clearly are complex, but they must be considered in deriving Chesapeake Bay dissolved oxygen criteria.

Biological processes such as respiration and photosynthesis can affect the concentration of dissolved oxygen before a new equilibrium can be reached with the atmosphere. As a result, for relatively short periods of time, or under sustained conditions of reduced physical mixing (i.e., the stratification of the water column), dissolved oxygen concentrations can be driven well below the point of saturation. They can decrease to zero (a condition known as anoxia), especially in deep or stratified bodies of water, or increase to a concentration of 20 mg liter$^{-1}$ (a condition known as supersaturation) during dense algal blooms.

## CHESAPEAKE BAY OXYGEN DYNAMICS

It is critical to take into account the natural processes that control oxygen dynamics in order to establish criteria that reflect natural conditions and protect different habitats. The Chesapeake Bay tends to have naturally reduced dissolved oxygen

conditions in its deeper waters because of its physical morphology and estuarine circulation. As in other estuarine systems (e.g., Boynton et al. 1982; Nixon 1988; Caddy 1993; Cloern 2001), the Chesapeake's highly productive waters, combined with sustained stratification, long residence times, low tidal energy and its tendency to retain and recycle nutrients, set the stage for lower dissolved oxygen conditions. The mesohaline mainstem Chesapeake Bay and lower reaches of the major tidal rivers have a stratified water column, which essentially prevents waters near the bottom from mixing with oxygenated surface waters. The recycling of nutrients and water-column stratification lead to severe reductions in dissolved oxygen concentrations during the warmer months of the year in deeper waters within and below the pycnocline layer.

This reduction in dissolved oxygen generally results from a host of additional biological and physical factors (e.g., Kemp and Boynton 1980; Kemp et al. 1992; Sanford et al. 1990; Boynton and Kemp 2000). The annual spring freshet delivers large volumes of fresh water to the Bay. The contribution of significant quantities of nutrients in the spring river flows, combined with increasing temperatures and light, produces a large increase in phytoplankton biomass. Phytoplankton not consumed by suspension feeders (such as zooplankton, oysters and menhaden) sink to the subpycnocline waters, where they are broken down by bacteria over a period of days or weeks (e.g., Malone et al. 1986; Tuttle et al. 1987; Malone et al. 1988). This loss of oxygen due to bacterial metabolism is exacerbated by restricted mixing with surface waters because of the onset of increased water-column stratification.

The Chesapeake Bay's nearshore shallow waters periodically experience episodes of low to no dissolved oxygen, in part because bottom water has been forced into the shallows by a combination of internal lateral tides and sustained winds (Carter et al. 1978; Tyler 1984; Seliger et al. 1985; Malone et al. 1986; Breitburg 1990; Sanford et al. 1990). Low dissolved oxygen conditions in the shallow waters of tidal tributaries are more often the result of local production and respiration than the incursion of bottom waters. Climatic conditions such as calm winds and several continuous cloudy days in a row can contribute to oxygen depletion in these shallow-water habitats. They can be exposed to episodes of extreme and rapid fluctuations in dissolved oxygen concentrations (Sanford et al. 1990). In depths as shallow as 4 meters, dissolved oxygen concentrations may decline to 0.5 mg liter$^{-1}$ for up to 10 hours (Breitburg 1990).

Diel cycles of low dissolved oxygen conditions often occur in nonstratified shallow waters where water-column respiration at night temporarily reduces dissolved oxygen levels (D'Avanzo and Kremer 1994). In nearshore waters of the mesohaline mainstem Chesapeake Bay, near-bottom dissolved oxygen concentrations are characterized by large diel fluctuations and daily minima during the late night and early morning hours of July and August (Breitburg 1990).

The timing and extent of reduced dissolved oxygen conditions in the Chesapeake Bay vary from year to year, driven largely by local weather patterns, the timing and

magnitude of freshwater river flows, the concurrent delivery of nutrients and sediments into tidal waters and the corresponding springtime phytoplankton bloom (Officer et al. 1984; Seliger et al. 1985; Boynton and Kemp 2000; Hagy 2002). In the Chesapeake Bay's mesohaline mainstem, these conditions generally occur from June through September but have been observed to occur as early as May. They may persist through early October, until the water column is fully mixed in the fall. The deeper waters of several Chesapeake Bay major tidal tributaries also can exhibit hypoxic and anoxic conditions (Hagy 2002).

Anoxia is the absence of oxygen. Because most field dissolved oxygen meters are only precise to ± 0.1 or 0.2 mg liter$^{-1}$, areas with measured oxygen concentrations of 0.2 mg liter$^{-1}$ or less are sometimes classified as anoxic. There is no accurate consensus on the scientific definition of hypoxia, but it is often defined as oxygen concentrations below 2 mg liter$^{-1}$ (U.S. scientific literature) or 2 ml liter$^{-1}$ (European scientific literature). These specific concentration-based definitions are problematic when applied in an effects context, because many species show reduced growth and altered behavior at oxygen levels above 2 mg liter$^{-1}$, and sensitive species experience mortality during prolonged exposure at these low concentrations. As an operational definition, hypoxia should be considered to be oxygen concentrations reduced from full saturation that impair living resources.

## LOW DISSOLVED OXYGEN: HISTORICAL AND RECENT PAST

Dissolved oxygen levels vary naturally in lakes, estuaries and oceans over varying temporal and spatial scales due to many biological, chemical and physical processes. In estuaries such as the Chesapeake Bay, freshwater inflow that influences water-column stratification; nutrient input and cycling; physical processes such as density-driven circulation; and tides, winds, water temperature and bacterial activity are among the most important factors. These processes can lead to large natural seasonal and interannual variability in oxygen levels in many parts of the Chesapeake Bay and its tidal tributaries.

Superimposed on this natural dissolved oxygen variability is a progressive increase in the intensity and frequency of hypoxia and anoxia over the past 100 to 150 years, most notably since the 1960s. This human-induced eutrophication is evident both from instrumental data and geochemical and faunal/floral 'proxies' of dissolved oxygen conditions obtained from the sedimentary record.

The instrumental record, while incomplete prior to the inception of the multi-agency Chesapeake Bay Monitoring Program in 1984, suggests that as early as the 1930s (Newcombe and Horne 1938) and especially since the 1960s (Taft et al. 1980), summer oxygen depletion has been recorded in the Chesapeake Bay. Officer et al. (1984), Malone (1992), Harding and Perry (1997) and Hagy (2002) provide useful

discussions of the instrumental record of dissolved oxygen and related parameters such as chlorophyll *a* across this multi-decade data record.

At issue is whether, and to what degree, dissolved oxygen reductions are a naturally occurring phenomenon in the Chesapeake Bay. Long sediment core records (17 meters to greater than 21 meters in length) indicate that the Chesapeake Bay formed about 7,500 years ago (Cronin et al. 2000; Colman et al. 2002) when the rising sea level after the final stage of Pleistocene deglaciation flooded the Susquehanna channel. The modern estuarine circulation and salinity regime probably began in the mid- to late Holocene epoch, about 4,000-5,000 years ago (in the regional climate of the early Holocene, Chesapeake Bay's salinity differed from that of the late Holocene). This is based on the appearance of 'pre-colonial' benthic foraminiferal, ostracode and dinoflagellate assemblages. It is against this mid- to late Holocene baseline that we can view the post-European settlement and modern dissolved oxygen regime of the Chesapeake Bay.

During the past decade, studies of the Chesapeake Bay's late Holocene dissolved oxygen record have been carried out using several proxies of past dissolved oxygen conditions, which are preserved in sediment cores that have been dated using the most advanced geochronological methods. These studies, using various indicators of past dissolved oxygen conditions, are reviewed in Cronin and Vann (2003) and provide information that puts the monitoring record of the modern Chesapeake Bay into a long-term perspective and permits an evaluation of natural variability in the context of restoration targets. The following types of measurements of oxygen-sensitive chemical and biological indicators have been used: nitrogen isotopes (Bratton et al. 2003); biogenic silica and diatom communities (Cooper and Brush 1991; Cooper 1995; Colman and Bratton 2003); molybdenum and other metals (Adelson et al. 2000; Zheng et al., in press); lipid biomarkers; acid volatile sulfur (AVS)/chromium reducible sulfur (CRS) ratios; total nitrogen and total organic carbon (Zimmerman and Canuel 2000); elemental analyses (Cornwell et al. 1996) and paleo-ecological reconstructions based on dinoflagellate cysts (Willard et al. 2003); and benthic foraminiferal assemblages (Karlsen et al. 2000). Although space precludes a comprehensive review of these studies, and the time period studied and level of quantification vary, several major themes emerge, which are summarized here.

First, the 20$^{th}$ century sedimentary record confirms the limited monitoring record of dissolved oxygen, documenting that there has been a progressive decrease in dissolved oxygen levels, including the periods of extensive anoxia in the deep-channel region of the Chesapeake Bay that have been prominent during the last 40 years. Most studies provide strong evidence that there was a greater frequency or duration of seasonal anoxia beginning in the late 1930s and 1940s and again around 1970, reaching unprecedented frequencies or duration in the past few decades in the mesohaline Chesapeake Bay and the lower reaches of several tidal tributaries. Clear evidence of these low dissolved oxygen conditions has been found in all geochemical and paleo-ecological indicators studied principally through their great impact on benthic and phytoplankton (both diatom and dinoflagellate) communities.

Second, extensive late 18th and 19th century land clearance also led to oxygen reduction and hypoxia, which exceeded levels characteristic of the previous 2,000 years. Best estimates for deep-channel mid-bay seasonal oxygen minima from 1750 to around 1950 are 0.3 to 1.4-2.8 mg liter$^{-1}$ and are based on a shift to dinoflagellate cyst assemblages of species tolerant of low dissolved oxygen conditions. This shift is characterized by a four- to fivefold increase in the flux of biogenic silica, a greater than twofold (5-10 millileter$^{-1}$) increase in nitrogen isotope ratios ($^{15}$N) and periods of common (though not dominant) *Ammonia parkinsoniana*, a facultative anaerobic foraminifer. These patterns are likely the result of increased sediment influx and nitrogen and phosphorous runoff due to extensive land clearance and agriculture.

Third, before the 17th century, dissolved oxygen proxy data suggest that dissolved oxygen levels in the deep channel of the Chesapeake Bay varied over decadal and interannual time scales. Although it is difficult to quantify the extremes, dissolved oxygen probably fell to 3 to 6 mg liter$^{-1}$, but rarely if ever fell below 1.4 to 2.8 mg liter$^{-1}$. These paleo-dissolved oxygen reconstructions are consistent with the Chesapeake Bay's natural tendency to experience seasonal oxygen reductions due to its bathymetry, freshwater-driven salinity stratification, high primary productivity and organic matter and nutrient regeneration (Boicourt 1992; Malone 1992; Boynton et al. 1995).

In summary, the main channel of the Chesapeake Bay most likely experienced reductions in dissolved oxygen before large-scale post-colonial land clearance took place, due to natural factors such as climate-driven variability in freshwater inflow. However, this progressive decline in summer oxygen minima, beginning in the 18th century and accelerating during the second half of the 20th century, is superimposed on interannual and decadal patterns of dissolved oxygen variability. Human activity during the post-colonial period has caused the trend towards hypoxia and most recently (especially after the1960s) anoxia in the main channel of the Chesapeake Bay and some of its larger tidal tributaries. The impact of these patterns has been observed in large-scale changes in benthos and phytoplankton communities, which are manifestations of habitat loss and degradation.

## APPROACH FOR DERIVING DISSOLVED OXYGEN CRITERIA

Against this backdrop, a set of dissolved oxygen criteria have been derived to protect Chesapeake Bay estuarine species living in different habitats that are influenced by the Bay's natural processes. The Chesapeake Bay dissolved oxygen criteria directly reflect natural oxygen dynamics. For example, instantaneous minimum to daily mean criterion values reflect short-term variations in oxygen concentrations, and seasonal application of deep-water and deep-channel criteria account for the natural effects of water-column stratification on oxygen concentrations. Oxygen dynamics and natural low- to no-oxygen conditions also were taken into account in developing

Chesapeake Bay Dissolved Oxygen Criteria Team member Dr. Thomas Cronin, of the U.S. Geological Survey (USGS), (surveyed five scientists[1] who have studied the history of anoxia and hypoxia in the Chesapeake Bay over decadal and centennial time scales, using geochemical and biological proxies from sediment cores and instrumental and historical records. The consensus of the five scientists is that the Chesapeake Bay was seasonally anoxic between 1900 and 1960. The seasonal anoxia was extensive in the deep channel and probably lasted several months. Similarly, between 1600 and 1900, the near-unanimous consensus is that the Bay was seasonally anoxic for probably weeks to months in the deep channel. One researcher had reservations about his group's earlier conclusion on definitive evidence of anoxia prior to 1900, but cannot exclude the possibility of anoxia during this period. Anoxia during the 1900–1960 period was probably geographically less extensive in the Bay and perhaps occurred less frequently (i.e., not every year) than after the 1960s. In addition to the geochemical and faunal proxies of past trends in oxygen depletion, experts cite the Sale and Skinner (1917) instrumental documentation of hypoxia and probable anoxia in the lower Potomac in 1912.

For the period prior to European colonization (~1600 AD), the consensus is that the deep channel of the Bay may have been briefly hypoxic (< 2 mg liter$^{-1}$), especially during relatively wet periods (which did occur, based on the paleoclimate record). Anoxia probably occurred only during exceptional conditions. It should be noted that the late 16th and much of the 17th century was an extremely dry period which was not conducive to oxygen depletion.

In sum, hypoxia, and probably periodic spatially-limited anoxia, occurred in the Bay prior to the large-scale application of fertilizer, but since the 1960s oxygen depletion has become much more severe.

These experts also unanimously believe that restoring the Bay to mid-20th century, pre-1960 conditions might be possible but very difficult (one expert suggested an 80 percent nitrogen reduction was necessary), in light of remnant nutrients in sediment in the Bay and behind dams, likely increased precipitation as the climate changes, population growth and other factors. Most researchers believe that restoring the Bay to conditions prior to 1900 is either impossible, or not realistic, simply due to the fact that the temporal variability (year-to-year and decadal) in 'naturally occurring' hypoxia renders a single target dissolved oxygen level impossible to define.

[1]T. M. Cronin (USGS, Reston, Virginia), S. Cooper (Bryn Athyn College), J. F. Bratton (USGS, Woods Hole, Massachusetts), A. Zimmerman (Pennsylvania State University), G. Helz (University of Maryland, College Park).

the refined tidal-water designated uses (see Appendix A; U.S. EPA 2003a), which factor in natural conditions leading to low dissolved oxygen concentrations.

The derivation of these regional criteria followed the methodologies outlined in the EPA's *Guidelines for Deriving Numerical National Water Quality for the Protection of Aquatic Organisms and their Uses* (U.S. EPA 1985), the risk-based approach used in developing the *Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen*

*(Saltwater): Cape Cod to Cape Hatteras* (U.S. EPA 2000) and the *Biological Evaluation on the CWA 304(a) Aquatic Life Criteria as part of the National Consultations, Methods Manual* (U.S. EPA, U.S. Fish and Wildlife Service and NOAA National Marine Fisheries Service, in draft). The resulting criteria factored in the physiological needs and habitats of the Chesapeake Bay's living resources and are designed to protect five distinct tidal-water designated uses (Appendix A; U.S. EPA 2003a).

Criteria for protecting the migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated uses were set at levels to protect the growth, recruitment and survival ecologically, recreationally and commercially important fish and shellfish species. Criteria applicable to deep-water seasonal fish and shellfish designated uses were set at levels to protect shellfish and juvenile and adult fish, and to foster the recruitment success of the bay anchovy. Criteria for deep-channel seasonal refuge designated uses were set to protect the survival of bottom sediment-dwelling worms and clams. These summer deep-water and deep-channel designated uses take into account the natural historic presence of low oxygen in these habitats and the likelihood that such conditions may persist (U.S. EPA 2003a).

## CHESAPEAKE BAY DISSOLVED OXYGEN RESTORATION GOAL FRAMEWORK

The Chesapeake Bay dissolved oxygen restoration goal was published in 1992 in response to the Chesapeake Executive Council's commitment to "develop and adopt guidelines for the protection of water quality and habitat conditions necessary to support the living resources found in the Chesapeake Bay system and to use these guidelines" (Chesapeake Executive Council 1987). The 1992 goal contained specific target dissolved oxygen concentrations for application over specified averaging periods and locations (Table III-1; Jordan et al. 1992).

Information on the effects of low dissolved oxygen concentrations was compiled for 14 target species of fish, mollusks and crustaceans, as well as for other benthic and planktonic communities in the Bay food web. These species were selected from a larger list of important species reported in *Habitat Requirements for Chesapeake Bay Living Resources, Second Edition* (Funderburk et al. 1991). The selection of target dissolved oxygen concentrations and their temporal and spatial applications followed an analysis of dissolved oxygen concentrations that would provide the levels of protection needed to achieve the restoration goal. Where data gaps existed, best professional judgment was used.

The original Chesapeake Bay dissolved oxygen restoration goal and its supporting framework made three significant breakthroughs for the derivation and management application of the Bay-specific dissolved oxygen criteria. First, the 1992 dissolved oxygen target concentrations varied with the vertical depth of the water column and horizontally across the Chesapeake Bay and its tidal tributaries, reflecting variations in the levels of water quality required for the protection of different habitats (see

**Table III-1.** 1992 Chesapeake Bay dissolved oxygen goal for restoration of living resource habitats.

The Chesapeake Bay dissolved oxygen goal for the restoration of living resource habitats is to provide for sufficient dissolved oxygen to support the survival, growth and reproduction of anadromous, estuarine and marine fish and invertebrates in the Chesapeake Bay and its tidal tributaries by achieving, to the greatest spatial and temporal extent possible, the following target concentrations of dissolved oxygen, and by maintaining the existing minimum concentration of dissolved oxygen in areas of the Chesapeake Bay and its tidal tributaries where dissolved oxygen concentrations fall above the recommended targets.

| Target Dissolved Oxygen Concentrations | Time and Location |
|---|---|
| Dissolved oxygen $\geq$ 1 mg liter$^{-1}$ | All times, everywhere. |
| 1.0 mg liter$^{-1}$ $\geq$ dissolved oxygen $\leq$ 3 mg liter$^{-1}$ | For no more than 12 hours, interval between excursions at least 48 hours, everywhere. |
| Monthly mean dissolved oxygen $\geq$ 5 mg liter$^{-1}$ | All times, throughout above-pycnocline[1] waters. |
| Dissolved oxygen $\geq$ 5 mg liter$^{-1}$ | All times, throughout above-pycnocline waters in spawning reaches, spawning rivers, and nursery areas. |

[1]The pycnocline is the portion of water column where density changes rapidly becaue of salinity and temperature.
Source: Jordan et al. 1992

Appendix A; U.S. EPA 2003a). Second, the averaging period for each target concentration was tailored to each habitat, understanding that short-term exposures to concentrations below the target concentrations were tolerable and could still protect living resources (see "Chesapeake Bay Dissolved Oxygen Criteria Derivation," page 40). Finally, the 1992 dissolved oxygen restoration goal contained a methodology through which water quality monitoring data and model scenario outputs, collected over varying time periods, could be assessed to calculate the percentage of time that areas of bottom habitat or volumes of water-column habitat would meet or exceed the applicable target dissolved oxygen concentrations (see Chapter VI).

## REGIONALIZING THE EPA VIRGINIAN PROVINCE SALTWATER DISSOLVED OXYGEN CRITERIA

The EPA's *Ambient Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras* (U.S. EPA 2000), here referred to as the Virginian Province criteria document, involved the development of an extensive database on dissolved

oxygen effects (Miller et al. 2002) and a close evaluation and synthesis of earlier data, published in peer-reviewed literature. Ultimately the criteria were derived using both traditional methodologies and a new biological risk-assessment framework. A mathematical model was used to integrate effects over time, replacing the concept of an averaging period, and protection limits were established for different life stages (i.e., larvae versus juveniles and adults). Where practical, data were selected and analyzed to conform to *Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses* (or *EPA Guidelines*, U.S. EPA 1985).

The Virginian Province criteria document addressed three areas of protection: 1) juvenile and adult survival, 2) growth effects and 3) larval recruitment effects. In doing so, it segregated effects on juveniles and adults from those on larvae. To address cumulative effects of low dissolved oxygen on larval recruitment to the juvenile life stage (i.e., larval survival time), a new biological approach using a mathematical model was taken. The model evaluated the effects of dissolved oxygen conditions on larvae by tracking the intensity and duration of low dissolved oxygen effects across the larval recruitment season (U.S. EPA 2000). Criteria to protect larvae were derived using data based on varying dissolved oxygen exposures for larval stages of nine sensitive estuarine and coastal organisms.

The juvenile and adult survival and growth criteria presented in the Virginian Province document set boundaries for judging the dissolved oxygen status of a given site. If dissolved oxygen concentrations are above the Virginian Province chronic growth criterion (4.8 mg liter$^{-1}$), then the site meets the objectives for protection. If the dissolved oxygen conditions remain above the Virginian Province juvenile/adult survival criterion (2.3 mg liter$^{-1}$) over a 24-hour period, the site meets the objectives. When the dissolved oxygen conditions fall between these two values, then the site requires further evaluation.

The Virginian Province criteria document supported the derivation of region-specific dissolved oxygen criteria tailored to the species, habitats and dissolved oxygen exposure regimes of varying estuarine, coastal and marine waters. The segregation by life stage allows the criteria to be tailored to protect the individual refined Chesapeake Bay tidal-water designated uses, which reflect the use of different habitats by different life stages (Appendix A). This segregation by life stage differs significantly in approach from traditional aquatic life water quality criteria. However, the Virginian Province criteria were not designed to address natural variations in dissolved oxygen concentrations from surface waters to greater water-column depths. If Chesapeake Bay-specific dissolved oxygen criteria had been derived using only a strict application of this criteria methodology, they would not be flexible enough to tailor each set of criteria to the refined tidal-water designated uses presented in Appendix A. The resulting criteria would be driven solely by larval effects data, irrespective of depth and season.

Therefore, the dissolved oxygen criteria specific to the Chesapeake Bay were derived through the regional application of the Virginian Province criteria and the application of both EPA published traditional toxicological and new EPA biological-based methodologies. Chesapeake Bay-specific science was factored into each step of the process. The extensive Virginian Province data base was supplemented with additional Chesapeake Bay-specific data from the scientific literature. The Virginian Province larval recruitment model parameters were adjusted to better reflect Chesapeake Bay conditions, data and species. Finally, steps were taken to ensure protection of species listed as threatened or endangered in Chesapeake Bay tidal waters following both national EPA guidelines and joint U.S. EPA, U.S. Fish and Wildlife and National Marine Fisheries Service national Endangered Species Act consultation methodologies. The Chesapeake Bay-specific dissolved oxygen criteria were derived with the full support of and technical assistance from the U.S. EPA Office of Research and Development's Atlantic Ecology Division and the U.S. EPA Office of Water's Office of Science and Technology.

## Chesapeake Bay Species

A total of 36 species of fish, crustaceans and mollusks were included in the Virginian Province criteria data base (U.S. EPA 2000). Only four are not resident Chesapeake Bay species (Table III-2, U.S. EPA 1998), including the green crab and the mysid *Americamysis bahia*. Both the American lobster and Atlantic surf clam have been observed in the Chesapeake Bay, but only near the Bay mouth, in high salinities. American lobster larvae require relatively low temperatures (20ºC) and high salinities (30 ppt) for successful development, and these conditions do not normally occur in the Chesapeake Bay.

The EPA guidelines on criteria recalculation, which allow regional and site-specific criteria derivation, state that species should be deleted from the effects data base only if the class is absent (U.S. EPA 1994). Emphasis is placed on deriving criteria using an effects data base that represents the range of sensitivity of tested and untested species from, in this case, the Chesapeake Bay and its tidal tributaries. As described below, including these four non-Chesapeake Bay species in the effects data base does not change the Bay-specific dissolved oxygen criteria. To ensure consistency with national EPA guidelines, no species were dropped from the original Virginian Province effects data base when deriving these Chesapeake Bay-specific criteria.

## Juvenile and Adult Survival Criteria

The criterion minimum concentration, or CMC, provides a lower limit for a 24-hour averaged concentration to protect juvenile and adult survival. The CMC for juvenile and adult survival was recalculated using a Chesapeake Bay-specific effects data base of 32 species of fish, crustaceans and mollusks (Table III-2). Dropping the four non-Chesapeake Bay species from the original Virginian Province data base resulted in a recalculated Chesapeake Bay-specific juvenile/adult survival CMC value of

**Table III-2.** U.S. EPA Virginian Province criteria data base species found in the Chesapeake Bay.

| Common Name | Scientific Name | Found in the Chesapeake Bay | | Notes |
|---|---|---|---|---|
| | | Species | Genus Only | |
| American lobster | *Homarus americanus* | (Yes) | - | 1 |
| Amphipod | *Ampelisca abdita* | Yes | - | |
| Atlantic menhaden | *Brevoortia tyrannus* | Yes | - | |
| Atlantic rock crab | *Cancer irroratus* | Yes | - | |
| Atlantic silverside | *Menidia menidia* | Yes | - | |
| Atlantic surfclam | *Spisula solidissima* | (Yes) | - | 2 |
| Blue crab | *Callinectes sapidus* | Yes | - | |
| Burry's octopus | *Octopus burryi* | No | Yes | 4 |
| Daggerblade grass shrimp | *Palaemonetes pugio* | Yes | - | |
| Eastern oyster | *Crassostrea virginica* | Yes | - | |
| Flatback mud crab | *Eurypanopeus depressus* | Yes | - | |
| Fourspine stickleback | *Apeltes quadracus* | Yes | - | |
| Green crab | *Carcinus maenas* | No | No | 6 |
| Hard clam | *Mercenaria mercenaria* | Yes | - | |
| Harris mud crab | *Rhithropanopeus harrisii* | Yes | - | |
| Inland silverside | *Menidia beryllina* | Yes | - | |
| Longfin squid | *Loligo pealeii* | (Yes) | - | 3 |
| Longnose spider crab | *Libinia dubia* | Yes | - | |
| Marsh grass shrimp | *Palaemonetes vulgaris* | Yes | - | |
| Mysid shrimp | *Americamysis bahia* | No | No | 7 |
| Naked goby | *Gobiosoma bosc* | Yes | - | |
| Northern sea robin | *Prionotus carolinus* | Yes | - | |
| Pipe fish | *Syngnathus fuscus* | Yes | - | |
| Rock crab | *Cancer irroratus* | Yes | - | |
| Sand shrimp | *Crangon septemspinosa* | Yes | - | |

*continued*

**Table III-2.** U.S. EPA Virginian Province criteria data base species found in the Chesapeake Bay *(continued).*

| Common Name | Scientific Name | Found in the Chesapeake Bay | | Notes |
|---|---|---|---|---|
| | | Species | Genus Only | |
| Say mud crab | *Dyspanopeus sayi* | Yes | – | 5 |
| Scup | *Stenotomus chrysops* | Yes | – | |
| Sheepshead minnow | *Cyprinodon variegatus* | Yes | – | |
| Skillet fish | *Gobiesox strumosus* | Yes | – | |
| Striped bass | *Morone saxatilis* | Yes | – | |
| Striped blenny | *Chasmodes bosquianus* | Yes | – | |
| Spot | *Leiostomus xanthurus* | Yes | – | |
| Summer flounder | *Paralichthys dentatus* | Yes | – | |
| Tautog | *Tautoga onitis* | Yes | – | |
| Windowpane flounder | *Scophthalmus aquosus* | Yes | – | |
| Winter flounder | *Pleuronectes americanus* | Yes | – | |

Notes:
1. Occasionally found in the Chesapeake Bay mouth region outside of the Bay Bridge/tunnel during blue crab winter dredge surveys.
2. Found near the Chesapeake Bay mouth at high salinities.
3. Found in the region around the Chesapeake Bay mouth.
4. *Octopus americanus* is found in the higher salinity reaches of the Chesapeake Bay.
5. Genus *Dyspanopeus* supercedes genus *Neopanope* (See Weiss, H. 1995. *Marine Animals of Southern New England and New York*, State Geological and Natural History Survey of Connecticut).
6. If found in the Chesapeake Bay, *Carcinus maenas* would be at the extreme southern edge of its range (See Gosner, K. 1979. *Field Guide to the Atlantic Seashore : Invertebrates and Seaweeds of the Atlantic Coast from the Bay of Fundy to Cape Hatteras*, Houghton Mifflin. Boston.). This species has not been documented in the Comprehensive List of Chesapeake Bay Basin Species (U.S. EPA 1998).
7. *Americamysis bahia* supercedes *Mysidopsis bahia*. (See Price W. W., R. W. Heard, L. Stuck 1994. Observations on the genus *Mysidopsis Sars*, 1864 with the designation of a new genus, *Americamysis*, and the descriptions of *Americamysis alleni* and *A. stucki* (Peracarida: Mysidacea: Mysidae), from the Gulf of Mexico. *Proceedings of the Biological Society of Washington* 107:680-698).

Sources: U.S. EPA 1998, 2000.

2.24 mg liter$^{-1}$, very close to the EPA Virginian Province criterion value of 2.27 mg liter$^{-1}$ (U.S. EPA 2000). To maintain consistency with EPA Virginian Province criteria and national EPA guidelines, no changes were made to the Virginian Province criteria value of 2.27 mg liter$^{-1}$ (rounded off to 2.3 mg liter$^{-1}$ for purposes of this criteria document), applied as a 1-day mean concentration.

## Larval and Juvenile Growth Criteria

The criterion value protecting against adverse effects on growth under continuous exposures, called the criterion continuous concentration (or CCC), when recalculated for only Chesapeake Bay species, increased 0.2 mg liter$^{-1}$ to a Chesapeake Bay-specific value of 5.0 mg liter$^{-1}$. To maintain consistency with EPA Virginian Province criteria and the national EPA criteria derivation guidelines, no changes were made to the Virginian Province criteria value of 4.8 mg liter$^{-1}$.

## Larval Recruitment Model Application

The Virginian Province criteria larval recruitment model was used only to confirm that the criterion values selected for the migratory fish spawning and nursery, shallow-water and open-water criteria fully protected larval recruitment. Only in the case of the deep-water criteria was application of the larval recruitment model central to deriving Chesapeake Bay-specific dissolved oxygen criteria values.

**Virginian Province Larval Recruitment Model.** The recruitment model is a discrete time, density-independent model consisting of several equations that allow the cumulative impact of low dissolved oxygen to be expressed as a proportion of the potential annual recruitment of a species. The model is run by inputting the necessary bioassay and biological information, selecting dissolved oxygen durations to model, and then, through an iterative process, assessing various dissolved oxygen concentrations until the desired percent recruitment impairment is obtained. The resulting pairs of duration and dissolved oxygen concentration become the recruitment curve. The process has been incorporated in a spreadsheet for simplicity. The model can be set up to handle unlimited and various life history stages. Its application for dissolved oxygen effects is to model larval recruitment to the juvenile stage.

The model's equations and the major assumptions used in its application are explained in Appendix E of the Virginian Province document (U.S. EPA 2000). The life history parameters in the model include larval development time, larval season, attrition rate and spatial distribution (e.g., vertical distribution). The magnitude of effects on recruitment is influenced by each of the four life history parameters. For instance, larval development time establishes the number of cohorts that entirely or partially co-occur within the interval of low dissolved oxygen stress. The second parameter, the length of the larval season, is a function of the spawning period, and also influences the relative number of cohorts that fall within the window of hypoxic

stress. The third life history variable, natural attrition rate, gauges the impact, if any, of slower growth and development of the larvae in response to low dissolved oxygen by tracking the associated increase in natural mortality (e.g., predation). The model assumes a constant rate of attrition, so increased residence time in the water column due to delayed development translates directly to decreased recruitment. Finally, the distribution of larvae in the water column determines the percentage of larvae from each cohort that would be exposed to reduced dissolved oxygen under stratified conditions.

The recruitment model assumes that the period of low dissolved oxygen occurs within the larval season (hypoxic events always begin at the end of the development time of the first larval cohort), and that hypoxic days are contiguous. Use of the current model also assumes that a new cohort occurs every day of the spawning season, and that each cohort is equal in size. Use of the model, however, does not require that a fresh cohort be available every day. Successful calculation of recruitment impairment only requires knowing the total number of cohorts available during a recruitment season (i.e., it does not matter whether they were created daily, weekly, monthly, etc.) and whether a cohort is exposed to hypoxia. The application of the model is further simplified by assuming that none of the life history parameters change in response to hypoxia.

**Chesapeake Bay Larval Recruitment Model Refinements.** A series of refinements were made to the Virginian Province criteria parameters for length of recruitment season and duration of larval development. These values were revised to reflect Chesapeake Bay-specific conditions (Table III-3).

**Crustaceans.** The Virginian Province criteria document states that the larval model for crustaceans includes all larval stages and the transition from larval to megalopal (post-larval) stage, but not the megalopal stage in its entirety (U.S. EPA 2000). Therefore, the duration used in the model was based on the duration of larval development, plus one day for molting to the megalopal stage. The following Chesapeake Bay-specific estimates of the duration of larval development are rounded to the nearest whole day: rock crab—22 days; say mud crab—17 days; lobster—15 days; spider crab—6 days; and grass shrimp—15 days. These estimates also are supported by a wide array of literature (Anger et al. 1981a; Anger et al. 1981b; Broad 1957; Chamberlain 1957; Costlow and Bookhout 1961; Johns 1981; Logan and Epifanio 1978; Maris 1986; Ryan 1956; Sandifer 1973; Sandifer and Van Engel 1971; Sasaki et al. 1986; Sastry 1970; Sastry 1977; Sastry and McCarthy 1973; Sulkin and Norman 1976; Wass 1972; Williams 1984).

The literature supports a larval release season (here termed the reproductive season) of 120 days or more for rock crab, say mud crab and spider crab, based on the presence of gravid females and larvae in field collections (Anger et al. 1981a; Anger et al. 1981b; Broad 1957; Chamberlain 1957; Costlow and Bookhout 1961; Johns 1981; Logan and Epifanio 1978; Maris 1986; Ryan 1956; Sandifer 1973; Sandifer

**Table III-3.** Original U.S. EPA Virginian Province saltwater dissolved oxygen criteria larval recruitment values and the revised recruitment season and larval development values reflecting Chesapeake Bay-specific conditions.

| Species | Length of Recruitment Season (days)[1] | Duration of Larval Development (days)[1] | Attrition Rate (percent per day) | Percentage Population Exposed to Hypoxic Event |
|---|---|---|---|---|
| Rock crab | 65/100 | 35/22 | 5% | 20% |
| Say mud crab | 66/90 | 21/17 | 5% | 75% |
| Flatback mud crab | 66/90 | 21/17 | 5% | 75% |
| Lobster | 95 | 35/15 | 5% | 20% |
| Spider crab | 66/80 | 21/6 | 5% | 50% |
| Silverside | 42/150 | 14 | 5% | 50% |
| Striped bass | 49/70 | 28 | 5% | 50% |
| Grass shrimp | 100/120 | 12/15 | 5% | 50% |
| Red drum | 49/140 | 21 | 5% | 50% |

[1] First value is the original Virginian Province-wide value; the second value following the slash is the Chesapeake Bay-specific value.

and Van Engel 1971; Sasaki et al. 1986; Sastry 1970; Sastry 1977; Sastry and McCarthy 1973; Sulkin and Norman 1976; Wass 1972; Williams 1984). Lobster larvae and adults are rarely found in the Chesapeake Bay, therefore, collection data were not available.

Grass shrimp have an extremely long reproductive season that extends even longer than the brachyurans. The Virginian Province criteria document implies that the actual period over which most of these crustaceans release larvae is only 30 to 40 days (except for grass shrimp). This was not supported in the literature for the Chesapeake Bay. However, given the interest in capturing "the period of predominant recruitment, rather than observance of the first and last dates for zoeal presence in the water column" (U.S. EPA 2000), one could reasonably state that brachyuran larvae are released over a 75-day period in the Chesapeake Bay. Grass shrimp larvae are released over a period of at least 100 days due to their greater reproductive flexibility. These reproductive season values, added to the duration of the larval development, provided the following values for the length of the recruitment season in the Chesapeake Bay: rock crab—100 days; mud crab—90 days; spider crab—80 days; and grass shrimp—120 days (Table III-3).

**Fishes.** In the Chesapeake Bay, striped bass spawn over a 30- to 40-day period. By adding in the duration of larval development of 28 to 50 days, a reasonable estimate for the recruitment season is 70 days (Grant and Olney 1991; McGovern and Olney 1996; Olney et al. 1991; Rutherford and Houde 1995; Secor and Houde 1995; Ulanowicz and Polgar 1980). It should be noted that most spawning in a given tributary may occur over a much shorter period of 7 to 21 days (Rutherford 1992; Olney et al. 1991). However, given the inability to predict which portion of the reproductive season will result in recruitment, it is important to provide water quality conditions that support recruitment for the duration of spawning season (Secor 2000; Secor and Houde 1995).

Silversides, along with other East Coast estuarine-dependent species, tend to show differences in the date of initiation of spawning and spawning duration from north to south (e.g., southern sites have longer durations). Silversides are serial batch spawners that spawn over a less than two-month period in the northern regions of the east coast, from two to three months around New York, and from three to four months in the Maryland portion of the Chesapeake Bay (Conover and Present 1990; Conover 1992; Gleason and Bengston 1996). A 140-day recruitment season factors in a 90-day reproductive season and a 50-day duration of larval development.

Red drum also are serial batch spawners. Documentation of the red drum spawning season is mostly for southern systems and varies between two months (Wilson and Neiland 1994; Rooker and Holt 1997) and three months (McMichael and Peters 1987). The 140-day recruitment season applied here factors in a 90-day reproductive season and a 50-day duration of larval development.

**Impairment Percentage.** Population growth of estuarine and coastal organisms may be more affected by mortality of the juvenile and adult stages than the larval stage. In nature only a small fraction of a season's larvae will make it to the juvenile/adult stage. Thus, removal of a single larva from exposure to low dissolved oxygen (which has a high probability of being removed naturally) is not nearly as important as the loss of a single juvenile (at each successive life stage—from egg to larva to juvenile to adult—the probability of survival to the next stage increases). Juveniles are much closer to the reproductive stage and represent the loss not only of the individual, but also of the potential larvae from that individual for the next season. In this regard, an individual larvae is not as important to the population as an individual juvenile or adult. Therefore, populations can tolerate different levels of impact at different stages of individual development (U.S. EPA 2000). At the same time, the criteria need to protect members of a species at all life stages so they can develop from an egg to an adult.

Protection against a greater than 5 percent cumulative reduction in larval seasonal recruitment due to exposure to low oxygen conditions was applied in the Chesapeake Bay-specific larval recruitment effects models, consistent with the level of protection selected for the Virginian Province criteria (U.S. EPA 2000). The selection of a 5 percent impairment of early life stages accords the same level of protection as that

set for adult and juvenile life stages through the CMC criteria. The 5 percent impairment also is consistent with EPA guidelines for deriving ambient aquatic life water quality criteria (U.S. EPA 1985). The 5 percent impairment sets the potential reduction in seasonal recruitment of affected species due to low dissolved oxygen exposure at a low level, relative to the cumulative effects of other natural and anthropogenic factors.

The EPA's criteria derivation guidelines and technical support documents do not state that the purpose of criteria is to prevent any losses; the purpose of the criteria is to prevent "unacceptable" losses. The EPA has acknowledged throughout the history of the criteria development process that criteria may allow some adverse effects to occur, e.g., the use of 95$^{th}$ percentile means that there is the possibility that 5 percent of the communities' genera will experience some impact (U.S. EPA 1985).

The EPA recognizes that large losses of larval life stages occur naturally. Some species may be able to withstand a greater than 5 percent loss of larvae from exposure to low dissolved oxygen or other causes without an appreciable effect on juvenile recruitment. However, this may not be the case for certain highly sensitive species or populations that already are highly stressed, such as threatened/endangered species where the 5 percent impairment is not applied.

In the absence of data showing how much impairment may be caused by low dissolved oxygen conditions alone and still have a minimal effect on natural larval recruitment to the juvenile stage for all species protected, a conservative level of acceptable impairment has been applied. The goal is to provide a level of protection from exposure to low dissolved oxygen that will not cause unacceptable loss to the juvenile recruitment class above what is expected to occur naturally.

## Regional Species Effects

The same species from different regions may react differently to low dissolved oxygen conditions. For example, populations from traditionally warmer waters may be less sensitive because they have adapted to lower concentrations of oxygen associated with native warmer temperatures. Alternatively, higher temperatures may cause warmer-water populations to need more dissolved oxygen and thereby make them more sensitive to lower concentrations.

Most of the effects data in the EPA Virginian Province saltwater dissolved oxygen criteria document were from EPA-sponsored laboratory tests conducted with species collected in the northern portion of the province. To determine whether such geographic differences exist, northern (Rhode Island) and southern populations (Georgia or Florida) of two invertebrates, the mud crab and the grass shrimp, and one fish, the inland silverside, were tested in the laboratory at non-stressful temperatures. Exposure-response relationships were similar for northern and southern populations of each species, supporting the use of data from one region to help develop safe dissolved oxygen limits for other regions (Coiro et al., unpublished data; see Appendix B).

## Temperature/Dissolved Oxygen Interactions

This document includes effects data collected at temperatures that are greater than 20ºC and many greater than 25ºC. Where there are data for the same species at multiple temperatures, for example, grass shrimp larvae tested at temperatures ranging from 20ºC to 30ºC (see Appendix B), there is no evidence for a temperature effect on sensitivity to hypoxia over the range of temperatures tested.

The findings reported in detail in Appendix B indicate that the low dissolved oxygen effects data were gathered over a range of different temperatures that did not influence the resulting effects findings. These findings further confirmed that test organisms from the northern portion of the Virginian Province were no more or less sensitive than organisms collected well south of the province boundaries. (See "Strengths and Limitations of the Criteria Derivation Procedures," p. 34, for a description of the potential interaction between dissolved oxygen effects and stressful temperatures.)

# APPLYING THE EPA FRESHWATER DISSOLVED OXYGEN CRITERIA

The Virginian Province saltwater criteria were derived largely from laboratory-based effects data using test conditions with salinities ranging from oligohaline to oceanic. Although a majority of the tests were run at salinities of greater than 15 ppt, data from the literature included tests whose estuarine species were exposed to salinities as low as 5 ppt. Many of the estuarine species tested tolerate a wide range of salinities, but the location of the U.S. EPA Office of Research and Development Atlantic Ecology Division laboratory at Narragansett Bay, Rhode Island, dictated that the tests be run at higher salinities. With extensive tidal-fresh (0-0.5 ppt) and oligohaline (> 0.5-5ppt) habitats in the upper Chesapeake Bay and upper reaches of most tidal tributaries, criteria established for these less saline habitats must protect resident species. To bridge this gap, the applicable EPA freshwater dissolved oxygen criteria were applied to ensure that the Chesapeake Bay-specific criteria protected freshwater species inhabiting tidal waters.

## Freshwater Dissolved Oxygen Criteria

The EPA freshwater criteria document, published in 1986, stipulated five limits for dissolved oxygen effects on warm-water species (Table III-4**,** U.S. EPA 1986). To protect early life stages, the criteria include a 7-day mean of 6 mg liter$^{-1}$ and an instantaneous minimum of 5 mg liter$^{-1}$. To protect other life stages, additional criteria were derived. These are a 30-day mean of 5.5 mg liter$^{-1}$, a 7-day mean of 4 mg liter$^{-1}$ and an instantaneous minimum of 3 mg liter$^{-1}$. Some of the most sensitive survival and growth responses reported for warm-water species in the freshwater criteria document were for early life stages of channel catfish and largemouth bass, both of which are present in tidal-fresh habitats throughout the Chesapeake Bay and its tidal tributaries (Murdy et al. 1997).

**Table III-4.** U.S. EPA freshwater dissolved oxygen water quality criteria (mg liter$^{-1}$) for warm-water species.

| Duration | Early Life Stages[1] | Other Life Stages |
|---|---|---|
| 30-day mean | NA[2] | 5.5 |
| 7-day mean | 6 | NA |
| 7-day mean minimum | NA | 4 |
| 1-day minimum[3] | 5 | 3 |

[1]Includes all embryonic and larval stages and all juvenile forms to 30 days following hatching.
[2]Not applicable.
[3]All minima should be considered as instantaneous concentrations to be achieved at all times.
Source: U.S. EPA 1986.

The freshwater dissolved oxygen criteria documentation contains data for effects on an extensive array of fish species. In addition, the freshwater document focuses on growth effects to early life stages, which are the more sensitive stages. Recognizing that the 1986 freshwater dissolved oxygen criteria were not derived following the EPA's 1985 criteria derivation guidelines, the EPA conducted a preliminary survey of the literature since the 1986 freshwater document was published and did find additional data that were consistent with the 1985 EPA guidelines. However, the effects data that were found (additional field observations and short-term [several hours] laboratory exposures), most of which focused on respiratory effects, indicated that the 1986 freshwater criteria were protective. Therefore, the EPA believes that its existing freshwater criteria accurately portray the expected effects of low dissolved oxygen on freshwater aquatic species.

## Early Life Stages

The EPA freshwater early life stage criteria were based on embryonic and larval data for the following eight species: largemouth bass, black crappie, white sucker, white bass, northern pike, channel catfish, walleye and smallmouth bass (U.S. EPA 1986). *Fishes of Chesapeake Bay* (Murdy et al. 1997) documents smallmouth bass as "occasional to common in Chesapeake Bay tributaries from Rappahannock northward, rare to occasional south of the Rappahannock, and absent from Eastern Shore streams and rivers." Regarding white suckers: "Found in all tributaries to Chesapeake Bay throughout the year, the white sucker occurs in nearly every kind of habitat..." The largemouth bass is "common to abundant in all tributaries of Chesapeake Bay." Black crappie were reported to be "occasional to abundant inhabitants in major tributaries of Chesapeake Bay." Finally, channel catfish were "common in all tributaries of Chesapeake Bay." (All references Murdy et al. 1997.)

Given that five of these species—largemouth bass, black crappie, white sucker, channel catfish and smallmouth bass—are resident in Bay tidal-fresh waters, the freshwater early life stage criteria are fully applicable to Chesapeake Bay tidal-fresh habitats. (See Figure 1 on page 14 and the text on pages 17-18 in the EPA's *Ambient Water Quality Criteria for Dissolved Oxygen [Freshwater]* for more details; U.S. EPA 1986.) No efforts were made to recalculate the national freshwater criteria using only Chesapeake Bay species, given the limited number of species used in deriving the 1986 criteria. Dropping any of the eight species would not provide an effects data set meeting the EPA's guidelines for criteria recalculation to address site-specific conditions (U.S. EPA 1994).

## Other Life Stages

The warm-water freshwater criteria that protect other life stages were derived from a much wider array of fish and invertebrate species, many of which occur in Chesapeake Bay tidal-fresh habitats (U.S. EPA 1998). These criteria apply to Chesapeake Bay habitats with salinities of less than 0.5 ppt. The national EPA freshwater criteria protecting other warm-water species life stages were not recalculated using only Chesapeake Bay species, for the same reasons described above.

Given the differences in the available effects data, the methodologies followed in deriving the freshwater dissolved oxygen criteria differed from those used in developing the Virginian Province dissolved oxygen criteria. In-depth descriptions of both methodologies can be found in each respective criteria document (U.S. EPA 1986, 2000).

## SPECIES LISTED AS THREATENED OR ENDANGERED

When a threatened or endangered species occurs at a site and sufficient data indicate that it is sensitive at concentrations above the recommended criteria, site-specific dissolved oxygen criteria may be derived (U.S. EPA 2000). Based on a review of all federal and Chesapeake Bay tidal water state lists of threatened or endangered species (U.S. Fish and Wildlife Service; National Oceanic and Atmospheric Administration; the states of Maryland, Virginia and Delaware and the District of Columbia), the only federally listed endangered species found to need protection from the effects of low dissolved oxygen conditions was shortnose sturgeon (U.S. EPA 2003b).

Shortnose sturgeon occur in the Chesapeake Bay and several tidal tributaries (Skjeveland et al. 2000; Mangold 2003; Spells 2003). Genetic evidence suggests that the shortnose captured in the Chesapeake Bay share the same gene pool with Delaware Bay shortnose sturgeon, and movement has been documented between the two bays through the C & D Canal (Welsh et al. 2002; Wirgin et al., in review).

Shortnose sturgeon have been federally protected since 1967 (National Marine Fisheries Service 1998). Chesapeake Bay shortnose sturgeon are listed as a Distinct Population Segment in the National Oceanic and Atmospheric Administration's National Marine Fisheries Service Shortnose Sturgeon Recovery Plan. Since 1996, 50 sub-adult and adult shortnose sturgeon have been captured in the upper Chesapeake Bay, Potomac River and Rappahannock River (Skjeveland et al. 2000). Mitochondrial DNA analysis indicated that these were a subset of the Delaware population's gene pool.

Currently two views are held on the status of shortnose sturgeon in the Chesapeake Bay. One view holds that shortnose sturgeon may continue to reproduce in the Bay, arguing that the genetic evidence is inconclusive or that the Delaware Bay and Chesapeake Bay populations may share the same gene pool. The other opinion is that the C & D Canal serves as an important migration corridor, and shortnose occurrences in the Chesapeake Bay result from immigration from the Delaware Bay.

Further, due to salinity preferences it is conceivable that their immigration (and recent occurrences) has been favored by the recent series of wet years. Several sturgeon population geneticists, ecologists and icthyologists favor this latter view (Secor 2003; Wirgin et al. in review; I. Wirgin, personal communication; J. Waldman, personal communication; J. Musick, personal communication). Regardless of whether shortnose sturgeon populations remain in the Chesapeake Bay, the Chesapeake Bay dissolved oxygen criteria have been derived to be protective of all life stages of both shortnose and Atlantic sturgeon.

## Sturgeon Dissolved Oxygen Sensitivity

Sturgeon in Chesapeake Bay and elsewhere are more sensitive to low dissolved oxygen conditions than most other fish. In comparison with other fishes, sturgeon have a limited behavioral and physiological capacity to respond to hypoxia (multiple references reviewed and cited by Secor and Niklitschek 2003). Sturgeon basal metabolism, growth, consumption and survival are all very sensitive to changes in oxygen levels, which may indicate their relatively poor ability to oxyregulate. In summer, temperatures greater than 20°C amplify the effect of hypoxia on sturgeon and other fishes due to a temperature-oxygen 'habitat squeeze' (Coutant 1987). Deep waters with temperatures that sturgeon prefer tend to have dissolved oxygen concentrations below the minimum that they require. Sturgeon are therefore either forced to occupy unsuitable habitats or have a reduction in habitat.

Several studies have directly addressed the lethal effects of hypoxia on sturgeon species important to the Chesapeake Bay. Jenkins et al. (1993) examined the effects of different salinities and dissolved oxygen levels on juveniles of the shortnose sturgeon *Acipenser brevirostrum.* The dissolved oxygen tests were all conducted at a mean temperature of 22.5°C. The authors state:

> Due to various constraints including limitations of facilities and test animals, strictly controlled and standardized methods could not be followed in all tests. The findings reported should be considered as preliminary until such time as more rigorous testing can be accomplished.

In addition, the authors report nominal[2] oxygen levels rather than those specific dissolved oxygen concentrations experienced during each replicate experiment. All experiments were conducted in freshwater. Still, strong evidence was presented that younger fish were differentially susceptible to low oxygen levels in comparison to older juveniles. Fish older than 77 days experienced minimal mortality at nominal levels 2.5 mg liter$^{-1}$, but at 2 mg liter$^{-1}$ experienced 24 to 38 percent mortality.

[2]The authors report that dissolved oxygen levels were monitored every 30 minutes throughout the 6-hour tests, and state that each parameter remained at "satisfactory levels." The dissolved oxygen values reported are 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 and 7.5 mg liter$^{-1}$. Since up to five replicates were used with as many as 12 measurements, it seems unlikely that these exact dissolved oxygen concentration values were maintained consistently throughout all the tests.

Younger fish experienced 18 to 38 percent mortality in the 3 mg liter$^{-1}$ treatment and >80 percent mortality in the 2.5 mg liter$^{-1}$ treatment. Mortality of juveniles 77 days or older at treatment levels ≥3.5 mg liter$^{-1}$ was not significantly different than control levels. Because only nominal dissolved oxygen concentrations were reported, the EPA could not derive $LC_{50}$ values for criteria derivation purposes based upon responses reported by Jenkins et al. (1993).

## Criterion Protective of Sturgeon

More rigorous tests with shortnose sturgeon were recently performed using young-of-the-year fish 77 to 134 days old (Campbell and Goodman 2003). Campbell and Goodman (2003) present four 24-hr $LC_{50}$ values for shortnose sturgeon (*Acipenser brevirostrum*). Three of these are from tests with non-stressful temperatures (22–26°C) for this species. The fourth test was conducted at 29°C and was considered to be a stressful temperature by the authors (Larry Goodman, personal communication). Fish from this fourth test also were exposed to temperatures as high as 31°C during the acclimation period immediately preceding their exposure to hypoxia. Since the data from the fourth test also include an effect due to temperature stress, they should be considered separately from data from the other three tests.

The current draft (December 2002) of the "National Consultation" on threatened and endangered species (being negotiated between the U.S. EPA, the U.S. Fish and Wildlife Service and the NOAA National Marine Fisheries Service) states:

> Where acute toxicity data are available for the species of interest, only these data will be used for designating the $LC_{50}$ for this species. If these data include more than one test, the geometric mean of the $LC_{50}$s of these tests will be used in risk calculations. If only one toxicity test has been conducted, the lower 95% confidence interval of the $LC_{50}$ from this test will be used.

Following this guidance the final $LC_{50}$ for shortnose sturgeon under ambient conditions of non-stressful temperatures would be the geometric mean of 2.2, 2.2 and 2.6 mg liter$^{-1}$, or 2.33 mg liter$^{-1}$. Under stressful temperatures, the $LC_{50}$ value that should be used would be 3.1 mg liter$^{-1}$ (this is the $LC_{50}$ of the 29°C test, since the 3.1 mg liter$^{-1}$ treatment resulted in exactly 50 percent mortality there was no 95 percent confidence interval) (Campbell and Goodman 2003).

Long-term exposures (10 days) of Atlantic sturgeon, *Acipenser oxyrinchus,* young-of-the-year (150 to 200 days old) to 2.8 to 3.3 mg liter$^{-1}$ at 26°C resulted in complete mortality over a 10-day period in three of four replicates (Secor and Gunderson 1998). The fourth replicate experienced 50 percent mortality. At 19°C and 2.3 to 3.2 mg liter$^{-1}$, only 12 to 25 percent mortality was recorded. There was insufficient data to calculate an $LC_{50}$ for 19°C (it was less than 2.70 mg liter$^{-1}$ [3], but could not determine how much less). However, based on survival data present in Secor and

[3]Based on daily dissolved oxygen data provided by the lead author, Dr. David Secor, University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, Maryland.

Gunderson (1998), a 96-hour $LC_{50}$ of 2.89 mg liter$^{-1}$ [3] was estimated for Atlantic sturgeon at 26°C. This value is very similar to the "high temperature" value of 3.1 mg liter$^{-1}$ calculated for shortnose sturgeon by Campbell and Goodman (2003). Data from Secor and Niklitschek (2001) show that shortnose sturgeon are more tolerant of higher temperatures than Atlantic sturgeon, which could explain why 26°C is not a stressful temperature for shortnose sturgeon (Campbell and Goodman 2003), but is for Atlantic sturgeon (Secor and Gunderson 1998). Alternatively, the temperature difference between the two species could be because the shortnose sturgeon were from Savannah River progeny and were held at higher temperatures than the Atlantic sturgeon, which came from Hudson River progeny.

Using the above data, the EPA calculated acute criteria for the protection of sturgeon survival in the Chesapeake Bay under both non-stressful and stressful temperatures. The only $LC_{50}$ value available for non-stressful temperatures that meets the requirements for criteria derivation based on the EPA's 1985 guidelines (U.S. EPA 1985) is the 24-hour 2.33 mg liter$^{-1}$ calculated above from Campbell and Goodman (2003). To be consistent with EPA guidelines, this value was used with the original Virginian Province criteria acute data set to recalculate the Final Acute Value (FAV). The new FAV, 2.12 mg liter$^{-1}$, is more protective than the 1.64 mg liter$^{-1}$ from the Virginia Province document, but still substantially lower than the 2.33-3.5 mg liter$^{-1}$ derived directly from the empirical study on shortnose sturgeon. Therefore, the EPA defaulted to the 2.33 mg liter$^{-1}$ value, multiplying it by 1.38[4] to arrive at a new CMC, 3.2 mg liter$^{-1}$ (rounded to two significant figures). This value is expected to be protective of sturgeon survival at non-stressful temperatures. Campbell and Goodman (2003) indicate that most of the mortality for shortnose sturgeon occurs within the first 2 to 4 hours of a test. Therefore, using this value as an instantaneous value should protect sturgeon under most conditions.

A higher dissolved oxygen criterion would be needed in areas and times of the year where sturgeon are to be protected and temperatures are likely to be considered stressful (e.g., 29°C and above for shortnose sturgeon). The simplest approach is to use the $LC_{50}$ value of 3.1 mg liter$^{-1}$ from the fourth test of Campbell and Goodman (2003). Multiplying this by 1.38 results in a high temperature CMC for shortnose sturgeon of 4.3 mg liter$^{-1}$.

To determine a criterion value that would also protect sturgeon from nonlethal effects, bioenergetic and behavioral responses were considered which had been derived from laboratory studies conducted on juvenile Atlantic and shortnose sturgeon (Niklitschek 2001; Secor and Niklitschek 2001). Growth was substantially reduced at 40 percent oxygen saturation compared to normal oxygen saturation

[4] This value is the geometric mean of the $LC_5/LC_{50}$ ratios from the Virginian Province document (U.S. EPA 2000). The ratio for the shortnose sturgeon tests from Campbell and Goodman (2003) was 1.30 based on an analysis of raw data provided by the co-author, Larry Goodman, U.S. Environmental Protection Agency, office of Research and Development, Gulf Ecology Division, Gulf Breeze, Florida. To be consistent with the Virginian Province document, EPA applied the 1.38 ratio.

conditions (greater than or equal to 70 percent saturation) for both species at temperatures of 20°C and 27°C. Metabolic and feeding rates declined at oxygen levels below 60 percent oxygen saturation at 20°C and 27°C. In behavior studies, juveniles of both sturgeon species actively selected 70 percent or 100 percent oxygen saturation levels over 40 percent oxygen saturation levels. Based on these findings, a 60 percent saturation level was deemed protective for sturgeon. This corresponds to 5 mg liter$^{-1}$ at 25°C. Therefore, a 5 mg liter$^{-1}$ Chesapeake Bay criterion protecting against adverse growth effects would protect sturgeon growth as well.

In accordance with Section 7 of the Endangered Species Act, the EPA is continuing consultation with the NOAA National Marine Fisheries Service to promote the recovery and protection of the endangered shortnose sturgeon in the Chesapeake Bay and its tidal tributaries.

## Historical and Potential Sturgeon Tidal Habitats in Chesapeake Bay

Atlantic and shortnose sturgeon probably most recently colonized the Chesapeake Bay 5,000–8,000 years ago after the last glaciation, when climate and the watershed's hydraulic regime became more stable (Custer 1986; Miller 2001; also see page 11). The Chesapeake Bay during this period already exhibited the two-layer circulation pattern. Thus, we should expect that deep-channel habitats during periods of strong stratification were hypoxic during the past 5,000 years, albeit not at the same spatial extent or severity that has occurred over the past 50 years (Officer et al. 1984; Cooper and Brush 1991). Atlantic sturgeon in other estuarine and coastal systems will use habitats greater than 15 meters in depth (see below), but these other systems do not exhibit the same characteristics of estuarine circulation, watershed areal extent and bathymetry that contribute to natural deep-water and deep-channel hypoxia in the mesohaline Chesapeake Bay.

The geochemical, paleo-ecological and instrumental record of the 20$^{th}$ century indicates that deep-channel regions have not served as potential habitats for sturgeon because seasonal (summer) anoxia and hyopxia have occurred most years, reaching levels below those required by sturgeon. Hypoxia, and probably periodic, spatially-limited anoxia occurred in the Chesapeake Bay prior to the large-scale application of fertilizer, but since the 1960s oxygen depletion has become much more severe (Hagy 2002), prohibiting sturgeon use of this habitat during summer months. Analysis of recent U.S. Fish and Wildlife Service sturgeon capture location data showed absence of sturgeon occurrences in deep-channel habitats during summer months (June 1 through September 30), but substantial numbers of occurrences in these same habitats during other seasons (U.S. EPA 2003b). In summary, based upon the recent relevant history of the Chesapeake Bay ecosystem, deep-channel regions in summer are not considered sturgeon habitats.

Deeper water-column regions may continue to provide temperature refuges, migration corridors and foraging for sturgeon in the absence of strong water-column

stratification (which results in dissolved oxygen concentrations well below saturation levels, due to restricted mixing with the well-oxygenated surface waters.) Recent fisheries-dependent data did not show overlap during summer months (June 1–September 30) between deep-water regions and sturgeon occurrences, but most gear deployed were for shallow waters (i.e., pound nets). During other months (October–May), deeper fishing gill nets captured sturgeon in both deep-channel and deep-water regions (U.S. EPA 2003b). Fishery-independent gill netting in the upper Chesapeake Bay above the Bay Bridge resulted in several Atlantic sturgeon captured in June and July at one station in pycnocline waters.

In other systems where strong water-column stratification does not occur to the degree observed in the Chesapeake Bay and its tidal tributaries, both sturgeon species are known to use deep-water habitats in summer months as thermal refuges. During the period of 1990–1999, very little summer deep-water habitat was predicted to support sturgeon production based on a bioenergetics model, due principally to pervasive hypoxia (Secor and Niklitschek, in press). Further, sturgeons are able to respond behaviorally to favorable gradients in dissolved oxygen (Secor and Niklitschek 2001).

Based on this evidence, pycnocline deep-water habitat does not comprise 'potential' habitats for sturgeon during periods of strong water-column stratification limiting exchange with overlying, more oxygenated waters. In the absence of strong water-column stratification, these deeper water-column habitats are considered open-water habitat and comprise 'potential' habitats for sturgeon.

Atlantic sturgeon occur at depths between 1 meter to more than 25 meters; shortnose sturgeon occur at depths between 1 and 12 meters (Kieffer and Kynard 1993; Savoy and Shake 2000: Welsh et al. 2000). In winter, Atlantic sturgeon select deeper habitats occurring in the Chesapeake Bay's deep channel (Secor et al. 2000; Welsh et al. 2000).

Distribution studies and laboratory experiments support the view that shortnose sturgeon prefer riverine and estuarine habitats over marine ones (e.g., Secor 2003). Shortnose adults have been reported occasionally in coastal waters up to 31 ppt, but typically occur within several kilometers of their natal estuaries (Dadswell et al. 1984; Kynard 1997). This contrasts with the sympatric Atlantic sturgeon, which are considered true *anadromous* fish that must migrate into coastal waters to complete their life cycles (Kynard 1997). In general, shortnose sturgeon do not invade salinities greater than 15 ppt, with centers of concentrations at less than 5 ppt for all life history stages during summer months (Dadswell et al. 1984; Brundage and Meadows 1982; Dovel et al. 1992; Geoghegan et al. 1992; Collins and Smith 1996; Bain 1997; Haley 1999). Atlantic sturgeon older than one year fully tolerate marine salinities and are expected to be distributed across all salinities, depending on season, reproduction and foraging conditions after their first year of life (Dovel and Berggen 1983; Dovel et al. 1992; Kieffer and Kynard 1993; Colligan et al. 1998; Secor et al. 2000).

Thus, Atlantic sturgeon are not limited by bathymetry and salinity in the Chesapeake Bay and would be expected to inhabit all tidal waters, including pycnocline and sub-pycnocline waters, if water quality conditions permitted. Shortnose sturgeon habitats would overlap those of Atlantic sturgeon for salinities less than 15 ppt. But there is strong evidence that both species historically have not used deep-water and deep-channel designated use habitats during the summer months (U.S. EPA 2003b) due to naturally pervasive low dissolved oxygen conditions (see above and the prior section titled "Low Dissolved Oxygen: Historical and Recent Past").

## SCIENTIFIC LITERATURE FINDINGS

For each tidal-water designated use-based set of Chesapeake Bay dissolved oxygen criteria, a review was conducted of the relevant dissolved oxygen effects literature beyond those data contained in the Virginian Province criteria document, to include recent published findings and Chesapeake Bay-specific data. These findings were used to confirm the derived criteria values and support the adoption of criteria with instantaneous minimum durations. In the case of the deep-channel designated use, the scientific literature formed the basis for the seasonal-based Chesapeake Bay deep-channel criterion value.

## INSTANTANEOUS MINIMUM VERSUS DAILY MEAN

The scientific literature provides clear evidence that mortality occurs rapidly from short-term exposure (less than 6 to 12 hours) to low oxygen concentrations (Magnusson et al. 1998; Breitburg 1992; Jenkins et al. 1993; Chesney and Houde 1989; Campbell and Goodman 2003). In a recent comprehensive review of the effects of hypoxia on coastal fishes and fisheries, Breitburg (2002) stated:

> Oxygen concentrations below those that result in the standardly calculated 50% mortality in 24 to 96 h exposure test can lead to mortality in minutes to a few hours. For example, in the case of naked gobies, exposure to dissolved oxygen concentrations of 0.25 mg liter$^{-1}$ leads to death in a matter of a few minutes (Breitburg 1992). As exposure time increases, the oxygen saturation that causes death approaches the saturation level that results in reduced respiration—typically a saturation level 2 to 3 times higher than found to be lethal in 24 h tests (Magnusson et al. 1998).
>
> Temperature is often an important cofactor determining when lethal conditions are reached because it can affect both the amount of oxygen that can dissolve in water, and the metabolic requirements of fish. Studies to date indicate that fish require higher oxygen saturations and higher dissolved oxygen concentrations for survival at higher temperatures.... The effects of exposure duration and temperature are thus very important to consider in setting water quality standards for dissolved oxygen concentration, highlighting the need to set absolute minima, instead of time-averaged minima, and the need to consider geographic variation in maximum water temperatures.

Data on laboratory tests of asphyxia and field data on fish kills associated with intrusions of hypoxic bottom water indicate that mortality rapidly occurs from short-term exposure to very low dissolved oxygen concentrations. Asphyxia occurs at about half the dissolved oxygen concentration resulting in reductions in respiration (Magnusson et al. 1998). For the species illustrated, respiration declines at dissolved oxygen concentrations of about 85 percent of the $LC_{50}$ concentration (see Figure 2 in Magnusson et al. 1998).

Asphyxia, as stated above, has been reported at dissolved oxygen concentrations well below the reported $LC_{50}$ concentrations. To ensure full protection of each of the five designated uses, an instantaneous minimum criterion has been recommended. In addition, a daily mean criterion value has been recommended for the deep-water use to ensure full protection of the open-water juvenile and adult fish that use deep-water habitats for short periods in summer to forage for food.

## STRENGTHS AND LIMITATIONS OF THE CRITERIA DERIVATION PROCEDURES

As with any science-based set of criteria, the approach used in deriving these criteria has its strengths and limitations. The dissolved oxygen criteria are designed to protect the five proposed designated uses under the conditions in which the underlying effects data were generated. Elevated temperatures, for example, will stress organisms regardless of the dissolved oxygen concentrations. The proposed conditions will protect the designated uses along with the application of other appropriate water quality criteria that protect against temperature, chemical contaminant and other related stresses.

The EPA recognizes that interactions among other stressors and dissolved oxygen exist. Conservative assumptions, documented in this chapter and associated appendices, were made to reflect these remaining uncertainties with regard to interactions with other stressors. Incorporation of arbitrary 'margins of safety' were not part of the Chesapeake Bay criteria derivation process, consistent with national EPA guidelines (U.S. EPA 1985). The EPA believes that the criteria provided in this document are protective under water quality conditions in which aquatic organism are not otherwise unduly stressed by other factors.

### Salinity Effects

The Virginian Province criteria document is geared toward >15 ppt salinities, with a subset of tests run at much lower salinities (e.g., striped bass larvae). However, low dissolved oxygen effects synthesized from the science literature used in deriving the EPA criteria included tests run at salinities lower than 15 ppt salinity (e.g., Burton et al. 1980, research on menhaden and spot). All tests were run at salinities found to be nonstressful to the respective organisms. These results and a review of the literature indicated that nonstressful salinity levels do not influence an organism's sensitivity to low dissolved oxygen.

## Temperature Effects

With the exception of the criterion derived to protect shortnose sturgeon, Chesapeake Bay criteria do not explicitly address potential interactions between varying stressful temperature levels and the effects of low dissolved oxygen. The amount of available dissolved oxygen changes as temperature changes, and the metabolic rates of organisms increase as temperature increases. In both cases, temperature directly affects organisms and their responses to dissolved oxygen conditions.

High temperatures and low dissolved oxygen concentrations often appear together. Generally, low dissolved oxygen concentrations would be more lethal at water temperatures approaching the upper thermal limit for a species. Surface or shoal regions of high temperature will cause fish to seek cooler habitats, yet these deeper habitats are more likely to contain hypoxic waters. The resulting 'habitat squeeze' (Coutant 1985) curtails summertime habitats and production (Brandt and Kirsch 1993; Secor and Niklitschek 2001). A number of species have shown heightened sensitivity to low dissolved oxygen concentrations at higher, yet nonlethal, temperatures (Breitburg et al. 2001). At this time sufficient data exist only for specific life history stages of some species (i.e., juvenile shortnose and Atlantic sturgeon) to fully quantify and build temperature and dissolved oxygen interactions into a set of Chesapeake Bay-specific dissolved oxygen criteria. Clearly, given the well-documented role of temperature and dissolved oxygen interactions in constraining the potential habitats of striped bass, sturgeon and other Chesapeake Bay fishes, more research and model development are needed.

The EPA does not think that a margin of safety for temperature effects is needed. Although having more data specific to an issue is always desirable, the available data are sufficient to derive dissolved oxygen criteria for the Chesapeake Bay that are protective of most species most of the time (which was the original intent of the EPA's 1985 national aquatic life criteria derivation guidelines). The data in Appendix B show that high, but nonstressful temperatures will not alter the dissolved oxygen criteria (some of these temperatures were as high as 30°C). The only rigorous data that are available for a single Chesapeake Bay species using nonstressful and stressful temperatures are for shortnose sturgeon (Campbell and Goodman 2003). These data have been used in the revised the Chesapeake Bay open-water dissolved oxygen criteria to derive protection limits specifically aimed at shortnose sturgeon in higher, stressful temperature waters.

## pH Effects

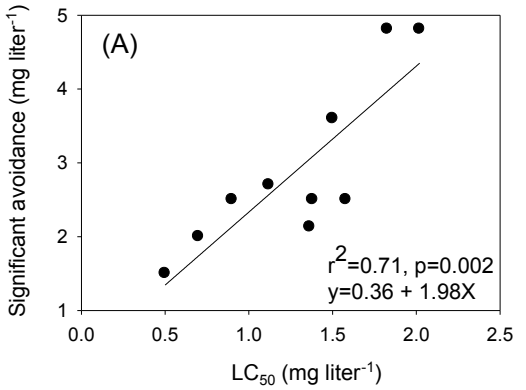
The interaction between pH levels and dissolved oxygen concentrations is more of an issue in laboratory experimentation and the analysis of laboratory-based effects data than in deriving and applying the dissolved oxygen criteria themselves. Given the great buffering capacity of seawater, pH, although a potentially important factor, is unlikely to change much in seawater. Existing pH water quality criteria, along with the application of the appropriate dissolved oxygen criteria, should be protective of the use.

## Behavioral Effects

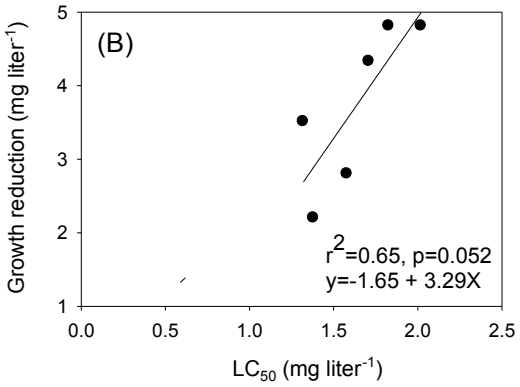
As Breitburg (2002) concluded from a recent extensive review of the scientific literature, clear evidence exists of behavioral responses to low dissolved oxygen conditions.

> Field studies have repeatedly shown that as oxygen concentrations decline, the abundance and diversity of demersal fishes decrease (e.g., Howell and Simpson 1994; Baden and Pihl 1996; Eby 2001; Breitburg et al. 2001). Bottom waters below approximately 2 mg liter$^{-1}$ have extremely depauperate fish populations. Some individual species appear to have threshold concentrations below which their densities decline precipitously (Howell and Simpson 1994; Baden and Pihl 1996; Eby 2001). However, because fish species vary in both physiological tolerance and behavior, total fish abundance and fish species richness tend to decline gradually with declining oxygen concentrations.
>
> Longer duration exposures to low oxygen and more severe hypoxia lead to avoidance of and emigration from affected habitat. All larval, juvenile and adult fishes that have been tested to date respond to oxygen gradients by moving upwards or laterally away from waters with physiologically stressful or potentially lethal dissolved oxygen towards higher oxygen concentrations (e.g., Deubler and Posner 1963; Stott and Buckley 1979; Breitburg 1994; Wannamaker and Rice 2000). Mortality from direct exposure to hypoxic and anoxic conditions is less than might otherwise occur because of this potential capacity for behavioral avoidance.
>
> Habitat loss due to hypoxia in coastal waters is, however, far greater than would be calculated based on the spatial extent of lethal conditions, because most fish avoid not only lethal oxygen concentrations but also those that would reduce growth and require greatly increased energy expenditures for ventilation. Field and sampling and laboratory experiments indicate that oxygen concentrations that are avoided tend to be 2 to 3 times higher than those that lead to 50 percent mortality in 24-to 96-hour exposures, and approximately equal to concentrations that have been shown to reduce growth rates in laboratory experiments.
>
> The net result of emigration and mortality is reduced diversity, abundance and production of fishes within the portion of the water column affected by low dissolved oxygen. Emigration leading to reduced densities of fishes even at oxygen concentrations approaching 40 to 50 percent saturation (3 to 4 mg liter$^{-1}$) is supported by the pattern of increasing number of species in trawl samples with increasing dissolved oxygen concentration in Long Island Sound (Howell and Simpson 1994) and Chesapeake Bay (Breitburg et al. 2001) and the increasing number of finfish individuals caught per trawl hour within increasing bottom dissolved oxygen off the Louisiana Coast in the Gulf of Mexico (Diaz and Solow 1999).

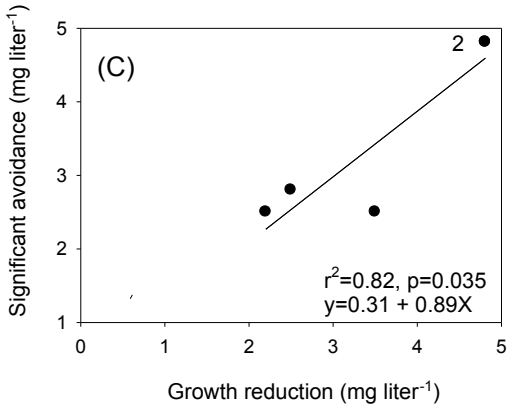
Concentrations associated with avoidance are very similar to those observed to result in adverse effects on growth (Breitburg 2002). Figure III-1 illustrates the relationship




Dissolved oxygen concentrations causing avoidance = 2.25*LC50




Dissolved oxygen concentrations causing growth reduction = 2.28*LC50




Dissolved oxygen concentrations causing avoidance = 0.98 * dissolved oxygen causing growth reduction

**Figure III-1.** Relationship between lethal dissolved oxygen concentrations and those resulting in reduced growth and behavioral avoidance of affected habitat. (a) $LC_{50}$ vs. avoidance behavior, (b) $LC_{50}$ vs. growth reduction, and (c) growth vs. avoidance behavior. Two identical points in (c) are indicated by the number 2 next to the data point. Data sources are as follows. Avoidance vs. mortality: Burton et al. 1980; Coutant 1985; Petersen and Petersen 1990; Pihl et al. 1991; Scholz and Waller 1992; Schurmann and Steffensen 1992; Howell and Simpson 1994; Petersen and Pihl 1995; Poucher and Coiro 1997; Wannamaker and Rice 2000; U.S. EPA 2000; Eby 2001. Growth vs. mortality: Burton et al. 1980; Petersen and Petersen 1990; Pihl et al. 1991; Scholz and Waller 1992; Schurmann and Steffensen 1992; Petersen and Pihl 1995; Chabot and Dutil 1999; U.S. EPA 2000; McNatt 2002. Avoidance vs. growth: Couton 1985; Pihl et al. 1991; Scholz and Waller 1992; Howell and Simpson 1994; Petersen and Pihl 1995; Poucher and Coiro 1997; U.S. EPA 2000; Eby 2001; and McNatt 2002. Only studies utilizing a range of dissolved oxygen concentrations are included in figures. Data from multiple studies on the same species were averaged. If responses were tested at several temperatures, the temperature with the most dissolved oxygen effects tested was selected.

Source: Breitburg 2002.

between dissolved oxygen concentrations that are lethal and those resulting in reduced growth and behavioral avoidance of the affected habitat. Regressions, calculated from data from a variety of sources, included $LC_{50}$ versus avoidance behavior, $LC_{50}$ versus growth reduction and growth versus avoidance behavior. Dissolved oxygen concentrations associated with avoidance were found to be 2.25 times the $LC_{50}$ concentration (Figure III-1a). Dissolved oxygen concentrations causing growth reduction were 2.28 times the $LC_{50}$ concentration (Figure III-1b). Dissolved oxygen concentrations causing avoidance were essentially the same as those concentrations causing growth reduction (Figure III-1c). Reduced growth and avoidance by fish occur at similar oxygen concentrations relative to lethal levels. Thus, protecting for one factor should protect for the other, if appropriate time durations are used.

The relationship between the average number of species per trawl across a range of dissolved oxygen concentrations provides additional evidence for a strong dissolved oxygen/behavioral connection that transcends individual estuarine and coastal systems (Figure III-2; Breitburg 2002). Using data from the Chesapeake Bay, Long Island Sound and Kattegat Sea, the number of species collected per trawl was shown to increase with increasing dissolved oxygen concentration in all three estuarine and coastal systems.

Individual species habitat requirements and the characteristics of habitats both determine the extent to which an ecosystem's habitats are used and contribute to the health and production of Chesapeake Bay living resources. Each species' behavioral responses, their predators and their prey can also be considered in deriving dissolved oxygen criteria. Based on the limited data on behavioral responses, we are not sure of the actual adverse effects that behavioral responses such as avoidance have on individuals, much less on whole populations. Although considerable data on behavioral avoidance of low oxygen habitats exist, we are unable to predict individual or population-level consequences of such avoidance.

Although it is true that we cannot directly evaluate the effects of avoidance in the same way that we can with effects on growth and survival, the EPA does not believe that a margin of safety for avoidance behavior is needed. The data reviewed by Breitburg (2002) clearly show that concentrations that have an effect on avoidance are nearly identical to those that affect growth. Therefore, criteria that protect growth should also be protective of habitat squeeze due to avoidance.

## Larval Recruitment Model

The larval recruitment model was used only in the actual derivation of the deep-water criteria when it was applied specifically to bay anchovy egg and larval life stages. In deriving the migratory spawning and nursery and open-water criteria, the larval recruitment model results for nine different species were used to ensure that the criteria based on other effects data would be fully protective of larval life stages.

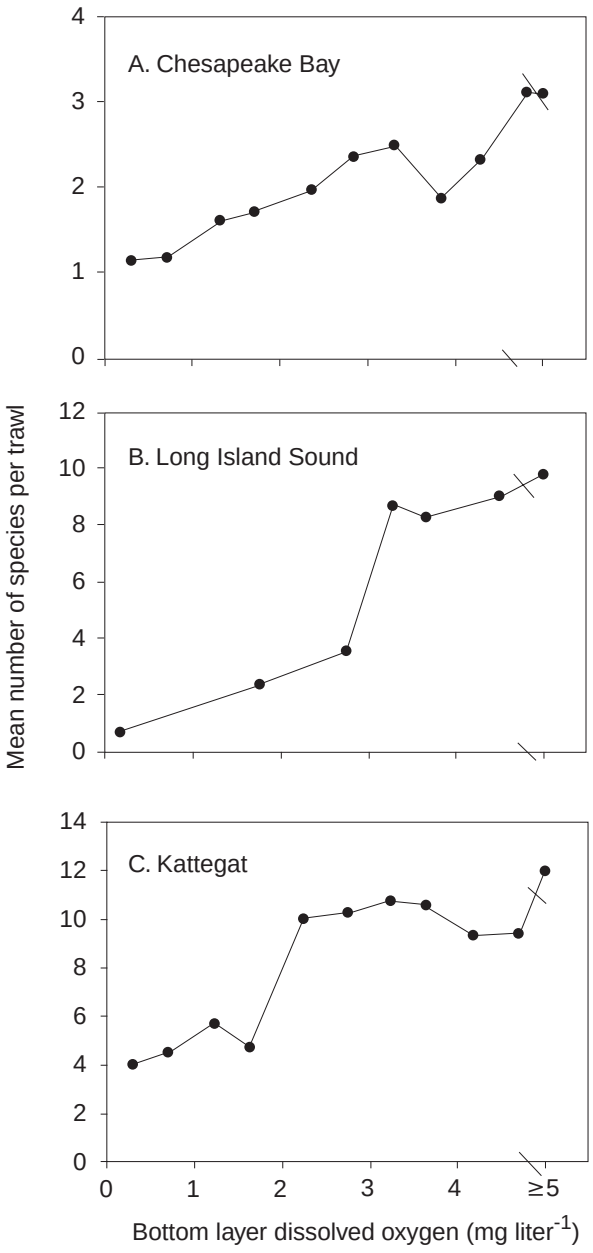



**Figure III-2.** Average number of species per trawl at a range of dissolved oxygen concentrations along the a) western shore of the Chesapeake Bay near the Calvert Cliffs Nuclear Power Plant (Breitberg and Kolesar, unpublished data), b) Long Island Sound (redrawn from Howell and Simpson 1994, figures 3 and 4), and c) Kattegat (Baden et al. 1990; Baden and Phil 1996). Data are averaged in approximately 0.5 mg liter$^{-1}$ intervals and for all data >0.5 mg liter$^{-1}$. Note variation in scale of vertical axes.

Source: Breitburg 2002.

Uncertainties remain with respect to the percent of the population exposed to low dissolved oxygen, the length of the actual spawning period and the protection of spawning events concentrated over short periods of time. In addition, the assumption implicit in the larval recruitment model is that all spawning days are equal.

Due to meteorological, food web and other influences, eggs hatched at different times during the spawning season are not expected to contribute equally to successful survival to juvenile and adult stages, nor are eggs produced continuously throughout the spawning season. In particular, species show spawning behaviors and early survival rates that depend on lunar tidal patterns, weather-driven changes to water quality (e.g., winds and temperature changes) and available forage for young. For example, it is well-documented that most striped bass survival can come from a relatively narrow period of time during the entire spawning period (Ulanowicz and Polgar 1980; Secor and Houde 1995; Secor 2000). Since we cannot predict when this smaller window may occur relative to specific hypoxic events, conservative assumptions must be made. These include always assuming in the recruitment model that hypoxia will occur during times of maximum offspring production.

A number of reports exist on the consequences of slow growth in terms of increased predation mortality. The model does not contain a variable for growth (it only deals with larval survival), however, it does increase the mortality (i.e., changes the sensitivity to hypoxia) with increasing exposure duration.

The EPA acknowledges uncertainties with the parameters in the larval recruitment model. This is why specific parameters within the model were chosen to be conservative. Specifically, spawning periods reflect when the bulk of spawning occurs, not just the first and last possible occurrence of a given species larvae in the water column. In addition, the model always assumes that a hypoxic event occurs during the spawning season of each species modeled. The percentages of each cohort that is exposed during a hypoxic event were also intended to be conservative.

## CHESAPEAKE BAY DISSOLVED OXYGEN CRITERIA DERIVATION

Chesapeake Bay dissolved oxygen criteria were established to protect estuarine living resources inhabiting five principal habitats: migratory spawning and nursery, shallow-water, open-water, deep-water and deep-channel. These five categories are drawn from the refined designated uses for the Chesapeake Bay and its tidal tributary waters (Figure III-3). See Appendix A and U.S. EPA 2003a for more detailed descriptions of the refined designated uses.

The EPA's *Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses* (U.S. EPA 1985) is the primary source on how to establish numerical criteria. Consistent with the national guidelines provided, scientific judgment took precedence over the specifics of the guidelines,

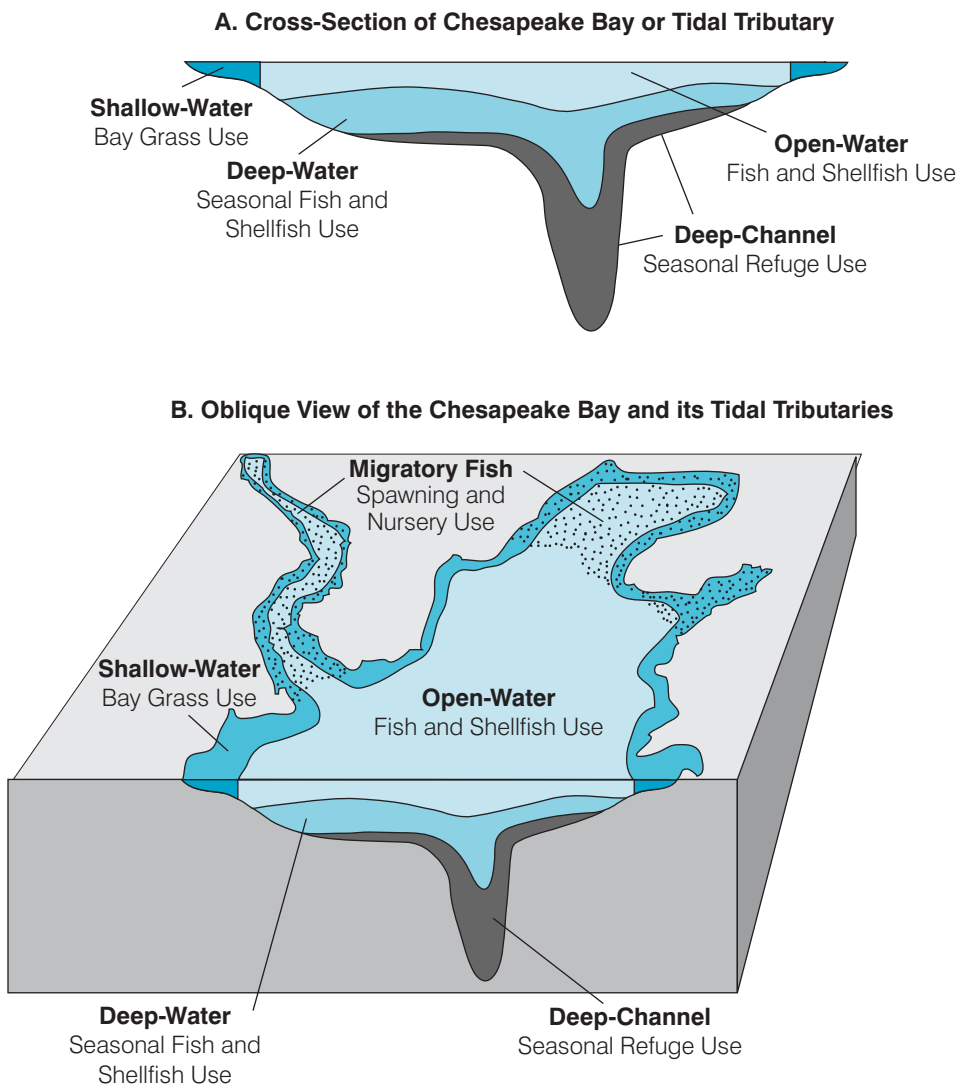



**Figure III-3.** Conceptual illustration of the five Chesapeake Bay designated use zones.

when warranted. A similar judgment was applied in the development of the 2000 EPA Virginian Province saltwater and the 1986 EPA freshwater dissolved oxygen criteria documents (U.S. EPA 1986, 2000).

The Chesapeake Bay dissolved oxygen criteria were derived using methodologies documented in the EPA Virginian Province saltwater criteria document and using criteria originally published in the EPA freshwater criteria document. The scientific rationale for modifications to the 1985 EPA guidelines for deriving the saltwater dissolved oxygen criteria for the Virginian Province and the national freshwater dissolved oxygen criteria are detailed in those peer-reviewed, EPA documents.

Criteria for migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated use habitats were set at levels to protect the survival, growth and reproduction of all species. Criteria that apply to deep-water seasonal fish and shellfish habitats in summer were set at levels to protect shellfish, the survival of juvenile and adult fish, and the recruitment success of the bay anchovy. Criteria for deep-channel seasonal refuge designated use habitats in summer were set to protect the survival of sediment-dwelling worms and clams.

## MIGRATORY FISH SPAWNING AND NURSERY DESIGNATED USE CRITERIA

Criteria that support the migratory fish spawning and nursery designated use must fully protect the "survival, growth and propagation of balanced indigenous populations of ecologically, recreationally and commercially important anadromous, semi-anadromous and tidal-fresh resident fish species inhabiting spawning and nursery grounds from February 1 through May 31" (Appendix A; U.S. EPA 2003a). This covers the survival and growth of all life stages—eggs, larvae, juveniles and adults—for a given number of species and their underlying food sources. As described below, the criteria are based on establishing dissolved oxygen concentrations to protect against losses in larval recruitment, growth effects on larvae and juveniles and the survival and growth effects on the early life stages of resident tidal-fresh species.

### Criteria Components

**Protection against Larval Recruitment Effects**. Applying the Virginian Province criteria larval recruitment effects model generates a relationship illustrated as a curve, projecting the cumulative loss of recruitment caused by exposure to low dissolved oxygen (Figure III-4). The number of acceptable days of exposure to low dissolved oxygen decreases as the severity of the low oxygen conditions increases. The migratory fish spawning and nursery designated use criteria must ensure protection of larvae as they are recruited into the juvenile/adult population. The Virginian Province criteria larval recruitment curve levels out at approximately 4.6 mg liter$^{-1}$ beyond 30 days of exposure (Figure III-4). By dropping non-Chesapeake Bay species and applying Chesapeake Bay-specific modifications to the larval recruitment model parameters, as described previously, a curve is generated that closely follows the original Virginian Province criteria curve but levels off just above 4.6 mg liter$^{-1}$. Dissolved oxygen concentrations and exposure durations falling above the Chesapeake Bay-specific curve, e.g., above 4.6 mg liter$^{-1}$ for 30 days, 3.4-3.5 mg liter$^{-1}$ for up to seven days and 2.7-2.8 liter$^{-1}$ at all times, would protect against larval recruitment effects.

**Protection for Early Life Stages for Resident Tidal-Fresh Species.** The EPA freshwater dissolved oxygen criteria set a 7-day mean of 6 mg liter$^{-1}$ and an instantaneous minimum of 5 mg liter$^{-1}$ to protect early life-stage, warm-water, freshwater species (Table III-4) (U.S. EPA 1986).

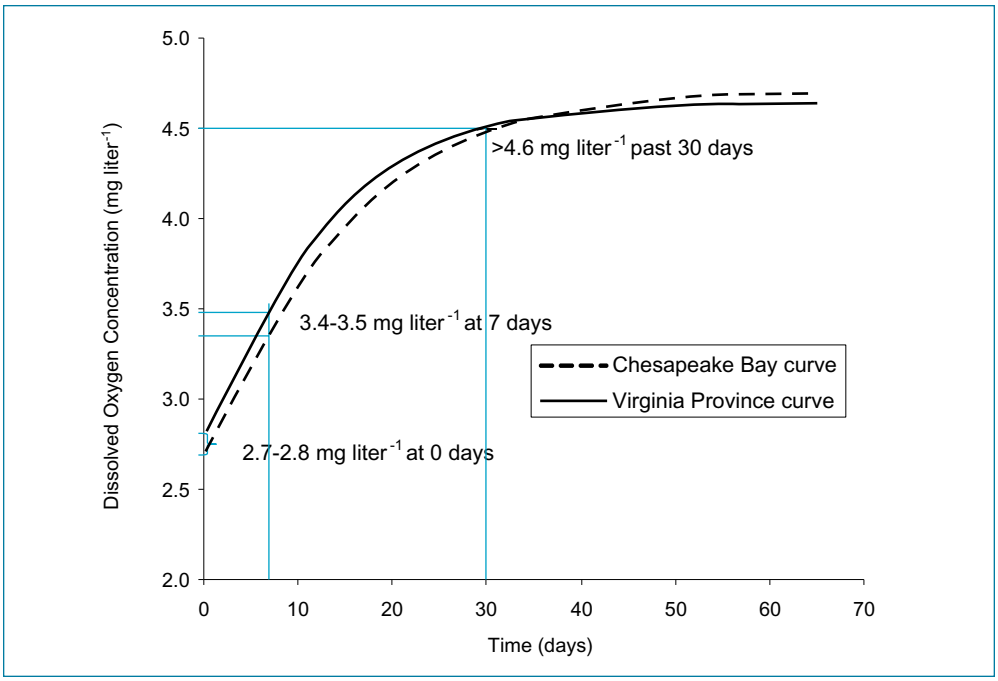



**Figure III-4.** Comparison of the Virginian Province-wide (—) and Chesapeake Bay-wide (---) larval recruitment effects.

**Protection against Growth Effects.** To ensure recruitment to the adult population, the Chesapeake Bay criteria must ensure protection against growth effects on rapidly developing larvae and juveniles. The Virginian Province criteria document recommends 4.8 mg liter$^{-1}$ as the threshold above which long-term, continuous exposures should not cause unacceptable growth effects (U.S. EPA 2000). As described previously, if the non-Chesapeake Bay species were removed from the Virginian Province criteria dissolved oxygen growth effects data base, a recalculated Chesapeake Bay-specific criterion would be 5 mg liter$^{-1}$.

These values were derived by observing the effects of low dissolved oxygen on larval and early juvenile life stages. Growth effects on these stages served as the basis for the chronic criterion because: 1) growth is generally the more sensitive endpoint measure upon exposure to low dissolved oxygen compared with survival; 2) results for other sublethal endpoints such as reproduction were limited; 3) the limited data available indicated that thresholds protecting against growth effects are likely to protect against reproductive effects; and 4) larval and juvenile life stages were more sensitive to effects from low dissolved oxygen than were adults (U.S. EPA 2000). In addition to higher dissolved oxygen requirements, fish eggs and larvae also are more vulnerable to low dissolved oxygen because of limitations in behavioral avoidance (Breitburg 2002).

**Protection against Effects on Threatened/Endangered Listed Species.** As documented previously, short-term exposures to dissolved oxygen concentrations

of > 3.2 mg liter$^{-1}$ on the order of several hours at nonstressful temperatures and longer-term exposures of 30 days or longer at > 5 mg liter$^{-1}$ will not impair the survival or growth of Atlantic and shortnose sturgeon (Secor and Niklitschek 2001, 2003; Niklitschek 2001; Secor and Gunderson 1998; Campbell and Goodman 2003). At stressful temperatures above 29°C, short-term exposures to dissolved oxygen concentrations >4.3 mg liter$^{-1}$ will not impair the survival of shortnose sturgeon.

**Additional Scientific Literature Findings.** Results from Brandt et al. (1998) indicate that striped bass food consumption and growth decline as oxygen levels decline. Continuous exposure to dissolved oxygen concentrations of 4 mg liter$^{-1}$ or less caused striped bass to lose weight, even though food was always unlimited. Previous experiments on the effects of oxygen levels on striped bass also have shown that dissolved oxygen concentrations of less than 3 to 4 mg liter$^{-1}$ adversely affect feeding (Chittenden 1971).

Jordan et al. (1992) summarized the literature supporting the adoption of the Chesapeake Bay restoration goal target concentration protecting anadromous spawning and nursery areas as follows.

> This target DO concentration (>5 mg liter$^{-1}$ at all times) was selected to protect the early life stages of striped bass, white perch, alewife, blueback herring, American shad, hickory shad and yellow perch. This concentration of DO will allow eggs to hatch normally (Bradford et al. 1968; O'Malley and Boone 1972; Marcy and Jacobson 1976; Harrell and Bayless 1981; Jones et al. 1988), as well as allow survival and growth of larval and juvenile stages of all anadromous target species (Tagatz 1961; Bogdanov et al. 1967; Krouse 1968; Bowker et al. 1969; Chittenden 1969, 1972, 1973; Meldrim et al. 1974; Rogers et al. 1980; Miller et al. 1982; Coutant 1985; ASMFC 1987; Jones et al. 1988). For example, concentrations of DO below 5 mg liter$^{-1}$ for any duration will not support normal hatching of striped bass eggs (O'Malley and Boone 1972). Although one hatchery operation was able to maintain striped bass fingerlings at DO concentrations of 3 to 4 mg liter$^{-1}$ (Churchill 1985). Bowker et al. (1969) found DO > 3.6 mg liter$^{-1}$ was required for survival of juveniles.

Across an array of temperatures (13–25°C) and salinities (5–25 ppt), Krouse (1968) observed complete mortality of striped bass at 1 mg liter$^{-1}$, 'minimal mortality' at 5 mg liter$^{-1}$ and 'intermediate survival' at 3 mg liter$^{-1}$ upon exposure of 72 hours. Some field observations have indicated that juveniles and adults of anadromous species prefer dissolved oxygen concentrations ≥ 6 mg liter$^{-1}$ (Hawkins 1979; Christie et al. 1981; Rothschild 1990). However, no lethal or sublethal effects other than possible avoidance have been documented for dissolved oxygen concentrations between 5 and 6 mg liter$^{-1}$.

## Rationale

The migratory spawning and nursery designated use criteria must ensure full protection for warm-water freshwater species' egg, larval and juvenile life stages, which

co-occur with the tidal-fresh and low-salinity migratory spawning and nursery habitats (Table III-5). To ensure full protection for resident tidal-fresh warm-water species' early life stages, a 7-day mean criterion of 6 mg liter$^{-1}$ and an instantaneous minimum criterion of 5 mg liter$^{-1}$ were selected, consistent with the EPA freshwater criteria (U.S. EPA 1986).

To ensure protection not only of survival and recruitment of larvae into the juvenile population but also to eliminate any potential for adverse effects on growth during the critical larvae and early juvenile life stages, an instantaneous minimum criterion of 5 mg liter$^{-1}$ was selected. The Virginian Province saltwater criteria document states that exposures to dissolved oxygen concentrations above this concentration should not result in any adverse effects on growth (U.S. EPA 2000). Given the lack of information on the population level consequences of short- versus long-term reductions in growth on the survival of larvae and juveniles, a specific averaging

**Table III-5.** Migratory fish spawning and nursery designated use dissolved oxygen criteria components.

| Criteria Components | Concentration | Duration | Source |
|---|---|---|---|
| Protection against growth effects | > 4.8 mg liter$^{-1}$ | - | U.S. EPA 2000 |
| Protection against larval recruitment effects | > 4.6 mg liter$^{-1}$<br>> 3.4-3.5 mg liter$^{-1}$<br>> 2.7-2.8 mg liter$^{-1}$ | 30 to 40 days<br>7 days<br>instantaneous minimum | U.S. EPA 2000 |
| Protection of early life stages for resident tidal freshwater species | > 6 mg liter$^{-1}$<br>> 5 mg liter$^{-1}$ | 7-day mean<br>instantaneous minimum | U.S. EPA 1986 |
| Protection against effects on threatened/endangered species (shortnose sturgeon) | > 5 mg liter$^{-1}$<br>> 3.5 mg liter$^{-1}$<br>> 3.2 mg liter$^{-1}$ [1]<br>> 4.3 mg liter$^{-1}$ [2] | 30 days<br>6 hours<br>2 hours<br>2 hours | Secor and Niklitschek 2003; Niklitschek 2001; Secor and Gunderson 1998; Jenkins et al. 1993; Campbell and Goodman 2003 |
| Additional published findings<br>- Growth effects on striped bass<br>- Protect early life stages<br>- Intermediate striped bass survival<br>- Full survival<br>- Preferred concentrations | <br>< 3 to 4 mg liter$^{-1}$<br>> 5 mg liter$^{-1}$<br>> 3mg liter$^{-1}$<br><br>>5 mg liter$^{-1}$<br>≥ 6 mg liter$^{-1}$ | <br>-<br>-<br>72 hours<br><br>72 hours<br>- | <br>Brandt et al. 1998; references in text<br>Krouse 1968<br><br>Krouse 1968<br>Hawkins 1979; Christie et al. 1981; Rothschild 1990 |

[1] Protective of survival at nonstressful temperatures.
[2] Protective of shortnose sturgeon at stressful temperatures (>29°C).

period was not recommended in the Virginian Province saltwater criteria. In the case of anadromous species, a narrow set of natural conditions (e.g., salinity, temperature) is required and a narrow time window exists for a successful spawn. Natural mortalities for larvae already are extremely high. As even short-term reductions in growth could influence advancement to the next stage through the impairment of survival and the ability to avoid predators, the criterion value that protects against growth effects is applied as an instantaneous minimum.

Setting the criterion duration of exposure as an instantaneous minimum is consistent with the instantaneous minimum duration for the 5 mg liter$^{-1}$ concentration criterion value from the EPA freshwater dissolved oxygen criteria for ensuring full protection of warm-water freshwater species' early life stages against short-term exposures (Table III-4; U.S. EPA 1986). The instantaneous minimum of the 5 mg liter$^{-1}$ criterion value also protects the survival and growth of shortnose sturgeon (Table III-5).

### Migratory Spawning and Nursery Criteria

The following dissolved oxygen criteria fully support the Chesapeake Bay migratory fish spawning and nursery designated use when applied from February 1 through May 31: a 7-day mean $\geq$ 6 mg liter$^{-1}$ applied to tidal-fresh waters with long-term averaged salinities up to 0.5 ppt; and an instantaneous minimum $\geq$ 5 mg liter$^{-1}$ applied across all the migratory fish spawning and nursery designated use habitats, regardless of salinity. See U.S. EPA 2003a for details on the selection of February 1 through May 31 as the time period for applying the migratory spawning and nursery designated use.

## OPEN-WATER FISH AND SHELLFISH DESIGNATED USE CRITERIA

Criteria that support the open-water designated use must fully protect the "survival, growth and propagation and growth of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish inhabiting open-water habitats" (Appendix A; U.S. EPA 2003a). The dissolved oxygen requirements for the species and communities inhabiting open- and shallow-water habitats are similar enough to ensure protection of both the open-water and shallow-water designated uses with a single set of criteria. The open-water criteria were based on establishing dissolved oxygen concentrations to protect against losses in larval recruitment, growth effects on larvae and juveniles and the survival of juveniles and adults in tidal-fresh to high-salinity habitats.

### Criteria Components

**Protection against Larval Recruitment Effects.** Applying the Virginian Province criteria model generates a relationship illustrated as a curve that projects the cumulative loss of recruitment caused by exposure to low dissolved oxygen. The number of acceptable days of exposure to low dissolved oxygen decreases as the

severity of the low oxygen conditions increases. The open-water designated use criteria must ensure protection of larvae as they recruit into the juvenile/adult population.

The Virginian Province larval recruitment effects curve levels out at approximately 4.6 mg liter$^{-1}$ beyond 30 days' exposure (Figure III-5). Dropping the non-Chesapeake Bay resident species and then applying a series of Chesapeake Bay-specific modifications to the larval recruitment model parameters, as described previously, yields a curve that follows the original Virginian Province criteria curve and also levels out around 4.6 mg liter$^{-1}$ beyond 30 days exposure (Figure III-5). Setting the larval exposure level to 100 percent[5] results in a curve that levels out at 4.8 mg liter$^{-1}$. The effects curves illustrated in Figure III-5 reflect the combined dissolved oxygen concentration and duration of exposure protective against a five percent or greater impact, thereby protecting 95 percent or greater of the seasonally produced offspring. Dissolved oxygen concentrations/exposure durations falling above the curve, e.g., above 2.7-2.9 mg liter$^{-1}$ at all times, above 3.4-3.6 mg liter$^{-1}$ for up to seven days, and above 4.6-4.8 mg liter$^{-1}$ for 30 days, would protect against larval recruitment effects greater than five percent in open-water designated use habitats.

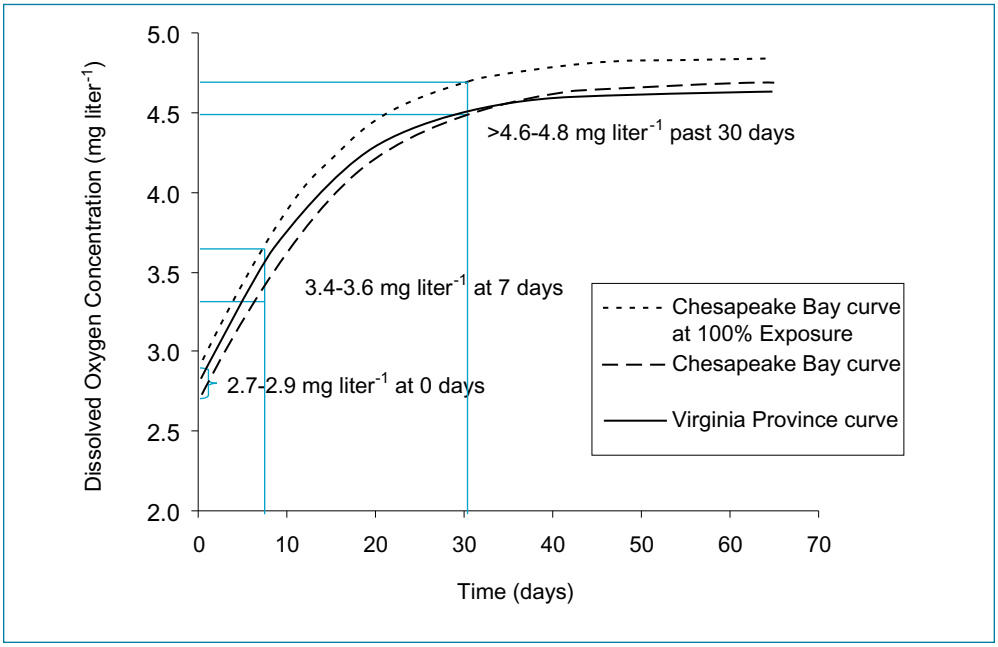



**Figure III-5.** Comparison of the Virginian Province-wide (—) and Chesapeake Bay specific larval recruitment effects at variable (---) and 100 percent ( . . . ) exposures.

[5] The larval recruitment model has a parameter for what percentage of a given cohort is exposed to low dissolved oxygen conditions.

**Protection of Juvenile/Adult Survival.** The Virginian Province criteria document recommends 2.3 mg liter$^{-1}$ as the threshold above which long-term, continuous exposures should not cause unacceptable lethal conditions for juvenile and adult fish and shellfish. As described below, this value does not protect the survival of shortnose sturgeon.

**Protection against Growth Effects.** To ensure recruitment to the adult population, the open-water designated use dissolved oxygen criteria must protect against growth effects on rapidly developing larvae and juveniles. The Virginian Province document recommends 4.8 mg liter$^{-1}$ as the threshold above which long-term, continuous exposures should not cause unacceptable growth effects. If the non-Chesapeake Bay species were to be removed from the Virginian Province growth effects data base, the recalculated Bay-specific criterion protective against growth effects would be 5 mg liter$^{-1}$.

This chronic criterion value was derived from laboratory evaluations of the effects of low dissolved oxygen on growth, principally with larval and early juvenile life stages. Growth effects on these early life stages were used as the basis of the chronic criterion because: 1) growth is generally the more sensitive endpoint measure upon exposure to low dissolved oxygen compared with survival; 2) results for other non-mortality related endpoints such as reproduction were very limited; 3) the limited data indicated that thresholds protecting against growth effects are likely to protect against negative reproductive effects; and 4) larval life stages were more sensitive to effects from low dissolved oxygen than were juveniles/adults (U.S. EPA 2000). The derivation of a dissolved oxygen criterion value of 5 mg liter$^{-1}$ to protect against growth effects is consistent with findings reported by Breitburg (2002) that dissolved oxygen concentrations causing growth reductions were 2.28 times the $LC_{50}$ concentration (2.28 x 1.64 = 3.7 mg liter$^{-1}$, where 1.64 is the Final Acute Value from the EPA Virginian Province document).

**Protection of Resident Tidal-Fresh Species.** The open-water fish and shellfish designated use criteria must also fully protect warm-water freshwater species that co-occur in tidal-fresh and low-salinity open- and shallow-water habitats. The EPA freshwater dissolved oxygen criteria set a 30-day mean of 5.5 mg liter$^{-1}$; a 7-day mean minimum of 4.0 mg liter$^{-1}$, and an instantaneous minimum of 3.0 mg liter$^{-1}$ to protect life stages for warm-water species beyond early life stages (Table III-4) (U.S. EPA 1986).

**Protection against Effects on Threatened/Endangered Listed Species.** As documented previously, short-term exposures of several hours to dissolved oxygen concentrations of > 3.2 mg liter$^{-1}$ at nonstressful temperatures and longer-term exposures of 30 days or more at > 5 mg liter$^{-1}$ would protect the survival and growth of Atlantic and shortnose sturgeon (Secor and Niklitschek 2001, 2003; Niklitschek 2001; Secor and Gunderson 1998; Campbell and Goodman 2003). At

stressful temperatures above 29°C, short-term exposures to dissolved oxygen concentration > 4.3 mg liter$^{-1}$ will not impair the survival of shortnose sturgeon.

**Additional Scientific Literature Findings.** As striped bass larvae begin their metamorphoses to the juvenile stage, they move into shallow-water habitats near shore and in shoal areas less than 2 meters deep (Boreman and Klauda 1988; Boynton et al. 1981; Setzler-Hamilton et al. 1981). Nursery areas for juvenile striped bass with dissolved oxygen concentrations greater than 5 mg liter$^{-1}$ are preferable, given findings that concentrations below 4 mg liter$^{-1}$ can adversely affect juvenile growth rates, feeding rates, habitat use and susceptibility to predation (e.g., Kramer 1987; Breitburg et al. 1994). Mortality of juvenile striped bass has been observed at dissolved oxygen concentrations < 3 mg liter$^{-1}$ (Chittenden 1972; Coutant 1985; Krouse 1968).

Results from trawls in Long Island Sound showed significant reductions in both species diversity and abundance at sites with dissolved oxygen < 2 mg liter$^{-1}$ (Howell and Simpson 1994). At open water-column sites with dissolved oxygen concentrations > 3 mg liter$^{-1}$, 15 of the 18 target species caught occurred with greater frequency compared with sites with concentrations < 2 mg liter$^{-1}$. Further research indicated that the total abundance of fish was relatively insensitive to low dissolved oxygen conditions, reaching normal levels at 1.5 mg liter$^{-1}$. However, total fish biomass and species richness were particularly sensitive, declining at dissolved oxygen concentrations of 3.7 mg liter$^{-1}$ and 3.5 mg liter$^{-1}$, respectively (Simpson 1995).

## Rationale

To ensure the full protection of survival and recruitment of larvae into the juvenile population, reduce the potential for adverse effects on growth and protect threatened or endangered species across tidal-fresh to high-salinity habitats, dissolved oxygen criteria values of a 30-day mean of 5.5 mg liter$^{-1}$ applied to tidal-fresh habitats with long- term averaged salinities up to 0.5 ppt; a 30-day mean of 5 mg liter$^{-1}$ applied to all other open-water habitats (> 0.5 ppt salinity); a 7-day mean of 4 mg liter$^{-1}$; and an instantaneous minimum of 3.2 mg liter$^{-1}$ were selected (Table III-6). At temperatures stressful to shortnose sturgeon (>29°C), a 4.3 mg liter$^{-1}$ instantaneous minimum criteria should apply.

The 5 mg liter$^{-1}$ value is based on the Virginian Province criterion protecting against growth effects (U.S. EPA 2000). The Virginian Province criteria document states that exposures to dissolved oxygen concentrations above this concentration will not result in any adverse effects on growth. However, the document recommended no specific duration. The extensive open-water habitats provide better opportunities for avoiding predators and seeking food than the more confined, geographically limited migratory spawning and nursery habitats. The 30-day mean averaging period for the 5 mg liter$^{-1}$ criterion value was selected to reflect current uncertainties over how much impact growth reduction has on juvenile and adult survival and reproduction in the shallow- and open-water Chesapeake Bay habitats. The 30-day mean averaging

**Table III-6.** Open-water fish and shellfish designated use dissolved oxygen criteria components.

| Criteria Components | Concentration | Duration | Source |
|---|---|---|---|
| Protection against larval recruitment effects | > 4.6-4.8 mg liter$^{-1}$<br>> 3.4-3.6 mg liter$^{-1}$<br>> 2.7-2.9 mg liter$^{-1}$ | 30 to 40 days<br>7 days<br>< 24 hours | U.S. EPA 2000 |
| Protection against growth effects | > 4.8 mg liter$^{-1}$ | - | U.S. EPA 2000 |
| Protection of juvenile/adult survival | > 2.3 mg liter$^{-1}$ | 24 hours | U.S. EPA 2000 |
| Protection for resident tidal freshwater species | > 5.5 mg liter$^{-1}$<br>> 4 mg liter$^{-1}$<br>> 3 mg liter$^{-1}$ | 30 days<br>7 days<br>instantaneous minimum | U.S. EPA 1986 |
| Protection against effects on threatened/endangered species (shortnose sturgeon) | > 5 mg liter$^{-1}$<br>> 3.5 mg liter$^{-1}$<br>> 3.2 mg liter$^{-1}$ [1]<br>> 4.3 mg liter$^{-1}$ [2] | 30 days<br>6 hours<br>2 hours<br>2 hours | Secor and Niklitschek 2003; Niklitschek 2001; Secor and Gunderson 1998; Jenkins et al. 1994; Campbell and Goodman 2003 |
| Additional published findings | | | |
| – Preferred striped bass juvenile habitat | > 5 mg liter$^{-1}$ | - | Kramer 1987; Breitburg et al. 1994 |
| – Juvenile striped bass growth, feeding effects | < 4 mg liter$^{-1}$ | - | Kramer 1987; Breitburg et al. 1994 |
| – Juvenile striped bass mortality | < 3 mg liter$^{-1}$ | - | Chittenden 1972; Coutant 1985; Krouse 1968 |
| – Total fish biomass declining | < 3.7 mg liter$^{-1}$ | - | Simpson 1995 |
| – Total fish species richness | < 3.5 mg liter$^{-1}$ | - | Simpson 1995 |

[1] Protective of survival at nonstressful temperatures.
[2] Protective of shortnose sturgeon at stress temperatures (> 29°C).

period is consistent with and fully protects against effects on larval recruitment (see Figure III-5 and text below) and is consistent with the duration protection of freshwater species.

The criterion values of a 30-day mean of 5 mg liter$^{-1}$, a 7-day mean of 4 mg liter$^{-1}$ and an instantaneous minimum of 3.2 mg liter$^{-1}$ fully protect larval recruitment. Depending on an assumption of partial or 100 percent exposure to low dissolved oxygen concentrations, larval recruitment would be protected at concentrations ranging between 4.6 and 4.8 mg liter$^{-1}$ beyond 30 days of exposure (Figure III-5). At seven days of exposure, concentrations between 3.4 and 3.6 mg liter$^{-1}$, extracted from the range of larval recruitment curves protects against effects. The 7-day mean, 4 mg liter$^{-1}$ concentration criterion value, therefore, protects recruitment. The instantaneous minimum 3.2 mg liter$^{-1}$ criterion would protect larval recruitment, given that the instantaneous minimum exposure level concentrations are between 2.7 to 2.9 mg liter$^{-1}$.

The instantaneous minimum 3.2 mg liter$^{-1}$ criterion will also protect the survival of juvenile and adult fish and shellfish species inhabiting shallow- and open-water habitats, given it has a higher value than the Virginian Province value of 2.3 mg liter$^{-1}$ (U.S. EPA 2000).

The 30-day mean 5.5 mg liter$^{-1}$ criterion value is consistent with the EPA freshwater dissolved oxygen criteria to protect warm-water freshwater species (U.S. EPA 1986). The other two components of the proposed open-water criteria—7-day mean of 4 mg liter$^{-1}$ and instantaneous minimum of 3.2 mg liter$^{-1}$—are also consistent with the EPA warm-water freshwater criteria (Table III-4).

The instantaneous minimum 3.2 mg liter$^{-1}$ criterion protects against lethal effects from short-term exposures to low dissolved oxygen for both Bay species of sturgeon. A 30-day mean 5 mg liter$^{-1}$ criterion protects against growth effects for longer-term exposures (Secor and Niklitschek 2001, 2003; Niklitschek 2001; Secor and Gunderson 1998). Application of the 3.2 mg liter$^{-1}$ criterion as an instantaneous minimum concentration is justified on the basis that effects on shortnose sturgeon were observed after just two hours' exposure (Campbell and Goodman 2003).

From October 1 through May 31, when the open-water fish and shellfish designated use extends through the water column into the seasonally defined deep-water seasonal fish and shellfish and deep-channel seasonal refuge designated use habitats, these habitats are important both to blue crabs and larger finfish species seeking refuge in deeper, warmer waters (e.g., striped bass, white perch, Atlantic croaker, shortnose sturgeon and Atlantic sturgeon) during the cooler months of the year (see Appendix A; U.S. EPA 2003a). The criterion values described above will provide the necessary levels of protection for all of these species, for both juvenile and adult life stages.

## Open-Water Criteria

The following criteria fully support both the Chesapeake Bay open-water fish and shellfish and shallow-water bay grass designated uses when applied year-round: a

30-day mean $\geq$ 5.5 mg liter$^{-1}$ applied to tidal-fresh habitats only with long-term averaged salinities of up to 0.5 ppt; a 30-day mean $\geq$ 5 mg liter$^{-1}$; a 7-day mean $\geq$ 4 mg liter$^{-1}$; and an instantaneous minimum $\geq$ 3.2 mg liter$^{-1}$. At temperatures stressful to shortnose sturgeon (>29°C), a 4.3 mg liter$^{-1}$ instantaneous minimum criteria should apply.

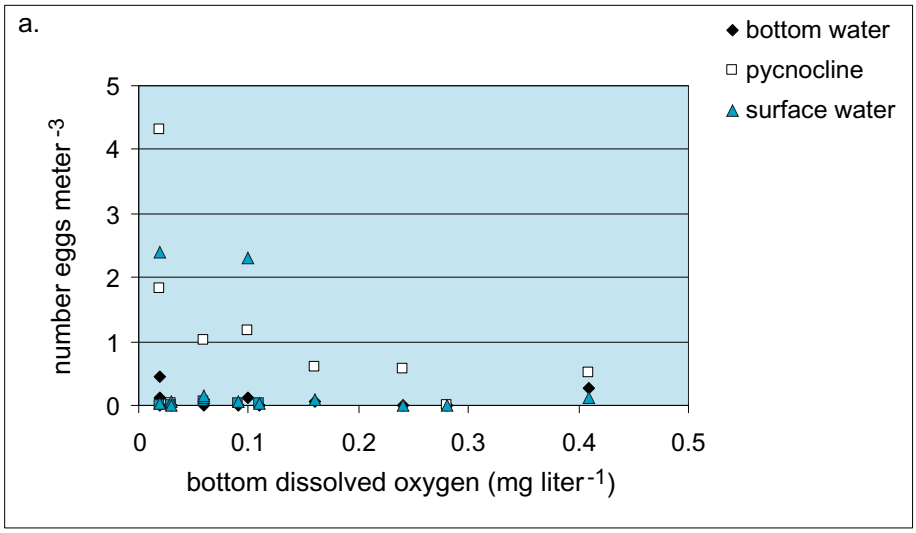
## DEEP-WATER SEASONAL FISH AND SHELLFISH DESIGNATED USE CRITERIA

In deep-water habitats, where the physical exchange of higher oxygenated waters in the upper water-column habitats is much reduced by density stratification and pycnocline waters are not reoxygenated by riverine or oceanic bottom waters, dissolved oxygen concentrations will naturally be lower during the warmer months of the year. Criteria to support the deep-water seasonal fish and shellfish designated use must fully "protect the survival, growth and propagation of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish species inhabiting deep-water habitats" (Appendix A; U.S. EPA 2003a).

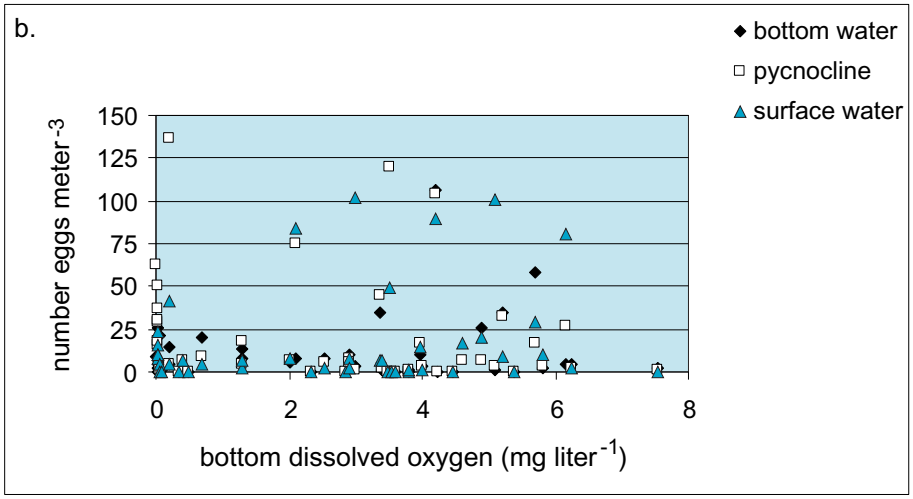
In the Chesapeake Bay, the bay anchovy is an abundant, ecologically significant fish likely to be affected by low dissolved oxygen conditions, given its life history. Although it is not a commercial species, the bay anchovy is prey for bluefish, weakfish and striped bass (Hartman and Brandt 1995), forms a link between zooplankton and predatory fish (Baird and Ulanowicz 1989) and represents from 60 to 90 percent of piscivorus fish diets on a seasonal basis (Hartman 1993). Bay anchovy spawn from May to September in the Chesapeake Bay, with a peak in June and July (Olney 1983; Dalton 1987) across a broad range of temperatures and salinities throughout the Chesapeake Bay (Dovel 1971; Houde and Zastrow 1991). Their spawning and nursery periods coincide with the presence of low dissolved oxygen conditions in the Chesapeake Bay and its tidal tributaries.

The hatchability of fish eggs is known to be influenced by the oxygen concentrations to which they are exposed during incubation (Rombough 1988). Chesney and Houde (1989) conducted laboratory experiments to test the effects of low dissolved oxygen conditions on the hatchability and survival of bay anchovy eggs and yolk-sac larvae. Their findings demonstrated that survival rates of bay anchovy eggs and larvae are likely to be affected when exposed to dissolved oxygen concentrations less than 3 mg liter$^{-1}$ and 2.5 mg liter$^{-1}$, respectively. Breitburg (1994) found very similar effects for 3- to 13-day post-hatch bay anchovy larvae, where 50 percent survival was observed at 2.1 mg liter$^{-1}$.

Bay anchovy routinely inhabit waters within the pycnocline region. Bay anchovy eggs have been found throughout the water column regardless of bottom layer oxygen concentrations in mesohaline areas of tributaries (Keister et al. 2000), but were retained in surface and pycnocline waters in the mesohaline mainstem Bay (North 2001; Breitburg et al., unpublished data; Figure III-6). MacGregor and Houde (1996) found that most bay anchovy eggs were distributed in water above the




(note: 1 surface value of 45/m3 deleted for clarity)




(note: 2 bottom values 274 and 413 eggs/m3 deleted for clarity)

**Figure III-6.** Illustration of bay anchovy egg densities observed in the surface mixed layer, within pycnocline and below pycnocline waters in the mesohaline portion of the Chesapeake Bay (a) and the mesohaline portion of the Patuxent River (b).

NOTE: one surface value of 45 eggs meter$^{-3}$ for the Chesapeake Bay and two bottom values of 274 and 413 eggs meter$^{-3}$ for Patuxent River deleted for clarity.

Sources: Breitburg et al. 2003; Breitburg et al., unpublished data; Keister et al. 2000.

pycnocline when below pycnocline waters had dissolved oxygen concentrations of < 2 mg liter$^{-1}$. Rilling and Houde (1999) observed bay anchovy eggs and larvae throughout the water column during June and July. Bay anchovy larvae are found throughout the water column when bottom oxygen concentrations are above 2 mg liter$^{-1}$ (Keister et al. 2000).

Environmental conditions present during the egg, larval or juvenile life stages strongly influence fish population dynamics. Key among these are changes in food supply for first-feeding larvae and factors that modify predation mortality for the highly vulnerable larval life stages. The majority of the species for which larval effects data are available within the Virginian Province criteria document do not routinely inhabit waters in the pycnocline layer. To derive a criteria to protect deep waters located within the pycnocline layer that are generally inhabited by bay anchovy and their eggs and larvae, a Chesapeake Bay-specific larval recruitment effects model was generated for the bay anchovy.

## Criteria Components

**Protection against Egg/Larval Recruitment Effects.** Two larval recruitment effect models were derived that are specific to the Chesapeake's bay anchovy, based on the original Virginian Province larval recruitment effects model (U.S. EPA 2000). The bay anchovy eggs effects model was based on a 5 percent impairment of eggs hatching to yolk-sac larvae, assuming a 100-day recruitment period and 1-day development period (Chesney and Houde 1989). The larvae-based recruitment effects model, also based on a 5 percent impairment, assumed that yolk-sac larvae and post-yolk larvae or feeding larvae had the same sensitivity.

A development period of 32 days was applied, based on Houde's work (1987), which documented an egg-to-larval duration of 33 days. One day was subtracted to reflect the egg stage (Chesney and Houde 1989), yielding the 32-day development period. A 132-day recruitment period was calculated by adding the 32-day development period to the 100-day recruitment period mentioned above.

A 50 percent exposure[6] to low dissolved oxygen concentrations was built into both the egg and larvae recruitment effects models. Field-based observations have indicated widespread distributions of bay anchovy eggs and larvae across the Bay's mainstem waters and throughout the water column except in subpycnocline waters with extremely low dissolved oxygen concentrations (MacGregor and Houde 1996; Rilling and Houde 1999; Keister et al. 2000; Breitburg et al. 2003).

The final separate survival curves for both the egg and larval recruitment effect models, illustrated in Figure III-7, were based on comparing the effects data from

[6] The larval recruitment model has a parameter for what percentage of a given cohort is exposed to low dissolved oxygen conditions.

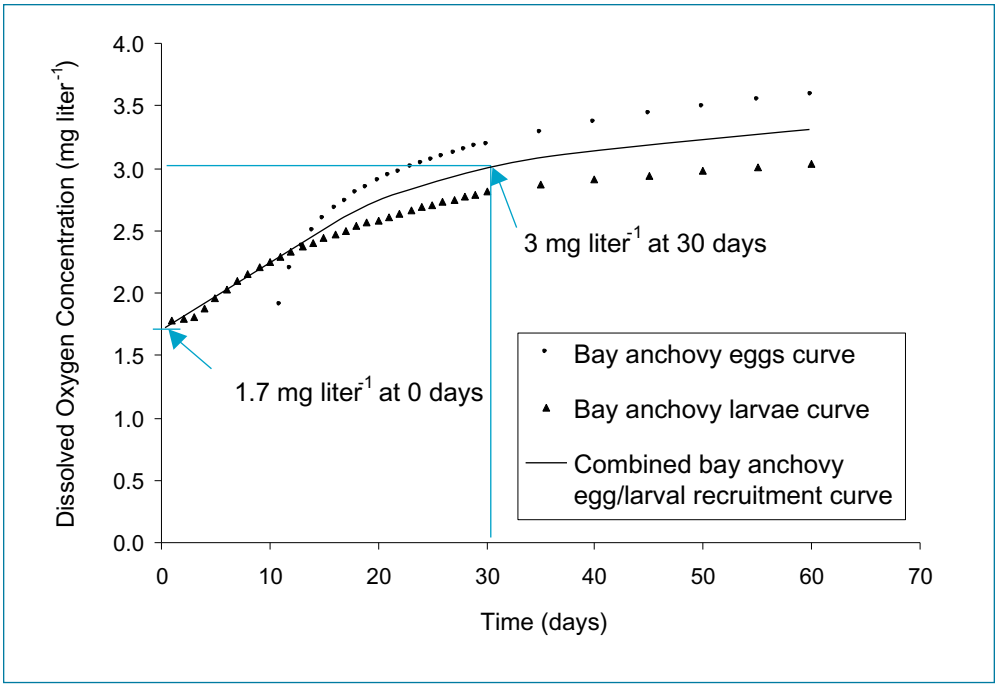



**Figure III-7.** Chesapeake Bay bay anchovy egg and larval recruitment effects curves.

Chesney and Houde (1989) with the final survival curve from Figure 5 in the Virginian Province saltwater criteria document (U.S. EPA 2000). A single combined egg/larval recruitment effects curve, based on the midpoint between the two individual effects curves, also is illustrated in Figure III-7. The effects curves illustrated in Figure III-7 reflect the combined dissolved oxygen concentration and duration of exposure protective against a 5 percent or greater impact, thereby protecting 95 percent of the seasonally produced offspring. Dissolved oxygen concentrations and exposure durations falling above the combined bay anchovy egg/larval recruitment curve—3 mg liter$^{-1}$ for 30 days and 1.7 mg liter$^{-1}$ at all times—would protect against egg and larval recruitment effects greater than 5 percent.

**Protection of Juvenile/Adult Survival.** The Virginian Province document recommends 2.3 mg liter$^{-1}$ as the threshold above which long-term, continuous exposures should not cause lethal conditions for juvenile and adult fish and shellfish (U.S. EPA 2000).

**Additional Scientific Literature Findings.** Breitburg et al. (2001) provide a synthesis of the acute sensitivities of an array of species that may inhabit the water column or near-bottom habitats in the deep-water designated use habitats.

> Adults and juveniles of most Chesapeake Bay species that have been tested have 24 hr $LC_{50}$ values near 1 mg l$^{-1}$ (i.e., approximately 13% saturation at 25°C and 18 psu). Acute toxicity tests have yielded 50% mortality rates with 24-hr exposures at 0.5-1.0 mg l$^{-1}$ for species such as

hogchoker (*Trinectes maculatus*), northern sea robin (*Prionotus carolinus*), spot (*Leiostomus xanthurus*; but $LC_{50}$ reported as >1 mg $l^{-1}$ by Phil et al. 1991) tautog (*Tautoga onitis*), windowpane flounder (*Scopthalmus aquosus*), and fourspine stickleback (*Apeltes quadracus*), and 50% mortality rates between 1.1 and 1.6 mg $l^{-1}$ for Atlantic menhaden (*Brevoortia tyrannus*), scup (*Stenotomus chrysops*), summer flounder (*Paralichthyus dentatus*), pipefish (*Syngnathus fuscus*) and striped bass (*Morone saxatilis*) (Pihl et al. 1991; Poucher and Coiro, 1997; Thursby et al. 2000 [cited here as U.S. EPA]). Thus, for nearly all species tested, the range of tolerances is quite low; only a 1.0 mg $l^{-1}$ difference separates the most and least sensitive species described above.

Although fewer species have been tested during the larval stage, larvae of species that occur in Chesapeake Bay appear to be somewhat more sensitive to low oxygen exposure than are most adults and juvenile. For example, 50% mortality with 24-h exposure occurs between 1.0 and 1.5 mg $l^{-1}$ for skilletfish (*Gobiesox strumosus*), naked goby (*Gobiosoma bosc*), and inland silverside (*Menidia beryllina*) larvae, while 50% mortality occurs at 1.8 to 2.5 mg $l^{-1}$ for larval red drum (*Sciaenops ocellatus*), bay anchovy (*Anchoa mitchilli*), striped blenny (*Chasmodes bosquianus*) and striped bass (Saksena and Joseph 1972; Breitburg 1994; Poucher and Coiro 1997). Field and laboratory observations indicate that lethal dissolved oxygen concentrations for skilletfish, naked goby and striped blenny adults are 1.0 mg $l^{-1}$ (Breitburg, unpublished data).

Embryo tolerances vary inconsistently in relation to tolerances of later stages; 50% mortality in 12-96 h occurs at a higher dissolved oxygen concentration than that for larval mortality for bay anchovy (2.8 mg $l^{-1}$), at a similar oxygen concentration as for larvae for inland silverside (1.25 mg $l^{-1}$), and at lower concentrations than that leading to larval mortality for winter flounder (*Pleuronectes americanus*; 0.7 mg $l^{-1}$) and naked goby (approximately 0.6 mg $l^{-1}$) (Chesney and Houde 1989; Poucher and Coiro 1997).

Roman et al. (1993) examined the distribution of two species of zooplankton copepods—*Acartia tonsa* and *Oithona colcarva*—through the water column in the Chesapeake Bay. *Acartia tonsa*, which regularly migrate from open water down to subpycnocline waters, were not found in bottom waters when oxygen concentrations were < 1 mg liter $^{-1}$. The highest concentration of zooplankton were found at the pycnocline level.

In a recent review of zooplankton responses to and ecological consequences of zooplankton exposure to low dissolved oxygen, Marcus (2001) synthesized the following literature findings.

Vargo and Sastry (1977) reported that 2-h $LD_{50}$ values for *Acartia tonsa* and *Eurytemora affinis* adults collected from the Pettaquamscutt River Basin, Rhode Island ranged from dissolved oxygen concentrations of 0.36 to 1.40 mg $l^{-1}$ and 0.57 to 1.40 mg $l^{-1}$ respectively. Roman et al. (1993) tested the oxygen tolerance of adults of *Acartia tonsa* and *Oithona*

*colcarva* from Chesapeake Bay. Survival was considerably less after 24 h in < 2.0 mg $l^{-1}$ oxygenated water.

Stalder and Marcus (1997) examined the 24-h survival of three coastal copepod species in response to low oxygen. *Acartia tonsa* showed excellent survival at concentrations as low as 1.43 mg $l^{-1}$. Between 1.29 and 0.86 mg $l^{-1}$ survival declined markedly and at 0.71 mg $l^{-1}$ mortality was 100%. *Labidocera aestiva* and *Centropages hamatus* were more sensitive to reduced dissolved oxygen concentrations. The survival of these species was significantly lower at 1.43 mg $l^{-1}$. The survival of nauplii of *Labidocera aestiva* and *Acartia tonsa* at low dissolved oxygen concentrations was generally better than adult survival.

## Rationale

Protecting the recruitment of bay anchovy eggs and larvae into the juvenile and adult population is crucial to the integrity of the Chesapeake Bay ecosystem. The bay anchovy is a primary food source for many fish species. To protect bay anchovy recruitment, criteria values of a 30-day mean of 3 mg $liter^{-1}$ and an instantaneous minimum of 1.7 mg $liter^{-1}$ were selected to best reflect the shape of the final combined bay anchovy egg and larval recruitment effects curve illustrated in Figure III-7.

This approach to criteria derivation is consistent with the approach to derive criteria protective against larval effects in open-water habitats. These approaches followed the guidelines published by the EPA in the Virginian Province dissolved oxygen criteria document (U.S. EPA 2000). The bay anchovy 12- to 24-hour post larvae hatch values from Chesney and Houde (1989) place bay anchovy larvae within the upper range of larval life stage sensitivities for all 17 fish and invertebrate species documented in the Virginian Province document (see Figure 4 on page 13 and Appendix D). The criteria derived to protect bay anchovy early life stages should be protective of other species that routinely inhabit deeper, pycnocline habitats.

The 1.7 mg $liter^{-1}$ criterion value was derived as the dissolved oxygen concentration where the combined egg/larval recruitment effects curve intercepted the y-axis (Figure III-7). Given that the y-axis intercept reflects 'time zero,' an instantaneous minimum duration was applied to the 1.7 mg $liter^{-1}$ criterion value. The 3 mg $liter^{-1}$ criterion value was derived as the approximate point where the combined egg/larval recruitment effects curve levels out. The flattening of the curve beyond this point indicates that dissolved oxygen concentrations much greater than 3 mg $liter^{-1}$ should not cause increased impairment of egg/larval recruitment over longer periods of exposure. The 3 mg $liter^{-1}$ concentration corresponded with 30 days on the x-axis (Figure III-7).

These criteria values and durations are supported by findings published in the scientific literature. Chesney and Houde (1989) evaluated 12- to 14-hour-old yolk-sac bay anchovy larvae over 12 hours, yielding the effects data used in running the bay

anchovy egg/larval recruitment models. In deep-water habitats, field observations support the presence of effects at durations of less than 24 hours, which supports the selection of the instantaneous minimum versus a daily average criterion concentration (Breitburg 1992). Magnusson et al. (1998) have indicated that asphyxia, as described previously, has been reported at dissolved oxygen concentrations well below (> 50 percent) the reported $LC_{50}$ concentrations. Given that the reported $LC_{50}$ values for bay anchovy larvae range from 2.1 to 2.8 mg liter$^{-1}$ (Chesney and Houde 1989; Breitburg 1994), an instantaneous minimum criteria value above 1.4 mg liter$^{-1}$ (50 percent of 2.8 mg liter$^{-1}$) is required to prevent lethal conditions at exposures of less than 24-hour averaged conditions. Given that the reported laboratory and field effects were manifested in less than 12 hours, an instantaneous minimum concentration is further justified as the temporal period for application of the 1.7 mg liter$^{-1}$ criterion value.

In addition to early life stages of bay anchovy, the instantaneous minimum of 1.7 mg liter$^{-1}$ protects juvenile and adult survival of those fish species commonly inhabiting water-column and bottom habitats within the pycnocline (e.g., spot, summer flounder and winter flounder; Table III-7). See also Table 1, page 8 in U.S. EPA (2000) for additional supporting effects data. This criterion value also will protect zooplankton, the principal prey of the bay anchovy and many other fish during their early life stages (Table III-7; Marcus 2001; Roman et al. 1993). Application of the Virginian Province saltwater criteria for juvenile/adult survival, 2.3 mg liter$^{-1}$ as a 1-day mean, will provide the required level of protection to short-term exposures to low dissolved oxygen in deep-water habitats (U.S. EPA 2000).

The open-water criteria that apply to the summer-only deep-water designated use habitats from October 1 through May 31 will protect Atlantic and shortnose sturgeon inhabiting these deep waters in the winter (Secor et al. 2000; Welsh et al. 2000). From June 1 to September 30, the deep-water designated use criteria will not fully protect Atlantic and shortnose sturgeon.

Historically, natural low dissolved oxygen conditions (< 3 mg liter$^{-1}$) in deep-water and deep-channel regions would have curtailed sturgeon access. Over the past several hundred years, sturgeon probably have not used deep-water and deep-channel designated use habitats during summer months due to 'naturally' pervasive hypoxia (see the sections above titled, "Low Dissolved Oxygen: Historical and Recent Past" and *"*Historical Potential Sturgeon Tidal Habitats"). Behavioral studies indicate that sturgeon are capable of avoiding these hypoxic regions (Niklitschek 2001) and probably have done so for centuries. On the other hand, deep-water and deep-channel designated use habitats do recover to normoxic conditions during the fall, winter and spring months. During these periods evidence supports a past and recent role for habitats as thermal refuge and migration corridors in the Chesapeake Bay.

This criterion also will protect open-water species with higher dissolved oxygen sensitivities that search for prey within these pycnocline habitats for short periods of time. Field data from other estuarine and coastal systems, such as Long Island Sound

**Table III-7.** Deep-water seasonal fish and shellfish designated use criteria components.

| Criteria Components | Concentration | Duration | Source |
|---|---|---|---|
| Protection against egg/larval recruitment effects | 3 mg liter$^{-1}$<br>1.7 mg liter$^{-1}$ | 30 days instantaneous minimum | Chesney and Houde 1989; Breitburg 1994; U.S. EPA 2000 |
| Protection of juvenile/adult survival | > 2.3 mg liter$^{-1}$ | 24 hours | U.S. EPA 2000 |
| Additional literature findings | | | |
| - 50 percent mortality for hogchoker, northern sea robin, spot | 0.5-1 mg liter$^{-1}$ | 24 hours | Reviewed in Breitburg et al. 2001 |
| - 50 percent mortality for tautog, windowpane flounder adults | > 1 mg liter$^{-1}$ | 24 hours | Reviewed in Breitburg et al. 2001; Pihl et al. 1991; |
| - 50 percent mortality for menhaden, summer flounder, pipefish, striped bass adults | 1.1-1.6 mg liter$^{-1}$ | 24 hours | Reviewed in Breitburg et al. 2001; Pihl et al. 1991; Poucher and Coiro 1997; U.S. EPA 2000 |
| - 50 percent mortality for skilletfish, naked goby, silverside larvae | 1-1.5 mg liter$^{-1}$ | 24 hours | Breitburg 1994; Poucher and Coiro 1997 |
| - 50 percent mortality for red drum, bay anchovy, striped blenny larvae | 1.8-2.5 mg liter$^{-1}$ | 24 hours | Saksena and Joseph 1972; Breitburg 1994; Poucher and Coiro 1997 |
| - Zooplankton habitat avoidance | < 1 mg liter$^{-1}$ | - | Roman et al. 1993 |
| - Reduced copepod nauplii abundance | < 1 mg liter$^{-1}$ | - | Qureshi and Rabalais 2001 |
| - 50 percent mortality for *Acartia tonsa* and *Eurytemora affinis* | 0.36-1.4 mg liter$^{-1}$ | 2 hours | Vargo and Sastry 1977 |
| - Mortality for *Acartia tonsa* and *Oithona colcarva* | < 2 mg liter$^{-1}$ | 24 hours | Roman et al. 1993 |
| - 100 percent mortality for copepods | 0.71 mg liter$^{-1}$ | 24 hours | Stalder and Marcus 1997 |
| - Reduced survival for copepods | <.86-1.3 mg liter$^{-1}$ | 24 hours | Stalder and Marcus 1997 |
| - *Acartia tonsa* survival | > 1.43 mg liter$^{-1}$ | 24 hours | Stalder and Marcus 1997 |

and Albemarle-Pamlico Sound, clearly indicate that open-water species will use pycnocline region habitats if dissolved oxygen concentrations are above levels that result in avoidance (e.g., Howell and Simpson 1994; Simpson 1995; Eby 2001).

### Recommended Criteria

The following criteria fully support the seasonal-based Chesapeake Bay deep-water designated use when applied from June 1 through September 30: a 30-day mean 3 mg liter$^{-1}$, a 1-day mean 2.3 mg liter$^{-1}$ and an instantaneous minimum 1.7 mg liter$^{-1}$.

## DEEP-CHANNEL SEASONAL REFUGE DESIGNATED USE CRITERIA

Deep-channel habitats are defined as the very deep water-column and adjacent bottom surficial sediment habitats located principally in the river channel at the lower reaches of the major rivers (e.g., the Potomac River) and along the spine of the middle mainstem Chesapeake Bay at depths below which seasonal anoxic (< 0.2 mg liter$^{-1}$ dissolved oxygen) to severe hypoxic conditions (< 1 mg liter$^{-1}$ dissolved oxygen) routinely set in and persist for extended periods of time under current conditions (Appendix A; U.S. EPA 2003a). From late spring to early fall, many of these deep-channel habitats are naturally exposed to very low dissolved oxygen concentration conditions. Under low dissolved oxygen conditions of 1 to 2 mg liter$^{-1}$, these habitats are suitable only for survival of benthic infaunal and epifaunal organisms.

Criteria that support the deep-channel designated use must fully protect the "survival of balanced, indigenous populations of ecologically important benthic infaunal and epifaunal worms and clams that provide food for bottom-feeding fish and crabs" (Appendix A; U.S. EPA 2003a). The seasonal-based deep-channel criteria are based on establishing dissolved oxygen concentrations to protect the survival of bottom sediment-dwelling worms and clams.

### Components

The infauna of the deep-channel habitat are the most tolerant of all infaunal benthic organisms in the Chesapeake Bay. Even if there were no problems with low dissolved oxygen conditions, the benthic organisms inhabiting unconsolidated mud habitats in these deep-channel designated use habitats probably would not change. Looking at benthos from deep-channel habitats in the Chesapeake Bay that are not hypoxic or anoxic, one finds the same benthic community species. On an annual basis, productivity is about the same for hypoxic versus non-hypoxic deep unconsolidated mud bottom sediment habitats in the mesohaline Chesapeake Bay (Diaz and Schaffner 1990). The factors that control what is present in these mesohaline benthic habitats are salinity and sediment type. Hypoxic conditions run a distant third (Holland et al. 1977). Hypoxic conditions change the benthic community structure periodically, but the pool from which these low oxygen habitats are recolonized after

a severe low-oxygen to no-oxygen event is still the limiting factor for a benthic community.

Benthic infauna have high tolerances to low dissolved oxygen conditions (~1 mg liter$^{-1}$) and many macrofaunal species demonstrate behavioral reactions before they eventually die (Diaz and Rosenberg 1995). For the mesohaline zone of estuaries, the critical dissolved oxygen level appears to be around 0.6–1.0 mg liter$^{-1}$ (Diaz and Rosenberg 1995; Table III-8). At the high end of this dissolved oxygen range, the bottom-dwelling community starts to lose moderately tolerant species, with more tolerant species dying off at the low end of the range. In estuaries and coastal systems exposed to seasonally varying low dissolved oxygen, the critical dissolved oxygen concentration is closer to 1 mg liter$^{-1}$ (Llanso 1992), with subtle reductions in dissolved oxygen concentration from 1 to 0.5 mg liter$^{-1}$ causing a full range of responses from behavioral to death (Llanso and Diaz 1994). In their synthesis of dissolved oxygen concentrations causing acute and chronic effects on Chesapeake Bay benthic infaunal organisms, Holland et al. (1989) found a similar range of oxygen concentrations that cause mortality or severe behavioral effects (Appendix C).

**Table III-8.** Deep-channel designated use criteria effects data.

| Effects Observed | Concentration | Source |
|---|---|---|
| – Mesohaline community mortality of moderately tolerant species | 1 mg liter$^{-1}$ | Numerous references cited in Diaz and Rosenberg 1995 |
| – Mesohaline community mortality of more tolerant species | 0.6 mg liter$^{-1}$ | Numerous references cited in Diaz and Rosenberg 1995 |
| – Behavioral to lethal responses observed | 0.5-1 mg liter$^{-1}$ | Llanso 1992; Llanso and Diaz 1994; references cited in Holland et al. 1989 |
| – Behavior, growth and production effects observed | < 2 mg liter$^{-1}$ | Diaz et al. 1992 |
| – Epifaunal community survival | 0.5-2 mg liter$^{-1}$ | Sagasti et al. 2000 |

In the deep channel of the Chesapeake Bay, communities of mud-burrowing worms and clams have a broad tolerance to a wide range of sediment types, salinities, dissolved oxygen concentrations and organic loadings. Several keystone Bay bottom-dwelling polychaete worm species—*Paraprionospio pinnata*, *Streblospio benedicti*, *Loimia medusa* and *Heteromastus filiformis*—are resistant to dissolved oxygen concentrations as low as 0.6 mg liter$^{-1}$ (Llanso and Diaz 1994; Diaz et al. 1992; Llanso 1991).

Extensive mortality is likely only under persistent exposure to very low dissolved oxygen concentrations (< 1 mg liter$^{-1}$) at higher summer temperatures in the Chesapeake Bay (Holland et al. 1977). Similar findings have been reported for other

estuarine and coastal systems (Rosenberg 1977; Jorgensen 1980; Stachowitsch 1984; Gaston 1985).

While the macrobenthic community itself often is found to be insensitive to low dissolved oxygen concentrations around 2 mg liter$^{-1}$, exposure of these bottom habitats to brief periods of dissolved oxygen concentrations < 2 mg liter$^{-1}$ affects behavior (resulting in decreased burrowing depth and exposure at the sediment surface), growth and production (Diaz et al. 1992). From a synthesis of 12 years of diverse observations and 5 years of remotely operated vehicle videotapes, Rabalais et al. (2001) reported stressed behavior, such as emergence from the sediments by burrowing invertebrates, at dissolved oxygen concentrations below 1.5 to 1 mg liter$^{-1}$. At dissolved oxygen concentrations of 1 to 1.5 mg liter$^{-1}$, they observed "even the most tolerant burrowing organisms, principally polychaetes, emerge partially or completely from their burrows and lie motionless on the bottom." Demersal feeding fish change their feeding habits quickly to take advantage of stressed macrobenthos that come to the sediment surface (Stachowitsch 1984; Jorgensen 1980), where they become more vulnerable to predation during or following a low dissolved oxygen event (Pihl et al. 1991, 1992).

Epifaunal communities living along the surfaces of bottom sediments in the Chesapeake Bay can persist with minimal changes in species composition and abundance under brief exposures to dissolved oxygen concentrations in the range of 0.5 to 2.0 mg liter$^{-1}$ (Sagasti et al. 2000).

For the unconsolidated mud benthic infaunal community of the mesohaline Chesapeake Bay where the deep-channel designated use habitats are located, 1 mg liter$^{-1}$ is protective of survival. The global scientific literature points towards 2 mg liter$^{-1}$ as the protective dissolved oxygen value, but this is the oxygen tolerance for higher salinity, more structured benthic communities and species. Between 2 and 3.5 mg liter$^{-1}$ there are definite behavioral changes for many species and mortality for sensitive species in these higher salinity habitats. For Chesapeake Bay species in similar higher salinity (polyhaline) habitats, 2 mg liter$^{-1}$ would be the dissolved oxygen minimum requirement. Benthic communities in these polyhaline habitats in the Chesapeake Bay will be protected by applying the open-water dissolved oxygen criteria year-round. However, for the mesohaline Chesapeake Bay where the hypoxic and anoxic conditions are focused during the summer months, the scientific literature for unconsolidated mud mesohaline benthic communities supports 1 mg liter$^{-1}$ as the bottom-line requirement. Dissolved oxygen concentrations of less than 1 mg liter$^{-1}$ lead to mortality for even tolerant species.

## Rationale

To ensure protection of the survival of bottom-dwelling worms and clams, an instantaneous minimum criterion of 1 mg liter$^{-1}$ was selected (Table III-9). As documented through the extensive scientific literature reported here, this value will protect against lethal effects from exposure to low dissolved oxygen. However, behavioral

**Table III-9.** Response patterns of Chesapeake Bay benthic organisms to declining dissolved oxygen concentrations (mg liter$^{-1}$).

| Response | Dissolved Oxygen | Species | Reference |
|---|---|---|---|
| ***Avoidance*** | | | |
| Infaunal swimming | 1.1 | *Paraprionospio pinnata* | Diaz et al. 1992 |
| | 0.5 | *Nereis succinea* | Sagasti et al. 2001 |
| Epifaunal off bottom | 0.5 | *Neopanope sayi* | Sagasti et al. 2001 |
| | 0.5 | *Callinectes sapidus* | Sagasti et al. 2001 |
| | 1 | *Stylochus ellipticus* | Sagasti et al. 2001 |
| | 1 | *Mitrella lunata* | Sagasti et al. 2001 |
| | 0.5 | *Dirodella obscura* | Sagasti et al. 2001 |
| | 1 | *Cratena kaoruae* | Sagasti et al. 2001 |
| ***Fauna, unable to leave or escape, initiate a series of sublethal responses*** | | | |
| Cessation of feeding | 0.5 | *Balanus improvisus* | Sagasti et al. 2001 |
| | 0.6 | *Streblospio benedicti* | Llanso 1991 |
| | 1 | *Loimia medusa* | Llanso and Diaz 1994 |
| | 1.1 | *Capitella* sp. | Warren 1977; Forbes and Lopez 1990 |
| Decreased activities not related to respiration | 0.5 | *Balanus improvisus* | Sagasti et al. 2001 |
| | 0.5 | *Conopeum tenuissimum* | Sagasti et al. 2001 |
| | 0.5 | *Membranipora tenuis* | Sagasti et al. 2001 |
| | 1 | *Cratena kaoruae* | Sagasti et al. 2001 |
| | 1 | *Stylochus ellipticus* | Sagasti et al. 2001 |
| | 1 | *Streblospio benedicti* | Llanso 1991 |
| Cessation of burrowing | 1.1 | *Capitella* sp. | Warren 1977 |

*continued*

**Table III-9.** Response patterns of Chesapeake Bay benthic organisms to declining dissolved oxygen concentrations (mg liter$^{-1}$) *(continued)*.

| Response | Dissolved Oxygen | Species | Reference |
|---|---|---|---|
| Emergence from tubes or burrows | 0.1-1.3 | *Ceriathiopis americanus* | Diaz, unpublished data |
| | 0.5 | *Sabellaria vulgaris* | Sagasti et al. 2001 |
| | 0.5 | *Polydora cornuta* | Sagasti et al. 2001 |
| | 0.7 | *Micropholis atra* | Diaz et al. 1992 |
| | 1 | *Hydroides dianthus* | Sagasti et al. 2001 |
| | 10% saturation | *Nereis diversicolor* | Vismann 1990 |
| Siphon stretching into water column | 0.1-1.0 | *Mya arenaria, Abra alba* | Jorgensen 1980 |
| Siphon or body stretching | 0.5 | *Molgula manhattensis* | Sagasti et al. 2001 |
| | 0.5 | *Diadumene leucolena* | Sagasti et al. 2001 |
| Floating on surface of water | 0.5 | *Diadumene leucolena* | Sagasti et al. 2001 |
| Formation of resting stage | 0.5 | *Membranipora tenuis* | Sagasti et al. 2001 |
| | 0.5 | *Conopeum tenuissimum* | Sagasti et al. 2001 |

Sources: Diaz and Rosenberg 1995; Sagasti et al. 2001.

changes leading to increased opportunities for predation are not protected by this criterion. These changes may benefit bottom-feeding fish and crabs, giving them direct access to food, albeit under potentially stressful water quality conditions.

The deep-channel criteria protect survival but not necessarily the growth of benthic infaunal and epifaunal species from June through September. However, Diaz and Schaffner (1990) reported that their evaluation of annual secondary productivity of hypoxic habitats in the Bay's deep-channel habitats indicated no significant reduction in productivity from low dissolved oxygen conditions. Therefore, the deep-channel criteria's failure to provide full protection against growth impairments is counteracted by growth during the rest of the year, when dissolved oxygen concentrations are naturally higher than 1 mg liter$^{-1}$, which leads to a net result of protection against growth impairment on an annual basis.

The instantaneous minimum value of 1 mg liter$^{-1}$ is much more protective of benthic infaunal organisms than a 1- or 7-day average. In the case of bottom-dwelling organisms, it is not the average condition that is most detrimental to the organisms but the absolute minimum dissolved oxygen. When dissolved oxygen drops significantly below 1 mg liter$^{-1}$ for even short periods of time (on the order of hours) mortality increases, even for tolerant species. Other deep-channel criteria with higher concentrations than 1 mg liter$^{-1}$ and with 1-, 7- or 30-day averaging periods were not derived for deep-channel designated use habitats, since dissolved oxygen concentrations are not expected to exceed 2 mg liter$^{-1}$ from June through September due to natural constraints.

### Deep-Channel Criteria

The instantaneous minimum 1 mg liter$^{-1}$ criterion fully supports the seasonal-based Chesapeake Bay deep-water designated use when applied from June 1 through September 30.

## CHESAPEAKE BAY DISSOLVED OXYGEN CRITERIA

The Chesapeake Bay dissolved oxygen criteria are structured to protect the five tidal-water designated uses and reflect the needs and habitats of Bay estuarine living resources (Table III-10). Criteria for the migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated uses were set at levels to protect the reproduction and survival of all organisms and against impairments to their growth. Criteria for deep-water habitats during seasons when the water column is significantly stratified were set at levels to protect juvenile and adult fish, shellfish and the recruitment success of the bay anchovy. Criteria for deep-channel habitats in summer were set to protect the survival of bottom sediment-dwelling worms and clams.

**Table III-10.** 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.

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chapter IV

# Water Clarity Criteria

## BACKGROUND

The loss of underwater bay grasses[1] from the shallow waters of the Chesapeake Bay, which was noted in the early 1960s, is a widespread, well-documented problem. Although other factors, such as climatic events and herbicide toxicity, may have contributed to the decline of underwater bay grasses in the Bay, the primary causes are nutrient over-enrichment and increased suspended sediments in the water and the associated reduction of light. The loss of underwater bay grass beds is of particular concern because these plants create rich animal habitats that support the growth of diverse fish and invertebrate populations. Similar declines in underwater bay grasses have been occurring worldwide with increasing frequency in the past several decades.

One of the major features contributing to the high productivity of the Chesapeake Bay has been the historical abundance of underwater bay grasses. There are more than 20 freshwater and marine species of rooted, submerged flowering plants in Chesapeake Bay tidal waters. These underwater bay grasses provide food for waterfowl and provide critical habitat for shellfish and fish. Underwater bay grasses also positively affect nutrient cycling, sediment stability and water turbidity.

The health and survival of these plant communities in the Chesapeake Bay and its tidal tributaries depend on suitable environmental conditions, which define the quality of underwater bay grass habitat. The key to restoring these critical habitats and food sources is to provide the necessary levels of light penetration in shallow waters to support their survival, growth and repropagation.

[1]The term *underwater bay grasses* refers to submerged vascular plants often referenced in the scientific literature as 'seagrasses' as well as submerged aquatic vegetation or SAV, not to be confused with emergent wetland plants.

## APPROACH

The Chesapeake Bay's scientific and resource management communities collaborated to produce two internationally recognized technical syntheses of information that support the quantitative habitat requirements for Chesapeake Bay underwater bay grasses (Batiuk et al. 1992; Batiuk et al. 2000). Key findings, the underlying light requirements and management-oriented diagnostic tools and restoration targets have been reported in the peer-reviewed scientific literature (Dennison et al. 1993; Gallegos 2001; Koch 2001; Kemp et al., in review). The two technical syntheses, along with Chesapeake Bay-specific research and field studies and recent model simulation and data evaluation, provide the scientific foundation for the Chesapeake Bay water clarity criteria described here. Readers are encouraged to consult these two syntheses and the resulting published papers for further details and documentation.

The Chesapeake Bay-specific water clarity criteria were derived in four stages: first, water column-based light requirements for underwater bay grass survival and growth were determined; second, factors contributing to water-column light attenuation were quantified; third, contributions from epiphytes to light attenuation at the leaf surface were factored into methods for estimating and diagnosing the components of total light attenuation; and fourth, a set of minimal requirements for light penetration through the water and at the leaf surface were determined to give the water clarity criteria values.

### THE RELATIONSHIPS BETWEEN WATER QUALITY, LIGHT AND UNDERWATER BAY GRASSES

The principal relationships between water quality conditions and light regimes for the growth of underwater bay grasses are illustrated in Figure IV-1. Incident light, which is partially reflected at the water surface, is attenuated through the water column above the underwater bay grasses by particulate matter (chlorophyll *a* and total suspended solids), by dissolved organic matter and by water itself. In most estuarine environments, the water-column light attenuation coefficient (called $K_d$) is dominated by contributions from chlorophyll *a* and total suspended solids.

Light that actually reaches the underwater bay grass leaves also is attenuated by the epiphytic material (i.e., algae, bacteria, detritus and sediment) that accumulates on the leaves. This epiphytic light attenuation coefficient (called $K_e$) increases exponentially with epiphyte biomass, where the slope of this relationship depends on the composition of the epiphytic material. Dissolved inorganic nitrogen (DIN) and phosphorous (DIP) in the water column stimulate the growth of epiphytic algae (as well as water-column algae), and suspended solids also can settle onto underwater bay grass leaves. Because epiphytic algae also require light to grow, water depth and water-column light attenuation constrain epiphyte accumulation on underwater bay

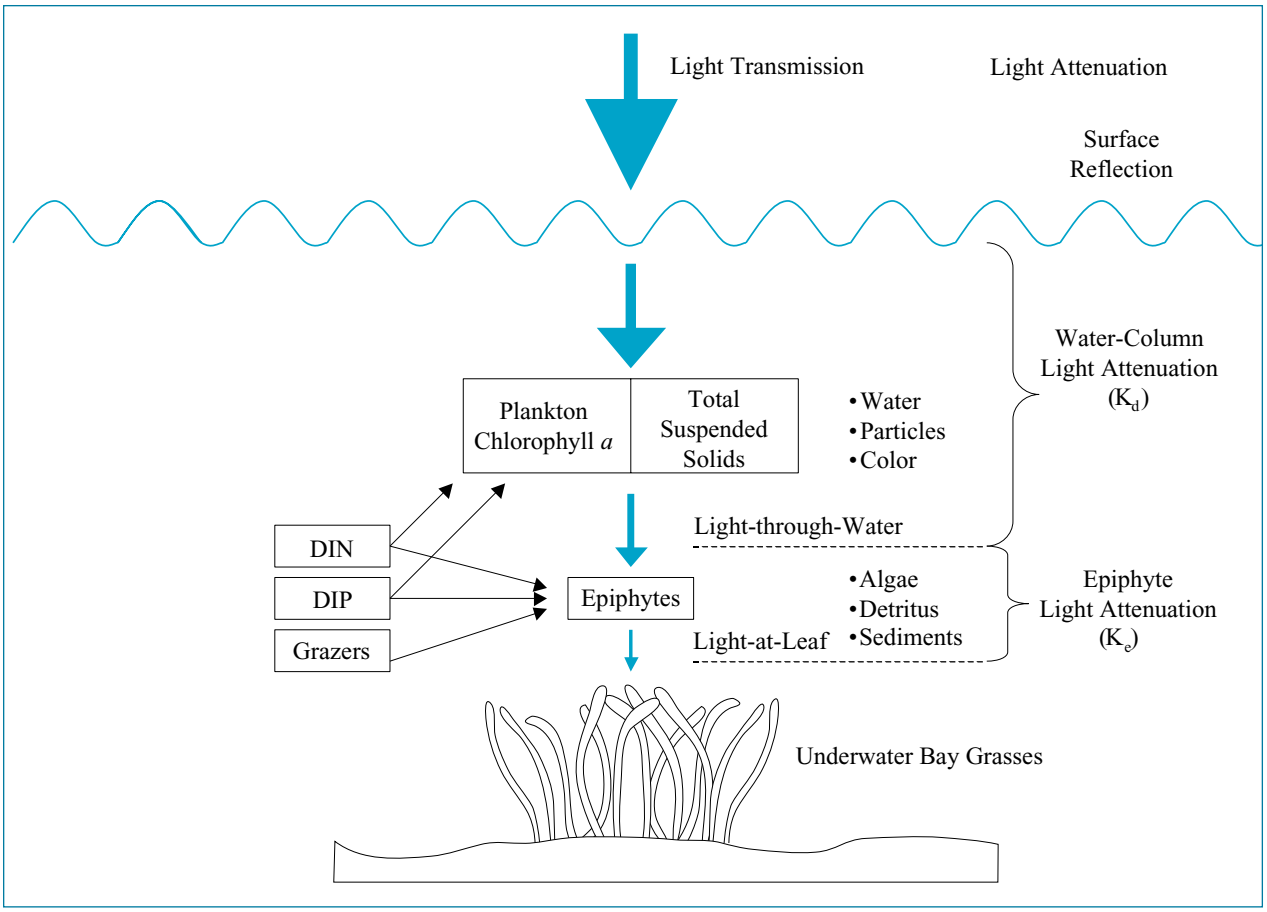


**Figure IV-1.** Availability of light for underwater bay grasses is influenced by water-column and at-the-leaf surface light attenuation processes. DIN = dissolved inorganic nitrogen and DIP = dissolved inorganic phosphorus.

grass leaves, and light attenuation by epiphytic material depends on the mass of both algae and total suspended solids settling on the leaves.

An algorithm was developed to compute the biomass of epiphytic algae and other materials attached to bay grass leaves and to estimate the light attenuation associated with these materials (Kemp et al., in review; Batiuk et al. 2000). The algorithm was verified by applying it to Chesapeake Bay water quality monitoring data. The results of these field verifications are documented in Chapter V, "Epiphyte Contribution to Light Attenuation at the Leaf Surface," in Batiuk et al. (2000).

The algorithm uses monitoring data for the water-column light attenuation coefficient (or Secchi depth), total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus concentrations to calculate the potential contribution of epiphytic materials to total light attenuation for bay grasses at a particular depth (Figure IV-2). Using a set of commonly monitored water quality parameters,

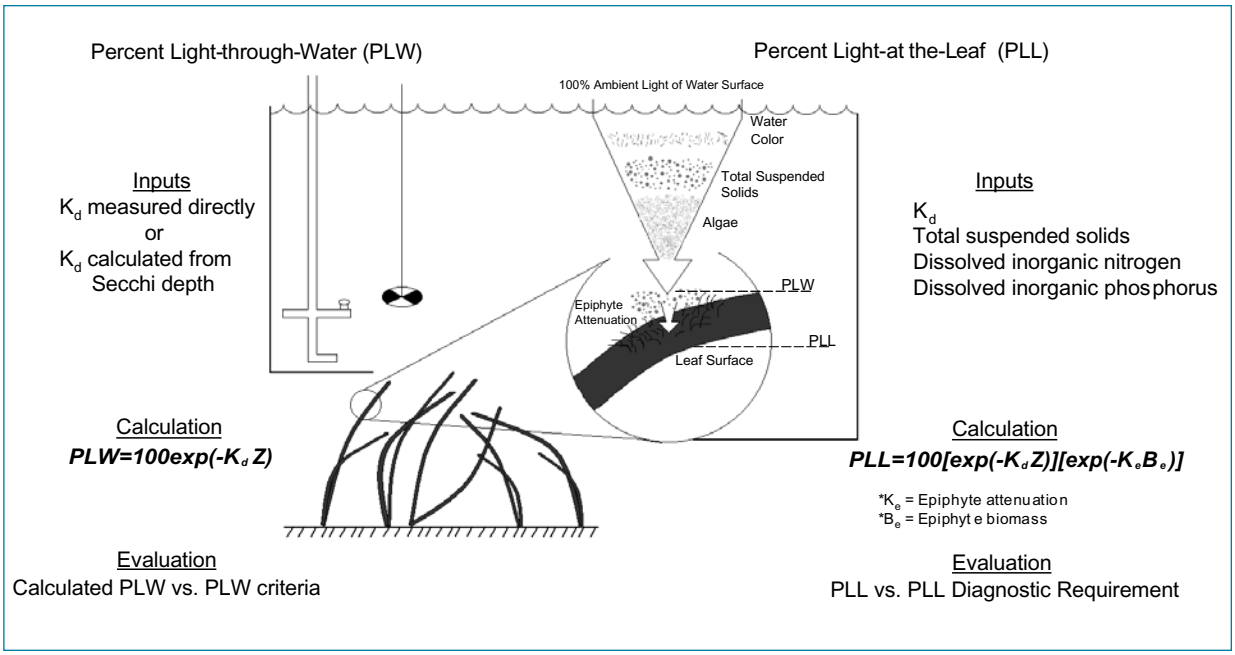


**Figure IV-2.** Illustration of the inputs, calculation and evaluation of the two percent-light parameters: percent light-through-water (PLW) and percent light-at-the-leaf (PLL).

attainment of the percent light-through-water (PLW) water clarity criteria (this chapter) and percent light-at-the-leaf (PLL) diagnostic parameter (Chapter IV) can be readily determined for any established restoration depth.

## DETERMINING LIGHT REQUIREMENTS

Much of the published literature values for underwater bay grass PLW minimum light requirements were derived from studies of underwater bay grass light requirements in which epiphyte accumulation on plant leaves was not controlled. Therefore, light measurements in those studies did not account for light attenuation due to epiphytes on the underwater bay grass leaves themselves. To determine the Chesapeake Bay water clarity criteria necessary to ensure that sufficient light reaches underwater bay grass leaves at a defined restoration depth, three lines of evidence were compared:

1. Applied the original 1992 underwater bay grasses habitat requirements parameter values to the new algorithm for calculating PLL (Figure IV-2), for each of the four salinity regimes;
2. Evaluated the results of light requirement studies from areas with few or no epiphytes; and
3. Compared median field measurements of the amount of light reaching plants' leaves (estimated through the PLL algorithm) along gradients of underwater bay grasses growth observed in the Chesapeake Bay and its tidal tributaries.

The derived minimum light requirements apply to the bottom sediment surface in order to accommodate plants with a variety of heights and plants just emerging from the bottom sediments.

## STRENGTHS AND LIMITATIONS OF THE CRITERIA DERIVATION PROCEDURES

### Scientific Syntheses

The water clarity criteria are based on a solid scientific foundation, synthesizing more than 20 years of Chesapeake Bay research and related worldwide findings. The criteria address the minimum light requirements of underwater bay grasses through the water column (this chapter) and a separate diagnostic tool addresses the plants' minimum light requirements at the leaf surface (Chapter VII), both applied at the depth of intended restoration necessary to support the designated use for shallow-water habitats (see U.S. EPA 2003).

The methods for determining attainment of the water clarity criteria use the Chesapeake Bay Program's water quality monitoring data generated across all Bay tidal waters (see Chapter VI). Management tools for diagnosing the relative contributions of various sources of light reduction through the water column and at the leaf surface have been developed in tandem with the PLW criteria values (see Chapter VII). The scientific basis for the criteria, diagnostic tools and criteria-attainment methodologies have been through independent peer reviews and have been published in peer-reviewed scientific journals (Dennison et al. 1993; Gallegos 2001; Koch 2001; Kemp et al., in review).

### Light Availability Studies

The minimum light requirements used in deriving the Chesapeake Bay water clarity criteria were based, in part, on data and models of light availability from freshwater, estuarine and marine environments. The EPA recognizes that relatively few studies of underwater bay grass light requirements have been conducted in lower salinity estuarine habitats. Most of the underwater plant species growing in the Chesapeake Bay and its tidal tributaries are, however, the same species as those that have been observed in light requirement studies of lakes, higher salinity estuarine and coastal marine habitats (see Chapter III and Appendix A in Batiuk et al. 2000). The EPA is confident that the findings of these lake, estuarine and marine studies are directly applicable to deriving the Chesapeake Bay water clarity criteria.

### Light Requirements for Sparse versus Dense UnderwaterBay Grass Beds

The Chesapeake Bay water clarity criteria call for sufficient light to address the collective minimum light requirements for all these underwater plants' growth and reproductive stages. The minimum light requirements of underwater plants in new,

sparse grass beds would be similar to those of individual plants in well-established, dense underwater bay grass beds. However, since the water clarity criteria were based in large part on relationships between existing underwater bay grasses and water quality conditions, the criteria are less likely to protect new or sparse grass beds, since existing, dense grass beds can directly influence their local water quality conditions. Water velocities, algal abundance and suspended sediment concentrations decrease inside dense, established underwater grass beds, improving water clarity compared with adjacent open-water habitats. Established underwater bay grass beds also are less likely to be affected by yearly fluctuations in water clarity (Moore et al. 1995; Moore 1996). Additionally, their capacity to produce more abundant seeds and propagules would improve their chances for revegetation (Orth et al. 1994). Unvegetated areas do not have these advantages; therefore, the light requirements for establishing new underwater grass beds are likely going to be greater.

The effect of improved water clarity on the restoration of underwater bay grasses is demonstrated by the resurgence of 12 underwater bay grass species to the upper tidal Potomac River by 1983. In the late 1930s, underwater bay grasses had virtually disappeared from the tidal-fresh Potomac. The decline coincided with nutrient enrichment, increased algal concentrations and extreme storms (Carter et al.1985; Rybicki and Carter 1986). Through the 1970s, high nitrogen and phosphorus concentrations from municipal wastewater treatment plants and loadings from other point and nonpoint sources fueled frequent algal blooms and decreased water clarity. Secchi depth measurements between 1978 and 1981 averaged < 0.6 meters over the growing season (corresponding to less than 9 percent light at the 1-meter depth). Beginning in the early 1980s, improved treatment plant technologies and a ban on phosphate detergents led to a reduction of nutrients and suspended solids, which resulted in a significant improvement to water clarity by 1988. When the growing season average Secchi depth improved to > 0.9 meters (corresponding to 20 percent light at 1-meter depth, a value much higher than the PLW criterion of 13 percent), water clarity had improved enough to spark a resurgence of underwater bay grasses in the Potomac River tidal-fresh zone (Carter and Rybicki 1994; Carter et al. 1994).

## Effective Depth of Photosynthesis/Application Depth Relationship

The ‘effective depth’ measures the water-column depth at which the active photosynthetic plant structures are located. For most plants grown from seed or from underground tubers or rhizomes, minimum light requirements are most crucial for newly formed leaves shortly after plants emerge from the bottom sediments. Therefore the ‘effective depth’ for newly emerging shoots is the total water depth. Additionally, although plants in the inner, shallower sections of a bed may extend toward the water surface, effectively reducing the ‘effective depth’ of water over the photosynthetic tissue compared to the actual water depth there, plants at the deepest colonizing edge of the beds are typically very short and sparse. At this point the ‘effective depth’ and the total water depth are again similar. Based on these two

important examples of the process of new bed formation and bed colonization, the application depth is defined as the total water depth.

## Plant Morphology's Influence on Determining Light Requirements

The size of a plant's reproductive structures and its morphology play key roles in survival during periods when light levels fall below minimum requirements at water-column depths of 1 meter or less. Species that produce large reproductive structures tolerate periods of poor water clarity better than those with small reproductive structures. Underwater plants that sprout from large reproductive structures (large tubers, for example) have greater stored energy reserves and, regardless of light levels, may elongate several decimeters towards the surface where light levels are more adequate. The reserves alone may provide enough energy to sustain survival for several weeks (Rybicki and Carter 2002).

If light levels are inadequate for short periods and become adequate thereafter, plants from large tubers may survive and grow to heights where their minimum light requirements are met. On the other hand, plants originating from small reproductive structures (such as small tubers or seeds) have smaller amounts of energy reserves and little elongation potential, and are more likely to become weak and brittle and to evanesce. Spring, therefore, is an especially critical period for plants with small reproductive structures.

Similarly, mature plants that are canopy-formers are more tolerant of poor water clarity than are meadow-forming species. If minimum light requirements are met at 0.5 meters but not at 1 meter, the taller canopy-formers are more likely to have their light requirement met than are shorter, meadow-formers growing at the same depth. The minimum light requirements used in deriving the water clarity criteria are meant to allow species of all growth types to survive at the desired restoration depth.

## Validation of Predicted versus Actual Bay Grass Distribution

Batiuk et al. (2000) documented their validation of the PLL diagnostic requirements by relating calculated PLL values to field data on underwater bay grass presence (over a 13-year record) in areas adjacent to water quality monitoring stations. Underwater bay grass presence was categorized as: always abundant (AA), always some (AS), sometimes none (SN), usually none (UN) and always none (AN). It was assumed that PLL value would exceed the minimum requirement in the AA areas and would be approximately equal to the requirement in the AS and SN areas. In fact, in tidal-fresh and oligohaline waters, the median values of PLL at the 0.5-meter and 1-meter depths were 5 to 8 percent and 1 to 3 percent in AS and SN areas, respectively, well below the minimum PLL requirement of 9 percent. The validation results were much closer in mesohaline and polyhaline waters.

Similar results were found in relating PLW to changes in underwater bay grass coverage from year to year in tidal-fresh and oligohaline waters (Batiuk et al. 2000).

Positive increases in bay grass coverage occurred even when the median PLW was considerably less than the minimum requirement at 1 meter (mean low water). Finally, the authors noted that, based on light requirements alone, underwater bay grasses often were found at depths greater than the predicted maximum. Clearly, data must continue to be collected to ensure consistency between predicted and actual underwater bay grass distribution.

## Natural Water Color

Color, listed as 'dissolved organic matter,' is one factor that attenuates light (see Figure IV-1). The quantitative role of color, accounted for directly as a component of light attenuation in both the PLW criteria and the PLL diagnostic requirement, is not addressed separately as a criterion, for several reasons. Color data are not collected in the Chesapeake Bay Water Quality Program. The only color data that exist for the Chesapeake Bay have been collected by research institutions, with sporadic spatial and temporal coverage. Color in the Chesapeake Bay's tidal waters is largely of natural origin, including the few tributaries on the Eastern Shore in which dissolved color concentrations are high, such as the Pocomoke River. Some decline in color might accompany a reduction in chlorophyll *a* as nutrient inputs are reduced, but currently there is no way to gauge the probable magnitude of such a response.

## Other Environmental Factors

Although light is the principal factor controlling the distribution of underwater bay grasses throughout the Chesapeake Bay, other biological, physical, geological and chemical factors may preclude their growth in particular sites even when minimum light requirements are met (Livingston et al. 1998). These factors include the availability of propagules (e.g., seeds and vegetative reproductive structures), salinity, temperature, water depth, tidal range, grazers, suitable sediment quality (organic content and grain size), sediment nutrients, wave action, current velocity and chemical contaminants (Koch 2001). Some of these factors operate directly on underwater plants, while others inhibit the interaction of underwater plants and light or their habitat.

Very high wave energy may prevent bay grasses from becoming established (due to the drag exerted on the plants and the constant sediment motion), even when the minimum light requirements are met (Clarke 1987). Waves and tides alter the light climate by changing the depth of the water through which light passes, and by resuspending bottom sediments, thereby increasing total suspended solids and associated light attenuation (Koch 2001).

Particle sinking and other sedimentological processes alter the texture, grain-size distribution and organic content of bottom sediments. These alterations can affect underwater bay grass growth by modifying the availability of nutrients in the sediments (Barko and Smart 1986) and by producing reduced sulfur compounds that are toxic to underwater plants (Carlson et al. 1994). In addition, pesticides and other

anthropogenic chemical contaminants tend to inhibit underwater bay grass growth. An extensive review of the literature has revealed that certain underwater bay grass species appear to have limited tolerance of certain physical, sedimentological and chemical variables (Koch 2001).

Attaining the water clarity criteria in a given underwater bay grass growing season does not guarantee the presence or return of underwater bay grasses, given the environmental factors described above. However, a wealth of scientific evidence indicates that not attaining the water clarity criteria at the desired restoration depth will prevent or severely reduce survival and propagation of underwater bay grasses, regardless of the status of other environmental factors (Dennison et al. 1993).

## Areas for Refinement

The process of deriving the water clarity criteria has brought areas requiring further research and understanding into focus. Particular attention should be paid to the relationships between epiphyte biomass and nutrient concentrations and flux, and between total suspended solids and the total mass of epiphytic material. Also, a better understanding of the relationships between water clarity and abundance of underwater bay grasses in lower salinity areas is needed. In addition, the published diagnostic PLL algorithm (see Chapter VII) has been documented both to under- and overestimate epiphyte biomass when compared with field observations.

Although the second technical synthesis (Batiuk et al. 2000) provided an initial consideration of physical, geological and chemical requirements for bay grass habitat, more work is needed to develop physical, geological and chemical measures of bay grass habitat suitability.

Finally, there is a general need for a better understanding of the minimum light requirements for the survival and growth of underwater grass species in various Chesapeake Bay tidal habitats, as well as the influence of other environmental factors on minimum light requirements. Detailed field and laboratory studies are needed to develop estimates of the minimum light required by each species, both for the survival of existing bay grass beds and reestablishment of underwater bay grasses in unvegetated sites. The area that remains most problematic is minimum light requirements for turbid, low-salinity habitats (particularly estuarine turbidity maximum zones) inhabited by canopy-forming plant species. The short-term temporal applications of the minimum light requirements need further study to determine the critical length of time required for underwater bay grasses to recover after short periods of extremely low light levels at various stages of the growing season.

The EPA maintains that these water clarity criteria reflect the best available science compiled and interpreted by recognized national and international scientific experts in this field. The criteria document recognizes and clearly documents known certainties and uncertainties, and where professional judgments have been exercised. In cases where such judgments have been made, these judgments have led to the publication of water clarity criteria that protects the full array of underwater bay grass species inhabiting Chesapeake Bay tidal waters.

## WATER CLARITY CRITERIA DERIVATION

### MINIMUM LIGHT REQUIREMENTS

Determining the PLW requirements for bay grass survival and growth involved an extensive search of the pertinent literature and examination of results from research and monitoring conducted in the Chesapeake Bay. A detailed documentation of this process can be found in Chapter III, "Light Requirements for SAV Survival and Growth" in Batiuk et al. 2000. The authors interpreted the information to determine the range of light requirements for individuals and groups of species occurring in the four major salinity zones of the Chesapeake Bay.

They found that the information fell into four general categories: (1) physiological studies of photosynthesis/irradiance relationships; (2) results of field observations of the maximum depth of underwater bay grass colonization and available light at that depth; (3) experiments involving the artificial or natural manipulation of light levels during long- or short-term growth studies; and (4) statistical models intended to generalize light requirements. These four categories are discussed in the order of their perceived utility for the purpose of determining minimum light requirements, with physiological studies considered the least useful and models and light manipulation experiments considered the most useful. The literature reviewed included lake, estuary and coastal marine studies throughout the world.

#### Photosynthesis-Irradiance Measurements

Numerous studies have presented photosynthesis-irradiance curves for underwater plants. Photosynthesis-irradiance curves are generated by exposing whole plants, leaves or leaf or stem sections to varying light intensities and measuring the rate of photosynthesis based on the generation of oxygen or consumption of carbon dioxide. Most photosynthesis-irradiance measurements are made in the laboratory, although some studies use ambient light and environmental conditions, with plants suspended in bottles at different water depths. As suggested by Zimmerman et al. (1989), it is questionable to use short-term photosynthesis-light experiments to estimate light-growth relationships and depth penetration, particularly when plants are not acclimated to experimental conditions. In addition to the balance between photosynthesis and respiration, estimates of minimum light requirements must consider other losses of plant organic carbon through herbivory, leaf sloughing and fragmentation as well as reproductive requirements.

#### Field Observations of Maximum Depth and Available Light

Numerous studies around the world link observations of the maximum depth to which an underwater grass species grows ($Z_{max}$) to the available light ($I_m$) at that depth (see Appendix A in Batiuk et al. 2000). Individual maximum-depth-of-

colonization studies were not particularly useful for setting up minimum light requirements for Chesapeake Bay environments. Most studies were of freshwater and oligohaline species in freshwater lakes, where the water was clear and the percent of surface light in midsummer on a clear day was not indicative of the plant's seasonal light environment. Determinations were based on the maximum depth at which the plants were rooted, disregarding chance fragments or propagules that might have established outlier populations and not survive an entire growing season (e.g., Moore 1996). Measurement frequency is a significant problem that should be considered in these studies. However, taken in the aggregate, these field observations serve as a basis for models that predict maximum depths of colonization or minimum light requirements (see section titled "Light Availability Models" below).

## Light Manipulation Experiments

Light requirements for the growth and survival of underwater bay grasses have been tested using short- to long-term studies under experimental light conditions. These studies were done *in situ*, in mesocosms where plants receive a measured percentage of ambient light, or in the laboratory where underwater plants are grown under constant light and temperature regimes. Most field studies were done using polyhaline and mesohaline species. In the case of prolonged field experiments, recovery of the plants was sometimes monitored. Some studies did not involve the actual manipulation of light levels; for example, Dunton (1994) involved natural shading by an algal bloom and continuous monitoring of light in Texas coastal bays, whereas Kimber et al. (1995) and Agami et al. (1984) suspended plants in buckets at specific depths and observed survival rates. Laboratory and mesocosm experiments under controlled light, temperature and flow conditions may substantially underestimate natural light requirements because of the absence of natural light variability, herbivory, fragmentation losses and tidal or riverine currents.

## Light Availability Models

In recent years attempts have been made to develop statistical regression models to quantify the relationship of light availability to the depth of underwater bay grass growth, based on the maximum depth of colonization and water-column light attenuation (Canfield et al. 1985; Chambers and Kalff 1985; Vant et al. 1986; Duarte 1991; Middleboe and Markager 1997). Models also have been developed to relate light availability to productivity, primarily in polyhaline species (Zimmerman et al. 1994), and to show the relationships of various factors affecting underwater bay grass survival (Wetzel and Neckles 1986). Since the models relating depth of colonization and water clarity tend to use large data sets from different habitats, they are considered more robust than models based on single studies or sites, yet some of the more robust models still depend on one-time observations at maximum depth or light availability from the literature.

Figure IV-3 shows a good correspondence among models. For lake species in general, a depth of 1 meter would be colonized when Secchi depth = 0.4 to 0.7 meters. The

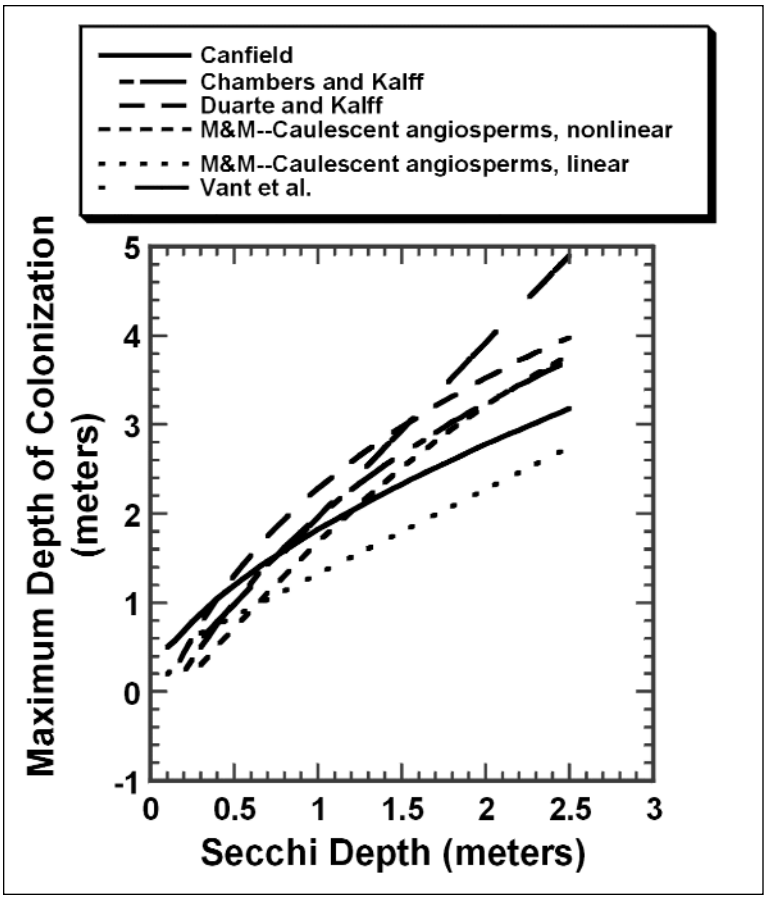


**Figure IV-3.** Relationship of maximum depth of colonization ($Z_{max}$) to Secchi depth for freshwater SAV species as modeled by Canfield et al. (1985), Chambers and Kaff (1985), Duarte and Kalff (1987), Middleboe and Markager (1997) and Vant et al. (1986).

0.4- to 0.7-meter range is comparable with the light constraints described by Carter and Rybicki in Batiuk et al. (1992). They suggested that when median seasonal Secchi depths were 0.7 meters, underwater bay grass beds would increase in size, whereas at Secchi depths less than 0.5 meters, revegetation would not occur. Between 0.5 and 0.7 meters, other factors, such as epiphyte loading, available sunshine, size and the number of tubers set in the previous year all play a role in determining survival.

Models relating maximum depth of colonization to Secchi depth or light attenuation and percent of surface irradiance for mesohaline and polyhaline species are summarized in Batiuk et al. (2000). Relationships between maximum depth of colonization and light attenuation coefficients indicate that for any specific light attenuation coefficient the maximum depth of colonization is greater for tidal-fresh and oligohaline species than for mesohaline and polyhaline species (see Figure III-4 in Batiuk et al. 2000). These studies indicate that there is a greater minimum light requirement for mesohaline and polyhaline species.

Examination of the four types of evidence for minimum light requirements discussed above—photosynthesis-irradiance curves, field observations, light manipulation and models—indicates that models were the best source of comparative information for developing minimum light requirements for the Chesapeake Bay (Batiuk et al. 2000). The shading experiments, although they did not help to refine the minimum light requirements, illuminated the complexity of plant success under reduced light conditions. Although the published literature did not provide specific numbers for Chesapeake Bay minimum light requirements, the information was used to guide decisions and suggest limiting factors.

A considerable fraction of the total studies on light requirements for underwater bay grasses were done in estuarine environments. Most of these were, however,

conducted in higher salinity mesohaline and polyhaline habitat areas, and virtually none are from lower salinity oligohaline and tidal-fresh portions of estuaries. The EPA recognizes that there is a need for continued research to improve the understanding of light requirements for underwater plants in these environments. Although results of these studies would certainly help to refine detailed knowledge of underwater bay grass light requirements and of how to apply these to predict plant survival in nature, the EPA is confident they will not change the broad foundations of the water clarity criteria.

The present criteria are based on studies involving virtually all of the important underwater bay grass species found in the Chesapeake Bay. Healthy populations of the two seagrasses found in the Bay, *Zostera marina* and *Ruppia maritima*, have been studied in environments of widely varying salinity. On the other hand, low-salinity regions of the upper Chesapeake Bay and its tributaries have historically provided habitat for many freshwater species that tolerate brackish conditions. There is no evidence that the light requirements for these species would be radically different in freshwater versus low-salinity estuarine habitats.

## Chesapeake Bay Research and Monitoring Findings

Research and monitoring results from the Chesapeake Bay also contributed to the derivation of the minimum light requirements, especially in tidal-fresh and oligohaline waters where limited scientific literature existed. Batiuk et al. (1992) established PLW requirements by salinity regime for the restoration of underwater bay grasses to a depth of 1 meter throughout the Chesapeake Bay: $K_d = 2\ m^{-1}$ in tidal-fresh and oligohaline regimes and $K_d = 1.5\ m^{-1}$ in mesohaline and polyhaline segments. Light attenuation coefficients are calculated using Beer's Law $I_z = I_o\exp(-K_dZ)$, where $I_o$ is light (photosynthetically active radiation [PAR]) measured just below the surface and $I_z$ is light measured at depth Z. Using the relationship

$$PLW = 100\exp(-K_dZ) \qquad \text{(Equation IV-1)}$$

where Z = depth in the water column, and setting Z = 1 meter, the Chesapeake Bay minimum seasonal percent light requirement as published in Batiuk et al. (1992) was 13.5 percent of ambient surface light in tidal-fresh and oligohaline environments and 22.3 percent of ambient surface light in mesohaline and polyhaline environments. More specific seasonal criteria were suggested by Carter and Rybicki in Batiuk et al. (1992) for the tidal Potomac River and estuary: $K_d = 2.2\ m^{-1}$ in tidal-fresh regions and $K_d = 2.7\ m^{-1}$ in oligohaline regions, which translated into PLW requirements of 11 percent in tidal-fresh and 7 percent in oligohaline habitats.

**Tidal-Fresh/Oligohaline Potomac River Findings.** From 1983 through 1996, underwater bay grass coverage in the tidal Potomac River varied greatly in both the tidal-fresh and oligohaline reaches. The change in underwater bay grass coverage from the previous year and the median PLW calculated from growing season Secchi

depth varied greatly, but both exhibited a general downward trend during this period. When the change in underwater bay grass coverage from the previous year is plotted against the median PLW at 1 meter during the underwater bay grass growing season (April 1 through October 31), underwater bay grasses increased with increases in the PLW. When median PLW was greater than 13 percent, underwater bay grass coverage showed only positive increases over three years. However, positive increases occurred even in years when median percent light at 1 meter was considerably less than 13 percent, indicating that other factors besides light also influence changes in coverage, or that underwater bay grasses were growing at depths < 1 meter.

A median growing season PLW of 13 percent at 1 meter is equivalent to a median Secchi depth of 0.7 meters or median $K_d$ =2.07, assuming $K_d$ = 1.45/Secchi depth. Secchi depth is only reported to 0.1 meters, so the error in the median measurements is ± 0.05 meter, median seasonal Secchi depth ranges from 0.65 to 0.75 meters and, therefore, $K_d$ ranges from 1.93 to 2.23 meter$^{-1}$. Carter, Rybicki and Landwehr reported in Batiuk et al. (2000) that for the tidal-fresh and oligohaline segments of the Potomac River, a corresponding range of PLW of 11 percent to 14.5 percent presented a boundary condition for a net increase in growth from year to year. It should also be noted that if other habitat conditions are favorable, underwater bay grasses may tolerate worse light conditions for a season, but not on a protracted basis.

**Tidal-Fresh Patuxent River Findings.** Between 1985 and 1996, light conditions at the tidal-fresh Patuxent River monitoring station PXT0402 (or TFI.5) improved. $K_d$ dropped from 6 meter$^{-1}$ to about 4 meter$^{-1}$ (Naylor, unpublished data reported in Batiuk et al. 2000) and average Secchi depth increased from 0.25 to 0.4 meters. During the last four years of this period, colonization by underwater bay grasses also increased, primarily in the shallow areas less than 0.5 meters deep. A $K_d$ of 4 meter$^{-1}$ results in 13.5 percent light at a depth of 0.5 meters. A second Patuxent River tidal-fresh water quality monitoring station (PXT0456 or TFI.4) also showed a significant increase in Secchi depth during the underwater bay grass growing season of this same period.

It appears that when the seasonal Secchi depth at monitoring station PXT0456 was greater than a threshold value of 0.35 meters, the underwater bay grass coverage continued to increase, whereas a Secchi depth below 0.35 meters coincided with a decrease in underwater bay grass coverage. A Secchi depth threshold of 0.35 meters for plants colonizing a depth of less than 0.5 meters is equivalent to a 0.68-meter Secchi depth threshold for plants colonizing a depth of less than 1 meter (as seen in the Potomac). Thus, it appears that similar threshold light conditions are required for successful recolonization in the tidal-fresh areas of both the Potomac and Patuxent rivers (Batiuk et al. 2000).

**Mesohaline Potomac River Findings.** In the mesohaline segment of the Potomac River, underwater bay grasses have continued to increase steadily since 1983, although the coverage remains relatively small compared to pre-1960 conditions. Colonization by underwater bay grasses has taken place primarily in areas less

than 1 meter deep. Midchannel light conditions are better in the mesohaline segment of the river compared to either the tidal-fresh or oligohaline segments, with the median seasonal Secchi depth generally never dropping below 1 meter for the period of 1983 through 1996. Secchi depth is only reported to 0.1 meters, so the error in the median measurements is at least ±0.05 meters. If median Secchi depth is 1 meter, then using a conversion factor of 1.45 to calculate $K_d$ median light conditions of 23.5 percent at 1-meter depth, with a range of 21.7 percent to 25.1 percent (Batiuk et al. 2000). Thus, the Chesapeake Bay water-column light requirements published previously by Batiuk et al. (1992) for mesohaline and polyhaline segments are consistent with those observed in the mesohaline region of the Potomac River where underwater bay grasses are recovering.

**Mesohaline/Polyhaline York River Findings.** Strong positive relationships between water clarity and the maximum depth of the growth of underwater plants have been demonstrated (Dennison et al. 1993; Duarte 1991; Olesen 1996). Assuming that a light requirement of approximately 22 percent of surface irradiance at the sediment surface is necessary for the long-term growth and survival of underwater bay grasses in high salinity regions of the Chesapeake Bay (Batiuk et al. 2000), the presence of underwater bay grasses to a depth of 1 to 1.5 meters below mean low water in this region would require light-attenuation coefficients of approximately 1 $meter^{-1}$ or 0.7 $meter^{-1}$, respectively. In the high mesohaline and polyhaline reaches of the lower York River, field measurements of $K_d$ have yielded long-term median values of 1 $meter^{-1}$ in the shallow littoral zone where underwater bay grasses have been consistently growing down to depths of 1 meter (Moore 1996; Moore et al. 2001).

## LIGHT-THROUGH-WATER REQUIREMENTS

Based on a thorough review of the results of shading experiments and model findings published in the scientific literature, a PLW value of greater than 20 percent is needed for the minimum light requirement of Chesapeake Bay polyhaline and mesohaline species (Batiuk et al. 2000). Consistent with the value derived from the scientific literature, the PLW requirement of 22 percent was determined for mesohaline and polyhaline regions of the Chesapeake Bay and its tidal tributaries by applying the appropriate 1992 underwater bay grass habitat requirement for $K_d$ of 1.5 $meter^{-1}$ to Equation IV-1 (Batiuk et al. 1992). This PLW requirement was confirmed by almost two decades of field observations in the mesohaline Potomac River and mesohaline/ polyhaline York River (Batiuk et al. 1992, 2000; Moore 1996; Moore et al. 2001) as discussed above.

Based on published model findings reviewed in detail by Carter, Rybicki and Landwehr in Batiuk et al. (2000) and confirmed by a review of the results of recent tidal Potomac and Patuxent River research and monitoring studies (see above), a PLW requirement of 13 percent was determined to apply to Chesapeake Bay tidal-fresh and oligohaline species. This light requirement was calculated using Equation IV-1 and the appropriate 1992 SAV habitat requirement for $K_d$ of 2 $meter^{-1}$ (Batiuk

et al. 1992). The PLW requirement also is consistent with the 13.5 percent value published by Dennison et al. (1993).

These PLW requirements were validated through a comprehensive analysis of 13 years (1985–1998) of Chesapeake Bay water quality monitoring data. The results were published in Chapter VII of Batiuk et al. (2000).

**Table IV-1.** Summary of Chesapeake Bay water clarity criteria for application to shallow-water bay grass designated use habitats (application depths given in 0.25 meter depth intervals.[2]

| 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 |

[2]Base on application of Equation IV-1, PLW = 100exp(-$K_d$Z), 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.

## CHESAPEAKE BAY WATER CLARITY CRITERIA

The Chesapeake Bay water clarity criteria are summarized in Table IV-1 as PLW and Secchi depth equivalents over a range of application depths. They reflect a set of minimum light requirements to protect underwater bay grass species found in the two sets of salinity regimes, that have different growth and reproductive strategies and individual light requirements. The water clarity criteria were derived to support the propagation and growth of a wide variety of species, including meadow formers and perennials, not just canopy formers and annuals. In tidal-fresh and oligohaline habitats, the water clarity criteria call for sufficient light to address the minimum requirements of meadow-forming species (e.g., *Vallisneria americana*, or wild celery), which generally need more light, as well as canopy-forming species (e.g., *Myriophyllum spicatum*, or milfoil), which require less. Water clarity criteria applicable to mesohaline and polyhaline habitats call for light conditions necessary for the survival and growth of the two principal species—widgeon grass (*Ruppia maritima*) and eelgrass (*Zostera marina*)—inhabiting the more saline shallow-water habitats of Chesapeake Bay and its tidal tributaries.

For these reasons, these Chesapeake Bay water clarity criteria, along with the appropriate dissolved oxygen and chlorophyll *a* criteria, fully support the "survival, growth and propagation of rooted underwater bay grasses necessary for the propagation and growth of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish inhabiting vegetated shallow-water habitats" (Appendix A; U.S. EPA 2003).

When these 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 will derive and publish criteria addressing water clarity-related impairments for open-water habitat when the necessary scientific data becomes available.

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chapter V

# Chlorophyll *a* Criteria

## BACKGROUND

Phytoplankton are small microscopic plants, or algae, drifting in the water column with the currents. They constitute a diverse group that contributes importantly to the base of the Chesapeake Bay's food web, linking nutrients and the energy of sunlight with small planktonic animals or zooplankton, forage fish, filter feeders such as oysters, bottom-dwelling worms and clams and fishes (Bay and Horowitz 1983; Tuttle et al. 1987; Malone et al. 1986; Heck 1987; Malone et al. 1988). The majority of the Chesapeake Bay's animals feed directly on phytoplankton or secondarily on the products of phytoplankton that support the 'microbial loop' (such as nonphotosynthetic flagellates, protozoa, bacteria and fungi), all of which support higher trophic levels. The Chesapeake Bay's 'carrying capacity' or its ability to support productive and diverse populations of flora and fauna, including highly valued species, depends largely on how well phytoplankton meet the nutritional needs both in quantity and quality of the various consumers.

## SCOPE AND MAGNITUDE OF NUTRIENT ENRICHMENT IN CHESAPEAKE BAY

Problems caused by nutrient over-enrichment are perhaps the longest-standing water quality issues created by people (Vollenweider 1992). Early marine scientists considered nutrients as a resource, not a problem (Brandt 1901) and considered ways to fertilize coastal seas to increase fisheries production. However, this was before human populations and land use activities to support these bourgeoning populations had reached today's levels, especially since about the 1960s. The problem is especially challenging in the Chesapeake Bay ecosystem because the Bay ecosystem's variable dynamics produce large, natural fluctuations. Superimposed onto these natural changes are those caused by human disturbance, and nutrient enrichment is only one among many other pressures experienced by the Bay ecosystem (Breitburg

et al. 1999). The scientific challenge persists because human disturbance often is subtle, indirect and sometimes is confounded by natural changes (Cloern 1996) that are not yet understood enough for predictive purposes. Anthropogenic nutrient enrichment of rivers—which deliver much of their nutrient loads to estuaries and shelf waters—has resulted, in the U.S. in nitrogen fluctuations 5 to 14 times greater than natural rates (Jaworski et al. 1997). Phosphorus loading to estuarine systems has increased two- to sixfold since 1900 (Conley 2000).

Nutrient over-enrichment can cause ecological symptoms in the Chesapeake Bay that impair designated uses, as defined by the Clean Water Act. Nutrient enrichment and changes in important grazer populations such as oysters, menhaden, zooplankton and benthic macroinvertebrates have potentially altered the natural equilibrium between phytoplankton production and consumption in the last century (Kennedy and Breisch 1981; Boynton et al. 1982; Officer et al. 1984; Marshall and Lacouture 1986; Nixon et al. 1986; Gerritsen et al. 1988; Newell 1988; Verity 1987; Malone et al. 1991; Malone 1992; Gerritsen et al. 1994; Hartman and Brandt 1995; and Kemp et al.1997). Phytoplankton populations currently reach very high concentrations (Filardo and Dunstan 1985; Boynton et al. 1982; Sellner et al. 1986; Magnien et al. 1992; Malone 1992; Haas and Wetzel 1993; Lacouture et al. 1993; Harding 1994; Glibert et al. 1995) and high production rates during the spring and summer (Sellner et al. 1986; Magnien et al. 1992; Lacouture et al. 1993; Marshall and Nesius 1996; Sin et al. 1999). Phytoplankton communities also are capable of supporting several potentially toxic taxa (Seliger et al. 1975; Ho and Zubkoff 1979; Luckenbach et al. 1993; Lewitus et al. 1995; Marshall 1995; Glibert et al. 2001).

Excess, uneaten phytoplankton accumulate in the water column and contribute to reduced water clarity and summer oxygen depletion in bottom waters, ultimately stressing the food webs they support (Neilson and Cronin 1981; Boynton et al. 1982; Harding et al. 1986; Seliger et al. 1985; Fisher et al. 1988; Malone 1992). Nutrient enrichment had already affected underwater bay grass distributions throughout much of the Chesapeake Bay by the early 1960s (Flemer et al. 1983; Orth and Moore 1983) and deep-channel hypoxia and anoxia has been confirmed to have been initiated during the early 1970s (Hagy 2002). Local nutrient over-enrichment problems occurred earlier in some Bay tidal tributaries; massive blue-green algae blooms in the upper tidal freshwater Potomac River Estuary began during the 1950s (Jaworski et al. 1972), and Baltimore Harbor experienced a widening hypoxia problem well-established by the mid-1800s (Capper et al. 1983).

## CHLOROPHYLL *A*: KEY INDICATOR OF PHYTOPLANKTON BIOMASS

Scientific interest and practical management needs required that the quantity of phytoplankton biomass in aquatic ecosystems be simply measured as an indicator of water quality and ecosystem health. It was discovered many decades ago that chlorophyll *a*, a ubiquitous photosynthetic pigment often associated with other pigments in freshwater and coastal marine phytoplankton, would serve as a useful indicator for

both the photosynthetic potential and biomass of phytoplankton (Flemer 1970). Thus, over the years, chlorophyll *a* has become a principal measure of the amount of phytoplankton present in a water body. Chlorophyll *a* also plays a direct role in reducing light penetration (Lorenzen 1972). Relatively rapid methods evolved to measure the concentration of chlorophyll *a* in discrete water samples and *in vivo* (Flemer 1969; U.S. EPA 1997). Methods have been developed to measure chlorophyll *a* using aerial surveillance techniques based on passive multispectral signals associated with phytoplankton (Harding 1992). As Harding and Perry (1997) wrote, "Chlorophyll *a* is a useful expression of phytoplankton biomass and is arguably the single most responsive indicator of N [nitrogen] and P [phosphorus] enrichment in this system [Chesapeake Bay]."

Compelling evidence indicates that reduced water clarity and low dissolved oxygen conditions improve when excess phytoplankton or blooms, measured as chlorophyll *a*, are substantially reduced (National Research Council 2001). Improvement in water clarity is a major issue for the recovery of the Bay's shallow-water underwater grasses (see Chapter IV); correcting the low dissolved oxygen problems that occur in the deeper waters of the mesohaline mainstem Chesapeake Bay and lower tidal tributaries has been a challenge to Chesapeake Bay restoration for decades (see Chapter III). High algal biomass present in small embayments may be associated with super-saturated dissolved oxygen conditions during the day and hypoxic to anoxic conditions during the early morning hours (D'Avanzo and Kremer 1994). Attaining the Chesapeake Bay dissolved oxygen and water clarity criteria will require reductions in chlorophyll *a* concentrations by reducing nutrient (yielding nutrient limitation) and sediment (resulting in light saturation) loadings.

In addition to the habitats described above that require chlorophyll *a* criteria, other locations in Chesapeake Bay tidal waters experience phytoplankton blooms that may not be directly associated with low dissolved oxygen and the shading of underwater bay grasses due to phytoplankton. Numerous small shallow-water embayments continue to experience inordinately high chlorophyll *a* concentrations. Some of these habitats may experience early-morning hypoxia or anoxia, while others may not have contained documented growth of underwater bay grasses before the baywide decline. In some parts of the Chesapeake Bay and its tidal tributaries, even reducing nutrient and sediment loadings to levels that would result in attaining the deep-water and deep-channel dissolved oxygen and shallow-water clarity criteria will not prevent harmful algal blooms or ensure the return of high quality food to open-water habitats. These areas include, but are not limited to, those without low oxygen conditions for hydrologic reasons (e.g., high mixing rates) and those in which reduced water clarity conditions are driven more by suspended sediments than by water-column algae. For these reasons, the EPA believes it is necessary to develop and adopt chlorophyll *a* criteria in addition to water clarity and dissolved oxygen criteria for the protection of Chesapeake Bay tidal waters.

## CHESAPEAKE BAY CHLOROPHYLL *A* CRITERIA

This chapter presents the EPA's recommended narrative chlorophyll *a* criteria, along with supporting numeric concentrations and methodological approaches to addressing nutrient-enrichment impairments related to the overabundance of algal biomass measured as chlorophyll *a*. 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 are expected to persist even after the Chesapeake Bay dissolved oxygen and water clarity criteria have been attained.

The narrative chlorophyll *a* criteria in Table V-1, derived in part through a review of other states' chlorophyll *a* water quality standards (Appendix D), are recommended for encompassing the full array of possible impairments, all of which may not manifest themselves within a particular water body at any one time. The site-specific nature of impairments caused by the overabundance of algal biomass supports state adoption of the EPA-recommended narrative criteria, with application of site-specific numeric criteria for localized waters addressing local algal-related impairments.

Because of the regional and site-specific nature of algal-related water quality impairments, baywide numerical criteria have not been published here. Therefore, the chlorophyll *a* concentrations tabulated in this document are not numerical EPA criteria. Along with the documented methodologies, the tabulated chlorophyll *a* concentrations are provided as a synthesis of the best available technical information for the states consideration and use in their development and adoption of more regional and site-specific numerical chlorophyll *a* criteria. States can use this information in deriving numerical translators for their narrative criteria, and use these for their narrative criteria, target chlorophyll *a* concentrations in concert with narrative criteria.

Several different approaches were evaluated to develop relationships among chlorophyll *a* concentrations and tidal-water designated uses. The states also should consider the strengths and limitations of each approach, as well as other available scientific and technical information, when deriving site-specific numerical chlorophyll *a* criteria or numerical translators for their narrative criteria.

**Table V-1.** 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. |

## SUPPORTING TECHNICAL INFORMATION AND METHODOLOGIES

Algae play a unique role at the base of the aquatic food web. The size and composition of the phytoplankton community strike a delicate balance between supporting a balanced, productive ecosystem and fueling severe impairments of water quality and natural ecological relationships. Given that an overabundance or a shift in species composition can yield diverse negative ecological consequences, the supporting chlorophyll *a* concentrations and methodologies have been structured to characterize an array of ecological conditions. They are based on decades of historical observations; scientific findings published in the international, peer-reviewed literature; field and laboratory experiments; historic Chesapeake Bay water quality data; and extensive Chesapeake Bay-specific research, monitoring and modeling.

### CONTEXT FOR THE NARRATIVE CHESAPEAKE BAY CHLOROPHYLL *A* CRITERIA

To interpret the narrative chlorophyll *a* criteria that will protect the designated uses of the Chesapeake Bay and its tributaries, various ecological conditions must be considered and different water quality impairments should be addressed. Table V-2 presents various water quality conditions along the continuum of trophic status or ecological conditions, framing the connections between algal growth and productivity, the various ecological and water quality consequences and, ultimately, designated uses for Chesapeake Bay tidal waters.

An *oligotrophic* status indicates conditions that are not signficantly affected by nutrient and sediment enrichment, typically characterized with low nutrient/low organic matter input or production. Under *mesotrophic* conditions, a water body is nutrient-enriched but still functions adequately without the enhanced production of algae having an adverse impact on the aquatic food web. When a water body reaches *eutrophic* conditions, excess production of algae can lead to low dissolved oxygen conditions, reduced water clarity, harmful algal blooms and other ecological impairments that reflect alterations of the aquatic food web. Aquatic systems that have become so overloaded with nutrients that they are unable to assimulate available nutrients are characterized as *hyper-* or *highly eutrophic*.

Estuarine scientists and managers have borrowed from the field of limnology such terms as oligotrophic, mesotrophic, eutrophic and hypereutrophic to reflect a range in symptoms of nutrient over-enrichment. The reality is that there is no scientific consensus on exactly what these terms mean for nutrient enrichment in estuaries. In the case of the Chesapeake Bay, Table V-2 establishes an ecosystem trophic status classification scheme useful for setting the context for the narrative Chesapeake Bay chlorophyll *a* criteria (see Table V-1) and supporting technical information and methodologies.

**Table V-2.** Trophic status, water quality, phytoplankton community and ecological function along a trophic continuum.

| Trophic Status | Oligotrophic | Mesotrophic | Eutrophic | Highly Eutrophic |
|---|---|---|---|---|
| | Near-pristine conditions; not significantly affected by nutrient enrichment | Experiencing some level of nutrient enrichment but still functioning adequately with an enhancement of productivity and without large impact on the structure of the food web | Significantly impacted by nutrient enrichment, excess primary production leading to dissolved oxygen, harmful algal blooms and other problems; food web structure significantly altered | Aquatic system so overloaded with nutrients those nutrients cannot be assimilated by the system and therefore nutrients are exported to adjacent waters; all the effects listed for eutrophic, but even more extreme |
| **Status in Chesapeake Bay Waters** | No examples of oligotrophic conditions currently in Chesapeake Bay waters | Occasionally found in some areas of the Chesapeake Bay and its tidal tributaries | Many areas in the Chesapeake Bay and its tidal tributaries are currently characterized as eutrophic | Areas in the tidal waters where very large load reductions are required to improve water quality; Back River in Maryland is an example |
| **Ecological Functions** | • Strong trophic coupling and nutrient recycling processes (ecosystem is efficient);<br>• No undesirable algal blooms;<br>•Algal growth often is nutrient-limited, with little accumulation of inorganic nitrogen or phosphorus;<br>• Habitat goals for bay grasses, phytoplankton, zooplankton, water-column fishes and bottom organisms met in all places;<br>• Food pathways to fish and higher trophic levels dominate | • Trophic coupling and nutrient recycling processes;<br>• A few undesirable algal blooms;<br>•Algal growth often is nutrient-limited, with little accumulation of inorganic nitrogen or phosphorus, and light-saturated;<br>• Habitat goals for bay grasses, phytoplankton, zooplankton, water column fishes and bottom organisms met in most places;<br>• Food pathways to fish and higher trophic levels dominate | • Sporadic trophic decoupling;<br>• Algal growth frequently limited by light, not nutrients; nutrient saturation occurs with significant accumulations of inorganic nitrogen and phosphorus;<br>• Transport of nutrients downstream;<br>• More frequent undesirable algal blooms;<br>• Organic matter buildup in bottom waters leading towards anoxia/hypoxia;<br>• Phytoplankton biomass is a frequent cause of water clarity impairment;<br>•Bay grasses stressed by reduced water clarity due to algal shading in the water column and epiphytic algae growth on leaf surfaces | • Persistent, significant trophic decoupling (inefficient ecosystem);<br>• Nutrient saturation /light limitation of algae growth with significant accumulations of nitrogen and phosphorus;<br>• Significant transport of nutrients downstream;<br>• More frequent undesirable algal blooms;<br>• Significant organic matter buildup in bottom waters leading towards anoxia/hypoxia;<br>• Phytoplankton biomass is a major cause of water clarity impairment;<br>•Bay grasses decline or are lost due to turbidity in water column and epiphytic algal growth on leaf surfaces;<br>• Food pathways to bacteria (microbial loop) dominate |
| **Bay Criteria Attainment** | Meets all water clarity and dissolved oxygen criteria | Meets water clarity and dissolved oxygen criteria most of the time | Often does not meet water clarity and dissolved oxygen criteria infrequently | Never meets water clarity and dissolved oxygen criteria |

The analogy equating *oligotrophic* with *pristine* is somewhat forced, because even before European contact, the Chesapeake Bay probably was never poor in nutrients (in the sense of an oligotrophic lake, for example, where likely a small watershed and a relatively impervious geology supplied very low nutrient loads). Proximity to terrestrial nutrient inputs, long residence times for nutrient recycling and generally shallow (8 meters average depth) conditions allowing fairly significant benthic-pelagic coupling are all factors that would prevent the Chesapeake Bay from ever being truly oligotrophic.

So, in a relative sense, the Chesapeake Bay might have been considered *mesotrophic* during these earlier times and became eutrophic as changes in land uses resulted in increased nutrient supplies. This is based on a definition of *eutrophic* as having excess algae, leading to the observed more frequent, persistent and intense periods of low to no dissolved oxygen and substantial reductions in water clarity. Tidal waters surrounded by intensely developed lands have become *hyper-eutrophic*. In a reference condition context, if a majority of Chesapeake Bay tidal waters are considered eutrophic now, a management goal might be to reduce nutrient loadings and, therefore, chlorophyll *a* concentrations, to achieve a more mesotrophic condition, in contrast to the present eutrophic to hypereutrophic situations.

## CHLOROPHYLL *A* CONCENTRATIONS CHARACTERISTIC OF VARIOUS ECOLOGICAL CONDITIONS

Described and documented below are the chlorophyll *a* concentrations characteristic of various ecological conditions within Chesapeake Bay tidal-water habitats.

### Historical Chlorophyll a Concentrations

Chlorophyll *a* concentrations that historically reflected a more balanced Bay ecosystem were quantified through reviews and evaluations of 1950s through 2000 data (Harding 1994; Harding and Perry 1997; Olson 2002). The chlorophyll *a* concentrations derived through this detailed analysis of historically observed concentrations are characteristic of a mesotrophic estuarine system.

**1950s to 1990s Concentration Trends.** Harding and Perry (1997) documented significantly increasing trends in chlorophyll *a* concentrations during the past several decades in the Chesapeake Bay mainstem. Surface mixed-layer concentrations increased five- to tenfold in the higher salinity mesohaline and polyhaline regions, with 1.5- to twofold increases observed in the tidal-fresh to oligohaline regions of the Bay. During this 50-year period, they documented three major patterns in freshwater flow to the Chesapeake Bay: a long period of low river flows during the 1960s, followed by a series of high flow years throughout most of the 1970s, with a mix of river flow levels in the following two decades, and the extreme droughts (1989) and near-record river flows (1993, 1994) reported toward the end of the data record. Harding and Perry (1997) applied an autoregressive moving-average procedure to

explain possible chlorophyll *a* concentrations over time strictly on the basis of observed freshwater inflow, salinity and temperature. When compared with observed concentration trends over decades, the significant increases in chlorophyll *a* could not be accounted for strictly by the variability of freshwater flow, salinity and temperature. The resulting trends could be explained by increased nutrient enrichment of the estuarine ecosystem.

Taking into account the effects of variable annual river flows, chlorophyll *a* concentrations were shown to respond to changes in nutrient loadings over the period of record. These historically observed chlorophyll *a* concentrations were more representative of mesotrophic conditions.

In oligohaline to tidal-fresh reaches of the Chesapeake Bay mainstem (regions V and VI, respectively), Harding and Perry (1997) documented an increasing trend in chlorophyll *a* concentrations from the 1950s to the 1970s, followed closely by a decreasing trend that has carried through into the 1990s (Table V-3; Figure V-1). The decreasing trends are likely due to significant decreases in phosphorus loadings to the Bay, resulting from widespread upgrades in wastewater treatment for phosphorus. Bans on phosphates in detergents also were enacted in states surrounding the Bay during the mid- to late 1980s. The phytoplankton in lower salinity systems where phosphorus has been limited have responded positively, and this has led to lower chlorophyll *a* concentrations, whereas comparable reductions in nitrogen loads have not yet been achieved, limiting opportunities for reduced phytoplankton biomass in the higher salinity regions of the mainstem Bay.

In the 1950s, recognizing limitations in the temporal and spatial coverage of the available data, regional mean chlorophyll *a* concentrations were 3.19 and 2.51 $\mu$g liter$^{-1}$in the tidal-fresh to low- salinity regions between the Susquehanna Flats and the Bay Bridge and between the Bay Bridge and the South River, respectively (regions VI and V, respectively, Harding and Perry 1997; see Figure V-1). Concentrations peaked at 15.59 $\mu$g liter$^{-1}$ (1960s) and 13.12 $\mu$g liter$^{-1}$ (1970s) in these two regions, respectively, and were recorded as regional means of 5.57 $\mu$g liter$^{-1}$ and 10.86 $\mu$g liter$^{-1}$during the 1985-1994 period.

In the higher salinity mesohaline regions—Region IV-South River down to the Patuxent River and Region III-Patuxent River south to the Rappahannock River—chlorophyll *a* concentrations increased 1.5- to twofold from the 1950s through the mid-1990s (Figure V-1; Harding and Perry 1997). Regional mean chlorophyll *a* concentrations ranged from 4.33 $\mu$g liter$^{-1}$ in the 1950s up to 8.20 $\mu$g liter$^{-1}$ for the period of 1985- 1994 in the mainstem Bay between the South and Patuxent rivers. At the same time, regional mean chlorophyll *a* concentrations were 3.58 $\mu$g liter$^{-1}$and 8.03 $\mu$g liter$^{-1}$, respectively, in the mainstem Bay between the Patuxent and Rappahannock rivers.

Harding and Perry (1997) reported the largest trends in the polyhaline regions of the mainstem Bay, where chlorophyll *a* concentrations increased five- to tenfold in nearly 50 years. In the mainstem Bay from the Rappahannock River down to

**Table V-3.** Chesapeake Bay mainstem surface chlorophyll a concentration ($\mu$g liter$^{-1}$) annual means for 1950 to 1994.

| Time Period | Region | Chlorophyll *a* Annual Mean | Number of Observations | Percent Difference[1] |
|---|---|---|---|---|
| **1950-1959** | I | 0.46 | 41 | - |
| | II | 1.21 | 18 | - |
| | III | 3.58 | 108 | - |
| | IV | 4.33 | 7 | - |
| | V | 3.19 | 15 | - |
| | VI | 2.51 | 18 | - |
| **1960-1969** | I | 1.89 | 8 | 310 |
| | II | 2.61 | 9 | 115 |
| | III | 7.09 | 28 | 98 |
| | IV | 7.48 | 58 | 73 |
| | V | 7.79 | 97 | 144 |
| | VI | 15.59 | 295 | 521 |
| **1970-1979** | I | 4.39 | 101 | 853 |
| | II | 6.89 | 31 | 468 |
| | III | 7.95 | 100 | 122 |
| | IV | 7.29 | 206 | 68 |
| | V | 13.12 | 324 | 311 |
| | VI | 12.90 | 845 | 414 |
| **1985-1994** | I | 5.49 | 1862 | 1093 |
| | II | 7.40 | 2350 | 510 |
| | III | 8.03 | 1261 | 124 |
| | IV | 8.20 | 1022 | 89 |
| | V | 10.86 | 1164 | 240 |
| | VI | 5.57 | 1005 | 122 |

[1] Percent difference of annual mean chlorophyll *a* concentration for each region is based upon a comparison with the corresponding chlorophyll *a* concentration in 1950-1959.

Source: Harding and Perry 1997.

Mobjack Bay (Region II; Figure V-1), regional chlorophyll *a* concentrations averaged 1.21 $\mu$g liter$^{-1}$ in the 1950s, but increased to 7.40 $\mu$g liter$^{-1}$ from 1985 to 1994. The regional mean chlorophyll *a* concentration of 0.46 $\mu$g liter$^{-1}$observed in the 1950s increased tenfold through the 1990s to 5.57 $\mu$g liter$^{-1}$in the mainstem Bay from Mobjack Bay to the mouth of the Bay.

**Benchmark Levels Derived from Analysis of the CBP Water-Quality Database.** Evaluating a similar time period of data using different methodologies,

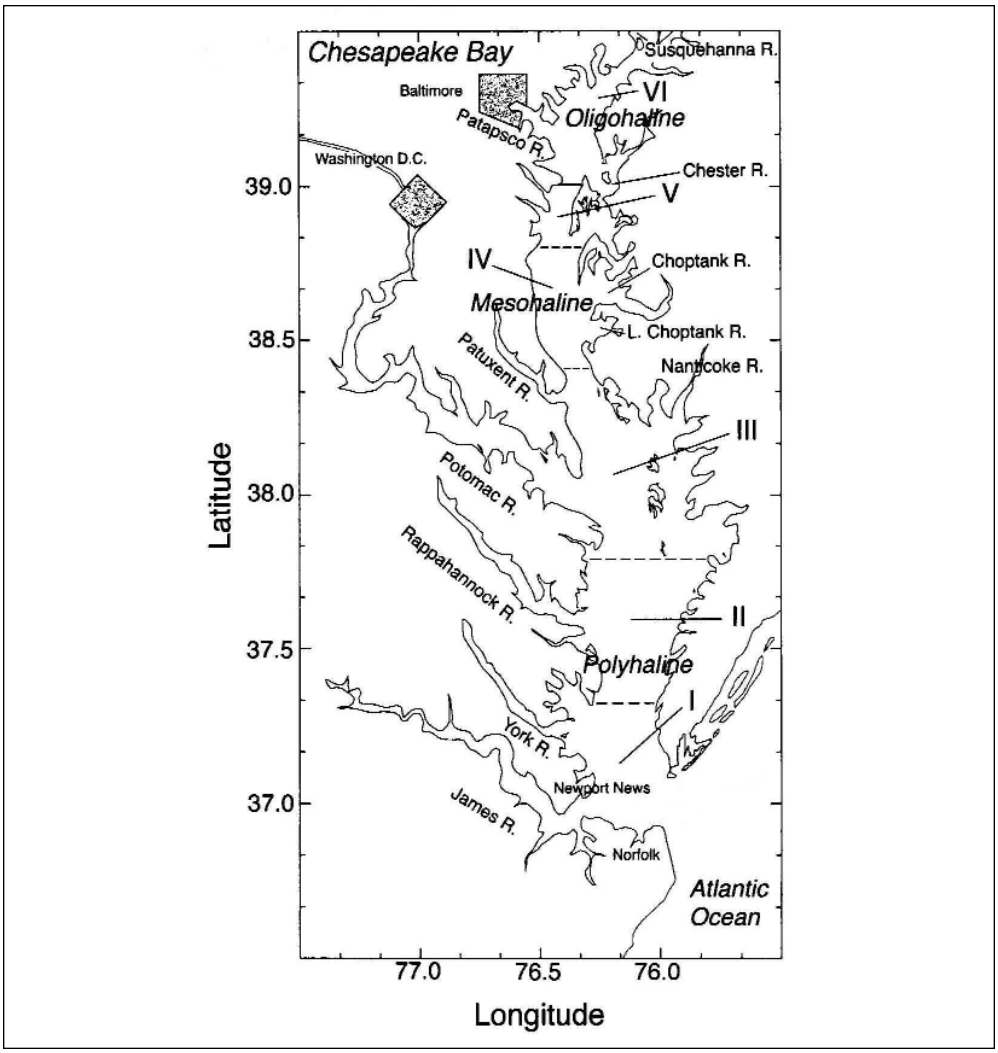


**Figure V-1.** The Chesapeake Bay showing locations of the six regions chosen to represent major salinity provinces of the estuary, the principal rivers draining into the Chesapeake Bay and major metropolitan areas.
Source: Harding and Perry 1997.

Olson (2002) reported a series of benchmark concentrations for chlorophyll *a* as well as for nitrogen, phosphorus and total suspended solids. Benchmark concentrations, derived from a 1985 to 1990 benchmark data set, were applied to the entire 1950s through late 1990s data set (Table V-4). Tabular summaries of decadal spring, summer and annual median chlorophyll *a* concentrations across five decades are documented in Appendix E, tables E-1 and E-2. Table V-5 summarizes the results of these reviews and evaluations of the extensive historical and recent chlorophyll *a* concentration data records.

**Strengths and Limitations.** Consideration of the historical chlorophyll *a* concentrations reflecting a more balanced, mesotrophic Chesapeake Bay ecosystem must be tempered by a recognition of the limited spatial and temporal coverage of

**Table V-4.** Historical chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) derived through applying relative status benchmark data.

| Season | Salinity Zone | Chlorophyll *a* Median | Chlorophyll *a* Mean | Chlorophyll *a* 90$^{th}$ Percentile | Number of Observations |
|---|---|---|---|---|---|
| **Annual** | Tidal-Fresh | 3.1 | 4.2 | 10.2 | 972 |
| | Oligohaline | 4.7 | 6.0 | 10.8 | 910 |
| | Mesohaline | 7.3 | 7.2 | 10.9 | 4192 |
| | Polyhaline | 4.4 | 4.3 | 7.0 | 1132 |
| **Spring** | Tidal-Fresh | 3.1 | 3.7 | 4.2 | 488 |
| | Oligohaline | 5.1 | 5.9 | 9.8 | 279 |
| | Mesohaline | 6.9 | 7.2 | 11.0 | 708 |
| | Polyhaline | 3.4 | 4.1 | 12.9 | 91 |
| **Summer** | Tidal-Fresh | 7.3 | 7.0 | 8.7 | 423 |
| | Oligohaline | 8.0 | 7.6 | 10.8 | 566 |
| | Mesohaline | 8.4 | 7.9 | 11.1 | 1677 |
| | Polyhaline | 4.3 | 3.7 | 6.0 | 341 |

Sources: Olson 2002.

**Table V-5.** Summary of historical Chesapeake Bay chlorophyll *a* concentrations ($\mu$g liter$^{-1}$).

| Salinity Regime | Harding and Perry (1997)-1950s Chesapeake Bay Mainstem Annual Mean Concentrations | Olson (2002)-1950s Chesapeake Bay and Tidal Tributaries Spring/Summer/ Annual Mean Concentrations | Olson (2002)–Relative Status Spring/Summer/ Annual Benchmark Concentrations |
|---|---|---|---|
| **Tidal-fresh** | 2.51 | 1.1 / 1.1 / - | 3.7 / 7.0 / 4.2 |
| **Oligohaline** | 2.51-3.19 | 2.3 / 2.0 / 3.1 | 5.9 / 7.6 / 6.0 |
| **Mesohaline** | 3.58-4.33 | 3.7 / 4.4 / 3.1 | 7.2 / 7.2 / 7.9 |
| **Polyhaline** | 0.46-1.21 | 3.9 / - / 3.2 | 4.1 / 3.7 / 4.3 |

Sources: Harding and Perry 1997; Olson 2002.

the available data for the 1950s and 1960s, as well as the different living resource communities present in the Bay's tidal habitats more than 50 years ago. The data limitations of the 1950s and 1960s data are particularly of concern in the lower portion of the Chesapeake Bay. The large reduction in filter-feeder (e.g., oysters, menhaden) populations has reduced the capacity of the Chesapeake Bay's living resources to assimilate nutrient loads and to maintain lower chlorophyll *a* concentrations. Thus, the changes in living resources may have affected chlorophyll *a*

concentrations as much as or more than the reverse. It should be noted that temporal trends alone do not demonstrate causal relations between chlorophyll *a* concentrations and specific ecological conditions.

## Literature Values Related to Trophic Status

Several influential scientific papers, synthesizing data from many different aquatic systems, describe conditions that were judged to reflect the trophic status of different water bodies (e.g., Wetzel 2001; Ryding and Rast 1989; Smith 1998). Chlorophyll *a* is the principal parameter quantified in these literature reviews. The information is drawn from a diversity of systems across the spectrum of healthy (oligotrophic) to severely stressed (eutrophic) water bodies.

Several papers in the literature synthesize data from many aquatic systems and focus on conditions that reflect different trophic states of water bodies. R. G. Wetzel's *Limnology* presents a table of phytoplankton-related trophic states based on hundreds of studies in freshwater systems (Wetzel 2001). His text defines eutrophic systems as having the same four dominant phytoplankton species as those currently found in most of the Chesapeake Bay system's tidal-fresh or oligohaline habitats and chlorophyll *a* concentrations greater than 10 $\mu$g liter$^{-1}$. A system is defined as eutrophic when it has: 1) very high productivity but mostly occurring in the lower trophic levels (e.g., algae, bacteria); 2) a simplified structure of biological components; and 3) reduced ability to withstand severe stresses and return to pre-stress conditions. In a eutrophic condition, "excessive inputs commonly seem to exceed the capacity of the ecosystem to be balanced, but in reality the systems are out of equilibrium only with respect to the freshwater chemical and biotic characteristics desired by man for specific purposes" (Wetzel 2001). Mesotrophic freshwater systems are defined by Wetzel (2001) as having chlorophyll *a* concentrations in the range of 2-15 $\mu$g liter$^{-1}$ (Table V-6).

**Table V-6.** Summary of aquatic system trophic status as characterized by mean chlorophyll *a* concentrations ($\mu$g liter$^{-1}$).

| Aquatic System | Trophic Status | Wetzel (2001) | Ryding and Rast (1989) | Smith et al. (1999) | Molvaer et al. (1997) | Novotny and Olem (1994) |
|---|---|---|---|---|---|---|
| **Fresh-water** | Eutrophic | >10 | 6.7-31 | 9-25 | - | >10 |
| | Mesotrophic | 2-15 | 3-7.4 | 3.5-9 | - | 4-10 |
| | Oligotrophic | 0.3-3 | 0.8-3.4 | <3.5 | - | <4 |
| **Marine** | Eutrophic | - | - | 3-5 | >7 | - |
| | Mesotrophic | - | - | 1-3 | 2-7 | - |
| | Oligotrophic | - | - | <1 | <2 | - |

Sources: Molvaer et al. 1997, Novotny and Olem 1994, Ryding and Rast 1989, Smith et al 1999, Wetzel 2001.

Ryding and Rast (1989) also deal with characteristics of eutrophication in lakes, based on surveys of hundreds of temperate lakes globally. In Table 4.2, they give the following boundary values for mean and peak chlorophyll *a* values ($\mu$g liter$^{-1}$), as follows:

| | Mean range | Peak Range |
|---|---|---|
| Oligotrophic | 0.8-3.4 | 2.6-7.6 |
| Mesotrophic | 3.0-7.4 | 8.9-29 |
| Eutrophic | 6.7-31 | 16.9-107 |

The peak range is for occasional blooms, and the mean ranges are those for annual geometric means, with outliers removed (see Table 4.2 in Ryding and Rast 1989). The ranges overlap slightly, and in fact the authors recommend using multiple parameters, including total phosphorus, total nitrogen, chlorophyll *a* and Secchi depth to classify the lakes. Using their criteria, much of the Chesapeake Bay would clearly be classified as 'eutrophic.'

In a review of lake and marine systems, Smith et al. (1999) equated mesotrophic status in lake systems to mean chlorophyll *a* concentrations ranging from 3.5 to 9 $\mu$g liter$^{-1}$. A chlorophyll *a* concentration range of 1 to 3 $\mu$g liter$^{-1}$ was equated with mesotrophic status in marine systems (assumed here to be principally polyhaline in terms of salinity). Smith et al. (1999) also published values characteristic of hyper-eutrophic lake (>25 $\mu$g liter$^{-1}$) and marine systems (>5 $\mu$g liter$^{-1}$) .

The Norwegian Environmental Protection Agency has constructed a system for classifying estuaries and coastal waters with respect to water quality and eutrophication using five classes of water quality (Molvaer et al. 1997). For salinities above 20 ppt, chlorophyll *a* concentrations below 2 $\mu$g liter$^{-1}$ are considered Class I or 'very good,' whereas concentrations above 20 $\mu$g liter$^{-1}$are classified as "very bad" or Class V waters. Sweden has adopted similar chlorophyll *a* water quality standards for its estuarine (1.3 to 2.0 $\mu$g liter$^{-1}$) and marine (1.0 to 1.5 $\mu$g liter$^{-1}$) waters that reflect the lower end of these concentration ranges (Sweden Environmental Protection Agency 2002).

**Strengths and Limitations.** The trophic classifications should be used with caution since the majority of the scientific literature-based values were developed for lake, coastal or marine systems, not temperate, partially mixed estuaries such as the Chesapeake Bay. In particular, marine ecosystems should not be considered directly comparable to polyhaline estuarine areas. The polyhaline areas of the Chesapeake Bay are in much closer proximity to land-based freshwater and nutrient inputs. Therefore, they should be expected to have higher nutrient concentrations and associated chlorophyll *a* concentrations than marine systems.

Trophic classifications are useful, general ecological concepts. However waters classified strictly by chlorophyll *a* concentrations may or may not experience all or any of the ecological conditions characteristic of that category (see Table V-2).

## Phytoplankton Growth-Limiting Water Quality Conditions and Related Chlorophyll *a* Concentrations

Biological communities found in pristine or minimally affected habitats provide essential information on how restoration efforts might improve ecosystem structures and functions. They also serve as references for measuring restoration progress. Chesapeake Bay water quality and phytoplankton data collected at Chesapeake Bay Program phytoplankton monitoring stations between 1984 and 2001 were analyzed to identify reference phytoplankton communities for Chesapeake tidal waters. The seasonal and salinity-specific reference communities were used to quantify chlorophyll *a* concentrations in the least-impaired water quality conditions currently found in the Chesapeake Bay.

For the purposes of deriving the reference communities, least-impaired water quality conditions were defined as the co-occurrence of high light penetration, low dissolved inorganic nitrogen and low dissolved inorganic phosphorus concentrations. Low dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus ($PO_4$) concentrations are below the threshold concentrations shown to limit phytoplankton growth in Chesapeake Bay waters (Fisher et al. 1999), whereas high light penetrations are the Secchi depth values identified by the Relative Status, or benchmark, method as 'good' (Olson 2002). The high light penetration levels are approximately the same as those necessary for restoring underwater bay grasses (Batiuk et at. 2000). Thresholds for DIN, $PO_4$ and Secchi depth for spring and summer across four salinity zones (tidal-fresh, oligohaline, mesohaline and polyhaline) were applied to the 1984 through 2001 Chesapeake Bay water quality monitoring database to bin the data records into six water quality categories. Reference communities were derived from the least impaired water quality categories found in each season-salinity regime.

Water quality conditions that met all three reference criteria ('better'/'best') between 1984 and 2001 occurred in 1.6 percent (spring) and 5.8 percent (summer) of the mesohaline biomonitoring samples, and 21.1 percent (spring) and 10.4 percent (summer) of the polyhaline water quality monitoring samples, so reference communities could be characterized directly from the data. Water quality conditions that met all the reference criteria rarely occurred in tidal-fresh and oligohaline salinities. In these cases, the 'mixed better light' category (see Appendix F for definition) was used as a surrogate, since values of most phytoplankton parameters (e.g., chlorophyll *a*, biomass, pheophytin and species composition) in this category closely resembled those in 'better'/'best' in mesohaline and polyhaline waters. For the spring mesohaline reference community, 'better'/'best' data were augmented with 'mixed better light' data to increase the number of data records. Chlorophyll *a* concentrations

observed in the phytoplankton reference communities are shown in Table V-7. The water quality binning method and identification of the phytoplankton reference communities are described in more detail in Appendix F.

It is important to realize that the chlorophyll *a* concentrations in Table V-7 reflect phytoplankton reference communities in the absence of robust grazer populations. There are no undisturbed sites in the Chesapeake Bay with a full complement of natural grazers. Harvesting and disease have significantly decreased Chesapeake oyster abundances (Newell 1988). Menhaden populations have declined to approximately 5 percent of 1970s levels (data from the Maryland Department of Natural Resources). Comparisons of historic and contemporary populations of mesozooplankton and benthos indicate that declines may also have occurred in these grazers. Median chlorophyll *a* concentrations in the reference communities are significantly lower than those in impaired waters, and algal blooms are absent. Reference community chlorophyll *a* concentrations are slightly higher than historic Chesapeake Bay concentrations and are typical of mesotrophic conditions. They indicate the chlorophyll *a* concentrations that could be attained in the present-day Chesapeake Bay with significant nutrient and sediment reductions, in the absence of robust populations of grazers. If key grazer populations are at least partially restored to historical levels, it is possible that the phytoplankton reference community chlorophyll *a* concentrations will approach 1950s levels (see Table V-3).

**Table V-7.** Chlorophyll *a* concentrations in the salinity- and season-based Chesapeake phytoplankton reference communities ($\mu$g liter$^{-1}$). The median and range (5%–95%) are shown. Reference community values are derived from samples with the least improved water quality conditions in the 1984–2001 Chesapeake Bay Program phytoplankton and water quality monitoring station data.

| Salinity Regime | Spring | Summer |
|---|---|---|
| **Tidal-Fresh** | 4.3 (1.0 - 13.5) | 8.6 (3.2 - 15.9) |
| **Oligohaline** | 9.6 (2.4 - 24.3) | 6.0 (2.5 - 25.2) |
| **Mesohaline** | 5.6 (2.2 - 24.6) | 7.1 (4.4 - 14.0) |
| **Polyhaline** | 2.9 (1.1 - 6.7) | 4.4 (1.7 - 8.7) |

Source: Chesapeake Bay Water Quality and Phytoplakton Monitoring Programs Databases. http://www.chesapeakebay.net/data

**Strengths and Limitations.** It is important to realize that these values were selected from samples subject with least-improved water quality, and they came from a larger data set obtained from generally nutrient- and sediment-enriched Chesapeake Bay. Under better water quality conditions (lower annual nutrient load-

ings, more zooplankton grazing and better trophic coupling), these chlorophyll *a* values might be even lower than those obtained under low current nutrient loadings due to the carryover of nutrients from previous high load conditions.

The phytoplankton reference community approach does not demonstrate any direct relationship between chlorophyll *a* concentrations and designated use impairments. However, this method does provide solid insights into how chlorophyll *a* concentrations will likely respond in estuarine systems as water quality improves, leading to more nutrient-limited, light saturated conditions.

Chlorophyll *a* concentrations do not always show a high correlation with algal biomass because after a bloom, some species of nonchlorophyll-bearing phytoplankton can feed on organic material (Livingston 2001).

**Research Needs.** Further analysis of the Chesapeake Bay monitoring databases could help determine if nitrogen, phosphorus or suspended sediment reductions or a combination thereof will be most effective in minimizing the occurrence of harmful algal blooms.

## Chlorophyll a Concentrations Characteristic of Potentially Harmful Algal Blooms

The scientific literature indicates that certain phytoplankton community taxonomic groups produce poor quality food and even toxins that impair the animals that feed on them (Roelke et al. 1999; Roelke 2000). Phytoplankton assemblages can become dominated by poor quality food taxonomic groups to an extent that the overall food quality of that phytoplankton assemblage becomes significantly reduced. Chlorophyll *a* concentrations were identified that corresponded to an increased probability that potentially harmful algal taxa would exceed specific impairment thresholds.

Several of the more than 700 phytoplankton species in the Chesapeake Bay are known to be harmful to consumers. Approximately 2 percent of these species have shown evidence of producing toxins (Marshall 1996). Some species, however, form blooms and can dominate the community at particular locations during specific times of the year. Some of these species are even capable of producing toxins.

The dinoflagellates, *Prorocentrum minimum* and *Cochlodinium heterolobatum,* which commonly bloom in spring and summer, respectively, in certain mesohaline areas of the estuary, have been shown to harm various life stages of the Eastern oyster, *Crassostrea virginica* (Ho and Zubkoff, 1979; Luckenbach et al. 1993; Wickfors and Smolowitz 1995). The dinoflagellate *Karlodinium micrum* has been associated with numerous fish kills in the Chesapeake Bay (Goshorn et al. 2003). In tidal-fresh regions, a colonial cyanophyte, *Microcystis aeruginosa*, forms surface blooms that cover the upper reaches of certain Bay tributaries for miles during the summer. This species has been documented to affect zooplankton communities under bloom conditions (Lampert 1981; Fulton and Paerl 1988).

The occurrence of harmful algal blooms is a complex, incompletely-understood phenomenon. Many harmful blooms cannot effectively be predicted or modeled at this time, and the physical, chemical and biological controls on many such blooms are not known. Nutrient concentrations or loads are only one of many environmental parameters that can potentially affect harmful algal blooms. For example, some harmful blooms may respond more to nutrient ratios than absolute concentrations, or may be regulated by top-down controls (e.g., grazer dynamics) more than by nutrient availability. This section represents a valuable compilation of information, focusing on several Chesapeake Bay species that have been observed to correlate with chlorophyll *a* concentrations. As illustrated below using the four previously cited species, the likelihood of bloom conditions being produced by some harmful or nuisance algal species tends to be associated with elevated chlorophyll *a* levels. Future monitoring and research is expected to provide more insight into the practicality and methodology for managing blooms of these and other species.

***Microcystis aeruginosa.*** A substantial body of literature deals with the negative effects of toxic cyanobacteria on the feeding, growth, behavior and survival of micro- and mesozooplankton. Numerous studies have documented the avoidance of ingestion of toxic and nontoxic strains of *Microcystis aeruginosa* by specific taxa of zooplankton (Clarke 1978; Lampert 1981; Gilbert and Bogdan 1984; Fulton and Paerl 1987, 1988; DeMott and Moxter 1991) while others indicate physiological and behavioral problems associated with its ingestion (Lampert 1981, 1982; Nizan et al. 1986; Fulton and Paerl 1987; DeMott et al. 1991; Henning et al. 1991).

From laboratory studies, 10,000 cells milliliter$^{-1}$ was determined to be the threshold above which zooplankton communities can be adversely altered by the poor food quality, large particle size of the colonies, increased density of particles in the water column or directly by the toxin (Lampert 1981; Fulton and Paerl 1987; Smith and Gilbert 1995). (See Appendix G for more detailed descriptions of the determination of the effects threshold.)

Upon matching the chlorophyll *a* concentrations to samples containing *M. aeruginosa*, normalized frequency distribution plots were constructed for *M. aeruginosa* bloom frequency and the frequency of both bloom and non-bloom abundances versus chlorophyll *a* concentrations (figures V-2 and V-3, respectively). Chlorophyll *a* concentrations <15 $\mu$g liter$^{-1}$ characterize *M. aeruginosa* concentrations less <10,000 cells milliliter$^{-1}$ (Figure V-2). Increasing concentrations of chlorophyll *a* above 15 $\mu$g liter$^{-1}$ leads to increasing frequencies of bloom samples > 10,000 cells milliliter$^{-1}$ (Figure V-3).

Colonies of *M. aeruginosa* vary in their cell counts but colony counts provide an additional measure of bloom conditions (Figure V-4). The ratio of cells per colony is approximately 17:1, providing an estimate of 588 colonies containing 10,000 cells as a translation to threshold levels for zooplankton community impacts.

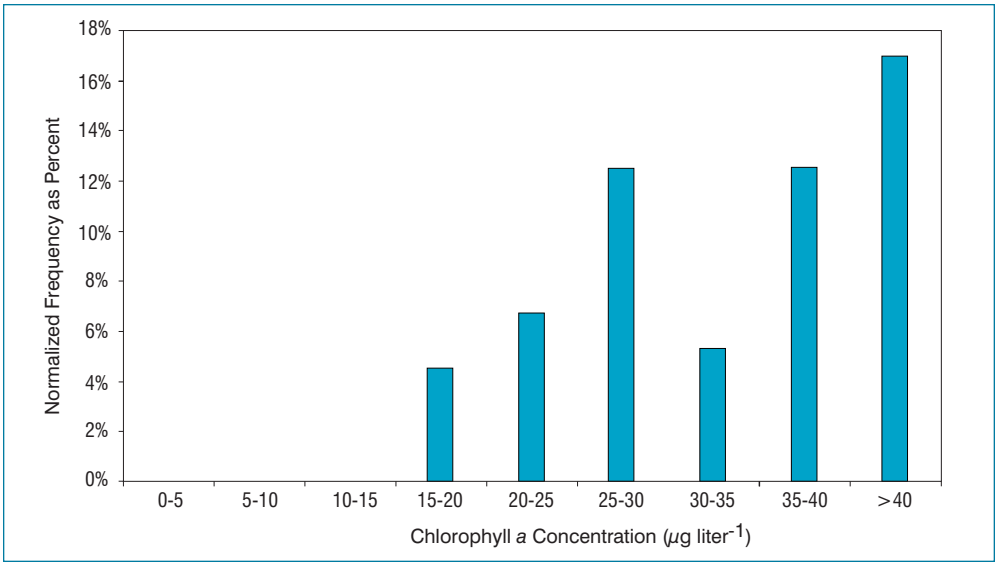


**Figure V-2.** Normalized frequency of *Microcystis aeruginosa* abundances above-threshold (i.e., >10,000 cells milliliter$^{-1}$) versus summer tidal fresh chlorophyll *a* concentration. The number of above-threshold *Microcystis aeruginosa* abundances in each chlorophyll *a* interval is divided by the total number of phytoplankton records in that interval. For summer tidal fresh, there were 16 above-threshold occurrences in a total of 266 samples.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

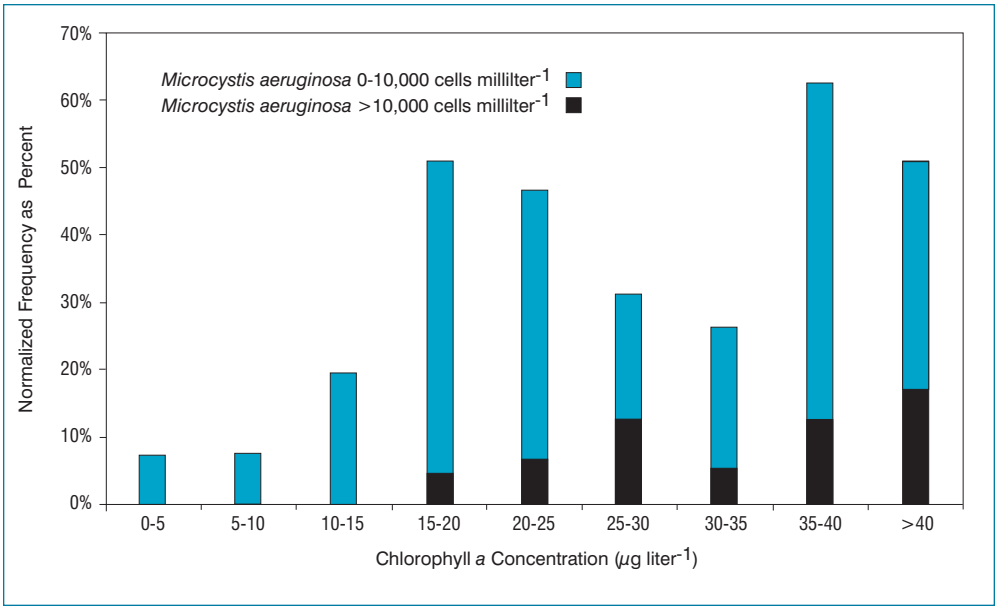


**Figure V-3.** Normalized frequency of above- and below-threshold *Microcystis aeruginosa* abundances versus summer tidal fresh chlorophyll *a* concentration. The number of above- and below-threshold *Microcystis aeruginosa* abundances in each chlorophyll interval is divided by the total number of phytoplankton records in that interval. For summer tidal fresh, there were 62 total occurrences of *Microcystis aeruginosa* in a total of 266 samples. The increasing trend in total occurrences of *Microcystis aeruginosa* identify it as an indicator species of eutrophication.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

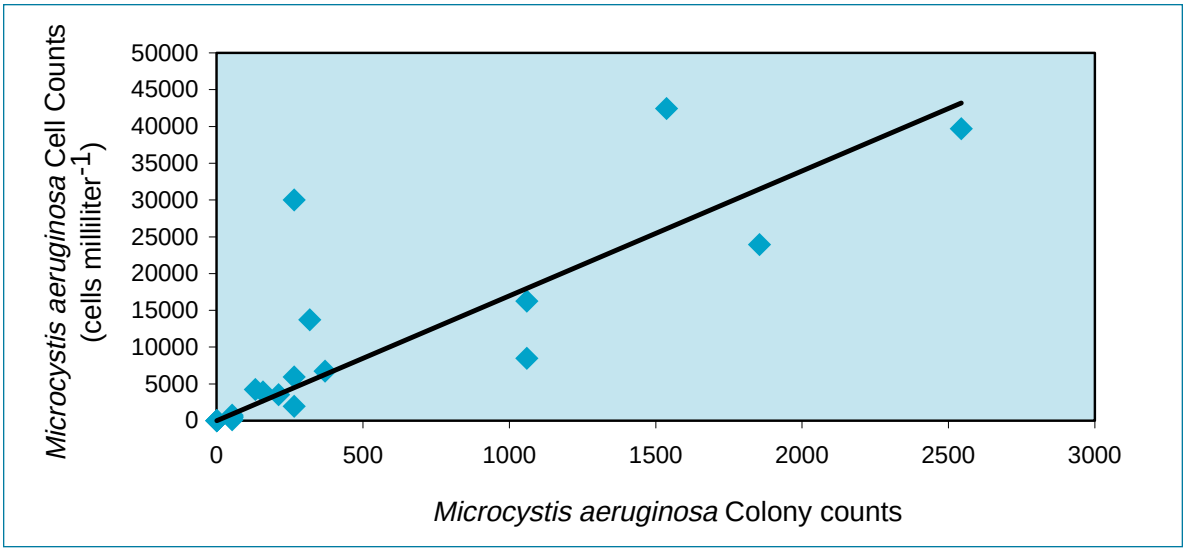


**Figure V-4.** Relationship of *Microcystis aeruginosa* colony counts versus cell counts. Cell counts=16.97 x colony counts; r2=0.66; n=20.

Source: Maryland Department of Natural Resources unpublished data.

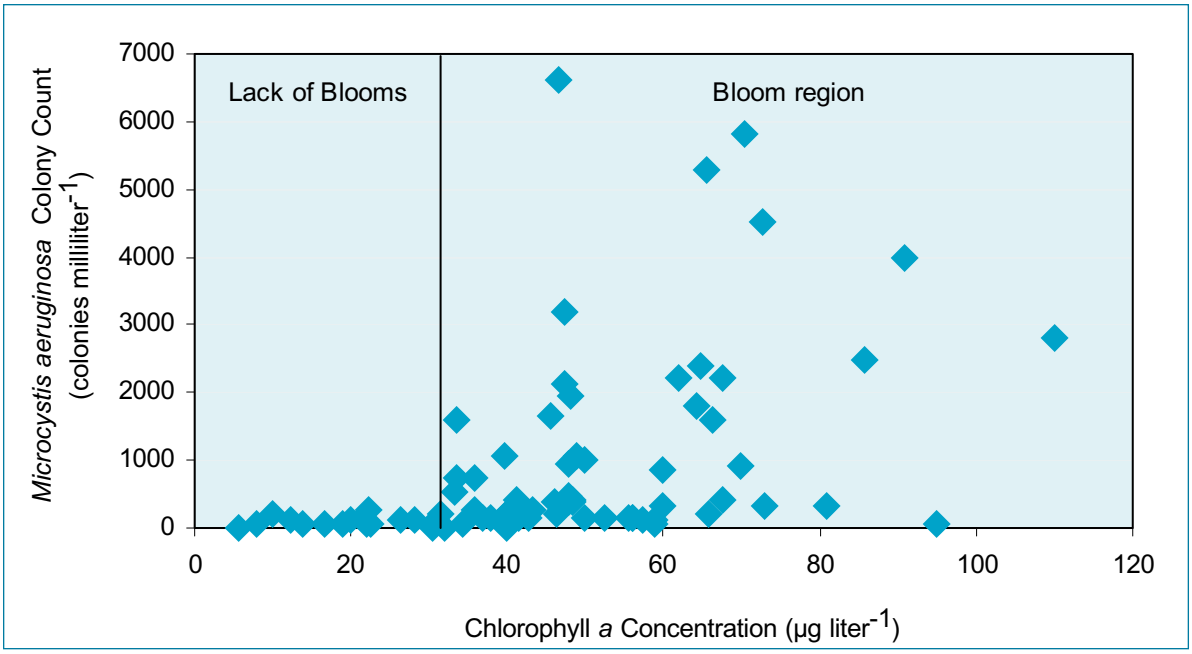


**Figure V-5.** *Microcystis aeruginosa* colony counts versus a gradient of chlorophyll *a* concentrations illustrating the boundary between bloom and non-bloom conditions.

Source: Maryland Department of Natural Resources unpublished data.

*M. aeruginosa* counts were made from water samples collected by the Maryland Department of Natural Resources through a separate water quality monitoring program from the tidal-fresh and oligohaline waters of Maryland's Chesapeake Bay. Between 1985 and 2000, *M. aeruginosa* colony counts showed low concentrations (<588 colonies milliliter$^{-1}$) and low variance between 0-33 $\mu$g liter$^{-1}$ chlorophyll *a* (Figure V-5). Beyond 33 $\mu$g liter$^{-1}$ chlorophyll *a*, the variance of colony counts increases significantly and counts exceeding the 588 colonies milliliter$^{-1}$ threshold increase to 42 percent beyond 33 $\mu$g liter$^{-1}$ chlorophyll *a*, providing a threshold and probability for potentially harmful blooms of this cyanobacteria with respect to chlorophyll *a* measures. The chlorophyll *a* range of 15-33 $\mu$g liter$^{-1}$ provides a threshold region between levels that protect against *M. aeruginosa* blooms versus conditions with a high likelihood for blooms.

One of the primary locations for *M. aeruginosa* blooms in the Chesapeake Bay estuary is the tidal-fresh Potomac River. Extensive blooms of *M. aeruginosa* were documented over the period of 1965-1983, before the initiation of the coordinated Chesapeake Bay monitoring program. During the period of 1965-1974, summer chlorophyll *a* concentrations in the vicinity of Indian Head (near monitoring station TF2.3) were typically above 50 $\mu$g liter$^{-1}$ and often exceeded 100 $\mu$g liter$^{-1}$ in the surface layer (Pheiffer 1975). During the same period, cyanobacteria blooms were extensive in this portion of the river in summer, although there are very few data reflecting cell densities. Total cyanobacteria densities ranged from 20,000–120,000 cells milliliter$^{-1}$ in the summer of 1971 near Possum Point (Simmons et al. 1974).

In 1983, a massive bloom of *M. aeruginosa* was documented in this portion of the Potomac River (mile 12 - mile 46) (Thomann et al. 1985). Chlorophyll *a* concentrations averaged over 200 $\mu$g liter$^{-1}$ for the Indian Head area in August 1983. Again, little species composition data is documented for this bloom.

With the initiation of the Chesapeake Bay phytoplankton monitoring program in August 1984, a steady flow of phytoplankton species composition and chlorophyll *a* data was recorded for a station in the tidal-fresh Potomac River near Indian Head (TF2.3). Figure V-6 summarizes these data for *M. aeruginosa* during the summer months of 1985–2002. The data show that the threshold is rarely exceeded during this period after 1988, but one can assume that during the severe blooms of the 1970s and early 1980s, this threshold may have been surpassed on a regular basis. The fact remains that this taxon is an impairment to zooplankton assemblages above a specific threshold and this threshold density has been surpassed on a number of occasions in the tidal-fresh Potomac River during the past several decades.

**Strengths and Limitations.** The strength of this line of evidence for establishing a chlorophyll *a* threshold for the tidal-fresh and oligohaline regions of the estuary lies in the evidence provided in the many laboratory and field studies that indicate adverse affects on zooplankton populations caused by cyanobacteria in general and, more specifically, by *M. aeruginosa*. *M. aeruginosa* has been found in many of the tidal-fresh locations sampled as part of the Chesapeake Bay water quality

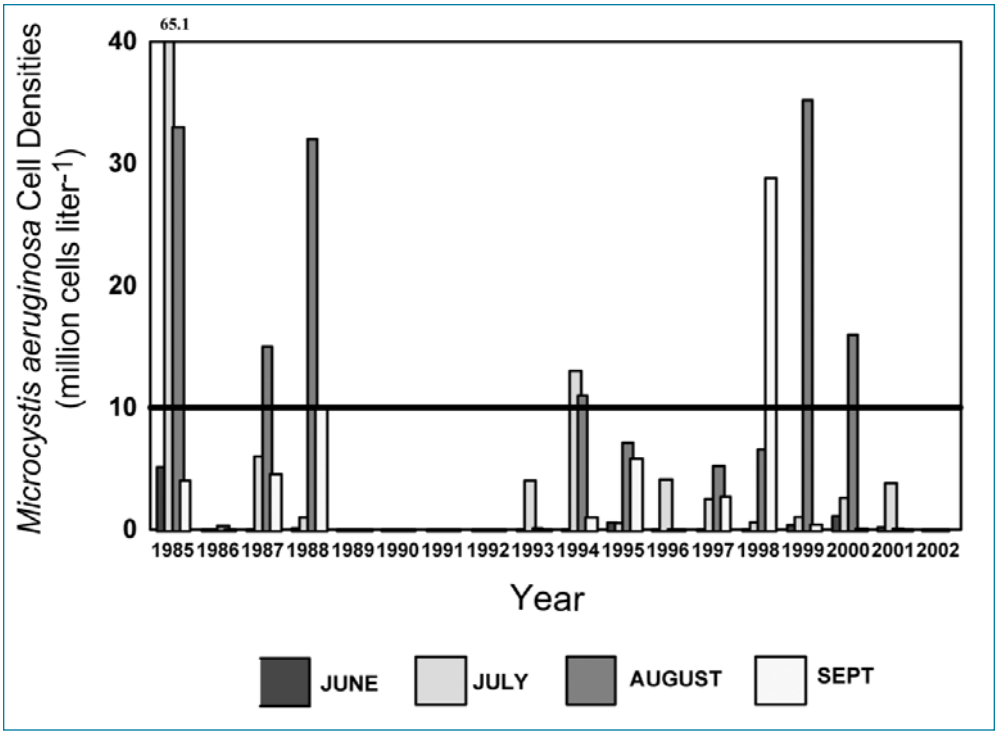


**Figure V-6.** Mean summer *Microcystis aeruginosa* cell densities from 1985–2002 from the surface mixed layer of the Potomac River tidal fresh phytoplankton monitoring station TF2.3.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

monitoring program, implying that this 'indicator' species is ubiquitous to this particular tidal-fresh habitat during the summer under certain hydrodynamic conditions and with a given set of nutrient requirements.

Numerous field studies have documented changes in zooplankton community structure associated with blooms of cyanobacteria in general (Infante and Riehl 1984; Orcutt and Pace 1984; Threlkeld 1986; Burns et al. 1989; Gilbert 1990; Fulton and Jones 1991). These studies most frequently cite the inability of many zooplankton taxa in using cyanobacteria as a nutritive food source. Therefore, it can reasonably be stated that high chlorophyll *a* concentrations in tidal-fresh and oligohaline regions of the Chesapeake Bay estuary in summer often are associated with high densities of cyanobacteria, which can adversely alter the zooplankton community structure in these areas.

Colony counts have a lower variance than, and a positive relationship to, *M. aeruginosa* cell counts, providing a robust indicator to describe bloom conditions. Both data sets in these analyses independently define a relatively narrow range of conditions that separate the bloom from non-bloom regions of the chlorophyll *a* gradient based on threshhold level effects on living resources of 10,000 cells milliliter$^{-1}$.

The threshold value for the cell density that affects zooplankton populations was derived from two laboratory studies citing impairment thresholds at very different cell densities (see Appendix G). A third study has been identified that documented negative effects on zooplankton at *M. aeruginosa* cell densities of 50,000 cells milliliter$^{-1}$, which is an intermediate value compared to the two previously cited studies (Smith and Gilbert 1995).

Some of the detrimental effect of *M. aeruginosa* on zooplankton assemblages is related to the toxin content of a particular strain of this cyanobacterium (one reason that the threshold density of the two laboratory studies is so different). The toxin content of the strains of *M. aeruginosa* found in the Chesapeake Bay has not been determined, which forced the extrapolation of the threshold for this document to be chosen as a midpoint between the thresholds of the two laboratory studies.

Colony counts are not interchangeable with cell counts, since the variance increases as the counts increase. The risks have been stated based on a threshold for zooplankton effects using an abundance of cells, while the risks to toxin production or toxic effects are less well understood in relation to cell or colony concentrations.

**Research Needs.** Two obvious research studies would strengthen this line of evidence. The first would be to assess the toxin content in the populations of *M. aeruginosa* found in various tidal-fresh regions of the Chesapeake Bay. The second would be to use some strains of the cyanobacterium in specific laboratory experiments that studied effects on zooplankton feeding, reproduction and survival at specific cell densities and associated chlorophyll *a* concentrations.

The estimate of colony counts as a threshold can be refined using the conversion with cell counts through results of the Chesapeake Bay phytoplankton monitoring program. Additional work is needed to correlate the concentration data with levels associated with detrimental levels of microcystin toxins in the ecosystem. Spatial and temporal resolution of *M. aeruginosa* levels in relation to cell and colony concentration would provide valuable information for any reassessment of the density driven thresholds being proposed.

***Prorocentrum minimum.*** *P. minimum* effects may be a function of bloom density or toxicity. In Japan in 1942, *P. minimum* was attributed as the cause of a shellfish poisoning in Japan in which 114 people died (Nagazima 1965, 1968). *P. minimum* isolated from a 1998 bloom in the Choptank River and subsequently grown in the laboratory was found to be toxic to scallops (G. H. Wickfors, personal communication). Blooms of *P. minimum* in the source intake waters to Virginia and Maryland oyster hatcheries were suspected to have caused oyster larvae mortality at the two hatcheries in 1998 (Mark Luckenbach and Don Merritt, personal communication). There has been no documented case of shellfish toxicity or mortality as a result of the 1998 *P. minimum* bloom in the Chesapeake Bay, but clearly the potential exists for toxic repercussions to shellfish and other organisms as a result of this bloom.

The *P. minimum* density of 3,000 cells milliliter$^{-1}$ was chosen as a threshold for the chlorophyll *a* criteria analysis based on laboratory analyses (Wickfors and Smolowitz 1995; Luckenbach et al. 1993; see Appendix G). When the threshold is applied to Chesapeake Bay phytoplankton monitoring program data, the normalized frequency distribution of chlorophyll *a* concentrations associated with bloom densities (>3,000 cells milliliter$^{-1}$) illustrates that concentrations > 5 $\mu$g liter$^{-1}$ can generate densities that may impair the survival of various life stages of oysters (Figure V-7). The likelihood of bloom level events tends to increase with increasing chlorophyll *a* concentrations (Figure V-8).

When the threshold is applied to Chesapeake Bay phytoplankton monitoring program data, the normalized frequency distribution of chlorophyll *a* concentrations associated with the *P. minimum* bloom densities (greater than 3,000 milliliter$^{-1}$) indicates a large increase at chlorophyll *a* concentrations of 25 to 30 $\mu$g liter$^{-1}$ (Figure V-9). More than 19 percent of samples containing *P. minimum* in mesohaline waters in spring are characterized by densities that exceed the threshold whereby oyster life stages are impaired and fall within the chlorophyll *a* range of 25 to 30 $\mu$g liter$^{-1}$. In addition, more than 70 percent of the above-threshold data for *P. minimum* occur at chlorophyll *a* concentrations greater than 25 $\mu$g liter$^{-1}$ (Figure V-10). These normalized frequency distributions thus indicate that chlorophyll *a* concentrations of greater than 25 $\mu$g liter$^{-1}$ in spring in mesohaline waters often are associated with densities of *P. minimum* that may impair the survival of various life stages of oysters.

In an analysis of a separate Maryland Department of Natural Resources database from 1985-2000, a probability analysis illustrated that no blooms of *P. minimum* occurred at or below chlorophyll *a* concentrations of 4 $\mu$g liter$^{-1}$ (Figure V-11). This analysis of an independent data set complements the previously described Chesapeake Bay Phytoplankton Monitoring Program database analysis confirming the low target chlorophyl *a* concentration needed to eliminate conditions for blooms of *P. minimum* in the mesohaline Chesapeake Bay. Figure V-11 shows that as the chlorophyll *a* concentration increases, the probability of detecting a *P minimum* bloom level above the 3,000 cells milliliter$^{-1}$ threshold in a sample increases in a non-linear fashion. The possibility increases rapidly at first above 4 $\mu$g liter$^{-1}$ and then slows as the maximum potential detection of 11 percent of samples is reached at high chlorophyll *a* concentrations. Maximum bloom probability was 11 percent in the spring, or 1 in every 9 samples when conditions are optimal. Protecting against the conditions for 50 percent of maximum bloom potential occurred at approximately 25-30 $\mu$g liter$^{-1}$ (Figure V-11).

Currently, the impairment thresholds are usually reached in spring in mesohaline waters, but *P. minimum* commonly occurs in both spring and summer in oligohaline, mesohaline and polyhaline habitats.

**Strengths and Limitations.** *P. minimum* blooms occur in many mesohaline portions of the estuary. The appearance of the major bloom events in these areas occur on regular seasonal basis. Therefore this would be a useful indicator species to monitor.

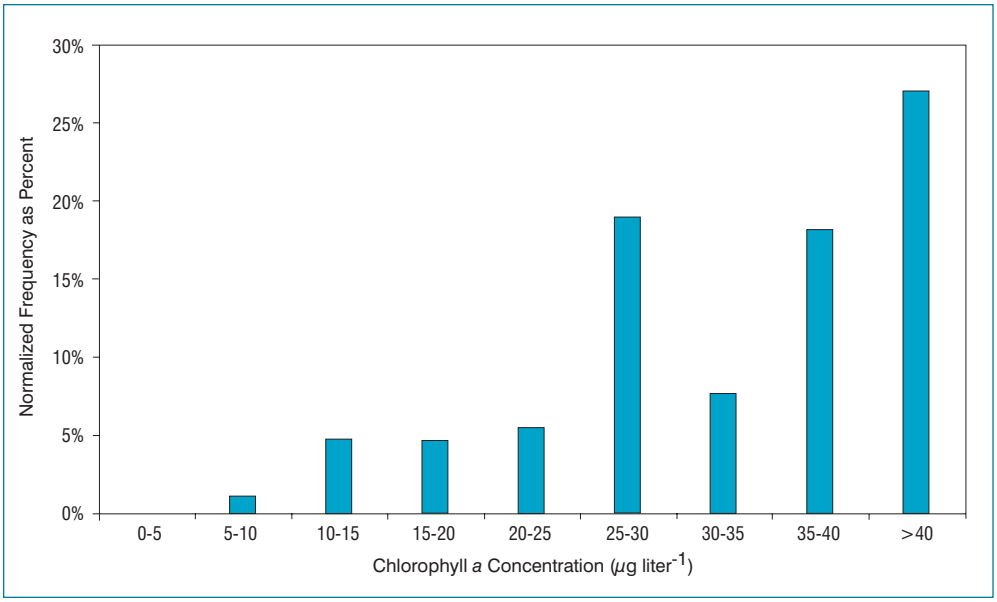


**Figure V-7.** Normalized frequency of *Microcystis aeruginosa* abundances above-threshold (i.e., >3,000 cells milliliter$^{-1}$) versus spring mesohaline Chesapeake Bay and tidal tributary chlorophyll *a* concentration. The number of above-threshold *Prorocentrum minimum* abundances in each chlorophyll *a* interval is divided by the total number of phytoplankton records in that interval. For spring mesohaline stations, there were 35 above-threshold occurrences out of a total of 648 sampling records.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

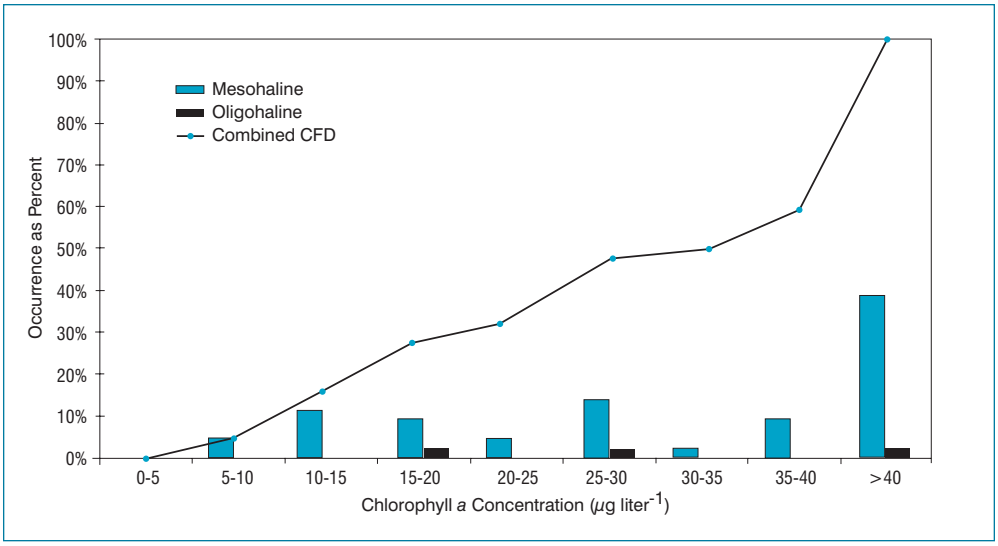


**Figure V-8.** All occurrences of *Prorocentrum minimum* abundances above threshold versus combined spring and summer, mesohaline and oligohaline Chesapeake Bay and tidal tributary chlorophyll *a* concentration. The number of above threshold *Prorocentrum minimum* densities in each chlorophyll *a* interval is divided by the total number of above-threshold densities (n=44).

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

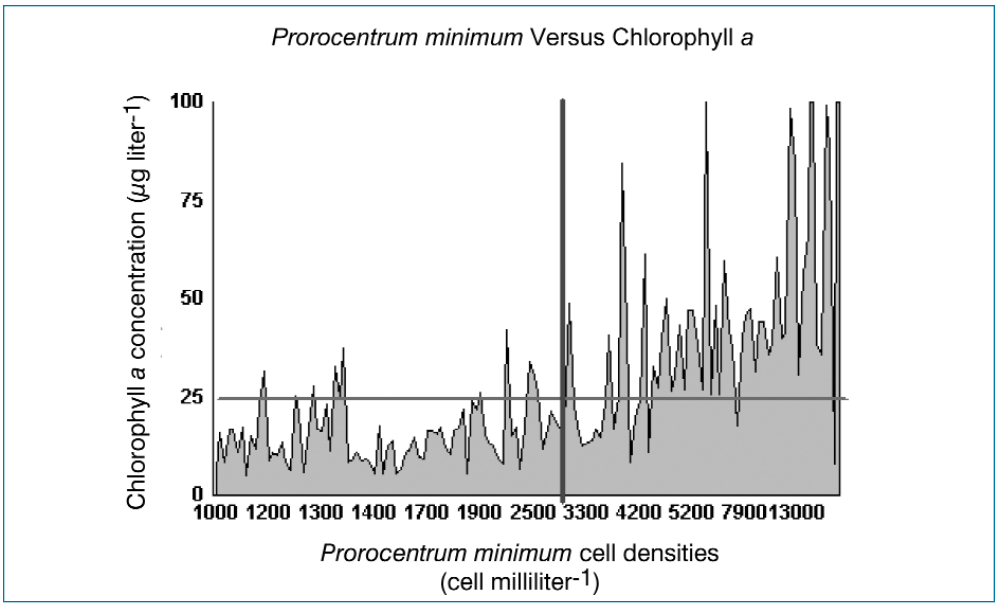


**Figure V-9.** *Prorocentrum minimum* cell densities and associated chlorophyll *a* concentrations in the Chesapeake Bay, 1985-2000. Cell density threshold associated with impacts on the oyster community is indicated by the vertical black line at 3,000 cells milliliter$^{-1}$.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

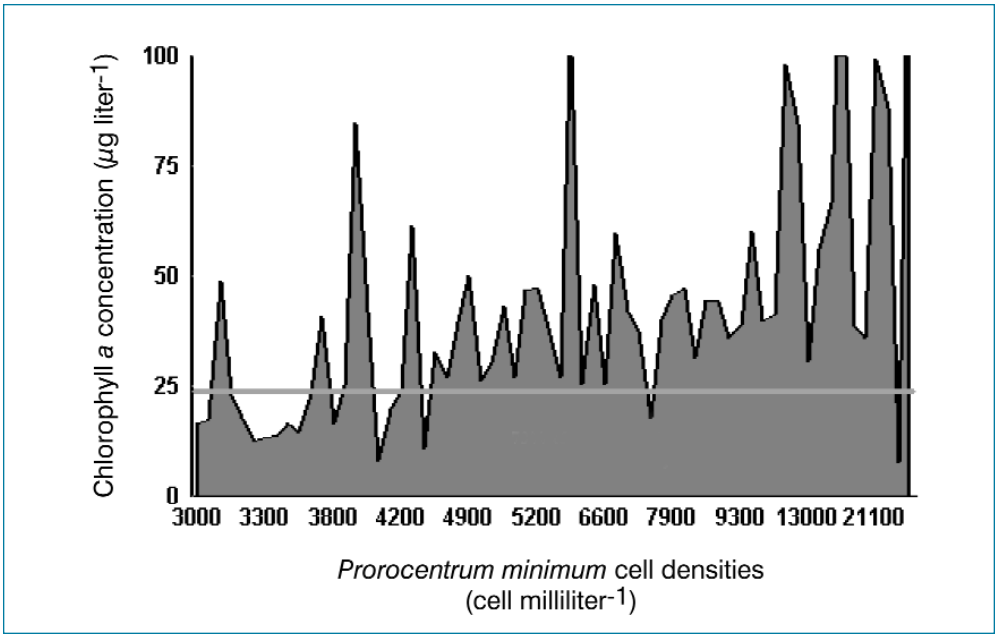


**Figure V-10.** Enlarged version of Figure V-9 focused on the *Prorocentrum minimum* cell densities and associated chlorophyll *a* concentrations above the 3,000 cells milliliter$^{-1}$ threshold. Over 73 percent of the 64 observed chlorophyll *a* concentrations are greater than 25 µg milliliter$^{-1}$.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

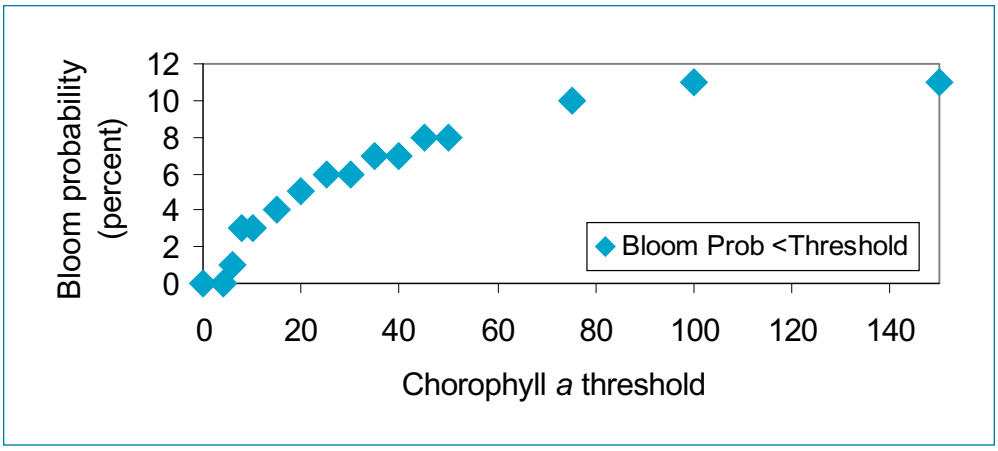


**Figure V-11.** Spring (March-May) *Prorocentrum minimum* bloom probability, 1985–2002, measured as a percent of the samples exceeding the 3,000 cells milliliter$^{-1}$ threshold plotted against each sample's measured chlorophyll *a* concentration.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database
http://www.chesapeakebay.net/data

This taxon's effects are fairly well-documented, although the toxin content of different strains seems to be variable. The consumer organism that has been tested, *Crassostrea virginica*, the Eastern oyster, is important economically and ecologically as a filter-feeder. The associated chlorophyll *a* threshold is well-defined based upon the historic data from the Chesapeake Bay water quality monitoring program. Both data sets used in these analyses independently defined a relatively narrow range of conditions that separate the bloom from non-bloom regions of the chlorophyll *a* gradient.

Toxin content of different strains of *P. minimum* varies. Although widespread anecdotal evidence suggests that oyster larvae are negatively affected by blooms of *P. minimum* in the Chesapeake Bay, no direct evidence supports this hypothesis. The value chosen as a threshold for impairment is extrapolated from several laboratory studies and does not pertain directly to the strains of *P. minimum* found in the Chesapeake Bay.

**Research Needs.** Clearly it is necessary to determine the toxin content and conditions conducive to toxin production of the Chesapeake Bay *P. minimum* strain. In addition, grazing studies using water from different bloom sites or cultures isolated from various bloom sites in the Bay would provide pertinent information on the potential effects of this dinoflagellate on oyster larvae and other filter-feeding organisms. These studies thus would be aimed at determining not only a threshold for cell densities but also an associated range of chlorophyll *a* concentrations.

Links between toxicity and density deserve further work as well as a determination of the frequency with which toxic strains of *P. minimum* occur in the Chesapeake

Bay. Defining density relationships to light field requirements is likely to be a fertile area of analysis with this species, since its distribution coincides with spring growth of underwater bay grass beds in the mesohaline portion of the Chesapeake Bay.

Additional studies also are needed to determine if adverse effects of *P. minimum* occur in mixed algal diets. Finally, research is needed to determine effective management strategies for *P. minimum*. This will require a better understanding of the physical, biological and chemical controls on blooms of this taxon.

***Cochlodinium heterolobatum.*** This species forms intense blooms in warm months at the mouth of the York River and in the lower Chesapeake Bay (Mackiernan 1968; Zubkoff and Warriner 1975; Zubkoff et al. 1979; Marshall 1995). The bloom appears to begin at the mouth of the York River and is dispersed into the lower Chesapeake Bay from this point of origin and has been documented to affect ~ 215 $km^2$ in this part of the estuary (Marshall 1995). In this bloom area, cell densities were generally >1,000 cells $milliliter^{-1}$. Laboratory studies indicated a threshold concentration of ~ 500 cells $milliliter^{-1}$ resulted in mortality of oyster larvae (Ho and Zubkoff 1979). Further analysis of these data published by Zubkoff et al. (1979) yielded a chlorophyll *a* concentration of approximately 50 $\mu g$ $liter^{-1}$ at the threshold concentration of 500 cells $milliliter^{-1}$.

***Karlodinium micrum.*** *K. micrum*, synonymous with *Gyrodinium galatheanum* Braarud and *Gymnodinium micrum*, and historically reported as *Gyrodinium estuariale* in Maryland, is a common and widespread estuarine dinoflagellate in the Chesapeake Bay. Recent work by Deeds et al. (2002) has demonstrated that Maryland isolates of the dinoflagellate produced toxins with hemolytic, cytotoxic and ichthyotoxic properties. Initial studies indicate *K. micrum* may produce sufficient toxin to result in fish mortality in the field at cell densities of 10,000 to 30,000 cells $milliliter^{-1}$ and above (Deeds et al. 2002; Goshorn et al. 2003).

*K. micrum* is present year-round in the water column of the Chesapeake Bay. Peak monthly average abundances occur between April and September, favoring mesohaline salinities and elevated concentrations showing a preferred temperature of 21.5-27.5°C (Goshorn et al. 2003). Between 1985 and 2002, there were 1,312 samples from approximately 7,000 collected from Maryland's Chesapeake Bay that contained *K. micrum*. Mean density of the cell counts when present was 589 cells $milliliter^{-1}$, with nine samples (0.7 percent) exceeding the potential lethal threshold of 10,000 cells $milliliter^{-1}$ (Goshorn et al. 2003).

A historical review of a fish kill database maintained by the Maryland Department of the Environment showed eight events where kills were associated with the presence of potential acutely lethal concentrations of *K. micrum* (Goshorn et al. 2003). Cell concentrations in these near-shore creek environments not sampled in routine monitoring provided a range in concentrations from 10,270 to 322,968 cells $milliliter^{-1}$. Deeds et al (2002) however, also report on fish kills in aquaculture ponds on the lower Eastern Shore of Maryland that implicate *K. micrum* in fish kill events

with densities > 10,000 cells milliliter$^{-1}$. Kempton et al. (2002) related *K. micrum* to a South Carolina fish kill in a brackish water retention pond with evidence of toxicity and concentrations of 64,000-68,000 cells milliliter$^{-1}$. Nielsen (1993) showed that juvenile cod exposed to 100,000 cells milliliter$^{-1}$ of *K. micrum* resulted in death within 2 days.

A subset of the *K. micrum* (n=684) database had chlorophyll *a*-associated data. *K. micrum* was more likely to exceed 2,000 cells milliliter$^{-1}$ when chlorophyll *a* concentrations exceeded 10 $\mu$g liter$^{-1}$ in open-water habitat (Figure V-12). One count exceeded the 10,000 cells milliliter$^{-1}$ boundary and the associated chlorophyll *a* was 75 $\mu$g liter$^{-1}$. Kempton et al. (2002) found chlorophyll *a* concentrations of 117 $\mu$g liter$^{-1}$ in association with acutely lethal concentrations (64,000-68,000 cells milliliter$^{-1}$) of *K. micrum* at the South Carolina fish kill site. Variance in *K. micrum* cell counts increases with increasing chlorophyll *a* measures suggesting the risk of acutely toxic levels coincidentally increasing with the rise in chlorophyll *a* out to 75 $\mu$g liter$^{-1}$. However, the present Maryland data set does not presently demonstrate a clear threshold level for chlorophyll *a* with acutely toxic boundary conditions of *K. micrum* densities.

**Strengths and Limitations.** *K. micrum* represents an abundant, relatively easy to identify potential harmful algal bloom species in the Chesapeake Bay. Maryland isolates from fish kill events have generated toxicity at many levels from cytotoxicity to hepatotoxicity and ichthyotoxicity. Lab results demonstrated acutely lethal levels of *K. micrum*. The aquatic life impairment associated with fish kills is clear.

Sublethal effects are essentially unknown. Concentration alone does not imply toxicity but co-occurring conditions that induce disintegration of the cells may be needed

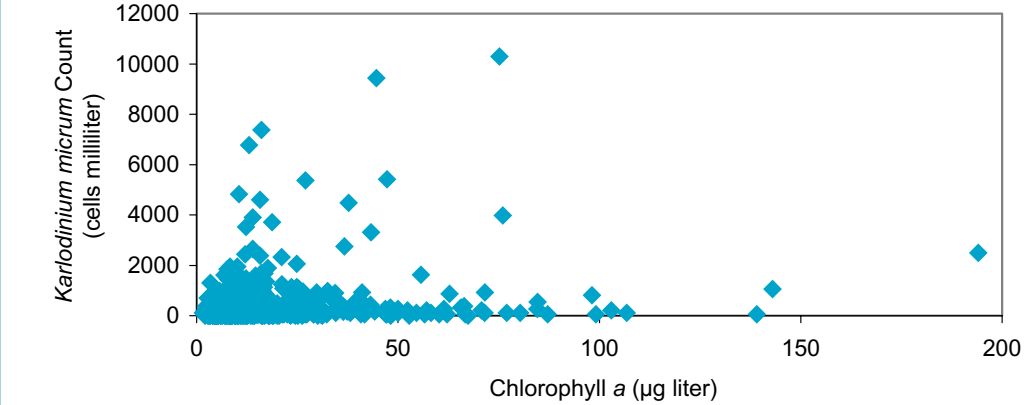


**Figure V-12.** *Karlodinium micrum* cell counts versus chlorophyll *a* concentrations in the Maryland portions of the Chesapeake Bay. A total of 684 samples are illustrated.

Source: Maryland Department of Natural Resources unpublished data.

in order for the toxins to be released (Deeds et al. 2002). The habitats where fish kills have been most commonly associated with potentially lethal densities of *K. micrum* are shallow-water and near-shore habitats, and small tributary systems (Goshorn et al. 2003), aquaculture facilities (Deeds et al. 2002) and brackish retention ponds (Kempton et al. 2002). To date, these habitats are not typical of areas routinely sampled by water quality monitoring programs of the Chesapeake Bay. Thus far, while the risk of acutely lethal concentrations increases with increasing chlorophyll *a*, only two instances are noted with chlorophyll *a* data at 75 $\mu$g liter$^{-1}$ (this chapter), 117 $\mu$g liter$^{-1}$ (Kempton et al. 2002) and > 10,000 cells milliliter$^{-1}$. Although the probability of elevated densities is higher when chlorophyll *a* exceeds 10 $\mu$g liter$^{-1}$, above this concentration there is no strong correlation between cell density and chlorophyll *a* concentration.

**Research Needs.** More detailed knowledge of the relationship between densities above the acute threshold boundary and chlorophyll *a* levels is needed from near-shore monitoring and fish kill responses to refine the critical range of chlorophyll *a* levels that we should avoid in managing for reducing levels of harmful algal blooms in the Chesapeake Bay. The sublethal effects of *K. micrum* on the environment is in an obvious area for further study. Understanding toxin concentration relationships of *K. micrum* under field conditions that result in cell disintegration enhancing the likelihood of toxin interaction with living resources also needs additional research. And it is necessary to better understand the physical, chemical and biological processes that control *K. micrum* blooms in order to develop even more effective management strategies.

## CHLOROPHYLL *A* CONCENTRATIONS CHARACTERISTIC OF TROPHIC-BASED CONDITIONS

Table V-8 categorizes, by trophic status, chlorophyll *a* concentrations that characterize desired (oligotrophic and mesotrophic) and stressed (eutrophic) ecological conditions in Chesapeake Bay open-water tidal habitats. These concentrations were drawn from scientific literature values related to trophic status, historically observed concentrations in the Chesapeake Bay and those characteristic of reference phytoplankton communities versus potentially harmful algal blooms.

Chlorophyll *a* concentrations characteristic of oligohaline conditions published by Ryding and Rast (1989), Wetzel (2001), Smith et al. (1999), Molvaer et al. (1997) and Novotny and Olem (1994) are listed first in Table V-8 in each salinity-regime specific row under the heading 'oligohaline conditions.' Seasonal mean chlorophyll *a* concentrations derived from Olson's analysis (2002) of the 1950s Chesapeake Bay mainstem chlorophyll *a* conditions using the same historical data set as Harding and Perry (1997) are listed next in each 'oligohaline conditions' salinity-regime specific row.

Mesotrophic conditions expressed as ranges of chlorophyll *a* concentrations characterized in the scientific literature by several authors (Ryding and Rast 1989; Wetzel

**Table V-8.** Summary of chlorophyll *a* concentrations reflecting trophic-based water quality, phytoplankton community and ecological conditions.

| Salinity Regime | Chlorophyll *a* Concentrations ($\mu$g liter$^{-1}$ | | | | | |
|---|---|---|---|---|---|---|
| | **Oligotrophic Conditions** | | **Mesotrophic Conditions** | | **Eutrophic Conditions** | |
| | Average or General Range | Peak Range | Average or General Range | Peak Range | Average or General Range | Peak Range |
| **Spring (March - May)** | | | | | | |
| Tidal-Fresh | 0.8 - 3.4[a]<br>0.3 - 3[b]<br><3.5[c]<br><4[e]<br>1.1[f] | 2.6 - 7.6[a] | 3.0 - 7.4[a]<br>2 - 15[b]<br>3.5 - 9[c]<br>4-10[e]<br>4.3[g]<br>15[i] | 8.9 - 29[a]<br>13.5[g] | 6.7 - 31[a]<br>10-500[b]<br>9-25[c]<br>>10[e]<br>6.7[h] | 16.9 - 107[a]<br>42.9[h]<br><33[i] |
| Oligohaline | 2.3[f] | | 9.6[g]<br>15[i] | 24.3[g] | 5.0[h] | 29.8[h]<br><33[i] |
| Mesohaline | 3.7[f] | | 5.6[g]<br>5[j] | 24.6[g] | 11.1[h] | 44.9[h]<br><25-30[j] |
| Polyhaline | <1[c]<br><2[d]<br>3.9[f] | | 1-3[c]<br>2 - 7[d]<br>2.9[g]<br>5[j] | 6.7[g] | 3-5[c]<br>>7[d]<br>9.1[h] | 18.0[h]<br><25-30[j] |
| **Summer (July - September)** | | | | | | |
| Tidal-Fresh | 0.8 - 3.4[a]<br>0.3 - 3[b]<br><4[e]<br>1.1[f] | 2.6 - 7.6[a] | 3.0 - 7.4[a]<br>2 - 15[b]<br>3.5 - 9[c]<br>4-10[e]<br>8.6[g] | 8.9 - 29[a]<br>15.9[g]<br>15[i] | 6.7 - 31[a]<br>10-500[b]<br>>10[e]<br>25.3[h] | 16.9 - 107[a]<br>62.1[h]<br>33[i] |
| Oligohaline | 2.0[f] | | 6.0[g] | 25.2[g]<br>15[i] | 17.1[h] | 60.5[h]<br>33[i] |
| Mesohaline | 4.4[f] | | 7.1[g]<br>5[j] | 14[g] | 12.2[h] | 52.5[h]<br><25-30[j] |
| Polyhaline | <1[c]<br><2[d] | | 1 - 3[c]<br>2 - 7[d]<br>4.4[g]<br>5[j] | 8.7[g] | 3-5[c]<br>>7[dc]<br>6.1[h] | 25.8[h]<br><25-30[j] |

[a]Ryding and Rast, 1989; [b]Wetzel, 2001; [c]Smith, 1998; [d]Molvaer et al., 1997; [e]Novotny and Olem, 1994; [f]Olson 2002; [g]Table V-7 this chapter; [h]Appendix F, Figure F-3 this volume; [i]*Microcystis aeruginosa* section this chapter; [j]*Prorocentrum minimum* section this chapter.

2001; Smith et al. 1999 and Novotny and Olem 1994) are listed first in each salinity-regime specific row first in Table V-8 under the 'mesotrophic conditions' column heading. The trophic status data shows a narrow range of chlorophyll *a* concentrations that characterize mesotrophic aquatic ecosystems (Table V-8). For freshwater areas, seasonal average chlorophyll *a* concentrations in mesotrophic systems should fall in the range of 2 to 15 $\mu$g liter$^{-1}$ with a mean around 7 $\mu$g liter$^{-1}$. In high-salinity marine ecosystems, mesotrophic status is characterized by seasonal average chlorophyll *a* concentrations from 1 to 7 $\mu$g liter$^{-1}$ with a mean around 3 $\mu$g liter$^{-1}$

The paired general and peak values that follow are the median and 95th percentile concentrations of chlorophyll *a* in waters supportive of the phytoplankton reference community. These chlorophyll *a* concentrations reflect conditions in which water clarity is sufficient for healthy algae and bay grasses growth and the concentrations of one or both of the critical nutrients are low enough to limit excess algal growth (e.g., 'best,' 'better' and sometimes the 'mixed better light' categories). The range of chlorophyll *a* concentrations that follow in the mesotrophic conditions' peak range column are those characteristic of algal communities not containing cell densities of *Microcystis aeruginosa* and *Prorocentrum minimum* exceeding thresholds above which adversely impact zooplankton and oyster communities, respectively.

The spring and summer chlorophyll *a* concentrations characterizing each of these salinity-based phytoplankton reference communities provide the most direct water quality measures of a more balanced phytoplankton assemblage (see Table V-7). Chlorophyll *a* concentrations characteristic of the phytoplankton reference communities, which straddle the boundary between mesotrophic and eutrophic (Table V-8) conditions, are higher than those observed in the 1950s (see Table V-5) which reflect oligotrophic conditions.

Ryding and Rast (1989); Wetzel (2001); Smith et al. (1999); Molvaer et al. (1997) and Novotny and Olem (1994) have all published ranges of chlorophyll *a* concentrations characterizing eutrophic conditions listed first in Table V-8 under the 'eutrophic conditions' in each salinity regime specific row. The paired general and peak range values listed next in each row are the median and 95$^{th}$ percentile concentrations, respectively, of chlorophyll *a* in waters categorized as 'poor' during the process for characterizing the reference phytoplankton communities (Appendix F, Figure F-1). These chlorophyll *a* concentrations reflect water quality conditions in which both critical nutrients (nitrogen and phosphorus) exceed the empirically determined growth-limiting thresholds for algae, and water clarity is not sufficient for healthy algae or underwater bay grasses growth. The range of chlorophyll *a* concentrations that follow in the eutrophic conditions' peak range column are those characteristic of harmful algal blooms exceeding cell density thresholds derived from literature-based values for *M. aeruginosa* and *P. minimum*.

Trends in chlorophyll *a* concentrations observed over the past fifty years indicate that water quality in many tidal habitats of the Chesapeake Bay has changed from oligotrophic-mesotrophic to eutrophic and even highly eutrophic. Chlorophyll *a*

concentrations in the highly saline waters at the mouth of the Chesapeake Bay were characteristic of oligotrophic marine conditions in the 1950s (<2 $\mu$g liter$^{-1}$). They now reflect mesotrophic conditions, with a mean concentration of 5.6 $\mu$g liter$^{-1}$ and maxima exceeding 18 $\mu$g liter$^{-1}$. Chlorophyll *a* concentrations in the middle and upper Chesapeake Bay mainstem were indicative of mesotrophic conditions during the 1950s, with mean concentrations well below 7 $\mu$g liter$^{-1}$. They now reflect eutrophic conditions, with mean chlorophyll *a* concentrations above 7 $\mu$g liter$^{-1}$ in mid-Bay waters and above 10 $\mu$g liter$^{-1}$ in the tidal-fresh, upper Chesapeake Bay waters. Peak concentrations often exceed 30 $\mu$g liter$^{-1}$.

Eutrophic conditions also characterize all the major Bay tidal tributaries. Smaller, urbanized watershed tidal tributaries with poor flushing, such as the Back River, experience highly eutrophic conditions. Excessive nutrient and sediment loadings are the cause of the shift towards eutrophic conditions in the Chesapeake Bay's tidal waters. The results are more deep-water habitats prone to anoxia, further losses of underwater bay grasses and more extensive harmful algal blooms.

Decisions on what chlorophyll *a* value should be applied to protect a designated use against a specific impairment should be made at local or regional water-body scales. More specific implementation procedures and guidelines are provided in Chapter VI.

## CHLOROPHYLL *A* CONCENTRATIONS PROTECTIVE AGAINST WATER QUALITY IMPAIRMENTS

### Contributions to Reduced Light Levels

Phytoplankton attenuate or reduce the amount of light reaching the leaves of bay grasses by absorbing or scattering the light (see Chapter IV). Additional reductions in light occur at the leaf surface, as the remaining light must pass through algal epiphytes and suspended solids settled there (see Appendix J). Chesapeake Bay scientists have developed a diagnostic tool to calculate the relative contributions of chlorophyll *a* versus total suspended solids to reducing light penetration through the water column (Batiuk et al. 2000; Gallegos 2001).

**Water-Column Diagnostic Tool.** Water-column attenuation of light measured by the light attenuation coefficient $K_d$ can be divided into contributions from four sources: water, dissolved organic matter (color), chlorophyll *a* and total suspended solids. The basic relationships can be expressed in a series of simple equations, which were combined to produce the equation for the percent water-column diagnostic tool (Gallegos 2001). The resulting equation calculates linear combinations of chlorophyll *a* and total suspended solids concentrations that just meet the percent light-through-water (PLW) criteria for a particular water-column depth at any site or season in the Chesapeake Bay and its tidal tributaries. This diagnostic tool can also be used to consider management options for improving water quality conditions when the water clarity criteria are not currently met (see Chapter VII).

**Derived Chlorophyll *a* Concentrations.** A finite yet significant number of possible chlorophyll *a* concentrations exist that support attainment of the percent light-through-water criteria, depending on the ambient total suspended solids concentration and water-column application depth. For the purpose of deriving chlorophyll *a* criteria applicable across a wide array of tidal habitats, total suspended solids concentrations were assumed to range from 5 to 20 mg liter-1 (Table V-9). The

**Table V-9.** Chlorophyll a concentrations ($\mu$g liter$^{-1}$) that reflect attainment of the Chesapeake Bay water clarity criteria given a range of total suspended solids concentrations and shallow-water application depths. Areas in gray indicate exceedance of the water clarity criteria.

| Total Suspended Solids (mg liter$^{-1}$) | Tidal-Fresh and Oligohaline | | | Mesohaline and Polyhaline | | |
|---|---|---|---|---|---|---|
| | Water-Column Depth (meters) | | | | | |
| | 0.5 m | 1 m | 2 m | 0.5 m | 1 m | 2 m |
| 5 | 199 | 71 | 9 | 122 | 34 | |
| 10 | 171 | 43 | | 95 | 8 | |
| 15 | 144 | 16 | | 68 | | |
| 20 | 116 | | | 42 | | |

water-column application depths were set at 0.5, 1 and 2 meters to reflect the range of shallow-water designated use boundary depths (U.S. EPA 2003).

Chlorophyll *a* concentrations of 16 $\mu$g liter$^{-1}$(tidal-fresh and oligohaline) and 8 $\mu$g liter$^{-1}$ (mesohaline and polyhaline) were identified as protective against negative water clarity effects. Values were selected as they corresponded with total suspended solids concentrations in the range of 10-15 mg liter$^{-1}$, which were previously identified as habitat requirements for underwater bay grasses (Batiuk et al. 1992; Dennison et al. 1993; Stevenson et al. 1993) and the 1-meter shallow-water application depth (mid-depth between 0.5 and 2 meters; U.S. EPA 2003).

**Strengths and Limitations.** The assignment of water clarity criteria application depths and the selection of appropriate total suspended solids ambient concentration assumptions should be made on a Chesapeake Bay Program segment by segment basis. These values will vary on temporal and spatial scales. In some regions, chlorophyll *a*/algal biomass is a negligible component of the total light attenuation, compared with non-algal solids. In such regions, chlorophyll *a* reductions would not be expected to significantly improve water clarity.

## Contribution to Low Dissolved Oxygen Conditions

Algae that are not consumed by zooplankton, oysters and fish becomes fuel, through its breakdown by the microbial community, for reducing dissolved oxygen levels. Seasonal chlorophyll *a* concentrations (e.g., algal biomass) that lead to desired

dissolved oxygen conditions can be estimated using the Chesapeake Bay water quality model.

The Chesapeake Bay watershed model and the 13,000-cell version of the Chesapeake Bay water quality model can be used to determine the seasonal average chlorophyll *a* concentrations associated with estimated nutrient and sediment reductions needed to attain the Chesapeake Bay dissolved oxygen criteria.

The model-simulated chlorophyll *a* levels were extracted from the nutrient and sediment loading reduction allocation scenario which attained the Chesapeake Bay dissolved oxygen criteria across all designated uses and tidal waters. The simulated chlorophyll *a* concentrations were compiled for spring (March-May) and summer (July-September) by salinity regime—tidal-fresh, oligohaline, mesohaline and polyhaline. The seasonal mean chlorophyll *a* concentration for each season and salinity regime combination was then calculated (Table V-10). See Chapter VI for details on how the Chesapeake Bay water quality model and Chesapeake Bay water quality monitoring results have been integrated for assessing criteria attainment under various management scenarios in support of setting loading allocations.

**Strengths and Limitations.** Like the water clarity criteria, the chlorophyll *a* concentrations that are needed to attain the dissolved oxygen criteria are expected to vary over temporal and spatial scales. Table V-10 shows the general relationship between chlorophyll *a* concentrations and attainment of the dissolved oxygen criteria. Depending on their location in the Chesapeake Bay system and hydrologic and hydrodynamic factors, individual segments or tributaries may exceed these concentrations without experiencing dissolved oxygen-related impairments.

**Table V-10.** Model-simulated seasonal mean and salinity regime-specific chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) estimated to characterize conditions supporting attainment of the Chesapeake Bay dissolved oxygen criteria.

| Season | Tidal-Fresh | Oligohaline | Mesohaline | Polyhaline |
|---|---|---|---|---|
| **Spring** | 4 | 5 | 6 | 5 |
| **Summer** | 12 | 7 | 5 | 4 |

## METHODOLOGIES FOR DERIVING WATERBODY-SPECIFIC CHLOROPHYLL *A* CRITERIA

### Water Clarity Impairment-Based Methodology

Regional and segment-specific chlorophyll *a* criteria can be derived to protect against water clarity impairments by applying the water-column diagnostic tool described previously. When applied to local and regional tidal waters, more site-specific assumptions about existing or anticipated ambient total suspended solids

concentrations and the shallow-water bay grasses designated use boundary depths can be factored into the derivation of the chlorophyll *a* criteria.

## Dissolved Oxygen Impairment-Based Methodology

Region-specific chlorophyll *a* concentrations can be derived by applying the Chesapeake Bay water quality model and analyzing the segment-specific results. Confidence in the derived chlorophyll *a* criteria can be increased by focusing on those Chesapeake Bay Program segments that are the principal contributors to low dissolved oxygen conditions due to an excess production of unconsumed algae.

## Nuisance Bloom-Based Methodology

Regional and segment-specific chlorophyll *a* targets can be derived using studies—either user perception surveys or algal condition assessments—to identify chlorophyll *a* concentrations that protect against nuisance blooms.

**User Perception Surveys.** User perception surveys can be conducted to rate a user's satisfaction with a water body's color, clarity and overall appearance. Surveys have been successfully applied in lake settings by several states, including Vermont and Minnesota. User perception surveys require careful design and their form depends on the type of water body and its uses. All such studies should include certain elements:

1. Surveys should be conducted in conjunction with water quality and phytoplankton monitoring to allow correlation of user perceptions with ambient conditions.
2. Commercial and recreational users should be targeted for the survey.
3. Questions should be worded to avoid bias.
4. Questions should focus on present, specific conditions rather than on general perceptions of the Chesapeake Bay's water quality.
5. Surveys should be conducted under a variety of water quality and sky conditions, and under a range of chlorophyll *a* and clarity conditions.
6. Surveys should be conducted in conjunction with objective, scientific assessments of algal conditions in the water body, as described below.

Vermont and Minnesota used lake user surveys to identify specific total phosphorus, chlorophyll *a* or Secchi disk values at which algal nuisances and impairment of recreation were perceived by the public (Heiskary and Walker 1988; Smeltzer and Heiskary 1990; North American Lake Management Society 1992). Using the results of a survey on physical appearance and recreation potential, Smeltzer and Heiskary (1990) defined the statistical relationships between eutrophication-related water

quality variables (Secchi and chlorophyll *a*) and user perceptions of lake quality in Minnesota and Vermont.

In Minnesota, surveyors calibrated user response by determining Secchi depth and chlorophyll *a* levels that correspond to perceived nuisance conditions or impairment of water uses. A nonparametric procedure was used to cross-tabulate the water quality measurements against the user categories. Results showed a distinct contrast between observations of 'definite algae' and 'high algae' for chlorophyll *a* measurements. Also, 'impaired swimming' and 'no swimming' ratings generally had chlorophyll *a* levels exceeding 20-40 $\mu$g liter$^{-1}$ (Heiskary and Walker 1988). In Minnesota some distinct ecoregional patterns in user perception emerged, whereby expectations were much greater in the deeper lakes of the northern forested region (similar to Vermont) as compared to the shallow prairie lakes of southern Minnesota.

The final steps necessary for setting chlorophyll *a* criteria include specifying the nuisance criterion (e.g., extreme chlorophyll *a* >30 $\mu$g liter$^{-1}$) or recreation potential and the acceptable risk level (i.e., probability that nuisance condition will be encountered 1 percent). Although Minnesota has not yet adopted total phosphorus or chlorophyll *a* criteria into water quality standards, the state used the methodology as a basis for setting lake management goals for total phosphorus. The various chlorophyll *a* and Secchi depth thresholds can be related to total phosphorus based on empirical relationships (e.g., total phosphorus and frequency of various levels of chlorophyll *a*) as noted in Heiskary and Walker (1988).

**Algal Condition Assessments.** Algal condition assessments involve qualitative descriptions and ordinal ratings of algal conditions by monitoring personnel. These constitute the 'scientific' version of the user perception survey. Qualitative information to be recorded includes the presence or absence of floating algae, its color, odor, etc. As with user perception surveys, algal condition assessment should be performed in conjunction with water quality and phytoplankton monitoring. It is highly recommended that states develop and apply standard indices for use with algal condition assessments. For example, Table V-11 provides an example developed for coastal waters in Oregon.

Algal condition assessments should be conducted by trained scientists or technicians. The more highly trained the personnel, the more detailed information can be collected on the size, texture and density of blooms. States that decide to pursue this approach should consider adding algal assessments to their existing Chesapeake Bay and tidal tributary monitoring programs. Ideally, user perception surveys and algal condition assessments would be conducted in tandem. However, algal condition assessments will have some utility for setting chlorophyll *a* targets independent of user perception surveys. It is expected that surveys and assessments would result in different chlorophyll *a* targets for different salinity regimes. For example, bright-green algae that form surface scums (e.g., *M. aeruginosa*) in some tidal freshwater segments might be more perceptible at lower chlorophyll *a* concentrations than brownish, more dispersed blooms.

**Table V-11.** Example of an algal condition index.

| Algal Index Value | Category | Description |
|---|---|---|
| 0 | Clear | Conditions vary from no algae to small populations visible to the naked eye. |
| 1 | Present | Some algae visible to the naked eye but present at low to medium levels. |
| 2 | Visible | Algae sufficiently concentrated that filaments or balls of algae are visible to the naked eye. May be scattered streaks of algae on water surface. |
| 3 | Scattered Surface Blooms | Surface mats of algae scattered. May be more abundant in localized areas if winds are calm. Some odor problems. |
| 4 | Extensive Surface Blooms | Large portions of the water surface covered by mats of algae. Windy conditions may temporarily eliminate mats, but they will quickly redevelop as winds become calm. Odor problems in localized areas. |

Source: Coastnet, 1996, *Sampling Procedures: A Manual for Estuary Monitoring*, prepared for the Coastnet Water quality Monitoring Project administered by the Oregon State University Extension Sea Grant Program, http://secchi.hmsc.orst.edu/coastnet/manual/index.html.

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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 = $100\exp(-K_dZ)$, 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 $K_d = 1.45/\text{Secchi depth}$.

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.

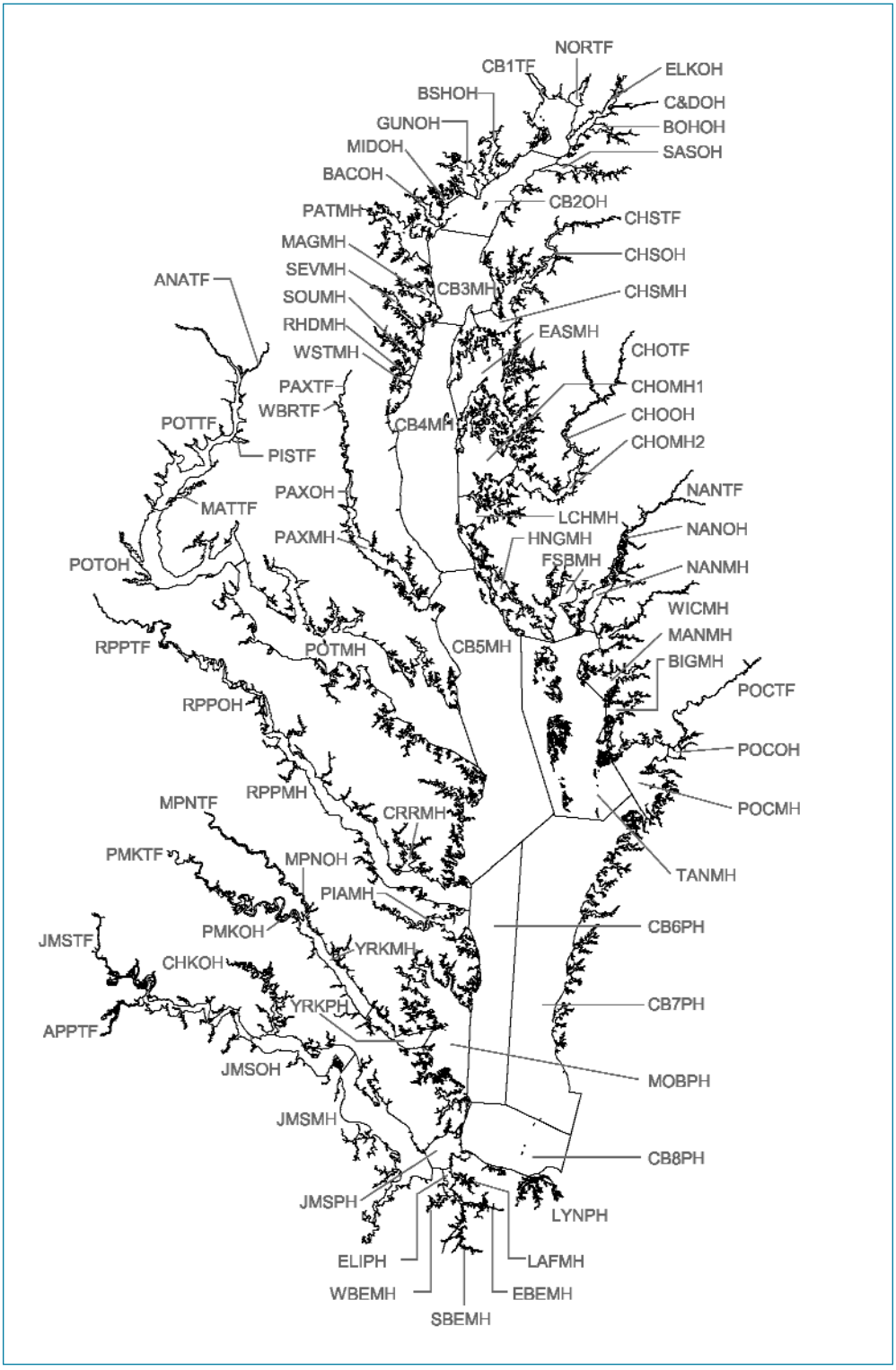


**Figure VI.** The geographical location of the 78 Chesapeake Bay Program segments.

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 loca-

tions 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 ($\mu$g 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).

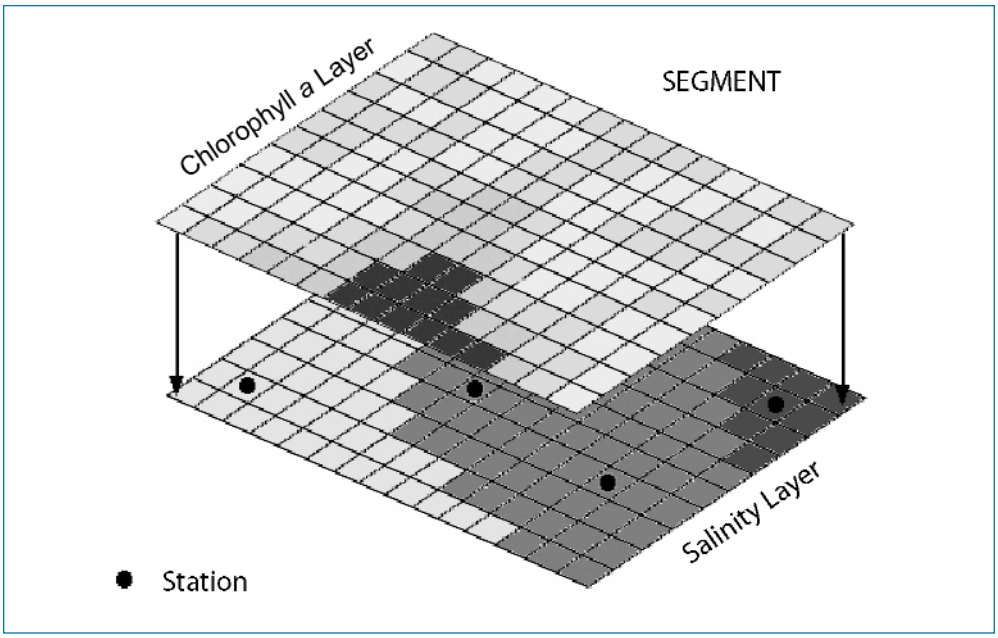


**Figure VI-3.** Chlorophyll *a* concentration values estimated for each interpolator cell are compared to the appropriate criterion value on a cell-by-cell basis to determine the spatial extent of exceedance.

## 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. CALCULATATION 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.

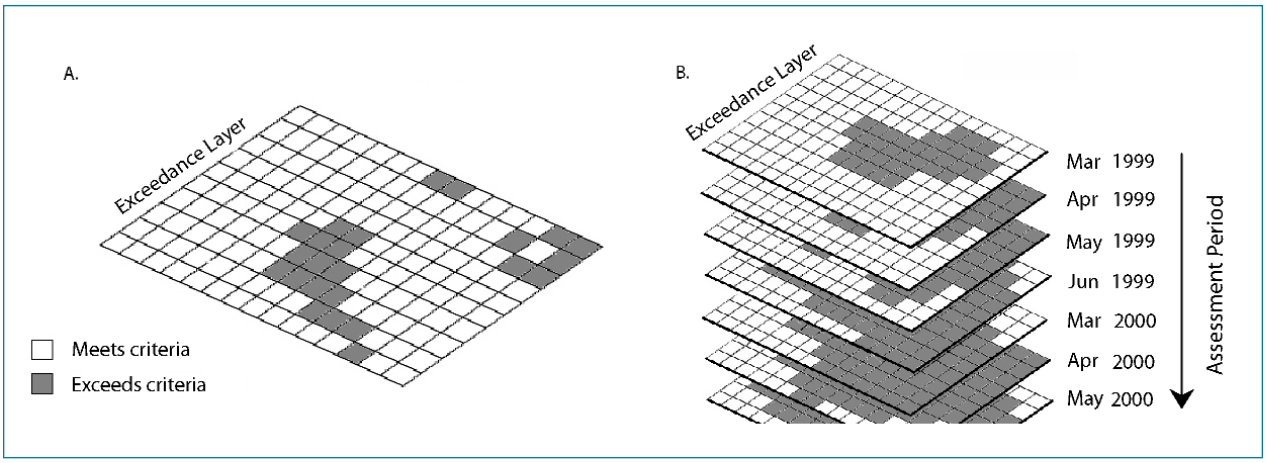


**Figure VI-4.** For a given sampling event, cells that exceed the criterion are determined by comparing the interpolator estimated water quality value in each cell (e.g., chlorophyll *a*) to the appropriate criterion value (a) as in Figure VI-3. The same process is repeated for each sampling event through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

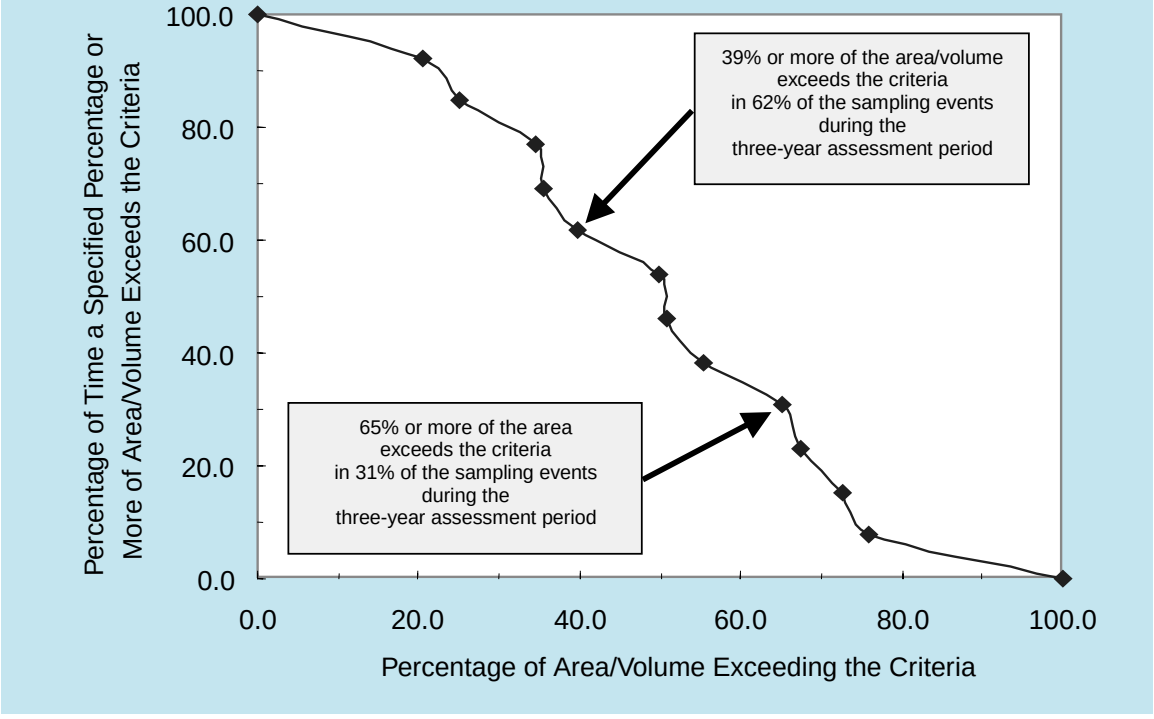


**Figure VI-7.** The horizontal axis is the spatial extent of criteria exceedance based on monitoring data extrapolated using spatial interpolation. The vertical axis is the cumulative frequency of criteria exceedance for the monitoring events conducted during the assessment period.

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

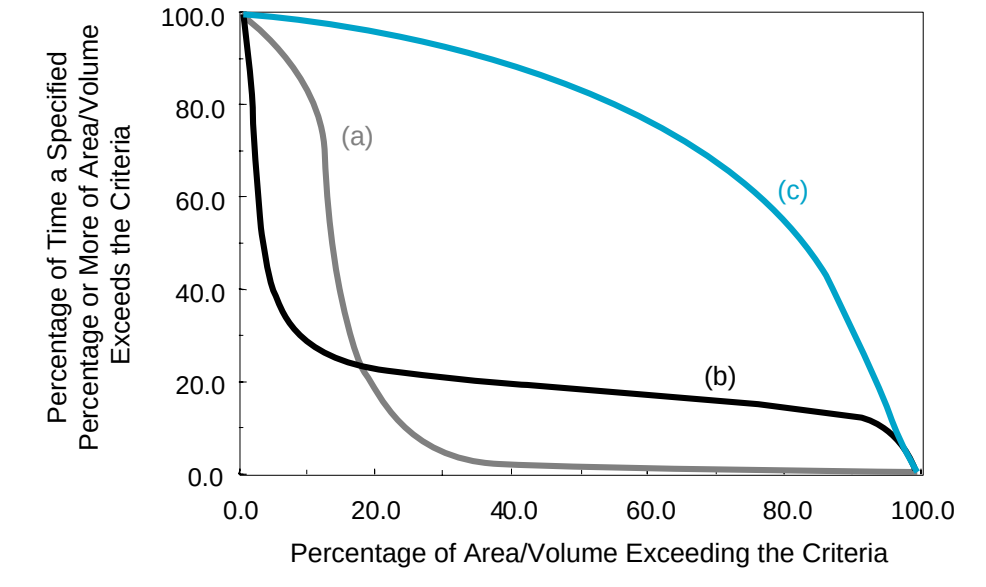


**Figure VI-8.** Use of cumulative frequency distribution to characterize patterns of water quality criteria exceedance. Curve (a) indicates that criteria are chronically exceeded in a relatively small portion of the spatial unit. Curve (b) indicates that criteria are exceeded over a large portion of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

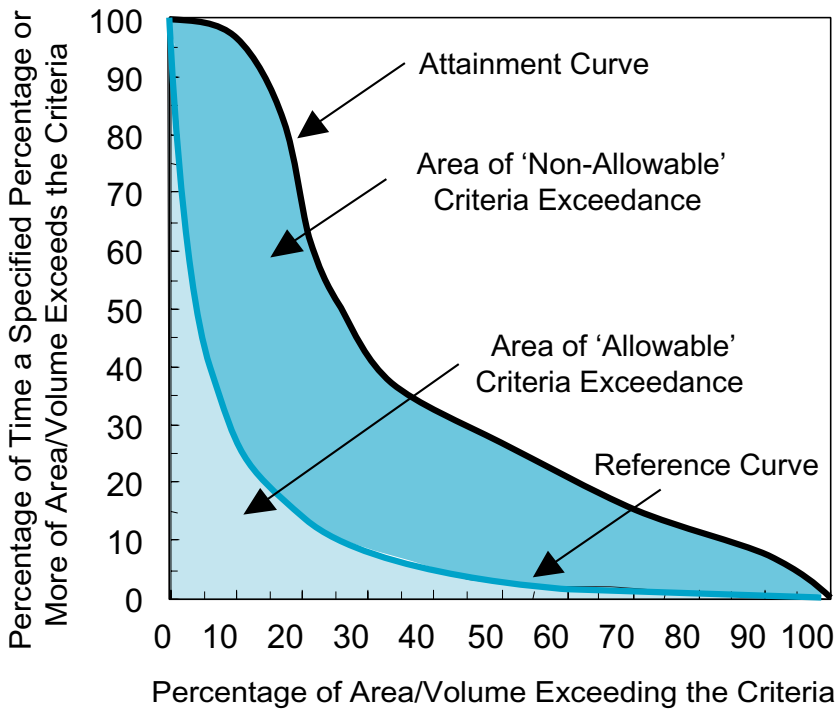


**Figure VI-9.** Light area reflects amount of 'allowable' criteria exceedance defined as the area under the reference curve (light line). Dark area reflects the amount of 'non-allowable' criteria exceedance defined as the area between the attainment curve (black line) and the reference curve.

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

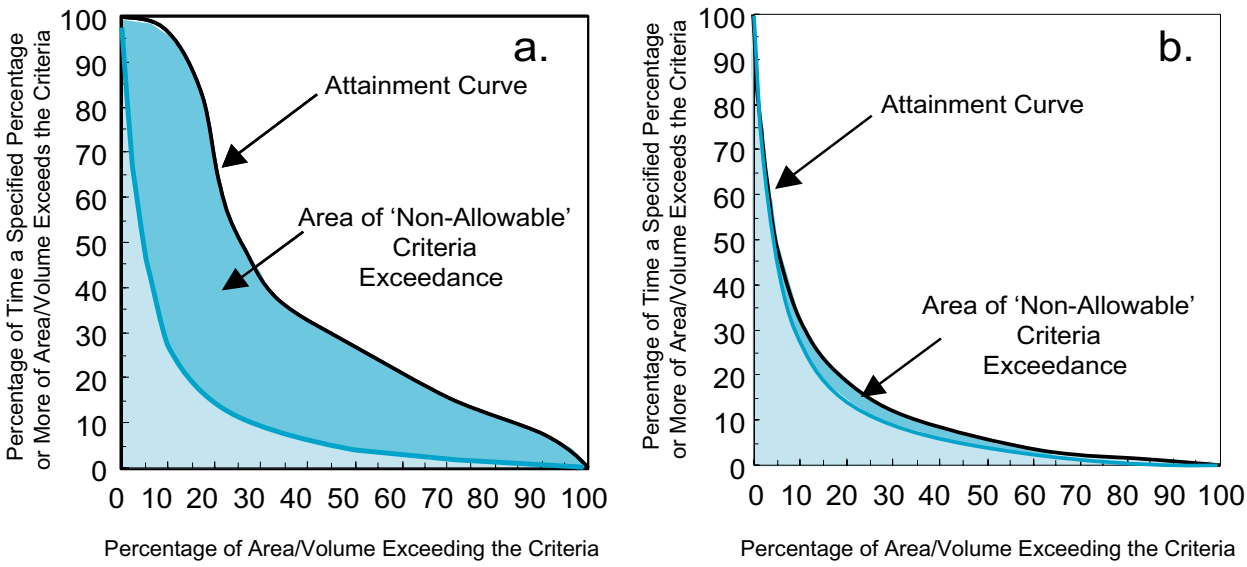


**Figure VI-10.** Light area reflects amount of 'allowable' criteria exceedance defined as the area under the reference curve (light line). Dark area reflects the amount of 'non-allowable' criteria exceedance defined as the area between the attainment curve (black line) and the reference curve.

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.

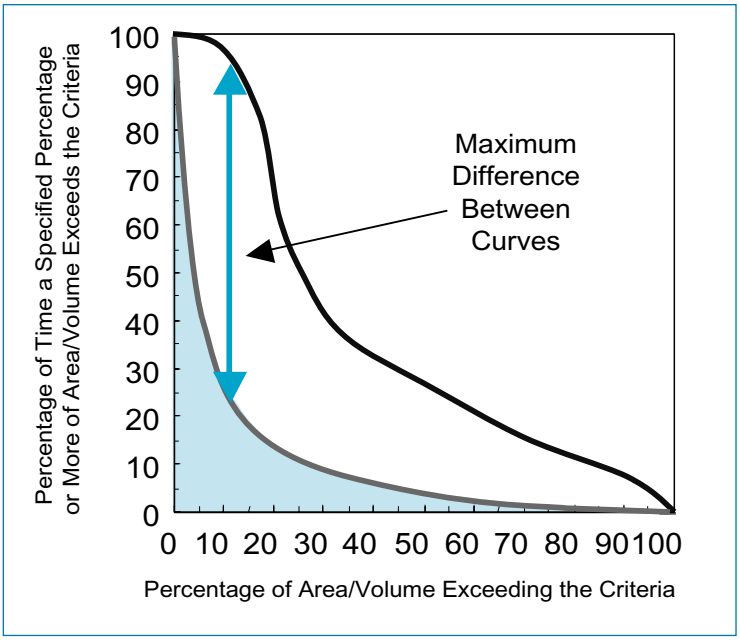


**Figure VI-11.** Illustration of the basis of the Kolmogorov-Smirnov statistical test for identifying statistically significant differences between cumulative density functions. In this case, the test is applied to identify statistically significant differences between the reference and attainment curves.

## 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

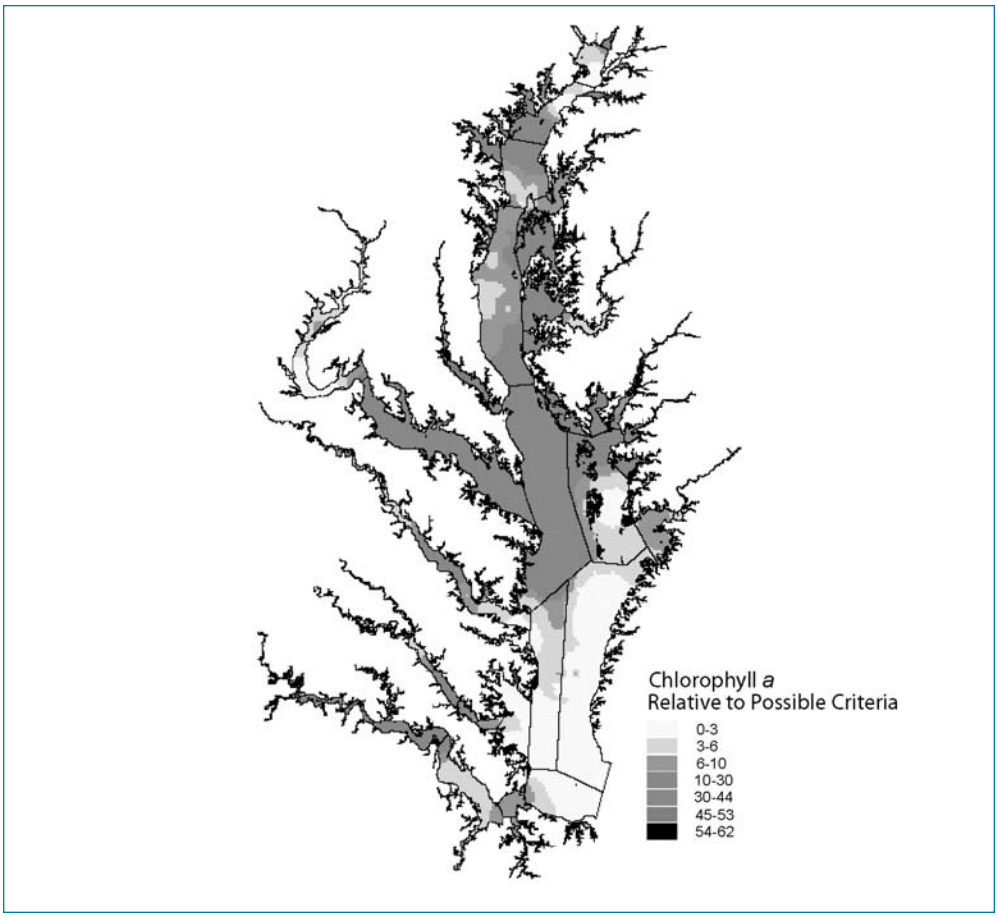


**Figure VI-12.** Example plot of chlorophyll *a* concentration ($\mu$g liter$^{-1}$) estimates generated through spatial interpolation for purposes of evaluating the magnitude of criteria exceedance.

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

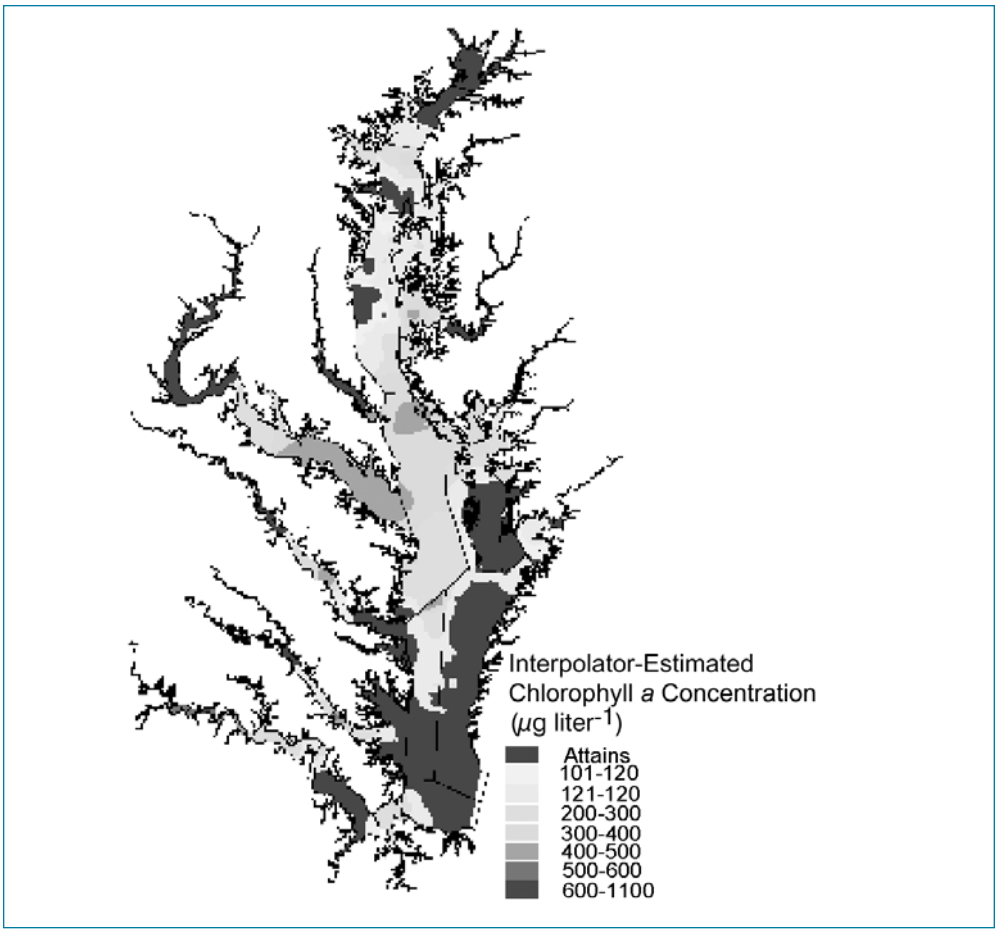


**Figure VI-13.** Example plot of chlorophyll *a* concentration ($\mu$g liter$^{-1}$) estimates generated through spatial interpolation, expressed as a percentage of a possible spring season criteria value, for purposes of evaluating the magnitude of criteria exceedance.

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).

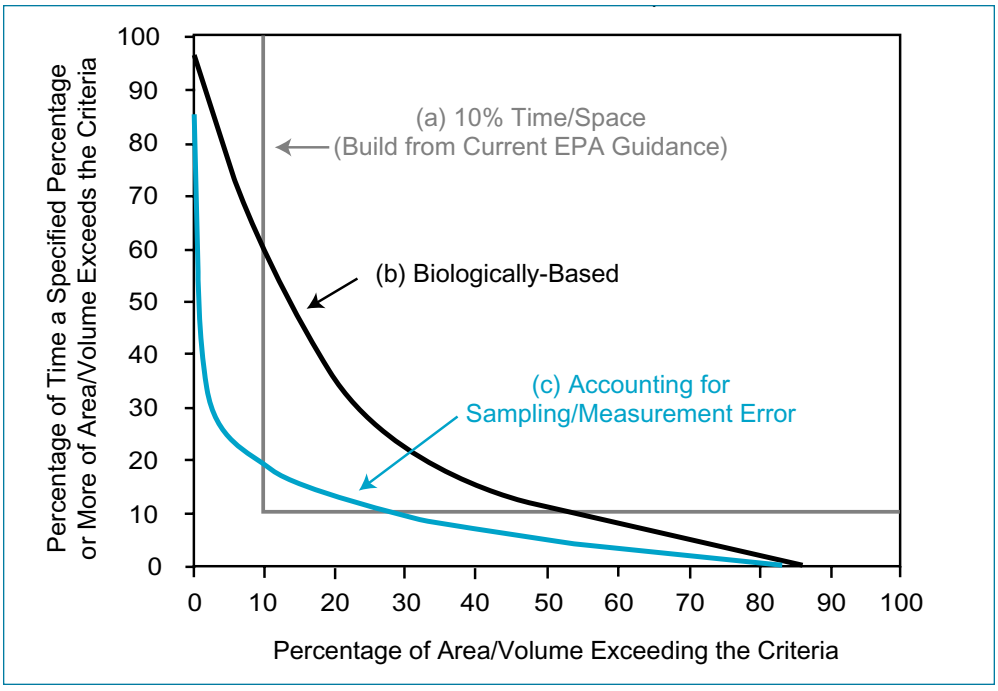


**Figure VI-14.** Three possible options for setting reference curves for application to the cumulative frequency distribution approach for defining criteria attainment: (a) fixed percentages based on policy decisions; (b) biological effects-based empirical field or laboratory data and; (c) observed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

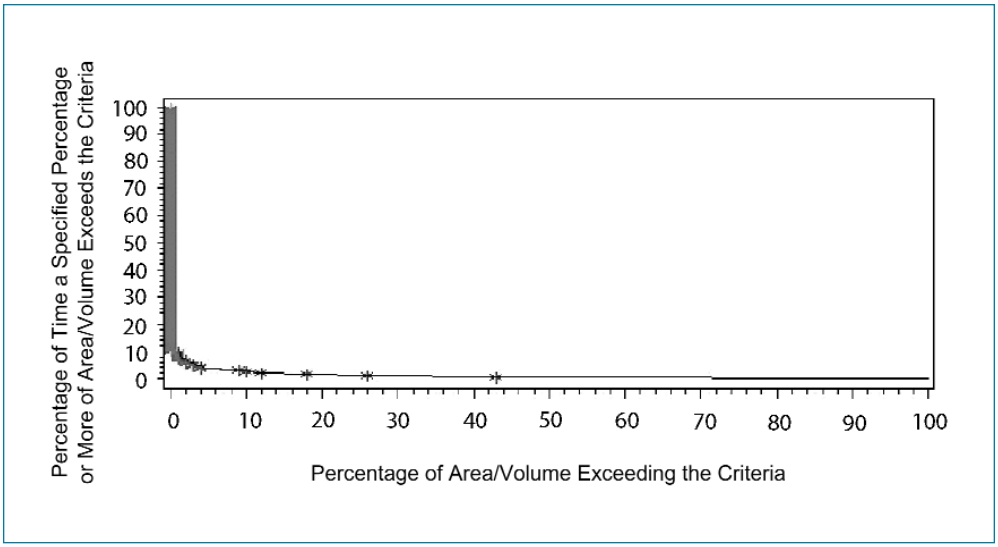


**Figure VI-15.** Initial attempt at developing a dissolved oxygen criteria reference curve for migratory, spawning and nursery habitat designated use areas using the 6 mg liter$^{-1}$ 7-day mean criterion assessed as a 30-day mean.

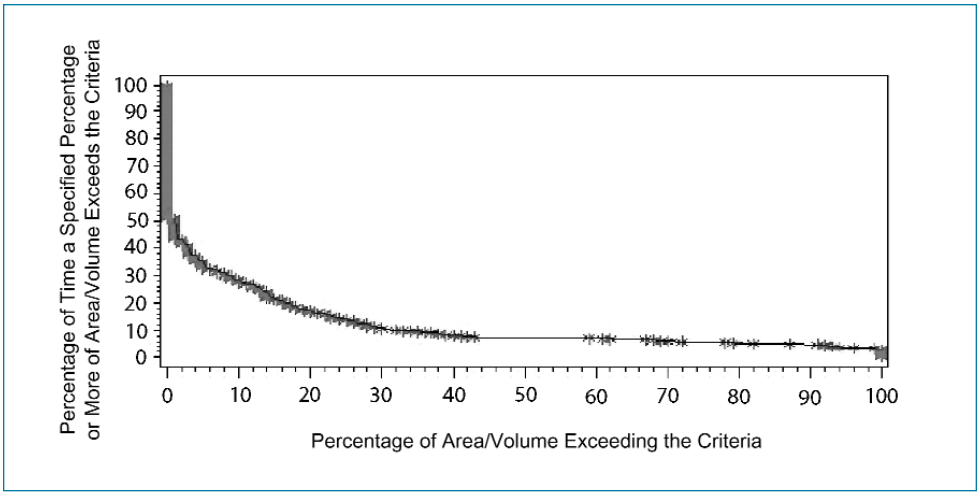


**Figure VI-16.** Dissolved oxygen criteria reference curve for defining criteria attainment in open-water designated use habitats.

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

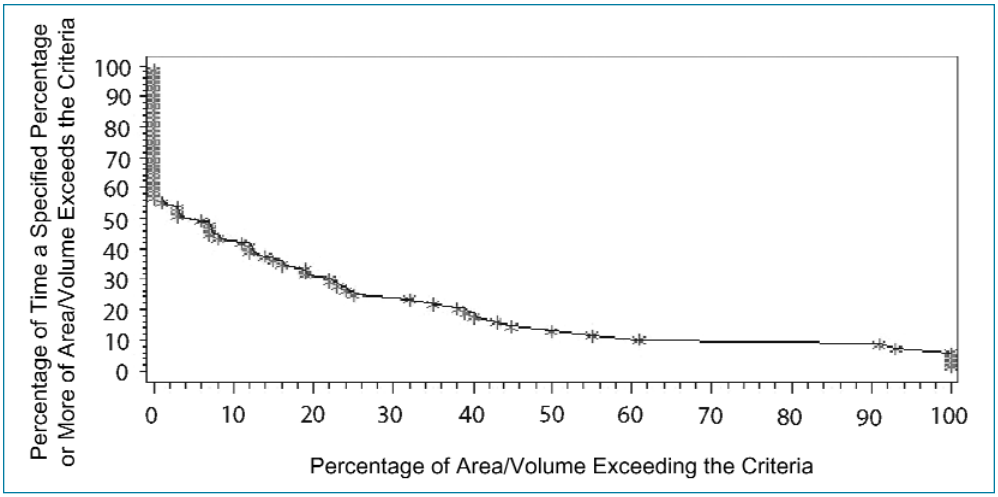


**Figure VI-17.** Dissolved oxygen criteria reference curve for defining criteria attainment in deep-water designated use habitats.

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

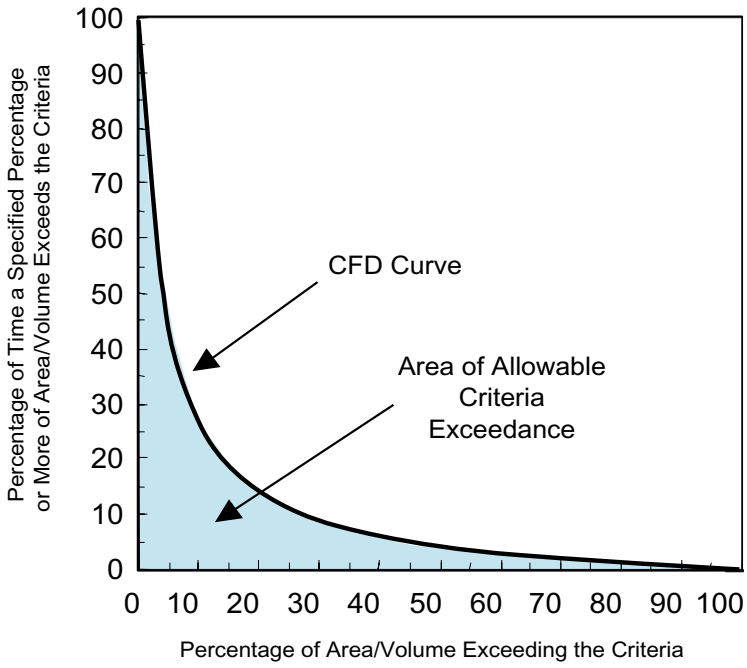


**Figure VI-18.** Cumulative frequency distribution curve in the shape of a hyperbolic curve that represents approximately 10 percent allowable exceedances equally distributed between time and space.

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 = $100\exp(-K_dZ)$, where Z is the target restoration depth and $K_d$, the coefficient of extinction, is estimated as $K_d = 1.45/\text{Secchi depth}$ (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. 152, for details). Appendix H also shows water clarity reference curves based strictly on growing season median assessments.

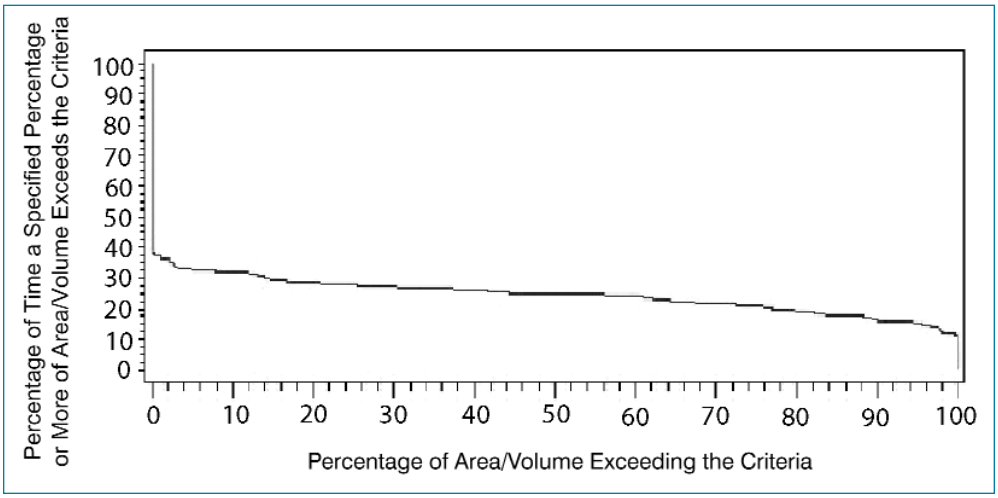


**Figure VI-19.** Water clarity criteria reference curve for defining criteria attainment in tidal-fresh/oligohaline shallow-water bay grass designated use habitats.

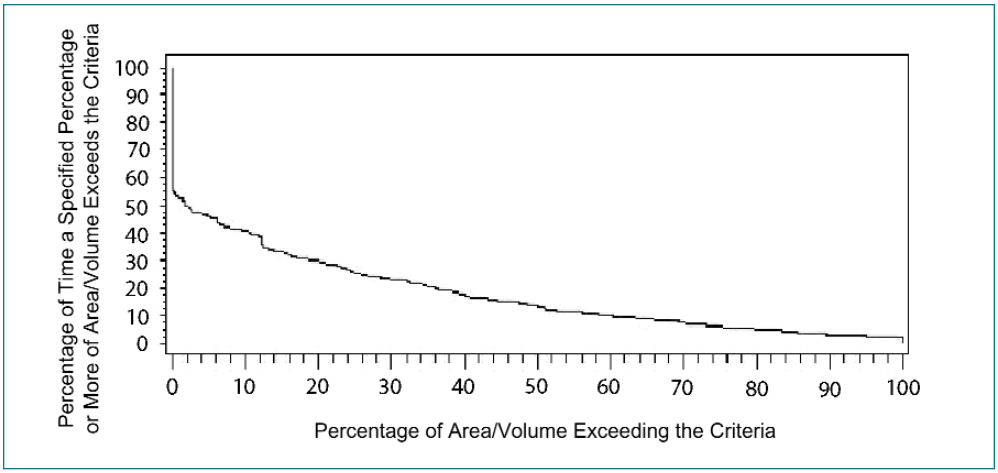


**Figure VI-20.** Water clarity criteria reference curve for defining criteria attainment in mesohaline/polyhaline shallow-water bay grass designated use habitats.

## 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 V-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

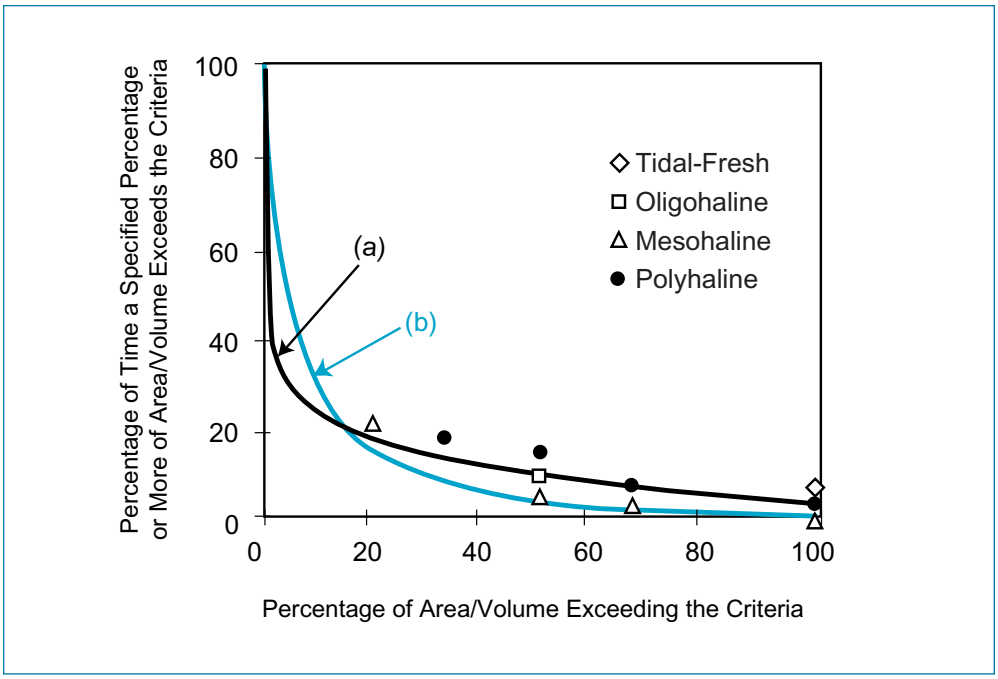


**Figure VI-21.** Cumulative frequency distribution of spring (March-May) chlorophyll *a* concentration exceeding the 95th percentile phytoplankton reference community values (a) compared with the normal distribution curve (b).

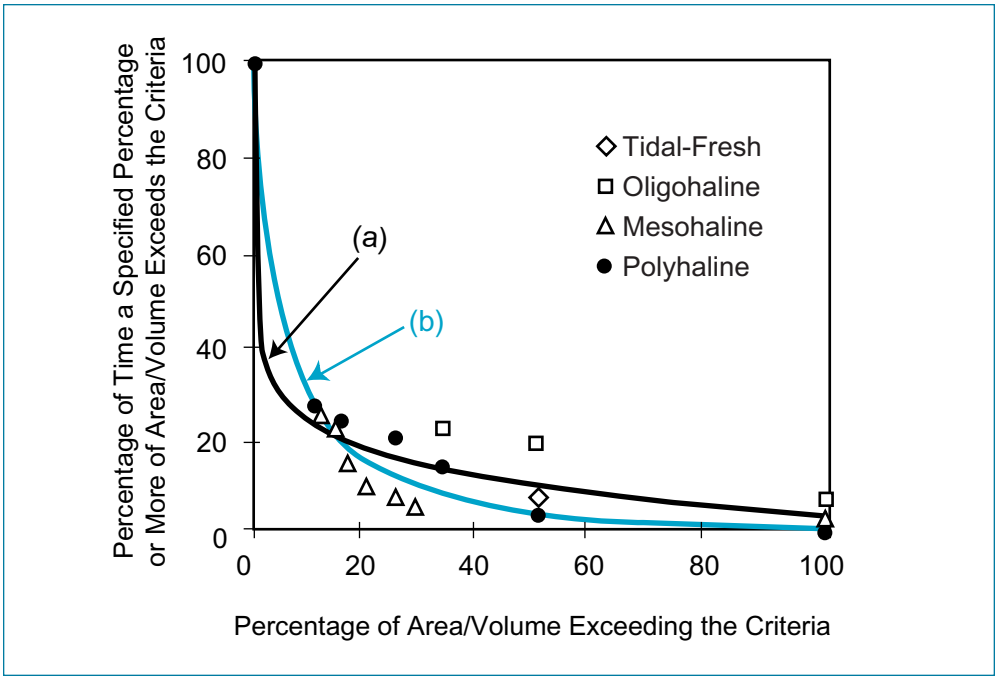


**Figure VI-22.** Cumulative frequency distribution of summer (July-September) chlorophyll *a* concentration exceeding the 95th percentile phytoplankton reference community values (a) compared with the normal distribution curve (b).

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.

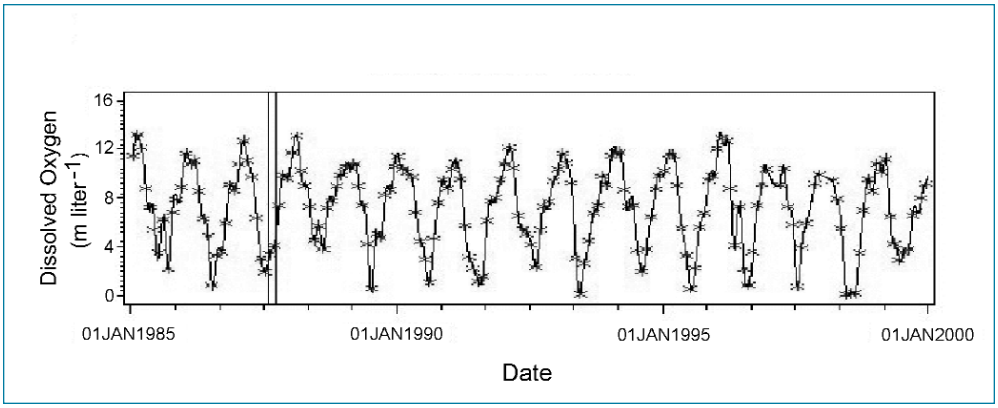


**Figure VI-23.** Observed monthly dissolved oxygen concentrations (*) at Chesapeake Bay Monitoring Program station CB4.2C (at the 8 to 10 meter depth) from January 1985 to January 2000 and the long-term 'forecast' (—) from application of the spectral equation.

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.

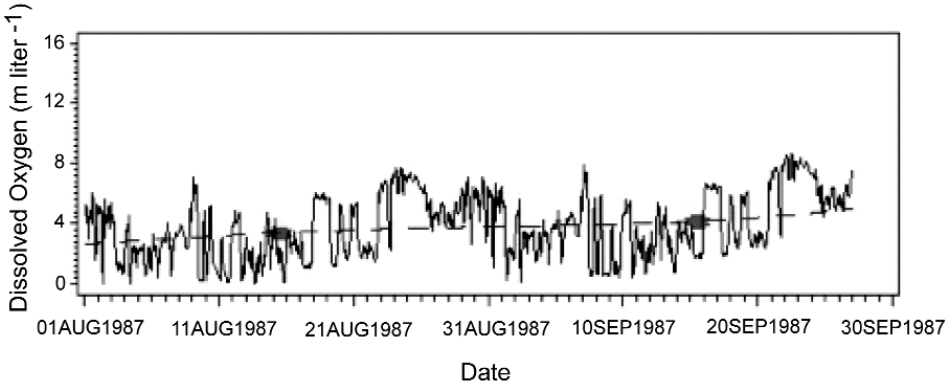


**Figure VI-24.** Expanded view from Figure VI-23 of the two-month period August–September 1987 synthetic data record obtained by combining the long- and short-term spectral equations.

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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chapter VII

# Diagnostic Procedures for Natural Processes and Criteria Nonattainment

## ADDRESSING NATURAL EXCEEDANCE OF THE CHESAPEAKE BAY CRITERIA

Through the refinement of tidal-water designated uses to better reflect natural habitats defined by season and physical features (e.g., bathymetry, stratification and hydrodynamic process) and the development of criteria that specifically support these uses, a full consideration of natural conditions has been directly interwoven into the two major components of state water quality standards. Within the recommended implementation procedures for defining criteria attainment, occasional exceedance of criteria, often natural in origin, has been directly accounted for in deriving and applying biologically based reference curves (see Chapter VI). Finally, possible errors in sampling and natural spatial and temporal variability have been accounted for, in part, through applying a statistical test for the significance of the observed nonattainment. Outside of extreme climatic events, application of the complete set of integrated Chesapeake Bay criteria, designated uses and attainment determination procedures will clearly identify nonattainment of desired water quality conditions due to anthropogenic impacts.

This combination of refined uses, habitat-tailored criteria and comprehensive implementation procedures factors in many circumstances, described below, in which natural conditions affect criteria attainment. In some situations extreme weather events or conditions may result in criteria exceedances beyond those accounted for in the combined criteria-uses-implementation procedures. In such situations, additional steps should be taken to quantify, where possible, exceedances that are due to natural events or conditions versus anthropogenic, pollutant-based stresses. This section describes known natural events or conditions that will influence attainment of the Chesapeake Bay dissolved oxygen, water clarity and chlorophyll *a* criteria. Tools that can be used to diagnose and quantify factors contributing to nonattainment also are described.

## NATURAL EXCURSIONS OF LOW DISSOLVED OXYGEN CONDITIONS

Physical (e.g., temperature, stratification or wind- and tide-driven mixing), chemical (e.g., salinity) and biological (e.g., respiration and photosynthesis) processes can independently and interactively affect the concentration of dissolved oxygen faster than new equilibrium can be reached with the atmosphere. As a result, for relatively short periods of time, or under sustained conditions of reduced physical mixing (i.e., stratification of the water column), dissolved oxygen concentrations can be driven well below saturation. Dissolved oxygen concentrations can decrease to near zero (anoxia), especially in deep or stratified bodies of water, or to 20 mg liter$^{1}$ (supersaturation) during dense algal blooms in surface waters.

The refined tidal-water designated uses were defined largely on the basis of natural conditions that divide the Bay and its tidal tributaries into different habitat zones. By devising Bay dissolved oxygen criteria to protect each designated use habitat, natural conditions that directly influence dissolved oxygen conditions have been largely accounted for through this process. In addition, by definition, the biologically-based reference curves derived for the respective designated uses directly incorporate allowable criteria exceedances due to natural causes in those habitats. The application of the statistical test of significant differences between the curves also addresses sampling error. Nevertheless, extreme occurrences in the natural processes may occur and the EPA strongly recommends that managers consider the natural factors listed below when evaluating criteria attainment.

### Temperature and Salinity Effects

The amount of oxygen dissolved in the water changes as a function of temperature, salinity, atmospheric pressure and biological and chemical processes. The equilibrium (or saturated) concentration of dissolved oxygen in natural waters ranges from about 6 to 14 mg liter$^{1}$. Seawater at equilibrium at a given temperature contains substantially less dissolved oxygen than freshwater. The higher the temperature and salinity, the lower the equilibrium dissolved oxygen concentration. The saturation concentration for dissolved oxygen decreases with increasing salinity (about -0.05 mg liter$^{1}$/psu$^{1}$) and increasing temperature (about -0.2 mg liter$^{1}$/$^{o}$C).

An analysis of the degree of saturation given existing temperature and salinity conditions within a designated use habitat can indicate whether these natural conditions will or are preventing criteria attainment. A spreadsheet analysis tool for conducting such analyses is described below and available on the Chesapeake Bay Program's web site at http://www.chesapeakebay.net/tools.

### High or Low River Flow Events

Because of its morphology and estuarine circulation, the Chesapeake Bay and some of its tidal tributaries have a natural tendency to produce reduced dissolved oxygen

conditions, particularly in deeper waters. The Chesapeake Bay's highly productive shallow waters, coupled with its tendency to retain, recycle and regenerate nutrients delivered from the atmosphere and surrounding watershed, create a nutrient-rich environment. The mainstem Chesapeake Bay and the major tidal rivers flowing off of shallower, broad shoal waters, along with the significant influx of freshwater flows, produce a stratified water column that prevents the water at the bottom from mixing with more highly oxygenated surface waters. The combination of nutrient retention and recycling and water-column stratification leads to severe reductions in dissolved oxygen concentrations, usually from June to September.

The timing and extent of hypoxic and anoxic water conditions vary from year to year because of regional weather patterns, the timing and magnitude of freshwater river flows, the flow of nutrients and sediments into tidal waters and the corresponding springtime phytoplankton bloom. The actual freshwater flow is the natural condition that should be considered in determining attainment. It is important to remember that under the low-flow conditions between 1950 and 1965, there was far less hypoxia in the mainstream Chesapeake Bay than there has been in the comparable low-flow years of the late-1980s to the present. Likewise, historical high-flow years produced less hypoxia and anoxia than current high-flow years (Hagy 2002). The impact from extremely high or low river flows can be evaluated by accounting for variations in the stratification of the water column. Basing the determination of the boundaries between the open-water, deep-water and deep-channel designated uses on sampling event calculations of the upper and lower pycnocline depths is the most straightforward means of addressing the effects of river flow on dissolved oxygen criteria attainment.

The data required to calculate sampling event-based pycnocline boundary depths can be found on the Chesapeake Bay Program's web site at http://www.chesapeakebay.net/data. Analysts are urged to use the Chesapeake Bay Water Quality Monitoring Program's protocol for calculating the upper and lower boundaries of the pycnocline (found at http://www.chesapeakebay.net/tools.htm), as this protocol was used to set the designated use boundaries. (Also see Appendix J in U.S. EPA 2003.) Extensive data on river flow can be found on the U.S. Geological Survey's Chesapeake Bay web site at http://chesapeake.usgs.gov.

## Upwelling of Hypoxic Water

Nearshore, shallow waters in the Chesapeake Bay periodically experience episodes of low- to no-dissolved-oxygen conditions that result in part from intrusions of bottom water forced onto the shallows by sustained winds. Such seiching events are natural, but a large percentage of the low dissolved oxygen that intrudes into these shallow habitats is not due to natural causes. Therefore, attaining the deep-water and deep-channel dissolved oxygen criteria will greatly reduce or even prevent the influx of oxygen-depleted bottom waters into the shallows.

These pycnocline seiche events often take place over time scales that are missed by the monitoring program's sampling frequency. When they have occurred during a sampling cruise, the seiching events result in a clear tilting of the pycnocline. Such events often are triggered by sustained winds in a single direction over a period of several days. To verify that observed tilting of the pycnocline and the resulting excursion of less than 5 mg liter[1] waters into shallow- and open-water designated use habitats were due to natural seiching events, it is recommended that offshore salinity with depth profiles and the wind direction and speed data be analyzed.

Extensive salinity with depth profile data are available on the Chesapeake Bay Program's web site at http://www.chesapeakebay.net/data. For the Chesapeake Bay's tidal waters, the best sources of information on continuous wind direction and speed are the Patuxent Naval Air Station, Baltimore-Washington International Airport and Norfolk International Airport[1]. Data from these wind monitoring stations can be accessed through the NOAA National Climatic Data Center at http://ww.ncdc.noaa.gov.

## Natural Diel Fluctuations

Diel cycles of low dissolved oxygen conditions often occur in nonstratified shallow waters where nightly water-column respiration temporarily depletes dissolved oxygen levels. The lowest dissolved oxygen readings, generally observed in the early morning hours from 0.5 to 2 hours after sunrise, are frequently missed by typical daytime shipboard water quality monitoring, where sampling usually starts in the morning and continues into the late afternoon. These diel fluctuations are the result of natural processes such as daily temperature cycles and photoperiod cycles, but anthropogenic stresses further exaggerate the fluctuations.

The Chesapeake Bay dissolved oxygen criteria were derived to protect aquatic animals in the defined designated uses during the applicable time frames, regardless of time of day. It should be noted that daytime measurements of dissolved oxygen may not fully reflect actual attainment of the criteria over the 24-hour cycle.

To achieve the most protective degree of criteria attainment, the oxygen dynamics of a particular water body should be characterized using oxygen meters that monitor semicontinuously. If diel fluctuations in oxygen conditions are found to exist, two further steps should be taken. The level of oxygen saturation should be analyzed to confirm that the criteria meet the given natural temperature and salinity conditions. Users also should build in a determination of diurnal minimum concentrations through translation or correction of fixed stations using semicontinuous buoy data.

[1] A time-series of hour/wind direction and velocity for 1985-1994 for each of these three stations was developed for use in the Chesapeake Bay water quality model. Wind data was adjusted to account for over-water conditions by multiplying the east-west component by a factor of 1.0, 1.43 and 1.25 for BWI, Patuxent and Norfolk, respectively. Likewise, the north-south component was multiplied by factors of 1.50, 2.05 and 1.25, respectively.

The Maryland Department of Natural Resources (MD DNR) is developing a method to temporally standardize dissolved oxygen measurements to a diurnal minimum. Averaged spring and summer data from MD DNR's continuous monitors indicate that dissolved oxygen minima are reached at approximately 6:30 a.m., while dissolved oxygen maxima are achieved at 3:30 p.m. These diurnal fluctuations in dissolved oxygen produce increasing values during water quality mapping cruises, where thousands of point samples are collected throughout a tributary over the course of several hours. In order to produce realistic interpolated surfaces of the spatially intensive monitoring data, the 'time of day' artifact must be removed from the dissolved oxygen data. MD DNR has chosen to standardize data to the dissolved oxygen minimum time of 6:30 a.m. to represent the worst conditions that living resources might face in the tributary, even though this methodology could just as easily be applied to other times of the day.

The first step in temporal standardization is to obtain a 15-minute interval average of continuous monitoring data during a two-week period that encompasses a water quality mapping cruise. The two-week average is somewhat arbitrary, but helps to filter out small-scale noise in the dissolved oxygen signal. In MD DNR's case, the two-week period will be reevaluated in the coming months with additional, concurrent continuous and spatial data collected in 2002. A third-order polynomial is fit to the two-week dissolved oxygen average from 5:30 a.m. (one hour before dissolved oxygen minimum) to one hour after the completion of the water quality mapping cruise of interest. The third-order polynomial model is used to back-calculate each water quality mapping sample to its theoretical 6:30 a.m. value. The standardized data is then put into geostatistical interpolation models to produce a dissolved oxygen minimum map.

Methods to incorporate multiple monitors into the standardization process should be developed. Also, the effect of chlorophyll *a* concentrations on dissolved oxygen concentrations should be studied and possibly included in the correction.

## Release of Organic Materials from Tidal Wetlands

Tidal wetlands are a valuable component of estuarine systems. They have been shown as net sinks for sediments (Neubauer et al. 2001) and in most cases also serve to remove nutrients from overlying water (Anderson et al. 1997). High rates of organic production, accompanied by high rates of respiration (Neubauer et al. 2000), can significantly reduce dissolved oxygen and enhance dissolved inorganic carbon levels both in sediment pore water and overlying water in wetland systems. Another process that can deplete dissolved oxygen in wetland sediments is nitrification, which converts ammonium to nitrite and nitrate (Tobias et al. 2001).

Studies of South Carolina estuaries demonstrate that small tidal salt marsh creeks have significantly lower dissolved oxygen levels than large tidal creeks (Van Dolah et al., in press). Cai et al. (1999, 2000) determined that a significant export of high dissolved inorganic carbon from marshes was responsible for the low dissolved oxygen concentrations observed in five estuaries in South Carolina and Georgia. In

a series of studies of the York River estuary, Raymond et al. (2000) showed that the system is supersaturated with respect to carbon dioxide pressure ($pCO_2$); conservative mixing diagrams demonstrated a mid-estuary source of dissolved organic carbon, which caused respiration to exceed production in the system. Further studies by Neubauer and Anderson (2003) showed that the export of dissolved inorganic carbon from tidal freshwater and saltwater marshes could account for approximately 47 percent of the excess dissolved inorganic carbon observed by Raymond et al. (2000) in the York River estuary.

These effects need to be considered in cases where there is a large wetland-to-water ratio or high residence times of water in extensive nearby wetlands. The Mattaponi and Pamunkey rivers, two large tidal tributaries to the York River in Virginia, are the two best examples of such systems in the Chesapeake Bay region. Computer simulation modeling may be used to help quantify the impact on dissolved oxygen criteria attainment.

## NATURAL REDUCTIONS IN WATER CLARITY LEVELS

The shallow-water bay grasses designated use excludes those habitats where natural physical factors (e.g., wave action) will prevent underwater bay grasses from ever growing. Other natural conditions found in potential and current underwater bay grass habitats (e.g., resuspension) are addressed using a comparison of ambient data with a biologically-based reference curve. This reference curve defines the water clarity criteria exceedances through time and space that can occur without impairing the underwater bay grass community.

### High Flow Events

High river flows resulting from major storms will carry elevated loads of suspended solids from the upper watersheds and lead to reduced water clarity levels in the midchannel and shallow-water habitats. According to recent U.S. Geological Survey studies, most of the sediment that has been delivered to free-flowing stream corridors occurred during land clearance in the 1800s. Much of the sediment mobilized from stream banks and adjacent flood plains and delivered to the tidal rivers and mainstem Chesapeake Bay may be these 'legacy' sediments. The U.S. Geological Survey is conducting research to determine the amount of sediment that is caused by recent erosion from land sources versus the sediment that is eroded from within the stream corridors themselves. The latest findings and extensive data on river flows can be found on the U.S. Geological Survey's Chesapeake Bay web site at http://chesapeake.usgs.gov.

The influence of high flow events is largely accounted for through the derivation (and application) of the biologically-based water clarity criteria reference curves. These reference curves were developed based on almost two decades' worth of underwater bay grass distributions and water quality data. The mid-1980s to early 2000s data record contains the full array of long-term drought to extreme storm events (e.g., hurricanes) to sustained, very wet hydrological conditions.

## Wind-Driven Events

Sustained high winds can cause shallow-water sediments to become resuspended and thus lead to reduced water clarity levels. The U.S. Geological Survey is identifying areas where poor water-clarity conditions are likely to exist due to wind-driven events. The latest research findings for management application can be found on the U.S. Geological Survey's Chesapeake Bay web site at http://chesapeake.usgs.gov. The biologically-based reference curves should account for allowable criteria exceedances due to such short-term wind-driven events.

## Estuarine Turbidity Maximum Zones

The area in the Bay's larger tidal tributaries and the upper Bay mainstem where the warmer, lighter freshwater flows first mix with saltier, denser water flowing upstream (originally from the coastal Atlantic Ocean) is called the zone of maximum turbidity, or estuarine turbidity maximum zone (Lin and Kuo 2001; Sanford et al. 2001). The intersection of these two water masses causes nutrients and sediment to be naturally mixed and continually resuspended. The general locations of these zones are illustrated in Figure VII-1, which was mapped using long-term salinity and total suspended solids records over the past 20 years. The actual location varies from year to year, depending on the timing and volume of freshwater flows.

The natural effect of the estuarine turbidity maximum zone on water clarity in shallow habitats has been directly factored into the selection of the Chesapeake Bay water clarity criteria application depths (see U.S. EPA 2003 for more details). The historical (1930s to early 1970s) and more recent (1978–2001) record of bay grasses distributions included the effects of the estuarine turbidity maximum zones located in the tidal tributaries and the mainstem Chesapeake Bay. The shallow-water bay grass designated use depth boundaries for Chesapeake Bay Program segments, within which the estuarine turbidity maximum zones are located, generally have lower water clarity application depths, reflecting the fact that total suspended solids concentrations would be naturally elevated leading to less water clarity (U.S. EPA 2003).

## Natural Water Color

Several tidal tributaries throughout the Chesapeake Bay drain extensive tidal, wetland-dominated watersheds. The organic materials from those areas tend to color or stain the water naturally, which reduces water clarity. A background level of water color was factored into the scientific basis for the Chesapeake Bay water-clarity criteria and the supporting diagnostic tools (see Batiuk et al. 2000 and Gallegos 2001 for details). However, in tidal-fresh habitats along the lower Eastern Shore where water color plays a significant role in reducing water clarity, the habitats were considered underwater bay grass no-growth zones. Since no shallow-water bay grass designated use applies in these habitats, the water clarity criteria do not apply (see U.S. EPA 2003 for details).

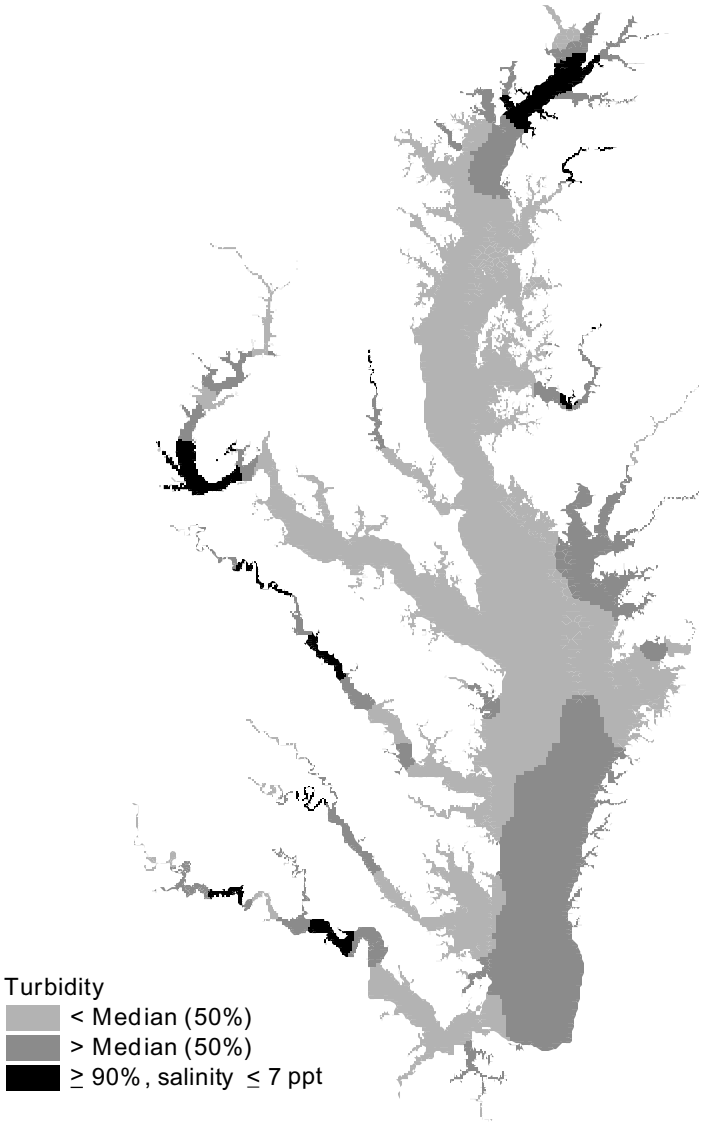


**Figure VII-1.** The estuarine turbidity maximum zone is generally found at the interface of fresh and salt water. It is illustrated here as the region within each river basin where mean concentration of total suspended solids is at or above the 90th percentile of concentrations measured within that basin in the last decade, i.e., between 1991–2000. The regions of lesser turbidity are divided into two categories: those with mean concentrations less than the median (50th percentile) or greater than the median, but less than the 90th percentile. 'Hot spots' of relatively high turbidity in downstream meso- and polyhaline areas are not shown. 'Major' basins are the mainstem Bay (including Mobjack Bay) and the Chester, Choptank, Nanticoke, Pocomoke, Patuxent, Potomac, Rappahannock, York and James rivers. In some of these river basins, the turbidity maximum is too far upriver to be clearly displayed on this map.

## NATURAL ELEVATED CHLOROPHYLL *A* CONCENTRATIONS

Many of the factors influencing chlorophyll *a* concentrations are related to physical processes affecting the residence time of a water mass in a tidal river, creek or embayment, and light penetration due to channel morphology or physical mixing. In regions or specific tidal-water habitats where these listed physical processes lead to chlorophyll *a*-related impairments, states should derive local scale numerical chlorophyll *a* criteria directly addressing these natural conditions.

### High Residence Time and Reduced Flushing Rates

In many small tidal rivers, the reduced flushing of more confined open-water habitats often leads to elevated chlorophyll *a* concentrations, given that phytoplankton populations are exposed to nutrient-enriched conditions for longer periods. Nutrient loadings that would not otherwise lead to increased chlorophyll *a* concentrations in well-flushed tidal open-water habitats generate bloom conditions in these smaller systems.

There has been relatively little analysis of the appropriateness and attainability of specific chlorophyll *a* values in poorly flushed tidal systems. For example, most of the analyses performed in support of generating chlorophyll *a* target concentrations have focused on well-flushed open-water systems (see Chapter V). Natural elevations of chlorophyll *a* should be considered when setting designated use boundaries and when setting specific numeric targets and criteria for addressing regional and local algal-related impairments.

Through the development and application of biologically-based reference curves, the numerical chlorophyll *a* criteria attainment methodology can factor in the spatial extent of criteria attainment or nonattainment. This allows for limited spatial extent with elevated chlorophyll *a* concentrations and larger spatial areas with lower, yet nonattaining, chlorophyll *a* concentrations. If a Chesapeake Bay Program segment contains a very high portion of tidal habitats with high residence times, more detailed analyses of the relative contribution of naturally reduced flushing rates versus excessive anthropogenic nutrient loadings should be undertaken.

### Channel Morphology

Tidal rivers and creeks with shallow and wide channels (versus narrower and deep channels) will tend to have higher chlorophyll *a* concentrations, given the greater volume of the photic zone relative to the total channel volume. In addition, the shallow and wide channels tend to be less well-flushed, allowing greater accumulation of phytoplankton and chlorophyll *a*.

### Natural Algal Blooms Independent of Nutrient Conditions

Although anthropogenic nutrient loading is a principal factor in the overall primary productivity of the Chesapeake Bay system, its relationship to blooms of specific taxa is not well understood. Such blooms have been observed to occur in the absence

of elevated nutrient conditions as a result of a complex set of physical, chemical and biological stimuli. Species composition data from the Chesapeake Bay Phytoplankton Monitoring Program should be consulted to determine if the observed algal bloom conditions are due principally to species that fall within this category. These phytoplankton monitoring data can be accessed through the Chesapeake Bay Program website at http://www.chesapeakebay.net/data.

## DIAGNOSING CAUSES OF CRITERIA NONATTAINMENT

### DISSOLVED OXYGEN CRITERIA

#### Percent Saturation

An analysis of the degree of saturation given existing temperature and salinity conditions within a designated use habitat can be performed by applying the following equation. For temperature in degrees Celsius and salinity in mg liter$^{-1}$:

dissolved oxygen saturation = 14.6244 – 0.367134(Temp°C) + 0.0044972 (Temp°C)2 – 0.0966(salinity) + 0.00205 (salinity) (Temp°C) + 0.0002739 (salinity)$^2$.

A spreadsheet version of this diagnostic analysis tool is available on the Chesapeake Bay Program's web site at http://www.chesapeakebay.net/tools.htm.

#### Chesapeake Bay Water Quality Model

As explained in Chapter VI, the Chesapeake Bay water quality model is linked to the Chesapeake Bay hydrodynamic model and uses complex nonlinear equations describing 26 state variables relevant to the simulation of dissolved oxygen, chlorophyll *a* and water clarity. 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 bottom sediments. This mass balance calculation is made for each model cell and for associated bottom sediment cells at each hourly time step. Estimates of dissolved oxygen from nutrient loads from the watershed and airshed are simulated in the tidal waters of the 35 major segments of the Chesapeake Bay and its tidal tributaries. This state-of-the-science modeling tool is available to management agencies and others to help diagnose the reasons behind nonattainment of the Chesapeake Bay dissolved oxygen criteria.

For the dissolved oxygen criteria, the daily output of dissolved oxygen concentration for 10 years (1985–1994) for the 13,000 cells provides a detailed estimate of the transport and transformation of nutrients and organic matter that ultimately consume oxygen in the waters of the Chesapeake Bay and its tidal tributaries. Influential aspects, such as the limiting nutrient, seasonal changes in dissolved oxygen, changes

in the nutrient flux of bottom sediments that change with bottom-water oxygen levels, and other temporal and spatial aspects of dissolved oxygen concentrations and dynamics, can be diagnosed by evaluating water quality model output to gain insights into the reasons behind nonattainment of the dissolved oxygen criteria.

## WATER CLARITY CRITERIA

In *Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat-Based Requirements and Restoration Targets: A Second Technical Synthesis*, a set of diagnostic tools were developed not only to better interpret the relative degree of achievement of the Bay water clarity criteria, but also to understand the relative contributions of different water quality parameters to overall light attenuation (Batiuk et al. 2000). Two management-oriented diagnostic tools have been developed. The water-column diagnostic tool quantifies the relative contributions to total light attenuation in the water column that is attributable to light absorption and scattering by total suspended solids and chlorophyll *a*. The leaf surface attenuation diagnostic tool further quantifies the light attenuation at the leaf surface attributable to epiphytes and total suspended solids settled out on the leaf surface. Both diagnostic tools are available as spreadsheet-based application tools and can be accessed through the Chesapeake Bay Program's web site at http://www.chesapeakebay.net /tools.htm.

### Water-Column Light Attenuation Diagnostic Tool

Water-column attenuation of light measured by the light attenuation coefficient, $K_d$, can be divided into contributions from four sources: water, dissolved organic matter, chlorophyll *a* and total suspended solids. The basic relationships can be expressed in a series of simple equations, which were combined to produce the equation for the water-column diagnostic tool (Gallegos 2001). The resulting equation calculates linear combinations of chlorophyll *a* and total suspended solids concentrations that just meet the percent light-through-water (PLW) criteria value for a particular depth at any site or season in the Chesapeake Bay and its tidal tributaries. This diagnostic tool can also be used to consider various management options for improving water quality conditions when the water clarity criteria are not currently met.

**Generation of Management Options.** The water-column diagnostic tool spreadsheet program calculates median water quality concentrations and evaluates them in relation to PLW criteria for growth to 0.5-, 1- and 2-meter restoration depths. Provisions are included for specifying a value for PLW criteria appropriate for mesohaline and polyhaline regions (22 percent) or for tidal-fresh and oligohaline areas (13 percent). When the observed median chlorophyll *a* and total suspended solids concentrations do not meet the PLW criteria, up to four target chlorophyll *a* and total suspended solids concentrations that do meet the PLW criteria are calculated based on four different management options (Figure VII-2). Under some

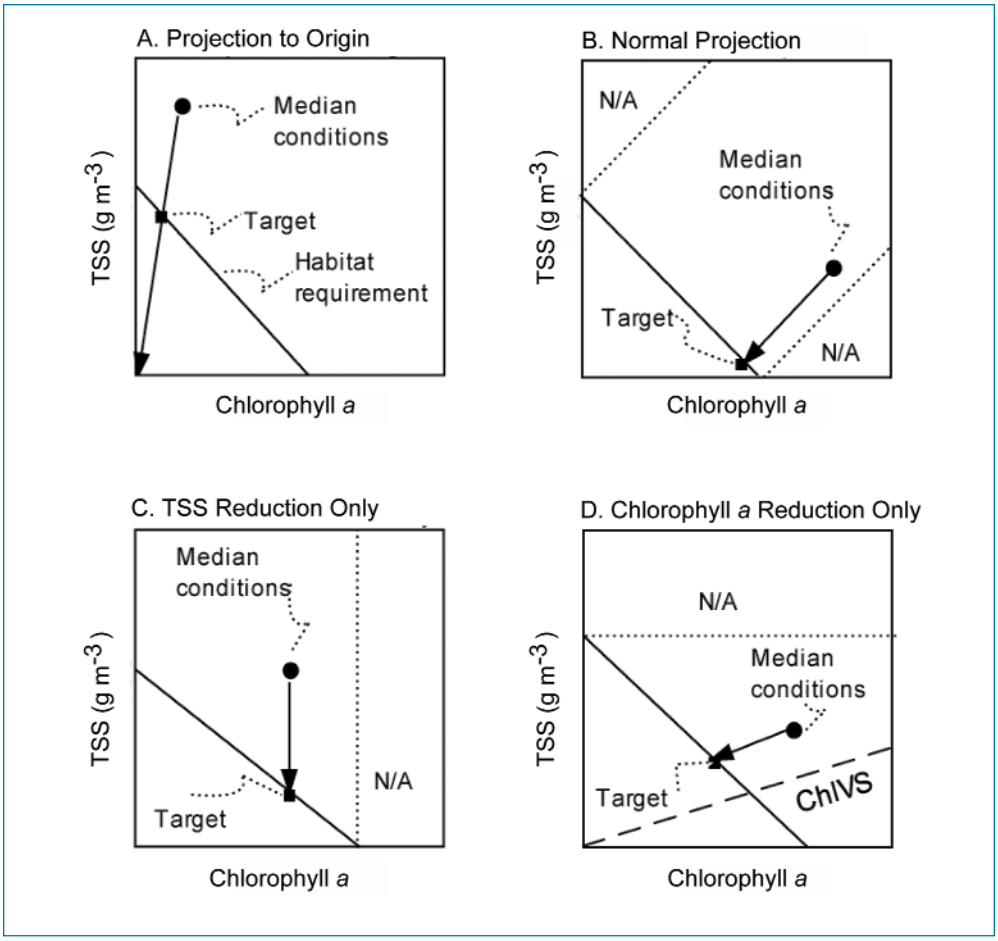


**Figure VII-2.** Illustration of management options for determining target concentrations of chlorophyll *a* and total suspended solids. It illustrates the use of the diagnostic tool to calculate target growing-season median concentrations of total suspended solids (TSS) and chlorophyll *a* for restoration of underwater bay grasses to a given depth. Target concentrations are calculated as the intersection of the percent light-through-water criteria line, with a line describing the reduction of median chlorophyll *a* and TSS concentrations calculated by one of four strategies: (A) projection to the origin (i.e., chlorophyll *a*=0, TSS=0); (B) normal projection, i.e., perpendicular to the percent light-through-water requirement; (C) reduction in total suspended solids only; and (D) reduction in chlorophyll *a* only. A strategy is not available (N/A) whenever the projection would result in a 'negative concentration.' In (D), reduction in chlorophyll *a* also reduces TSS due to the dry weight of chlorophyll *a*, and therefore moves the median parallel to the line (long dashes) for ChlVS, which describes the minimum contribution of chlorophyll *a* to TSS.

conditions, some of the management options are not available because a 'negative' chlorophyll *a* or total suspended solids concentration would be calculated.

**Option 1** is based on projections from existing median conditions to the origin (Figure VII-2a). This option calculates target chlorophyll *a* and total suspended solids concentrations as the intersection of the PLW criteria line with the line connecting the existing median concentration and the origin, i.e., chlorophyll *a* = 0, TSS = 0. Option 1 always results in positive concentrations of both chlorophyll *a* and total suspended solids.

**Option 2** is based on normal projections (Figure VII-2b). It calculates target chlorophyll *a* and total suspended solids concentrations as the projection from existing median conditions perpendicular to the PLW criteria. Geometrically, Option 2 requires the least overall reductions in chlorophyll *a* and total suspended solids concentrations. In practice, target chlorophyll *a* and total suspended solids concentrations for the normal projection, when permissible (i.e., no negative concentrations are calculated), are frequently very similar to those calculated in Option 1 using projection to the origin.

**Option 3** is based on a total suspended solids reduction only (Figure VII-2c). This option calculates target chlorophyll *a* and total suspended solids concentrations, assuming the target can be met only by reducing the concentration of total suspended solids. Option 3 is not available whenever the median chlorophyll *a* exceeds the total suspended solids = 0 intercept. When a system is nutrient-saturated and light-limited, a reduction of total suspended solids alone poses the risk of relieving light limitation and promoting further phytoplankton growth. Such a tendency is indicated on the diagnostic tool plot whenever data points tend to align parallel to the PLW criteria lines (Figure VII-2c).

**Option 4** is based on a chlorophyll *a* reduction only. This option calculates target chlorophyll *a* and total suspended solids concentrations, assuming that the target can be met only by reducing the concentration of chlorophyll *a* (Figure VII-2d). Due to the suspended solids removed by reduction of phytoplankton and associated carbon, i.e., ChlV, the target total suspended solids concentration reported for Option 4 is actually lower than the existing median. Option 4 is not available whenever the median total suspended solids concentration exceeds the chlorophyll *a* = 0 intercept of the PLW criteria line.

The precision of the calculations implies a degree of control over water quality conditions that clearly is not always attainable. Nevertheless, reporting of four potential targets provides managers with an overall view of the magnitude of the necessary reductions and some of the available tradeoffs. Furthermore, the spreadsheet reports the frequency with which the PLW criteria for each restoration depth are not achieved by the individual measurements.

**Evaluating Management Options.** Option 1 will likely be the most useful for generating target concentrations because it always results in the calculation of positive concentrations. Also, most efforts to control loadings involve a reduction of total

runoff, which reduces both suspended solids and nutrients. Under certain conditions managers may choose to apply Option 3, when data plots indicate that attenuation is dominated by flood-borne or resuspended sediments (Figure VII-3a). Similarly, Option 4 may be useful when diagnostic plots indicate that light attenuation is dominated by algal blooms (Figure VII-3b). For details on how best to evaluate the four possible management options, refer to *Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat-Based Requirements and Restoration Targets: A Second Technical Synthesis* (Batiuk et al. 2000, pp. 47-49).

## Leaf Surface Light Attenuation Diagnostic Tool

Building from the diagnosis and quantification of water-column contributions to attenuation of light, a second diagnostic tool focuses on how changes in water quality variables alter the light available to underwater plant leaves and considers effects of light attenuation resulting from substances both in the overlying water column (phytoplankton, suspended particles and dissolved organics) and attached to underwater bay grass leaves (epiphytic algae, organic detritus and inorganic particles). A simple model was developed to calculate photosynthetically available radiation (PAR) at the leaf surface for plants growing at a given restoration depth (Z) under specific water quality conditions. The computed value for PAR at the plant leaves is compared to the applicable Bay water clarity criteria.

The overall objective is to apply this model using water quality monitoring data to estimate growing season mean light levels at bay grass leaves for a particular site or geographic region. The calculated light levels at bay grass leaves are then compared to the applicable light-at-the-leaf water clarity requirement to assess whether water quality conditions are suitable to support the survival and growth of underwater bay grasses. The relative contributions of water-column versus epiphytic substances in attenuating incident light to underwater bay grass leaves also are computed. The scientific basis of this model is described in detail in Batiuk et al. (2000) and Kemp et al. (in review).

**Generating Diagnostics.** To compute median PAR at the bay grass leaf surface, the diagnostic spreadsheet model requires underwater bay grass growing season medians for four water quality variables: 1) dissolved inorganic nitrogen (nitrate + nitrite + ammonia), or DIN; 2) dissolved inorganic phosphorus (primarily phosphate), or DIP; 3) total suspended solids (TSS); and 4) diffuse downwelling PAR attenuation coefficient ($K_d$). Values for $K_d$ are either obtained from direct measurements of decrease in PAR with water depth using a cosine-corrected sensor, or calculated from observations on the depth at which a Secchi disk disappears (see Chapter III in Batiuk et al. 2000 for the details on the recommended Secchi depth/$K_d$ conversion of $K_d$ = 1.45/Secchi depth). The restoration depth is defined by the Chesapeake Bay Program segment-specific shallow-water designated use outer depth boundary (U.S. EPA 2003). Figure VII-4 and Table VII-1 lays out the steps for running the spreadsheet model, the data required, and the scientific basis for the calculation.

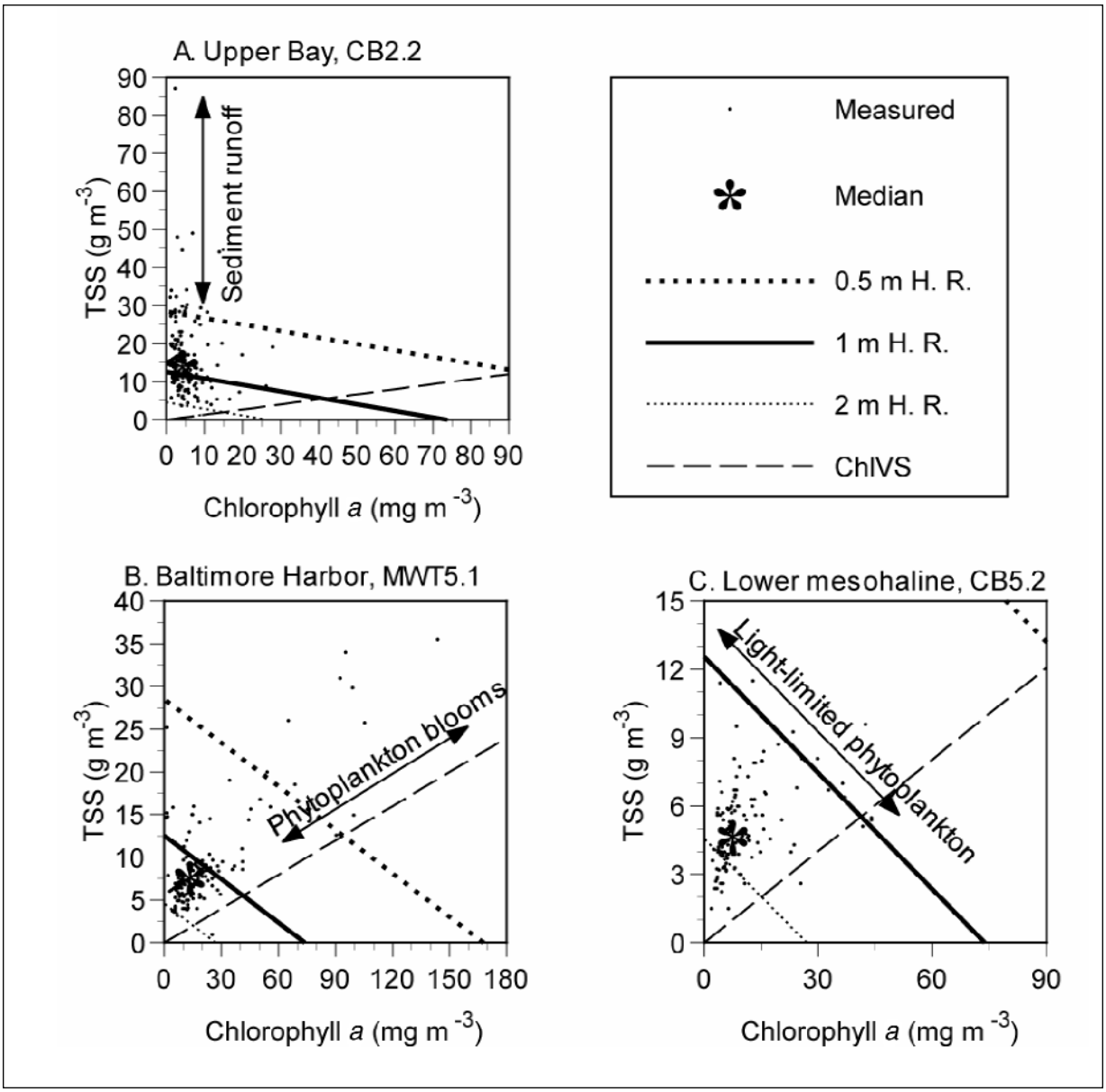


**Figure VII-3.** Application of the water column light attenuation diagnostic tool to two mainstem Chesapeake Bay stations and one tidal tributary station, which demonstrates three primary modes of variation in the data: (A) variation in diffuse attenuation coefficients is dominated by (flow-related) changes in concentrations of total suspended solids (TSS) (upper Chesapeake Bay station, CB2.2); (B) variations in attenuation coefficients is dominated by changes in chlorophyll *a* concentration (Baltimore Harbor, MWT 5.1); and (C) maximum chlorophyll *a* concentration varies inversely with TSS, indicating light-limited phytoplankton (lower middle Chesapeake Bay, CB5.2). Plots show individual measurements (points) and growing season median (asterisk) in relation to the percent light-through-water (PLW) criteria for restoration to depths of 0.5m (short dashes), 1m (solid line) and 2m (dotted line); and PLW calculated by equations IV-1 and J-1 (see Chapter IV and Appendix J). Note the change in scale. Approximate minimum contribution of chlorophyll *a* to TSS (ChlVS) is calculated by Equation IV-11 (long dashes) in Batiuk et al. 2000. The data is from the Chesapeake Bay Water Quality Monitoring Program, April through October, 1986-1996.

Sources: Batiuk et al. 2000; Gallegos 2001.

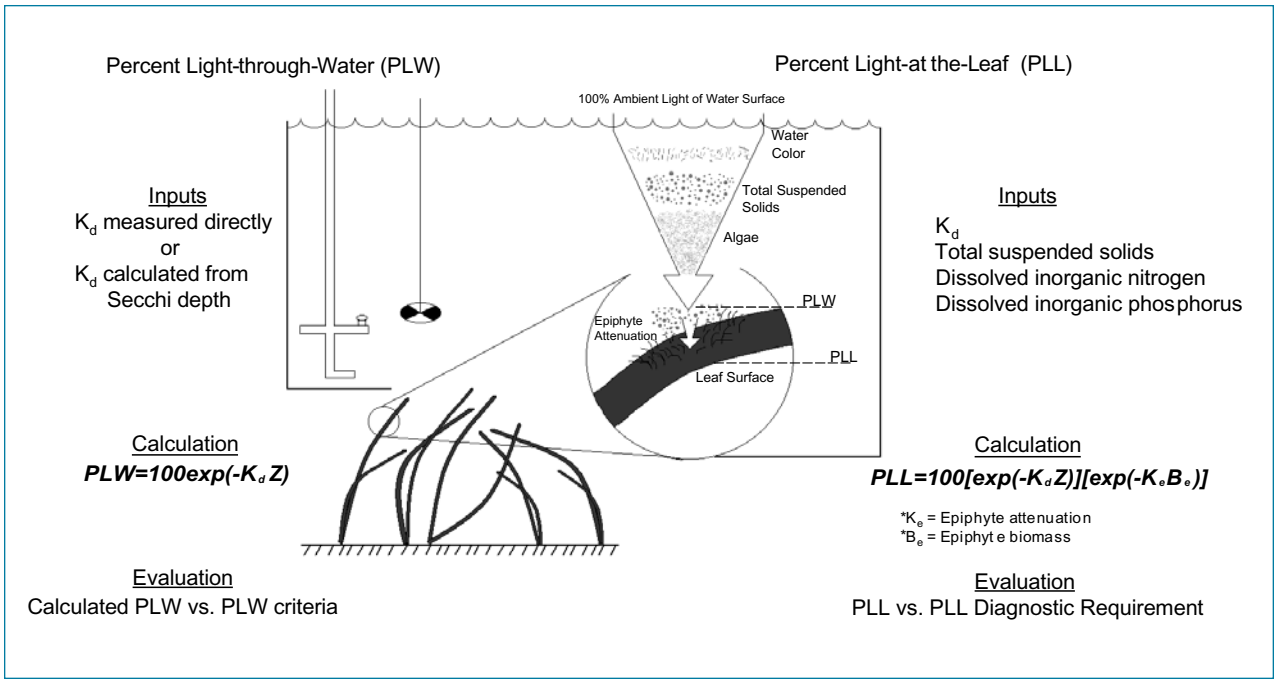


**Figure VII-4.** Illustration of percent light-at-the-leaf (PLL) and percent light-through-water (PLW) calculation comparisons for underwater bay grasses in the Chesapeake Bay.
Source: Batiuk et al. 2000

**Evaluating Diagnostic Outputs.** To examine the components of light attenuation, as determined by the spreadsheet percent light-at-the-leaf (PLL) calculator, several fields in addition to PLL are shown. This permits insight into the contribution to light total attenuation from the water column, leaf surface epiphytes and leaf surface total suspended solids (TSS). The additional fields are:

- **PLW—percent-light-through-water.** Comparing PLL to PLW gives an indication of the contribution of leaf surface light attenuation to the total attenuation.
- **PLLnoTSS—PLL calculated without TSS light attenuation.** Indicates the relative importance of epiphytes and TSS.
- **%EpiAtten.** Refers to the percentage of the light attenuation on the leaf surface that is due to the growth of epiphytes.
- **%LeafTSSAtten**. Refers to the percentage of the light attenuation on the leaf surface that is due to deposited TSS.
- **Requirement.** Indicates whether the calculated PLL meets or fails the PLL diagnostic minimum light requirement. Assessment takes into account the salinity regime of the station.

**Table VII-1.** Summary of the approach to estimate photosynthetically available radiation at the leaf surface of underwater bay grasses using water quality data routinely monitored in the Chesapeake Bay.

| Step in Model Calculation<br>Functional Relation | Input Data | Source of Model Relationship | Units |
|---|---|---|---|
| 1) Decide limiting nutrient<br>DIN/DIP > 16 , use DIP<br>DIN/DIP ≤ 16 , use DIN | DIN, DIP | Fisher et al. 1992 | $\mu$M |
| 2) Derive general equation to calculate epiphyte biomass<br>$B_e = (B_e)_m [1 + 208 (DIN^{-KN(OD)})]^{-1}$<br>• $(B_e)_m$ = maximum $B_e$ value<br>• $K_{N(OD)}$ = characteristic coeff. | DIN, DIP | Numerical model (Madden and Kemp 1996) | $B_e$, $gCgC^{-1}$<br>DIN, $\mu$M<br>$K_{N(OD)}$, none |
| 3) Calculate PAR effect on $K_{N(OD)}$ and $(B_e)_m$<br>$(B_e)_m = 2.2 - [0.251 (OD^{1.23})]$<br>• OD = Optical Depth = $(K_d)(Z)$<br>$K_{N(OD)} = 2.32 (1 - 0.031 OD^{1.42})$ | $K_d$, Z | Numerical model (Madden and Kemp 1996) | $K_d$, $m_{-1}$<br>Z, m |
| 4) Calculate epiphyte dry weight<br>$B_{de} = 0.107$ TSS + 0.832 $B_e$ | TSS<br>$B_e$ | Regression from experimental data (e.g., Staver 1984) | TSS, mg $l_{-1}$<br>$B_e$, mg chl $gdw^{-1}$<br>$B_{de}$, gdw $gdw^{-1}$ |
| 5) Calculate epiphyte biomass-specific PAR attenuation coeff.<br>$K_e = 0.07 + 0.32 (B_e/B_{de})^{-0.88}$ | $B_e$,<br>$B_{de}$ | Regression from experimental and field data | $B_e$, $\mu$g chl $cm^{-2}$<br>$B_{de}$ , mg dw $cm^{-2}$<br>$K_e$, cm2 $\mu$g $chl^{-1}$ |
| 6) Calculate PAR at SAV leaves ($I_{ze}$)<br>$I_{ze}/I_o = [\exp(-K_dZ)][\exp(-K_eB_e)]$ | DIN, DIP,<br>$K_d$, TSS, Z | Combining steps 1–5 (from above) | DIN, $\mu$M<br>DIP, $\mu$M<br>TSS, mg $l^{-1}$<br>$K_d$, $m^{-1}$ |
| 7) Compare SAV leaf PAR with Light-at-the-Leaf Requirement | $I_{ze}/I_o$ | See Chapter VII in Batiuk et al. 2000 | % |

Note that units used for specific variables change at different steps in calculation, but are consistent with conventions of data and model sources.

Source: Batiuk et al. 2000.

### Chesapeake Bay Water Quality Model

Outputs from the Chesapeake Bay water quality model include quantification of the various components of light attenuation from sediment, algae or color. Further evaluation of the relative contributions of these various components of light attenuation can provide insights into the reasons behind nonattainment of the water clarity criteria.

## CHLOROPHYLL *A* CRITERIA

### Chesapeake Bay Water Quality Model

The Chesapeake Bay community also has access to water-quality models that represent excellent tools for diagnosing the causes for nonattainment of the chlorophyll *a* criteria. Time and space aspects of the criteria and the understanding of the fundamental behavior and significant influences on chlorophyll *a* in the Chesapeake Bay designated use habitats is based primarily on resource limitation of algae. Resource limitation on the growth of algae include nitrogen and phosphorus limitation, light limitation and, for diatoms, limitation of silica. Interactions of the chlorophyll *a* and water clarity criteria include algal self-shading and light attenuation due to sediment or the color imparted to natural waters due to dissolved organic material. Through the Chesapeake Bay water quality model, the total fate and transformation of algae based on the Monod structure of temperature corrected algal growth operating on a hourly time step can be evaluated. Diagnostics of chlorophyll *a* criteria nonattainment that can be examined through model outputs include nitrogen and phosphorus limitation, light limitation and, for diatoms, limitation of silica. See the Water Clarity section above for diagnostics related to factors limiting light.

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appendix A

# Refined Designated Uses for the Chesapeake Bay and Tidal Tributaries

## BACKGROUND

Federal water quality standards regulations establish that states must specify appropriate water uses to be achieved and protected. Current designated uses applied to the waters of the Chesapeake Bay and its tidal tributaries do not fully reflect natural conditions and are too broad in their definition of 'use' to support the adoption of more habitat-specific aquatic life criteria. Furthermore, they change across jurisdictional borders in the same body of water.

Under the federal water quality standards regulation, states may adopt subcategories of uses, seasonal uses and may remove uses under certain conditions (including natural, physical and socio-economic conditions). If a state wishes to remove or establish a subcategory of a designated use that requires a less stringent water quality criteria, the state must conduct a use-attainability study. States must also demonstrate that all water uses present on or after November 28, 1975, will always be protected.

The *Chesapeake 2000* agreement and the subsequent six state, District of Columbia and EPA memoranda of understanding challenged the Bay watershed jurisdictions to, "by 2010, correct the nutrient- and sediment-related problems in the Chesapeake Bay and its tidal tributaries sufficiently to remove the Bay and the tidal portions of its tributaries from the list of impaired waters under the Clean Water Act" (Chesapeake Executive Council 2000; Chesapeake Bay Watershed Partners 2001).

These agreements included commitments to "define the water quality conditions necessary to protect aquatic living resources" by 2001 and to have the jurisdictions with tidal waters "use their best efforts to adopt new or revised water quality standards consistent with the defined water quality conditions" by 2003. Against this backdrop of a renewed commitment to restore Bay water quality (in part through the adoption of a consistent set of Chesapeake Bay water quality criteria as state standards), it was recommended that the underlying tidal-water designated uses must be refined to better reflect desired Bay water quality conditions.

In considering the refinement of the tidal-water designated uses, the six Bay watershed states and the District of Columbia should take into account five principal considerations:

- Habitats used in common by sets of species and during particular life stages should be delineated as separate designated uses;
- Natural variations in water quality should be accounted for by the designated uses;
- Seasonal uses of different habitats should be factored into the designated uses;
- The Chesapeake Bay criteria for dissolved oxygen, water clarity and chlorophyll *a* should be tailored to support each designated use; and
- The refined designated uses applied to the Chesapeake Bay and its tidal tributaries will support the federal Clean Water Act and state goals for uses existing in these water since 1975 and for potential uses not currently met.

The five proposed designated uses were derived to reflect the habitats of an array of recreationally, commercially and ecologically important species. The supporting prey communities were given full consideration along with the 'target species' in defining the designated uses. The Chesapeake Bay criteria were based on effects data from a wide array of species and biological communities to capture the range of sensitivities of the thousands of aquatic species inhabiting the Chesapeake Bay and tidal tributary estuarine habitats. As the U.S. Environmental Protection Agency (2003a) documents extensively, the only species formally listed as threatened or endangered that would be affected by the Chesapeake Bay criteria was the shortnose sturgeon. Low dissolved oxygen effects data for shortnose sturgeon were part of the larger scientific data base used to derive the Chesapeake Bay dissolved oxygen criteria.

This appendix broadly describes the five designated uses and the general boundaries between the migratory fish spawning and nursery; shallow-water bay grass; open-water fish and shellfish; deep-water seasonal fish and shellfish; and deep-channel seasonal refuge designated use habitats (Table A-1). Figure 1 in the Executive Summary illustrates the conceptual framework of the refined tidal-water designated uses. More detailed descriptions of and documentation on the five designated uses are published in the *Technical Support Document for the Identification of Chesapeake Bay Designated Uses and Attainability* (U.S. EPA 2003b).

## CHESAPEAKE BAY TIDAL-WATER DESIGNATED USES

The following descriptions of designated uses provide the context for deriving dissolved oxygen, water clarity and chlorophyll *a* water quality criteria for the Chesapeake Bay provided in this *Regional Criteria Guidance*. Correct application of water quality criteria depends on the accurate delineation of these designated uses. For example, each of these designated uses have distinct dissolved oxygen criteria derived to match the respective level of protection required.

Table A-1. General descriptions of the five proposed Chesapeake Bay tidal-water designated uses.

| |
|---|
| **Migratory Fish Spawning and Nursery Designated Use:** Aims to protect migratory finfish during the late winter/spring spawning and nursery season in tidal freshwater to low-salinity habitats. This habitat zone is primarily found in the upper reaches of many Bay tidal rivers and creeks and the upper mainstem Chesapeake Bay and will benefit several species including striped bass, perch, shad, herring and sturgeon. |
| **Shallow-Water Designated Use:** Designed to protect underwater bay grasses and the many fish and crab species that depend on the shallow-water habitat provided by grass beds. |
| **Open-Water Fish and Shellfish Designated Use:** Designed to protect water quality in the surface water habitats within tidal creeks, rivers, embayments and the mainstem Chesapeake Bay year-round. This use aims to protect diverse populations of sportfish, including striped bass, bluefish, mackerel and seatrout, bait fish such as menhaden and silversides, as well as the listed shortnose sturgeon. |
| **Deep-Water Seasonal Fish and Shellfish Designated Use:** Aims to protect living resources inhabiting the deeper transitional water column and bottom habitats between the well-mixed surface waters and the very deep channels during the summer months. This use protects many bottom-feeding fish, crabs and oysters, as well as other important species, including the bay anchovy. |
| **Deep-Channel Seasonal Refuge Designated Use:** Designed to protect bottom sediment-dwelling worms and small clams that act as food for bottom-feeding fish and crabs in the very deep channel in summer. The deep-channel designated use recognizes that low dissolved oxygen conditions prevail in the deepest portions of this habitat zone and will naturally have very low to no oxygen during the summer. |

The watershed states with tidally influenced Chesapeake Bay waters—Maryland, Virginia, Delaware and the District of Columbia—have the ultimate responsibility for defining and adopting the designated uses into their state water quality standards. These uses will be adopted as subcategories of current state tidal-water designated uses, which are designed to protect aquatic life. The formal process for refining designated uses will meet the requirements of the Clean Water Act. The adopted designated uses will protect existing aquatic and human uses of the tidal waters that have been present since 1975, as well as potential uses. The specific use definitions and the spatial application of the final designated uses will undergo public review and the four jurisdictions' respective regulatory adoption processes prior to final approval by EPA.

## MIGRATORY FISH SPAWNING AND NURSERY DESIGNATED USE

Waters with this designated use support the survival, growth and propagation of balanced indigenous populations of ecologically, recreationally and commercially

important anadromous, semi-anadromous and tidal-fresh resident fish species inhabiting spawning and nursery grounds from February 1 through May 31.

Chesapeake Bay tidal waters support spawning areas and juvenile nurseries for a host of anadromous and semi-anadromous fish, important not only to Chesapeake Bay fishery populations, but also to those of the entire East Coast, such as striped bass. The eggs, larvae and early juveniles of anadromous and semi-anadromous species often have more sensitive habitat quality requirements than other species and life stages (Funderburk et al. 1991; Jordan et al. 1992). Thus, the combined migratory spawning and nursery habitats were delineated as a refined tidal-water designated use for the Chesapeake Bay and its tidal tributaries.

### Designated Use Boundary Delineation

The boundaries of the migratory fish spawning and nursery designated use are broadly delineated from the upriver extent of tidally influenced waters to the downriver and lower Bay spawning and nursery habitats that have been determined through a composite of all targeted anadromous and semi-anadromous fish species' spawning and nursery habitats. Free-flowing streams and rivers, where several of the target species (such as shad and river herring) migrate for spawning, are protected through other existing state water quality standards.

From February 1 through May 31, the migratory fish spawning and nursery designated use coincides with and, therefore, encompasses portions of the shallow-water bay grass and open- water fish and shellfish designated use habitats. Therefore, the horizontal and vertical delineations for the migratory fish spawning and nursery designated use are the same as those of the open-water fish and shellfish designated uses. For those areas designated for migratory spawning and nursery uses, the designated use extends horizontally from the intertidal zone (mean low water) across the body of water to the adjacent intertidal zone, and down through the water column to the bottom sediment-water interface.

## SHALLOW-WATER BAY GRASS DESIGNATED USE

Waters with this designated use support the survival, growth and propagation of rooted, underwater bay grasses necessary for the propagation and growth of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish inhabiting vegetated shallow-water habitats.

### Designated Use Rationale

The shallow-water bay grass designated use protects a wide variety of species, such as largemouth bass and pickerel, which inhabit vegetated tidal-fresh and low-salinity habitats; juvenile speckled sea trout in vegetated higher salinity areas; and blue crabs that inhabit vegetated shallow-water habitats covering the full range of salinities encountered in the Chesapeake Bay and its tidal tributaries. Underwater bay grasses,

the critical community that the designated use protects, provide the shelter and food that make shallow-water habitats so unique and integral to the productivity of the Chesapeake Bay ecosystem. Many Chesapeake Bay species depend on vegetated shallow-water habitats at some point during their life cycle (Funderburk et al. 1991). Given the unique nature of this habitat and its critical importance to the Chesapeake Bay ecosystem, shallow waters were delineated as a refined tidal-water designated use for the Chesapeake Bay and its tidal tributaries.

The shallow-water bay grass designated use is intended specifically to delineate the habitats where the water clarity criteria would apply. The open-water fish and shellfish designated use and the accompanying dissolved oxygen criteria will fully protect the biological communities inhabiting shallow-water habitats. The open-water fish and shellfish designated use extends into the intertidal zone and protects shallow-water organisms that do not depend on bay grasses. The seasonal shallow-water bay grass designated use, similar to the migratory fish spawning and nursery use, actually coincides with the year-round open-water designated use and provides specific protection for underwater bay grasses through the application of water clarity criteria.

### Designated Use Boundary Delineation

The shallow-water bay grass designated use covers tidally influenced waters from the intertidal zone to a Chesapeake Bay Program segment-specific depth contour from 0.5 to 2 meters. The shallow-water designated use applies during the bay grass growing season: April 1 through October 31 for tidal-fresh, oligohaline and mesohaline segments, and March 1 through May 31 and September 1 through November 30 for polyhaline segments.

## OPEN-WATER FISH AND SHELLFISH DESIGNATED USE

Waters with this designated use support the survival, growth and propagation of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish species inhabiting open-water habitats.

### Designated Use Rationale

The natural temperature and salinity stratification of open waters influence dissolved oxygen concentrations, and thus the distribution of Chesapeake Bay species. Waters located above the pycnocline with higher oxygen levels support a different community of species than deeper waters from late spring to early fall. Several well-known species that inhabit these open waters are menhaden, striped bass and bluefish. Their habitat requirements and prey needs differ from those of species and communities inhabiting deeper water habitats during the summer months.

### Designated Use Boundary Delineation

From June 1 through September 30, the open-water designated use includes tidally influenced waters extending horizontally from the shoreline measured at mean low

water, to the adjacent shoreline, and extending through the water column to the bottom. If the presence of a pycnocline prevents oxygen replenishment, the open-water fish and shellfish designated use extends only as far as the upper boundary of the pycnocline. If a pycnocline exists but other physical circulation patterns (such as the inflow of oxygen-rich oceanic bottom waters) provide oxygen replenishment to the deep waters, the open-water fish and shellfish designated use extends to the bottom water-sediment interface.

From October 1 through May 31, the boundaries of the open-water designated use include all tidally influenced waters extending horizontally from the shoreline, measured at mean low water, to the adjacent shoreline, and down into the water column to the bottom water-sediment interface.

## DEEP-WATER SEASONAL FISH AND SHELLFISH DESIGNATED USE

Waters with this designated use protect the survival, growth and propagation of balanced, indigenous populations of important fish and shellfish species inhabiting deep-water habitats.

### Designated Use Boundary Delineation

This designated use refers to tidally influenced waters located between the measured depths of the upper and lower boundaries of the pycnocline, where a measured pycnocline is present and presents a barrier to oxygen replenishment from June 1 through September 30. In some areas, the deep-water designated use extends from the upper boundary of the pycnocline down to the sediment/water interface at the bottom, where a lower boundary of the pycnocline is not calculated due to the depth of the water column.

## DEEP-CHANNEL SEASONAL REFUGE DESIGNATED USE

Waters within this designated use must protect the survival of balanced, indigenous populations of ecologically important benthic infaunal and epifaunal worms and clams, which provide food for bottom-feeding fish and crabs.

### Designated Use Boundary Delineation

Deep-channel seasonal refuge designated use waters are defined as tidally influenced waters at depths greater than the measured lower boundary of the pycnocline in isolated deep channels. The deep-channel designated use is defined laterally by bathymetry of the trough and vertically by the lower boundary of the pycnocline above, and below, at the sediment-water interface on the bottom.

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appendix B

# Sensitivity to Low Dissolved Oxygen Concentrations for Northern and Southern Atlantic Coast Populations of Selected Test Species

This appendix provides the following lines of evidence to support the conclusion that the data used in the calculation of the Virginian Province saltwater dissolved oxygen criteria (U.S. EPA 2000) are appropriate for the Chesapeake Bay dissolved oxygen criteria development.

For the juvenile criterion (Final Acute Value), most test temperatures ranged from 19°C to 30°C. Three species were tested at temperatures less than 19°C: *Homarus americanus* (15°C), *Carcinus maenus* (10°C) and *Rithropanopeus harrisii* (10°C). Fourteen genera were tested at 19°C to 21.5°C and eight genera were tested at 23°C to 30°C. Figure B-1 shows the cumulative rank plot for genus mean acute values (GMAV) using data from Appendix B of the Virginian Province saltwater dissolved oxygen criteria document (U.S. EPA 2000). The data were segregated into '20°C' and '26°C'groups, representing the 14 and 8 genera groups mentioned above, respectively. Plots of the two sets of data overlap, showing that both groups give a similar estimate of the range for the juvenile community's sensitivity to hypoxia. The criteria minimum concentrations (CMC) calculated for the two sets of data are likewise very similar, 2.36 mg/L for the '20°C' group, and 2.26 mg/L for the '26°C' group.

The same type of analysis was conducted using the 24-hour larval $LC_{50}$ data (lethal concentration at which 50 percent mortality of the test organisms was observed) from Appendix D of the Virginian Province document (Figure B-2; U.S. EPA 2000). The temperature ranges were also similar, 18°C to 22°C for the '20°C' group, and 23°C to 30°C for the '26°C' group. There were 14 genera in the former and 9 genera in the latter. The conclusion is the same for larvae as for juveniles, a similar distribution of community sensitivity to hypoxia for both sets of temperatures.

In addition to the data from the Virginian Province document, the EPA has conducted tests comparing the sensitivity to hypoxia for northern and southern populations of two invertebrates (the mud crab, *Dyspanopeus sayi* and the grass shrimp, *Palaemonetes vulgarus,* larvae for both species) and one fish (the inland silverside, *Menidia beryllina,* juveniles and larvae; Thursby, personal communication). All of the northern populations were from Rhode Island. The southern populations of

invertebrates were from Georgia, and the fish were from Florida. The exposure response data are shown in figures B-3 through B-6. The northern and southern populations of each species responded similarly to low dissolved oxygen conditions, even though they were conducted at different temperatures.

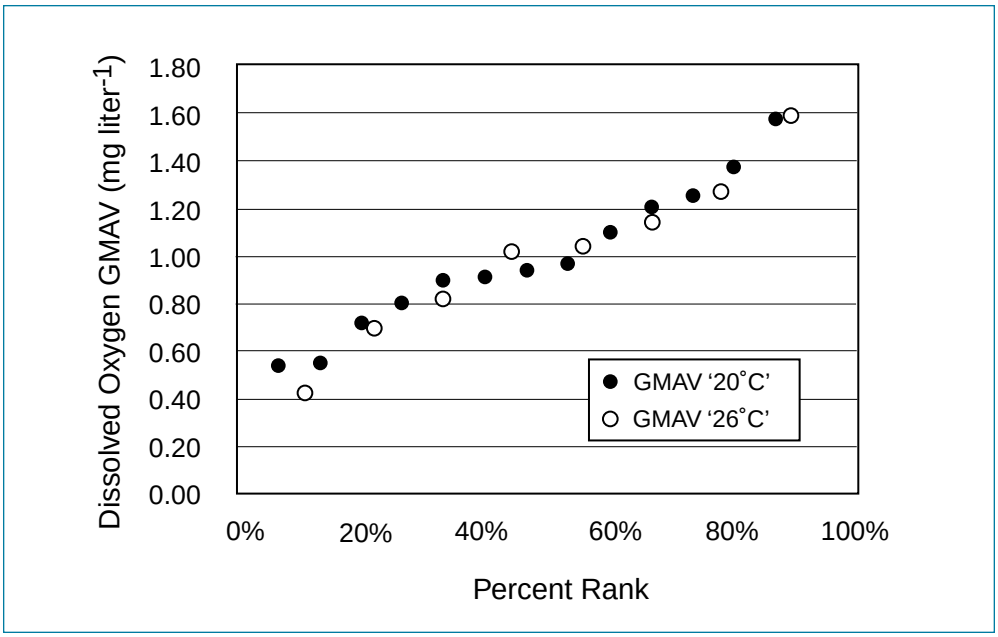


**Figure B-1.** Plot of juvenile genus mean acute values (GMAVs ) against percent rank. Data are from Appendix B in the Virginian Province saltwater dissolved oxygen criteria document (U.S. EPA 2000).

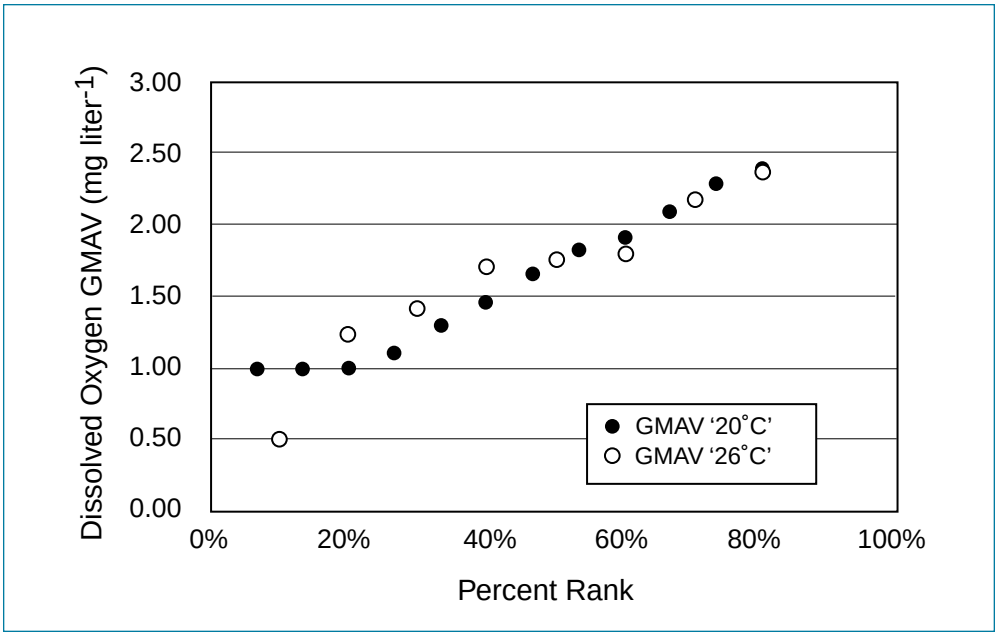


**Figure B-2.** Plot of larval genus mean acute values (GMAVs ) against percent rank. Data are from Appendix D in the Virginian Province saltwater dissolved oxygen criteria document (U.S. EPA 2000).

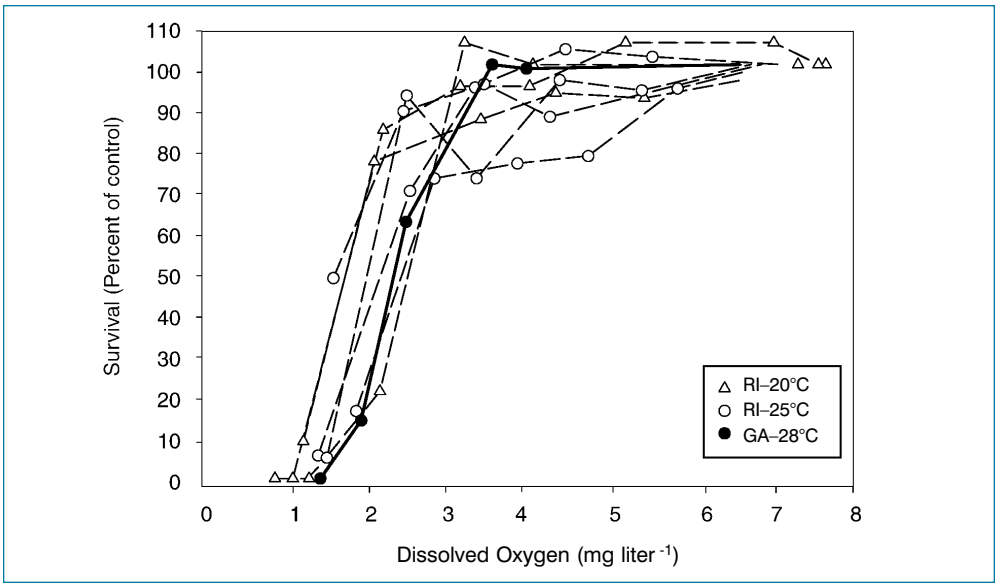


**Figure B-3.** Ninety-six hour dose-response for larvae of the marsh grass shrimp *Palaemonetes vulgaris* exposed to various levels of low dissolved oxygen. Open symbols are for tests conducted with populations from Rhode Island (RI) (three at 20°C and four at 25°C). The closed circles are data for a population from Georgia (GA) conducted at 28°C. All of the RI data are from tests included in the Virginian Province saltwater dissolved oxygen criteria document and are listed in Poucher and Coiro (1997). Tests were initiated with larval less than 24 hours old.

Source: U.S. EPA 2000.

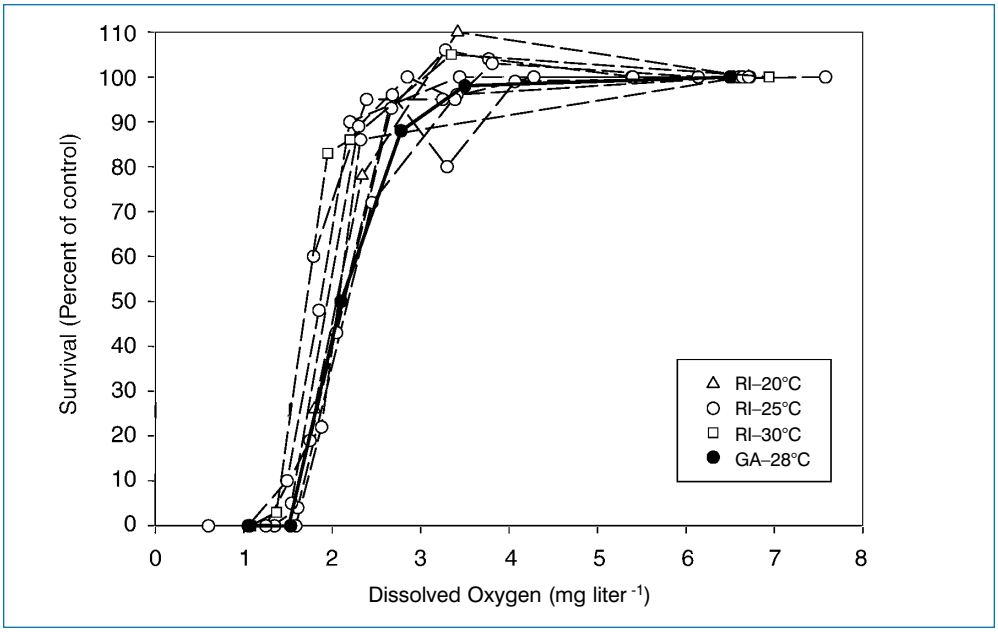


**Figure B-4.** Ninety-six hour dose-response for larvae of the Say mud crab *Dyspanopeus sayi* exposed to various levels of low dissolved oxygen. Open symbols are for tests conducted with populations from Rhode Island (RI) (one at 20°C, seven at 25°C, and one at 30°C). The closed circles are data for a population from Georgia (GA) conducted at 28°C. All of the Rhode Island data are from tests included in the Virginian Province saltwater dissolved oxygen criteria document and are listed in Poucher and Coiro (1997). Tests were initiated with larval animals ranging from stage 1 to stage 3 in development.

Source: U.S. EPA 2000.

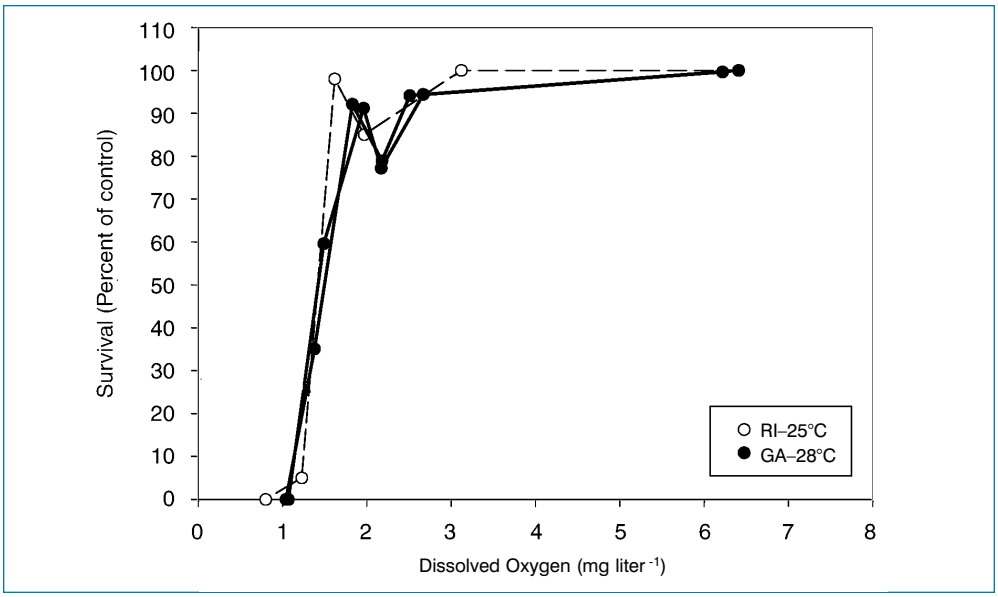


**Figure B-5.** Ninety-six hour dose-response for larvae of the inland silverside *Menidia beryllina* exposed to various levels of low dissolved oxygen at two temperatures. Open circles are for a test conducted with a population from Rhode Island (RI) (25°C) and closed circles are for two tests with a population from Georgia (GA) conducted at 28°C. The Rhode Island data are from a test listed in Poucher and Coiro (1997). Tests were initiated with 7-day-old larvae.

Source: U.S. EPA 2000.

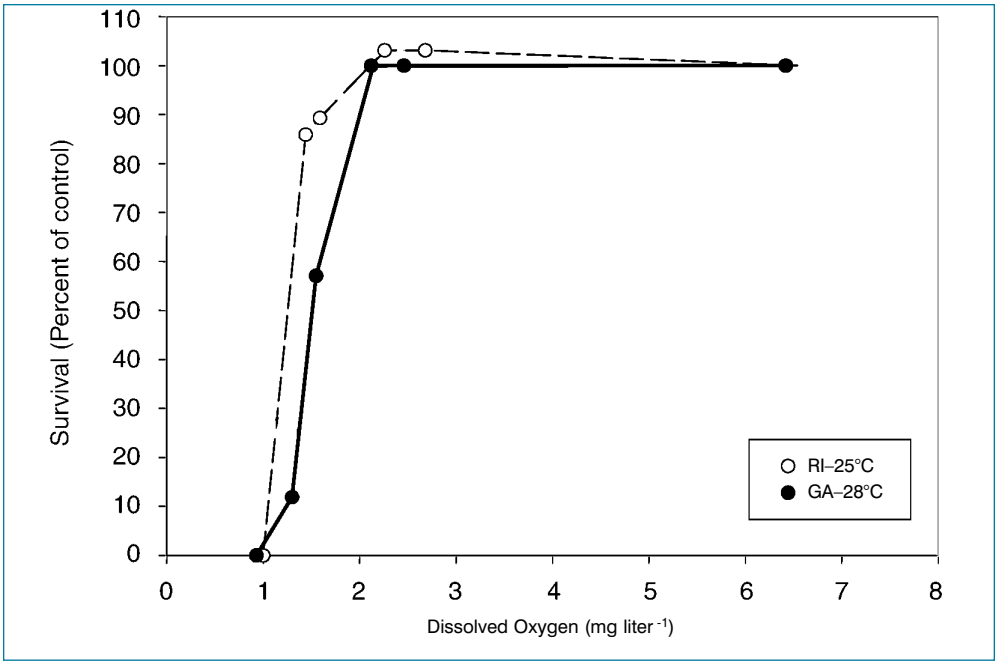


**Figure B-6.** Seventy-two hour dose-response for juveniles of the inland silverside *Menidia beryllina* exposed to various levels of low dissolved oxygen at two temperatures. Open circles are for *a* test conducted with a population from Rhode Island (RI) (25°C) and closed circles are for a test with a population from Georgia (GA) conducted at 28°C.

Source: U.S. EPA 2000.

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appendix C

# Summary of Literature on the Tolerance of Chesapeake Bay Macrobenthic Species to Low Dissolved Oxygen Conditions

| Species | Life Stage | Dissolved Oxygen (mg liter$^{-1}$) | Temp (°C) | Observed Response | Reference |
|---|---|---|---|---|---|
| **Mollusca** | | | | | |
| *Abra alba* | Adult | 0 | 10 | $LD_{50}$ in 200 hrs | Dries and Theede 1974 |
| *Cardium edule* | Adult | 0 | 10 | 50% mortality in 7 days | Thamdrup 1935 referenced in O'Connor (unpublished manuscript) |
| | Adult | 0.15 | 10 | 50% mortality in 102 hrs (4.3 days) without sulfide, 96 hrs (4 days) with sulfide (50 mg liter$^{-1}$ $Na_2S.9H_2O$ | Theede et al. 1969; Theede 1973 |
| *Carium lamarki* | Adult | 0 | 10 | $LD_{50}$ in - 220 hrs (9.2 days) | Dries and Theede 1974 |
| *Littorina littoria* | Adult | 0.15 | 10 | $LD_{50}$ in 365 hrs (15.2 days) without sulfide, 180 hrs (7.5 days) with sulfide; 50 mg liter$^{-1}$ | Theede et al. 1969; Theede 1973 |
| *Littorina saxatilus* | Adult | 0.15 | 10 | $LD_{50}$ in 365 hrs (15.2 days) without sulfide, 72 hrs (3 days) with sulfide; 50 mg liter$^{-1}$ | Theede et al. 1969; Theede 1973 |
| *Macoma balthica* | Adult | 0 | 10 | 4% mortality in 7 days | Thamdrup 1935; referenced in O'Conner (unpublished manuscript) |
| | Adult | 0 | 10 | $LD_{50}$ in 500 hrs (20.8 days) | Dries and Theede 1974 |
| *Mercenaria mercenaria* | Larvae | 0.9-2.4 | 25 | Reduced growth | Morrison 1971 |
| | | 0.2 | 25 | 100% mortality in 14 days | Morrison 1971 |
| | NR | 0.9 | 25 | 0% mortality in 14 days | Morrison 1971 |

| Species | Life Stage | Dissolved Oxygen (mg liter$^{-1}$) | Temp (°C) | Observed Response | Reference |
|---|---|---|---|---|---|
| | Juvenile/ Adult (31-38 mm) | 5.7 | 19-24 | Maximum burrowing rate | Savage 1976 |
| | NR | 0.9-1.8 | 17-24 | Reduced burrowing rate | Savage 1976 |
| | NR | 0.9 | 19 | No mortality in 21 days and 30 days (two trials) | Savage 1976 |
| *Mulina lateralis* | Juvenile (5 mm) | 0 | 10 | $LT_{50}$ in 10.5 days without sulfide, 4.3 days with sulfide; 644 mg liter$^{-1}$ $Na_2S.9H_2O$ | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 20 | $LT_{50}$ in 7.5 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| *Mulina lateralis* | NR | 0 | 30 | $LT_{50}$ in 2 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | Adult (10 mm) | 0 | 10 | $LT_{50}$ in 10 days without sulfide, 3.8 days with sulfide; 644 mg liter$^{-1}$ $Na_2S.9H_2O$ | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 20 | $LT_{50}$ in 2.5 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 30 | $LT_{50}$ in 1.8 days | Shumway and Scott 1983; referenced in O'conner (unpublished manuscript) |
| *Mya arenaria* | NR | 0 | 'very low' | Survived for 'weeks' | Collip 1921; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 14 | Survived 8 days | Collip 1921; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 31 | Survived 1 day | Collip 1921; referenced in O'Conner (unpublished manuscript) |

| Species | Life Stage | Dissolved Oxygen (mg liter$^{-1}$) | Temp (°C) | Observed Response | Reference |
|---|---|---|---|---|---|
| *Mya arenaria* | Adult | 0.2 | 10 | $LC_{50}$ in 21 days without sulfide, 17 days with sulfide. | Theede et al. 1969; Theede 1973; referenced in O'Conner (unpublished manuscript) |
| *Mytilus edulis* | Adult | 0.2 | 10 | $LC_{50}$ in 35 days without sulfide, 25 days with sulfide | Theede et al. 1969; Theede 1973; referenced in O'Conner (unpublished manuscript) |
| | Adult | 0 | 10 | 20% mortality in 7 days | Thamdrup 1935; referenced in O'Conner (unpublished manuscript) |
| *Spisula solidissima* | Adult (49-64 mm) | 5.3-6.0 | 11-22 | Maximum burrowing rate | Savage 1976 |
| | NR | 0.8-1.6 | 11-22 | Reduced burrowing rate, mortality | Savage 1976 |
| | NR | 1.6 | 21.7 | 1 of 9 dead in 5 days | Savage 1976 |
| | NR | 0.9 | 21.0 | 3 of 9 dead in 5 days | Savage 1976 |
| | Juvenile/ Adult (31-28mm) | 5.7 | 19-24 | Maximum burrowing rate | Savage 1976 |
| | NR | 0.9-1.8 | 17-24 | Reduced burrowing rate | Savage 1976 |
| *Spisula solidissima* | NR | 0.9 | 19 | No mortality in 21 days and 30 days (two trials) | Savage 1976 |
| *Mulinia lateralis* | Juvenile (5 mm) | 0 | 10 | $LT_{50}$ in 10.5 days without sulfide, 4.3 with sulfide; 644 mg liter$^{-1}$ $Na_2S.9H_2O$ | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 20 | $LT_{50}$ in 7.5 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 30 | $LT_{50}$ in 2 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |

| Species | Life Stage | Dissolved Oxygen (mg liter$^{-1}$) | Temp (°C) | Observed Response | Reference |
|---|---|---|---|---|---|
| | Adult (10 mm) | 0 | 10 | $LT_{50}$ in 10 days without sulfide, 3.8 days with sulfide; 644 mg liter$^{-1}$ $Na_2S.9H_2O$ | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 20 | $LT_{50}$ in 2.5 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | NR | 0 | 30 | $LT_{50}$ in 1.8 days | Shumway and Scott 1983; referenced in O'Conner (unpublished manuscript) |
| | Adult (100 mm) | 1.0 | 10 | $LC_{50}$ in 15 days; initial mortality in 8 days; total mortality in 30 days | Thurberg and Goodlett 1979 |
| *Mulinia lateralis* | NR | 3.0 | 10 | No mortality in 2 months | Thurberg and Goodlett 1979 |
| | Juvenile/ Adult (3.7-5 cm) | 1.0 | 10 | $LC_{50}$ in 7 days | Thurberg and Goodlett 1979 |
| | Juvenile/ Adult (3.8-4.6 cm) | 2.0 | 10 | $LC_{50}$ in 21 days | Thurberg and Goodlett 1979 |
| **Polychaeta** | | | | | |
| *Capitella capitata* | Adult | 0 | 12 | Mortality in 8 days | Jacubowa and Malm 1931; referenced in O'Conner (unpublished manuscript) |
| *Capitomastus minimus* | Adult | 0 | 12 | Mortality in 8 days | Jacubowa and Malm 1931; referenced in O'Conner (unpublished manuscript) |
| *Etoeone picta* | Adult | 0 | 12 | Mortality in 6 days | Jacubowa and Malm 1931; referenced in O'Conner (unpublished manuscript) |
| *Glycera convoluta* | Adult | 0 | 12 | Mortality in 10 days | Jacubowa and Malm 1931; referenced in O'Conner (unpublished manuscript) |

| Species | Life Stage | Dissolved Oxygen (mg liter$^{-1}$) | Temp (°C) | Observed Response | Reference |
|---|---|---|---|---|---|
| *Harmothae incerta* | Adult | 0 | 12 | Mortality in 5 days | Jacubowa and Malm 1931; referenced in O'Conner (unpublished manuscript) |
| *Nephtys ciliata* | Adult | 0 | 10 | $LD_{50}$ in 140 hr (5.8 days) | Dries and Theede 1974 |
| *Nerevis diversicolor* | Adult | 0.2 | 10 | $LC_{50}$ in 5 days without sulfide, 4 days with sulfide; referenced in O'Conner (unpublished manuscript) | Theede et al. 1969; Theede 1973 |
| | Adult | 0 | 10 | $LD_{50}$ in 120 hrs (5 days) | Dries and Theede 1974 |
| | Adult | 0 | 6-8 | 72 hrs with no mortality; ATP conc. 59% of initial value (after 72 hrs) | Schottler 1979 |
| *Nereis pelagica* | Adult | 0 | 6-8 | 40% mortality after 36 hrs; ATP conc. 51% of initial value (after 72 hrs) | Schottler 1979 |
| *Nereis virens* | Adult | 0 | 6-8 | 72 hrs with no mortality; ATP conc. 57% of initial value (after 72 hrs) | Schottler 1979 |
| *Pectinaria neapolitana* | Adult | 0 | 12 | Mortality in 8 days | Jacubowa and Malm 1931; referenced in O'Conner (unpublished manuscript) |
| *Terebellides stroemi* | Adult | 0 | 10 | $LD_{50}$ in 72 hrs (3 days) | Dries and Theede 1974 |

Source: Holland et al. 1989.

NR = not reported.
$LC_{50}$ = lethal concentration at which 50 percent mortality of the test organisms was observed.
$LD_{50}$ = lethal dose (same as $LC_{50}$).
$LT_{50}$ = lethal threshold (same as $LC_{50}$).

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appendix D

# Narrative, Numerical and Method-based Chlorophyll *a* Criteria Adopted as Water Quality Standards by States Across the U.S.

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria | |
|---|---|---|---|
| Alabama | Narrative criteria for specific lakes and reservoirs<br>- Walter F. George<br>- West Point<br>- Weiss | Numeric chlorophyll *a* criteria<br>-16 µg liter$^{-1}$<br>-27 µg liter$^{-1}$<br>-20 µg liter$^{-1}$ | Chlorophyll *a* levels set for samples collected between April-October. Samples collected monthly at deepest points. |
| Alaska | (1) Fresh water<br>(A) water supply<br>(i) drinking, culinary and food processing;<br>(ii) agriculture, including irrigation and stock watering;<br>(iii) aquaculture;<br>(iv) industrial;<br>(B) water recreation<br>(i) contact recreation;<br>(ii) secondary recreation;<br>(C) growth and propagation of fish, shellfish, other aquatic life and wildlife; and<br>(2) Marine water<br>(A) water supply<br>(i) aquaculture;<br>(ii) seafood processing;<br>(iii) industrial;<br>(B) water recreation<br>(i) contact recreation;<br>(ii) secondary recreation;<br>(C) growth and propagation of fish, shellfish, other aquatic life and wildlife; and<br>(D) harvesting for consumption of raw mollusks or other raw aquatic life. | Narrative criteria<br>Aesthetic Qualities<br>CRITERIA<br>All waters free from substances attributable to wastewater or other discharges that:<br>(5) Produce undesirable or nuisance aquatic life. | |
| Arizona | Designated uses of a surface water may include full body contact, partial body contact, domestic water source, fish consumption, aquatic and wildlife (warm-water fishery), aquatic and wildlife (ephemeral), aquatic and wildlife (effluent dependent water) agricultural irrigation, and agricultural livestock watering. The designated uses for specific waters are listed in Appendix B of the article. | **R 18-11-108 Narrative Water Quality Standards**<br>A. A surface water shall be free from pollutants in amounts or combinations that: 6) cause the growth of algae or aquatic plants that inhibit or prohibit the habitation, growth or propagation of other aquatic life or that impair recreational uses. | |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria | |
|---|---|---|---|
| California Water Quality Control Board Region 5 | Central Valley Sacramento and San Joaquin River Basins | Wineries with stills produce substantial quantities of stillage waste which is high in concentrations of BOD and nitrogen. The stillage is normally discharged directly to land without any prior treatment. There is a potential for the waste to affect water quality and to create nuisance conditions. A study has been conducted to develop recommendations for minimizing water quality effects and nuisance conditions resulting from land application of stillage waste. There is a need to implement guidelines for land disposal of stillage waste that can be used by the industry as a general indication of minimum disposal practices when accompanied with suitable soil, weather, groundwater and other conditions affecting the discharge. | |
| California Water Quality Control Board | San Francisco Bay/ Sacramento-San Joaquin Delta Estuary | Water Quality Compliance and Baseline Monitoring Monthly monitoring for chlorophyll *a* at several stations. Water Quality Objective: To prevent nuisance. | |
| California Water Quality Control Board Region 2 | San Francisco Bay region | One criterion to protect the aesthetic value of water used for recreation from excessive algal growth is based on chlorophyll *a*.<br>Biostimulatory substances can cause high chlorophyll *a* level rise. | |
| Colorado | Numeric water quality criteria by designated use and for indicated rivers and streams. | Bear Creek Reservoir …Traditionally, the average concentration of chlorophyll *a* has been selected by the commission as the indicator of lake condition. For Bear Creek Reservoir, however, peak algal biomass (chlorophyll *a*) was selected as the most important of these indicators upon which to assess trophic response because algal blooms are most often associated with impaired uses. To achieve the goal of change in trophic status, a 16 percent reduction in the frequency of nuisance algal blooms during the growing season would need to be achieved, as well as a reduction in frequency and magnitude of the peak chlorophyll *a* concentrations. | |
| Connecticut | Inland Surface waters<br>-Class AA<br>Existing or proposed drinking water supply; fish and wildlife habitat; recreational use; agricultural, industrial supply and other purposes (recreational uses may be restricted).<br>-Class A<br>Potential drinking water supply; fish and wildlife habitat; recreational use; agricultural, industrial supply and other legitimate uses, including navigation.<br>-Class B<br>Recreational use; fish and wildlife habitat; agricultural and industrial supply and other legitimate uses, including navigation.<br>-Class C and Class D (goal to be class A or B) | Lake: Oligotrophic<br>May be class A, AA or class B water. | 0-2 µg liter$^{-1}$ mid-summer |
| | | Lake: Mesotrophic<br>May be Class AA, Class A, or Class B. | 2-15 µg liter$^{-1}$ mid-summer |
| | | Lake: Eutrophic<br>May be **C**lass AA, Class A, or Class B water. | 15-30 µg liter$^{-1}$ mid-summer |
| | | Lake: Highly Eutrophic<br>May be **C**lass AA, Class A, or Class B water. | 30+ µg liter$^{-1}$ mid-summer |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Georgia | Chlorophyll *a* criteria for only Lakes and Major Lake tributaries | West Point Lake: shall not exceed 27 µg liter$^{-1}$ (April-October)<br>Walter F. George Lake: shall not exceed 18 µg liter$^{-1}$ (April-October)<br>Lake Jackson: shall not exceed 20 µg liter$^{-1}$ (April – October)<br>Lake Alatoona<br>Upstream from the Dam – 10 µg liter$^{-1}$<br>Allatoona Creek upstream from I-75 10 µg liter$^{-1}$<br>Mid-Lake downstream from Kellogg Creek – 10µg liter$^{-1}$<br>Little River upstream from Highway 205 – 15 µg liter$^{-1}$<br>Etowah River upstream from Sweetwater Creek– 12 µg liter$^{-1}$<br>Lake Sidney Lanier<br>Upstream from the Flowery Branch confluence – 5 µg liter$^{-1}$<br>At Browns Bridge Road (State Road 369) – 5 µg liter$^{-1}$<br>At Bolling Bridge (State Road 53) on Chestatee River – 10 µg liter$^{-1}$<br>At Lanier Bridge (State Road 53) on Chattahoochee River – 10 µg liter$^{-1}$ |
| Hawaii | Criteria for all Estuaries except Pearl Harbor | Chlorophyll *a* (µg liter$^{-1}$) – geometric mean not to exceed the given value of 2.00 µg liter$^{-1}$. Not to exceed the given value more than 10 percent of the time 5.00 µg liter$^{-1}$. Not to exceed the given value more than 2 percent of the times of 10.00 µg liter$^{-1}$. |
| | Criteria for Pearl Harbor Estuary | Chlorophyll *a* (µg liter$^{-1}$) – geometric mean not to exceed the given value of 3.50 µg liter$^{-1}$. Not to exceed the given value more than 10 percent of the time – 10.00 µg liter$^{-1}$. Not to exceed the given value more than 2 percent of the time – 20.00 µg liter$^{-1}$. |
| | Open coastal waters (note that criteria for open coastal waters differ, based on fresh water discharge.) | Chlorophyll *a* (µg liter$^{-1}$) – geometric mean not to exceed the given value of 0.30 µg liter$^{-1}$*, 0.15 µg liter$^{-1}$**<br>Not to exceed the given value more than 10 percent of the time – 0.90 µg liter$^{-1}$*, 0.50 µg liter$^{-1}$**<br>Not to exceed the given value more than 2 percent of the time – 1.75 µg liter$^{-1}$*, 1.00 µg liter$^{-1}$**<br>*"Wet" criteria apply when the coastal waters receive more than three million gallons per day of fresh water discharge per shoreline mile.<br>** "Dry" criteria apply when the open coastal waters receive less than three million gallons per day of fresh water discharge per shoreline mile. |
| | Oceanic waters | Chlorophyll *a*<br>0.06 µg liter$^{-1}$ – geometric mean not to exceed the given value<br>0.12 µg liter$^{-1}$ – not to exceed the given value more than 10 percent of the time<br>0.20 µg liter$^{-1}$ – not to exceed the given value more than 2 percent of the time |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Idaho | All waters | Excess Nutrients. Surface waters of the state shall be free from excess nutrients that can cause visible slime growths or other nuisance aquatic growths impairing designated beneficial uses. |
| Iowa | By designated uses<br>General use segments.<br><br>Designated use segments:<br>Primary contact recreation (Class "A").<br>Cold water aquatic life (Class "B (CW)").<br>High quality water (Class "HQ").<br>High quality resource water (Class "HQR").<br>Significant resource warm water (Class "B(WW)").<br>Limited resource warm water (Class"B(LR)").<br>Lakes and wetlands (Class "B(LW)").<br>Drinking water supply (Class "C"). | **General Water Quality criteria**<br>b. Such waters shall be free from floating debris, oil, grease, scum and other floating materials attributable to wastewater discharges or agricultural practices in amounts sufficient to create a nuisance.<br><br>c. Such waters shall be free from materials attributable to wastewater discharges or agricultural practices producing objectionable color, odor or other aesthetically objectionable conditions. |
| Kansas | Aquatic Life support use<br><br>Recreation use | Nutrients. The introduction of plant nutrients into streams, lakes or wetlands from artificial sources shall be controlled to prevent the accelerated succession or replacement of aquatic biota or the production of undesirable quantities or kinds of aquatic life.<br><br>The introduction of plant nutrients into surface waters designated for primary or secondary contact recreational use shall be controlled to prevent the development of objectionable concentrations of algae or algal by-products or nuisance growths of submersed, floating or emergent aquatic vegetation. |
| Louisiana | Narrative criteria for all waters | Nutrients. The naturally occurring range of nitrogen-phosphorous ratios shall be maintained. This range shall not apply to designated intermittent streams. To establish the appropriate range of ratios and compensate for natural seasonal fluctuations, the administrative authority will use site-specific studies to establish limits for nutrients. Nutrient concentrations that produce aquatic growth to the extent that it creates a public nuisance or interferes with designated water uses shall not be added to any surface waters. |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria | |
|---|---|---|---|
| Maine | All Lakes<br><br>1. Class GPA waters. Class GPA shall be the sole classification of great ponds and natural ponds and lakes less than 10 acres in size.<br>B. Class GPA waters shall be described by their trophic state based on measures of the chlorophyll *a* content, Secchi disk transparency, total phosphorus content and other appropriate criteria. Class GPA waters shall have a stable or decreasing trophic state, subject only to natural fluctuations and shall be free of culturally induced algal blooms which impair their use and enjoyment. | Trophic state - Maine Trophic State Index (TSI) Trophic state is the ability of a body of water to produce algae and other aquatic plants. The trophic state of a body of water is a function of its nutrient content and may be estimated using the Maine Trophic State Index (TSI) as follows….<br>In addition, a scale of 0 to 100 is established in order to measure the trophic state or degree of enrichment of lakes due to nutrient input. | TSI = 70 log (mean chlorophyll *a* + 0.7) |
| Massachusetts | All waterbody - Narrative criteria | Control of Eutrophication. …there shall be no new or increased point source discharge of nutrients primarily phosphorus and nitrogen that would encourage cultural eutrophication or the growth of weeds or algae in these Lakes or ponds. Any existing point source discharge containing nutrients in concentration which encourage eutrophication or growth of weeds or algae in these lakes or ponds shall be provided with all reasonable control for non-point source. | |
| Michigan | All waters narrative criteria | **R 323.1060 Plant nutrient**<br>Nutrients shall be limited to the extent necessary to prevent stimulation of growths of aquatic rooted, attached, suspended, and floating plants, fungi or bacteria which are or may become injurious to the designated uses of the waters of the state. | |
| Minnesota | Narrative criteria for all waters | Nuisance conditions prohibited.<br>-Excessive growths of aquatic plants, or other offensive or harmful effects. | |
| Missouri | General criteria for all waters | Waters shall be free from substances or conditions in sufficient amounts to cause unsightly color or turbidity, offensive odor or prevent full maintenance of beneficial uses. | |
| Montana | Eight classifications by designated use | (h) No increases of carcinogenic, bioconcentrating, toxic or harmful parameters, pesticides and organic and inorganic materials, including heavy metals, above naturally occurring concentrations, are allowed. | |
| Nebraska | Agricultural use | This use applies to all surface waters of the state**.** To be aesthetically acceptable, waters shall be free from human-induced pollution which causes: 1) noxious odors; 2) floating, suspended, colloidal, or settleable materials that produce objectionable films, colors, turbidity, or deposits; and 3) the occurrence of u**n**desirable or nuisance aquatic life (e.g., algal blooms). Surface waters shall also be free of junk, refuse, and discarded dead animals. | |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Nevada | Lake Mead - 445A.194 Requirements to maintain existing higher quality for area of Lake Mead; standards for beneficial uses for area not covered by NAC 445A. 196. (NRS 445A.425, 445A.520)<br><br>Designated use<br>Recreation involving contact with water, propagation of aquatic life, including, without limitation, a warm water fishery, recreation not involving contact with water and municipal or domestic supply, or both. | Chlorophyll *a* –µg liter$^{-1}$ requirement to maintain existing Higher Quality<br>b. The requirements for chlorophyll *a* are:<br>(1) Not more than one monthly mean in a calendar year at Station 3 may exceed 45 µg liter$^{-1}$.<br>(2) The mean for chlorophyll *a* in summer (July 1 - September 30) must not exceed 40 µg liter$^{-1}$ at Station 3, and the mean for 4 consecutive summer years must not exceed 30 µg liter$^{-1}$. The sample must be collected from the center of the channel and must be representative of the top 5 meters of the channel. "Station 3" means the center of the channel at which the depth is from 16 to 18 meters.<br>(3) The mean for chlorophyll *a* in the growing season (April l-September 30) must not exceed 16 µg liter$^{-1}$ at LM4 and 9 µg liter$^{-1}$ at LMS. LM4 is located just outside of the Las Vegas Bay launch ramp and marina, next to buoy RW "1." LM5 is located next to buoy RW "A" with the southshore landmark of Cresent Island.<br>(4) The mean for chlorophyll *a* in the growing season (April I - September 30) must not exceed 5 µg liter$^{-1}$ in the open water of Boulder Basin, Virgin Basin, Gregg Basin and Pierce Basin. The single value must not exceed 10 µg liter$^{-1}$ for more than 5 percent of the samples.<br>(5) Not less than 2 samples must be collected between the months of March and October. During months when only one sample is available, that value must be used in place of the monthly mean. |
| New Hampshire | Narrative criteria related to all waters | e) There shall be no new or increased discharge(s) containing phosphorus or nitrogen to tributaries of lakes or ponds that would contribute to cultural eutrophication or growth of weeds or algae in such lakes and ponds. |
| New Jersey | Narrative criteria for all waters | 2. Except as due to natural conditions, nutrients shall not be allowed in concentrations that cause objectionable algal densities, nuisance aquatic vegetation, or otherwise render the waters unsuitable for the designated uses.<br><br>3. Activities resulting in the non-point discharge of nutrients shall implement the best management practices determined by the Department to be necessary to protect the existing or designated uses. |
| New Mexico | Narrative criteria for all waters | E. Plant Nutrients: Plant nutrients from other than natural causes shall not be present in concentrations which will produce undesirable aquatic life or result in a dominance of nuisance species in surface waters of the State. |
| New York | Narrative criteria for all State waters | Waters shall contain no phosphorus and nitrogen in amounts that will result in growths of algae, weeds and slimes that will impair the waters for their best usage. |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| North Carolina | Freshwater – Class C waters and tidal salt water<br>For lakes and reservoirs and other waters subject to growths of macroscopic and microscopic vegetation not designated as trout waters<br><br>Lakes, reservoirs and other waters subject to growths of macroscopic or microscopic vegetation designated as trout waters ( not applicable to lakes and reservoirs less that 10 acres in surface area) | Not to exceed 40 µg liter$^{-1}$<br><br>Not to exceed 15 µg liter$^{-1}$ |
| North Dakota | 1) Municipal and domestic water.<br><br>2) Recreation Fishing and Wildlife<br><br>3) Agricultural uses<br><br>4) Industrial water | 1) Free from substances attributable to municipal, industrial, or other discharges or agricultural practices that will cause the formation of putrescent or otherwise objectionable sludge deposits.<br>(2) Free from floating debris, oil, scum, and other floating materials attributable to municipal, industrial, or other discharges or agricultural practices in sufficient amounts to be unsightly or deleterious.<br>(3) Free from materials attributable to municipal, industrial, or other discharges or agricultural practices producing color, odor, or other conditions to such a degree as to create a nuisance or render any undesirable taste to fish flesh or, in any way, make fish inedible. |
| Ohio | Narrative criteria for all waters | 3745-1-04 Criteria applicable to all waters.<br>(E) Free from nutrients entering the waters as a result of human activity in concentrations that create nuisance growths of aquatic weeds and algae. |
| Oklahoma | Narrative criteria for all waters | To determine excess nutrient by using Carlson's Trophic State Index. Using chlorophyll *a,* a value of 62 or greater, is otherwise listed as "NLW" in Appendix A of chapter. Water are to be designated as "Nutrient-limited watershed" which means a watershed of a waterbody with a designated beneficial use which is adversely affected by excess nutrients as determined by Carlson's Trophic State Index.<br><br>A) Narrative criterion applicable to all waters of the state. Nutrients from point source discharges or other sources shall not cause excessive growth of periphyton, phytoplankton, or aquatic macrophyte communities which impairs any existing or designated beneficial use. |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria | |
|---|---|---|---|
| Oregon | Water use designation by basin. | **340-041-0150**<br>**Nuisance Phytoplankton Growth**<br>The following values and implementation program shall be applied to lakes, reservoirs, estuaries and streams, except for ponds and reservoirs less than ten acres in surface area, marshes and saline lakes:<br>(1) The following average chlorophyll *a* values shall be used to identify water bodies where phytoplankton may impair the recognized beneficial uses:<br>(a) Natural lakes which thermally stratify: 0.01 mg liter$^{-1}$;<br>(b) Natural lakes which do not thermally stratify, reservoirs, rivers and estuaries: 0.015 mg liter$^{-1}$;<br>(c) Average chlorophyll *a* values shall be based on the following methodology (or other methods approved by the Department): A minimum of three samples collected over any three consecutive months at a minimum of one representative location (e.g., above the deepest point of a lake or reservoir or at a point mid-flow of a river) from samples integrated from the surface to a depth equal to twice the Secchi depth or the bottom (the lesser of the two depths); analytical and quality assurance methods shall be in accordance with the most recent edition of *Standard Methods for the examination of Water and Wastewater.* | |
| Rhode Island | Narrative criteria related for all waters | **Freshwater**<br>10 b. None in such concentration that would impair any usages specifically assigned to said Class or cause undesirable or nuisance aquatic species associated with cultural eutrophication, nor cause exceedance of the criterion of 10(a) above in a downstream lake, pond, or reservoir. | **Seawater**<br>Where waters have low tidal flushing rates, applicable treatment to prevent or minimize accelerated or cultural eutrophication may be required for regulated nonpoint source activities. |
| South Dakota | (1) Domestic water supply waters;<br>(2) Coldwater permanent fish life propagation waters;<br>(3) Coldwater marginal fish life propagation waters;<br>(4) Warmwater permanent fish life propagation waters;<br>(5) Warmwater semipermanent fish life propagation waters;<br>(6) Warmwater marginal fish life propagation waters;<br>(7) Immersion recreation waters;<br>(8) Limited contact recreation waters;<br>(9) Fish and wildlife propagation, recreation, and stock watering waters;<br>(10) Irrigation waters; and<br>(11) Commerce and industry waters. | **74:51:01:09. Nuisance aquatic life.**<br>Materials which produce nuisance aquatic life may not be discharged or mused to be discharged into surface waters of the state in concentrations that impair a beneficial use or create a human health problem. | |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Texas | Narrative criteria for all waters | **§307.4. General Criteria.**<br>(e) Nutrient parameters. Nutrients from permitted discharges or other controllable sources shall not cause excessive growth of aquatic vegetation which impairs an existing, attainable, or designated use. Site-specific nutrient criteria, nutrient permit limitations, and/or separate rules to control nutrients in individual watersheds will be established where appropriate after notice and opportunity for public participation and proper hearing. |
| Utah | **High Quality Waters – Category 1, 2, 3**<br>6.1 Class 1 – Protected for use as a raw water source for domestic water systems.<br>a. Class 1A – Reserved.<br>b. Class 1B – Reserved.<br>c. Class 1C – Protected for domestic purposes with prior treatment by treatment processes as required by the Utah Division of Drinking Water<br>6.2 Class 2 – Protected for recreational use and aesthetics.<br>a. Class 2A – Protected for primary contact recreation such as swimming.<br>b. Class 2B – Protected for secondary contact recreation such as boating, wading, or similar uses.<br>6.3 Class 3 – Protected for use by aquatic wildlife.<br>a. Class 3A – Protected for cold water species of game fish and other cold water aquatic life, including the necessary aquatic organisms in their food chain.<br>b. Class 3B – Protected for warm water species of game fish and other warm water aquatic life, including the necessary aquatic organisms in their food chain.<br>c. Class 3C – Protected for non-game fish and other aquatic life, including the necessary aquatic organisms in their food chain.<br>d. Class 3D – Protected for waterfowl, shore birds and other water-oriented wildlife not included in Classes 3A, 3B, or 3C, including the necessary aquatic organisms in their food chain.<br>e. Class 3E – Severely habitat-limited waters. Narrative standards will be applied to protect these waters for aquatic wildlife.<br>6.4 Class 4 – Protected for agricultural uses including irrigation of crops and stock watering.<br>6.5 Class 5 – The Great Salt Lake. Protected for primary and secondary contact recreation, aquatic wildlife, and mineral extraction. | **7.2 Narrative Standards**<br>It shall be unlawful, and a violation of these regulations, for any person to discharge or place any waste or other substance in such a way as will be or may become offensive such as unnatural deposits, floating debris, oil, scum or other nuisances such as color, odor or taste; or cause conditions which produce undesirable aquatic life or which produce objectionable tastes in edible aquatic organisms; or result in concentrations or combinations of substances which produce undesirable physiological responses in desirable resident fish, or other desirable aquatic life, or undesirable human health effects, as determined by bioassay or other tests performed in accordance with standard procedures. |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Virginia | Narrative criteria/plan of action for all state waters. | The Board recognizes that nutrients are contributing to undesirable growths of aquatic plant life in surface waters of the Commonwealth. This standard establishes a designation of "nutrient enriched waters". Designations of surface waters of the Commonwealth as “nutrient enriched waters" are determined by the Board based upon an evaluation of the historical water quality data for one or more of the following indicators of nutrient enrichment: chlorophyll *a* concentrations, dissolved oxygen fluctuations, and concentrations of total phosphorus. |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Washington | - Class AA (extraordinary)<br>Water quality of this class shall markedly and uniformly exceed the requirements for all or substantially all uses.<br>Characteristic uses:<br>i) water supply (domestic, agricultural, industrial)<br>ii) stock watering<br>iii) fish and shellfish *<br>iv) wildlife habitats<br>v) Recreation<br>vi) Commerce and navigation<br>vii) Aesthetic Values **<br>- Class A (excellent)<br>Same as class AA except for fecal coliform levels are lower in the AA category in freshwater.<br>- Class B (good)<br>Water quality for this class shall meet or exceed the requirements for most uses.<br>Characteristic uses:<br>i) water supply (industrial and agricultural)<br>(all other uses stay the same as above classes; different numeric criteria for DO and fecal coliform.)<br>- Class C (fair)<br>Water quality of this class shall meet or exceed the requirements of selected essential uses.<br>i) water supply (industrial) (different criteria for DO and fecal coliform in this class).<br>Lake class<br>-Establishing Lake Nutrient criteria | **Narrative or Numeric Chlorophyll *a* Standards**<br>Lakes in the Willamette, East Cascade Foothills, or Blue Mountain ecoregions do not have recommended values and need to have lake-specific studies in order to receive criteria as described in (c)(i) of this subsection.<br>(b) The following actions are recommended if ambient monitoring of a lake shows the epilimnetic total phosphorus concentration, as shown in Table 1 of this section, is below the action value for an ecoregion:<br>(i) Determine trophic status from existing or newly gathered data. The recommended minimum sampling to determine trophic status is calculated as the mean of four or more samples collected from the epilimnion between June through September in one or more consecutive years. Sampling must be spread throughout the season.<br>(ii) Propose criteria at or below the upper limit of the trophic state; or (iii) Conduct lake-specific study to determine and propose to adopt appropriate criteria as described in (c) of this subsection. (c) The following actions are recommended if ambient monitoring of a lake shows total phosphorus to exceed the action value for an ecoregion shown in Table 1 of this section or where recommended ecoregional action values do not exist:<br>(i) Conduct a lake-specific study to evaluate the characteristic uses of the lake. A lake-specific study may vary depending on the source or threat of impairment. Phytoplankton blooms, toxic phytoplankton, or excessive aquatic plants, are examples of various sources of impairment. The following are examples of quantitative measures that a study may describe: Total phosphorus, total nitrogen, chlorophyll-a, dissolved oxygen in the hypolimnion if thermally stratified, pH, hardness, or other measures of existing conditions and potential changes in any one of these parameters.<br>(ii) Determine appropriate total phosphorus concentrations or other nutrient criteria to protect characteristic lake uses. If the existing total phosphorus concentration is protective of characteristic lake uses, then set criteria at existing total phosphorus concentration. If the existing total phosphorus concentration is not protective of the existing characteristic lake uses, then set criteria at a protective concentration. Proposals to adopt appropriate total phosphorus criteria to protect characteristic uses must be developed by considering technical information and stakeholder input as part of a public involvement process equivalent to the Administrative Procedure Act (chapter 34.05 RCW).<br>(iii) Determine if the proposed total phosphorus criteria necessary to protect characteristic uses is achievable. If the recommended criterion is not achievable and if the characteristic use the criterion is intended to protect is not an existing use, then a higher criterion may be proposed in conformance with 40 CFR part 131.10.<br>(d) The department will consider proposed lake-specific nutrient criteria during any water quality standards rule making that follows development of a proposal. Adoption by rule formally establishes the criteria for that lake. |

| State | Water Body Type or Designated Use | Numeric or Narrative Chlorophyll *a* Criteria |
|---|---|---|
| Wyoming | Surface water classes and uses.<br>1) Class 1 – Those surface waters in which no further water quality degradation by point source discharge other than from dams will be allowed.<br>2) Class 2 – Those surface waters, other than those classified as Class 1, which are determined to support game fish.<br>3) Class 3 –Those surface waters, other than those classified as Class 1, which are determined to be presently supporting non-game fish only.<br>4) Class 4 – Those surface waters, other than those classified as Class 1, which are determined to not have the hydrologic or natural water quality potential to support fish and include all intermittent and ephemeral streams. Class 4 waters shall receive protection for agricultural uses and wildlife watering.<br>(i) USES<br>(a) Agriculture;<br>(b) Protection and propagation of fish and wildlife;<br>(c) Industry;<br>(d) Human consumption;<br>(e) Recreation;<br>(f) Scenic value. | **Section 28. Undesirable Aquatic Life**.<br>All Wyoming surface waters shall be free from substances and conditions or combinations thereof which are attributable to municipal, industrial or other dischargers or agricultural practices, in concentrations which produce undesirable aquatic life. |

**Source:** http://www.epa.gov/ost/standards/wqslibrary/

appendix E

# 1950s–1990s Chesapeake Bay and Tidal Tributary Chlorophyll *a* Concentrations by Chesapeake Bay Program Segment

## HISTORICAL DATA SETS

The earliest water quality data in the Chesapeake Bay Program data base date from the early 1950s. Thus, the historical era referred to here extends from the early 1950s to 1984, when the coordinated baywide Chesapeake Bay Monitoring Program began. Most of the early studies focused on the physical and chemical characterization of tidal waters. Sometimes measurements of phosphorus species, usually orthophosphate, and chlorophyll *a* were taken. The impetus for more nutrient measurements came during the 1960s (possibly exacerbated by the severe drought in that decade) and 1970s with the increasing awareness of the Chesapeake Bay's eutrophication and other signs of degradation. Nitrate measurements were collected more frequently, and measurements of a larger suite of phosphorus and nitrogen species began to be collected. Estimates of total phosphorus and total nitrogen are infrequent in the historical data, however.

Data from the Johns Hopkins University Chesapeake Bay Institute and the U.S. Environmental Protection Agency's Annapolis Field Office constitute the largest contributions to the historical database. Maryland and Virginia state monitoring programs provided data from various state waters. In Virginia, other major contributors to the historical database were the Virginia Institute of Marine Science and the Virginia State Water Control Board slack water surveys. The database also includes many smaller data sets including, among others, data from University of Maryland researchers and from environmental impact studies of electric power generation in Maryland.

Historical to present chlorophyll *a* concentration data are presented by Chesapeake Bay Program segment within decades (1950s-1990s) in Table E-1. Table E-2 presents the same chlorophyll *a* data by Chesapeake Bay Program segment across the same decades.

## BENCHMARK CHLOROPHYLL *A* DATA ASSESSMENT

The historical and current monitoring data sets (through 1999) were pooled, and the surface (sampling depth ≤ 1.5 meters) values of the parameters were retained. Each data point was associated with a segment (from the original Chesapeake Bay Program segmentation scheme) and a salinity regime. Salinity regimes were defined as: tidal-fresh 0-0.5 ppt; oligohaline >0.5-5.0 ppt; mesohaline > 5-18 ppt and polyhaline >18 ppt.

If a salinity measurement was associated with the value, then that measurement determined the regime. Otherwise, the regime was assumed from the median salinity of the segment in which the measurement was taken. Values were further identified according to decade (1950s through 1990s) and season. The seasons that were included were: annual (January through December), spring (March, April and May) and summer (June, July, August and September).

The individual data values were assessed using the Chesapeake Bay Program method for calculating relative status (Alden and Perry 1997). The method uses the logistic distribution of values in a reference data set to assess values in a test data set. The procedure yields a score between 0 and 100 for each test value. The reference data, in this case, were Chesapeake Bay Program Water Quality Monitoring data from 1985 through 1990, which includes the largest number of stations and greatest seasonal coverage of the monitoring program's history to date. It thus provided the best available spatial and temporal coverage of the historical record. The time period also represented a relatively wide variety of flow and other climatic conditions, although none was particularly extreme.

The reference and test data sets were similarly partitioned by depth, segment, salinity zone and season. For each reference grouping, the logistic distribution of values was obtained and cutoff points representing the upper, middle and lower thirds of the distribution were determined. For nitrogen, phosphorus, chlorophyll *a* and suspended solids, high values are undesirable, therefore, the cutoff points represented 'poor', 'fair' and 'good' quality conditions, respectively, in this context. The status procedure scored each test value between 0 and 100, based on the distribution of the complementary reference distribution. Then, for each parameter/segment/salinity zone/decade/season, the median score was calculated for each calendar month, from which the median score for the season was obtained. The season median scores were categorized as 'good', 'fair' or 'poor' by using the reference cutoff points and adjusted slightly for the number of observations in the test data.

Each segment/zone/decade/season was then evaluated as representing 'healthy' nutrient and sediment levels. To qualify, none of the critical parameters—total nitrogen, total phosphorus, chlorophyll *a* or total suspended solids—could have a 'poor' assessment; only one parameter could have a 'fair' assessment and one or more parameters had to be 'good'. Benchmark levels for each parameter were then derived from this set of reference locations by extracting the values only from the

reference locations in which the parameter of interest was assessed as 'good'. These values were then pooled by salinity regime and decade and, ultimately, by salinity regime alone.

## LITERATURE CITED

Alden, R. W. III and E. S. Perry 1997. *Presenting Measurements of Status: Report to the Chesapeake Bay Program Monitoring Subcommittee's Data Analysis Workgroup.* Chesapeake Bay Program, Annapolis, Maryland.

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1950 | Northern Chesapeake Bay | – | – | – | – | 1.4 | 1 |
| | Upper Chesapeake Bay | 1.1 | 1 | – | – | 2.2 | 7 |
| | Upper Central Chesapeake Bay | – | – | 1.7 | 1 | 3.2 | 10 |
| | Middle Central Chesapeake Bay | 3.1 | 3 | 2.1 | 1 | 4.0 | 13 |
| | Lower Chesapeake Bay | 14.1 | 3 | 5.6 | 1 | 7.0 | 16 |
| | Western Lower Chesapeake Bay | – | – | – | – | 0.7 | 8 |
| | Eastern Lower Chesapeake Bay | 7.9 | 3 | – | – | 4.2 | 19 |
| | Mouth of the Chesapeake Bay | – | – | – | – | 1.6 | 8 |
| | Outside of Ches. Bay Mouth | – | – | 2.0 | 1 | 2.2 | 2 |
| | Northeast River | – | – | – | – | – | – |
| | Elk/Bohemia Rivers | – | – | – | – | – | – |
| | Sassafras River | – | – | – | – | – | – |
| | Chester River | – | – | – | – | – | – |
| | Eastern Bay | – | – | 0.5 | 1 | 1.5 | 3 |
| | Choptank River | 2.4 | 2 | 3.4 | 3 | 2.8 | 7 |
| | Lower Choptank River | 6.9 | 1 | 1.7 | 3 | 2.6 | 5 |
| | Nanticoke River | – | – | – | – | – | – |
| | Wicomico River | – | – | – | – | – | – |
| | Manokin River | – | – | – | – | – | – |
| | Big Annemessex River | – | – | – | – | – | – |
| | Tangier Sound | – | – | 11.8 | 1 | 4.3 | 8 |
| | Pocomoke River | – | – | – | – | – | – |
| | Bush River | – | – | – | – | – | – |
| | Gunpowder River | – | – | – | – | – | – |
| | Middle River | – | – | – | – | – | – |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1950 | Back River | – | – | – | – | – | – |
| | Patapsco River | – | – | – | – | 7.5 | 1 |
| | Magothy River | – | – | – | – | – | – |
| | Severn River | – | – | – | – | – | – |
| | South/Rhode/West Rivers | – | – | – | – | – | – |
| | Upper Patuxent River | 2.6 | 1 | 1.7 | 2 | 1.7 | 4 |
| | Middle Patuxent River | – | – | 2.1 | 2 | 2.9 | 3 |
| | Lower Patuxent River | 5.3 | 3 | 3.3 | 4 | 2.6 | 14 |
| | Upper Potomac River | – | – | – | – | – | – |
| | Middle Potomac River | – | – | 26.7 | 1 | 26.7 | 1 |
| | Lower Potomac River | 10.8 | 2 | 5.0 | 12 | 6.1 | 23 |
| | Upper Rappahannock River | – | – | – | – | – | – |
| | Middle Rappahannock River | – | – | – | – | 3.7 | 2 |
| | Lower Rappahannock River | 8.2 | 1 | – | – | 4.3 | 6 |
| | Upper York River | – | – | – | – | – | – |
| | Middle York River | – | – | – | – | 2.0 | 1 |
| | Lower York River | 4.5 | 1 | – | – | 1.8 | 3 |
| | Mobjack Bay | – | – | – | – | 0.6 | 2 |
| | Upper James River | – | – | – | – | – | – |
| | Middle James River | – | – | – | – | – | – |
| | Lower James River | – | – | 3.3 | 19 | 2.3 | 28 |
| 1960 | Northern Chesapeake Bay | 6.1 | 8 | 18.2 | 11 | 12.4 | 31 |
| | Upper Chesapeake Bay | 7.0 | 10 | 25.9 | 15 | 15.9 | 42 |
| | Upper Central Chesapeake Bay | 6.9 | 29 | 18.2 | 59 | 11.5 | 122 |
| | Middle Central Chesapeake Bay | 3.9 | 18 | 11.1 | 25 | 7.4 | 69 |
| | Lower Chesapeake Bay | 2.4 | 7 | 10.9 | 12 | 9.7 | 28 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu g$ liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1960 | Western Lower Chesapeake Bay | – | – | – | – | – | – |
| | Eastern Lower Chesapeake Bay | 5.5 | 1 | 1.2 | 2 | 2.0 | 5 |
| | Mouth of the Chesapeake Bay | – | – | – | – | – | – |
| | Outside the Ches. Bay Mouth | 1.1 | 2 | 0.8 | 4 | 1.0 | 8 |
| | Northeast River | – | – | – | – | – | – |
| | Elk/Bohemia Rivers | – | – | – | – | – | – |
| | Sassafras River | – | – | 18.1 | 3 | 20.8 | 5 |
| | Chester River | 5.2 | 11 | 8.7 | 14 | 5.6 | 36 |
| | Eastern Bay | 5.3 | 27 | 9.2 | 39 | 6.5 | 94 |
| | Choptank River | – | – | – | – | – | – |
| | Lower Choptank River | – | – | – | – | – | – |
| | Nanticoke River | – | – | – | – | – | – |
| | Wicomico River | – | – | – | – | – | – |
| | Manokin River | – | – | – | – | – | – |
| | Big Annemessex River | – | – | – | – | – | – |
| | Tangier Sound | – | – | – | – | – | – |
| | Pocomoke River | – | – | – | – | – | – |
| | Bush River | – | – | – | – | – | – |
| | Gunpowder River | – | – | – | – | – | – |
| | Middle River | – | – | – | – | – | – |
| | Back River | – | – | 7.7 | 1 | 30.9 | 3 |
| | Patapsco River | 18.7 | 17 | 47.1 | 41 | 41.9 | 64 |
| | Magothy River | 8.6 | 13 | 12.5 | 21 | 11.5 | 56 |
| | Severn River | 7.1 | 12 | 15.9 | 22 | 10.8 | 60 |
| | South/Rhode/West Rivers | 6.3 | 17 | 15.4 | 38 | 11.1 | 73 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu g$ liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1960 | Upper Patuxent River | 20.1 | 18 | 32.0 | 43 | 22.5 | 65 |
| | Middle Patuxent River | 15.0 | 2 | 24.8 | 4 | 21.5 | 6 |
| | Lower Patuxent River | 19.9 | 2 | 20.5 | 4 | 20.3 | 6 |
| | Upper Potomac River | 24.3 | 50 | 59.1 | 81 | 38.7 | 176 |
| | Middle Potomac River | 8.1 | 26 | 29.3 | 35 | 23.6 | 83 |
| | Lower Potomac River | 8.5 | 24 | 18.7 | 33 | 13.7 | 76 |
| | Upper Rappahannock River | – | – | – | – | – | – |
| | Middle Rappahannock River | – | – | – | – | – | – |
| | Lower Rappahannock River | – | – | – | – | – | – |
| | Upper York River | – | – | – | – | – | – |
| | Middle York River | – | – | – | – | – | – |
| | Lower York River | – | – | – | – | – | – |
| | Mobjack Bay | – | – | – | – | – | – |
| | Upper James River | – | – | – | – | – | – |
| | Middle James River | – | – | – | – | – | – |
| | Lower James River | 12.8 | 2 | – | – | 12.8 | 2 |
| 1970 | Northern Chesapeake Bay | 11.7 | 28 | 19.3 | 66 | 12.1 | 116 |
| | Upper Chesapeake Bay | 9.6 | 26 | 15.4 | 66 | 10.6 | 125 |
| | Upper Central Chesapeake Bay | 14.2 | 156 | 20.7 | 266 | 14.8 | 589 |
| | Middle Central Chesapeake Bay | 11.5 | 99 | 10.5 | 142 | 9.7 | 325 |
| | Lower Chesapeake Bay | 11.5 | 29 | 7.7 | 35 | 8.1 | 94 |
| | Western Lower Chesapeake Bay | – | – | 11.0 | 1 | 11.0 | 1 |
| | Eastern Lower Chesapeake Bay | 14.7 | 13 | 4.8 | 17 | 7.3 | 45 |
| | Mouth of the Chesapeake Bay | 14.8 | 4 | 7.7 | 14 | 8.7 | 29 |
| | Outside the Ches. Bay Mouth | 5.1 | 7 | 3.5 | 8 | 4.2 | 31 |
| | Northeast River | 40.0 | 11 | 54.9 | 35 | 49.0 | 53 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu g$ liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1970 | Elk/Bohemia Rivers | 27.3 | 62 | 28.8 | 136 | 25.9 | 248 |
| | Sassafras River | 42.2 | 26 | 43.1 | 61 | 46.8 | 106 |
| | Chester River | 18.2 | 42 | 25.6 | 84 | 22.7 | 159 |
| | Eastern Bay | 6.5 | 84 | 21.7 | 89 | 14.0 | 226 |
| | Choptank River | 18.4 | 99 | 17.1 | 121 | 18.8 | 276 |
| | Lower Choptank River | 11.1 | 37 | 21.5 | 60 | 17.2 | 103 |
| | Nanticoke River | 32.5 | 37 | 22.9 | 80 | 26.7 | 168 |
| | Wicomico River | 36.7 | 31 | 41.9 | 42 | 31.4 | 101 |
| | Manokin River | 15.5 | 3 | 7.2 | 5 | 12.2 | 8 |
| | Big Annemessex River | – | – | 18.2 | 6 | 18.2 | 6 |
| | Tangier River | 20.3 | 37 | 16.6 | 57 | 27.6 | 113 |
| | Pocomoke River | 23.1 | 43 | 19 | 63 | 19.9 | 146 |
| | Bush River | 7.3 | 4 | 13.2 | 12 | 10.1 | 25 |
| | Gunpowder River | 7.6 | 24 | 7.3 | 39 | 9.7 | 94 |
| | Middle River | 14.7 | 8 | 28.2 | 8 | 17.7 | 19 |
| | Back River | 55.7 | 115 | 61.5 | 167 | 58.3 | 392 |
| | Patapsco River | 14.1 | 36 | 40.9 | 77 | 23.4 | 162 |
| | Magothy River | 33.8 | 40 | 37.8 | 50 | 32.7 | 129 |
| | Severn River | 22.2 | 12 | 32.1 | 43 | 24.8 | 75 |
| | South/Rhode/West Rivers | 25.2 | 31 | 29.7 | 84 | 29.4 | 157 |
| | Upper Patuxent River | 10.9 | 37 | 15.8 | 68 | 14.3 | 147 |
| | Middle Patuxent River | 31.3 | 2 | 18.1 | 8 | 16.8 | 14 |
| | Lower Patuxent River | 10.9 | 4 | 15.7 | 5 | 11.5 | 12 |
| | Upper Potomac River | 17.9 | 142 | 31.0 | 286 | 18.0 | 559 |
| | Middle Potomac River | 20.0 | 78 | 19.3 | 142 | 16.6 | 288 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu g$ liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1970 | Lower Potomac River | 8.0 | 40 | 8.9 | 65 | 11.2 | 140 |
| | Upper Rappahannock River | 2.1 | 66 | 9.4 | 142 | 5.7 | 313 |
| | Middle Rappahannock River | 6.4 | 13 | 6.6 | 29 | 5.6 | 65 |
| | Lower Rappahannock River | 6.8 | 14 | 8.0 | 35 | 7.5 | 76 |
| | Upper York River | 3.9 | 18 | 9.8 | 107 | 7.2 | 170 |
| | Middle York River | 5.0 | 24 | 9.8 | 109 | 7.2 | 167 |
| | Lower York River | 7.8 | 8 | 5.7 | 21 | 5.8 | 35 |
| | Mobjack Bay | 8.3 | 16 | 7.4 | 42 | 6.5 | 69 |
| | Upper James River | 5.5 | 55 | 8.9 | 187 | 5.2 | 345 |
| | Middle James River | 7.7 | 19 | 4.6 | 75 | 4.6 | 137 |
| | Lower James River | 7.6 | 9 | 3.8 | 43 | 3.6 | 73 |
| 1980 | Northern Chesapeake Bay | 7.6 | 20 | 10.9 | 28 | 7.8 | 68 |
| | Upper Central Chesapeake Bay | 8.4 | 38 | 10.1 | 55 | 7.3 | 135 |
| | Upper Central Chesapeake Bay | 11.5 | 87 | 14.7 | 152 | 10.7 | 362 |
| | Middle Central Chesapeake Bay | 10.4 | 155 | 10.7 | 225 | 9.4 | 590 |
| | Lower Chesapeake Bay | 10.3 | 111 | 9.0 | 158 | 8.6 | 454 |
| | Western Lower Chesapeake Bay | 7.2 | 60 | 8.7 | 80 | 7.6 | 236 |
| | Eastern Lower Chesapeake Bay | 6.2 | 140 | 5.8 | 187 | 6.5 | 543 |
| | Mouth of the Chesapeake Bay | 5.8 | 45 | 4.9 | 62 | 5.5 | 181 |
| | Outside the Ches. Bay Mouth | 6.0 | 1 | 2.5 | 2 | 4.0 | 5 |
| | Northeast River | 23.7 | 11 | 54.3 | 17 | 31.9 | 44 |
| | Elk/Bohemia Rivers | 18.1 | 34 | 9.9 | 52 | 10.1 | 141 |
| | Sassafras River | 34.3 | 12 | 70.2 | 15 | 47.9 | 45 |
| | Chester River | 8.1 | 46 | 16.0 | 83 | 10.5 | 205 |
| | Eastern Bay | 4.3 | 14 | 10.2 | 23 | 6.6 | 58 |
| | Choptank River | 7.0 | 34 | 17.4 | 57 | 11.2 | 138 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1980 | Lower Choptank River | 6.4 | 26 | 9.3 | 44 | 7.0 | 107 |
| | Nanticoke River | 11.4 | 23 | 18.0 | 32 | 13.1 | 90 |
| | Wicomico River | 6.6 | 11 | 19.6 | 16 | 11.3 | 44 |
| | Manokin River | 8.2 | 12 | 13.8 | 16 | 9.0 | 43 |
| | Big Annemessex River | 5.0 | 12 | 10.0 | 16 | 6.5 | 43 |
| | Tangier Sound | 9.5 | 65 | 10.7 | 86 | 8.2 | 237 |
| | Pocomoke River | 4.2 | 12 | 11.2 | 15 | 8.9 | 45 |
| | Bush River | 17.6 | 13 | 42.9 | 22 | 25.3 | 53 |
| | Gunpowder River | 22.3 | 11 | 20.5 | 24 | 17.5 | 53 |
| | Middle River | 14.8 | 11 | 24.2 | 19 | 19.8 | 48 |
| | Back River | 105.5 | 13 | 101.8 | 38 | 83.7 | 87 |
| | Patapsco River | 17.5 | 22 | 50.3 | 44 | 29.3 | 95 |
| | Magothy River | 10.0 | 13 | 22.1 | 19 | 15.0 | 51 |
| | Severn River | 13.0 | 10 | 22.8 | 18 | 16.8 | 47 |
| | South/Rhode/West Rivers | 14.9 | 42 | 23.8 | 58 | 16.5 | 157 |
| | Upper Patuxent River | 4.7 | 94 | 18.4 | 160 | 9.2 | 414 |
| | Middle Patuxent River | 15.5 | 13 | 14.2 | 26 | 17.1 | 65 |
| | Lower Patuxent River | 14.7 | 52 | 11.4 | 95 | 11.4 | 245 |
| | Upper Potomac River | 4.5 | 95 | 15.9 | 121 | 7.9 | 336 |
| | Middle Potomac River | 7.4 | 62 | 7.4 | 79 | 5.8 | 224 |
| | Lower Potomac River | 18.2 | 31 | 10.3 | 43 | 10.7 | 120 |
| | Upper Rappahannock River | 4.1 | 30 | 15.2 | 53 | 8.4 | 124 |
| | Middle Rappahannock River | 22.1 | 24 | 10.8 | 39 | 12.5 | 103 |
| | Lower Rappahannock River | 10.9 | 78 | 8.9 | 120 | 8.3 | 324 |
| | Upper York River | 3.1 | 24 | 5.1 | 40 | 3.8 | 102 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued).*

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1980 | Middle York River | 5.4 | 36 | 11.0 | 60 | 7.0 | 152 |
| | Lower York River | 13.5 | 36 | 8.3 | 59 | 9.7 | 151 |
| | Mobjack Bay | 6.3 | 60 | 8.4 | 80 | 6.9 | 236 |
| | Upper James River | 10.2 | 65 | 20.7 | 114 | 11.2 | 283 |
| | Middle James River | 13.8 | 24 | 17.3 | 40 | 13.7 | 100 |
| | Lower James River | 13.8 | 88 | 6.2 | 140 | 9.6 | 349 |
| 1990 | Northern Chesapeake Bay | 6.6 | 27 | 8.6 | 40 | 5.8 | 102 |
| | Upper Chesapeake Bay | 5.0 | 58 | 6.3 | 79 | 4.2 | 220 |
| | Upper Central Chesapeake Bay | 7.6 | 147 | 14.3 | 200 | 9.0 | 487 |
| | Middle Central Chesapeake Bay | 7.5 | 300 | 9.9 | 400 | 8.1 | 929 |
| | Lower Chesapeake Bay | 9.5 | 210 | 8.5 | 279 | 8.0 | 819 |
| | Western Lower Chesapeake Bay | 7.1 | 118 | 7.5 | 159 | 6.7 | 475 |
| | Eastern Lower Chesapeake Bay | 6.6 | 264 | 6.8 | 359 | 6.5 | 1059 |
| | Mouth of the Chesapeake Bay | 6.3 | 88 | 5.6 | 120 | 5.8 | 354 |
| | Outside the Ches. Bay Mouth | – | – | – | – | – | – |
| | Northeast River | 23.0 | 27 | 53.5 | 38 | 31.4 | 105 |
| | Elk/Bohemia Rivers | 6.9 | 88 | 6.5 | 113 | 5.9 | 326 |
| | Sassafras River | 39.6 | 29 | 66.9 | 35 | 46.1 | 113 |
| | Chester River | 10.6 | 89 | 20.3 | 117 | 13.2 | 350 |
| | Eastern Bay | 8.3 | 30 | 12.8 | 39 | 9.2 | 117 |
| | Choptank River | 13.3 | 60 | 19.9 | 78 | 12.8 | 234 |
| | Lower Choptank River | 7.4 | 60 | 8.4 | 78 | 7.4 | 229 |
| | Nanticoke River | 10.4 | 60 | 26.9 | 74 | 15.5 | 226 |
| | Wicomico River | 8.1 | 29 | 14.3 | 36 | 10.6 | 112 |
| | Manokin River | 11.8 | 30 | 11.2 | 36 | 9.8 | 111 |
| | Big Annemessex River | 7.5 | 30 | 9.6 | 35 | 7.4 | 112 |

**Table E-1.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu g$ liter$^{-1}$) by Chesapeake Bay Program segment within decade: 1950s–1990s *(continued)*.

| Decade | Chesapeake Bay Program Segment | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| 1990 | Tangier Sound | 10.8 | 147 | 10.6 | 189 | 9.3 | 566 |
| | Pocomoke River | 2.1 | 30 | 7.5 | 39 | 4.6 | 113 |
| | Bush River | 26.4 | 28 | 50.9 | 37 | 31.0 | 106 |
| | Gunpowder River | 21.5 | 29 | 18.6 | 38 | 17.0 | 106 |
| | Middle River | 20.1 | 29 | 12.8 | 38 | 13.5 | 107 |
| | Back River | 104.2 | 29 | 82.4 | 38 | 75.7 | 107 |
| | Patapsco River | 15.5 | 29 | 36.1 | 39 | 22.3 | 113 |
| | Magothy River | 12.2 | 29 | 18.3 | 37 | 13.6 | 110 |
| | Severn River | 13.2 | 30 | 19.4 | 35 | 14.4 | 109 |
| | South/Rhode/West Rivers | 12.4 | 89 | 18.4 | 110 | 13.0 | 315 |
| | Upper Patuxent River | 5.9 | 234 | 15.9 | 307 | 8.7 | 863 |
| | Middle Patuxent River | 17.8 | 30 | 15.6 | 39 | 15.6 | 118 |
| | Lower Patuxent River | 10.7 | 120 | 13.0 | 156 | 10.4 | 472 |
| | Upper Potomac River | 6.0 | 174 | 20.3 | 233 | 9.8 | 655 |
| | Middle Potomac River | 5.0 | 93 | 8.4 | 121 | 5.6 | 350 |
| | Lower Potomac River | 10.8 | 60 | 9.4 | 80 | 8.7 | 228 |
| | Upper Rappahannock River | 3.6 | 149 | 14.1 | 209 | 7.3 | 563 |
| | Middle Rappahannock River | 9.0 | 66 | 11.0 | 85 | 8.5 | 250 |
| | Lower Rappahannock River | 8.2 | 187 | 7.9 | 250 | 7.1 | 727 |
| | Upper York River | 1.5 | 64 | 4.4 | 79 | 2.5 | 240 |
| | Middle York River | 3.5 | 92 | 13.3 | 118 | 7.4 | 349 |
| | Lower York River | 10.3 | 97 | 7.6 | 125 | 7.6 | 371 |
| | Mobjack Bay | 7.3 | 125 | 8.5 | 167 | 7.3 | 502 |
| | Upper James River | 6.3 | 210 | 16.3 | 284 | 8.9 | 813 |
| | Middle James River | 13.3 | 64 | 14.1 | 85 | 11.1 | 245 |
| | Lower James River | 10.7 | 331 | 7.9 | 447 | 7.7 | 1295 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| CB1 | 1950 | - | - | - | - | 1.4 | 1 |
| CB1 | 1960 | 6.1 | 8 | 18.2 | 11 | 12.4 | 31 |
| CB1 | 1970 | 11.7 | 28 | 19.3 | 66 | 12.1 | 116 |
| CB1 | 1980 | 7.6 | 20 | 10.9 | 28 | 7.8 | 68 |
| CB1 | 1990 | 6.6 | 27 | 8.6 | 40 | 5.8 | 102 |
| CB2 | 1950 | 1.1 | 1 | - | - | 2.2 | 7 |
| CB2 | 1960 | 7.0 | 10 | 25.9 | 15 | 15.9 | 42 |
| CB2 | 1970 | 9.6 | 26 | 15.4 | 66 | 10.6 | 125 |
| CB2 | 1980 | 8.4 | 38 | 10.1 | 55 | 7.3 | 135 |
| CB2 | 1990 | 5.0 | 58 | 6.3 | 79 | 4.2 | 220 |
| CB3 | 1950 | - | - | 1.7 | 1 | 3.2 | 10 |
| CB3 | 1960 | 6.9 | 29 | 18.2 | 59 | 11.5 | 122 |
| CB3 | 1970 | 14.2 | 156 | 20.7 | 266 | 14.8 | 589 |
| CB3 | 1980 | 11.5 | 87 | 14.7 | 152 | 10.7 | 362 |
| CB3 | 1990 | 7.6 | 147 | 14.3 | 200 | 9.0 | 487 |
| CB4 | 1950 | 3.1 | 3 | 2.1 | 1 | 4.0 | 13 |
| CB4 | 1960 | 3.9 | 18 | 11.1 | 25 | 7.4 | 69 |
| CB4 | 1970 | 11.5 | 99 | 10.5 | 142 | 9.7 | 325 |
| CB4 | 1980 | 10.4 | 155 | 10.7 | 225 | 9.4 | 590 |
| CB4 | 1990 | 7.5 | 300 | 9.9 | 400 | 8.1 | 929 |
| CB5 | 1950 | 14.1 | 3 | 5.6 | 1 | 7.0 | 16 |
| CB5 | 1960 | 2.4 | 7 | 10.9 | 12 | 9.7 | 28 |
| CB5 | 1970 | 11.5 | 29 | 7.7 | 35 | 8.1 | 94 |
| CB5 | 1980 | 10.3 | 111 | 9.0 | 158 | 8.6 | 454 |
| CB5 | 1990 | 9.5 | 210 | 8.5 | 279 | 8.0 | 819 |
| CB6 | 1950 | - | - | - | - | 0.7 | 8 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued).*

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| CB6 | 1960 | - | - | - | - | - | - |
| CB6 | 1970 | - | - | 11.0 | 1 | 11.0 | 1 |
| CB6 | 1980 | 7.2 | 60 | 8.7 | 80 | 7.6 | 236 |
| CB6 | 1990 | 7.1 | 118 | 7.5 | 159 | 6.7 | 475 |
| CB7 | 1950 | 7.9 | 3 | - | - | 4.2 | 19 |
| CB7 | 1960 | 5.5 | 1 | 1.2 | 2 | 2.0 | 5 |
| CB7 | 1970 | 14.7 | 13 | 4.8 | 17 | 7.3 | 45 |
| CB7 | 1980 | 6.2 | 140 | 5.8 | 187 | 6.5 | 543 |
| CB7 | 1990 | 6.6 | 264 | 6.8 | 359 | 6.5 | 1059 |
| CB8 | 1950 | - | - | - | - | 1.6 | 8 |
| CB8 | 1960 | - | - | - | - | - | |
| CB8 | 1970 | 14.8 | 4 | 7.7 | 14 | 8.7 | 29 |
| CB8 | 1980 | 5.8 | 45 | 4.9 | 62 | 5.5 | 181 |
| CB8 | 1990 | 6.3 | 88 | 5.6 | 120 | 5.8 | 354 |
| MOUTH | 1950 | - | - | 2.0 | 1 | 2.2 | 2 |
| MOUTH | 1960 | 1.1 | 2 | 0.8 | 4 | 1.0 | 8 |
| MOUTH | 1970 | 5.1 | 7 | 3.5 | 8 | 4.2 | 31 |
| MOUTH | 1980 | 6.0 | 1 | 2.5 | 2 | 4.0 | 5 |
| MOUTH | 1990 | - | - | - | - | - | - |
| ET1 | 1950 | - | - | - | - | - | - |
| ET1 | 1960 | - | - | - | - | - | - |
| ET1 | 1970 | 40.0 | 11 | 54.9 | 35 | 49.0 | 53 |
| ET1 | 1980 | 23.7 | 11 | 54.3 | 17 | 31.9 | 44 |
| ET1 | 1990 | 23.0 | 27 | 53.5 | 38 | 31.4 | 105 |
| ET2 | 1950 | - | - | - | - | - | - |
| ET2 | 1960 | - | - | - | - | - | - |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued)*.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| ET2 | 1970 | 27.3 | 62 | 28.8 | 136 | 25.9 | 248 |
| ET2 | 1980 | 18.1 | 34 | 9.9 | 52 | 10.1 | 141 |
| ET2 | 1990 | 6.9 | 88 | 6.5 | 113 | 5.9 | 326 |
| ET3 | 1950 | - | - | - | - | - | - |
| ET3 | 1960 | - | - | 18.1 | 3 | 20.8 | 5 |
| ET3 | 1970 | 42.2 | 26 | 43.1 | 61 | 46.8 | 106 |
| ET3 | 1980 | 34.3 | 12 | 70.2 | 15 | 47.9 | 45 |
| ET3 | 1990 | 39.6 | 29 | 66.9 | 35 | 46.1 | 113 |
| ET4 | 1950 | - | - | - | - | - | - |
| ET4 | 1960 | 5.2 | 11 | 8.7 | 14 | 5.6 | 36 |
| ET4 | 1970 | 18.2 | 42 | 25.6 | 84 | 22.7 | 159 |
| ET4 | 1980 | 8.1 | 46 | 16.0 | 83 | 10.5 | 205 |
| ET4 | 1990 | 10.6 | 89 | 20.3 | 117 | 13.2 | 350 |
| EE1 | 1950 | - | - | 0.5 | 1 | 1.5 | 3 |
| EE1 | 1960 | 5.3 | 27 | 9.2 | 39 | 6.5 | 94 |
| EE1 | 1970 | 6.5 | 84 | 21.7 | 89 | 14.0 | 226 |
| EE1 | 1980 | 4.3 | 14 | 10.2 | 23 | 6.6 | 58 |
| EE1 | 1990 | 8.3 | 30 | 12.8 | 39 | 9.2 | 117 |
| ET5 | 1950 | 2.4 | 2 | 3.4 | 3 | 2.8 | 7 |
| ET5 | 1960 | - | - | - | - | - | - |
| ET5 | 1970 | 18.4 | 99 | 17.1 | 121 | 18.8 | 276 |
| ET5 | 1980 | 7.0 | 34 | 17.4 | 57 | 11.2 | 138 |
| ET5 | 1990 | 13.3 | 60 | 19.9 | 78 | 12.8 | 234 |
| EE2 | 1950 | 6.9 | 1 | 1.7 | 3 | 2.6 | 5 |
| EE2 | 1960 | - | - | - | - | - | - |
| EE2 | 1970 | 11.1 | 37 | 21.5 | 60 | 17.2 | 103 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued)*.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| EE2 | 1980 | 6.4 | 26 | 9.3 | 44 | 7.0 | 107 |
| EE2 | 1990 | 7.4 | 60 | 8.4 | 78 | 7.4 | 229 |
| EE3 | 1950 | - | - | 11.8 | 1 | 4.3 | 8 |
| EE3 | 1960 | - | - | - | - | - | - |
| EE3 | 1970 | 20.3 | 37 | 16.6 | 57 | 27.6 | 113 |
| EE3 | 1980 | 9.5 | 65 | 10.7 | 86 | 8.2 | 237 |
| EE3 | 1990 | 10.8 | 147 | 10.6 | 189 | 9.3 | 566 |
| ET6 | 1950 | - | - | - | - | - | - |
| ET6 | 1960 | - | - | - | - | - | - |
| ET6 | 1970 | 32.5 | 37 | 22.9 | 80 | 26.7 | 168 |
| ET6 | 1980 | 11.4 | 23 | 18.0 | 32 | 13.1 | 90 |
| ET6 | 1990 | 10.4 | 60 | 26.9 | 74 | 15.5 | 226 |
| ET7 | 1950 | - | - | - | - | - | - |
| ET7 | 1960 | - | - | - | - | - | - |
| ET7 | 1970 | 36.7 | 31 | 41.9 | 42 | 31.4 | 101 |
| ET7 | 1980 | 6.6 | 11 | 19.6 | 16 | 11.3 | 44 |
| ET7 | 1990 | 8.1 | 29 | 14.3 | 36 | 10.6 | 112 |
| ET8 | 1950 | - | - | - | - | - | - |
| ET8 | 1960 | - | - | - | - | - | - |
| ET8 | 1970 | 15.5 | 3 | 7.2 | 5 | 12.2 | 8 |
| ET8 | 1980 | 8.2 | 12 | 13.8 | 16 | 9.0 | 43 |
| ET8 | 1990 | 11.8 | 30 | 11.2 | 36 | 9.8 | 111 |
| ET9 | 1950 | - | - | - | - | - | - |
| ET9 | 1960 | - | - | - | - | - | - |
| ET9 | 1970 | - | - | 18.2 | 6 | 18.2 | 6 |
| ET9 | 1980 | 5.0 | 12 | 10.0 | 16 | 6.5 | 43 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued)*.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| ET9 | 1990 | 7.5 | 30 | 9.6 | 35 | 7.4 | 112 |
| ET10 | 1950 | - | - | - | - | - | - |
| ET10 | 1960 | - | - | - | - | - | - |
| ET10 | 1970 | 23.1 | 43 | 19.0 | 63 | 19.9 | 146 |
| ET10 | 1980 | 4.2 | 12 | 11.2 | 15 | 8.9 | 45 |
| ET10 | 1990 | 2.1 | 30 | 7.5 | 39 | 4.6 | 113 |
| WT1 | 1950 | - | - | - | - | - | - |
| WT1 | 1960 | - | - | - | - | - | - |
| WT1 | 1970 | 7.3 | 4 | 13.2 | 12 | 10.1 | 25 |
| WT1 | 1980 | 17.6 | 13 | 42.9 | 22 | 25.3 | 53 |
| WT1 | 1990 | 26.4 | 28 | 50.9 | 37 | 31.0 | 106 |
| WT2 | 1950 | - | - | - | - | - | - |
| WT2 | 1960 | - | - | - | - | - | - |
| WT2 | 1970 | 7.6 | 24 | 7.3 | 39 | 9.7 | 94 |
| WT2 | 1980 | 22.3 | 11 | 20.5 | 24 | 17.5 | 53 |
| WT2 | 1990 | 21.5 | 29 | 18.6 | 38 | 17.0 | 106 |
| WT3 | 1950 | - | - | - | - | - | - |
| WT3 | 1960 | - | - | - | - | - | - |
| WT3 | 1970 | 14.7 | 8 | 28.2 | 8 | 17.7 | 19 |
| WT3 | 1980 | 14.8 | 11 | 24.2 | 19 | 19.8 | 48 |
| WT3 | 1990 | 20.1 | 29 | 12.8 | 38 | 13.5 | 107 |
| WT4 | 1950 | - | - | - | - | - | - |
| WT4 | 1960 | - | - | 7.7 | 1 | 30.9 | 3 |
| WT4 | 1970 | 55.7 | 115 | 61.5 | 167 | 58.3 | 392 |
| WT4 | 1980 | 105.5 | 13 | 101.8 | 38 | 83.7 | 87 |
| WT4 | 1990 | 104.2 | 29 | 82.4 | 38 | 75.7 | 107 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued)*.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| WT5 | 1950 | - | - | - | - | 7.5 | 1 |
| WT5 | 1960 | 18.7 | 17 | 47.1 | 41 | 41.9 | 64 |
| WT5 | 1970 | 14.1 | 36 | 40.9 | 77 | 23.4 | 162 |
| WT5 | 1980 | 17.5 | 22 | 50.3 | 44 | 29.3 | 95 |
| WT5 | 1990 | 15.5 | 29 | 36.1 | 39 | 22.3 | 113 |
| WT6 | 1950 | - | - | - | - | - | - |
| WT6 | 1960 | 8.6 | 13 | 12.5 | 21 | 11.5 | 56 |
| WT6 | 1970 | 33.8 | 40 | 37.8 | 50 | 32.7 | 129 |
| WT6 | 1980 | 10.0 | 13 | 22.1 | 19 | 15.0 | 51 |
| WT6 | 1990 | 12.2 | 29 | 18.3 | 37 | 13.6 | 110 |
| WT7 | 1950 | - | - | - | - | - | - |
| WT7 | 1960 | 7.1 | 12 | 15.9 | 22 | 10.8 | 60 |
| WT7 | 1970 | 22.2 | 12 | 32.1 | 43 | 24.8 | 75 |
| WT7 | 1980 | 13.0 | 10 | 22.8 | 18 | 16.8 | 47 |
| WT7 | 1990 | 13.2 | 30 | 19.4 | 35 | 14.4 | 109 |
| WT8 | 1950 | - | - | - | - | - | - |
| WT8 | 1960 | 6.3 | 17 | 15.4 | 38 | 11.1 | 73 |
| WT8 | 1970 | 25.2 | 31 | 29.7 | 84 | 29.4 | 157 |
| WT8 | 1980 | 14.9 | 42 | 23.8 | 58 | 16.5 | 157 |
| WT8 | 1990 | 12.4 | 89 | 18.4 | 110 | 13.0 | 315 |
| TF1 | 1950 | 2.6 | 1 | 1.7 | 2 | 1.7 | 4 |
| TF1 | 1960 | 20.1 | 18 | 32.0 | 43 | 22.5 | 65 |
| TF1 | 1970 | 10.9 | 37 | 15.8 | 68 | 14.3 | 147 |
| TF1 | 1980 | 4.7 | 94 | 18.4 | 160 | 9.2 | 414 |
| TF1 | 1990 | 5.9 | 234 | 15.9 | 307 | 8.7 | 863 |
| RET1 | 1950 | - | - | 2.1 | 2 | 2.9 | 3 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued).*

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| RET1 | 1960 | 15.0 | 2 | 24.8 | 4 | 21.5 | 6 |
| RET1 | 1970 | 31.3 | 2 | 18.1 | 8 | 16.8 | 14 |
| RET1 | 1980 | 15.5 | 13 | 14.2 | 26 | 17.1 | 65 |
| RET1 | 1990 | 17.8 | 30 | 15.6 | 39 | 15.6 | 118 |
| LE1 | 1950 | 5.3 | 3 | 3.3 | 4 | 2.6 | 14 |
| LE1 | 1960 | 19.9 | 2 | 20.5 | 4 | 20.3 | 6 |
| LE1 | 1970 | 10.9 | 4 | 15.7 | 5 | 11.5 | 12 |
| LE1 | 1980 | 14.7 | 52 | 11.4 | 95 | 11.4 | 245 |
| LE1 | 1990 | 10.7 | 120 | 13.0 | 156 | 10.4 | 472 |
| TF2 | 1950 | - | - | - | - | - | - |
| TF2 | 1960 | 24.3 | 50 | 59.1 | 81 | 38.7 | 176 |
| TF2 | 1970 | 17.9 | 142 | 31.0 | 286 | 18.0 | 559 |
| TF2 | 1980 | 4.5 | 95 | 15.9 | 121 | 7.9 | 336 |
| TF2 | 1990 | 6.0 | 174 | 20.3 | 233 | 9.8 | 655 |
| RET2 | 1950 | - | - | 26.7 | 1 | 26.7 | 1 |
| RET2 | 1960 | 8.1 | 26 | 29.3 | 35 | 23.6 | 83 |
| RET2 | 1970 | 20.0 | 78 | 19.3 | 142 | 16.6 | 288 |
| RET2 | 1980 | 7.4 | 62 | 7.4 | 79 | 5.8 | 224 |
| RET2 | 1990 | 5.0 | 93 | 8.4 | 121 | 5.6 | 350 |
| LE2 | 1950 | 10.8 | 2 | 5.0 | 12 | 6.1 | 23 |
| LE2 | 1960 | 8.5 | 24 | 18.7 | 33 | 13.7 | 76 |
| LE2 | 1970 | 8.0 | 40 | 8.9 | 65 | 11.2 | 140 |
| LE2 | 1980 | 18.2 | 31 | 10.3 | 43 | 10.7 | 120 |
| LE2 | 1990 | 10.8 | 60 | 9.4 | 80 | 8.7 | 228 |
| TF3 | 1950 | - | - | - | - | - | - |
| TF3 | 1960 | - | - | - | - | - | - |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued)*.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| TF3 | 1970 | 2.1 | 66 | 9.4 | 142 | 5.7 | 313 |
| TF3 | 1980 | 4.1 | 30 | 15.2 | 53 | 8.4 | 124 |
| TF3 | 1990 | 3.6 | 149 | 14.1 | 209 | 7.3 | 563 |
| RET3 | 1950 | - | - | - | - | 3.7 | 2 |
| RET3 | 1960 | - | - | - | - | - | - |
| RET3 | 1970 | 6.4 | 13 | 6.6 | 29 | 5.6 | 65 |
| RET3 | 1980 | 22.1 | 24 | 10.8 | 39 | 12.5 | 103 |
| RET3 | 1990 | 9.0 | 66 | 11.0 | 85 | 8.5 | 250 |
| LE3 | 1950 | 8.2 | 1 | - | - | 4.3 | 6 |
| LE3 | 1960 | - | - | - | - | - | - |
| LE3 | 1970 | 6.8 | 14 | 8.0 | 35 | 7.5 | 76 |
| LE3 | 1980 | 10.9 | 78 | 8.9 | 120 | 8.3 | 324 |
| LE3 | 1990 | 8.2 | 187 | 7.9 | 250 | 7.1 | 727 |
| TF4 | 1950 | - | - | - | - | - | - |
| TF4 | 1960 | - | - | - | - | - | - |
| TF4 | 1970 | 3.9 | 18 | 9.8 | 107 | 7.2 | 170 |
| TF4 | 1980 | 3.1 | 24 | 5.1 | 40 | 3.8 | 102 |
| TF4 | 1990 | 1.5 | 64 | 4.4 | 79 | 2.5 | 240 |
| RET4 | 1950 | - | - | - | - | 2.0 | 1 |
| RET4 | 1960 | - | - | - | - | - | - |
| RET4 | 1970 | 5.0 | 24 | 9.8 | 109 | 7.2 | 167 |
| RET4 | 1980 | 5.4 | 36 | 11.0 | 60 | 7.0 | 152 |
| RET4 | 1990 | 3.5 | 92 | 13.3 | 118 | 7.4 | 349 |
| LE4 | 1950 | 4.5 | 1 | - | - | 1.8 | 3 |
| LE4 | 1960 | - | - | - | - | - | - |
| LE4 | 1970 | 7.8 | 8 | 5.7 | 21 | 5.8 | 35 |

**Table E-2.** Chesapeake Bay and tidal tributaries chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) by segment across decades: 1950s–1990s *(continued)*.

| Segment | Decade | Spring Mean | (N) | Summer Mean | (N) | Annual Mean | (N) |
|---|---|---|---|---|---|---|---|
| LE4 | 1980 | 13.5 | 36 | 8.3 | 59 | 9.7 | 151 |
| LE4 | 1990 | 10.3 | 97 | 7.6 | 125 | 7.6 | 371 |
| WE4 | 1950 | - | - | - | - | 0.6 | 2 |
| WE4 | 1960 | - | - | - | - | - | - |
| WE4 | 1970 | 8.3 | 16 | 7.4 | 42 | 6.5 | 69 |
| WE4 | 1980 | 6.3 | 60 | 8.4 | 80 | 6.9 | 236 |
| WE4 | 1990 | 7.3 | 125 | 8.5 | 167 | 7.3 | 502 |
| TF5 | 1950 | - | - | - | - | - | - |
| TF5 | 1960 | - | - | - | - | - | - |
| TF5 | 1970 | 5.5 | 55 | 8.9 | 187 | 5.2 | 345 |
| TF5 | 1980 | 10.2 | 65 | 20.7 | 114 | 11.2 | 283 |
| TF5 | 1990 | 6.3 | 210 | 16.3 | 284 | 8.9 | 813 |
| RET5 | 1950 | - | - | - | - | - | - |
| RET5 | 1960 | - | - | - | - | - | - |
| RET5 | 1970 | 7.7 | 19 | 4.6 | 75 | 4.6 | 137 |
| RET5 | 1980 | 13.8 | 24 | 17.3 | 40 | 13.7 | 100 |
| RET5 | 1990 | 13.3 | 64 | 14.1 | 85 | 11.1 | 245 |
| LE5 | 1950 | - | - | 3.3 | 19 | 2.3 | 28 |
| LE5 | 1960 | 12.8 | 2 | - | - | 12.8 | 2 |
| LE5 | 1970 | 7.6 | 9 | 3.8 | 43 | 3.6 | 73 |
| LE5 | 1980 | 13.8 | 88 | 6.2 | 140 | 9.6 | 349 |
| LE5 | 1990 | 10.7 | 331 | 7.9 | 447 | 7.7 | 1295 |

appendix F

# Phytoplankton Reference Community Data Analyses

This appendix describes various analyses performed with the 1984-2001 Chesapeake Bay Program water quality and plankton monitoring data that supported determination of the phytoplankton reference community chlorophyll *a* concentrations reported in Chapter V.

## REFERENCE PHYTOPLANKTON COMMUNITIES AND WATER QUALITY CONDITION CLASSIFICATIONS

Biological populations found in pristine or minimally impaired habitats provide essential information about how restoration efforts might improve ecosystem structure and function. Called 'reference communities,' these populations serve as benchmarks for measuring ecosystem impairment. Ecosystem impairment is assessed with a suite of physical, chemical and biological performance indicators which are measurable attributes of the ecosystem linked directly to restoration objectives. The properties of the performance indicators in biological reference communities furnish the evaluation (scoring) criteria needed to quantify ecosystem impairment at other sites (National Research Council 1992). Chlorophyll *a* has long been used as a surrogate measure of phytoplankton biomass and as a performance indicator of nutrient enrichment across a wide spectrum of aquatic systems (see Chapter V). Chlorophyll *a* as an indicator is directly linked to a restoration objective of the Chesapeake Bay Program, namely the reduction of excess, uneaten phytoplankton that accumulates in the water column and contributes to reduced water clarity and summer oxygen depletion in bottom waters, ultimately stressing the food webs the phytoplankton support.

Chlorophyll *a* concentrations for season- and salinity-specific phytoplankton reference communities for Chesapeake Bay tidal waters are described in this appendix and elsewhere (Buchanan et al., in review). The reference communities are based on phytoplankton populations currently found in waters least impaired by poor water clarity and nutrients in excess of phytoplankton growth requirements. Water quality

condition classifications were determined with three parameters crucial to phytoplankton growth: light penetration (measured as Secchi depth), dissolved inorganic nitrogen (DIN) and ortho-phosphate ($PO_4$).

## ANALYSIS APPROACH

Chesapeake Bay water quality and phytoplankton data collected at Chesapeake Bay Program biomonitoring stations between 1984 and 2001 were first analyzed to identify samples that were least impaired by poor water clarity and excess nutrients. Seasonal and salinity-specific phytoplankton 'reference' communities for the Chesapeake Bay were then derived from the populations in those samples. The reference communities are used in this analysis to quantify chlorophyll *a* concentrations in the least-impaired water quality conditions currently found in the Chesapeake Bay and its tidal tributaries.

The Chesapeake Bay Monitoring Program has coordinated the year-round collection of plankton and water quality data at more than 26 stations for all salinity zones in the Chesapeake Bay mainstem and its major tidal tributaries since August 1984. Data for some parameters were collected over shorter periods or only by one state. The primary data and data documentation are available at http://www.chesapeakebay.net/data. Phytoplankton parameters that are measured (primary data) or derived from measured data include chlorophyll *a*, pheophytin, species abundances, biomasses of individual species in the nano (2–20 micron) and micro (20–200 micron) size fractions, phytoplankton biomass in pico (<2 micron) size fractions, average cell size of the nano-micro phytoplankton and the ratio of phytoplankton biomass (as carbon) to chlorophyll *a*. Productivity cannot be used for baywide analyses because Maryland and Virginia methodologies are different. In this study, water quality and phytoplankton data from the mixed upper layer of the water column (usually identified as 'above-pycnocline,' or AP) were analyzed, with the exception of a few tidal-fresh stations where samples were from the whole water column (WC). Data from each sampling event at an individual station were sorted into two seasons and four salinity zones for examination: spring (March, April and May) and summer (July, August and September); and tidal-fresh (0.0 to 0.5 ppt), oligohaline (>0.5 to 5.0 ppt), mesohaline (>5.0 to18.0 ppt) and polyhaline (>18.0 ppt). This minimizes the influence of season and salinity regime on the analysis.

Phytoplankton and water quality data within each season-salinity group were binned (further grouped) into six categories using Secchi depth, DIN and $PO_4$ thresholds shown in tables F-1 and F-2. The thresholds classify the Secchi depth, DIN, and $PO_4$ values of each data record as 'worst,' 'poor,' 'better,' or 'best'. The DIN and $PO_4$ thresholds separating 'better' and 'poor' values in tables F-1 and F-2 have been experimentally shown to be resource limitation thresholds for natural Chesapeake Bay phytoplankton populations (Fisher et al. 1988, 1999; Thomas Fisher personal communication). The Secchi depth thresholds separating 'better' and 'poor' values were empirically determined from the monitoring data using the Relative Status, or benchmark, method (Olson 2002). The 'better' water clarity levels are those

**Table F-1.** Spring (March through May) classification criteria for determining 'worst', 'poor', 'better' and 'best' water quality parameter conditions. Key: Secchi-Secchi depth (meters); DIN-average dissolved organic nitrogen in surface mixed layer (mg liter$^{1}$); $PO_4$—average orthophosphate (SRP) in surface mixed layer (mg liter$^{1}$); TF—tidal fresh salinities (0 to 0.5 ppt); OH—oligohaline salinities (>0.5 to 5 ppt); MH—mesohaline salinties (>5 to 18 ppt); PH—polyhaline (>18 ppt). The 25th percentile, median and 75th percentile of the parameter's values at stations identified as 'good' by the Relative Status Method are given for comparison purposes. See Buchanan et al. (in review) for details.

| Parameter | | Selected Spring Classification Criteria | | | | Relative Status Method |
|---|---|---|---|---|---|---|
| | | Worst | Poor | Better | Best | *25th%/median/75th%* |
| Secchi | TF | <0.7 | =<0.9 | >0.9 | >1.1 | *0.7 \| 0.9 \| 1.10* |
| Secchi | OH | <0.5 | =<0.7 | >0.7 | >1.1 | *0.5 \| 0.7 \| 1.10* |
| Secchi | MH | <1.35 | =<1.8 | >1.8 | >2.25 | *1.35 \| 1.80 \| 2.25* |
| Secchi | PH | <1.6 | =<2.15 | >2.15 | >2.55 | *1.6 \| 2.15 \| 2.55* |
| | | Worst | Poor | Better | Best | *75th%/median/25th%* |
| DIN | TF | >.585 | >0.070 | =<0.070 | <0.030 | *.585 \| .434 \| .290* |
| DIN | OH | >.885 | >0.070 | =<0.070 | <0.030 | *.885 \| .680 \| .464* |
| DIN | MH | >.265 | >0.070 | =<0.070 | <0.030 | *.265 \| .150 \| .070* |
| DIN | PH | >.070 | >0.070 | =<0.070 | <0.030 | *.063 \| .020 \| .011* |
| | | Worst | Poor | Better | Best | *75th%/median/25th%* |
| $PO_4$ (SRP) | TF | >0.020 | >0.003 | =<0.003 | =<0.003 | *.020 \| .136 \| .010* |
| $PO_4$ (SRP) | OH | >0.010 | >0.003 | =<0.003 | =<0.003 | *.010 \| .005 \| .004* |
| $PO_4$ (SRP) | MH | >0.003 | >0.002 | =<0.002 | =<0.002 | *.003 \| .002 \| .0006* |
| $PO_4$ (SRP) | PH | >0.005 | >0.003 | =<0.003 | =<0.003 | *.005 \| .004 \| .0007* |

associated with the least impaired stations currently monitored in the Chesapeake Bay. They also approximate the light levels required for growth of underwater bay grasses (Batiuk et al. 2000). For the purpose of establishing phytoplankton reference communities, a water quality parameter classification of 'worst or 'poor' is considered impaired while a water quality parameter classification of 'better' or 'best' is considered unimpaired.

When all three parameters were classified as 'worst,' the data record was placed in the 'worst' water quality category. When all three parameters classified as 'poor' or 'worst' (includes all 'worst'), the data record was placed in the 'poor' water quality category. 'Poor' and 'worst' water quality conditions are characterized by low levels of light, and concentrations of DIN and $PO_4$ that exceed phytoplankton nutrient requirements. 'Worst' is an extreme subset of 'poor.' Similarly, when all three parameters classified as 'best,' the data record was placed in the 'best' water quality category. When all three classified as 'best' or 'better' (includes all 'best'), the data record was placed in the 'better' water quality category. 'better' and 'best' water quality conditions had high levels of light and limiting (low) concentrations of DIN and $PO_4$. 'Best' is an extreme subset of 'better'. Data records were placed in a

**Table F-2.** Summer (July through September) classification criteria for determining 'worst', 'poor,' 'better,' and 'best' water quality parameter conditions. Key: Secchi-Secchi depth (meters); DIN-average dissolved organic nitrogen in surface mixed layer (mg liter$^{1}$); $PO_4$—average orthophosphate (SRP) in surface mixed layer (mg liter$^{1}$); TF—tidal fresh salinities (0 to 0.5 ppt); OH—oligohaline salinities (>0.5 to 5 ppt); MH—mesohaline salinties (>5 to 18 ppt); PH—polyhaline (>18 ppt). The 25th percentile, median and 75th percentile of the parameter's values at stations identified as 'good' by the Relative Status Method are given for comparison purposes. See Buchanan et al. (in review) for details.

| Parameter | | Selected Summer Classification Criteria | | | | Relative Status Method |
|---|---|---|---|---|---|---|
| | | Worst | Poor | Better | Best | *25th%/median/75th%* |
| Secchi | TF | <0.6 | =<0.8 | >0.8 | >1.0 | *0.6 \| 0.8 \| 1.0* |
| Secchi | OH | <0.55 | =<0.6 | >0.6 | >0.7 | *0.55 \| 0.6 \| 0.7* |
| Secchi | MH | <1.2 | =<1.45 | >1.45 | >1.7 | *1.2 \| 1.45 \| 1.7* |
| Secchi | PH | <1.55 | =<1.85 | >1.85 | >2.35 | *1.55 \| 1.85 \| 2.35* |
| | | Worst | Poor | Better | Best | *75th%/median/25th%* |
| DIN | TF | >.390 | >0.070 | =<0.070 | <0.030 | *.390 \| .240 \| .125* |
| DIN | OH | >.090 | >0.070 | =<0.070 | <0.030 | *.090 \| .050 \| .028* |
| DIN | MH | >.074 | >0.070 | =<0.070 | <0.030 | *.074 \| .035 \| .014* |
| DIN | PH | >.070 | >0.070 | =<0.070 | <0.030 | *.028 \| .011 \| .008* |
| | | Worst | Poor | Better | Best | *75th%/median/25th%* |
| $PO_4$ (SRP) | TF | >0.025 | >0.003 | =<0.003 | =<0.003 | *.025 \| .020 \| .010* |
| $PO_4$ (SRP) | OH | >0.010 | >0.003 | =<0.003 | =<0.003 | *.010 \| .009 \| .004* |
| $PO_4$ (SRP) | MH | >0.008 | >0.002 | =<0.002 | =<0.002 | *.008 \| .005 \| .0035* |
| $PO_4$ (SRP) | PH | >0.010 | >0.003 | =<0.003 | =<0.003 | *.010 \| .008 \| .005* |

'mixed poor light' category if Secchi depth classified as 'poor' or 'worst' and one or both of the nutrient parameters classified as 'better' or 'best'. Data records were placed in a 'mixed better light' category if Secchi depth classified as 'better' or 'best' and one or both of the nutrient parameters classified as 'poor' or 'worst'.

## SUMMARY OF CHLOROPHYLL *A* RESULTS

The 'better' water quality conditions (includes 'best') occurred in 1.6 percent (spring) and 5.8 percent (summer) of the mesohaline biomonitoring records, and 21.1 percent (spring) and 10.4 percent (summer) of the polyhaline biomonitoring records collected between 1984 and 2001. Therefore, reference communities could be characterized directly from the phytoplankton associated with these least-impaired water quality data. Because values of most phytoplankton parameters in the mesohaline and polyhaline 'mixed better light' categories, including chlorophyll *a*, closely resembled those in 'better' categories, 'mixed better light' data were used to augment the small number of spring mesohaline 'better' data records. Median chlorophyll *a* concentrations were 5.6 (spring) and 7.1 (summer) $\mu$g liter$^{-1}$ in the

mesohaline reference communities, and 2.9 (spring) and 4.4 (summer) $\mu$g liter$^{-1}$ in the polyhaline reference communities. Reference community chlorophyll *a* values are within the 2-7 $\mu$g liter$^{-1}$ range identified by Molvaer et al. (1997) for mesotrophic marine waters, but are slightly higher than the 1-3 $\mu$g liter$^{-1}$ chlorophyll *a* range identified as mesotrophic by Smith et al. (1990). They can be considered high mesotrophic. The reference community medians are 50 percent (spring) and 58 percent (summer) of the Poor category median concentrations in mesohaline waters and 32 percent (spring) and 72 percent (summer) of the 'poor' category median concentrations in polyhaline waters. These differences are significant (Wilcoxon test, $p<0.01$). Chlorophyll *a* concentrations in the 'poor' categories classify as eutrophic in mesohaline waters and borderline eutrophic in polyhaline waters.

Tidal-fresh and oligohaline reference community chlorophyll *a* concentrations are based primarily on phytoplankton in the 'mixed better light' water quality category, which is the least impaired category commonly found in low salinity waters of the Chesapeake Bay. 'Better' water quality conditions occurred in less than 1 percent of all samples. The combined 'mixed better light' and 'better' categories occurred in 4.7 percent (spring) and 21.5 percent (summer) of the tidal fresh biomonitoring records and in 18.7 percent (spring) and 29.9 percent (summer) of the oligohaline biomonitoring records collected between 1984 and 2001. Median chlorophyll *a* concentrations were 4.3 (spring) and 8.6 (summer) $\mu$g liter$^{-1}$ in the tidal fresh reference communities, and 9.6 (spring) and 6.0 (summer) $\mu$g liter$^{-1}$ in the oligohaline reference communities. Reference community chlorophyll *a* values are within the ranges identified by Wetzel (2001) and Novotny and Olem (1994) for mesotrophic fresh waters, but sometimes exceed the ranges identified by Smith et al. (1998) and Ryding and Rast (1989). These values can be considered high mesotrophic. Median chlorophyll *a* concentrations of the reference community are 64 percent (spring) and 34 percent (summer) of those in tidal fresh 'poor' category waters, and 52 percent (spring) and 35 percent (summer) of those in oligohaline 'poor' category waters. These differences are significant (Wilcoxon test, $p<0.01$). Chlorophyll *a* concentrations in the tidal-fresh and oligohaline 'poor' categories classify as eutrophic to highly eutrophic.

Reference communities were also distinguishable from 'poor' category phytoplankton populations by their smaller chlorophyll *a* ranges (Figure F-1). Typically, ranges of chlorophyll *a* concentrations in the reference communities were $^1/_5$ to ½ the span of those in 'poor' water quality conditions. The large ranges of chlorophyll *a* concentrations found in the 'worst,' 'poor,' and 'mixed poor light' water quality categories of all salinity zones demonstrate the occurrence of frequent algal blooms in these categories. Marshall et. al. (in draft) show that the species compositions of phytoplankton associated with the lowest quartile (minimum—25$^{th}$ percentile) of chlorophyll *a* values in 'worst', 'poor' and 'mixed poor light' water quality conditions are generally mixed, while species compositions in the highest quartile of chlorophyll values (75$^{th}$ percentile–maximum) are dominated by 'bloom-forming' species. Mesohaline and polyhaline bloom-forming species include the diatoms

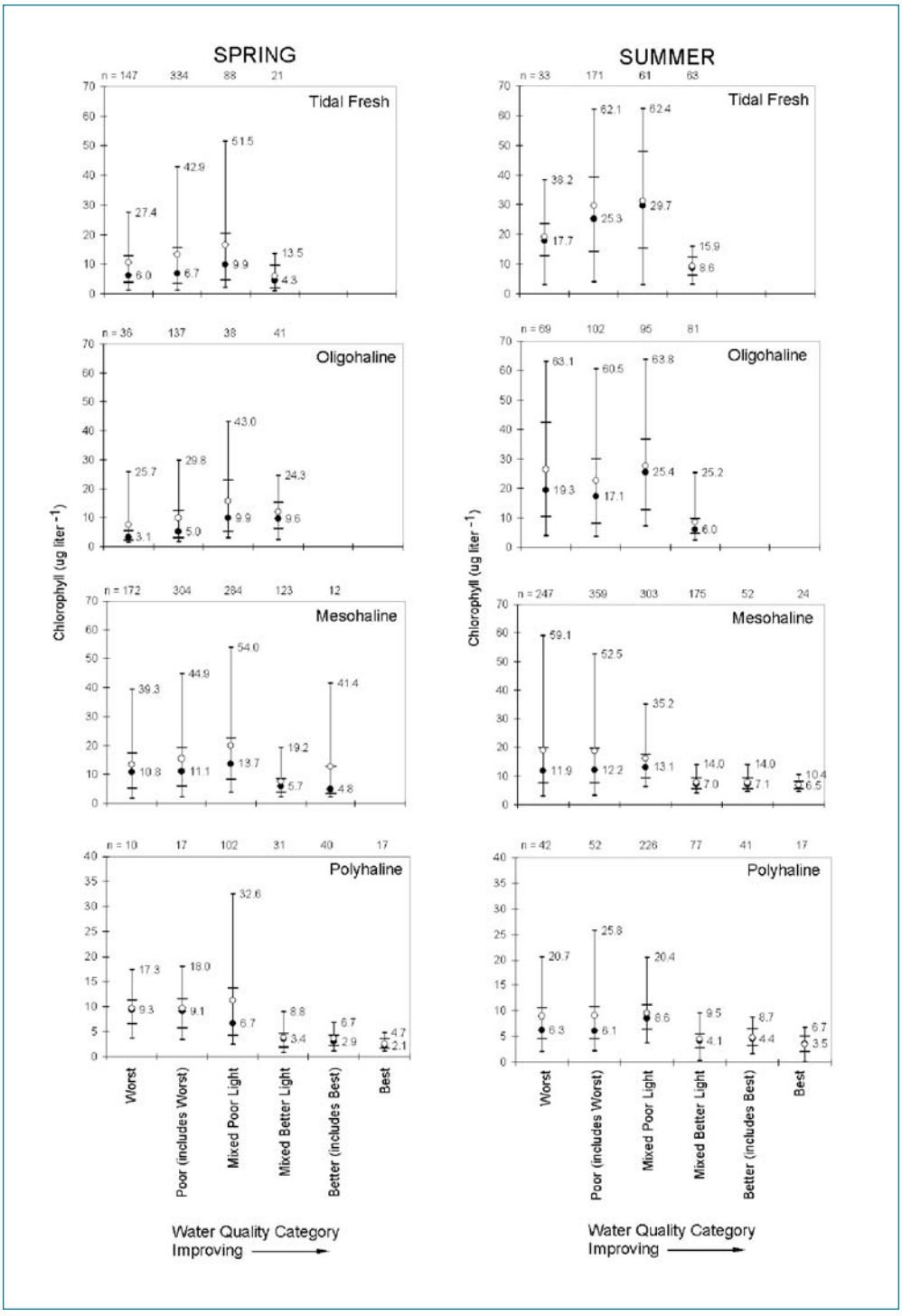


**Figure F-1:** Chlorophyll *a* concentrations ($\mu$g liter$^{-1}$) for six water quality conditions in eight season-salinity groups (see text for details). Symbols: median (•), average (°), and 5$^{th}$, 25$^{th}$, 75$^{th}$ and 95$^{th}$ percentiles (—). Median and 95$^{th}$ percentile values are shown. A blank indicates <10 data points were available in the water quality category.

*Chaetoceros* spp., *Cyclotella* spp. and (at times) the small, unidentified centric diatom, and the dinoflagellates *Gymnodinium* spp., *Katodinium rotundatum* and *Prorocentrum minimum*. Tidal-fresh and oligohaline bloom-forming species include colonial bluegreens such as *Microcystis aeruginosa*, filamentous bluegreen genera such as *Oscillatoria* and *Raphidiopsis*, diatoms such as *Coscinodiscus* spp., *Leptocylindrus minimus*, small unidentified centrics and *Melosira varians*, greens such as *Coelastrum* spp., and the dinoflagellate *Gymnodinium* spp. Coincident water quality data suggests the high chlorophyll *a* groups in 'worst,' 'poor,' and 'mixed poor light' conditions may represent blooms at their peak, while the low chlorophyll *a* groups may represent populations unable to use the available nutrients and blooming due to low light levels. Specifically, DIN concentrations in the high chlorophyll *a* groups are sometimes as little as half of those in the low chlorophyll *a* groups, indicating increased nitrogen utilization in the high chlorophyll *a* groups.

The ranges of chlorophyll *a* concentrations ($5^{th}$ percentile–$95^{th}$ percentile) observed in the phytoplankton reference communities indicate the peak concentrations that should be expected in populations currently inhabiting unimpaired Chesapeake waters. Chlorophyll *a* concentrations above these peak values constitute excess phytoplankton production fueled by high nutrient concentrations and are potentially harmful to the Chesapeake ecosystem. Peak chlorophyll *a* concentrations of the reference communities, expressed as $\mu$g liter$^{-1}$, are 13.5 (tidal-fresh), 24.3 (oligohaline), 24.6 (mesohaline) and 6.7 (polyhaline) in spring, and 15.9 (tidal-fresh), 25.2 (oligohaline), 14.0 (mesohaline) and 8.7 (polyhaline) in summer.

## LITERATURE CITED

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appendix G

# Data Supporting Determination of Adverse Affect Thresholds for Potentially Harmful Algal Bloom Species

## *MICROCYSTIS AERUGINOSA* EFFECTS TRESHOLD

A substantial body of literature deals with the negative effects of toxic cyanobacteria on the feeding, growth, behavior and survival of micro- and mesozooplankton. Numerous studies have documented the avoidance of ingestion of toxic and nontoxic strains of *Microcystis aeruginosa* by specific taxa of zooplankton (Clarke 1978; Lampert 1981; Gilbert and Bogdan 1984; Fulton and Paerl 1987, 1988; DeMott and Moxter 1991) while others indicate physiological and behavioral problems associated with the ingestion of *Microcystis aeruginosa* (Lampert 1981, 1982; Nizan et al. 1986; Fulton and Paerl 1987; DeMott et al. 1991; Henning et al. 1991).

Fulton and Paerl's study (1987) indicated that a unicellular strain of *Microcystis aeruginosa* (concentrations of 100,000 cells milliliter$^{-1}$) was toxic to and failed to support populations of *Keratella mixta*, *Diaphanosoma bracyurum*, *Daphnia ambigua* and *Bosmina longirostris* (a rotifer and three cladocerans, respectively). Other studies have shown additional evidence of inhibitory effects of *Microcystis aeruginosa*. For instance, Penaloza et al. (1990), showed that water-soluble fractions of *Microcystis aeruginosa* were toxic to several rotifers, a copepod and a cladoceran. De Mott et al. (1991) showed that a calanoid copepod was more sensitive to purified microcystin than the cladoceran that he used in his experiments. Nutritionally, many zooplankton have been shown to grow poorly on *Microcystis aeruginosa* because it lacks certain fatty acids (Ahlgren et al. 1990). The results of these studies indicate a deleterious effect exerted by blooms of *Microcystis aeruginosa* on zooplankton communities. Two studies were chosen in the context of deriving thresholds for impairment because they used densities of cells that could be used to evaluate data from the Chesapeake Bay Monitoring Program and ultimately translated into chlorophyll *a* concentrations. Without doing direct experiments on inhibitory effects of the Chesapeake Bay strains of *Microcystis aeruginosa* on zooplankton populations, certain assumptions of comparable toxicity were made for the purposes of setting thresholds.

Numerous laboratory studies also have documented the acute effects of toxins from the cyanobacterium *Microcystis aeruginosa* on fish (Erickson et al. 1986; Rabergh et al. 1991; Keshavanath et al. 1994; Beveridge et al. 1993; Tencalla et al. 1994; Bury et al. 1995). Several instances of fish kills resulting from cyanobacterial blooms also have been documented (Erickson et al. 1986; Penaloza et al. 1990; Rabergh et al. 1991). These studies indicate a variety of negative effects, including inhibition of filtering rate, liver damage, disturbed ionic regulation, behavioral changes and mortality. However, these studies addressed the potential damage from the standpoint of toxin concentrations, not actual cell densities of the phytoplankton species itself. Therefore, it was not possible to deduce a specific quantitative chlorophyll *a* threshold whereby fish can be assessed as being negatively affected by blooms of *Microcystis aeruginosa*.

Two laboratory studies were chosen to determine the threshold at which a negative impact on the zooplankton community occurs–an impact in which the zooplankton community structure is altered by the poor food quality, large particle size of the colonies, increased density of particles in the water column or directly by the toxin. Lampert (1981) conducted a laboratory feeding study in which densities as low as 1,400 cells milliliter$^{-1}$ of *Microcystis aeruginosa* resulted in the feeding inhibition of zooplankton. Similarly, Fulton and Paerl (1987) conducted grazing experiments in which the inhibitory threshold of *Microcystis aeruginosa* ranged from 10,000-100,000 cells milliliter$^{-1}$, but was most clearly demonstrated at concentrations of 100,000 cells milliliter$^{-1}$. Since there is a difference of two orders of magnitudes between the two studies, an intermediate concentration of 10,000 cells milliliter$^{-1}$ was chosen for exhibiting an inhibitory effect on zooplankton feeding.

It should be noted that a third study has been identified which documented negative impacts on zooplankton at *Microcystis aeruginosa* cell densities of 50,000 cells milliliter$^{-1}$ which is an intermediate value compared to the two previously cited studies (Smith and Gilbert 1995).

## *PROROCENTRUM MINIMUM* EFFECTS THRESHOLD

Certain strains of *Prorocentrum minimum* are toxic. In Japan in 1942, *Prorocentrum minimum* was attributed as the cause of a shellfish poisoning in Japan in which 114 people died (Nagazima 1965, 1968). *Prorocentrum minimum* isolated from a 1998 bloom in the Choptank River and subsequently grown in the laboratory was found toxic to scallops (Wickfors, personal communication). Blooms of *Prorocentrum minimum* in the source intake water to Virginia and Maryland oyster hatcheries were suspected to have caused oyster larvae mortality at the two hatcheries in 1998 (Luckenbach and Merritt, personal communication). There has been no documented case of shellfish toxicity or mortality as a result of the 1998 *Prorocentrum minimum* bloom in the Chesapeake Bay, but clearly the potential exists for toxic repercussions to shellfish and other organisms as a result of this bloom.

Embryonic development of the Eastern oyster (*Crassostrea virginica)* was not affected by living cells or extracts of *Prorocentrum minimum*, however, larvae showed poor growth and poor development of the digestive system when fed *Prorocentrum minimum* (approximately 4,000 cells milliliter$^{-1}$) (Wickfors and Smolowitz 1995). Juvenile oysters adapted to digesting *Prorocentrum minimum*, but only after a two-week period. The study concludes that feeding *Prorocentrum minimum* to oyster larvae resulted in clear detrimental effects, but it was not apparent whether the effects were from toxicity or starvation. In addition, it was concluded that some component of the *Prorocentrum minimum* cell interfered with cellular digestive processes in oyster larvae and spat.

The Wickfors and Smolowitz (1995) study also showed detrimental effects of various diets containing different proportions of *Prorocentrum minimum* to oyster larvae and newly set spat. The larvae showed consistently poorer survival and growth in the different experimental diets and only those fed the diet with no *Prorocentrum minimum* or one-third the maximum concentration developed into pedi-veligers and set. Both life stages showed difficulties in the digestive system after *Prorocentrum minimum* became a major component of their diet. The study concludes that *Prorocentrum minimum* blooms impaired the survival, growth and development of oyster larvae. That the study did not reveal whether the cause of these detrimental effects was toxicity or starvation is important to the derivation of numeric chlorophyll *a* criteria or target concentrations. The highest density used in the study was 3,900 cells milliliter$^{-1}$ and detrimental effects were seen at densities of ~ 2,600 cells milliliter$^{-1}$ in a mixed diet. The study is, however, useful in establishing that 1) *Prorocentrum minimum* is detrimental to oyster life stages and 2) specific densities of cells cause impairment.

Another laboratory study indicated more intense impairment of Eastern oyster life stages when they were subjected to bloom concentrations of *Prorocentrum minimum* (Luckenbach et al. 1993). Growth rates were minimal at cell densities of 3,000 cells milliliter$^{-1}$, as an inverse relationship was documented between grazing rate and cell density. Ultimately, mortality resulted for 43 percent of the juvenile oysters that were subjected to this same density of *Prorocentrum minimum* cells.

The 1993 Luckenbach study was designed to test the effects of *Prorocentrum minimum* on the growth and survival of the Eastern oyster. The momentum for this study came from observations over many years made at the Virginia Institute of Marine Science oyster hatchery over many years on the impact of dinoflagellate blooms on the oyster populations in the hatchery. These observations are unpublished but still noteworthy. They include the observation that adult oysters do not spawn in the presence of bloom densities of *Prorocentrum minimum* and that early larval development is impaired and high mortalities occur in the presence of high densities of this dinoflagellate. The study used densities between 8,900-25,000 cells milliliter$^{-1}$ for the 100 percent bloom density and 2,964-8,250 cells milliliter$^{-1}$ for a 33 percent bloom density. Mortalities of 100 percent for juvenile oysters took place

in the 100 percent bloom diet, while 43 percent mortality was observed in the 33 percent bloom diet.

The density of 3,000 cells milliliter$^{-1}$ that was chosen as a threshold for the chlorophyll *a* criteria analysis is based on the results of these two studies, whereby detrimental effects were documented at cell densities of 2,600 cells milliliter$^{-1}$ in one study and 2,964-8,250 cells milliliter$^{-1}$ in the other study. Neither study was aimed specifically at determining the threshold of impairment for *Prorocentrum minimum*, but impairments took place in both studies at a bloom density of around 3,000 cells milliliter$^{-1}$. The fact that two different strains of *Prorocentrum minimum* were used in the two studies and negative effects occurred at a very similar density, gives credence to using 3,000 cells milliliter$^{-1}$ as a threshold for impairment.

## *COCHLODINIUM HETEROLOBATUM* EFFECTS THRESHOLD

This species forms intense blooms in warm months at the mouth of the York River and in the lower Chesapeake Bay (Mackiernan 1968; Zubkoff and Warriner 1975; Zubkoff et al. 1979; Marshall 1995). Laboratory studies indicated a threshold concentration of ~ 500 cells milliliter$^{-1}$ whereby calcium uptake was depressed and mortality of larvae was significantly elevated (Ho and Zubkoff 1979). Above densities of ~ 1000 cells milliliter$^{-1}$, calcium uptake was negligible and mortality extremely high. Mortality was attributed to 'spatial competition' rather than a 'toxic secretion' (although this chain-forming dinoflagellate produces copious amounts of mucilage; Lacouture, personal communication). The densities of this organism during bloom conditions far exceeds these values and the extent of these densities can cover tens of square miles (Mackiernan 1968; Zubkoff et al. 1979; Marshall 1995).

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appendix H

# Derivation of Cumulative Frequency Distribution Criteria Attainment Reference Curves

Building from the descriptions of reference curves in Chapter VI, this appendix provides more detailed description of the process and options considered in deriving the open-water and deep-water dissolved oxygen reference curves and the water clarity criteria reference curves.

## DISSOLVED OXYGEN REFERENCE CURVES

The Chesapeake Bay dissolved oxygen criteria have several duration components: 30-day mean, 7-day mean, 1-day mean and instantaneous minimum. At this time, reference curves have been developed only for the 30-day mean component.

### OPEN-WATER CRITERIA REFERENCE CURVES

The open-water designated use includes surface and surface-mixed water above a pycnocline. It also includes waters deeper in the water column where there is no vertical density barrier (pycnocline) or where a vertical barrier is present but does not prevent exchange with oxygenated water horizontally.

The dissolved oxygen criteria are based primarily on target species that are ecologically and commercially valuable and have high oxygen requirements. If the criteria are protective of these species, then by default they are protective of other species with lower oxygen requirements. Ideally, a reference curve for the open-water criteria would be based on dissolved oxygen data collected in this habitat at times and places where these sensitive species are known to thrive. Unfortunately, there is a lack of open-water column estuarine fish/shellfish-based indices of biotic integrity, or similar biological indicator, in addition to the lack of adequate fisheries-independent data over the necessary geographic area and time period. Therefore, surrogate indicators of 'healthy' open-water water quality conditions were employed. To validate the reference areas, the same indicators were used to identify 'unhealthy conditions.' Criteria attainment curves were derived for both groups for comparison.

Four approaches to defining 'healthy' locations by Chesapeake Bay Program segment were examined for the open-water designated use. Approach 1 identified Chesapeake Bay Program segments with 'good' and 'poor' water quality conditions using water quality parameters not including dissolved oxygen. Reference and validation curves were derived using interpolated dissolved oxygen concentration data from the reference and validation segments. Approach 2 ranked the Chesapeake Bay Program segments in order based on seasonal median dissolved oxygen concentration (spring and summer, separately). Criteria attainment curves of the highest and lowest 14 segments (10 percent and 10 percent, respectively for a total of 20 percent) were used to derive reference and validation curves using the interpolated dissolved oxygen monitoring data. In Approach 3, all the polyhaline Chesapeake Bay Program segments were selected and similarly processed for comparison with the other approaches, given these segments were the most likely to have the highest dissolved oxygen values and least impaired biological communities. Approach 4 involved selecting open-water CBP interpolator cells from locations (segment, year and season) where healthy and stressed benthic communities were found (see "Deep-Water Reference Curves," below, for more details). All the data for this analysis came from the Chesapeake Bay Water Quality Monitoring Program database, with the years 1985 through 1994 selected to reflect the years of hydrology currently evaluated through the Chesapeake Bay water quality model (see Chapter VI).

## Approach 1: Reference and Validation Curves Using Water Quality Status

The Chesapeake Bay Program's Tidal Monitoring and Analysis Workgroup developed a procedure to assess relative status for situations 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 the parameter in a 'benchmark' data set as a standard against which individual data points are assessed. The assessments are done separately within salinity classification and generally within depth layers. The median score of the individual data points is then calculated for any user-specified time and space grouping. In the present context, 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.

For this analysis, the combined status assessments for total nitrogen, total phosphorus, chlorophyll *a* and total suspended solids were used to select reference and validation locations. Using the above procedure, surface concentrations of the four parameters for each Chesapeake Bay Program segment, year and season (spring and summer) were assessed to yield an assessment of 'good', 'fair' or 'poor' for each parameter. Each segment/year/season was further evaluated. To qualify as a reference location, at least three out of four water quality parameters had to be 'good' and only one parameter could be 'fair'. To qualify as a validation location, at least three parameters had to be 'poor,' the other could be 'fair' and none could be 'good.' The lists of reference and validation locations using this approach are found in Tables H-1 through H-4.

**Table H-1.** Reference locations for spring open-water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

| Segment | Years | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| BOHOH | 1994 | | | | | | | | | |
| CB2OH | 1985 | 1986 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | |
| CB4MH | 1985 | 1989 | 1992 | | | | | | | |
| CB5MH | 1985 | 1986 | 1989 | 1991 | 1992 | | | | | |
| CB6PH | 1989 | | | | | | | | | |
| CB7PH | 1989 | | | | | | | | | |
| CB8PH | 1989 | 1991 | 1992 | | | | | | | |
| CHKOH | 1985 | 1986 | 1987 | | | | | | | |
| CRRMH | 1985 | 1986 | 1988 | 1989 | 1992 | | | | | |
| EASMH | 1987 | | | | | | | | | |
| ELKOH | 1991 | | | | | | | | | |
| JMSOH | 1985 | 1986 | 1987 | | | | | | | |
| JMSTF | 1992 | 1993 | | | | | | | | |
| MIDOH | 1993 | | | | | | | | | |
| MPNOH | 1985 | | | | | | | | | |
| MPNTF | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| PAXMH | 1992 | | | | | | | | | |
| PIAMH | 1985 | 1986 | 1989 | 1992 | 1994 | | | | | |
| PMKTF | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1993 | 1994 | |
| RPPMH | 1989 | | | | | | | | | |
| RPPOH | 1985 | 1986 | 1987 | | | | | | | |
| RPPTF | 1985 | 1986 | 1987 | 1991 | 1992 | | | | | |
| TANMH | 1986 | | | | | | | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

**Table H-2.** Validation locations for spring open water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

| Segment | Years |
|---|---|
| BIGMH | 1990 |
| BOHOH | 1986 1990 1992 1993 |
| C&DOH | 1986 1987 |
| CB3MH | 1990 |
| CB6PH | 1993 |
| CB7PH | 1993 |
| CB8PH | 1987 1993 |
| CHOMH2 | 1986 1989 1990 1994 |
| CHOOH | 1985 1987 1988 1993 1994 |
| CHSMH | 1985 |
| CHSOH | 1985 1986 1988 1990 1991 1992 1993 1994 |
| EBEMH | 1989 1991 1993 1994 |
| ELIPH | 1987 1988 1989 1990 1991 1992 1993 |
| ELKOH | 1986 1987 |
| FSBMH | 1986 1987 1990 1991 1993 |
| GUNOH | 1988 1991 |
| JMSMH | 1988 1989 1991 1992 1993 |
| JMSOH | 1990 |
| JMSPH | 1985 1986 1987 1988 1990 1991 1992 1993 1994 |
| LAFMH | 1989 1990 |
| MAGMH | 1985 1986 1989 1990 |
| MANMH | 1987 1990 1994 |
| MOBPH | 1987 1993 1994 |
| NANMH | 1986 1987 1988 1990 1991 1992 1993 1994 |
| NANTF | 1986 1988 1990 1992 1993 |
| PAXMH | 1986 1990 |
| PAXOH | 1986 1988 |
| PAXTF | 1986 1989 1990 1991 1994 |
| POCMH | 1993 1994 |
| POTMH | 1990 1991 |
| RHDMH | 1991 |
| RPPMH | 1990 1991 |
| SBEMH | 1989 1991 1993 1994 |
| SEVMH | 1991 1993 |
| SOUMH | 1985 1990 1992 |
| TANMH | 1987 |
| WBEMH | 1989 1990 1991 1992 1993 1994 |
| WICMH | 1986 1987 1988 1989 1990 1991 1992 1993 1994 |
| WSTMH | 1986 1988 1991 |
| YRKMH | 1989 1991 1992 |
| YRKPH | 1986 1987 1988 1990 1991 1993 1994 |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

**Table H-3.** Reference locations for summer open-water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

| Segment | Years | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| BIGMH | 1993 | | | | | | | | | |
| CB1TF | 1985 | 1986 | 1987 | 1990 | 1991 | 1992 | 1993 | 1994 | | |
| CB2OH | 1985 | 1986 | 1987 | 1988 | 1990 | 1991 | 1992 | 1993 | 1994 | |
| CB3MH | 1992 | 1993 | | | | | | | | |
| CB4MH | 1985 | 1986 | 1987 | 1988 | 1990 | 1991 | 1992 | 1993 | 1994 | |
| CB5MH | 1985 | 1986 | 1987 | 1988 | 1990 | 1991 | 1992 | 1993 | 1994 | |
| CB7PH | 1986 | 1987 | | | | | | | | |
| CB8PH | 1986 | 1987 | 1988 | 1990 | 1991 | | | | | |
| CHKOH | 1985 | 1992 | | | | | | | | |
| CRRMH | 1987 | 1988 | 1991 | 1992 | | | | | | |
| EASMH | 1986 | | | | | | | | | |
| ELKOH | 1991 | 1992 | 1994 | | | | | | | |
| GUNOH | 1985 | | | | | | | | | |
| JMSOH | 1985 | 1986 | 1987 | 1990 | 1994 | | | | | |
| JMSTF | 1991 | 1992 | | | | | | | | |
| LCHMH | 1986 | | | | | | | | | |
| MATTF | 1987 | | | | | | | | | |
| MIDOH | 1990 | 1991 | 1993 | 1994 | | | | | | |
| MPNOH | 1985 | 1986 | | | | | | | | |
| MPNTF | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| PIAMH | 1985 | 1986 | 1987 | 1992 | 1993 | | | | | |
| PISTF | 1986 | 1987 | | | | | | | | |
| PMKOH | 1985 | | | | | | | | | |
| PMKTF | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1994 | | |
| POTMH | 1985 | 1986 | 1987 | 1991 | | | | | | |
| POTOH | 1986 | 1987 | 1988 | 1989 | 1990 | | | | | |
| POTTF | 1987 | 1989 | 1990 | | | | | | | |
| RPPMH | 1985 | 1986 | 1987 | | | | | | | |
| RPPOH | 1985 | 1986 | 1987 | 1988 | 1991 | 1992 | 1994 | | | |
| RPPTF | 1992 | 1994 | | | | | | | | |
| TANMH | 1986 | | | | | | | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

**Table H-4.** Validation for summer open-water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

| CBP Segment | Years | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| APPTF | 1988 | 1990 | 1991 | 1992 | 1993 | | | | | |
| BOHOH | 1986 | 1987 | 1988 | 1989 | 1992 | 1994 | | | | |
| BSHOH | 1985 | 1989 | | | | | | | | |
| CB6PH | 1989 | | | | | | | | | |
| CHOMH2 | 1989 | 1990 | 1991 | 1994 | | | | | | |
| CHOOH | 1985 | 1986 | 1987 | 1990 | 1991 | 1994 | | | | |
| CHSMH | 1989 | 1990 | 1993 | | | | | | | |
| CHSOH | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| ELIPH | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | |
| FSBMH | 1988 | 1989 | | | | | | | | |
| GUNOH | 1993 | | | | | | | | | |
| JMSMH | 1989 | | | | | | | | | |
| JMSPH | 1987 | 1989 | 1991 | 1992 | 1993 | 1994 | | | | |
| LAFMH | 1989 | 1990 | | | | | | | | |
| LCHMH | 1989 | | | | | | | | | |
| MAGMH | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1994 | | | |
| MANMH | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1993 | 1994 | | |
| MOBPH | 1986 | 1989 | 1990 | 1991 | 1993 | | | | | |
| NANMH | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1993 | 1994 | | |
| NANTF | 1989 | 1990 | 1992 | 1993 | 1994 | | | | | |
| NORTF | 1989 | | | | | | | | | |
| PATMH | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| PAXMH | 1988 | 1989 | 1993 | | | | | | | |
| PAXOH | 1986 | 1989 | 1992 | 1994 | | | | | | |
| PAXTF | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| POCMH | 1989 | 1994 | | | | | | | | |
| POTTF | 1994 | | | | | | | | | |
| RHDMH | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | | |
| SASOH | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1993 | | | |
| SBEMH | 1992 | 1993 | 1994 | | | | | | | |
| SEVMH | 1985 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1994 | | |
| SOUMH | 1987 | 1988 | 1989 | 1990 | 1991 | 1994 | | | | |
| WBEMH | 1989 | 1990 | 1991 | 1992 | | | | | | |
| WICMH | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1993 | 1994 | | |
| WSTMH | 1985 | 1987 | 1988 | 1989 | 1990 | 1991 | 1994 | | | |
| YRKMH | 1987 | 1989 | 1990 | 1991 | 1993 | | | | | |
| YRKPH | 1986 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Monthly mean dissolved oxygen concentration data were then interpolated basinwide for each month, 1985 to 1994. In addition, a basinwide 'master' interpolated 3-dimensional grid file was created in which each cell has a Chesapeake Bay segment assignment and a static Designated Use assignment (open-water [OW], deep-water [DW] and deep-channel [DC]) based on proposed tidal water designated use boundaries (U.S. EPA 2003). Each cell could thus be identified by the appropriate dissolved oxygen concentration(s) associated with its respective designated use.

For each monthly baywide interpolation, the dissolved oxygen concentration in each open-water designated use cell was compared to the appropriate criteria concentration for the season, and the percent of cells passing/failing the criteria calculated for each segment/designated use. Using the respective lists of 'good' and 'bad' locations (segment_years), the data for the reference and validation segments were extracted and pooled in separate groups. For example, segment POCMH in spring 1993 and 1994 were identified as validation locations. The percent volume failing the criterion in POCMH was calculated for each month—February, March, April and May of 1993 and 1994—and pooled with the percent-volume-failing data from other similarly identified locations. Then, the cumulative frequency distribution attainment curves were derived for each pooled group. Figures H-1 and H-2 show the open-water designated use dissolved oxygen criteria reference and validation curves for the spring and summer seasons generated applying water quality status approach.

It is clear that both reference (hatched line) and validation (solid line) areas meet the spring 30- day 5 mg liter$^{-1}$ criterion almost all if not 100 percent of the time. If there are areas that do not meet this criterion in spring, this method does not detect them. There also is little apparent distinction between the illustrated reference and validation curves in summer (Figure H-2).

However, when the summer data are separated by salinity zone (figures H-3 and H-4), there are distinct differences between the reference and validation curves. In tidal fresh and oligohaline segments, overall exceedance is low, but reference areas have more apparent exceedance than validation areas. The reverse is true for meso-

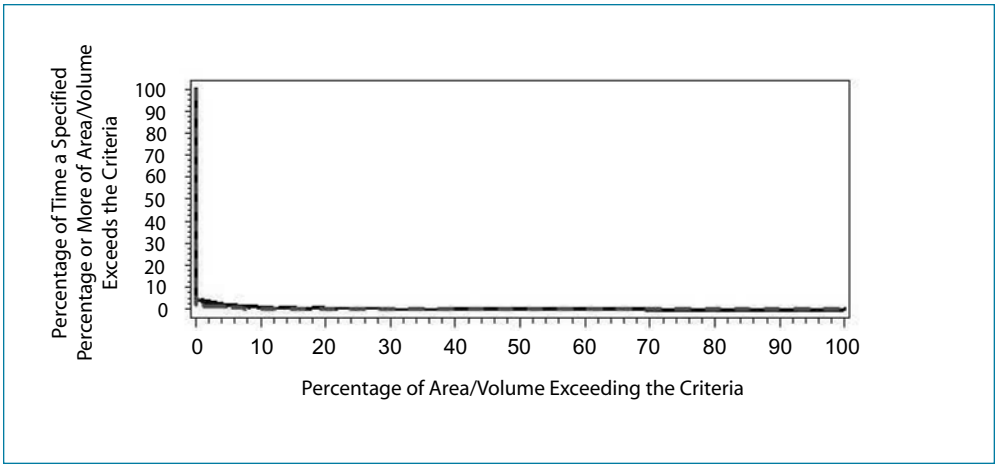


**Figure H-1.** Spring open-water reference (hatched line) and validation (solid line) curves: water quality status approach.

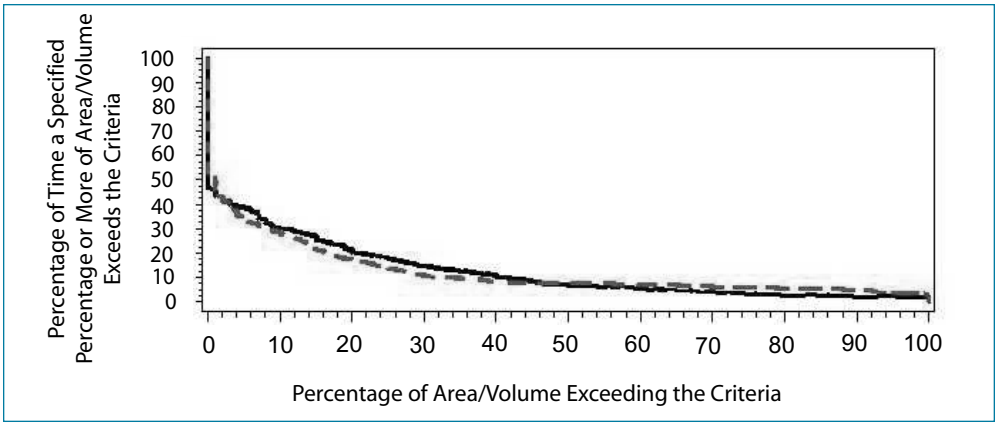


**Figure H-2.** Summer open-water reference (hatched) and validation (solid line) curves: water quality status.

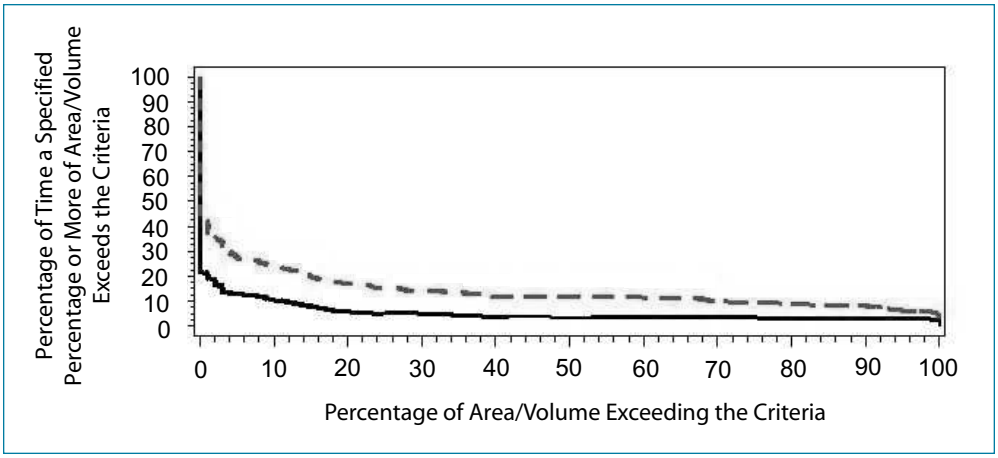


**Figure H-3:** Lower salinity summer open water reference (hatched line) and validation (solid line) curves: water quality status approach.

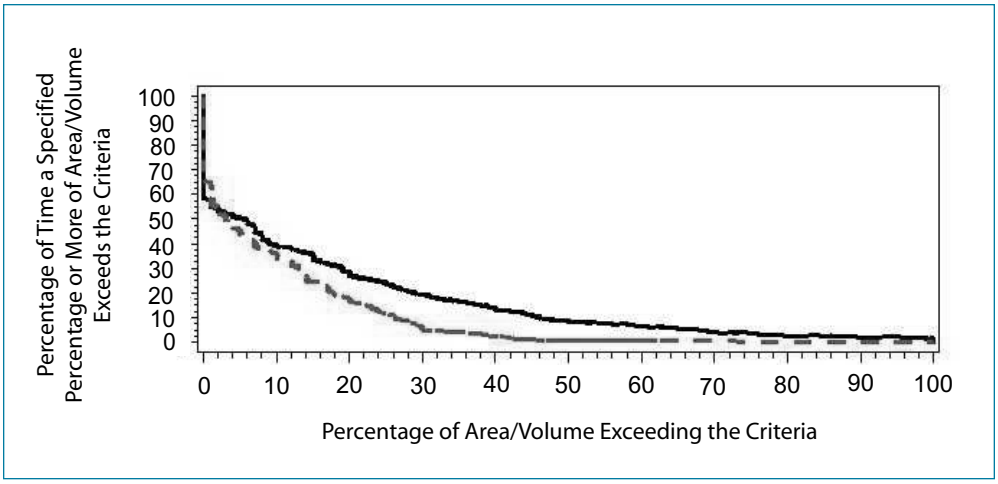


**Figure H-4.** Higher salinity summer open water reference (hatched line) and validation (solid line) curves: water quality status approach.

haline-polyhaline segments where exceedance is generally greater. An important point to remember is that, while we usually think of the open-water habitat as the surface-mixed layer, the open-water criteria are applicable throughout the water column in areas that do not experience chronic vertical stratification. There are such areas in the basin that are quite deep but usually do not have a pycnocline. These areas are more commonly found in mesohaline and polyhaline segments than in the tidal-fresh and oligohaline waters. This is one likely factor in the difference between the reference and validation curves. Another factor could be that surface waters in the validation segments in the tidal-fresh and oligohaline zones are more affected by the oxygen-generating processes of algal blooms, whereas the mesohaline and polyhaline validation segments are more affected by oxygen-consumptive processes occurring in the deep water layers beneath them.

The cumulative frequency distribution curves for reference locations using the water quality status method show that areas with low nutrients, chlorophyll *a* and suspended solids levels also have dissolved oxygen levels that do not greatly exceed the applicable criterion. On the other hand, the validation curves suggest these parameters are not good indicators of locations with dissolved oxygen criteria attainment levels. The mesohaline and polyhaline curve shows some nonattainment, but conditions are far better than those reflected in the validation curve derived from the ranking exercise described below. This result is essentially as expected since, in most of the Chesapeake Bay and tidal tributaries, the link between the water quality parameters and dissolved oxygen has a number of intermediate steps and the dissolved oxygen response to water quality parameters is often displaced in time or space or both.

## Approach 2: Segments with Highest and Lowest Long-term Dissolved Oxygen Concentrations

The ranking procedure for selecting reference and validation segments was based on observed (i.e., not interpolated) data. Dissolved oxygen measurements are available for each monitoring station at 1- to 2-meter intervals from surface to bottom. The depth of the pycnocline, if one existed, also is available. For this analysis, all dissolved oxygen measurements above the pycnocline, or the shallower of all measurements above 7 meters or above the bottom if there was no pycnocline, were assumed to be in open-water designated use habitats. To control for supersaturating conditions, dissolved oxygen concentrations that were above saturation levels (calculated from temperature and salinity measured concurrently) were set down to the saturation level.

Spring (March through May) and summer (June through September) data were averaged first by date and station; then by month and segment; then the $10^{th}$, $50^{th}$ and $90^{th}$ percentiles of the monthly segment averages were calculated for spring and summer seasons over the 1985-1994 period. The seasonal median, i.e., $50^{th}$ percentile, was used to rank the segments (tables H-5 and H-6). Some segments were excluded, resulting in 67 segments that were ranked. The excluded Chesapeake Bay Program

**Table H-5.** Chesapeake Bay Program segments listed in order of spring open-water designated use, seasonal median dissolved oxygen concentration.

| CBP Segment | Median | Mean | 10th percentile | 90th percentile |
|---|---|---|---|---|
| WICMH | 8.0 | 8.4 | 6.2 | 11.5 |
| PMKTF | 8.0 | 8.1 | 6.3 | 10.1 |
| YRKMH | 8.0 | 8.1 | 6.3 | 10.3 |
| POCTF | 8.1 | 7.9 | 5.4 | 10.2 |
| MPNOH | 8.1 | 8.1 | 6.1 | 10.3 |
| PMKOH | 8.1 | 8.2 | 6.2 | 10.3 |
| CHOOH | 8.6 | 8.9 | 7.2 | 10.9 |
| MPNTF | 8.7 | 8.6 | 6.9 | 10.5 |
| PAXOH | 8.7 | 8.8 | 7.0 | 10.8 |
| YRKPH | 8.7 | 8.7 | 7.0 | 10.3 |
| ELIMH | 8.8 | 8.8 | 6.5 | 11.0 |
| ELIPH | 8.8 | 8.8 | 7.1 | 10.7 |
| JMSMH | 8.9 | 9.0 | 7.4 | 10.7 |
| FSBMH | 8.9 | 9.3 | 7.4 | 11.7 |
| RPPTF | 9.0 | 9.3 | 7.3 | 11.3 |
| CHSOH | 9.1 | 9.1 | 7.3 | 10.8 |
| MANMH | 9.1 | 9.1 | 7.4 | 10.9 |
| JMSPH | 9.1 | 9.2 | 7.5 | 11.1 |
| NANMH | 9.1 | 9.3 | 7.4 | 11.1 |
| MOBPH | 9.1 | 9.2 | 7.7 | 10.7 |
| RPPOH | 9.2 | 9.2 | 7.4 | 11.0 |
| POTOH | 9.2 | 9.4 | 7.8 | 11.4 |
| APPTF | 9.2 | 9.4 | 8.0 | 11.2 |
| POCMH | 9.2 | 9.3 | 7.9 | 10.9 |
| BIGMH | 9.3 | 9.3 | 7.5 | 11.1 |
| CB8PH | 9.3 | 9.3 | 8.0 | 10.9 |
| PAXTF | 9.3 | 9.2 | 7.3 | 10.6 |
| TANMH | 9.4 | 9.3 | 7.4 | 11.2 |
| PATMH | 9.4 | 9.4 | 7.7 | 11.0 |
| RPPMH | 9.4 | 9.2 | 7.3 | 10.9 |
| CHOMH2 | 9.4 | 9.4 | 7.6 | 11.4 |
| CRRMH | 9.4 | 9.2 | 7.1 | 10.9 |
| CHKOH | 9.4 | 9.2 | 7.1 | 11.1 |
| JMSOH | 9.5 | 9.4 | 7.9 | 11.0 |
| CB7PH | 9.5 | 9.4 | 7.9 | 10.9 |
| PIAMH | 9.6 | 9.6 | 8.0 | 11.2 |
| PAXMH | 9.6 | 9.3 | 6.9 | 11.2 |
| MAGMH | 9.6 | 9.7 | 7.5 | 11.5 |
| NANTF | 9.6 | 9.5 | 7.5 | 11.4 |
| CHSMH | 9.6 | 9.8 | 8.1 | 11.7 |
| POTTF | 9.7 | 9.8 | 7.9 | 11.8 |
| RHDMH | 9.7 | 9.6 | 7.8 | 11.6 |
| WSTMH | 9.7 | 9.7 | 7.4 | 11.9 |
| CB6PH | 9.7 | 9.7 | 8.0 | 11.2 |
| JMSTF | 9.7 | 9.6 | 8.2 | 10.8 |
| CB3MH | 9.7 | 9.4 | 7.6 | 11.2 |
| SOUMH | 9.7 | 9.2 | 5.8 | 11.5 |
| CB2OH | 9.7 | 9.8 | 7.5 | 11.8 |
| POTMH | 9.7 | 9.7 | 7.9 | 11.7 |
| BSHOH | 9.8 | 10.0 | 8.1 | 12.0 |
| C&DOH | 9.8 | 10.0 | 8.0 | 12.0 |
| BACOH | 9.9 | 9.9 | 8.0 | 12.0 |
| EASMH | 9.9 | 9.9 | 8.0 | 11.5 |
| PISTF | 9.9 | 10.1 | 7.9 | 11.9 |
| SEVMH | 9.9 | 9.8 | 7.7 | 11.7 |
| LCHMH | 9.9 | 9.8 | 8.3 | 11.4 |
| CB5MH | 10.0 | 10.0 | 8.3 | 11.5 |
| MATTF | 10.0 | 10.0 | 8.5 | 11.7 |
| ELKOH | 10.0 | 10.1 | 8.3 | 12.1 |
| CB4MH | 10.1 | 9.9 | 8.1 | 11.4 |
| CHOMH1 | 10.1 | 9.8 | 7.8 | 11.3 |
| SASOH | 10.1 | 10.1 | 8.4 | 11.9 |
| MIDOH | 10.3 | 10.3 | 8.7 | 12.2 |
| NORTF | 10.4 | 10.5 | 9.2 | 12.3 |
| BOHOH | 10.4 | 10.2 | 8.6 | 12.4 |
| GUNOH | 10.5 | 10.4 | 8.6 | 12.1 |
| CB1TF | 11.0 | 10.7 | 8.6 | 12.5 |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

**Table H-6.** Chesapeake Bay segments listed in order of summer dissolved oxygen designated use, seasonal median dissolved oxygen concentration.

| CBP Segment | Median | Mean | 10th percentile | 90th percentile | CBP Segment | Median | Mean | 10th percentile | 90th percentile |
|---|---|---|---|---|---|---|---|---|---|
| SOUMH | 4.2 | 4.5 | 2.7 | 7.1 | FSBMH | 6.6 | 6.5 | 5.8 | 7.3 |
| MAGMH | 4.7 | 4.8 | 3.3 | 6.9 | ELKOH | 6.6 | 6.5 | 5.8 | 7.2 |
| PMKTF | 4.9 | 5.0 | 4.4 | 5.8 | CHSMH | 6.6 | 6.5 | 5.8 | 7.3 |
| MPNOH | 4.9 | 4.9 | 4.0 | 5.6 | RHDMH | 6.6 | 6.6 | 5.5 | 7.9 |
| POCTF | 4.9 | 5.1 | 3.7 | 7.1 | POTTF | 6.6 | 6.6 | 6.0 | 7.2 |
| PMKOH | 5.0 | 4.9 | 4.1 | 5.7 | JMSOH | 6.7 | 6.7 | 6.1 | 7.2 |
| YRKMH | 5.2 | 5.2 | 4.5 | 5.8 | CB6PH | 6.7 | 6.8 | 6.2 | 7.5 |
| PAXMH | 5.4 | 5.4 | 4.8 | 6.1 | POCMH | 6.7 | 6.7 | 6.3 | 7.3 |
| YRKPH | 5.5 | 5.5 | 4.9 | 6.2 | LCHMH | 6.7 | 6.7 | 5.9 | 7.5 |
| MPNTF | 5.5 | 5.5 | 4.6 | 6.4 | PIAMH | 6.7 | 6.6 | 5.7 | 7.4 |
| ELIMH | 5.6 | 5.7 | 4.4 | 7.1 | CB4MH | 6.7 | 6.6 | 6.0 | 7.2 |
| ELIPH | 5.6 | 5.7 | 4.6 | 6.8 | CB7PH | 6.8 | 6.9 | 6.4 | 7.3 |
| WICMH | 5.8 | 5.7 | 4.6 | 6.8 | CHOMH1 | 6.8 | 6.9 | 6.3 | 7.6 |
| CRRMH | 5.9 | 5.8 | 4.5 | 6.8 | SASOH | 6.8 | 6.5 | 4.1 | 8.0 |
| SEVMH | 5.9 | 5.9 | 5.1 | 7.6 | CB5MH | 6.9 | 6.9 | 6.4 | 7.5 |
| PAXOH | 5.9 | 5.9 | 4.9 | 7.0 | BIGMH | 6.9 | 6.9 | 6.3 | 7.4 |
| CHOMH2 | 6.0 | 6.0 | 5.3 | 6.8 | EASMH | 6.9 | 6.9 | 6.2 | 7.5 |
| PATMH | 6.1 | 6.0 | 4.8 | 7.0 | CB8PH | 6.9 | 6.9 | 6.4 | 7.5 |
| POTMH | 6.1 | 6.1 | 5.4 | 6.8 | BOHOH | 7.0 | 7.1 | 5.7 | 8.3 |
| WSTMH | 6.1 | 6.1 | 5.0 | 7.5 | CB1TF | 7.0 | 7.0 | 6.4 | 7.8 |
| JMSMH | 6.2 | 6.2 | 5.6 | 6.7 | JMSTF | 7.0 | 7.0 | 6.4 | 7.5 |
| RPPMH | 6.2 | 6.2 | 5.5 | 6.7 | PISTF | 7.0 | 6.7 | 5.4 | 7.6 |
| CB3MH | 6.2 | 6.1 | 5.4 | 6.8 | APPTF | 7.2 | 7.1 | 5.8 | 8.0 |
| CHOOH | 6.3 | 6.3 | 5.4 | 7.2 | RPPTF | 7.2 | 7.2 | 6.6 | 8.0 |
| POTOH | 6.3 | 6.3 | 5.6 | .1 | PAXTF | 7.2 | 7.1 | 6.0 | 8.1 |
| CB2OH | 6.4 | 6.3 | 5.6 | 6.8 | MIDOH | 7.3 | 7.1 | 5.7 | 8.0 |
| NANMH | 6.4 | 6.4 | 5.7 | 7.4 | CHSOH | 7.3 | 7.2 | 6.1 | 8.3 |
| CHKOH | 6.5 | 6.4 | 5.3 | 7.4 | NANTF | 7.4 | 7.1 | 5.9 | 8.3 |
| C&DOH | 6.5 | 6.5 | 5.8 | 7.2 | GUNOH | 7.5 | 7.3 | 6.1 | 8.5 |
| TANMH | 6.5 | 6.5 | 5.9 | 7.1 | BACOH | 7.7 | 7.3 | 5.5 | 8.5 |
| MOBPH | 6.5 | 6.4 | 5.6 | 7.0 | BSHOH | 7.8 | 7.4 | 5.5 | 8.7 |
| JMSPH | 6.5 | 6.6 | 6.0 | 7.2 | NORTF | 7.9 | 7.8 | 7.2 | 8.4 |
| MANMH | 6.6 | 6.6 | 5.9 | 7.2 | MATTF | 7.9 | 7.9 | 7.4 | 8.6 |
| RPPOH | 6.6 | 6.5 | 5.7 | 7.3 | | | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

segments were: the Western Branch of the Patuxent River (WBRTF) because it is a small water body dominated by a waste water treatment plant; the mesohaline tributaries of the Elizabeth River (SBEMH, EBEMH, and WBEMH) because the dissolved oxygen interpolations did not extend to those segments or the data record was too short; and the Lafayette River (LAFMH) because it contains no water quality monitoring station. Within season, the highest ranked 14 segments made up the list of reference locations and the lowest ranked 14 segments constituted the list of validation locations.

Monthly mean dissolved oxygen concentration data were then interpolated basin-wide for each spring and summer month, 1985 to 1994. For each interpolation, the dissolved oxygen concentration in each cell qualifying as open-water was compared to the appropriate criteria concentration for the month, and the percent of cells passing/failing the criteria was calculated for each segment or designated use. Using the respective lists of 'good' and 'bad' locations, the data for the reference and validation segments were extracted, pooled and plotted (Figure H-5).

The reference curve (hatched line) using this approach looks too good to be true. The Chesapeake Bay Program segments with the highest dissolved oxygen levels include a number of segments known to be eutrophic, with high chlorophyll *a* concentrations. These segments are likely to have elevated daytime dissolved oxygen concentrations due to the addition of oxygen from photosynthesis, but these are also frequently associated with nighttime dissolved oxygen sags when photosynthesis stops and respiration increases. This curve is, therefore, not a valid reference curve.

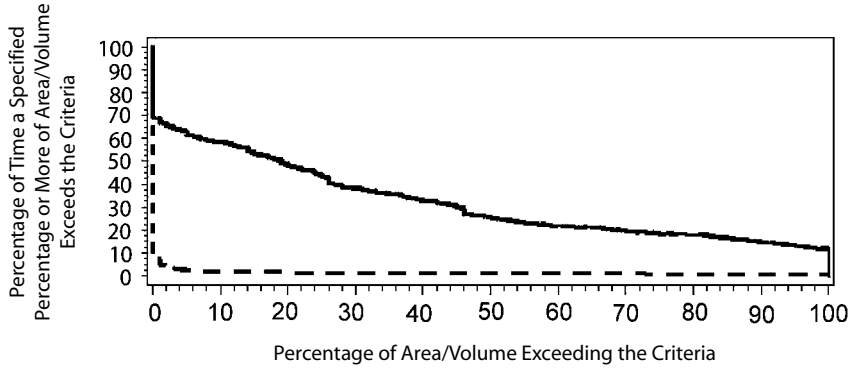


**Figure H-5.** Open water reference and validation curves for summer based on the best and worst ~20 percent of all segments approach.

## Approach 3: Using only Polyhaline Segments

In this exercise, the interpolated data sets from Chesapeake Bay Program segments western lower Chesapeake Bay (CB6PH), eastern lower Chesapeake Bay (CB7PH), mouth of the Chesapeake Bay (CB8PH), mouth of the York River (YRKPH), Mobjack Bay (MOBPH), mouth of the James River (JMSPH) and Elizabeth River (ELIPH) were processed as described above. The percent attainment for each month in spring and summer seasons was calculated for the open-water designated use cells in each polyhaline segment. These data were pooled and a cumulative frequency distribution curve generated for each season. The cumulative frequency distribution curve for summer is shown below (Figure H-6). In the ranking exercise above, the York (YRKPH) and Elizabeth (ELIPH) river segments fell in the lowest ranked group of 14 segments while the other polyhaline segments were scattered in the middle range in both spring and summer seasons (see tables H-5 and H-6, respectively).

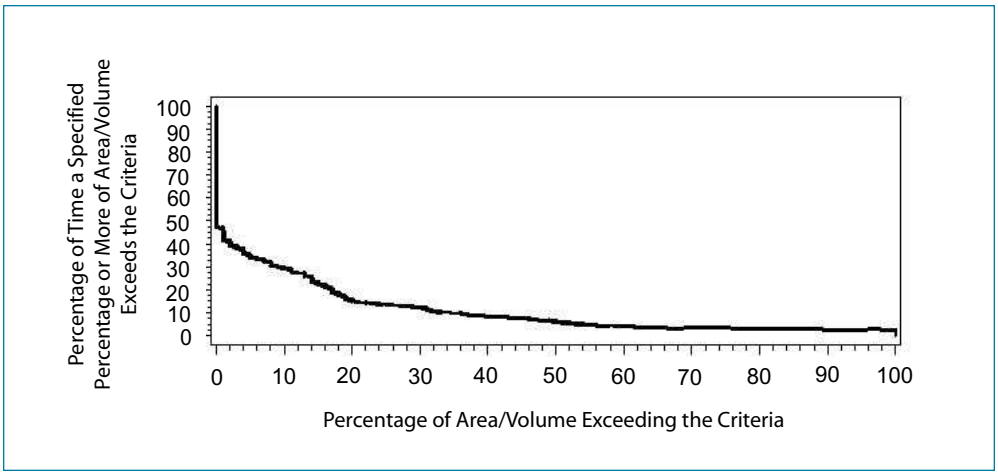


**Figure H-6.** Summer open water reference curve: polyhaline segments only approach.

With regard to this reference curve and all of the validation curves, it should be noted that summer temperature and salinity conditions, particularly in the Elizabeth River and occasionally elsewhere, can be such that oxygen saturation concentrations are below the open-water dissolved oxygen criterion concentration, and it is impossible to meet the criteria due to natural physical conditions. According to proposed implementation guidance, nonattainment is forgiven under those conditions. In this analysis, nonattainment for this reason was not taken into account and, depending on how often such conditions occurr, this and the other curves may be more accurate.

## Approach 4: Reference and Validation Curves using Benthic Community Health

Benthic community health is the reference and validation site identifier for the deep-water reference curves. In the absence of other biologically-based indicators for open-water, open-water reference curves based on benthic health were explored for

comparison with the other approaches. The logic was that Chesapeake Bay benthic organisms have a high tolerance for low dissolved oxygen concentrations, thus healthy benthos in open-water habitat would not necessarily indicate that the 30-day mean of 5 mg liter$^{-1}$ was met. On the other hand, a stressed benthic community in an open-water designated use habitat could indicate that dissolved oxygen criteria in the habitat zone were *not* met.

Reference and validation locations (tables H-7 and H-8, respectively) were identified by methods described below (see section titled "Deep Water Criteria Reference Curves") and the frequency and extent of criterion attainment were processed as described below and similar to the other approaches for open-water. Figure H-7 shows the curves resulting from pooling all reference and validation segments in their respective groups. Figures H-8 and H-9 show the results further segregating segments by salinity zone.

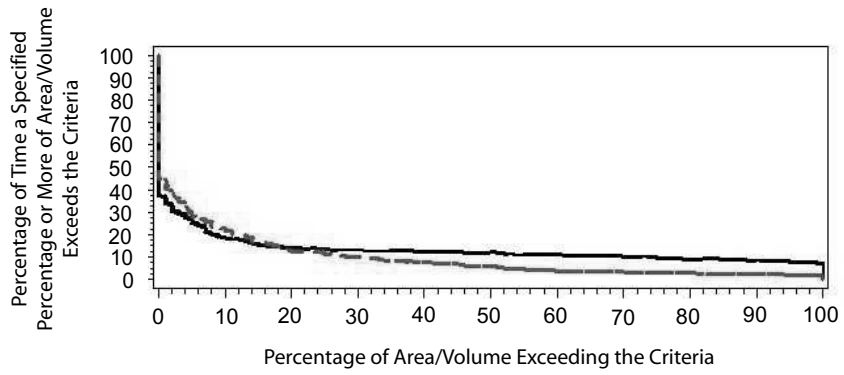


**Figure H-7.** Summer open-water dissolved oxygen criteria reference (hatched line) and validation (solid line) curves based on the benthic index of biotic integrity.

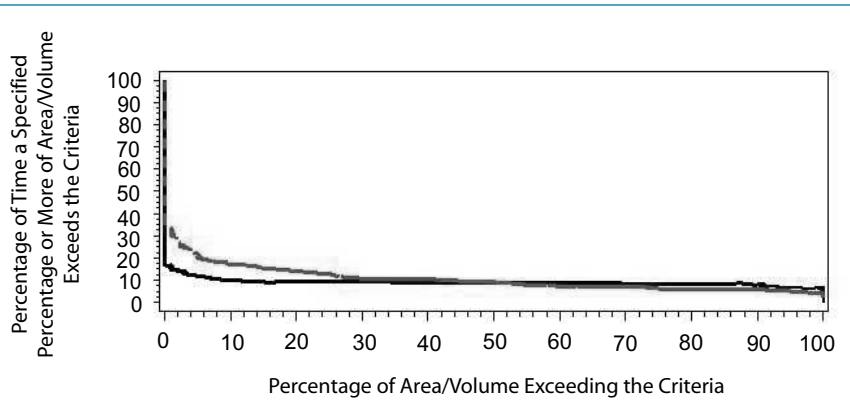


**Figure H-8.** Lower salinity summer open-water reference (hatched line) and validation (solid line) curves: benthic community health approach.

**Table H-7.** Reference locations based on benthic index ≥3 for summer open-water dissolved oxygen criteria reference curve (Approach 4).

| CBP Segment | Years | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CB1TF | 1985 | 1987 | 1990 | 1991 | 1992 | | | | |
| CB2OH | 1986 | 1988 | | | | | | | |
| CB3MH | 1988 | 1993 | 1994 | | | | | | |
| CB6PH | 1986 | 1990 | 1991 | 1992 | 1993 | | | | |
| CB7PH | 1988 | 1990 | 1992 | 1993 | 1994 | | | | |
| CB8PH | 1985 | 1986 | 1987 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| CHOMH1 | 1987 | | | | | | | | |
| CHOMH2 | 1986 | 1993 | 1994 | | | | | | |
| CHSMH | 1986 | 1987 | | | | | | | |
| CHSOH | 1992 | | | | | | | | |
| ELKOH | 1986 | 1992 | | | | | | | |
| JMSMH | 1985 | 1988 | 1990 | 1991 | 1992 | 1994 | | | |
| JMSOH | 1988 | | | | | | | | |
| JMSPH | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 1994 |
| JMSTF | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 1994 |
| NANMH | 1986 | 1988 | | | | | | | |
| PAXMH | 1987 | 1988 | | | | | | | |
| PAXOH | 1986 | 1987 | | | | | | | |
| PAXTF | 1987 | 1994 | | | | | | | |
| PMKTF | 1991 | 1992 | 1993 | 1994 | | | | | |
| POTOH | 1986 | 1987 | 1988 | | | | | | |
| POTTF | 1988 | | | | | | | | |
| RPPMH | 1985 | 1986 | 1987 | 1988 | 1990 | 1992 | | | |
| RPPOH | 1988 | 1992 | | | | | | | |
| SASOH | 1992 | | | | | | | | |
| YRKMH | 1985 | 1986 | 1987 | 1988 | 1990 | | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

**Table H-8.** Validation locations based on benthic index <3 for summer open-water dissolved oxygen criteria reference curve (Approach 4).

| CBP Segment | Years | | | | | | |
|---|---|---|---|---|---|---|---|
| BIGMH | 1994 | | | | | | |
| CB1TF | 1986 | 1989 | | | | | |
| CB2OH | 1987 | | | | | | |
| CB5MH | 1986 | 1987 | 1989 | 1992 | | | |
| CB6PH | 1987 | 1988 | | | | | |
| CB8PH | 1988 | | | | | | |
| CHOMH1 | 1986 | 1988 | 1994 | | | | |
| CHOMH2 | 1988 | | | | | | |
| CHOOH | 1986 | 1987 | 1988 | 1992 | 1994 | | |
| CHOTF | 1991 | 1992 | | | | | |
| CHSMH | 1990 | | | | | | |
| EASMH | 1994 | | | | | | |
| ELKOH | 1987 | 1989 | 1990 | 1994 | | | |
| HNGMH | 1994 | | | | | | |
| JMSMH | 1986 | 1987 | 1989 | 1993 | | | |
| JMSOH | 1985 | 1986 | 1987 | 1989 | 1991 | 1992 | 1994 |
| LCHMH | 1985 | 1994 | | | | | |
| PATMH | 1985 | 1987 | | | | | |
| PAXOH | 1994 | | | | | | |
| PAXTF | 1989 | | | | | | |
| PMKTF | 1985 | 1986 | 1987 | 1988 | 1990 | | |
| POTTF | 1986 | | | | | | |
| RPPMH | 1994 | | | | | | |
| RPPOH | 1985 | 1986 | 1987 | 1990 | 1991 | 1993 | 1994 |
| SASOH | 1991 | | | | | | |
| SBEMH | 1989 | 1990 | 1991 | 1992 | 1993 | | |
| YRKMH | 1993 | 1994 | | | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

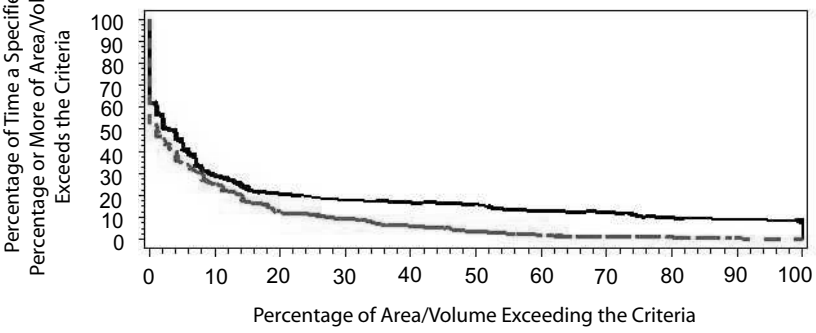


**Figure H-9.** Higher salinity summer open-water reference (hatched line) and validation (solid line) curves: benthic community health approach.

In the tidal-fresh and oligohaline group, the two curves based on benthic health are not very different from one another and both show little overall exceedance (Figure H-8). Nevertheless, the reference curve appears to have slightly more exceedance than the validation curve. By contrast, the two curves in the higher salinity group are differentiated from each other and the reference curve shows more attainment (i.e., less exceedance) than the validation curve (Figure H-8).

## DEEP-WATER CRITERIA REFERENCE CURVES

Chesapeake Bay benthic communities are relatively tolerant of lower oxygen concentrations and able to compensate for periodic hypoxia. A dissolved oxygen concentration of 2 mg liter$^{-1}$ is considered the lower threshold below which benthic communities start to become severely stressed. A healthy benthic community, therefore, could indicate that dissolved oxygen conditions are meeting the deep-water 30-day mean 3 mg liter$^{-1}$ criterion, but would not necessarily indicate that the open-water 30-day mean 5 mg liter$^{-1}$ criterion was met.

A baywide, long-term benthic monitoring program has been in place since before 1985. Samples are collected at fixed and random locations in the summer season, usually in August/September. A benthic index of biological integrity (benthic-IBI) has been developed to assess the status of benthic communities (Weisberg et al. 1997). The benthic IBI is based on a number of parameters, some depending on salinity zone. Abundance, biomass, species diversity and pollution sensitivity are some of the attributes on which the index is based. Each of the attributes is scored on a scale of 1 to 5 against a benchmark community. The benthic-IBI is the average of these scores and also ranges from 1 to 5.

Chesapeake Bay Program segments with benthic communities having an index of 3 were considered healthy. It was further assumed that if the community was not stressed, then the dissolved oxygen conditions were likely to have been adequate for

the previous one to two months of the summer. Thus, in this analysis, if a healthy benthic sample identified a reference location and it was not otherwise disqualified by a sample indicating stress, then data for the whole season for that segment/designated use/season_year were included in the reference distribution. Each benthic sample is identified by latitude/longitude, segment and bottom depth. This analysis identified each site by year (assuming months June through September), segment and depth. It did not take into account a station's specific location within the segment.

The Chesapeake Bay benthic-IBI results from 1985 through 1994 were assessed as either 3 ('healthy'/'good') or <3 ('stressed'/'not good') and then associated with season_year (in this case summer), segment and designated use, based on season and sample depth. 'Healthy' locations were accumulated as the reference distribution. 'Stressed' locations were accumulated as the validation distribution. If both healthy and stressed sites occurred within the same segment, designated use and season_year, the location was excluded from both reference and validation distributions. A listing of the reference and validation locations identified in this way is attached (tables H-9 and H-10, respectively).

For this exercise, like those described earlier, a baywide master grid file was used in which each cell has a Chesapeake Bay Program segment assignment and fixed designated use assignment. In a few segments, both open-water and deep-water designations occur at the same depth. Because of time limitations,the location of healthy benthic samples was identified only by segment and depth, not by specific latitude/longitude, i.e., not by specific grid cell. (Note: Using GIS to locate the comparable grid cell precisely for each sample would improve the analysis greatly, but complicate the process.) Thus, when a 'healthy' benthic sample was found at a segment depth where both open-water and deep-water designated uses were defined, both were included in their respective list of reference or validation locations.

Monthly mean dissolved oxygen concentration data were interpolated basinwide for each summer month, June through September, from 1985 through 1994. For each interpolation, each cell's dissolved oxygen concentration was compared to the appropriate criteria concentration for the month and designated use, as indicated in the master grid, and the percent of cells passing/failing the criteria calculated for

**Table H-9.** Reference locations based on benthic index ≥3 for summer deep-water dissolved oxygen criteria reference curve.

| CBP Segment | Years | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CB3MH | 1992 | | | | | | | |
| CB6PH | 1985 | 1986 | 1987 | 1988 | 1991 | 1992 | 1993 | 1994 |
| CB7PH | 1985 | 1986 | 1991 | | | | | |
| CHSMH | 1992 | 1993 | | | | | | |
| PAXMH | 1992 | | | | | | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

**Table H-10.** Validation locations based on benthic index <3 for summer deep-water dissolved oxygen criteria reference curve.

| CBP Segment | Years | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CB3MH | 1989 | 1990 | 1991 | 1993 | | | | |
| CB4MH | 1986 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
| CB5MH | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | | |
| CB6PH | 1990 | | | | | | | |
| CB7PH | 1987 | | | | | | | |
| CHSMH | 1989 | | | | | | | |
| EASMH | 1986 | | | | | | | |
| PATMH | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | | |
| PAXMH | 1987 | 1988 | 1989 | 1990 | 1993 | 1994 | | |
| POTMH | 1985 | 1986 | 1987 | 1988 | 1990 | 1991 | 1993 | 1994 |
| RPPMH | 1985 | 1986 | 1988 | 1990 | 1991 | 1993 | 1994 | |
| YRKPH | 1988 | 1990 | 1991 | 1992 | 1993 | 1994 | | |

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay/net/data

each segment/designated use. Using the respective lists of locations/dates, the data for the reference and validation locations were extracted, pooled and plotted (Figure H-10). This approach illustrates a substantial difference between the attainment curves of healthy and stressed sites. The curves would likely be different (i.e., likely reduce nonattainment in the reference curve and increasing nonattainment in the validation curve) if the location selection process were made more specific as described earlier.

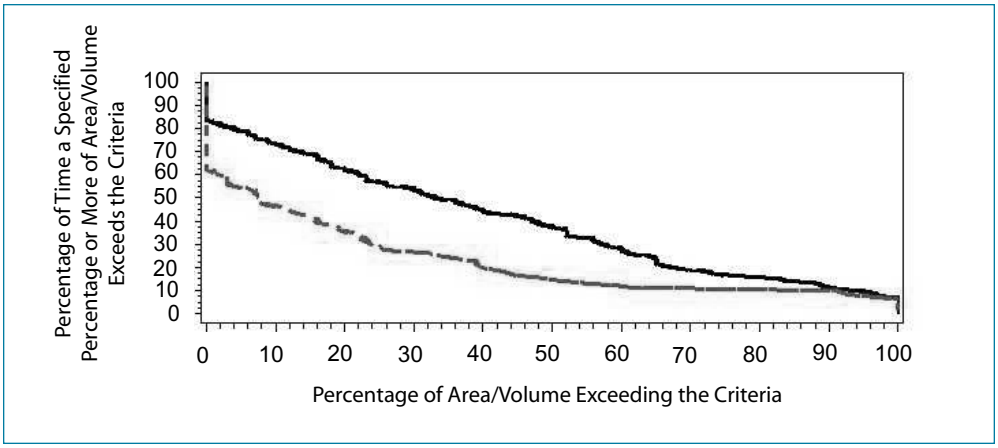


**Figure H-10.** Summer deep-water reference (hatched line) and validation (solid line) curves: benthic community healt approach.

## WATER CLARITY CRITERIA REFERENCE CURVES

The water clarity criteria were developed to be protective of underwater bay grasses. The criteria apply to the months within the underwater bay grasses growing seasons and are specific to salinity zone. Reference areas in each salinity zone were selected by a team of resource managers and underwater bay grasses scientists based on an extensive review of the available distribution and abundance data record (over 20 years). Chesapeake Bay Program segments or partial segments were identified where underwater bay grasses distributions had increased significantly in recent years and had been present historically (Table H-11). Reference curves were developed for percent light-through-water (PLW), which is obtained by $PLW=100exp(-K_dZ)$, where Z is the applicaton depth and $K_d$ is a light factor, derived here from Secchi depth ($K_d$= 1.45/Secchi depth); see Chapter VI for more detail on implementation of the water clarity criteria. Application depth (Z) was based on photographic or other evidence of growth at that depth plus one-half the tide depth in the segment. The empirical evidence, with the one-half tide height added, provided a range of depths from which an appropriate depth was selected for inclusion in the PLW calculation. In some segments, full attainment was achieved at the deepest depth of the range. In those cases, Z was increased at 0.1 meter increments until exceedance was detected.

**Table H-11.** Chesapeake Bay Program segments or partial segments used to establish the water clarity criteria reference curves.

| CBP Segment | Restoration Target Depth (meters) | Minimum Retoration Target Depth (meters) | Maximum Restoration Target Depth (meters) | Selected Restoration Target Depth (meters) |
|---|---|---|---|---|
| CB1TF | 2.0 | 0.5 | 1.3 | 0.9 |
| GUNOH | 2.0 | 0.25 | 0.8 | 0.5 |
| MATTF | 2.0 | 0.25 | 0.8 | 0.5 |
| PISTF | 2.0 | 0.5 | 1.5 | 0.5 |
| POTTF | 2.0 | 0.5 | 1.4 | 0.6 |
| POTOH | 2.0 | 0.5 | 1.2 | 0.75 |
| CB6PH | 2.0 | 0.5 | 1.3 | 1.3 |
| CB7PH | 1.0 | 0.5 | 1.3 | 1.3 |
| CHOMH1 | 2.0 | 0.5 | 1.3 | 1.25 |
| EASMH | 2.0 | 0.25 | 0.8 | 1.1 |
| MOBPH | 2.0 | 0.5 | 1.5 | 1.2 |
| TANMH | 2.0 | 0.5 | 1.3 | 0.9 |
| YRKPH | 2.0 | 0.25 | 1.0 | 1.2 |

Source: Chesapeake Bay Water Quality Monitoring Program database http://www.chesapeakebay.net/data

Like the methods used to determine attainment of the dissolved oxygen criteria, ambient light data collected as part of the Chesapeake Bay water quality monitoring program were averaged monthly and interpolated (using the log transformation). PLW was calculated for each surface cell using the selected Z depth and the interpolated (back transformed) value for $K_d$. The PLW value for each cell was compared to the appropriate criterion for the segment's salinity zone and the cell area designated as failing or passing the criterion. The spatial extent of attainment, i.e., the percent area failing the criterion, was tallied for each month in the underwater bay grass growing season for all years 1985 through 1994, and also for more recent years through 2000. The monthly figures for percent attainment in each segment were pooled within salinity classification: tidal-fresh oligohaline and mesohaline polyhaline and the cumulative frequency distribution calculated and plotted. Note that segment CB7PH was not included in order to balance the relative contributions from the different salinity zones. The plots were very similar with and without segment CB7PH. The reference curves from the 1985-94 period (figures H-11 and H-12) are consistent with the curves developed for the other criteria. The reference curves for 1995-2000 are shown for comparison (figures H-13 and H-14).

It should be noted that the PLW minimum light requirement parameter was originally developed as a seasonal median measure. For assessing the criteria attainment, light availability is evaluated on a monthly basis, recognizing that available light could be less than the requirement level (i.e, 13 percent and 22 percent in lower and higher salinity waters, respectively) about half the time, and that exceedances will be more frequent than if the criteria were assessed on a seasonal basis. Because both criteria attainment and reference curves will be assessed in the same way, the additional exceedance should be accounted for by the reference curve. Figures H-15 and H-16 illustrate the lower and higher salinity water clarity reference curves, respectively, resulting from assessment on a seasonal median basis.

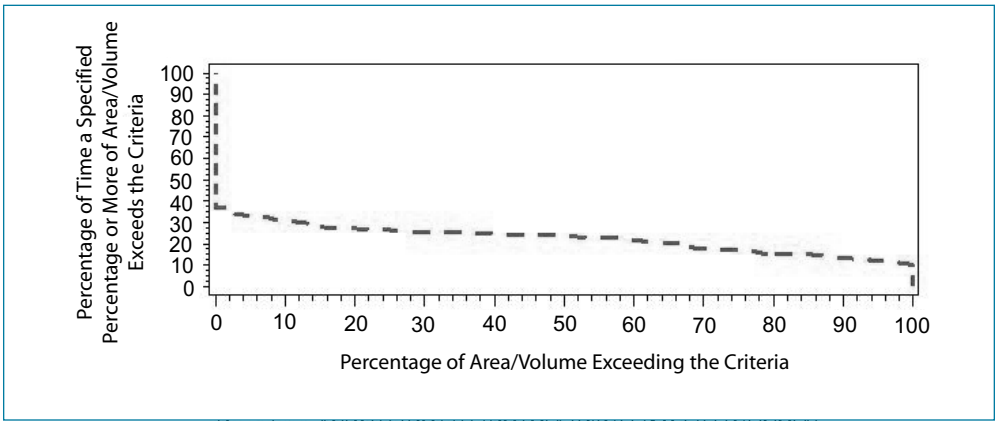


**Figure H-11.** Lower salinity water clarity reference curve: 1985–1994.

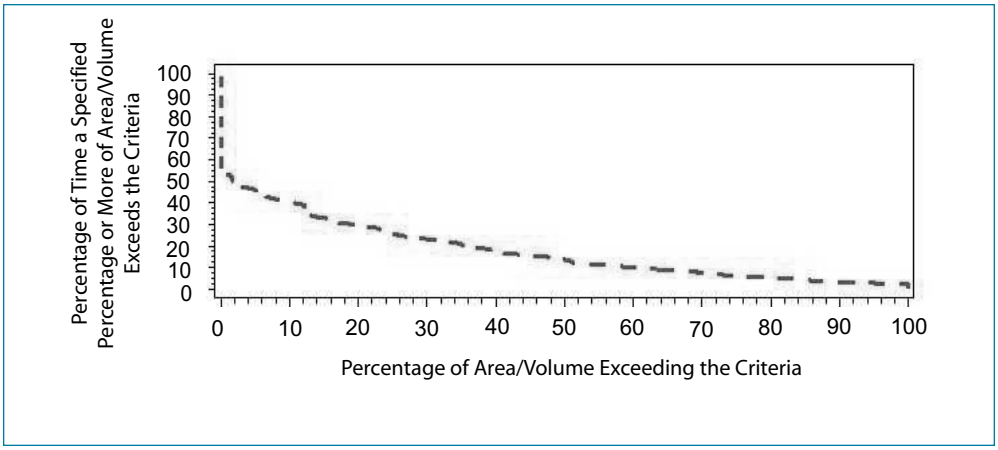


**Figure H-12.** Higher salinity water clarity reference curve: 1985–1994.

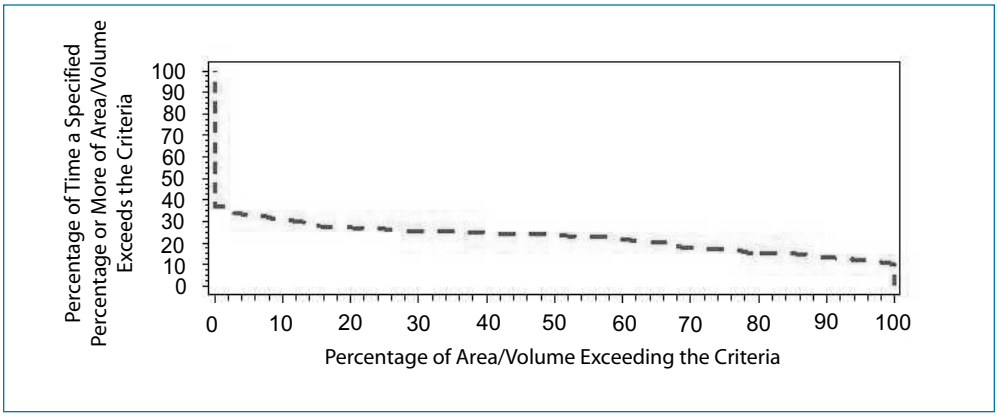


**Figure H-13.** Lower salinity water clarity reference curve: 1995–2000.

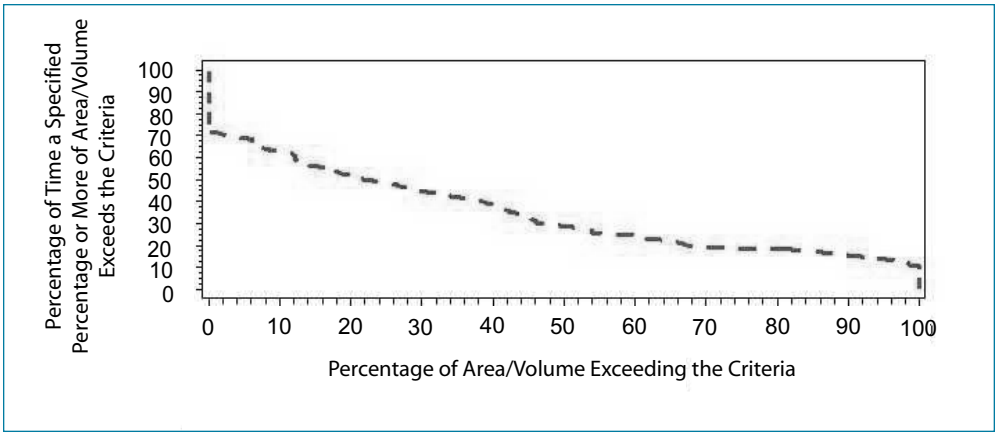


**Figure H-14.** Higher salinity water clarity reference curve: 1995–2000.

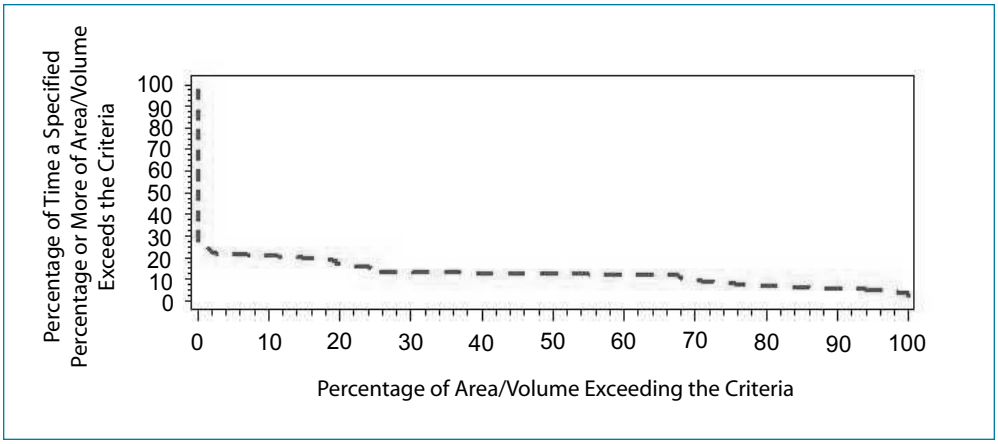


**Figure H-15.** Higher salinity water clarity reference curve: seasonal median

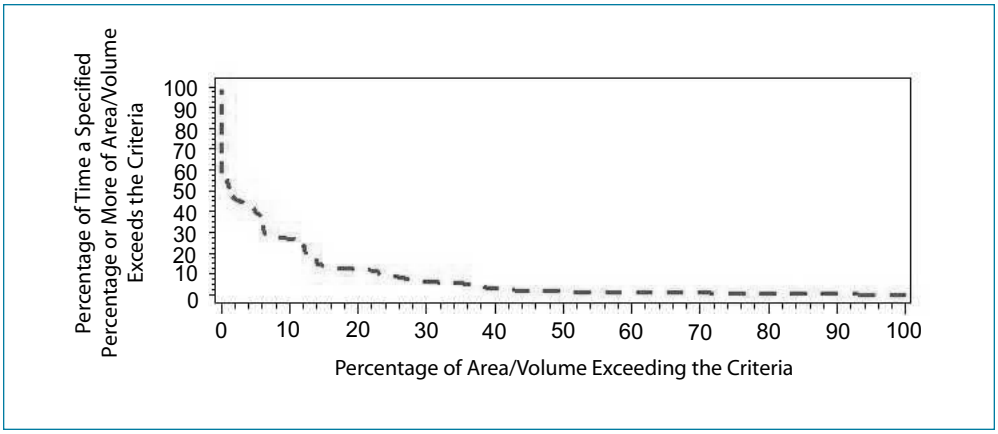


**Figure H-16.** Higher salinity water clarity reference curve: seasonal median.

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Alden, R. W. III, and E. S. Perry 1997. *Presenting Measurements of Status: Report to the Chesapeake Bay Program Monitoring Subcommittee's Data Analysis Workgroup*. Chesapeake Bay Program, Annapolis, Maryland.

Weisberg, S. B., J. A. Ranasinghe, D. M. Dauer, L. C. Schaffner, R. J. Diaz, and J. B. Frithsen. 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. *Estuaries* 20:149-158.

appendix I

# Analytical Approaches for Assessing Short-Duration Dissolved Oxygen Criteria

The Chesapeake Bay dissolved oxygen criteria have several different durations: 30-day mean, 7-day mean, daily mean and instantaneous minimum. Users' ability to assess these criteria and to have certainty in the results depends on the time scale of available data and on the ability 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 assessment of attainment for some geographic regions and for some short-term criteria elements must be waived for the time being or must be based on statistical methods that estimate probable attainment. Several approaches to addressing the duration issue are described below in more detail.

## LOGISTIC REGRESSION MODELS USING ROUTINE FIXED-STATION MONITORING DATA

This method is a modification and significant update of 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 in areas where dissolved oxygen concentrations ranged above and below goal target concentrations (figures I-1 and I-2).

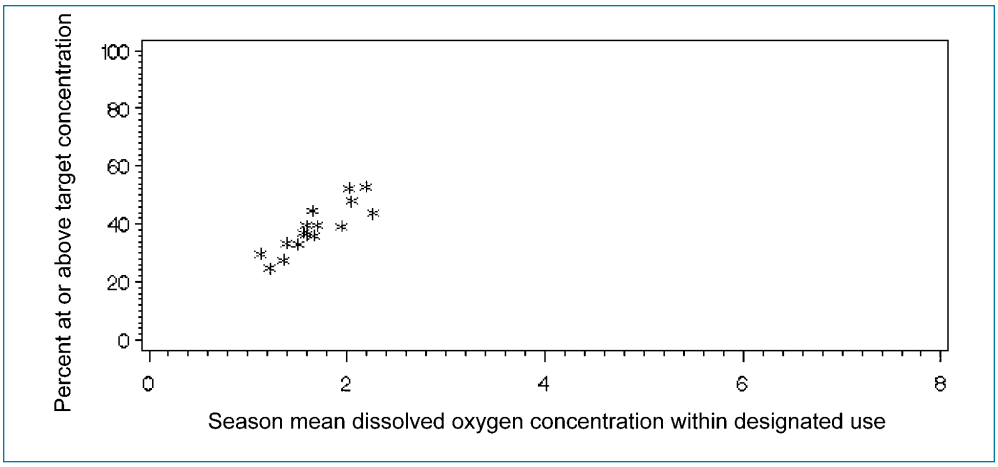


**Figure I-1:** Percent of Summer dissolved oxygen concentrations above 1.7 mg liter$^{-1}$ in segment CB3MH deep-water designated use habitat.

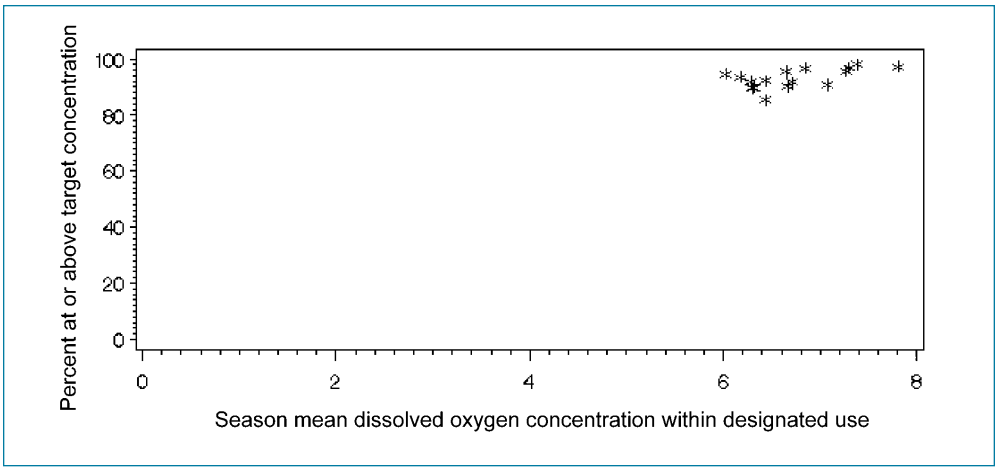


**Figure I-2.** Percent of Summer dissolved oxygen concentrations above 3 mg liter$^{-1}$ in segment CB3MH open-water designated use habitat.

The relationships were then expressed as regression equations, which could be used to predict the percentage of observations above or below target for any seasonal mean. By extension, the 'percentage of observations' applied both to space and time within a segment. Most of this pilot work was done for mainstem Chesapeake Bay segments that were relatively densely populated with fixed monitoring stations laterally and longitudinally. Because of the spatial density of stations, the range of potential dissolved oxygen exposure that any particular point might experience over a tidal cycle was captured in the models. Contemporaneous, semicontinuous dissolved oxygen measurements made with in situ sensors deployed on buoys were used to validate the model estimates. The models did not predict the extreme minima

recorded in the continuous record, but were able accurately to predict the frequency of observations below the mean, 5th and 95th percentile concentrations over a month's time (Jordan et al. 1992).

With benefit of the long (more than 16 yrs) record of the Chesapeake Bay tidal-water quality monitoring program and the density of measurements (the vertical dissolved oxygen profile is characterized at 1- to 2-meter intervals), the simple 1992 regression models have been improved. These enhanced models use logistic regression, which is better suited to percent distributions (i.e., distributions between 0 and 100). The models are now month- and depth-specific in many segments. These models can be adapted and applied to estimate attainment of the instantaneous minimum dissolved oxygen criterion, if the user considers that the minimum criterion is not met if the dissolved oxygen concentration is below the criterion value *at any time and anywhere* in the segment-designated use.

The first step is to reconstruct the models using the cruise-by-cruise three-dimensional interpolations of dissolved oxygen monitoring data. That is, collect the percent volume passing/failing the criterion at each depth in a segment month by month from, for example, 1985 through 1998, and model the relationship of percent volume failing/passing the criterion as a function of the monthly mean of that segment/depth as represented by all the cells in the grid. Using the interpolated data should improve the spatial representation within the segment.

To assess current attainment, for 1999-2001 for example, the user would interpolate the monthly average dissolved oxygen concentrations across all tidal waters, as before, for each month of the season to be evaluated in the assessment period, e.g., the summer period including June through September. Then the month/segment/depth-specific model appropriate for the designated use and cell location would be applied to estimate the percent of time each cell was likely to be below the instantaneous minimum, based on the cell's interpolated monthly average. If the model predicts that the cell is above the minimum dissolved oxygen level less than 99-100 percent of the time, then the cell is not in attainment. Each cell is assessed in this way and its volume added to the 'failing' or 'passing' category. Ultimately, the percent of total volume failing or passing the criterion within the segment and designated use is calculated for each month. The monthly percentages are tallied over all months in the season in the assessment period and the cumulative frequency distribution is calculated. Except for the use of the logistic regression model, each of the steps is consistent with assessment methods of the other criteria (see Chapter VI for details).

The following is a sample attainment model for Chesapeake Bay Program segment CB3MH for the open-water instantaneous minimum 3.2 mg liter[1] criterion. This model was based on fixed station data, not on interpolated data as proposed above.

> If the time frame is September through March, attainment is likely to be 100 percent, regardless of depth. For other months, the estimated percent attainment is estimated by

LGT = 1.0757 x (mean monthly dissolved oxygen concentration)
-0.0724 x (depth in meters)
-1.8576 for April
-2.9219 for May
-2.7982 for June
-2.8341 for July
-2.5443 for August.

Percent attainment = 100 exp(lgt) / (1 + exp(lgt)).

The figures below illustrate attainment curves for segment CB3MH for summer deep-water designated use, where the instantaneous minimum criterion is 1.7 mg liter$^{-1}$ (Figure I-3) and open-water designated use, where the instantaneous minimum of 3.2 mg liter$^{-1}$ criterion applies (Fig. I-4).

At this time the method has not been adequately validated in areas other than the mainstem Chesapeake Bay. It is, therefore, premature to recommend its implementation for formally assessing criteria attainment. The issue is not so much the method itself, but how well the midchannel stations represent the flanks and surrounding waters where station density is low. The models are only as good as the information on which they are developed. The day-time sampling schedule cannot detect nocturnal lows in shallow areas or other areas where dissolved oxygen is quickly regenerated. In the mainstem Chesapeake Bay, however, the dissolved oxygen 'memory' in the deep waters represents, to some extent, the night-time dissolved oxygen sags and the station density captures exposure diversity. In other areas and designated uses, hypoxia is more ephemeral temporally and the density of fixed-monitoring stations is reduced spatially so the models are likely to be weaker.

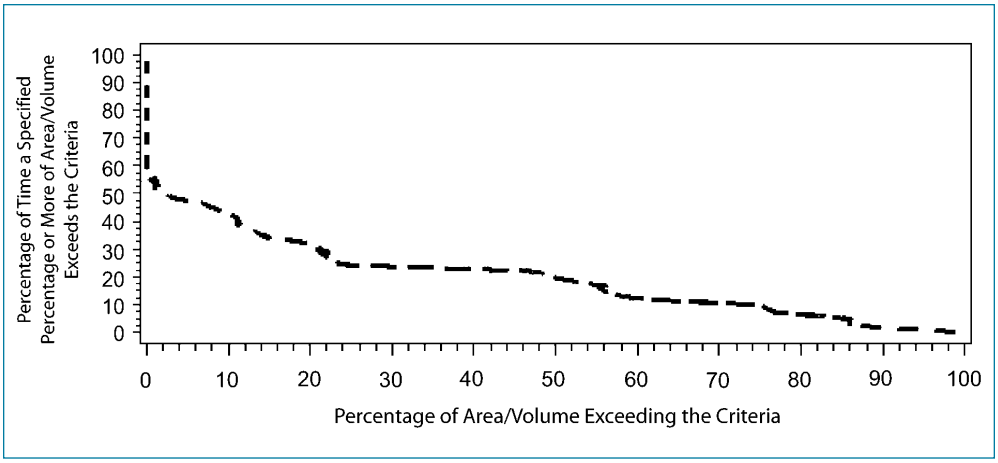


**Figure I-3.** Summer instantaneous minimum deep-water dissolved oxygen 1.7 mg liter$^{-1}$ criterion attainment curve for segment CB3MH based on application of the logistic regression model.

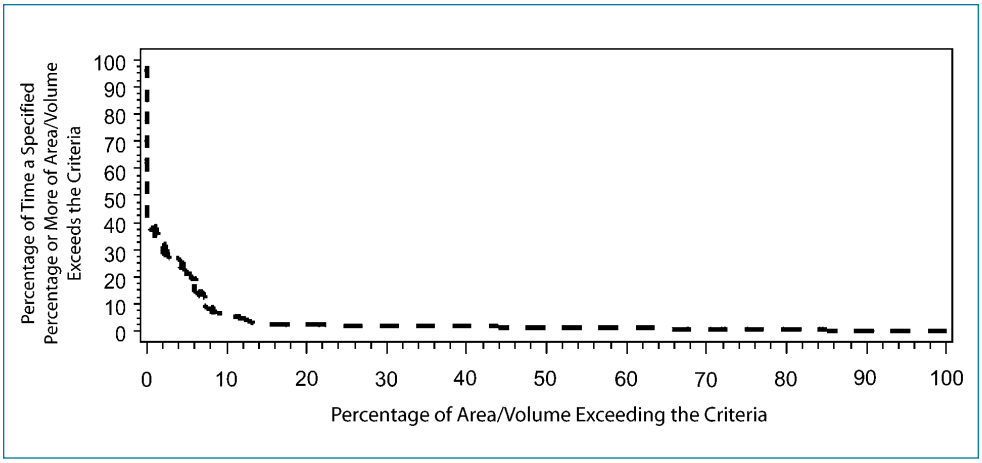


**Figure I-4.** Summer instantaneous minimum open-water dissolved oxygen 3.2 mg liter$^{-1}$ criterion attainment curve for segment CB3MH based on application of the logistic regression model.

## SYNTHETIC, CLOSE-INTERVAL DATA SETS CREATED BY COMBINING SHORT- AND LONG-TERM PATTERNS OF VARIATION IDENTIFIED THROUGH SPECTRAL ANALYSIS

It is critical to obtain real time information about the ephemeral and episodic events of low dissolved oxygen. However, it is not possible for the states or other partners to collect such information over vast regions of the Chesapeake Bay and over the length of time that would be required to address the short duration (i.e., the 7-day mean, 1-day mean, instantaneous minimum) criteria directly. The following methodology is proposed to address the short interval criteria by integrating information from the long-term, low-frequency monitoring program with short-term, high-frequency monitoring that can be accomplished using in-situ semi-continuous data recorders.

The method, still in development, is an adaptation of work by Neerchal (1992). The method combines temporal variability information from the long-term, low-frequency monitoring data with that from short-term, high-frequency data such as collected with in situ continuous recording devices. Since these devices are often deployed using moored buoys, the associated data are referred to as 'buoy data'.

The method uses spectral analysis to extract the cyclical components of the long- and short-term dissolved oxygen time series records and combines them to create a synthesized time-series data set with data synthesized at user-specified time steps. The synthetic data have the annual and seasonal cyclic and trend characteristics of the long-term record as well as the tidal, diurnal and other periodic characteristics of the short-term, high-frequency record. At present, the synthetic data are hourly, with

cyclic components limited to two cycles per day. The synthetic data are then analyzed like any other data set relative to the specific elements of the criteria.

The spectral equation for the long-term data (such as the Chesapeake Bay water quality monitoring program data) is

a) $$x_t^{lt} = \bar{x}^{lt} + \sum_{k=1}^{ltm} a_k^{lt} \cos(2\pi f_k^{lt} t) + b_k^{lt} \sin(2\pi f_k^{lt} t)$$ (Equation I-1)

where ltm n/2, $f^{lt}_k$ = fourier frequencies, t = time in months, a,b = spectral coefficients, and $x^{lt}_t$ = data.

The spectral equation for the *short-term* data (for example, from an *in situ* dissolved oxygen data recorder) is

b) $$x_t^{st} = \bar{x}^{st} + \sum_{k=1}^{stm} a_k^{st} \cos(2\pi f_k^{st} t) + b_k^{st} \sin(2\pi f_k^{st} t)$$ (Equation I-2)

where stm n/2, $f^{st}_k$ = fourier frequencies, t = time in hours, a,b = spectral coefficients, and $x^{st}_t$ = data.

The equation for the spectral forecast (for the synthetic data set) is

c) $$x_t^{lt} = \bar{x}^{lt} + \sum_{k=1}^{m1} a_k^{lt} \cos(2\pi f_k^{lt} t) + b_k^{lt} \sin(2\pi f_k^{lt} t) + \sum_{k=1}^{m2} a_k^{st} \cos(2\pi f_k^{st} t) + b_k^{st} \sin(2\pi f_k^{st} t)$$ (Equation I-3)

where t = time scaled to suit f, $m^1$ < ltm, is chosen to exclude high frequencies that would be duplicated in the short-term equation (>½ cycle per month), and $m^2$ < stm is chosen to exclude frequencies too high to be important (>2 cycles per day).

## A SAMPLE APPLICATION OF THE METHOD

The example application below uses long-term data from station CB4.2C, a monitoring station in the mid-region of the Chesapeake Bay, and a two-month series of continuous dissolved oxygen measurements at a buoy deployment in the vicinity of that station at approximately 9 meters below the surface. Figure I-5 shows the observed monthly dissolved oxygen concentrations (asterisks) at station CB4.2C (8-10-meter depth) and the long-term forecast (line) from the spectral equation.

The synthetic data record is obtained by combining the long- and short-term equations (Figure I- 6). A sample two-month period, August-September, 1987, indicated by the two vertical parallel reference lines in Figure I-5, is expanded in Figure I-6.

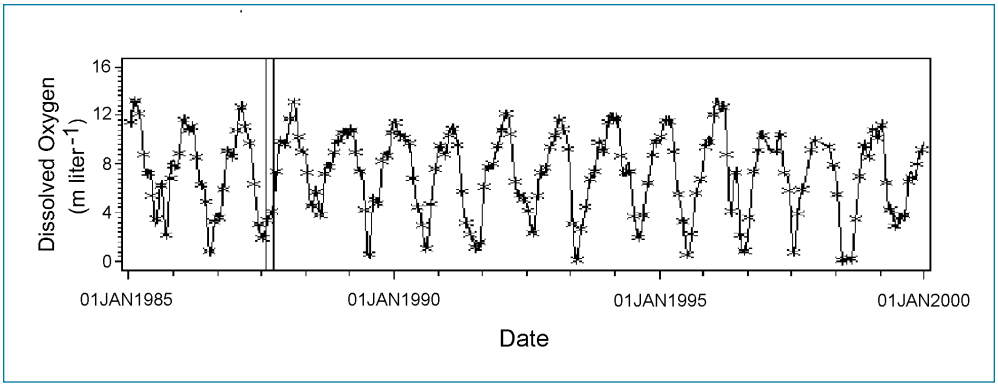


**Figure I-5.** Observed monthly dissolved oxygen concentrations (*) at Chesapeake Bay Monitoring Program Station CB4.2C (at the 8- to 10-meter depth) from January 1985 to January 2000 and the long-term 'forecast' (—) from application of the spectral equation.

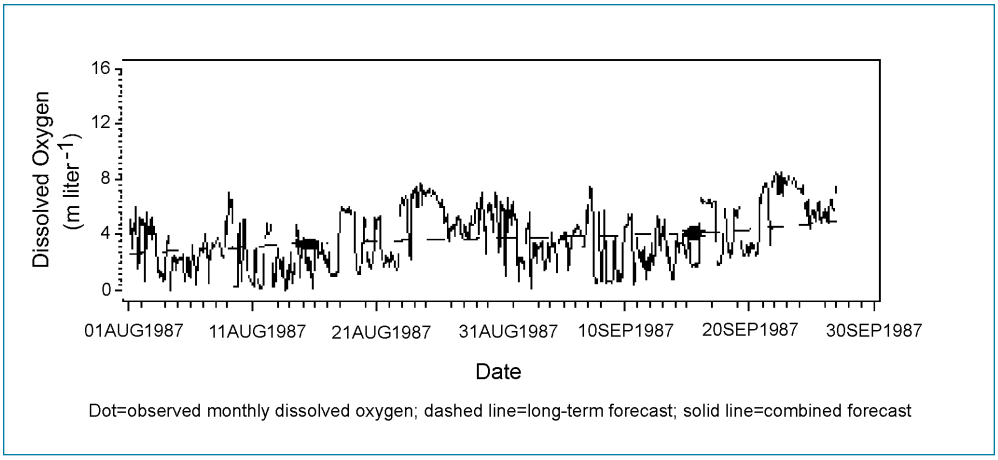


**Figure I-6.** Expanded view from Figure VI-23 of the two-month period August-September 1987 synthetic data record obtained by combining the long- and short-term spectral equations.

Some major difficulties beyond the cost and labor involved in deploying sensors, which are substantial to begin with, must be overcome to implement this methodology. The spectral forecasts are essentially temporal interpolations that can be sampled analytically. The forecasts do not lend themselves easily to an analysis of spatial extent of criteria attainment. For other criteria assessments, the direct measures of dissolved oxygen in the environment—temporal snap shots—are interpolated using the Chesapeake Bay Program interpolator, and the spatial extent of attainment is assessed. Then, the frequencies of the many spatial extent measurements are collected into a cumulative frequency distribution. The spectral analysis methodology developed thus far has yet to incorporate the assessment of spatial extent. Three-dimensional spatial interpolations at the 10-, 20- and 30-minute short-interval frequencies is a computational impracticality. Furthermore, more information is

needed to determine the sphere of representativeness for the short-term, high-frequency patterns, both vertically and horizontally.

Some compromises will doubtless be required. New pilot projects, some of which are already underway, and additional analysis of current data already at hand will answer some of these questions and provide some basic underpinnings. Also, due to the rapidly developing technology in this area, changes and new, unforeseen opportunities are likely to present themselves. The importance of the short duration criteria to the protection of many of the Chesapeake Bay's target species and communities has been demonstrated. As Bay scientists and managers move forward with developing assessment tools, it would be prudent to seize new opportunities as technology evolves.

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appendix J

# Development of Chesapeake Bay Percent Light-at-the-Leaf Diagnostic Requirements

The amount of ambient surface light required at the leaf surface to support underwater bay grasses survival, growth and propagation was determined by comparing the results of the following three lines of evidence: application of the 1992 bay grass habitat requirements; accounting for epiphytic light attenuation; and comparison of field conditions and bay grass growth gradients.

## CALCULATION USING THE 1992 BAY GRASS HABITAT REQUIREMENTS

A set of percent light-at-the-leaf (PLL) requirements was derived by applying the salinity regime-based values for the 1992 Bay grass habitat requirements for $K_d$, dissolved inorganic nitrogen, dissolved inorganic phosphorus and total suspended solids (Table J-1; Batiuk et al. 1992) into the algorithm (Equation J-1) for determining PLL:

$$PLL=100[\exp(-K_d Z)][\exp(-K_e B_e)] \qquad \text{(Equation J-1).}$$

See Table VII-1 in Chapter VII for how $K_e$ and $B_e$ are calculated in Equation J-1. Using this algorithm, a PLL value of 8.3 percent was calculated for tidal-fresh and oligohaline salinity regimes. The calculated PLL value was 17.3 percent in mesohaline regimes and 13.5 percent in polyhaline regimes. The mesohaline and polyhaline PLL values differed, despite having the same 1992 $K_d$, total suspended solids and dissolved inorganic nitrogen habitat requirements, because their dissolved inorganic phosphorus bay grass habitat requirements for the two regimes differed (Batiuk et al. 1992; Dennison et al. 1993). By applying the 1992 underwater bay grass habitat requirements, the PLL requirements of 8 percent for tidal- fresh/oligohaline habitats and 15 percent (the average of 17.3 and 13.5 values) for mesohaline and polyhaline habitats were derived from this line of evidence.

**Table J-1.** The 1992 underwater bay grasses habitat requirements for the Chesapeake Bay and its tidal tributaries.

| Salinity Regime | Bay Grass Growing Season | Light Attenuation Coefficient (meter$^{-1}$) | Total Suspended Solids (mg liter$^{-1}$) | Chlorophyll *a* (μg liter$^{-1}$) | Dissolved Inorganic Phosphorus (mg liter$^{-1}$) | Dissolved Inorganic Nitrogen (mg liter$^{-1}$) |
|---|---|---|---|---|---|---|
| Tidal-fresh | April-October | 1.5 | <15 | <15 | <0.02 | none |
| Oligohaline | April-October | 1.5 | <15 | <15 | <0.02 | none |
| Mesohaline | April-October | 2.0 | <15 | <15 | <0.01 | <0.15 |
| Polyhaline | March-May, Sept.-November | 2.0 | <15 | <15 | <0.02 | <0.15 |

Source: Batiuk et al. 1992.

## ACCOUNTING FOR EPIPHYTIC LIGHT ATTENUATION

As noted in Chapter IV, the scientific studies used to derive the percent light-through-water (PLW) criteria did not consider the shading effects of epiphytes, which grow on underwater plant leaves at all depths and on experimentally shaded plants in the field. Several studies in various estuarine habitats indicate that light attenuation by epiphytic communities tends to contribute an additional 15 to 50 percent shading on underwater plants (e.g., Bulthuis and Woelkerling 1983; van Dijk 1993). A detailed study of turtlegrass beds in Florida coastal waters (Dixon 2000) showed that, while light levels at the maximum depth of seagrass colonization averaged about 22 percent of surface irradiance (PLW), epiphytic attenuation reduced this to approximately 14 percent of the surface light that is actually available for plant photosynthesis (PLL). This represents an average of approximately 35 percent more shading by epiphytes.

Light attenuation by epiphytic material appears to be important throughout the Chesapeake Bay, contributing 20 to 60 percent more attenuation (beyond the PLW) in the tidal-fresh and oligohaline regions, where nutrient and total suspended solids concentrations were highest, and 10 to 50 percent in the less turbid mesohaline and polyhaline regions (Figure J-1). These calculated contributions of epiphyte shading are consistent with the values derived for PLW and PLL by applying the 1992 bay grass habitat requirement values (see Table J-1) in equations IV-1 and J-1, respectively, where PLL represents approximately 30 percent additional light reduction beyond PLW.

Epiphytic material was assumed to make a 30 percent additional contribution to light attenuation throughout Chesapeake Bay shallow-water habitats. This figure was based on literature values for seagrass minimum light requirements, where epiphyte effects were either avoided with experimental manipulation (e.g., Czerny and

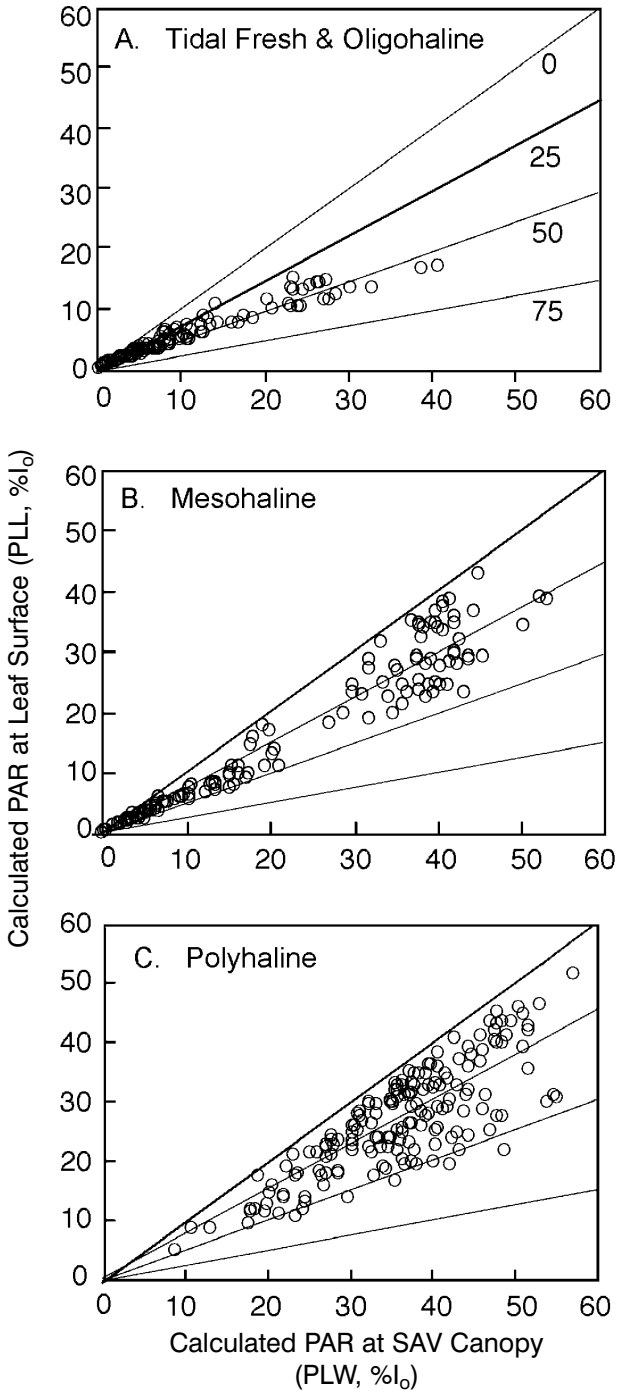


**Figure J-1.** Comparing values for percent light-at-the-leaf (PLL) and percent light-through-water (PLW) calculated for Z=1 meter using equations IV-1 and J-1 for water quality monitoring stations in Virginia portion of the Chesapeake Bay for 1985–1996 in three salinity regimes. Lines indicate position of points where epiphyte attenuation reduced ambient light levels at the leaf surface by 0, 25, 50 and 75 percent.

Dunton 1995) or taken into account with direct measurement (e.g., Dixon 2000) and results from analysis of Chesapeake Bay data.

Accounting for the epiphytic contribution to light attenuation, PLL requirements for mesohaline/polyhaline and tidal-fresh/oligohaline habitats were calculated to be 15 percent and 9 percent of surface irradiance, respectively. These values, which represent the minimum PLL needed to support bay grasses growth, include the additional 30 percent epiphytic light attenuation beyond the respective PLW requirements. For mesohaline/polyhaline habitats, factoring the additional 30 percent epiphytic light attenuation into the 22 percent PLW requirement yields a 15 percent PLL requirement as 30% = 100(22-15)/22[1]. A 9 percent PLL requirement for tidal-fresh/oligohaline habitats was derived by factoring the additional 30 percent epiphytic light attenuation into the 13 percent PLW requirement, as 30% = 100(13-9)/13.

The derived underwater bay grass PLW and PLL requirements for the Chesapeake Bay's mesohaline and polyhaline habitats (22 percent and 15 percent surface light, respectively) are remarkably close to the respective values of 22 percent and 14 percent surface light derived through field experimentation for turtlegrass in Florida (Dixon 2000).

## COMPARISON OF FIELD CONDITIONS AND BAY GRASSES GROWTH GRADIENTS

Medians of nearshore water quality data (from the Choptank and York rivers) and Chesapeake Bay Monitoring Program midchannel data were assessed for relationships between the calculated PLL values, bay grasses growth categories and the proposed mesohaline/polyhaline and tidal-fresh/oligohaline PLL requirements of 15 percent and 9 percent, respectively. The calculated PLL values from observed water quality conditions associated with 'persistent' and 'fluctuating' bay grass beds were either very close or well above the PLL requirements, or the limited set of deviations could be readily explained (Batiuk et al. 2000). These diagnostic PLL requirements were further validated through a comprehensive analysis of 14 years (1985-1998) of Chesapeake Bay water quality monitoring data. The validation results were published in Chapter VII in Batiuk et al. (2000). From these three lines of evidence, PLL requirements of 15 percent ambient surface light for mesohaline/polyhaline habitats and 9 percent surface light for tidal-fresh/oligohaline habitats were established.

[1]6.6 percent represents 30 percent attenuation of the 22 percent light-through-water requirement. Therefore, light-at-the-leaf requirement is 15.4 percent, which is rounded down to 15 percent.

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