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Agency

Region III
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Program Office

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Division

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In coordination with the Office of Water/Office of Science and Technology, Washington, D.C., and the states of Delaware, Maryland, New York, Pennsylvania, Virginia and West Virginia and the District of Columbia

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

## 2007 Addendum

July 2007

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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.

*and*

the states of
Delaware, Maryland, New York,
Pennsylvania, Virginia and
West Virginia and the District of Columbia

# Contents

# Acknowledgments

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This document resulted from the collaborative expertise and talents of the Chesapeake Bay Program's state agency, federal agency, and academic institutional partners. The 25 principal authors (listed first) and contributing authors (listed in alphabetical order) follow by chapter. Unless noted, author affiliations are listed under the specific workgroup or committee acknowledgments. Chapter 1: Richard Batiuk; Chapter 2: Steve Preston; Chapter 3: Steve Preston; Chapter 4: Richard Batiuk, David Jasinski, Marcia Olson, and Gary Shenk; Chapter 5: Richard Batiuk; Chapter 6: Elgin Perry, Richard Batiuk, and Larry Harding (University of Maryland Center for Environmental Science); Chapter 7: Bruce Michael, Rick Hoffman, Mary Ellen Ley, Ken Moore, Elgin Perry, and Mark Trice; Chapter 8: Larry Merrill, Mark Barath, Richard Batiuk, and Richard Eskin; Appendix A: David Secor; Mary Christman; Frank Curriero; David Jasinski; Steve Preston; Ken Reckhow; and Mark Trice; Appendix B: Gary Shenk; Appendix C: Steve Preston; Appendix D: Lowell Bahner (NOAA Chesapeake Bay Office), David Jasinski, and Gary Shenk; Appendix E: Gary Shenk, Marcia Olson, and Elgin Perry; Appendices F, G, and H: Gary Shenk; Appendix I: Bruce Michael; Appendix J: Mark Barath; Appendix K: Roberto Llanso (Versar), Dan Dauer (Old Dominion University), Mike Lane (Old Dominion University), and Jon Volstead (Versar); and Appendix L: Dan Dauer, Mike Lane, and Roberto Llanso.

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## SCIENCE AND TECHNICAL ADVISORY COMMITTEE

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The contributions of the independent scientific peer reviewers—selected and convened by the Chesapeake Bay Program's Scientific and Technical Advisory Committee based on their recognized national expertise and drawn from institutions and agencies across the country—are hereby acknowledged.

Without the efforts of the hundreds of colleagues involved in all aspects of field collection, laboratory analysis, management, and interpretation of Chesapeake Bay Monitoring Program data over the past two decades, these criteria could not have been derived and the criteria assessment procedures could not have been developed.

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# chapter i

# Introduction

In April 2003, the U.S. Environmental Protection Agency (EPA) published the *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries* (*Regional Criteria Guidance*) in cooperation with and on behalf of the six watershed states—New York, Pennsylvania, Maryland, Delaware, Virginia, and West Virginia—and the District of Columbia. The culmination of three years of work, the criteria document resulted directly from the collective contributions of hundreds of regional scientists, technical staff, and agency managers as well as the independent review by recognized scientific experts across the country (U.S. EPA 2003).

In October 2004, EPA published the first addendum to the 2003 *Regional Criteria Guidance* (U.S. EPA 2004). The addendum provided additional guidance on:

- Applying the temperature-based open-water dissolved oxygen criteria required to protect the endangered shortnose sturgeon;
- Assessing attainment of the instantaneous minimum and 7-day mean dissolved oxygen criteria using monthly mean water quality monitoring data;
- Deriving site-specific dissolved oxygen criteria and assessing criteria attainment of those tidal systems where the extensive adjacent tidal wetlands cause naturally low dissolved oxygen levels;
- Delineating the upper and lower boundaries of the pycnocline that defines the vertical boundaries distinguishing open-water, deep-water, and deep-channel designated uses;
- Applying, in combination, the numerical water clarity criteria to shallow water habitats and submerged aquatic vegetation restoration goal acreages for defining attainment of the shallow-water bay grass designated use; and
- Determining where numerical chlorophyll *a* criteria should apply to local Chesapeake Bay and tidal tributary waters.

From 2004 through early 2006, Delaware, Maryland, Virginia, and the District of Columbia adopted: the EPA-published Chesapeake Bay water quality criteria for dissolved oxygen, water clarity, and chlorophyll *a*; the EPA-recommended tidal water designated uses; and the EPA-established criteria assessment procedures into their respective state water quality standards regulations. All four jurisdictions[1] promulgated narrative chlorophyll *a* criteria in their standards regulations. Virginia promulgated numerical segment- and season-specific chlorophyll *a* criteria for the tidal James River. The District of Columbia promulgated numerical chlorophyll *a* criteria for its reach of the tidal Potomac River and its remaining tidal waters, having previously adopted numerical chlorophyll *a* criteria for protection of the tidal Anacostia River.

The April 2003 *Regional Criteria Guidance* and the October 2004 addendum documents published the criteria attainment assessment methods (U.S. EPA 2003, 2004). These methods characterize the spatial and temporal variability of the appropriate water quality parameters and provide a clear basis for deciding whether a criterion or set of criteria protecting a designated use in a specific segment of the mainstem Chesapeake Bay or one of the tidal tributaries or embayments were in attainment. The methods were quite detailed; however, specific technical and procedural issues remained in applying the methods as specified in the original publication by EPA from April 2003. These issues required resolution to allow Delaware, Maryland, Virginia, and the District of Columbia to assess attainment of their new Chesapeake Bay water quality standards regulations fully.

This second addendum documents the revised, refined, and new criteria assessment methods for the published Chesapeake Bay dissolved oxygen, water clarity, and chlorophyll *a* criteria.

- **Chapter 2** documents refinements to and recommendations for further development of the spatial interpolation and statistical aspects of the overall Chesapeake Bay water quality criteria attainment assessment methodology.
- **Chapter 3** documents the resolution of and recommended procedures for addressing a series of overarching Chesapeake Bay water quality criteria assessment issues.
- **Chapter 4** documents refinements and additions to the procedures for assessing the previously published Chesapeake Bay dissolved oxygen criteria.
- **Chapter 5** documents refinements and additions to the procedures for assessing the previously published Chesapeake Bay water clarity criteria and determining attainment of the shallow-water bay grass designated use.
- **Chapter 6** documents refinements and additions to the procedures for assessing attainment of state-adopted numerical concentration-based chlorophyll *a* criteria.

[1]References throughout the text to "states" or "jurisdictions" means a collective reference to the states of Delaware and Maryland, the Commonwealth of Virginia, and the District of Columbia. All four have Chesapeake Bay tidal waters within their jurisdictional boundaries.

- **Chapter 7** documents new recommended methodologies and procedures for using shallow-water monitoring data in assessing attainment of Chesapeake Bay water quality criteria and tidal water designated uses.
- **Chapter 8** documents a recommended 303(d) list decision-making framework for assessment of Chesapeake Bay and its tidal tributaries and embayments.

This document represents the second formal addendum to the 2003 Chesapeake Bay water quality criteria document; as such, readers should regard the sections in this document as new or replacement chapters and appendices to the original published report. The criteria attainment assessment procedures published in this addendum replace and otherwise supercede similar criteria assessment procedures originally published in the *2003 Regional Criteria Guidance* and 2004 addendum (U.S. EPA 2003, 2004). Publication of future addendums by EPA on behalf of the Chesapeake Bay Program watershed jurisdictional partners is likely as continued scientific research and management applications reveal new insights and knowledge that should be incorporated into revisions of state water quality standards regulations in upcoming triennial reviews.

## LITERATURE CITED

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

U.S. Environmental Protection Agency. 2004. *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for Chesapeake Bay and Its Tidal Tributaries – 2004 Addendum*. EPA 903-R-04-005. Region III Chesapeake Bay Program Office, Annapolis, MD.

chapter ii

# Refinements to the Chesapeake Bay Water Quality Criteria Assessment Methodology

## BACKGROUND

The Chesapeake Bay water quality criteria were designed to protect the ecological integrity of the Bay's tidal waters. To ensure that the criteria are being attained and the Chesapeake Bay ecosystem is, in fact, protected, adequate means to measure and evaluate water quality relative to the criteria must exist. The Bay is a highly diverse and variable system; these characteristics make precise assessment of water quality criteria attainment difficult. Thus, it is critical to design both a data collection system and a data analysis methodology carefully to make the best use of existing resources and provide the best possible assessment of water quality criteria attainment. Such a design can inform stakeholders about the status of impairments and whether the impairments have been removed once management actions have resulted in the achievement of the desired restoration goals.

To address the need for enhanced water quality criteria assessments brought on by the states' adoption of new Chesapeake Bay water quality standards, the Chesapeake Bay Program[1] redesigned its tidal monitoring network to provide a framework for interpreting the data. To the extent possible (within funding constraints), existing monitoring programs were either enhanced to support criteria assessment or new monitoring programs were established to address monitoring gaps. Given the diversity of tidal habitats throughout the Bay, establishing a comprehensive tidal monitoring network required different types of monitoring.

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[1]The Chesapeake Bay Program, formed in 1983 by the first Chesapeake Bay agreement, is a unique regional partnership guiding the restoration of the Chesapeake Bay and its tidal tributaries. On water quality issues, the Chesapeake Bay Program partners include Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, the District of Columbia, the Chesapeake Bay Commission, the U.S. Environmental Protection Agency, over 20 other federal agencies, academic institutions, local governments, and citizen groups.

Developing a methodology for assessing criteria attainment using these data was also critical. Ideally the criteria assessment methodology would prove useful in several ways: 1) it could be applied consistently for many water quality criteria components; 2) it would provide a common framework for assessing data collected over multiple scales; 3) it would provide a basis for using as much of the information contained in the collected data as possible; 4) it would provide a clear basis for making decisions on criteria attainment; and 5) it would provide diagnostic information regarding the spatial and temporal patterns of criteria violations. The cumulative frequency diagram (CFD) approach, described in the original 2003 Chesapeake Bay water quality criteria document, was designed with many of these objectives in mind (U.S. EPA 2003a).

## OVERVIEW OF THE CFD ASSESSMENT METHODOLOGY

The original 2003 Chesapeake Bay water-quality criteria document fully describes the CFD methodology (Chapter 6, pages **154–178**), but is summarized briefly here (U.S. EPA 2003a). Criteria assessment using the CFD methodology is based on interpolation within a spatially defined grid. Described later in this chapter, this grid-based interpolation provides the spatial framework for use of all of the data. It weights each data location according to the amount of area (or volume) it represents. Water quality parameter levels in all interpolator grid cells are estimated based on interpolation algorithms, providing a complete "map" of water quality throughout the assessed area (Figure II-1). Water quality parameter levels in each grid cell are compared to the applicable criteria levels to establish an estimate of the spatial extent of criteria exceedance (non-attainment). Aggregating the total amount of space (area or volume) in which the criteria are exceeded provides a basis for estimating the percentage of the spatial assessment unit (designated use within a segment) in which the criteria were exceeded for that monitoring cruise. These measures of criteria exceedance are then compiled over the entire assessment period to develop a cumulative frequency diagram, or CFD. The CFD is a well-known and well-established statistical procedure commonly used to describe hydrologic and environmental data (Helsel and Hirsch 1992).

The CFD assessment methodology evolved from the need to allow for variability in water quality parameters due to unusual events. For the water quality parameter to be assessed, a criterion threshold is established; when the threshold is exceeded, the system is considered impaired. All water quality parameters, however, are inherently variable in space and time. Because of this variability, it is unlikely that even a healthy Chesapeake Bay ecosystem will attain the threshold absolutely in all places and at all times.

Spatially, small regions may persistently exceed the criteria's threshold due to poor flushing or other natural conditions. Such areas should not automatically lead to the assumption that the entire assessment unit is impaired. Similar logic applies in the

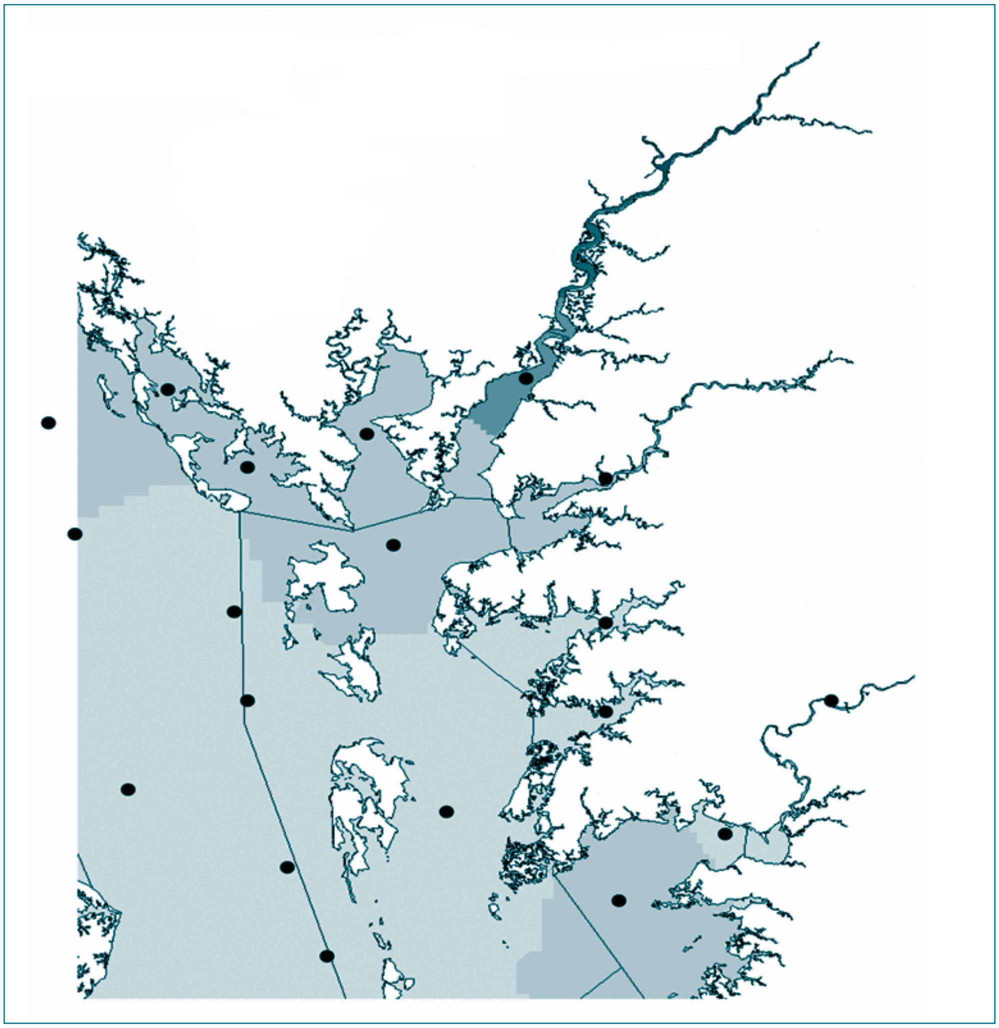

**Figure II-1.** Example of interpolation of Chesapeake Bay water quality data.

temporal dimension. Water quality in a large area of a segment may exceed the criteria's threshold for a short time. If this degradation proves infrequent and short-lived with the segment quickly returning to a healthy state, this situation does not represent an impairment of the ecologically defined designated use of the segment.

Recognition that ephemeral exceedances of the criterion's threshold in time or space do not represent persistent impairment of the segment's designated use ultimately led to the development of a criteria assessment methodology that deems such exceedances as acceptable. Persistent, widespread criteria exceedance, however, is considered an impairment of the segment's designated use (U.S. EPA 2003a).

The criteria assessment methodology determines how much of the spatial assessment unit is not in compliance with the criteria (percent of space) for each moment in time. In the second step of the methodology, a determination is made of how often (percent of time) a segment is out of attainment by more than a fixed percent of space. The results of these queries can be presented in graphical form with percent of time plotted against percent of space.

Figure II-2 illustrates a typical CFD based on 12 measures of spatial extent of criteria exceedance over time. In general, if a segment is in attainment with the criterion, then one expects a high frequency of dates for which the percent out of attainment is low. In this case, the CFD should descend rapidly from the upper left corner, pass not far from the lower left corner, and then proceed to the lower right corner. The line in Figure II-2 shows the typical hyperbolic shape commonly observed using the CFD to assess water quality criteria in the Chesapeake Bay. The closer the CFD curve comes to the origin (lower left corner), the better the attainment of the assessed segment. A curve that is far from the origin indicates that a larger percent of space in the segment is out of attainment and the probability of use impairment increases.

The CFD methodology offers many advantages over other criteria assessment approaches. Through interpolation, it provides a method for using data collected in areas surrounding the area of interest (the spatial assessment unit). This factor is important since the sample size of observations within a spatial assessment unit may not be sufficient to determine the area (or volume) of exceedance within the unit accurately. The method also weights the data collected from a given location according to the amount of area (or volume) that the location represents. This capability is important because data may be collected from locations that do not represent

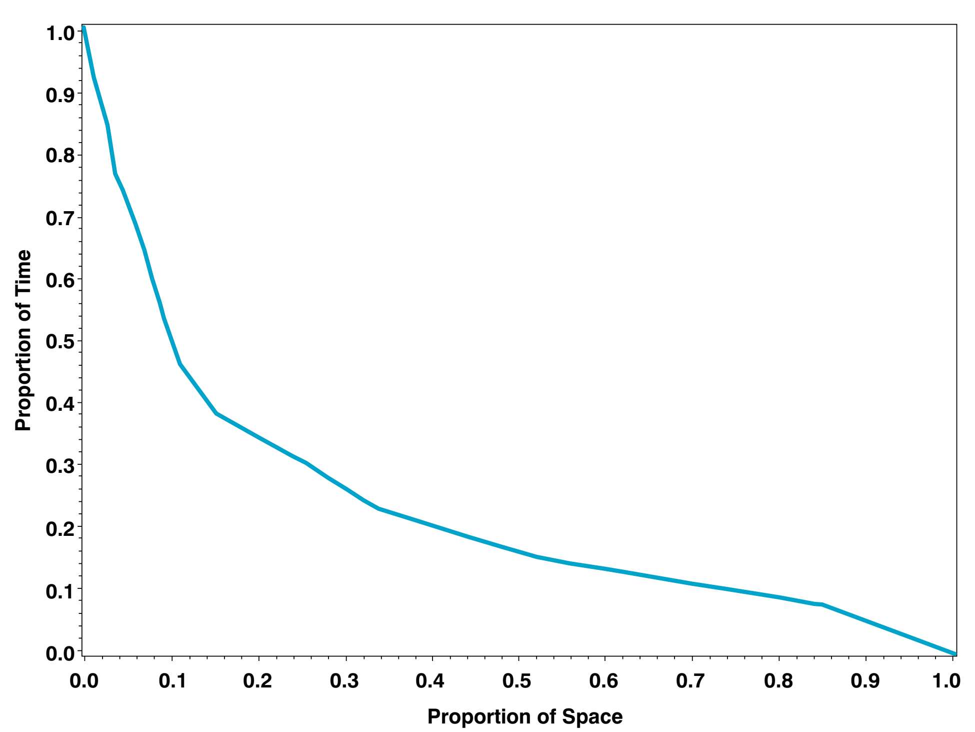


**Figure II-2.** A water quality criteria attainment assessment cumulative frequency diagram (CFD) based on 12 measures of the spatial extent of criteria exceedance over time.

all areas of the spatial assessment unit; providing equal weight to such data could bias the assessments.

A second advantage is that the CFD incorporates the spatial-temporal pattern of criteria exceedance into the assessment. The shape of the curve offers information on patterns of exceedance in space and time. Such information may prove helpful in understanding the causes of impairments (see page 162 in U.S. EPA 2003a).

A third advantage is that it bases the assessment on biologically determined patterns of allowable criteria exceedance. Reference curves are ideally developed in the same way as assessment curves and should reflect the degree of criteria exceedance that can be withstood by the ecological communities without impairing the designated use. Thus, comparison of the assessment curve to the reference curve ensures that any allowable criteria exceedances do not occur in a spatial or temporal pattern that could, in reality, represent impairment at the scale of the entire assessment unit (see pages 162–178 in U.S. EPA 2003a). Local persistent effects could still have high impairment.

Finally, the combined elements of the CFD criteria assessment methodology fully and effectively address all five factors used to determine attainment of designated uses: magnitude, duration, frequency, space, and time. After conducting a national review of TMDL programs, the National Research Council (2001) concluded that establishing these conditions is crucial for successful application of state water quality standards.

The CFD methodology is a new and innovative method of water quality criteria assessment, representing an improvement over methods used in other parts of the country (STAC 2006). The standard practice for assessing compliance with water quality criteria throughout the United States is by sampling monthly at a fixed set of stations and gauging compliance strictly from a count of exceedances of those samples. Sampling stations are typically located for convenience (e.g., accessibility). Consequently, reluctance to re-evaluate and change location (so as to maintain a time series at a fixed point) is common; no consideration is given to the representativeness of the sample for the space/time not sampled.

Most assessments are based simply on EPA assessment guidance in which all samples in a given area were compiled; attainment was assumed if no more than 10 percent of the samples exceeded the standard (U.S. EPA 1997). In this approach, all samples are assumed to be fully representative of the specified space and time and are simply combined as if they were random samples from a uniform population. This approach was necessary in the past because the technology did not exist for a more rigorous method of data analysis; however, it neglected spatial and temporal patterns in the criteria measures. The CFD approach was designed to characterize these spatial and temporal patterns and weight samples more accurately based on the amount of space or time that they actually represent.

The CFD methodology was first applied in the Chesapeake Bay for the most recent 303(d) listing cycle, completed in the spring of 2006 and based on data from 2002 through 2004. The CFDs were developed and used primarily for the dissolved oxygen open-water and deep-water 30-day mean criteria because insufficient data and data analysis techniques existed to assess the higher-frequency dissolved oxygen criteria components. Similarly, the water clarity criteria were not assessed based on the CFD because few tidal systems had sufficient shallow-water monitoring data for an assessment.

In fall 2005, the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC) established a scientific panel to review and refine the CFD assessment methodology. Nationally recognized academic experts in spatial and environmental statistics made up the panel. The STAC-convened panel concluded that the CFD approach is both feasible and innovative, qualifies as the best available science, and represents an improvement over criteria assessment methods used in the past (STAC 2006).

The panel also recognized, however, that the approach remains in the early stages of management application. It stated that the CFD approach deserves further directed study and analysis to evaluate the bias and imprecision that can occur due to limitations in available data and in current interpolation and CFD algorithms (STAC 2006). This chapter provides guidance for criteria assessment application, summarizes findings from the CFD evaluations, and offers recommendations for further refinement of the CFD assessment methodology. Appendix A provides a complete copy of the scientific panel's final report.

## DESCRIPTION AND EVALUATION OF THE CFD-BASED ASSESSMENT METHODOLOGY

The methodology for estimating the CFD is most easily described as a series of eight steps as shown in Table II-1. These steps, described below, provide a framework for considering the process and are elucidated by a simple example. More detailed discussions of each step follow later in this chapter.

### EXAMPLE CFD-BASED CRITERIA ASSESSMENT

To illustrate the CFD criteria assessment methodology, a simple theoretical example based on a small data set can prove useful. Assume a segment for which the interpolation grid is 4 cells by 4 cells. In reality, the number of grid cells is much larger (hundreds to thousands), but this small grid is illustrative. Also assume that data were collected on five distinct dates, and that each date is representative of the appropriate time scale (in an actual application, data would be collected over many more dates). The criterion threshold for this fictitious water quality parameter is 3.

**Table II-1.** Steps for constructing and assessing criteria attainment using cumulative frequency diagrams (CFDs).

1. Collect data from a spatial network of locations on several dates during the assessment period.

2. For each date, interpolate the data spatially over the entire system to obtain estimates of water quality using a two- or three-dimensional grid of interpolation cells.

3. Aggregate interpolations to the appropriate temporal scale (e.g., if evaluating the 30-day mean, take the average of all interpolations for each date in the month).

4. For each interpolator cell, assess whether the applicable criterion is exceeded.

5. For each assessment unit, compute the percentage of interpolator cells that exceed the criterion as an estimate of the percent of area (or volume) within the spatial assessment unit that exceeds the criterion.

6. Rank the percent of area estimates for the set of all sample days in the assessment period from largest to smallest and sequentially assign to these ranked percents a value that estimates percent of time. Add the end points of (100%, 0%) and (0%, 100%).

7. Plot the paired percent of area (or volume) and percent of time data on a graph with the percent of area on the x-axis and percent of time on the y-axis. The resultant plot is the assessment cumulative frequency diagram or CFD.

8. Compare the assessment CFD (from step 7) to the appropriate reference CFD. If at any point the assessment CFD exceeds the reference CFD (i.e., a given level of spatial noncompliance occurs more often than allowed for a given amount of time), then the criterion is in non-attainment. Consequently, the segment fails to meet that designated use.

An illustration of the eight steps for computing the CFD for these simplified constraints is shown on the facing page. The three columns show the first three steps. Column 1 provides fictional data for five dates for five fixed locations in a two-dimensional grid. Column 2 shows a fictional interpolation of these data to cover the entire grid. Column 3 gives the compliance status of each cell in the grid with 1 indicating non-attainment and 0 signifying attainment.

In this hypothetical example, the assessment curve is clearly greater than the reference curve and in non-attainment of the criterion, therefore, the designated use is not met. EPA recommends that any exceedance of the attainment CFD above the reference CFD should be considered non-attainment of the criterion and, consequently, the designated use.

**Step 1. Collect data at known locations.**

Date 1

| | | | |
|---|---|---|---|
| 3 | | | 3 |
| | | 5 | |
| | | | |
| 2 | | | 1 |

Date 2

| | | | |
|---|---|---|---|
| 1 | | | 1 |
| | | 3 | |
| | | | |
| 1 | | | 1 |

Date 3

| | | | |
|---|---|---|---|
| 4 | | | 2 |
| | | 2 | |
| | | | |
| 1 | | | 1 |

Date 4

| | | | |
|---|---|---|---|
| 1 | | | 4 |
| | | 2 | |
| | | | |
| 4 | | | 1 |

Date 5

| | | | |
|---|---|---|---|
| 1 | | | 3 |
| | | 2 | |
| | | | |
| 1 | | | 1 |

**Step 2. Interpolate the data to grid cells.**

Date 1

| | | | |
|---|---|---|---|
| 3 | 4 | 5 | 3 |
| 4 | 4 | 5 | 2 |
| 3 | 3 | 4 | 1 |
| 2 | 3 | 3 | 1 |

Date 2

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 1 |
| 2 | 2 | 3 | 2 |
| 1 | 3 | 2 | 1 |
| 1 | 1 | 1 | 1 |

Date 3

| | | | |
|---|---|---|---|
| 4 | 3 | 2 | 2 |
| 3 | 2 | 2 | 1 |
| 2 | 2 | 1 | 1 |
| 1 | 1 | 1 | 1 |

Date 4

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 2 | 2 | 2 | 3 |
| 3 | 3 | 2 | 1 |
| 4 | 3 | 1 | 1 |

Date 5

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 3 |
| 2 | 2 | 2 | 2 |
| 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 |

**Steps 3-4. Determine attainment status of each cell.**

Date 1

| | | | |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 0 |
| 1 | 1 | 1 | 0 |
| 0 | 1 | 1 | 0 |

Date 2

| | | | |
|---|---|---|---|
| 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 0 |

Date 3

| | | | |
|---|---|---|---|
| 1 | 1 | 0 | 0 |
| 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

Date 4

| | | | |
|---|---|---|---|
| 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 0 |
| 1 | 1 | 0 | 0 |

Date 5

| | | | |
|---|---|---|---|
| 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

**Step 5: Determine percent attainment by date.**

| Sample date | Percent space |
|---|---|
| Date 1 | 75.00% |
| Date 2 | 18.75% |
| Date 3 | 18.75% |
| Date 4 | 43.75% |
| Date 5 | 12.50% |

**Step 6. Rank the percent of space values and assign percent of time as (100*R/(N+1)), where R is rank and N is sample size.**

| Sample date | Ranked percent space | Percent time |
|---|---|---|
| | 100% | 0% |
| Date 1 | 75.00% | 16.67% |
| Date 4 | 43.75% | 33.33% |
| Date 2 | 18.75% | 50.00% |
| Date 3 | 18.75% | 66.67% |
| Date 5 | 12.50% | 83.33% |
| | 0% | 100% |

**Steps 7 and 8.** Figure II-3 illustrates the plot of this theoretical assessment CFD and the comparison to a hypothetical reference curve. In this hypothetical example, the assessment area shows non-attainment. For a percent area of 18.75, the allowable frequency on the reference curve is about 17 percent. That is, 18.75 percent of the segment area should not be out of attainment more that 17 percent of the time. For Date 3, the estimated frequency of 18.75 percent of segment area in non-attainment is 66.67 percent. Thus the frequency of 18.75 percent of space out of attainment exceeds the 17 percent allowed. The reference curve is exceeded for dates 4 and 1 as well.[2]

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[2]In this cumulative distribution framework, the actual date is not relevant. One should not infer that non-attainment occurred on that date if the data point associated with a date falls above the reference. The date is used here as a label for each coordinate pair.

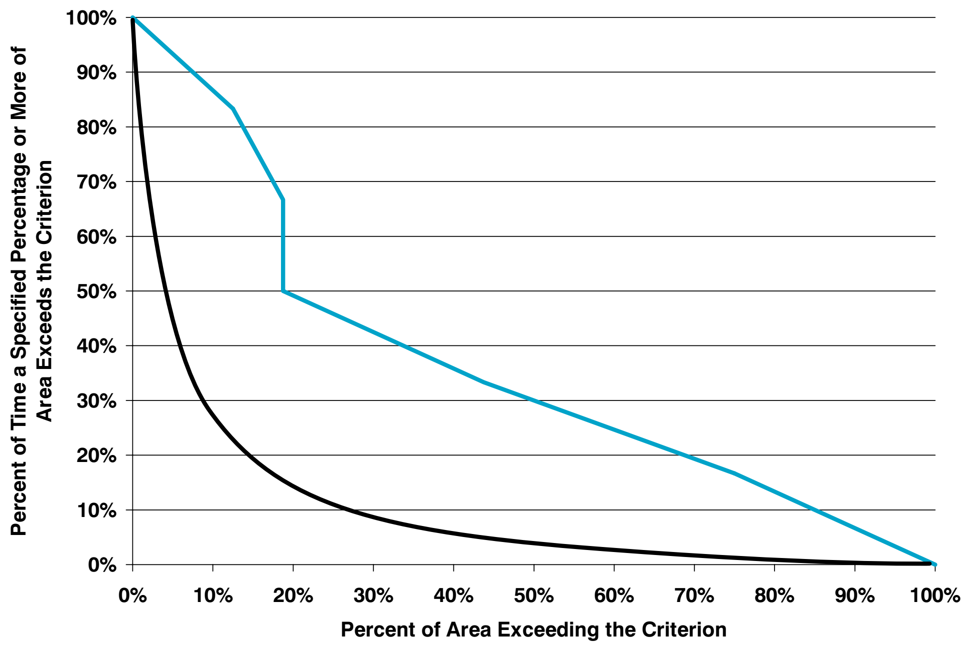


**Figure II-3.** Graphical representation of the CFD from the above theoretical example assessment curve (blue) with a hypothetical reference curve (black).

## CFD REFERENCE CURVES

Two approaches are feasible in defining the reference curves proposed for use in the CFD assessment methodology. One is biologically based and identifies appropriate regions of the Bay, its tidal tributaries, and its embayments that have healthy biological indicators and are in attainment of their designated use (U.S. EPA 2003a). The CFDs are developed for these areas in the same way that assessment CFDs would be developed elsewhere. Curves generated for biologically healthy tidal areas are considered “reference” curves.

For example, healthy benthic indices of biotic integrity (IBI) scores might be used as indicators of adequate bottom dissolved oxygen (Weisberg et al. 1997; U.S. EPA 2003a). Thus, after stratifying by salinity zone and perhaps other factors, a series of dissolved oxygen reference CFD curves could be developed from the existing monitoring database. One advantage of this approach is that each biological reference curve could be tailored to each designated-use-based criteria component. This technique tailors the pattern of criteria exceedance that the part of the Bay ecosystem could tolerate and remain healthy to the protected species and biological communities and the specific criterion component. Thus, each reference curve may have a somewhat different shape (see pages 168–177 in U.S. EPA 2003a).

In some cases, development of a biologically-based reference curve is not possible due to lack of data describing the health of the relevant species or biological communities. Such cases require a different approach. The EPA recommends use of a default reference curve in situations for which a biologically based reference curve remains unavailable. This default reference curve is defined as a hyperbolic curve that encompasses no more than 10 percent of the area of the CFD graph (percent of space multiplied by percent of time) (see page 174 in U.S. EPA 2003a) (Figure II-4). The default reference curve has the following important properties: 1) the plot is symmetric about the 1:1 line; 2) the plot is hyperbolic; 3) the total area under the curve equals 10 percent; and 4) the ends of the curve pass through x- and y-axis intercepts (100, 0) and (0, 100), respectively.

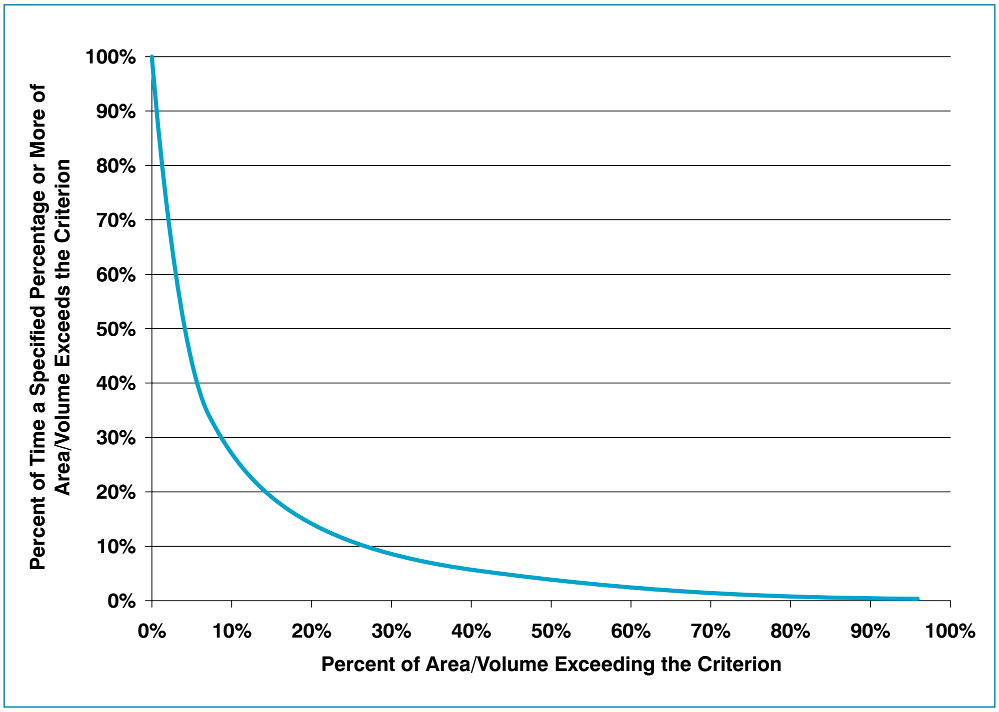


**Figure II-4.** Default reference curve for application in the attainment assessment of Chesapeake Bay water quality criteria for which biologically based reference curves cannot be derived.

Figure II-4 is defined by the equation:

$$(x + b)(y + b) = a \qquad \text{Equation 1}$$

where: $b = 0.0429945$ and $a = b^2 + b$.

No specific theoretical basis underlies this definition of the default reference curve, but the definition does provide equal weight to exceedances occurring in either space or time. This approach is appropriate since no information exists to indicate that either time or space should take precedence. Selection of the 10 percent value is based on its consistency with past national EPA guidance (U.S. EPA 1997). The default reference curve is hyperbolic, making it similar in shape to biologically based reference curves. In fact, the shape of the default reference curve is quite similar to some of the established biologically based reference curves, such as the 30-day mean open-water dissolved oxygen reference curve (Figure II-5).

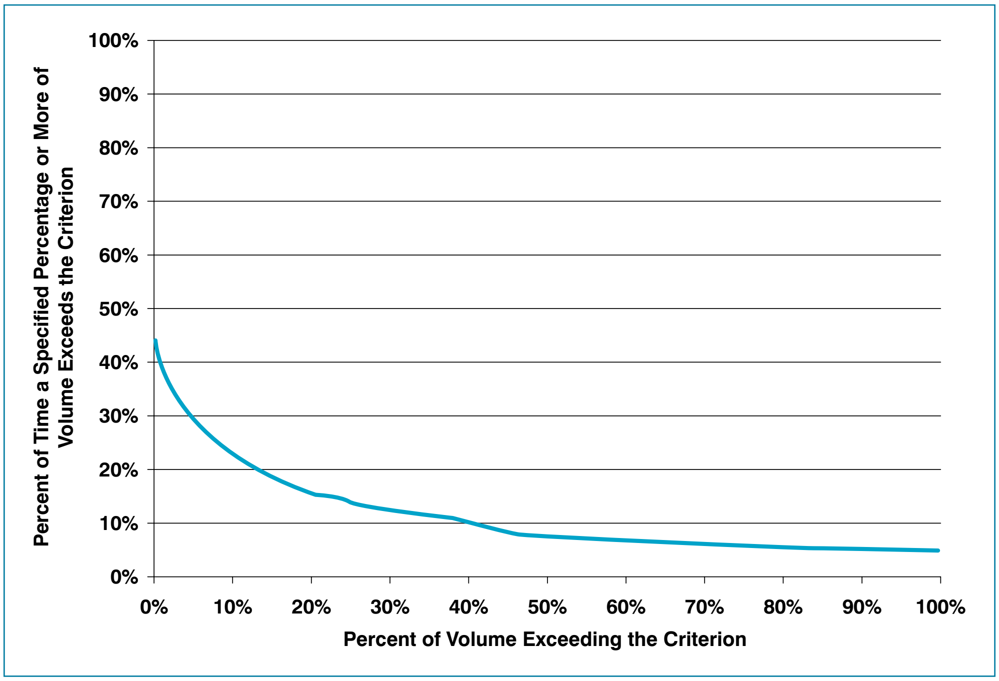


**Figure II-5.** Biological reference curve for 30-day mean open-water dissolved oxygen criterion applied for assessment during the summer months (June–September) only.

A default reference curve, defined as a hyperbolic curve encompassing no more than 10 percent frequency exceedances, was also considered. Such a curve is based on a simple model:

$$x_{ij} = u + a_i + b_j \qquad \text{Equation 2}$$

where a is temporal term with variance $\Phi^2_a$ and b is spatial term with $\Phi^2_b$. The variance of $x_{ij}$ is $\Phi^2_a + \Phi^2_b = \Phi^2$. The standard deviation of $x_{ij}$ is $\mathrm{sqrt}(\Phi^2) = \Phi$. Ten percent of the $x_{ij}$ should fall above $u + 1.2815 * \Phi$ where 1.2815 is the 90th percentile of the standard normal distribution. Thus, assuming normality, a population with equal spatial and temporal variance and a mean that is $1.2815 * \Phi$ below the threshold criterion should have an exceedance rate of 10 percent over space and time. Figure II-6 shows the CFD for the 10 percent frequency exceedance default reference curve in black.

Also plotted on this same axis in blue in Figure II-6 is a default reference curve based on 10 percent of the area of the percent space x percent time (the default reference curve described previously and illustrated in Figure II-4). This evaluation was undertaken given an approach to deriving and assessing attainment of numerical chlorophyll *a* criteria is based largely on thresholds that should rarely be exceeded in healthy populations (e.g., the 90$^{th}$ percentile). These two curves are very close in shape, further supporting the use of the default reference based on a 10 percent area under the curve. The EPA recommends use of the default reference curve, illustrated in Figure III-4 and defined by Equation 1, when an applicable biologically-based reference curve is not available.

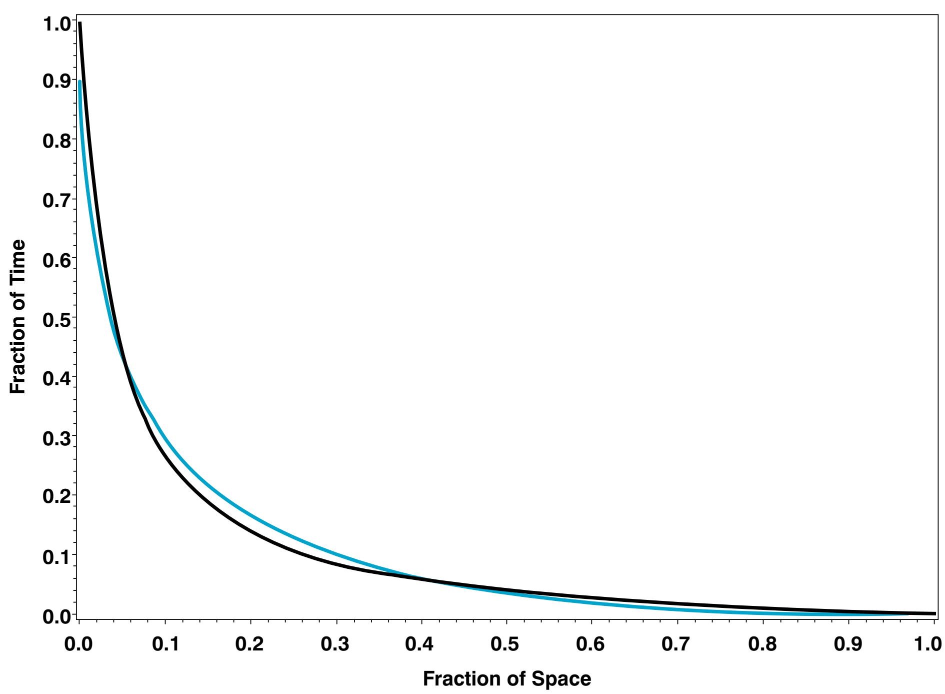


**Figure II-6.** Comparison of hyperbolic curves based on 10 percent of area under the curve (blue) and 10 percent frequency exceedance (black).

## COMPARING ASSESSMENT AND REFERENCE CURVES

Reference curves are more or less continuously defined while assessment curves have relatively few discrete measures. Biological reference curves can contain hundreds of points; the default reference curve has an infinite number of points. By contrast, curves for three-year assessments of summer (June–September) monthly means will have 12 data points with the curve defined by linear interpolation between neighboring points. For this reason, it is possible for portions of the assessment curve to be above the reference curve even without any measured point exceeding the reference curve. This situation becomes more comprehensible by understanding that reference curves typically have positive curvature and that this curvature can dip below the line between consecutive points on the assessment curve, causing a spurious, non-allowable exceedance.

To address this problem, the EPA recommends that reference curves be evaluated only at the temporal axis points in the assessment curve as illustrated in Figure II-7. For non-continuous biological reference curves, the points should be interpolated from neighboring points. Appendix B provides a detailed description of the complete Chesapeake Bay water quality criteria attainment assessment methodology.

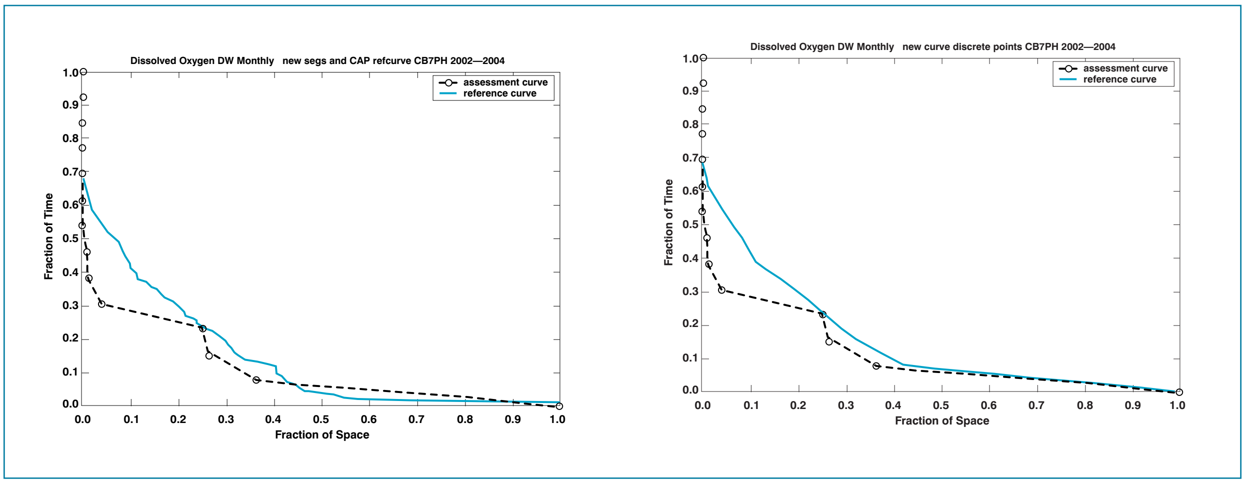


**Figure II-7.** The graph on the left (A) shows spurious non-attainment as the reference curve passes below the assessment curve between points. The graph on the right (B) shows attainment as the reference and assessment curves are evaluated at the same temporal axis points.

## DEVELOPMENT OF A STATISTICAL DECISION-MAKING FRAMEWORK

A statistical framework for making decisions on water quality criteria attainment based on the CFD methodology would yield additional information on the certainty of the attainment decisions. It would also help direct appropriate monitoring strategies to reduce uncertainties. However, many theoretical obstacles remain in developing such a framework. The CFD methodology is a new and innovative approach to water quality criteria assessment. The relatively recent application of this methodology to criteria assessment suggests that conducting further evaluations and making improvements should prove constructive. The following section discusses the steps in applying the CFD methodology.

### Step 1—Data Collection

One of the advantages of the CFD approach is that it can accommodate a variety of input data and still arrive at the same assessment endpoint. Data collection methods currently in place include: fixed-station data, cruise track data, continuous monitoring data, aircraft flight path data, and satellite imagery data. Because of the interpolation step, all of these data can be used with varying degrees of success to estimate the total spatial distribution (to the limit of interpolator pixel size) of a water quality parameter.

### Step 2—Interpolation

Interpolation can place data collected at various spatial densities on a common footing. On the one hand, this capability is advantageous because data collected at different spatial densities are available for the criteria assessment process. On the other hand, it can be misleading to accept interpolated surfaces from different data sources as equivalent without qualifying each interpolation with a measure of the estimation error associated with each data type. Clearly, an interpolation based on hundreds of points per segment (such as cruise track data) more accurately reflects the true non-attainment percentage when compared to an interpolation based on two or three points per segment (such as a fixed-station data). Of the various types of interpolation algorithms available and reviewed, kriging is best positioned to address this issue (STAC 2006). Kriging offers advantages over inverse distance weighting in that it provides the best assessment of the estimation error associated with interpolation, but has not been implemented to date. Other methods, such as interpolating polynomials, splines, and locally weighted regression methods, should also be explored.

### Step 3—Temporal Aggregation of Interpolations

Depending on the interpolation method and the statistics available, it may be possible to calculate the probability of exceedance of the temporal mean at each point given the likely variance and the value(s) observed during the period. This step is necessary to calculate probabilities in the following step.

### Step 4—Pointwise Compliance

Determining the percent attainment of each grid cell from each interpolation seems simple. If the estimated value for a grid cell is above (chlorophyll *a*) or below (dissolved oxygen, water clarity) the criterion, then that cell is not in attainment.

While interpolation allows for standardization of many types of data, pointwise attainment determination allows for standardization of many criteria. Because attainment is determined at moments in time and points in space, it is possible to vary the criterion in time and space. If different levels of a water quality constituent are acceptable in different seasons, then the criterion can vary seasonally. It is possible to implement different criteria over space for a segment that bridges, for example, oligohaline and mesohaline salinity regimes. It might even be possible to let the criterion be a continuous function of some ancillary variable such as temperature or salinity, although this situation requires that such data exist for every interpolator cell. The only requirement is that the final attainment determination be “yes” or “no” for each interpolator cell.

Currently, limited pointwise attainment determination compliance has been implemented. For example, the open-water 30-day mean dissolved oxygen criterion is 5 mg×liter$^{-1}$, except when the ambient salinity drops below 0.5 psu and the criterion becomes 5.5 mg×liter$^{-1}$ (U.S. EPA 2003a). During the summer months, the open-water designated use boundaries are selected based on local density conditions reflecting stratification of the water column.

Even the simplicity of this concept diminishes when examining interpolation error. Consider the assessment of two interpolator cells from an interpolation based on cruise track data. While both interpolations could have the same value, each could have a different level of error. Such different levels of error could mean that these were different probabilities that the criteria were actually exceeded. For the simple assessment of non-attainment, however, they count the same. Thus, one advantage of a statistical framework is that it accounts for different levels of error throughout the interpolation grid and these error levels could be incorporated into a single overall assessment of attainment.

### Step 5—Percent Non-Attainment in Space

Computing a percentage should also be simple. The estimate is simply 100 times the number of cells not in attainment divided by the total number of cells. As a rule, the uncertainty of a binary process can be modeled using a binomial distribution. The issue of uncertainty described in step 3 propagates into computing the percent of attainment for a segment. In addition, estimated values for interpolator cells have a complex dependence structure, ruling out a simple binomial model. The rules governing the uncertainty of this step are also complex. The mathematics for modeling this propagation of error are feasible, but have not yet been developed.

### Step 6—Percent of Time

While the CFD's percent-of-space coordinate provides a simple interpretation of the percent of the spatial assessment unit that is out of attainment on a given date, the percent-of-time coordinate is not simply the percent of time out of attainment at a given point. Instead this coordinate is interpreted similarly to that of a cumulative distribution function; it represents the percent of time that the associated spatial percent of non-attainment is exceeded. For example, if the (percent space, percent time) coordinates for a point on the CFD are (90, 10), the spatial percent of non-attainment is greater than or equal to 90 percent about 10 percent of the time.

This step is very similar to computing an empirical distribution function, which is an estimator of a cumulative distribution function. This similarity brings to mind statistical inference tools associated with empirical distribution functions—the Kolmogorov-Smirnov, Shapiro-Wilk, Anderson-Darling, or Cramer-von Mises — as candidates for inference about the CFD (STAC 2006). These procedures model uncertainty as a function of sample size only (in this case, the number of sample dates). Since they do not account for uncertainty associated with the number of samples collected in space (i.e., number of sampling stations), this indicates that they are to provide a statistical framework that truly accounts for error in Chesapeake Bay water quality criteria assessments.

### Steps 7 and 8—Plotting and Comparing the Curves

When comparing the assessment curve to the reference curve, the issue of uncertainty becomes most important. The preceding discussion clearly indicates that uncertainty in the assessment curve represents an accumulation of uncertainty generated in and propagated through the preceding steps. If the reference curve is biologically based, it is derived under the same system of error propagation. Developing the statistical algorithms to quantify this uncertainty poses a challenge.

Even if the uncertainty can be properly quantified, the issue of who gets the benefit of doubt due to this uncertainty can prove difficult to resolve.

This problem of uncertainty in the regulatory process is widespread and not limited to the CFD approach. Nonetheless, it must be dealt with. One option is to require that the assessment curve be significantly above the reference curve to establish non-attainment. This option protects the regulated party from being deemed out of attainment due to random effects. If assessment CFD curves are not accurately determined, however, it could lead to poor protection of environmental health and designated uses. A second option is to require that the assessment curve be significantly below the reference curve to establish attainment. This option results in strong protection of the environmental resource, but could lead to the regulated party implementing unnecessary and expensive management actions.

Some compromise between these extremes is needed. The simplest compromise is to ignore variability and compare the assessment curve to the reference curve. As long as unbiased estimation is implemented for both the assessment curve and the reference curve, this third option will result in roughly equal numbers of false positive (declaring non-attainment when, in fact, compliance exists) and false negative (declaring attainment when, in fact, non-attainment exists) results. This last approach is balanced and the one currently recommended by EPA. Under this approach, however, no mechanism exists to motivate error reduction by improving the data sets on which the criteria assessments are based.

## RESULTS OF THE SCIENTIFIC EVALUATION

Beginning in fall 2005, the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC) appointed a panel of scientists to evaluate and refine the CFD water quality criteria assessment methodology. Evaluations included tests on the effects of: 1) sample densities in time and space; 2) varying levels of attainment; and 3) varying degrees of spatial and temporal covariance. Appendix A provides a complete copy of the panel's final report while Appendix C offers a narrative evaluation of the options for spatial interpolation.

In general, the STAC panel analysis and review indicated that the CFD approach can combine spatial and temporal data to support inferences on attainment or exceedance of the water quality criteria (STAC 2006). The panel viewed the CFD approach as innovative — one that has general application in water quality criteria assessments. In comparison to other jurisdictional authorities, the Chesapeake Bay Program has taken a lead in monitoring and assessment based upon scientific design (designated uses) and emphasis on statistical evidence. Advancement in the CFD approach should provide an important precedent for states outside the Chesapeake Bay region. Because the CFD is both feasible and innovative, the panel felt that it qualifies as the best available approach. On the other hand, the panel recognized that the approach remains nascent and deserves further directed study and analyses to evaluate the bias and imprecision that can occur due to small sample densities, non-independence in temporal trends, and inadequate spatial interpolations.

The panel found that the CFD approach in its current form is feasible, but requires additional research to further refine and strengthen it as a statistical tool. The CFD builds on important statistical theory related to cumulative distribution functions; as such, its statistical properties can be simulated and deduced. In its analyses, the STAC panel showed that constructing confidence ellipses that support inferences related to threshold curves or other tests of spatial and temporal compliance are feasible. Understanding fundamental properties of how the CFD represents likely covariances of attainment in time and space and how temporal and spatial correlations interact with sample size effects require additional research. Further, researchers must also analyze biases across regions and designated-use segments. The panel expects that two to three years of directed research and development are necessary to identify and measure potential sources of bias and imprecision for criteria attainment determinations.

In the near future, the panel foresees that the CFD approach will prove particularly powerful when linked to continuous spatial data streams through the cruise-track monitoring program, and when able to utilize continuous temporal data generated through further deployment of remote sensing platforms in the Chesapeake Bay (e.g., Chesapeake Bay Observing System). These data sets will allow greater precision and accuracy in both threshold and attainment determinations made using the CFD approach.

The STAC panel concluded that success of the CFD-based assessment rests upon decision rules related to the biological reference curves. These curves represent desired segment-designated use water quality outcomes and reflect sources of acceptable natural variability (STAC 2006). The reference and attainment curves should follow the same general approach in derivation: water quality data collection, spatial interpolation, comparison to biologically based water quality criteria, and combination of space-time attainment data through a CFD. Therefore, the biological reference curves allow implementation of a tolerance threshold presuming the data used to derive the reference curve were sampled similarly to the assessment curve.

That is, the reference curve defines the degree to which criteria violations can be tolerated without resulting in impairment of the designated use.

Bias and uncertainty are driven in CFD curves by sample densities in time and space. Therefore, the STAC panel advised that similar sample densities be used in the derivation of assessment and reference curves. As such densities are not always feasible, additional analytical methods are needed to weight sampling densities equally between attainment and reference curves.

## APPLICATION OF THE CFD-BASED ASSESSMENT METHODOLOGY

### RECOMMENDATIONS FOR APPLICATION OF THE CFD-BASED METHODOLOGY

As stated above, the CFD-based water quality criteria assessment methodology offers the potential for significant benefit in accurately assessing Chesapeake Bay water quality criteria attainment. As the STAC CFD Review Panel has indicated, however, that the methodology is new and additional evaluations and refinements should be performed (STAC 2006) (Appendix A). The EPA agrees with the panel's conclusions, strongly supports the findings that further research is needed, and will support those efforts in whatever way possible in the coming years. In the meantime, the EPA recommends the following approach in undertaking Chesapeake Bay water quality criteria assessments.

As described above, the Chesapeake Bay Program collects data at two different scales for water quality criteria attainment assessment. In each case, the design of data collection program focuses on assessments at a specific scale. The fixed-station data are designed for segment and baywide assessments and the shallow-water monitoring data are designed to assess the small tidal tributaries and the Bay's shallow-water habitats. Given the different scales, separate interpolations are likely necessary using the most appropriate interpolation algorithm. The STAC CFD Review Panel evaluated two possible options for spatial interpolation, recommending kriging as the better of the two alternatives (STAC 2006). Kriging, however, has not been fully developed for application in Chesapeake Bay water quality criteria attainment assessment.

Until kriging is fully developed as an option for whole-Bay assessment based on the fixed-station data, the EPA recommends that spatial interpolations continue using the current Chesapeake Bay Program's inverse distance weighting (IDW) algorithm-based interpolator (Appendix D). Spatial interpolation of the fixed-station data for assessment of criteria attainment in the mainstem Bay and major tidal tributaries requires several specific capabilities including: 1) the data must be interpolated in three-dimensions (i.e., with depth); 2) the data must be interpolated into the tidal tributaries and around bends in these tidal rivers; and 3) the interpolation needs to be automated to complete large number of criteria assessments efficiently and routinely. These capabilities are not currently available using a kriging algorithm, but the Chesapeake Bay Program IDW interpolator is designed with these capabilities in mind. Thus, the EPA recommends that large-scale interpolations (segment, baywide) continue to be based on the fixed-stations data be performed using the Chesapeake Bay Program IDW interpolator. As kriging is developed further for use, this option may be recommended in the future.

For the criteria assessment of small tidal tributaries and the Bay's shallow-water habitats based on data from the shallow-water monitoring program, the EPA recommends implementation of a kriging algorithm, where possible. The shallow-water monitoring program yields data to assess criteria attainment in relatively few systems at any one time. Thus, it is possible to provide the more focused evaluations of individual interpolations that kriging requires. Furthermore, the intensive data collection provided by the shallow-water monitoring program is particularly conducive to detailed statistical analysis. To utilize the data's information fully, a more thorough statistical interpolation procedure, such as kriging, should be implemented. The shallow-water systems are highly dynamic and thus better characterized by more intensive data collection combined with a more rigorous statistical interpolation algorithm. For these reasons, the EPA recommends that kriging be implemented, where possible, for criteria assessment based on shallow-water monitoring data.

Given the recommendation above, the EPA further advises that the states develop the expertise to perform spatial interpolation based on statistical methods. Assessment of the shallow waters will largely fall to the states, with some support from the Chesapeake Bay Program Office. Guidelines are being developed for the use of kriging in shallow-water criteria assessment. The procedure is detailed, however, and requires expertise in geographic information systems, spatial statistics, and computer programming. Questions remain about how best to implement kriging as an option for spatial interpolation. The EPA plans to provide support through the Chesapeake Bay Program Office to ensure that spatial interpolations based on kriging are performed consistently for all shallow waters of the Bay when practical.

In general, most of the tidal waters of the Chesapeake Bay mainstem and major tributaries remain impaired. This judgment was confirmed by the assessments performed during the 2006 303(d) listing cycle and by listing decisions made prior to that time. The 2006 assessments indicated that many of the assessment units were far out of attainment with little need to confirm the conclusions through statistical analysis. As restoration efforts proceed and more Bay tidal waters approach attainment of their designated uses, then statistical procedures may become important to ensure that waters are properly removed from the 303(d) list as soon as possible. Given that it may require several years for the Bay to respond to management actions, there is ample time to conduct the studies necessary to develop the required statistical decision-making framework based on the CFD. The EPA recommends that assessment of criteria attainment continue as in 2006 when the decision rule was that any criterion exceedance greater than that of the appropriate reference curve indicates non-attainment of that criterion and, therefore, the designated use.

## RECOMMENDATIONS FOR FUTURE REFINEMENT OF THE CFD-BASED ASSESSMENT METHODOLOGY

As part of its conclusions, the STAC CFD Review Panel identified several critical remaining issues requiring resolution in the near future (STAC 2006). The EPA agrees with the recommendations for future development and advises that the Chesapeake Bay Program partners ensure that the work is completed in a timely, appropriate manner.

The following list identifies some of the critical aspects requiring further research as recommended by STAC (2006). See Appendix A for additional details.

1. **Effects of Sampling Density on CFD Results.** The CFD is a special case of an unbiased estimator for a cumulative distribution function of a population. Like the cumulative distribution function, the CFD is a function of the mean and the variance of the population under assessment. The better the mean and variance are characterized with sample data, the more accurate the shape of the CFD. As the sampling density increases, the estimated CFD begins to approach the true CFD. If the sampling density is low, however, then sampling error could become important with the potential to affect the shape of the CFD and ultimately the accuracy of the compliance assessment. Furthermore, the potential for sample size to affect the shape could create an attainment assessment bias if the reference curve and assessment curve are based on different sampling densities. Conditional simulation methods developed by the STAC panel show promise in resolving these issues and mitigating potential biases caused by sample size differences.
2. **Choice of Interpolation Method,** The STAC panel's research considered several interpolation methods and outlined the features of each (Table C-1 in Appendix C). These features illustrated tradeoffs between ease of implementation and maximizing information garnered from the data. Further work is needed to compare the features to the requirements of wide-scale implementation of Chesapeake Bay criteria assessment procedures and to formulate a plan for tractable implementation that results in credible assessments. One strategy is to implement easily performed analysis (e.g., IDW) as a screening tool to identify cases for which attainment/non-attainment is clear, and then implement more labor-intensive methods (e.g., kriging) for cases in which attainment is more difficult to resolve.
3. **Three-Dimensional Interpolation.** Assessments of the dissolved oxygen criteria attainment requires three-dimensional interpolation. The field of three-dimensional interpolation, however, is not as highly developed as that of two-dimensional interpolation. Efforts are needed to evaluate research in three-dimensional interpolation further and to seek additional outside scientific input

and review to implement the best available technology for this aspect of criteria assessment.

4. **High-Density Temporal Data.** As currently formulated, criteria assessment for most of the Bay's open waters are based on "snapshots" in time of the spatial extent of criteria exceedance estimated through interpolation. Data collected for use in interpolation span several days given the large area being sampled. New technologies should soon be capable of producing high-density data in both space and time. Interpolation should accommodate data collected densely in space. It is unclear, however, how the CFD process will accommodate data that are densely clustered in time. Further work is needed to evaluate methods to fully utilize the temporally intensive data currently being collected.

5. **Implementation and Review.** As a rule of thumb, the best test of any new procedure is putting it to work with stakeholder involvement. Through its Criteria Assessment Protocols Workgroup, the Chesapeake Bay Program has already established a forum for resolving the details of CFD implementation. At appropriate intervals in this process, however, the Chesapeake Bay Program should seek independent scientific and technical review of the implementation status of the assessment methodology.

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chapter iii

# Application of Chesapeake Bay Water Quality Criteria Assessment Procedures

## BACKGROUND

Beginning in the late 1990s and continuing through 2003, the Chesapeake Bay Program partners developed new Chesapeake Bay water quality criteria designed specifically to protect the ecological health of the Bay (U.S. EPA 2003a). Delaware, Maryland, and Virginia, along with the District of Columbia, then adopted these criteria and new tidal water designated uses into their water quality standards regulations. The states' new Chesapeake Bay water quality standards were applied for the first time in each state's 2006 Clean Water Act 303(d) listing cycle.

The four jurisdictions also adopted criteria assessment methods — published by EPA in 2003 and in a 2004 addendum — into state water quality standards regulations (U.S. EPA 2003a, 2004a). The methods characterize the spatial and temporal variability of the appropriate water quality parameters, while providing a clear basis for determining whether a portion of the Bay's tidal waters reached attainment of the applicable designated use. Despite the methods' detail, technical limitations remained for their complete application. This chapter and those that follow address many of the prior technical limitations. Continued efforts to develop further refinements to the criteria assessment methodology in specific areas, however, will likely remain.

In addition to the technical limitations, obstacles related to the states' transition from an old set of water quality standards to the newer, more detailed Chesapeake Bay water quality standards also existed. Differences occurred in the spatial extent of past listing/delisting decisions. New water quality criteria components also exist that have never been previously assessed. Furthermore, the mechanisms and processes used to report listings in the past required updating to allow reporting based on the states' new Chesapeake Bay water quality standards regulations. As with the technical limitations referenced above, an ongoing effort to refine and update the methodology for making future listing decisions based on the new Chesapeake Bay water quality standards will also be required (see Chapter 8 for further details).

## ASSESSMENT UNITS, SEGMENTATION, AND SUB-SEGMENTATION

To assess attainment of the Chesapeake Bay water quality criteria, the spatial and temporal extent over which they apply must be defined. The temporal extent is defined implicitly for each component of the states' Chesapeake Bay water quality standards. Described on page 150 in the 2003 EPA Chesapeake Bay water quality criteria document (U.S. EPA 2003a) and adopted into the jurisdictions' water quality standards regulations, the spatial extent is defined by the intersection of a Chesapeake Bay Program segment (U.S. EPA 2004b, 2005a) and each tidal water designated use (U.S. EPA 2003b, 2004c). The spatial units defined by this intersection are referred to as "spatial assessment units." The intent is for each unit to be assessed and listed independently on each jurisdiction's 303(d) list (part 1 through part 5) (see Chapter 8 for further details).

The scale of the Chesapeake Bay spatial assessment units is large, with selection based specifically on conditions in the Bay and on the factors affecting these conditions. The Chesapeake Bay Program segments themselves were based on salinity regimes, circulation patterns, and other natural physical features, but are generally reflective of variations in water quality conditions and living resource communities (U.S. EPA 2004b, 2005a). Thus, these segments serve as appropriate spatial units for measuring the scope of water quality impairments in the Chesapeake Bay, its tidal tributaries, and its embayments. They also work at a logical scale for developing necessary management plans (TMDLs). Many of the water quality impairments currently extend over large areas of the Bay and its tidal tributaries, so performing assessments and reporting on these impairments at the segment scale are both appropriate. Developing management plans at this scale is also appropriate since multiple jurisdictions often contribute to impairments.

Even though the scale of the spatial assessment units is suitable, in many cases it varied from the scale of past tidal water quality criteria attainment assessments. The change in scale introduced several challenges to the states as they implemented the new Chesapeake Bay water quality criteria and tidal water designated uses. Boundaries of some previously established state assessment units were moved or shrunk to address the spatial variability in some state water quality standards assessment measures. Furthermore, management decisions (e.g., listing certain waters as impaired, developing TMDLs) had already been made based on the previously established assessment units and were being implemented at the time the new Chesapeake Bay water quality standards were adopted into state regulation. Thus, it was necessary to establish procedures for transitioning to new spatial assessment units and relating prior management decisions to new assessments that were sometimes defined at a different spatial scale.

In general, the states could address the differences in boundary locations by making small adjustments to state-defined spatial units. Primarily, adjustments consisted of small changes in the boundaries of the previously state-defined assessment units to make them coincident with the boundaries of the larger Chesapeake Bay Program segments. This way, the smaller assessment units nest within the larger ones and the larger-scale assessment results can be attributed to each of the smaller units within. The approach allows states to remain consistent with previous listing decisions while accounting for the broader designated-use-segment-assessment results on their 303(d) lists.

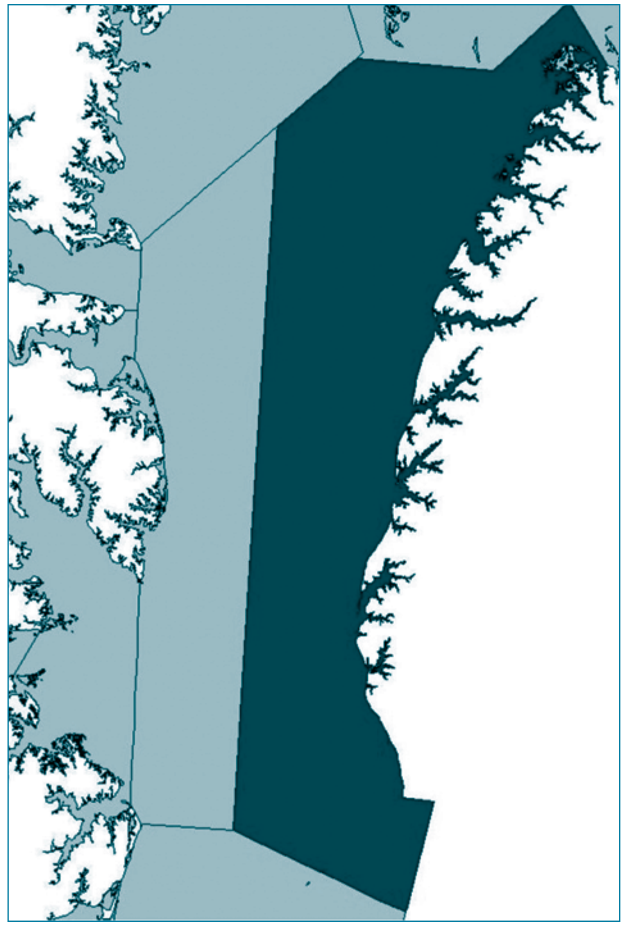

**Figure III-1.** Segment CB7PH covering the southeastern portion of the Chesapeake Bay in Virginia.
Source: U.S. EPA 2004b.

In some cases, adoption of the new Chesapeake Bay spatial assessment units represented a less detailed and possibly less precise assessment of water-quality criteria attainment. For example, Figure III-1 illustrates Chesapeake Bay Program segment CB7PH, which covers the southeastern portion of the mainstem Chesapeake within Virginia. As is typical in most of the Bay, the shoreline is extremely complex with many small tidal rivers, creeks, and embayments. These smaller tidal habitats may have different water quality than the mainstem Bay section of the segment due to different circulation patterns or land uses or pollution sources that dominate local water quality conditions. These smaller tidal habitats may even have monitoring information that demonstrates the differences in water quality conditions. In such a case, it may make sense to separate the smaller tidal river, creek, or embayment from the main assessment unit by subdividing it to create a new smaller spatial unit for separate assessment. Thus, the states have the option to "sub-segment" larger units to characterize conditions in specific parts of the Bay, its tidal tributaries, and embayments more precisely.

Allowing jurisdictions to subdivide the larger segments is consistent with national EPA guidance and with EPA-published Chesapeake Bay water quality criteria assessment guidance, which both provide specific considerations for sub-segmenting water bodies for criteria assessment and listing decisions (U.S. EPA 2003a, 2005b). Published EPA guidance states that waters can be partitioned "to represent homogeneity in physical, biological or chemical conditions." The EPA recommends that jurisdictions use similar principles in deciding to subdivide the larger Chesapeake Bay assessment units. A state's decision to sub-segment an existing segment should be based on: 1) clear physical, biological, or chemical differences that can be documented; 2) homogeneity of water quality in the water body under consideration; and 3) confirmed future availability of monitoring data in the new sub-segment to provide the capability to assess conditions and allow a determination regarding its 303(d) list status. In all cases, there should be *a priori* knowledge of the conditions that support a decision to subdivide, and preferably specific data that demonstrate how conditions differ in the area under scrutiny. Documentation of this information should be made available for review as part of the 303(d) listing cycle for which a new subdivided segment is initially assessed. Jurisdictions need to ensure that any sub-segmentation is fully consistent with their state's water quality standard regulations.

The EPA discourages states from subdividing segments simply to remove smaller areas from an impaired waters list. Given the tidal exchange that occurs among all segments, conditions in one segment can potentially affect adjacent segments. A sub-segment that is prematurely removed from the impaired waters list might require placement back on the impaired waters list in the next listing cycle due to adverse conditions in the original segment.

Maryland and Virginia have already adopted specific sub-segments into their state's water quality standards regulations in several tidal tributaries and embayments. The 2004 addendum to the 2003 Chesapeake Bay use attainability and designated-use document contains detailed documentation supporting these state-defined, adopted sub-segmentations (U.S. EPA 2004c).

## DATA FOR USE IN CHESAPEAKE BAY CRITERIA ASSESSMENTS

To assess Chesapeake Bay water quality criteria attainment, the data used must prove adequate. Consistent with the 2003 EPA Chesapeake Bay criteria assessment guidance, the data should be of known quality and adequate quantity, as well as representative of the tidal water designated use habitat under assessment (U.S. EPA 2003a). Documented QA/QC programs should ensure data quality; such documentation should be publicly available for evaluation. A sufficient amount of data should exist to provide a defensible degree of accuracy and precision given the expected level of variability in the assessed tidal water body. The data should also be representative of the spatial assessment unit as a whole so the resulting assessment is not biased toward any one portion. While the EPA provides no minimum requirements for each of these data characteristics, they should be maximized to the extent possible to ensure that criteria assessments are scientifically defensible.

Opinions range broadly on the quantity of data required for criteria assessment. On one extreme, some believe that sufficient data should be collected to capture all the temporal and spatial variability to ensure that the criteria and designated uses are attained in space and time. On the other extreme, some suggest that the state agency manager should determine if a designated use is being attained based on available information—even if it is anecdotal.

For the Chesapeake Bay and its tidal tributaries, the EPA recommends basing all water quality criteria assessments on monitoring data. These data should be collected over a three-year period immediately prior to the year of the listing cycle, unless non-attainment is definitively established in less time (as described in Chapter 7). Furthermore, the monitoring program for data collection should optimize quality, quantity, and representativeness as described above.

The Chesapeake Bay Program partners continue to fund and conduct an extensive baywide, coordinated water quality monitoring program, much of which supports water quality criteria assessment. Water quality monitoring takes place at more than 150 sites throughout the mainstem Chesapeake Bay and its tidal tributary waters (Figure III-2). Samples are collected at each of the fixed stations on a monthly or semi-monthly basis with data gathered since the mid-1980s (Chesapeake Bay Program 1989). The fixed-station network provides consistent data over the entire mainstem Bay, major tidal tributaries, and larger embayments. The data are useful in assessing the published Bay water quality criteria in the open-water, deep-water, deep-channel, and migratory and spawning designated uses.

Use of the fixed-station network is limited for criteria assessments in the shallow-water designated use habitats because the data scale is not appropriate. This network also proves limited in many smaller tidal tributaries and embayments, which have no or very few stations. To address these limitations, the Chesapeake Bay Program partners developed a Shallow-water Monitoring Program to provide data collected intensively in space and time in the Bay's shallow-water habitats. Chapter 7 describes this program and the details of data application for criteria assessment.

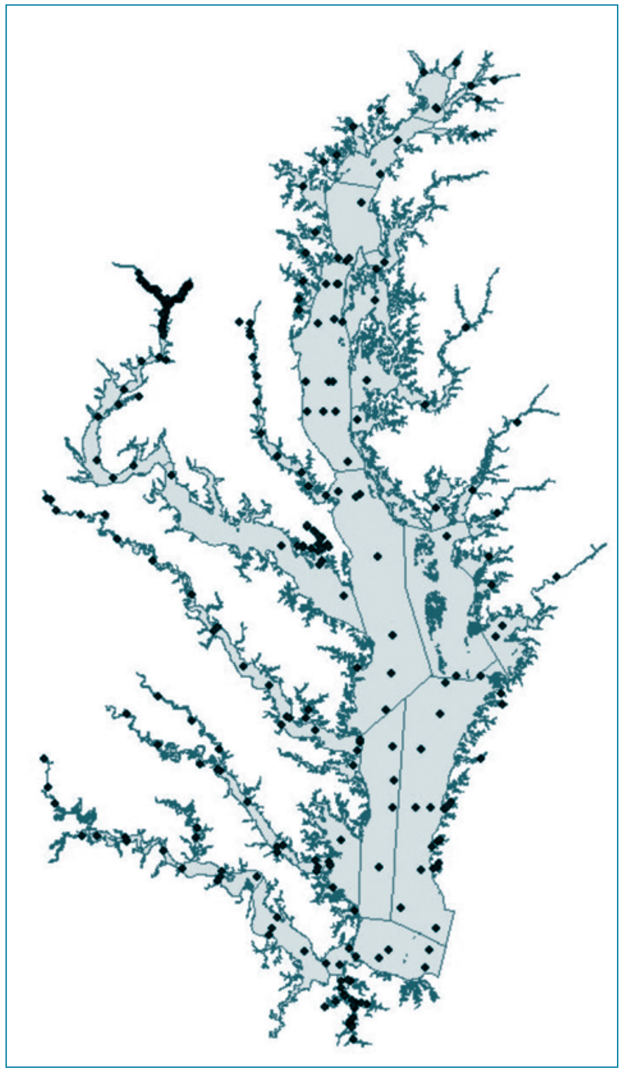

**Figure III-2.** Locations of the sites that make up the fixed station network of the Chesapeake Bay Water Quality Monitoring Program.

Source: Chesapeake Bay Program 1989.

The 2003 EPA Chesapeake Bay water quality criteria document describes the extent of data collection needed to assess the state's Chesapeake Bay water quality standards (U.S. EPA 2003a). Three levels of effort are described for each criterion: marginal, adequate, and recommended (see pages 178–196 in U.S. EPA 2003a). The "marginal" level of monitoring is the minimum data collection needed to support criteria assessment. At this level, data may not be of the right type or in sufficient quantity to assess all of the applicable criteria components. In general, this level of monitoring assumes that only the fixed-station data are available for criteria assessment. The "adequate" level of monitoring assumes that the fixed-station monitoring program will be combined with limited intensive data collection (e.g., temporally continuous monitoring for dissolved oxygen) to ensure that data are collected to support the assessment of all the applicable criteria components (e.g., 30-day, 7-day, and 1-day means, instantaneous minimum) in some spatial assessment units. The "recommended" level of monitoring assumes that the fixed-station monitoring program will be combined with intensive data collection in all spatial assessment units. Funding is not currently available to support monitoring at the "recommended" level. The fixed-station monitoring is expected to continue into the future, so data should be available at the "marginal" level for all spatial assessment units. With the implementation of the Chesapeake Bay shallow-water monitoring program in 2001, combined with a growing network of high-frequency observing system deployed in the Bay tidal waters, monitoring will reach the "adequate" level across all spatial assessment units with time.

To enhance the monitoring information from the coordinated Chesapeake Bay water quality and shallow-water monitoring programs, jurisdictions are encouraged to include data from other sources as appropriate. Consistent with the 2003 EPA-published Chesapeake Bay water quality criteria assessment guidance, the states and the District are encouraged to compile data from sources such as state and federal monitoring agencies, local governments, universities, environmental organizations, and citizen monitoring groups (U.S. EPA 2003a). Such data could prove significant in enhancing the spatial coverage of the existing Chesapeake Bay water quality monitoring program. The jurisdictions must ensure, however, that the data are appropriate for use in the Chesapeake Bay criteria attainment assessment methodology. Data need to be of documented quality and adequate quantity as indicated above.

The jurisdictions also must ensure that the data are collected at an appropriate scale and are representative of a given area or volume of a specific spatial assessment unit. The Chesapeake Bay Program spatial interpolator uses data collected at all locations and defines how much of that area or volume can be characterized by data from a particular location (see Chapter 2 and Appendix D for details). Thus, a small tidal embayment may be characterized by data from a single site. If that site is not located properly (e.g., in a small creek, off a pier in shallow water, off a beach), the assessment of the entire embayment may rest on potentially biased information. Similarly, if data are collected intermittently at some sites, the spatial assessment unit may be characterized inconsistently at times.

To use data collected through non-Chesapeake Bay Program monitoring programs in Chesapeake Bay water quality criteria assessments, they must be merged with the Chesapeake Bay Program monitoring program data appropriately. The assumption is that these water quality data were collected on different time (more infrequent) and space (well away from the mid-channel river, mainstem) scales than the Chesapeake Bay Water Quality Monitoring Program data. Therefore, these other data will be assigned a cruise designation based on the monthly collection time so that they can be interpolated along with the Chesapeake Bay Water Quality Monitoring Program data to generate the cumulative frequency distribution (see Chapter 2 and Appendix B for details).

The states are encouraged to seek data from sources beyond the Chesapeake Bay Water Quality Monitoring Program, but should use such data with care to avoid biasing the assessment results for any particular portion of the tidal waters. Ideally, the states would work with the collecting agencies and institutions in advance to ensure that the data are collected appropriately for use in interpolation and the overall CFD-based criteria assessment methodology.

In addition to data collected by government and non-profit agencies, the states are also encouraged to work with agencies, organizations, or other entities subject to regulation, but with an interest in contributing data for use in the criteria attainment assessment process. Such agencies may be able to provide additional monitoring resources and significant amounts of supplementary data. Provided that an adequate QA/QC program is in place to ensure that the data are accurate, representative, and of known quality, these regulated agencies or entities may significantly benefit the criteria assessment process.

The Hampton Roads Sanitation District in Virginia is one such example. The District has worked with the Virginia Department of Environmental Quality and the Virginia Institute of Marine Science to establish its own shallow-water monitoring program. The Virginia Department of Environmental Quality can use the data generated by the program to assess the state's dissolved oxygen, water clarity, and chlorophyll *a* criteria in the lower tidal James River. Other similar organizations of regulated stakeholders may also wish to provide similar data.

## UPDATING THE CRITERIA ASSESSMENT FRAMEWORK

The criteria assessment methodology developed for the Chesapeake Bay water quality criteria standards will require continued refinement into the future. The technical details of the methodology continue to be refined through research and experience with application. This document describes many new refinements that will assist the jurisdictions with their criteria assessment process and listing decisions. More refinements are expected over the coming years. Furthermore, better understanding is developing with time as more data are collected. New monitoring programs (e.g., shallow-water monitoring) are offering new insight into the processes that affect water quality conditions in the Chesapeake Bay. This enhanced understanding will help fine-tune the requirements necessary for protection of the Bay ecosystem. Given that continued refinements of the criteria assessment methodology are expected, it is recommended that the jurisdictions plan continued updates to their Chesapeake Bay water quality standards regulations through their existing triennial review process. The EPA commits to providing the information needed for updating the states' water quality standards through publication of recommended refinements to the criteria assessment procedures (such as in this addendum). The publication of any future addendums to the 2003 Chesapeake Bay criteria document will come in advance of the jurisdictions' triennial reviews for use in justifying needed changes to the state's water quality standards regulations.

One example of the expected refinements to the criteria assessment methodology is the development of a statistical basis for decision-making using the CFD (see Chapter 2 and Appendices A and C for further details). Since the Chesapeake Bay criteria assessment methodology was first published in 2003, interest has grown in developing an accounting of error in the assessment process. Research has been underway over the past years to develop such a methodology. The technical details are challenging, however, and research has not yet led to a solution. Progress has occurred over the last year; a statistical framework could possibly be developed for adoption into the state's water quality standards in upcoming 303(d) listing cycles. Other refinements may be developed for monitoring programs and the interpolation procedures. The EPA encourages states to prepare for adopting such refinements to their criteria assessment procedures into future regulations.

Reference curves provide a second example of expected refinements. As more data are collected, the capability for better defining the amount and pattern of criteria exceedance that the system can withstand will continually improve. While major changes to the reference curves are not expected, updating the reference curves with additional data will improve the states' ability to assess Chesapeake tidal waters accurately. With the prior agreement of the watershed jurisdictions, the EPA will update the reference curves with new data and publish the revised curves in future criteria document addenda. The jurisdictions will then need to adopt the new reference curves into their water quality standards regulations through their regular triennial review processes.

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chapter iv

# Refinements to the Chesapeake Bay Dissolved Oxygen Criteria Assessment Procedures

## BACKGROUND

In 2003, the EPA published detailed criteria for dissolved oxygen tailored to different habitats within the Chesapeake Bay and its tidal tributaries (U.S. EPA 2003a) (Table IV-1). Oxygen is critical to most forms of life in the Bay; it must be available in adequate concentrations to support overall ecosystem health. Minimum concentrations of oxygen must be present to support the wide range of species requiring protection as well as their various life stages.

Dissolved oxygen criteria were established for Chesapeake Bay that varied in space and time to provide levels of protection for different key species and communities. The criteria were also designed around several lengths of time to reflect the varying oxygen tolerances for different life stages (e.g., larval, juvenile, adult) and effects (e.g., mortality, growth, behavior). Thus, the dissolved oxygen criteria include multiple components. Each component includes a target of dissolved oxygen concentration, the duration of time over which the concentration is averaged, the space (designated-use area) where the criterion applies, and a time (season, month) when the criterion applies.

The dissolved oxygen criteria include 30-day, 7-day, and 1-day means along with an instantaneous minimum. Each of these criteria components applies to a specific season, such as the migratory spawning nursery period or the summer months (June through September) or all-year round. Each also relates to one of four tidal-water designated uses, according to the species and biological communities to be protected (U.S. EPA 2003a, 2003c). The EPA published, and the states adopted into their water quality standards regulations, dissolved oxygen criteria protective of migratory and spawning, open-water, deep-water, and deep-channel designated-use habitats (U.S. EPA 2003a) (Table IV-1).

**Table IV-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 (> 29EC), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg·liter$^{-1}$ will protect survival of this listed sturgeon species.

Assessing dissolved oxygen criteria attainment is challenging because of the complexity of both the criteria and the Bay itself. To fully assess all the criteria components, data need to be collected at a spatial intensity that adequately represents the four designated-use habitats of Chesapeake Bay tidal waters at different times of the year (U.S. EPA 2003c, 2004b). Similarly, data must be collected during all the applicable seasons and at frequencies sufficient to address the various criteria duration components. The different dissolved oxygen criteria apply to different designated-use areas and multiple criteria apply to the same designated-use area. The dissolved oxygen criteria components also apply over different time periods to protect species during critical life stages or during particularly stressful times of the year. To fully assess each dissolved oxygen component in each designated-use habitat over the appropriate time periods will require an extensive monitoring program and a detailed assessment methodology. The Chesapeake Bay Program currently conducts extensive water quality monitoring throughout the Bay tidal waters and the EPA published a detailed dissolved oxygen criteria assessment methodology with the new water quality criteria (Chesapeake Bay Program 1989; U.S. EPA 2003a, 2004a). The existing Bay water quality monitoring was not sufficient to cover all the criteria components, however, and some details in the assessment methodology remain unresolved.

For the 2006 303(d) listing cycle, the states' listing decisions were based primarily on previous listings. Tidal waters that had been listed as impaired in 2004 were not removed from part 5 of their listing unless all the applicable criteria components were shown in attainment (see Chapter 8 for further details). The Chesapeake Bay Program partners had the capacity (data, assessment methodology) to assess only the 30-day mean dissolved oxygen criteria and, in some cases, the instantaneous minimum dissolved oxygen criteria. The remaining dissolved oxygen criteria were not assessed because the existing water quality monitoring programs and the published assessment methodologies were inadequate for full assessment. In most spatial assessment units, the 30-day mean criterion was not attained and those assessment units would have been listed whether or not the other applicable dissolved oxygen criteria were also assessed (Figure IV-1). In many smaller tidal tributaries, however, the 30-day mean criterion was attained and those spatial assessment units were listed either as "impaired" (part 5) due to previous listing or

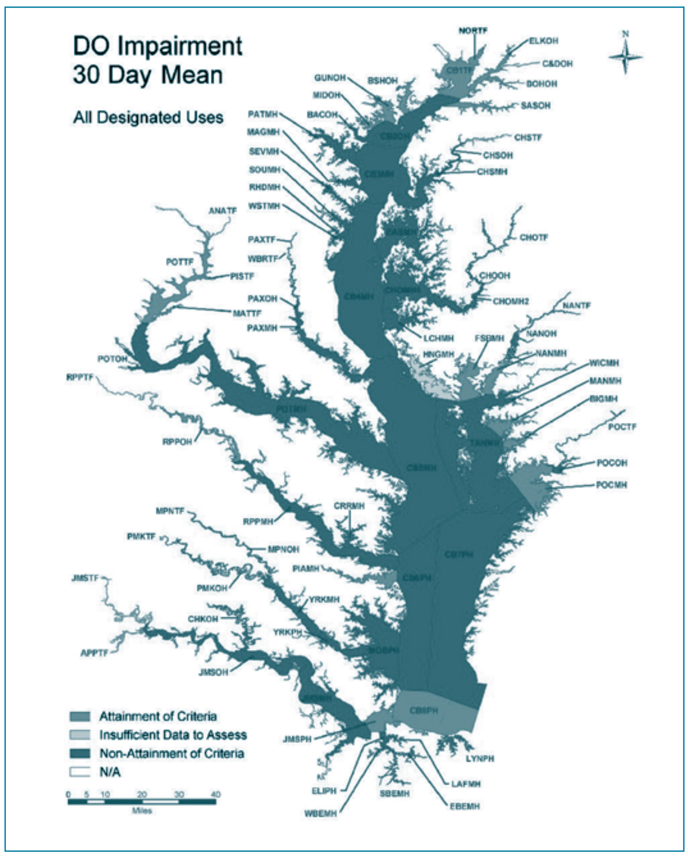


**Figure IV-1.** Listing status of the Chesapeake Bay open-water designated use based on dissolved oxygen standards.

as having “insufficient data to assess” (part 3). As nutrient loads are reduced and Bay water quality improves, assessing the complete array of applicable dissolved oxygen criteria to remove spatial assessment units from the “impaired” list will become more critical.

Since Chesapeake Bay dissolved oxygen criteria were published in 2003, the capability of fully assessing all the dissolved oxygen criteria for all four designated uses over all applicable time periods has progressed, but some limitations remain. The refined and expanded dissolved oxygen criteria assessment methodologies documented in this chapter replace the methodologies previously published by U.S. EPA (2003a, 2004a). Work should continue in refining these methodologies to reduce uncertainty further and to increase confidence in the resulting assessments. Developing, validating, and publishing EPA-recommended methodologies for assessing the full array of Chesapeake Bay dissolved oxygen criteria duration components will also prove critical.

## TEMPORAL PERIODS FOR ASSESSMENT OF DISSOLVED OXYGEN CRITERIA

To assess dissolved oxygen criteria attainment, the time span over which the criteria apply must be clearly defined. In some cases, the temporal period is defined implicitly as part of the criteria. For example, the dissolved oxygen criteria protective of the migratory fish spawning and nursery habitat designated use apply only to that time of year when spawning fish (and the resultant eggs and early juveniles) require higher dissolved oxygen levels compared to the rest of the year. In this example, dissolved oxygen criteria attainment should be assessed over the entire spawning season (February 1 through May 31) (U.S. EPA 2003a). Similarly, dissolved oxygen criteria in the deep-water and deep-channel designated uses apply only during the summer months — June 1 through September 30 — when the Bay stratifies and naturally reinforces the potential for lower dissolved oxygen concentrations in deeper waters. Therefore, assessment of dissolved oxygen criteria attainment in the deep-water and deep-channel designated uses should also be performed over the entire 4-month summer season (U.S. EPA 2003a). In all these cases, data are collected over the entire criteria season in each of the three years of the assessment period and these data are used to develop the cumulative frequency diagram (CFD) for assessing dissolved oxygen criteria attainment (see Chapter 2 and Appendix B for additional details).

Open water is the only tidal water designated use in which the dissolved oxygen criteria apply year-round (U.S. EPA 2003a). In general, the Bay is most vulnerable to low dissolved oxygen during the summer when temperatures are high, oxygen solubility is low, and biological consumption of oxygen rises to its greatest level. Periods of low dissolved oxygen can also occur during the rest of the year, sometimes caused by high loading with subsequent slow consumption of organic material. The open-water dissolved oxygen criteria are designed to provide protection of open-water habitat fish and shellfish communities at all times of the year. In spite of the year-round application of these criteria, natural processes complicate the use of a single, year-round assessment. Cooler temperatures affect the solubility of oxygen and allow higher concentrations compared to similar organic loading conditions in warmer months. Consequently, dissolved oxygen concentrations have a large natural variability range. Detecting human effects in the presence of that greater variability often proves difficult. For this reason, as part of the dissolved oxygen criteria development process, the EPA originally intended that the year-round open-water dissolved oxygen criteria (see Table III-10, page 66 in U.S. EPA 2003a) be assessed in each season (see pages 150–151 in U.S. EPA 2003a). During the 2006 303(d) listing cycle, confusion arose as to the appropriate time period for open-water dissolved oxygen assessment. The criteria were clearly defined over the full annual cycle, but the stated intent was to assess them on a seasonal basis. Furthermore, the 2003 EPA Chesapeake Bay criteria document itself did not provide consistent guidance; it referred to assessment on both an annual basis and a seasonal one (U.S. EPA 2003a).

Based on a re-evaluation of the underlying scientific basis for Chesapeake Bay dissolved oxygen criteria, the EPA recommends that jurisdictions assess attainment of the open-water dissolved oxygen criteria separately over two time periods: summer (June 1 through September 30) and non-summer (January 1 through May 31 and October 1 through December 31). The open-water dissolved oxygen criteria were largely derived to protect open-water species during the summer when elevated temperatures, higher salinities, and naturally low dissolved oxygen levels occur (U.S. EPA 2003a). Given that summer is a critical period for many species, it should be assessed separately. The potential for dissolved oxygen impairments are lower in the non-summer period due to greater natural dissolved oxygen solubility and lower biological oxygen consumption—both due to lower water column temperatures. Nevertheless, low dissolved oxygen levels sometimes occur during other times of the year making a separate dissolved oxygen criteria assessment necessary for the non-summer period. The separate criteria assessments for summer and non-summer seasons will support year-round protective dissolved oxygen concentrations in the open-water designated-use habitats.

## DISSOLVED OXYGEN CRITERIA ASSESSMENTS IN SHALLOW VERSUS OPEN WATERS

The open-water designated-use boundary is explicitly defined as including "tidally influenced waters extending horizontally from the shoreline to the adjacent shoreline" (see page 71 in U.S. EPA 2003c). Further, on page 68, the U.S. EPA (2003c) states that:

> *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 designated use extends into the intertidal zone and protects shallow-water organisms beyond underwater bay grasses.*

Unless a state has specifically delineated a sub-segment within a segment, attainment of the open-water designated use will be based on dissolved oxygen criteria attainment for the entire volume of the open-water designated use within the segment. Neither the need nor the requirement exists for a separate assessment of dissolved oxygen criteria attainment strictly within shallow waters (0–2 meters in depth). The importance of acquiring better temporal and spatial coverage of dissolved oxygen conditions in these shallow-depth habitats is not diminished however, since conditions in these areas vary greatly from the open water of the mid channels where the fixed stations are located. Shallow-water monitoring will provide the data needed to characterize dissolved oxygen conditions in shallow-water habitats more fully (see Chapter 7 for further details).

## ASSESSMENT OF SHORT-DURATION DISSOLVED OXYGEN CRITERIA

Historically, the Chesapeake Bay Water Quality Monitoring Program consisted primarily of fixed-station monitoring conducted on a monthly or twice-monthly basis (Chesapeake Bay Program 1989). This sampling design was primarily intended to assess long-term trends in water quality and the status of living resources, capturing variability over decadal, annual, and seasonal time scales. The fixed-station monitoring was adapted to assess the 30-day mean dissolved oxygen criteria to measure dissolved oxygen throughout the Bay and its tidal tributaries and embayments. This system ensures at least one set of measurements for each month.

The individual monthly estimates are considered accurate, although imprecise, since the sample sizes are small (n = 1 or 2). This imprecision is likely to be mitigated by the many estimates of monthly means (e.g., multiple months over the 3-year assessment period), which are combined into each single assessment of criteria attainment (see Chapter 2 and Appendix B for additional details). The monthly and twice-monthly fixed-station data are not adequate to assess attainment of the 7-day and 1-day mean dissolved oxygen criteria directly because the sampling frequency rests outside the defined time intervals and is unable to capture the short-term variability.

For the 2006 303(d) listing cycle, only three of the dissolved oxygen criteria components were assessed. The 30-day mean open-water criterion was determined in all of the assessment units of Chesapeake Bay using the fixed-station data and the CFD assessment methodology. In spatial assessment units where deep-water and/or deep-channel designated uses exist, the 30-day mean deep-water criterion and the instantaneous minimum deep-channel criterion were also determined using the fixed-station data.

The rationale behind the assessment of the instantaneous minimum deep-channel criterion was based on the long-term fixed station data record in the deep-channel locations which shows that dissolved oxygen does not vary strongly through time in the deep channel during the summer months because of the physical isolation from the atmosphere and the photic zone. Dissolved oxygen concentrations remain relatively constant; therefore, a 30-day mean should be similar to any instantaneous measure (see section below).

No assessments were made of the 7-day and 1-day mean dissolved oxygen criteria because the data were considered inadequate (as described above). In most cases, this situation did not affect listing decisions because many spatial assessment units did not attain the 30-day mean criterion (see Figure IV-1) and all criteria components need to be attained to justify removal from the impaired list (part 5). The 30-day mean criterion was attained in some cases. These spatial assessment units, if not previously listed on part 5, were placed in part 3 of the states' lists for waters with insufficient data (see Chapter 8 for further details). As water quality conditions improve in Chesapeake Bay, a method to assess higher frequency dissolved oxygen criteria will be needed so that spatial assessment units in attainment with all applicable dissolved oxygen criteria components can be removed from the state's impaired waters list (see Appendix E).

Until the EPA publishes methodologies for assessing the 7-day mean, 1-day mean and instantaneous minimum open-water and deep-water dissolved oxygen criteria components, the agency recommends that the states rely strictly on the assessment of the 30-day mean open-water and deep-water dissolved oxygen criteria for listing decisions. For those open-water and deep-water designated-use segments in which the 30-day mean criteria are not in attainment, the jurisdictions should list the designated-use-segment on part 5 as impaired in the absence of data and/or methodologies for assessing the remaining criteria components. For those designated-use segments in which the 30-day mean criteria are in attainment, the jurisdictions should generate additional data and apply the criteria assessment procedures to assess attainment of the 7-day mean, 1-day mean, and instantaneous minimum criteria components.

## DISSOLVED OXYGEN REFERENCE CURVES

### SUMMER OPEN-WATER AND DEEP-WATER DISSOLVED OXYGEN CRITERIA REFERENCE CURVES

Reference curves for both the 30-day mean open-water (June 1–September 30 only) and 30-day mean deep-water dissolved oxygen criteria were based on criteria levels that would not impair biological communities (U.S. EPA 2003a). Reference areas for derivation of the 2003 published deep-water reference curves were identified using a measure of benthic community health—the Chesapeake Bay benthic index of biological integrity or benthic-IBI (Weisberg et al. 1997). Sessile benthic communities are good indicators of the water quality of the overlying waters. Although relatively tolerant of lower oxygen concentrations, a dissolved oxygen concentration of 2 mg·liter$^{-1}$ is the threshold below which benthic infaunal communities become severely stressed (numerous references cited in Chapter 3 of U.S. EPA 2003a). A healthy benthic community, therefore, could indicate allowable time and space exceedances of the dissolved oxygen criteria that will not impair the biological community.

Benthic infaunal community samples are collected as part of the long-term Chesapeake Bay Benthic Monitoring Program at fixed and random locations during the summer, usually in August to September. If the benthic-IBI of that sample is "good," (in this case 3 or more on a scale of 1 to 5), dissolved oxygen conditions were likely adequate for the previous one to two months (Dauer et al. 2005).

In order to ensure greater consistency in deriving the open-water and deep-water reference curves, factor in the state-adopted designated-use boundaries and take advantage of a full two decades on monitoring data, both reference curves were updated. To develop updated open-water and deep-water reference curves, the monthly fixed and random station locations for the benthic-IBI data from 1985 to 2005 were matched with the monthly open-water and deep-water designated-use boundaries for the same time period. This updated approach differs from the original method published by the EPA (2003a), which used a single designated-use boundary coverage for the entire data record. An additional difference is that previously this method was used to define only the deep-water reference curve. The open-water reference curve was based on an analysis in which "good" water quality conditions were defined for reference segments by year (see Appendix H in U.S. EPA 2003a).

Reference locations were identified by sorting the resulting data set by year, segment, and designated use. If a designated use in a given segment in a given year had only "good" benthic-IBI scores (≥3), then the dissolved oxygen data for that segment, designated use, and summer period (June–September) can be used to compute a reference curve. Appendix F lists these use-segment-year combinations. Separate CFDs were generated for open-water and deep-water designated-use habitats from the entire data set of summer dissolved oxygen data from all reference locations over the 1985–2005 data record. Figures IV-2 and IV-3 respectively illustrate the resultant June–September open-water and deep-water dissolved oxygen criteria reference curves. Appendix G documents the equations for the reference curves.

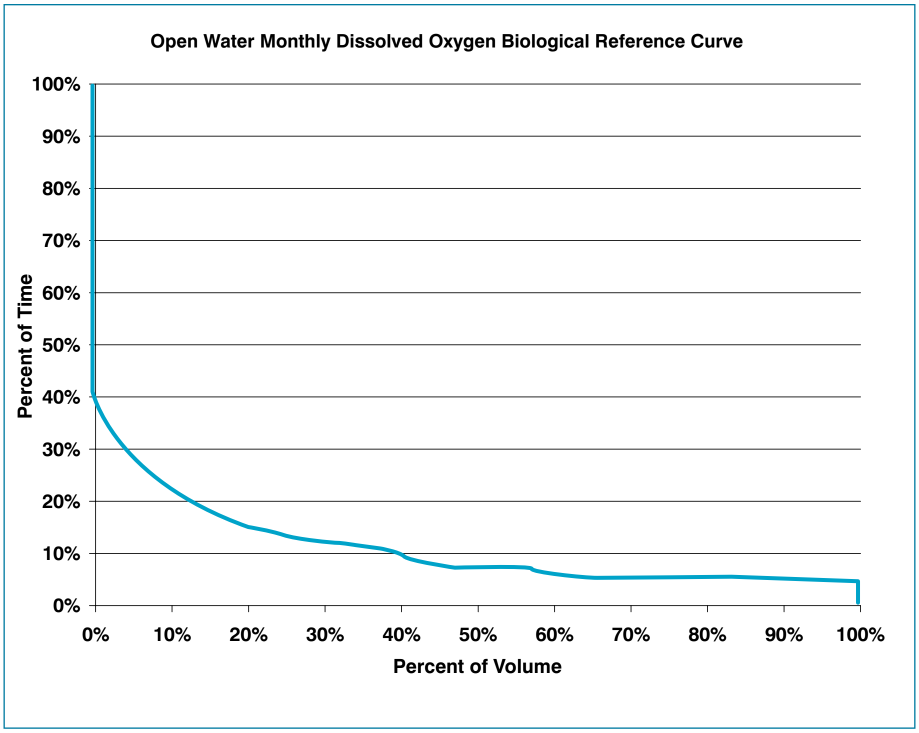


**Figure IV-2.** Chesapeake Bay open-water 30-day mean dissolved oxygen criterion biological reference curve applicable only during the June 1 through September 30 assessment period.

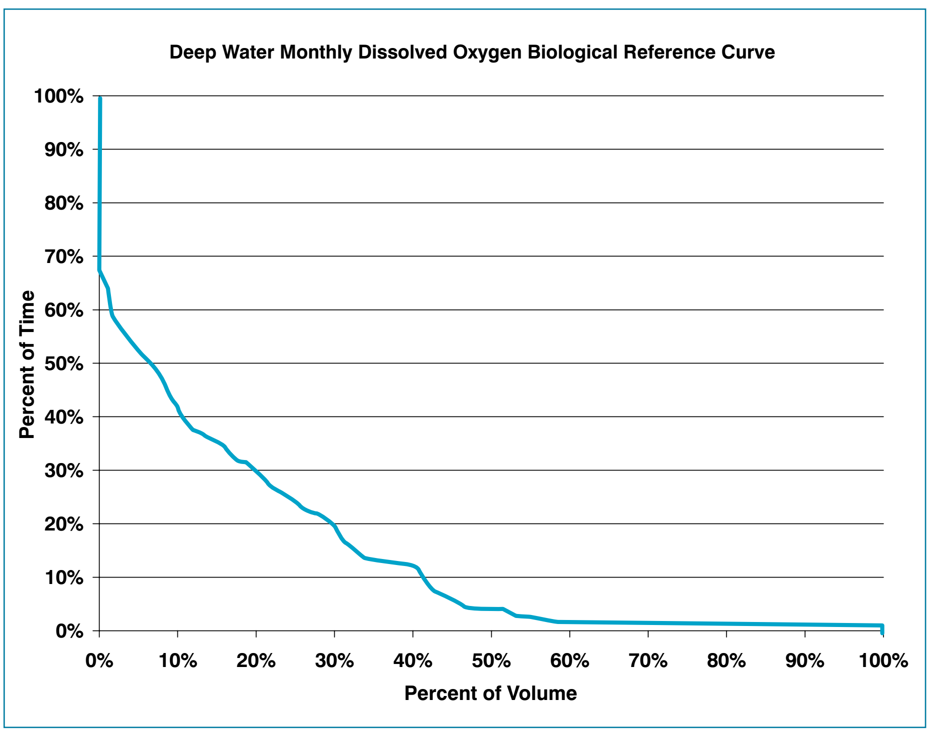


**Figure IV-3.** Chesapeake Bay deep-water 30-day mean dissolved oxygen criterion biological reference curve.

## NON-SUMMER OPEN-WATER DISSOLVED OXYGEN CRITERIA REFERENCE CURVE

The default reference curve, illustrated in Figure II-4 in Chapter 2, should be used in the assessment of the 30-day mean, open-water dissolved oxygen criteria during the non-summer months (January 1 through May 31 and October 1 through December 31). The necessary biological indices and data were not available to support derivation of a biologically based reference curve for open-water habitats during the non-summer months.

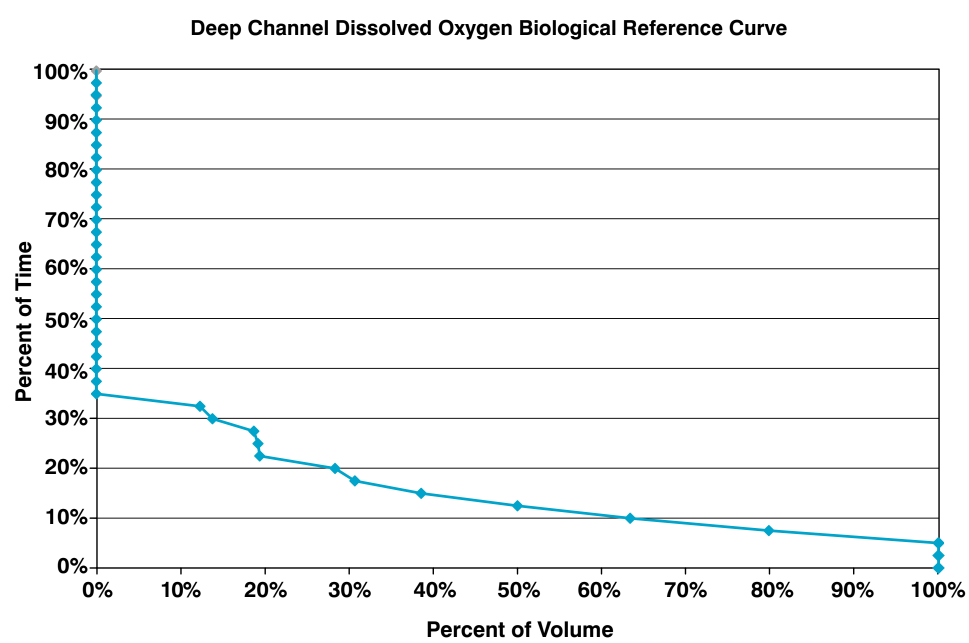


**Figure IV-4.** Chesapeake Bay deep-channel dissolved oxygen criterion biological reference curve.

## ASSESSMENT OF DEEP-CHANNEL INSTANTANEOUS MINIMUM DISSOLVED OXYGEN CRITERIA

The April 2003 Chesapeake Bay water quality criteria document provides conflicting guidance in the use of reference curves for assessing attainment of the four instantaneous minimum dissolved oxygen criteria. Pages 170 to 173 in U.S. EPA 2003a display and discuss reference curves for migratory spawning and nursery, open-water, deep-water, and deep-channel criteria attainment assessment. All four sets of designated-use specific criteria include a use-specific instantaneous minimum criterion. With the exception of the deep-channel criteria (page 173 in U.S. EPA 2003a), none of these sections specifically describe whether a reference curve should be applied in assessing attainment of the respective instantaneous minimum criteria. The reader is left with the sense that the published reference curves should be applied to all the dissolved oxygen criteria, regardless of the stated duration.

All four instantaneous minimum criteria for protection of the four designated uses—migratory spawning and nursery, open-water, deep-water, and deep-channel—protect against mortality from very short-term exposure to low dissolved oxygen concentrations (U.S. EPA 2003a). The other dissolved oxygen criteria with specific averaging periods (30-day, 7-day, and 1-day means) protect against impairments—including growth, respiration, and behavioral/avoidance—for which the impairments will not impact the designated use. The 2003 EPA criteria guidance stated that there were no "biologically acceptable exceedances of the applicable criteria" for the instantaneous minimum criteria, given that the impairment is death (page 151 in U.S. EPA 2003a).

While updating the methodology for deriving the open-water and deep-water designated-use dissolved oxygen criteria reference curves for the 30-day mean criteria (described above), there were times and locations in the Chesapeake Bay for which healthy benthic infaunal communities still existed despite exceedance of the 1 $mg \cdot liter^{-1}$ instantaneous minimum criterion. The EPA recommends, therefore, that attainment assessment of the instantaneous minimum deep-channel dissolved oxygen criteria be conducted with the CFD methodology using the deep-channel biological reference curve (Figure IV-4; Appendices F and G).

## USE OF PERCENT SATURATION AS DISSOLVED OXYGEN CRITERIA

Several Chesapeake Bay scientists have called for future publication of dissolved oxygen criteria based on percent saturation (not concentration) and for state adoption of such percent-saturation-based criteria into the states' water quality standards regulations. They cite fisheries physiology research showing that the pressure gradient between the surrounding water and the blood running through the fishes' gills that truly determines whether sufficient oxygen exists in the water to support aquatic life. For example, Dutil and Chabot (2001) reported:

> *Fishes have developed several mechanisms to secure more oxygen from their environment in critical situations such as low oxygen availability (Hoar and Randall 1984). When the partial pressure of oxygen in the environment drops below some critical limit, however, the pressure gradient between blood and water may not allow the fish to deliver as much oxygen to its tissues as needed to meet metabolic requirements associated with ingestion, digestion, growth and activity. Thus critical thresholds may vary through time in demersal fish species and are best described in terms of partial pressure of oxygen or percent saturation.*

These scientists also note that the amount of dissolved oxygen dissolved declines as temperature and salinity increase. For example, fully saturated freshwater at 20ºC holds 9.28 mg·liter$^{-1}$ of oxygen, but fully saturated seawater at the same temperature only contains 7.58 mg·liter$^{-1}$ of oxygen. Seawater at 1ºC can hold 11.38 mg·liter$^{-1}$ of oxygen; at 30ºC it can hold only 6.37 mg·liter$^{-1}$ oxygen. As for the aquatic organisms, research indicates that percent saturation drives the oxygen diffusion supplying their respiratory demands.

Concentration-based, not percent-saturation-based, criteria were published given the lack of reporting dissolved oxygen concentrations in terms of percent saturation in the extensive effects database used to derive the Chesapeake Bay dissolved oxygen criteria (U.S. EPA 2000). In addition, the lack of salinity and temperature values for each data point in the laboratory-based low dissolved oxygen effects database prevented calculation of the concentration-based effects data into percent saturation numbers.

Following publication of the *Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras*, EPA scientists evaluated the implications of recommending dissolved oxygen criteria as percent saturation versus concentration (U.S. EPA 2000). In an addendum to the 2000 Virginian Province saltwater dissolved oxygen criteria document, the U.S. EPA (2003b) reported:

> *A standard based on percent saturation has a wide range of differences in partial pressure (2.14–4.01 Torr), which decreases with increasing temperature. The opposite is more desirable, however, since respiratory demand increases with temperature. Thus standards based on percent saturation are likely to overprotect during winter and potentially underprotect in summer, when organisms need the most oxygen. A standard based on concentration provides a more uniform difference in partial pressure over the temperatures used (2.45–2.72 Torr). Even though the range of difference is smaller, it still increases with temperature. Thus a standard based on absolute concentration is more likely to create stable physiological conditions for animals throughout the year.*

Scientists from the EPA have generated a version of the EPA Virginian Province saltwater dissolved oxygen criteria as percent saturation for the State of Maine (G. Thursby, personal communication). At this time, however, the EPA does not have the scientific basis to recommend a set of Chesapeake Bay dissolved oxygen criteria in terms of percent saturation.

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chapter V

# Refinements to the Shallow-Water Designated-Use Assessment Procedures

## BACKGROUND

Submerged aquatic vegetation (SAV) is a critically important component of the Chesapeake Bay ecosystem. These underwater plants provide habitat used by many fish and shellfish species and provide food for migratory waterfowl, while also improving water quality by generating oxygen, stabilizing sediment, and taking up nutrients. Historically, the Chesapeake Bay was once known for its extensive SAV beds. During the 1960s, however, much of the SAV disappeared. Poor water clarity, caused by excessive algal growth and high levels of suspended sediment (Dennison et al. 1993), was the primary factor in the decline of these beds. Both of these water quality impairments result from human activities in the Chesapeake watershed that cause excessive nutrient and sediment loadings to the Bay.

In 2003, after consultation with the watershed jurisdictions, the EPA published water clarity criteria, SAV restoration goals, and shallow-water Bay grass designated-use delineations for the Chesapeake Bay as well as its tidal tributaries and embayments (U.S. EPA 2003a, 2003b). When applied as state water quality standards regulations, these standards define the water clarity needed in delineated shallow-water habitats to support SAV restoration to agreed-upon acreages.

The water clarity criteria and SAV restoration goals were designed to define attainment of the shallow-water Bay grass designated use in three ways (U.S. EPA 2003a, 2004a). First, once the targeted acreage of SAV in a given segment is reached, that segment is considered in attainment of the shallow-water Bay grass designated use. Measurement of SAV goal restoration attainment is based on annual aerial surveys in which the beds are photographed and mapped, acreages quantified, and the single best year of acreage determined. Second, if sufficient shallow-water area with the water clarity necessary to achieve restoration of the targeted SAV acres exists, then the segment is considered in attainment. These "water clarity acres" are measured by routinely mapping water clarity using data from the Chesapeake Bay Shallow-water Monitoring Program (see Chapter 7 for details). Third, if the water-clarity criteria were attained throughout the shallow-water designated use reaching to a specific depth contour (segment-specific water clarity criteria application depth) based on the cumulative frequency diagram (CFD) assessment methodology, then the segment is also considered in attainment of this designated use. Like the water clarity acres approach, the CFD-based assessment would be performed using data from the shallow-water monitoring program (see Chapter 7 for details).

For the 2006 Impaired Water 303(d) listing cycle, insufficient data existed to assess water clarity criteria attainment in nearly all of the Chesapeake Bay segments' shallow-water bay grass designated-use habitats. The SAV acreages have been quantified for many years (annually since 1984), however, and this data collection is expected to continue. Thus, the 2006 assessments used SAV acreages over the three-year assessment period from 2001 through 2004. If the single best year of SAV coverage from that period exceeded the established, state-adopted SAV restoration goal, then the segment's shallow-water designated use was deemed in attainment. If the SAV restoration goal was not attained, then the segment's shallow-water designated use was listed either as impaired (category 5) or as insufficient data (category 3) since shallow-water monitoring data were unavailable for the segment.

The procedures for assessing attainment of the Chesapeake Bay shallow-water designated use using the water clarity criteria and SAV restoration acreages, first published by EPA in 2003, were broadly defined and had not been extensively applied in the Chesapeake Bay prior to the 2006 303(d) listing cycle (U.S. EPA 2003a, 2003b). The jurisdictions and the EPA identified and resolved many issues during the first baywide application. This chapter provides detailed and refined guidance on the assessment of the water clarity criteria and the SAV restoration goals. Ultimately, the chapter evaluates attainment of the shallow-water bay grass designated use. This guidance replaces the applicable criteria assessment methodologies previously published by the U.S. EPA (2003a, 2003b, 2004a, 2004c).

## SHALLOW-WATER DESIGNATED-USE ATTAINMENT ASSESSMENT

The shallow-water bay grass designated use is considered in attainment if sufficient acres of SAV are observed within the segment or enough acres of shallow-water habitat meet the applicable water clarity criteria to support restoration of the desired SAV acreage for that segment (U.S. EPA 2003a, 2003b). Assessment of either measure, or a combination of both, serves as the basis for determining attainment or impairment of the shallow-water bay grass designated use.

Given SAV is the ultimate biological measure of attainment of the designated use, in the absence of sufficient shallow-water monitoring data necessary to determine the available water clarity acres or assess water clarity criteria attainment using the CFD-based criteria assessment procedure, the EPA recommends the States assess shallow-water bay grass designated use attainment/impairment based on the acres of aerial mapped SAV.

If a shallow-water bay grass designated use segment meets its SAV restoration acreage, that designated use-segment is considered in attainment of the designated use and should be listed on part 2.

If a shallow-water bay grass designated use segment does not meet its SAV restoration acreage and sufficient shallow–water monitoring data is available, the jurisdiction can then assess attainment of the designated use using water clarity acres or water clarity criteria as described below. If the water clarity acres/water clarity criteria are met/attained based on assessment of spatially intensive shallow-water monitoring data, then that designated use-segment is considered in attainment of the shallow-water bay grasses designated use and should be listed on part 2.

If the water clarity acres/water clarity criteria are not met/attained based on assessment of shallow-water monitoring data, or if there is insufficient data to make a determination using water clarity acres, then that designated use-segment is considered not in attainment of the shallow-water bay grasses designated use and should be listed on part 5.

For those segments that contain the shallow-water bay grass designated use, attainment of this use should be assessed with the following procedure:

> If the segment's **single best year SAV acreage** (described below) drawn from the most recent three-year period of available data is equal to or greater then the state adopted SAV restoration acreage for that segment, then that segment is considered to be in attainment of its shallow-water bay grass designated use. If the segment's single best year SAV acreage is less than the state adopted SAV restoration acreage for that segment, the state should then proceed to assess water clarity acres if sufficient shallow-water data is available, otherwise, the segment is not in attainment.
>
> If the segment's **water clarity acres** (defined below) calculated from the most recent three-year period of available shallow-water monitoring water clarity data is equal to or greater than state adopted water clarity restoration acreage for that segment, then that segment is considered to be in attainment of its shallow-water bay grass designated use. If the segment's water clarity acres are less than the state adopted water clarity restoration acreage for that segment, then that segment is considered not to be in attainment of its shallow-water designated use unless SAV acreage data indicate attainment.

A jurisdiction may also choose to apply the **CFD-based assessment of water clarity criteria**, described in more detail below, in place of water clarity acres, to assess attainment of the segment's shallow-water bay grass designated use.

Given that SAV is the ultimate biological measure of attainment of the designated use, the EPA recommends a specific sequence of criteria assessment: assessment of SAV acres meeting the segment-specific restoration acres first, followed by assessment of water clarity acres or water clarity criteria attainment. In the absence of sufficient shallow-water monitoring data to determine the available water clarity acres or assess water clarity criteria attainment using the CFD-based procedure, the

EPA recommends that the states assess shallow-water bay grass designated-use attainment based on the acres of mapped SAV (see Chapter 8).

## ASSESSMENT BASED ON THE SINGLE BEST YEAR OF SAV

Baywide and segment-specific SAV restoration goals were defined for the Chesapeake Bay by evaluating the historical (1930s–1970s) and more recent (1980s–2000) SAV distributions (U.S. EPA 2003b). Historical aerial photographs, available for selected years in the 1930s, 1950s, and 1960s, were converted to digital maps. Then acreages of SAV for all photographed shallow-water areas in Chesapeake Bay, its tidal tributaries and embayments were quantified. To set restoration goals for the Bay, the single best year of SAV coverage was defined as the restoration goal for each segment. The combined individual restoration acreages yielded a baywide goal of 185,000 acres. (See pages 105–122 in U.S. EPA 2003b for detailed documentation on the entire goal-setting process.)

This baywide restoration goal was established "to reflect the historical abundance, measured as acreage and density from the 1930's to present" as committed to in the *Chesapeake 2000* agreement (Chesapeake Executive Council 2000) and essentially represents the "existing use" as defined by the Clean Water Act. The single-best-year approach was necessary because a common basis was needed to define the area of SAV that should be present. The historical photography was not consistent through time for all areas of the Bay and SAV acreages varied through time. Since at least some coverage was available for most of the Bay, the single best year offered the best option for setting goals (in selected cases with little or incomplete historical data, a composite of multiple years of historical data was used to define the "single best year") (U.S. EPA 2003b).

Because the segment-based SAV restoration goals were established based on the principle of a "single best year," the assessment of attaining that goal within an individual Chesapeake Bay Program segment's shallow-water bay grass designated-use habitat is defined in a similar manner. Attainment of the SAV restoration goal is reached when the single best year of SAV acreage during the applicable preceding three-year assessment period equals or exceeds the established goal (defined as "SAV restoration acres" in the states' water quality standards regulations) for that segment.

In nine segments, SAV restoration goals were not published in 2003 because no SAV was mapped in the available historical photography or through the baywide aerial survey (U.S. EPA 2003b). At the same time, existing information does not support delineation of these entire segments as SAV no-grow zones following the detailed decision rules documented by the U.S. EPA (2003b). The EPA recommends the jurisdictions maintain the shallow-water designated use in the nine segments that didn't have an SAV restoration goal published in 2003 but were previously determined not to be an SAV no-grow zone (Table V-1).

**Table V-1.** Recommended tidal-water designated uses by Chesapeake Bay Program segment and state-adopted sub-segment. Updated version of Table IV-3 originally published on pages 62–63 of the 2003 *Technical Support Document for Identification of Chesapeake Bay Designated Uses and Attainability* (U.S. EPA 2003b). The asterisks (*) indicate that no numerical SAV restoration acreage goal was published in 2003 for the shallow-water designated use of that segment. See Table V-2 for the nine new segment numerical SAV restoration averages. The absence of an "X" in the shallow-water designated-use column indicates that segment has been entirely delineated as an SAV no-grow zone and the shallow-water bay grass designated use should not apply to that segment.

| Chesapeake Bay Program Segment Name | CBP Segment | Juris-diction | Migratory Spawning and Nursery (Feb. 1–May 31) | Open-Water (Year-Round) | Deep-Water (June 1–Sept. 30) | Deep-Channel (June 1–Sept. 30) | Shallow-Water (SAV growing season) |
|---|---|---|---|---|---|---|---|
| Northern Chesapeake Bay | CB1TF1 | MD | x | x | | | x |
| Northern Chesapeake Bay | CB1TF2 | MD | x | x | | | x |
| Upper Chesapeake Bay | CB2OH | MD | x | x | | | x |
| Upper Central Chesapeake Bay | CB3MH | MD | x | x | x | x | x |
| Middle Central Chesapeake Bay | CB4MH | MD | x | x | x | x | x |
| Lower Central Chesapeake Bay | CB5MH | MD | | x | x | x | x |
| Lower Central Chesapeake Bay | CB5MH | VA | | x | x | x | x |
| Western Lower Chesapeake Bay | CB6PH | VA | | x | x | | x |
| Eastern Lower Chesapeake Bay | CB7PH | VA | | x | x | | x |
| Mouth of the Chesapeake Bay | CB8PH | VA | | x | | | x |
| Bush River | BSHOH | MD | x | x | | | x |
| Gunpowder River | GUNOH1 | MD | x | x | | | x |
| Gunpowder River | GUNOH2 | MD | x | x | | | x |
| Middle River | MIDOH | MD | x | x | | | x |
| Back River | BACOH | MD | x | x | | | x* |
| Patapsco River | PATMH | MD | x | x | x | | x |
| Magothy River | MAGMH | MD | x | x | | | x |
| Severn River | SEVMH | MD | x | x | | | x |
| South River | SOUMH | MD | x | x | | | x |
| Rhode River | RHDMH | MD | x | x | | | x |
| West River | WSTMH | MD | x | x | | | x |
| Upper Patuxent River | PAXTF | MD | x | x | | | x |
| Western Branch (Patuxent R.) | WBRTF | MD | x | x | | | x* |
| Middle Patuxent River | PAXOH | MD | x | x | | | x |
| Lower Patuxent River | PAXMH1 | MD | x | x | x | | x |
| Lower Patuxent River | PAXMH2 | MD | x | x | x | | x |
| Lower Patuxent River | PAXMH3 | MD | x | x | x | | x |
| Lower Patuxent River | PAXMH4 | MD | x | x | x | | x |
| Lower Patuxent River | PAXMH5 | MD | x | x | x | | x |
| Lower Patuxent River | PAXMH6 | MD | x | x | x | | x |
| Upper Potomac River | POTTF | DC | x | x | | | x |
| Upper Potomac River | POTTF | MD | x | x | | | x |
| Upper Potomac River | POTTF | VA | x | x | | | x |

*continued*

**Table V-1.** (continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Anacostia River | ANATF | DC | x | x | | | x |
| Anacostia River | ANATF | MD | x | x | | | x |
| Piscataway Creek | PISTF | MD | x | x | | | x |
| Mattawoman Creek | MATTF | MD | x | x | | | x |
| Middle Potomac River | POTOH1 | MD | x | x | | | x |
| Middle Potomac River | POTOH2 | MD | x | x | | | x |
| Middle Potomac River | POTOH3 | MD | x | x | | | x |
| Middle Potomac River | POTOH | VA | x | x | | | x |
| Lower Potomac River | POTMH | MD | x | x | x | x | x |
| Lower Potomac River | POTMH | VA | x | x | x | x | x |
| Upper Rappahannock River | RPPTF | VA | x | x | | | x |
| Middle Rappahannock River | RPPOH | VA | x | x | | | x* |
| Lower Rappahannock River | RPPMH | VA | x | x | x | x | x |
| Corrotoman River | CRRMH | VA | x | x | | | x |
| Piankatank River | PIAMH | VA | | x | | | x |
| Upper Mattaponi River | MPNTF | VA | x | x | | | x |
| Lower Mattaponi River | MPNOH | VA | x | x | | | x* |
| Upper Pamunkey River | PMKTF | VA | x | x | | | x |
| Lower Pamunkey River | PMKOH | VA | x | x | | | x* |
| Middle York River | YRKMH | VA | x | x | | | x |
| Lower York River | YRKPH | VA | | x | x | | x |
| Mobjack Bay | MOBPH | VA | | x | x | | x |
| Upper James River | JMSTF1 | VA | x | x | | | x |
| Upper James River | JMSTF2 | VA | x | x | | | x |
| Appomattox River | APPTF | VA | x | x | | | x |
| Middle James River | JMSOH | VA | x | x | | | x |
| Chickahominy River | CHKOH | VA | x | x | | | x |
| Lower James River | JMSMH | VA | x | x | | | x |
| Mouth of the James River | JMSPH | VA | | x | | | x |
| Western Branch Elizabeth River | WBEMH | VA | | x | | | |
| Southern Branch Elizabeth River | SBEMH | VA | | x | | | |
| Eastern Branch Elizabeth River | EBEMH | VA | | x | | | |
| Lafayette River | LAFMH | VA | | x | | | |
| Mouth of the Elizabeth River | ELIPH | VA | | x | x | x | |
| Lynnhaven River | LYNPH | VA | | x | | | x |
| Northeast River | NORTF | VA | x | x | | | x |
| C&D Canal | C&DOH | DE | x | x | | | x |
| C&D Canal | C&DOH | MD | x | x | | | x |
| Bohemia River | BOHOH | MD | x | x | | | x |
| Elk River | ELKOH1 | MD | x | x | | | x |
| Elk River | ELKOH2 | MD | x | x | | | x |
| Sassafras River | SASOH1 | MD | x | x | | | x |

**Table V-1.** (continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sassafras River | SASOH2 | MD | x | x | | | x |
| Upper Chester River | CHSTF | MD | x | x | | | x* |
| Middle Chester River | CHSOH | MD | x | x | | | x |
| Lower Chester River | CHSMH | MD | x | x | x | x | x |
| Eastern Bay | EASMH | MD | | x | x | x | x |
| Upper Choptank River | CHOTF | MD | x | x | | | |
| Middle Choptank River | CHOOH | MD | x | x | | | x |
| Lower Choptank River | CHOMH2 | MD | x | x | | | x |
| Mouth of the Choptank River | CHOMH1 | MD | x | x | | | x |
| Little Choptank River | LCHMH | MD | | x | | | x |
| Honga River | HNGMH | MD | | x | | | x |
| Fishing Bay | FSBMH | MD | x | x | | | x |
| Upper Nanticoke River | NANTF | MD | x | x | | | |
| Upper Nanticoke River | NANTF | DE | x | x | | | x* |
| Middle Nanticoke River | NANOH | MD | x | x | | | x |
| Lower Nanticoke River | NANMH | MD | x | x | | | x |
| Wicomico River | WICMH | MD | x | x | | | x |
| Manokin River | MANMH1 | MD | x | x | | | x |
| Manokin River | MANMH2 | MD | x | x | | | x |
| Big Annemessex River | BIGMH1 | MD | x | x | | | x |
| Big Annemessex River | BIGMH2 | MD | x | x | | | x |
| Upper Pocomoke River | POCTF | MD | x | x | | | |
| Middle Pocomoke River | POCOH | MD | x | x | | | x* |
| Middle Pocomoke River | POCOH | VA | x | x | | | x* |
| Lower Pocomoke River | POCMH | MD | x | x | | | x |
| Lower Pocomoke River | POCMH | VA | x | x | | | x |
| Tangier Sound | TANMH1 | MD | | x | | | x |
| Tangier Sound | TANMH2 | MD | | x | | | x |
| Tangier Sound | TANMH | VA | | x | | | x |

Source: U.S. EPA 2003b, 2004b, 2004c, 2005

To determine attainment of the shallow-water bay grass designated use, SAV restoration goals for these nine segments were established based on the total surface acre between the shoreline and the 0.5-meter depth contour divided by the 2.5 water clarity acres multiplier (Table V-2). Any SAV no-grow zones within the individual segments were removed before conducting the above calculations.

## ASSESSMENT BASED ON WATER CLARITY ACRES

The EPA has determined that the shallow-water designated use is protected when there is restoration of SAV to the targeted restoration acreages or when a sufficient area of shallow-water habitat contains required levels of water clarity, accounting for

Table V-2. SAV restoration goals for segments that had no published acreage goals in 2003.

| Chesapeake Bay Program Segment | Segment Name | Shallow-Water Habitat Area[1] (Acres) | SAV Restoration Goal[2] (Acres) |
|---|---|---|---|
| ANATF (MD) | Anacostia River-Maryland | -[3] | -[3] |
| BACHOH | Back River | 850 | 340 |
| C&DOH (DE) | C&D Canal-Delaware | 15 | 6 |
| C&DOH (MD) | C&D Canal-Maryland | 83 | 33 |
| CHSTF | Upper Chester River | 574 | 230 |
| MPNOH | Lower Mattaponi River | 323 | 129 |
| NANTF (DE) | Upper Nanticoke River-Delaware | 370 | 148 |
| PAXMH3 | Lower Patuxent River Sub-Segment 3 | -[3] | -[3] |
| PAXMH6 | Lower Patuxent River Sub-Segment 6 | -[3] | -[3] |
| PMKOH | Lower Pamunkey River | 423 | 169 |
| POCOH (MD) | Middle Pocomoke River-Maryland | 56 | 22 |
| POCOH (VA) | Middle Pocomoke River-Virginia | 167 | 67 |
| RPPOH | Middle Rappahannock River | 1,226 | 490 |
| WBRTF | Western Branch Patuxent River | -[3] | -[3] |

[1]Determined as total surface area of the segment from adjacent shoreline out to the 0.5-meter depth contour at mean low water minus any delineated SAV no-grow zone within the segment.
[2]Calculated as the shallow-water habitat area divided by 2.5 (the water clarity acres multiplier) (see U.S. EPA 2003a).
[3]No (or very limited) bathymetry data were available, therefore, no shallow-water habitat area or SAV restoration goal acreage could be calculated.

vegetated bottom habitat. Based on the decades long record of published documentation on SAV light requirements (Batiuk et al. 1992, 2000; Dennison et al 1993; Kemp et al. 2001; U.S. EPA 2003a, 2004a), the EPA recommends that an attainment determination based on water clarity acres be based on 2.5 times each acre needed to meet the restoration goal acreage.

A water clarity acre is defined as an acre of shallow-water bay grass designated-use bottom habitat, located anywhere between the 2-meter depth contour and the adjacent shoreline inclusively, which has been observed to achieve the applicable salinity-regime-specific water clarity criteria. A water clarity acre cannot be defined within a delineated SAV no-grow zone (see pages 41–55 in U.S. EPA 2004c for narrative descriptions and maps of those zones). For segments in which the resultant water clarity acreage exceeds the total acres of shallow-water habitat from the shoreline out to the 2-meter depth contour, the water clarity restoration acreage will be set at the total acreage out to the 2-meter depth contour.

Assessment of attaining a segment's water clarity restoration acreage should be based on calculation of the arithmetic mean of the year-by-year arithmetic means of a month-by-month accounting of water clarity acres over the three-year SAV growing season assessment period. Calculation of water clarity acres should be based on spatially intensive shallow-water monitoring turbidity data converted to Kd (light attenuation coefficient), interpolated as described in Chapter 2 and then compared to the corresponding Kd threshold assigned to each interpolator grid cell. The total acreage of an interpolator grid cell is added to the running total water clarity acres for a segment when the interpolated Kd for that cell is less than or equal to the Kd threshold assigned to that cell.

The Kd value based on achieving the applicable water clarity criteria at the 2-meter depth will apply to all interpolator grid cells with centroids within the 2-meter to 1-meter depth contours. All interpolator grid cells with centroids that lie within the area bounded by the shoreline and the 1-meter contour will be assigned the Kd value for the 1-meter depth.

If the segment's single best year of water clarity acres, as calculated above, is equal to or greater than the segment's water clarity restoration acreage, then that segment has attained the shallow-water bay grass designated use. If the segment's single best year of water clarity acres is less than the segment's water clarity restoration acreage, then the segment is in non-attainment of this designated use.

The EPA recommends the states adopt one of two approaches to calculating water clarity acres. Both methodologies directly account for progress towards meeting the SAV restoration goal acreage and measurement of suitable shallow water habitat acreage necessary to support restoration of the remaining SAV beds needed to reach the goal acreage.

The first methodology was originally published in the 2004 Chesapeake Bay water quality criteria addendum (U.S. EPA 2004a). This methodology assesses attainment of the shallow-water bay grass designated use in a segment through a combination of mapped SAV acreage <u>and</u> meeting the applicable water clarity criteria in an additional, unvegetated shallow water surface area equal to 2.5 times the remaining SAV acreage necessary to meet the segment's restoration goal (SAV restoration goal acreage minus the mapped SAV acreage). In other words, a segment's shallow-water bay grass designated use would be considered in attainment if there is sufficient acres of shallow-water habitat meeting the applicable water clarity criteria to support restoration of the remaining acres of SAV, beyond the SAV beds already mapped, necessary to reach that segment's SAV restoration goal acreage. These measurements of SAV acreages and water clarity levels would be drawn from three years of data as previously described in the *Regional Criteria Guidance* (U.S. EPA 2003a).

Here's a hypothetical example of this first methodology for determining attainment of the shallow-water bay grass designated use using both mapped SAV acreage and shallow-water habitat acreage meeting the water clarity criteria. Segment X has an SAV restoration goal acreage of 1,400 acres. Over the past three years, SAV beds totaling 1,100 acres have been mapped within the segment. Therefore, the remaining SAV acreage necessary to meet the segment's restoration goal is 1,400 acres (segment SAV restoration goal) minus 1,100 acres (SAV acres currently mapped) or 300 acres. Beyond the currently vegetated shallow-water habitat, an additional

750 acres of shallow-water habitat (2.5 multiplier times 300 acres) is needed to attain the water clarity criteria to determine this segment is attaining its shallow-water bay grass designated use.

The second methodology directly accounts for mapped acres of SAV within the calculation of water clarity acres. As part of the month-by-month accounting of water clarity acres, over the three-year SAV growing season assessment period, interpolator cells containing any mapped SAV beds are counted towards the total water clarity acres.

Here's a hypothetical example of this second methodology for determining attainment of the shallow-water bay grass use using both mapped SAV acreage and shallow-water habitat acreage meeting the water clarity criteria. Segment Y has an SAV restoration goal acreage of 1,400 acres. Applying the 2.5 multiplier, this segment also has a water clarity restoration acreage of 3,500 acres. Over the past three years, SAV beds totaling 1,100 acres have been mapped within the segment each year. During each growing season's accounting of water clarity acres, these 1,100 acres of mapped SAV beds are directly counted towards the growing season arithmetic mean water clarity acreage. Therefore, accounting directly for 1,100 acres of mapped SAV beds as water clarity acres, an additional 2,400 acres (3,500 water clarity restoration acres minus 1,100 acres of mapped SAV) of shallow-water habitat is needed to attain the water clarity criteria to determine this segment is attaining its shallow-water bay grass designated use.

### ASSESSMENT BASED ON CFD-BASED WATER CLARITY CRITERIA ATTAINMENT

A jurisdiction may choose to apply the CFD-based assessment of water clarity criteria to evaluate attainment of the segment's shallow-water bay grass designated use (U.S. EPA 2003a, 2004a). To attain the designated use, the segment must meet the applicable water clarity criteria throughout the applicable shallow-water habitat (from the shoreline out to the segment-specific water clarity criteria application depth contour) (see Table IV-13 on pages 115–117 in U.S. EPA 2003b) over three SAV growing seasons, factoring in allowable exceedances using the appropriate salinity-regime-based biological reference curve (see Figures V-1, V-2). Chapter 2 and Appendix B document the application of the CFD-based criteria attainment assessment in detail. Chapter 7 deals with the specific elements of the shallow-water criteria attainment assessment procedures using a CFD-based evaluation.

## SHALLOW-WATER DESIGNATED USES AND SAV NO-GROW ZONES

Shoreline habitats of 2 meters or less (where SAV is never expected to grow due to extreme wave energy, permanent physical alterations, natural discoloration of the water, and no functional shallow-water habitat from river channeling) were designated as SAV no-grow zones (see pages 108–110 in U.S. EPA 2003b). In the 39 segments with SAV no-grow zones, 31 of the segments have such zones extending over a portion of the segment (see Table V-1 on page 42 in U.S. EPA 2004c). In these segments, an area delineated as an SAV no-grow zone should simply be left out of any assessment of shallow-water designated-use attainment based on water-clarity acres or on a CFD-based assessment of water clarity criteria attainment.

In the case of the eight segments where the entire shallow-water area was delineated as an SAV no-grow zone (see pages 108–110 in U.S. EPA 2003b), the best available information indicates the shallow-water bay grass designated use is not appropriate. The EPA recommends that this designated use not apply to (or that it be removed from) any segment in which the area encompassing the entire 2 meters or less shallow-water habitat be delineated as an SAV no-grow zone (Table V-1).

Table V-1 is an updated version of Table IV-3 originally published on pages 62–63 in the 2003 *Technical Support Document for Identification of Chesapeake Bay Designated Uses and Attainability* (U.S. EPA 2003b). This revised table documents the above-described segments that are entirely SAV no-grow zones (where the shallow-water bay grass designated use does not apply) or had no previously established SAV restoration goal. This table includes a list of all the Chesapeake Bay Program segments in the Chesapeake Bay, its tidal tributaries, and its embayments (U.S. EPA 2004b, 2005) as well as the sub-segments delineated by Maryland and Virginia (U.S. EPA 2004c).

## WATER CLARITY CRITERIA REFERENCE CURVES

The original 2003 Chesapeake Bay water quality criteria document included biological reference curves to assess attainment of the water clarity criteria using the CFD methodology (see pages 173–176 and Appendix H in U.S. EPA 2003a). Those reference curves were developed using data collected as part of the Chesapeake Bay Water Quality Monitoring Program in which the monitoring stations are located in open, mid-channel areas of Chesapeake Bay, its tidal tributaries, and its embayments. Use of the fixed-station, mid-channel water quality data was necessary even though these data are not necessarily representative of the Bay's shallow-water habitats; sufficient data more representative of the shallow-water habitats were not available (see Chapter 9 in Batiuk et al. 2000).

Efforts are underway through the Chesapeake Bay Shallow-water Monitoring Program to collect water clarity data for use in generating more appropriate biological reference curves. These data are being collected (see Chapter 7 for additional detail) in the same way that shallow-water designated use areas will be assessed. The resulting biological reference curves will, therefore, be directly comparable to the CFD assessment curves (see Chapter 2 for further details). Further refinement of the existing published water clarity criteria biological reference curves (e.g., updating with more recent mid-channel data, developing four salinity-regime-based curves) is not warranted at this time given ongoing collection of more appropriate shallow-water data. In the interim, the EPA recommends that states assess their water clarity criteria using the CFD methodology which uses existing published biological reference curves to define the amount and pattern of allowable criteria exceedances.

Figure V-1 illustrates the biological reference curve that states should apply in the CFD-based water clarity criteria assessment of tidal fresh and oligohaline segments with shallow-water bay grass designated uses. Figure V-2 illustrates the biological reference curve that should be applied in the assessment of mesohaline and polyhaline segments with shallow-water bay grass designated uses. Appendix H in this document provides the equations for the Chesapeake Bay water clarity criteria biological reference curves. Preliminary results from evaluation of limited shallow-water monitoring data indicate that biological reference curves generated from mid-channel data (Figures V-1 and V-2) and those generated from shallow-water monitoring data (see Figure VII-11 in Chapter 7) are quite similar in overall shape and levels of allowable exceedances.

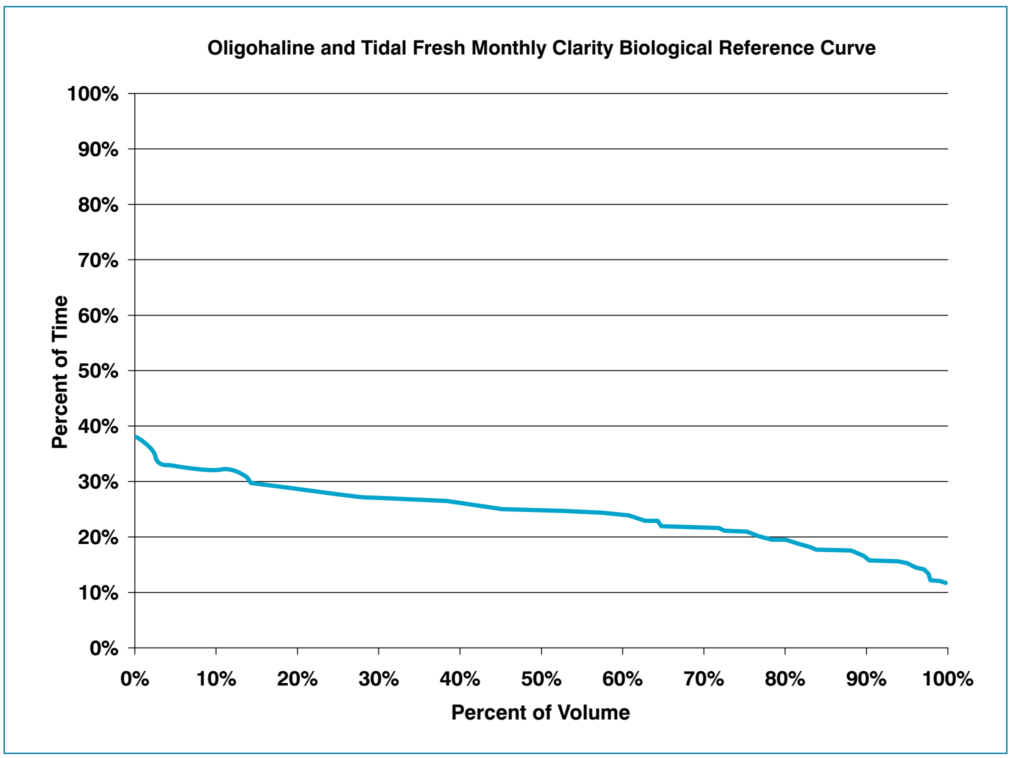


**Figure V-1.** Chesapeake Bay water clarity criterion biological reference curve for application to tidal fresh and oligohaline shallow-water designated-use habitats.

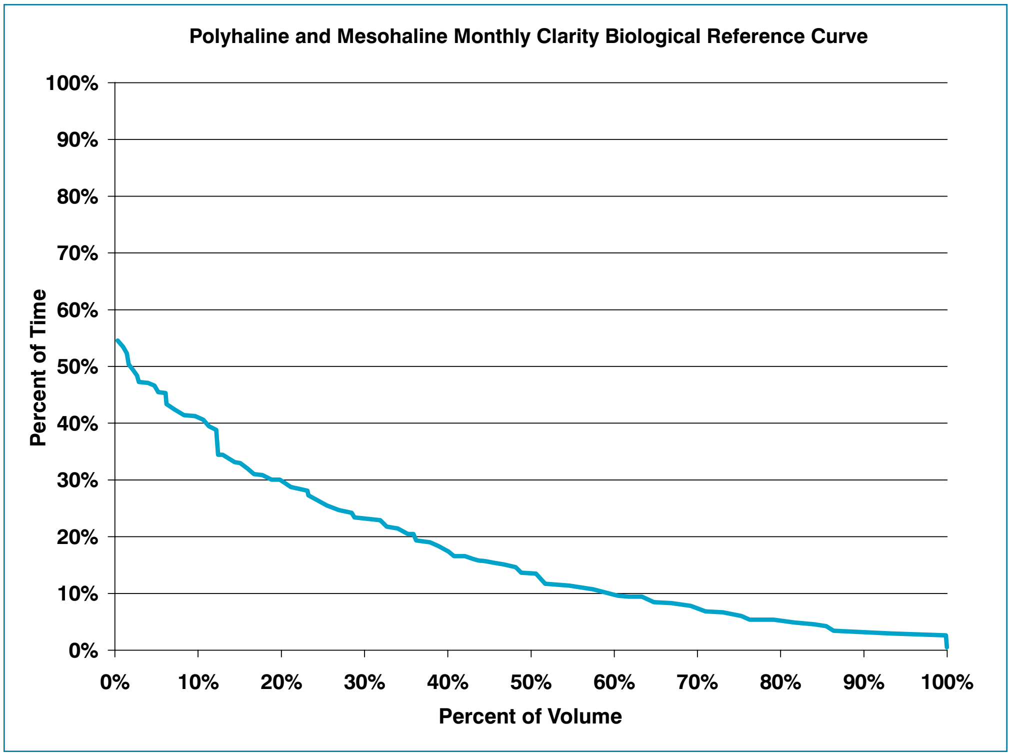


**Figure V-2.** Chesapeake Bay water clarity criterion biological reference curve for application to mesohaline and polyhaline shallow-water designated-use habitats.

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# chapter VI
# Chlorophyll *a* Criteria Assessment Procedures

## STATE WATER QUALITY STANDARDS

With publication of the April 2003 *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries*, the EPA provided the states with a recommended narrative (non-numerical) chlorophyll *a* criterion applicable to all of the Chesapeake Bay and its tidal tributary waters (Table VI-1) (U.S. EPA 2003). From 2004 through early 2006, Virginia and the District of Columbia adopted numerical chlorophyll *a* criteria for application in the tidal James River (Virginia) and across all the District's jurisdictional tidal waters. Both jurisdictions determined that algae-related designated use impairments would likely persist in these tidal waters even after attainment of applicable dissolved oxygen and water clarity criteria. The technical information supporting adoption of numerical chlorophyll *a* criteria by Virginia and the District was published in the 2003 Chesapeake Bay water quality criteria document (U.S. EPA 2003). Maryland and Delaware adopted narrative chlorophyll *a* criteria into their water quality standards regulations (Table VI-1).

**Table VI-1.** 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. |

Source: U.S. EPA 2003.

# CHLOROPHYLL *A* CRITERIA ASSESSMENT PROCEDURES

## CHLOROPHYLL *A* CRITERIA REFERENCE CURVE

To assess attainment of the State adopted numerical chlorophyll *a* concentration-based criteria, it was necessary to establish a reference curve for use in the CFD criteria attainment assessment process (U.S. EPA 2003). In the case of chlorophyll *a* criteria where a biologically-based reference curve is not available, EPA recommends the states use of the default reference curve described in Chapter 2 (see Figure II-4 and Equation 1).

## CHLOROPHYLL *A* CRITERIA ASSESSMENT

A criterion threshold is a concentration that should rarely be exceeded by a "population" of concentration data exhibiting healthy levels. The state-adopted concentration-based chlorophyll *a* criteria values are threshold concentrations that should only be exceeded infrequently since a low number of naturally occurring exceedances occur even in a healthy phytoplankton population. The assessment of chlorophyll *a* criteria attainment, therefore, should use the CFD-based assessment method described in Chapter 2 that applies the default reference curve. These Chesapeake Bay chlorophyll *a* criteria apply only to those seasons and salinity-based habitats for which they were defined to protect against applicable human health and aquatic life impairments. Each season—spring (March 1-May 31) and summer (July 1–September 30)—should be assessed separately to evaluate chlorophyll *a* criteria attainment.

Assessments of seasonal mean chlorophyll *a* criteria should be based on seasonal averages of interpolated data sets. To calculate the seasonal averages, each interpolated cruise within a season should be averaged on a point-by-point basis in matching interpolator grid cells. Spatial violation rates should be calculated for each seasonally aggregated interpolation in an assessment period. For example, for a summer open-water seasonal chlorophyll *a* criteria assessment of a three-year assessment period, three seasonal average interpolations representing each season (Year 1 Summer, Year 2 summer, Year 3 summer) should be used.

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chapter vii

# Shallow-water Monitoring and Application for Criteria Assessment

## DESIGN AND APPROACH FOR CHESAPEAKE BAY SHALLOW-WATER MONITORING

In July 2001, the Chesapeake Bay Program Monitoring and Analysis Subcommittee's Tidal Monitoring and Analysis Workgroup formed a Tidal Monitoring Design Team that undertook the redesigning of the Chesapeake Bay Tidal Monitoring Network. Over the next two years, the Design Team set goals and objectives, reviewed the existing Chesapeake Bay monitoring design, evaluated potential new monitoring strategies, and made recommendations for implementing a network to provide the requisite data and support to address the Chesapeake Bay Program's programmatic goals and objectives.

The new Tidal Monitoring Network focused on meeting the water quality protection and restoration goals and objectives of the *Chesapeake 2000* agreement (Chesapeake Executive Council 2000). The network's primary objective is to supply the water quality monitoring information needed to assess the new water quality criteria for dissolved oxygen, water clarity, and chlorophyll *a* — ultimately with the goal of removing the Chesapeake Bay and its tidal rivers from the list of impaired waters. Secondary network objectives are to provide information for defining the nutrient and sediment conditions necessary for protecting living resources and vital habitats. Water quality data would also support refinement, calibration, and validation of the Chesapeake Bay Water Quality/Sediment Transport Model.

The design of the new Tidal Monitoring Network emphasized monitoring of the shallow-water designated use areas. In a 1999 study, the Maryland Department of Natural Resources investigated the validity of using mid-channel data to assess nearshore areas. The 13-tributary study examined water quality at 127 nearshore stations and compared the data to 54 adjacent mid-channel stations (Karrh 1999; Batiuk et al. 2000). The study found wide variations between nearshore and mid-channel data, both within and between tributaries. Based on this finding, the researchers concluded that decisions to use mid-channel data to characterize nearshore conditions should be made on a site-by-site basis. Figure VII-1 illustrates this variability, showing situations in which a single, mid-channel data point would not adequately represent suspended solids and chlorophyll *a* in shallow areas. The Design Team concluded that monitoring of shallow, nearshore waters must have greater spatial coverage to obtain an accurate representation of these parameters.

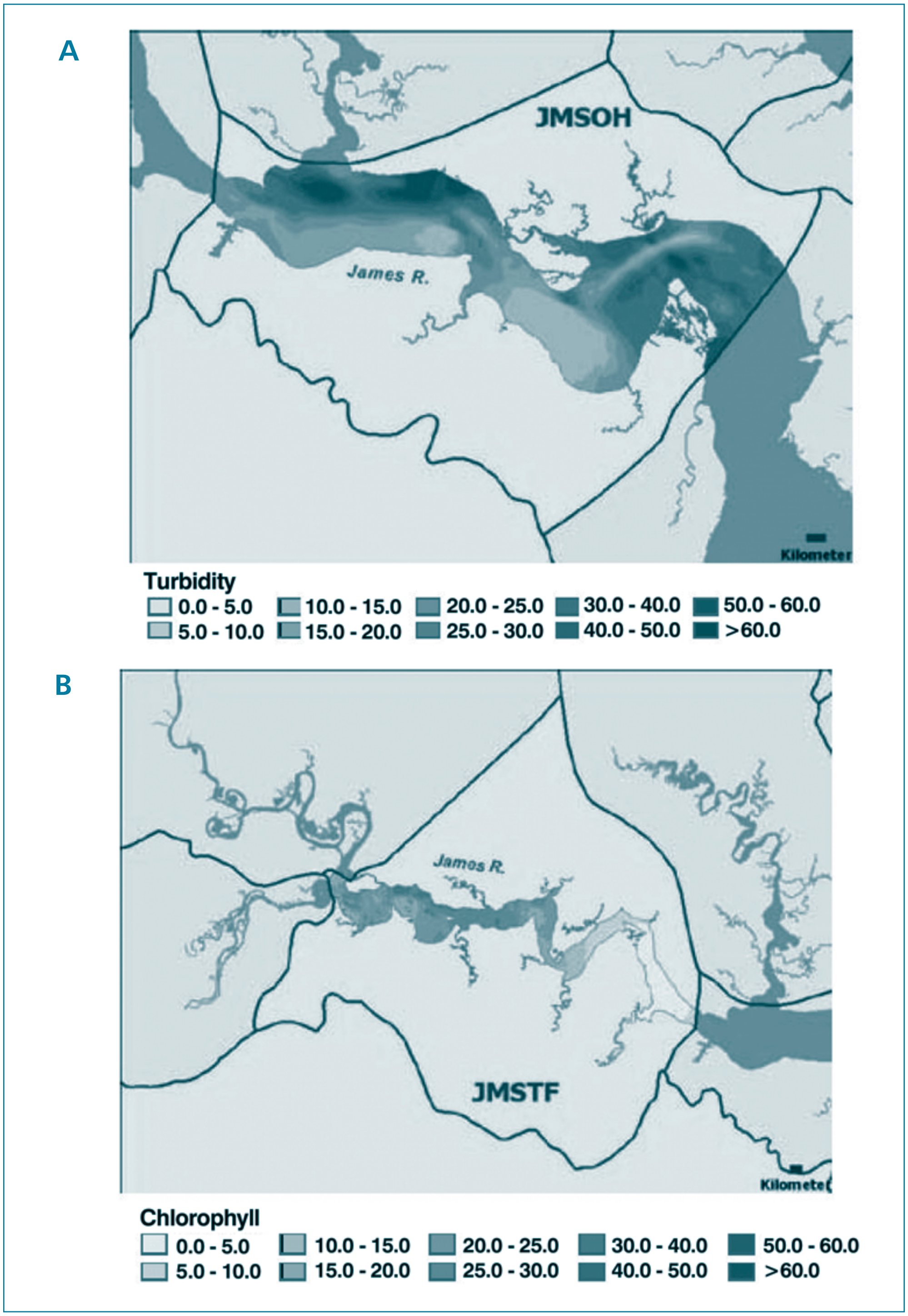


**Figure VII-1.** Spatial distribution of turbidity (A) and chlorophyll *a* (B) in the tidal James River.
Source: Virginia Institute of Marine Science—www2.vims.edu/vecos/

To capture the temporal variability of dissolved oxygen, the new Tidal Monitoring Network incorporated high-frequency monitoring stations in surface and nearshore locations. Since then, the dissolved oxygen criteria assessment procedure has been modified to project the results of open-water dissolved oxygen assessments onto adjacent shallow-water, designated-use areas, instead of conducting a separate shallow-water assessment (see Chapter 4 for details). The design for collecting high-frequency dissolved oxygen data will likely be modified to represent dissolved oxygen concentrations in open-water, designated-use habitats more accurately.

## SHALLOW-WATER MONITORING DESIGN

The intensive shallow-water monitoring program design is based on two innovative technologies that were extensively tested in Maryland's Magothy and Severn rivers as well as Tangier Sound from 1999 to 2002. The Dataflow water quality mapping component collects high-resolution surface data from both open tidal-tributary and shallow waters. The shallow-water buoy system collects high-frequency (near-continuous) temporal data at specific locations, resulting in a data set that better represents dissolved oxygen, chlorophyll *a*, and water clarity in time and space in smaller tidal tributaries, small embayments, and shallow-water habitats. In 2003, the Maryland Department of Natural Resources, the University of Maryland's Chesapeake Biological Laboratory, the Virginia Department of Environmental Quality, and the Virginia Institute of Marine Sciences initiated the new Chesapeake Bay Shallow-water Monitoring Program. The two states and their partners closely coordinate development of the monitoring schedules, equipment, methodologies, and quality assurance procedures to ensure baywide compatibility and comparability.

The Shallow-water Monitoring Program is based on two components that collect spatially and temporally intensive data. Known as "Dataflow," the spatially intensive component includes a sensor array and a GPS system that provide data continuously along a boat track in both shallow- and open-water designated-use areas. These data can be used to develop detailed maps of water quality conditions. The temporally intensive component is known as "continuous monitoring" and includes a sensor array at fixed locations that provides data continuously through time. These data reflect episodic changes in water quality or signify extremes in water quality conditions.

The existing shallow-water monitoring design is based upon a three-year assessment period. Data are collected from all segments within a tidal tributary or embayment during the same three years. Both Dataflow sampling and continuous buoys are deployed for the same time period. The three-year assessment provides adequate time to account for variation in both weather and hydrologic conditions (see page 151 in U.S.EPA 2003a). Assessments using fewer than three years of shallow-water monitoring data are discussed in the section *Schedule for Assessment of Shallow-water Designated Use Habitats* below.

To adequately assess water quality criteria in shallow-water habitats and tidal tributary open-water designated-use habitats, the EPA recommends that the states conduct Dataflow monitoring from April through October in tidal fresh, oligohaline, and mesohaline segments and from March through November in polyhaline segments. These assessment periods for the water clarity criteria were based on the growing seasons for the salinity-based SAV plant communities (U.S. EPA 2003a).

## CONTINUOUS MONITORING COMPONENT

Continuous monitoring data are collected to assess the variability of water quality parameters throughout the day. Temporally intensive data help explain the relationships and timing among algal blooms, low dissolved oxygen, and nutrient additions. Although previous convention suggested that shallow-water habitats did not experience significant low dissolved oxygen levels, continuous monitoring data are proving otherwise. The lowest dissolved oxygen levels often occur between 4:00 and 6:00 a.m. when, historically, little information has been collected.

The continuous monitoring program component employs automated YSI 6600 EDS water quality data sondes. Maryland and Virginia have agreed to use similar instruments, when possible, to ensure consistent methodology and comparability across Chesapeake Bay segments. The YSI 6600 sonde directly measures dissolved oxygen, fluorescence (an indication of chlorophyll *a*), turbidity (an indication of water clarity), temperature, salinity, and pH. The Maryland Department of Natural Resources Chesapeake Bay Shallow-water Monitoring Program Quality Assurance Project Plan (see page 32 in Maryland Department of Natural Resources 2006) documents the YSI instrument parameters, range, resolution, units, and accuracy. Fluorescence is correlated to chlorophyll *a*, the measurement used for assessing attainment of the chlorophyll *a* criteria. Turbidity is correlated to $K_d$ (light attenuation coefficient), the measurement used to assess attainment of the water clarity criteria.

The initial design recommended two shallow-water buoy deployments in each segment, but often, resources limit the number of buoys to one per site. The buoys are programmed to take measurements every 15 minutes for the six parameters listed above. They are deployed off piers or pylons, either 1-meter below the surface or at a fixed depth of 0.3 meters above the bottom, generally in waters of 2-meters or less in depth (Figure VII-2).

Instruments are exchanged every one to two weeks, depending on biofouling and following strict calibration protocols (Virginia Institute of Marine Science 2005). Field crews collect samples to calibrate fluorescence and turbidity instrument readings, respectively, with chlorophyll *a* and light attenuation. The monitors are positioned at representative sites both up- and down-river.

Both Maryland and Virginia have rigorous shallow-water monitoring quality assurance/quality control (QA/QC) programs. The QA/QC protocols remain consistent between states; the Chesapeake Bay Program Quality Assurance Officer and the Chesapeake Bay Program's Analytical Methods and Quality Assurance Workgroup have reviewed these protocols.

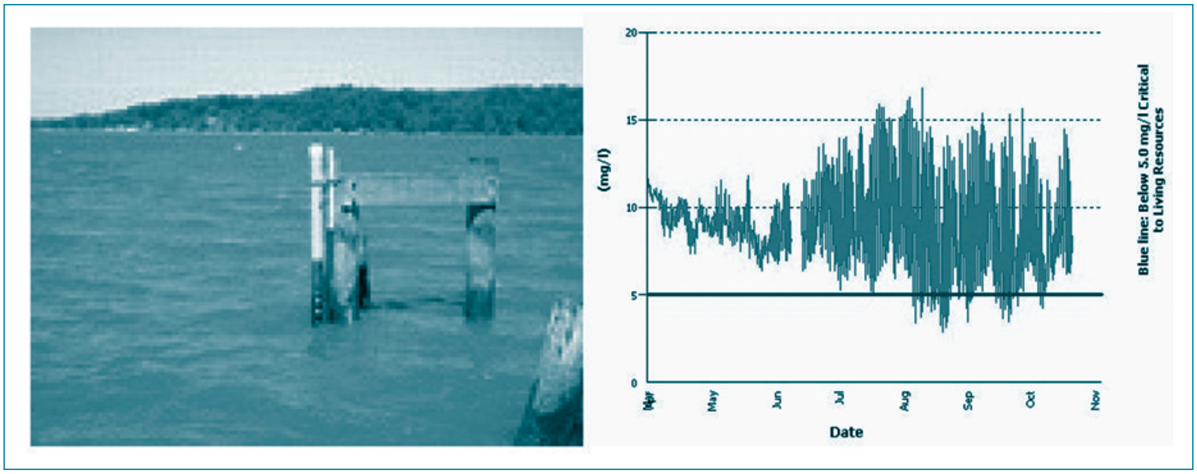


**Figure VII-2.** Example of a continuous monitoring site and the generated 2004 dissolved oxygen data record at Fenwick Point in the Potomac River, Maryland.

Source: Maryland Department of Natural Resources — www.eyesonthebay.net

Overlap periods occur at each continuous monitoring site by using multiple sondes during routine biweekly maintenance runs to determine instrument drift. Instruments are pre- and post-calibrated and must meet rigorous QA/QC protocols. Two instruments are dedicated to each site. When one instrument is removed from the site for maintenance, it is measured against the newly calibrated instrument. At the same time, a field crew member takes a full suite of calibration samples for laboratory analysis.

Satellite and cellular telemetry are implemented at a subset of continuous monitoring sites where resources permit. Data from these sites are assessed on a daily basis. Maryland shallow-water continuous monitoring data are available in near- or real-time on the Department of Natural Resources “Eyes on the Bay” website (www.eyesonthebay.net) (Figure VII-3). Virginia shallow-water continuous monitoring data are available on the Virginia Institute of Marine Sciences website (www2.vims.edu/vecos/). The Chesapeake Bay Program website’s data hub (www.chesapeakebay.net/data) offers access to the complete quality assured Shallow-water Monitoring Program datasets for Maryland and Virginia.

## WATER QUALITY MAPPING COMPONENT

The main purpose for collecting high-resolution water quality data is to provide reliable water quality criteria assessments. However, Dataflow monitoring also provides insight into spatial complexities and localized phenomena and information for water quality modeling in shallow waters (STAC 2005). The data are useful in producing maps of the extent and patchiness of algal blooms, seasonal and inter-annual progressions, and localized water quality impairments.

The Dataflow system is a small, fast-moving vessel that pumps surface water continuously from 0.5 meters below the water surface through a chamber surrounding the

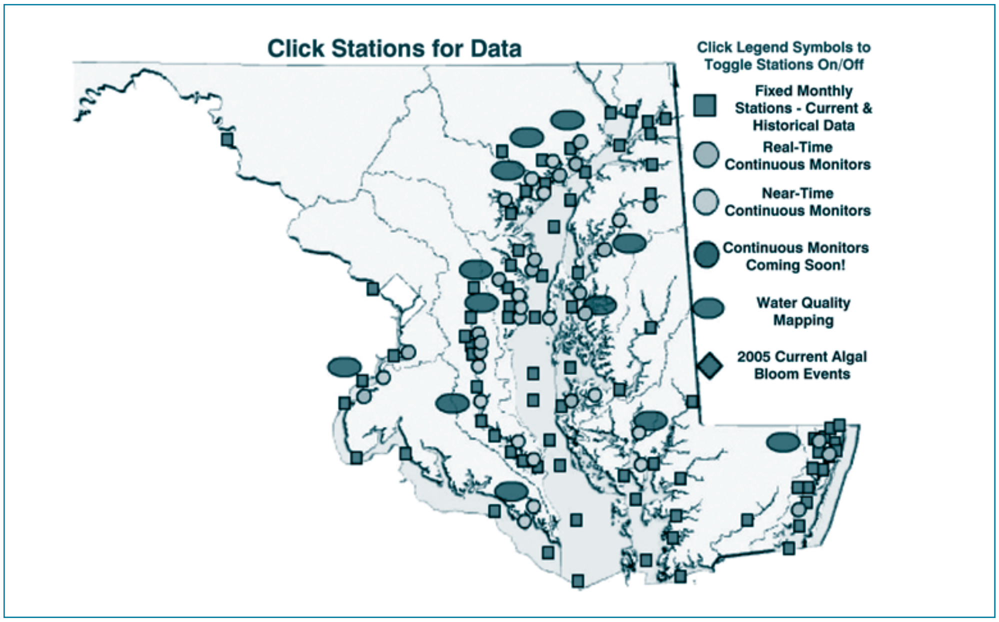


**Figure VII-3.** The 2005 fixed dataflow and continuous monitoring station map from the Maryland Department of Natural Resources' "Eyes on the Bay" website.
Source: Maryland Department of Natural Resources — www.eyesonthebay.net.

probes of a YSI 6600 sonde (http://mddnr.chesapeakebay.net/sim/dataflow_instrumentation.cfm). The system uses the same YSI 6600 sonde as the continuous monitoring buoys and measures the same suite of six parameters—dissolved oxygen, fluorescence, turbidity, temperature, salinity, and pH. A Global Positioning System (GPS) unit is integrated into the computer system to measure the spatial position of each recorded measurement. Data are collected every four seconds as the boat follows a cruise track that traverses between shallow and open waters. These data are then interpolated to provide a high-resolution map of surface water quality conditions (see Chapter 2 for further details). Each segment is mapped monthly from April through October or March through November. The vessel stops at different locations throughout a segment for discrete measurements of photosynthetically active radiation (PAR), Secchi depth, and dissolved oxygen along with collection of water samples for laboratory analysis of chlorophyll *a* (for use as calibration data). These "calibration" sites often overlap with existing open-water fixed-station sites and continuous monitoring sites; they represent the dynamic range of water quality in that segment.

## SCHEDULE FOR ASSESSMENT OF SHALLOW-WATER DESIGNATED-USE HABITATS

The current level of shallow-water monitoring is insufficient to conduct detailed water quality criteria assessments in all Chesapeake Bay shallow-water habitats by the *Chesapeake 2000* agreement deadline of 2010 (Chesapeake Executive Council 2000). Three possible actions might remedy this problem. The first is extending the deadline beyond 2010 for assessment of all Bay shallow-water habitats. The second is identifying additional resources to expand the monitoring needed to meet the 2010 deadline. The third option is assessing segments for fewer than three years if noncompliance of the segment is established. All three options are addressed below. Accurately assessing how many segments can be assessed by each action remains impossible however, since determining the availability of additional resources or establishing how many segments might need fewer than three years of monitoring if noncompliance is established cannot be predicted.

## EXTENDING THE TIMEFRAME

The Chesapeake Bay Program partners have not approved extending the shallow-water clarity criteria assessment timeframe beyond 2010. The current deadline will not be met due to a lack of adequate resources to implement the shallow-water monitoring program design agreed upon by the Chesapeake Bay Program and the participating states and thoroughly reviewed by the Chesapeake Bay Program Scientific Technical Advisory Committee (STAC 2005). Significant progress has been made to accelerate the assessment schedule. Although intensive shallow-water monitoring water clarity monitoring data will not be available in all segments, attainment of the shallow-water bay grass designated use for those segments that contain an SAV restoration acreage would be assessed by comparing each segment's single-best SAV acreage from the most recent three-year period with the jurisdiction's adopted segment-specific SAV restoration acreage (see Chapters 5 and 8 for further details). In this way, each shallow-water designated-use segment could have some assessment completed each year.

## ADDITIONAL RESOURCES

Maryland, Virginia, and the EPA are actively seeking additional resources to expand shallow-water monitoring in order to accelerate the schedule for completing baywide assessments. In 2003, when Maryland and Virginia implemented shallow-water monitoring in 11 Maryland segments and seven Virginia segments, it was estimated that it would take until 2018 to assess all 78 Chesapeake Bay Program segments over a three-year period on a rotating basis. Since the Shallow-water Monitoring Program's initial implementation, both Maryland and Virginia have developed partnerships with county governments (e.g., Anne Arundel and Harford counties in Maryland), municipal agencies (e.g., Hampton Roads Sanitation District in Virginia), and federal agencies (e.g., NOAA's National Estuarine Research System) and secured additional state funding to accelerate monitoring of all segments. Based on these new partnerships, current expanded resources, and segment assessment over a three-year period, it is estimated that Maryland will complete all its shallow-water assessments by the year 2014 and Virginia will complete all its shallow-water assessments by 2015. Figures VII-4 and VII-5 depict the current tentative schedule for shallow-water monitoring and assessment of Maryland and Virginia segments, respectively. New sources of funding continue to materialize and the schedules indicated by Figures VII-4 and VII-5 will change in response to funding adjustments.

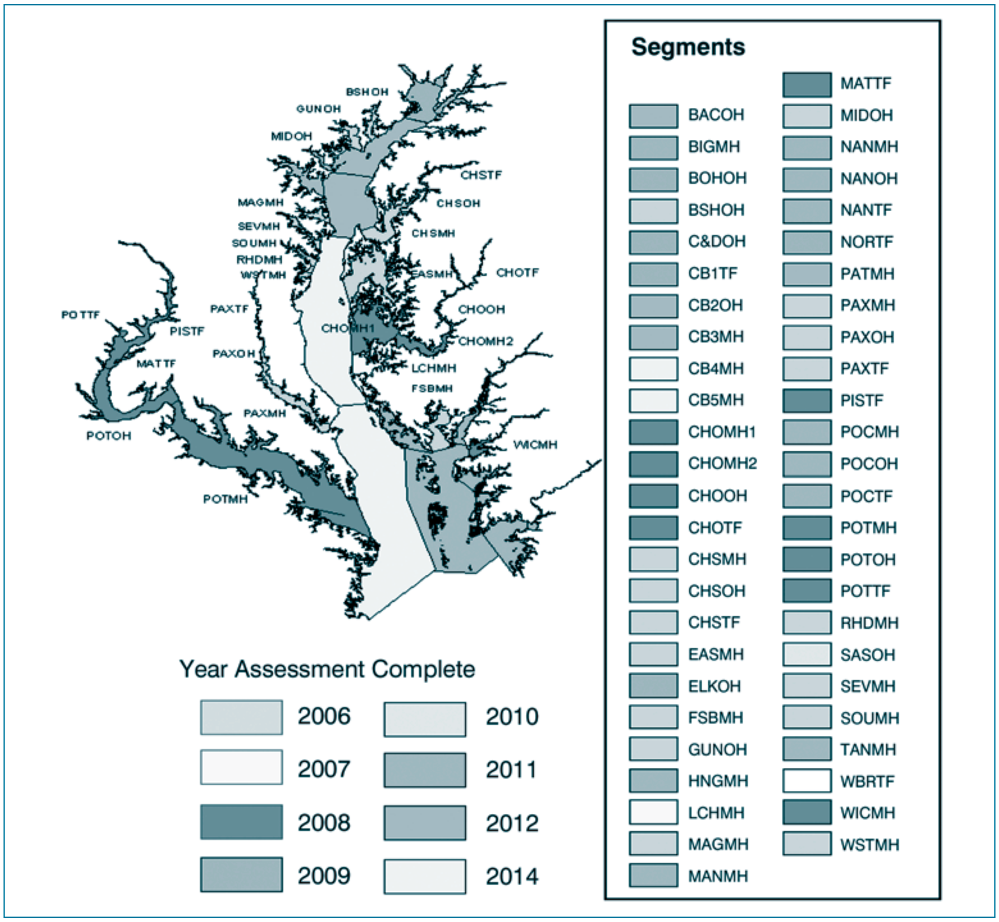


**Figure VII-4.** Schedule for shallow-water monitoring of Maryland's Chesapeake Bay segments.

Source: Maryland Department of Natural Resources

## ASSESSMENTS BASED ON REDUCED MONITORING

The three-year assessment period was established to account for inter-annual variations in weather and hydrologic conditions (U.S. EPA 2003a). If conditions are seriously degraded, a state having fewer than three years of data can establish noncompliance by applying the CFD-based criteria assessment methodology as follows.

First, at the start of a segment's shallow-water monitoring, assume 100 percent compliance in all three years of the coming assessment period. Second, after the first year of monitoring, a state should develop a CFD based on the collected data, assuming all other planned sampling dates for the next two years had 100 percent compliance with the applicable criterion. Finally, if the resultant assessment CFD indicates that the segment will be in violation (compared to the applicable reference CFD) no matter what happens in the following two years, then conclude that the segment is out of compliance for the full assessment period and move the Shallow-water Monitoring Program to another segment.

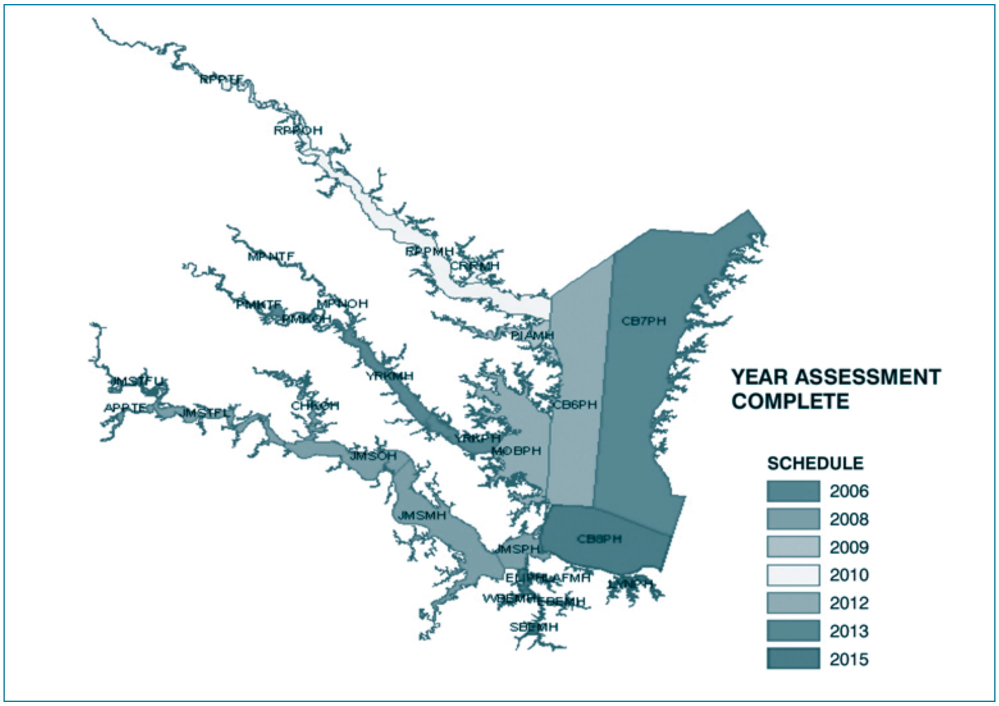


**Figure VII-5.** Schedule for shallow-water monitoring of Virginia's Chesapeake Bay segments.
Source: Maryland Department of Natural Resources

To illustrate this approach, two hypothetical scenarios are illustrated below. In the first example (Figure VII-6), it is assumed that monitoring was conducted for one year and that full attainment was achieved during all scheduled sampling dates over the next two years. The shallow-water monitoring over the first year indicated that on all of the dates, the applicable criterion was violated in 15 percent or more of the segment. The CFD indicates that the segment would be in noncompliance even if all future sampling dates had 100 percent compliance. In this case, the state could have decided to move the monitoring effort to a new shallow-water segment even after a single year of study.

In the second example (Figure VII-7), the same assumptions are made and monitoring is conducted over one year. In this case, however, criteria exceedance is much less extensive spatially and the CFD indicates that full compliance could be possible if the current level of attainment is found in future monitoring. Since neither compliance nor noncompliance could be established during the first year, shallow-water monitoring would need to continue. The same analysis could take place after the second year of monitoring and the decision could be revisited. It may turn out that a full three years of monitoring are necessary to determine if the segment remained in full compliance.

Although determining noncompliance in fewer than three years works in theory, the yearly segment data must be analyzed in time to adequately design and implement a sampling scheme for a new segment. The states must have the flexibility to deploy

| Cruise Number | Cruise Year | Cruise Month | % of Space | % of Time | Ref Curve |
|---|---|---|---|---|---|
| | | | 1 | 0.00 | 0.00 |
| 1 | 1 | May | 0.7 | 0.05 | 0.02 |
| 2 | 1 | June | 0.45 | 0.11 | 0.05 |
| 3 | 1 | July | 0.3 | 0.16 | 0.09 |
| 4 | 1 | August | 0.25 | 0.21 | 0.11 |
| 5 | 1 | September | 0.2 | 0.26 | 0.14 |
| 6 | 1 | October | 0.15 | 0.32 | 0.19 |
| 7 | 2 | May | 0 | 0.37 | 1.00 |
| 8 | 2 | June | 0 | 0.37 | 1.00 |
| 9 | 2 | July | 0 | 0.37 | 1.00 |
| 10 | 2 | August | 0 | 0.37 | 1.00 |
| 11 | 2 | September | 0 | 0.37 | 1.00 |
| 12 | 2 | October | 0 | 0.37 | 1.00 |
| 13 | 3 | May | 0 | 0.37 | 1.00 |
| 14 | 3 | June | 0 | 0.37 | 1.00 |
| 15 | 3 | July | 0 | 0.37 | 1.00 |
| 16 | 3 | August | 0 | 0.37 | 1.00 |
| 17 | 3 | September | 0 | 0.37 | 1.00 |
| 18 | 3 | October | 0 | 0.37 | 1.00 |

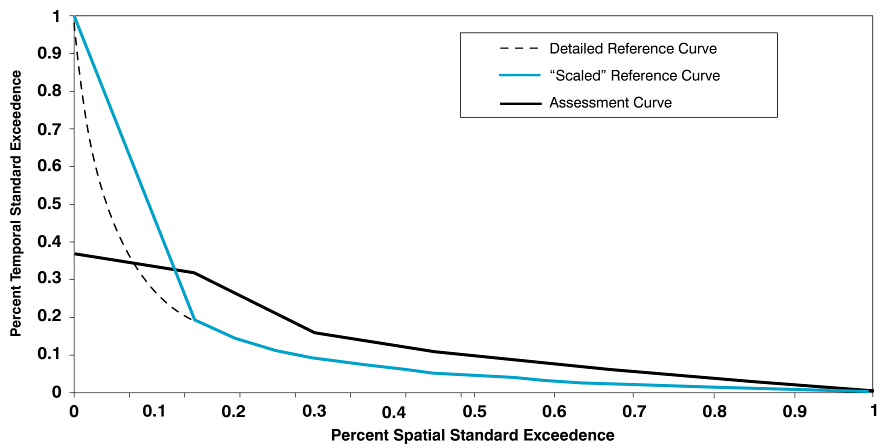


**Figure VII-6.** Scenario 1: noncompliance established after one year of shallow-water monitoring.

resources to different systems. Often, implementation of a monitoring program for a segment requires the coordination of various stakeholders and potential partners, the leveraging of resources, and the allocation of field crews.

The Chesapeake Bay Program's Scientific and Technical Advisory Committee has recommended that the tributary systems be assessed in their entirety for the full three-year period rather than evaluating individual segments of a tributary in different years (STAC 2005). This recommendation is particularly important for the larger tidal tributaries such as the Patuxent, Potomac, Rappahannock, York, and James rivers. These systems have tidal fresh, oligohaline, mesohaline, and polyhaline segments, all of which influence each other. To understand the vast ecosystem

| Cruise Number | Cruise Year | Cruise Month | % of Space | % of Time | Ref Curve |
|---|---|---|---|---|---|
| | | | 1 | 0.00 | 0.00 |
| 1 | 1 | May | 0.4 | 0.05 | 0.06 |
| 2 | 1 | June | 0.2 | 0.11 | 0.14 |
| 3 | 1 | July | 0.12 | 0.16 | 0.23 |
| 4 | 1 | August | 0.09 | 0.21 | 0.29 |
| 5 | 1 | September | 0.05 | 0.26 | 0.44 |
| 6 | 1 | October | 0.03 | 0.32 | 0.57 |
| 7 | 2 | May | 0 | 0.37 | 1.00 |
| 8 | 2 | June | 0 | 0.37 | 1.00 |
| 9 | 2 | July | 0 | 0.37 | 1.00 |
| 10 | 2 | August | 0 | 0.37 | 1.00 |
| 11 | 2 | September | 0 | 0.37 | 1.00 |
| 12 | 2 | October | 0 | 0.37 | 1.00 |
| 13 | 3 | May | 0 | 0.37 | 1.00 |
| 14 | 3 | June | 0 | 0.37 | 1.00 |
| 15 | 3 | July | 0 | 0.37 | 1.00 |
| 16 | 3 | August | 0 | 0.37 | 1.00 |
| 17 | 3 | September | 0 | 0.37 | 1.00 |
| 18 | 3 | October | 0 | 0.37 | 1.00 |

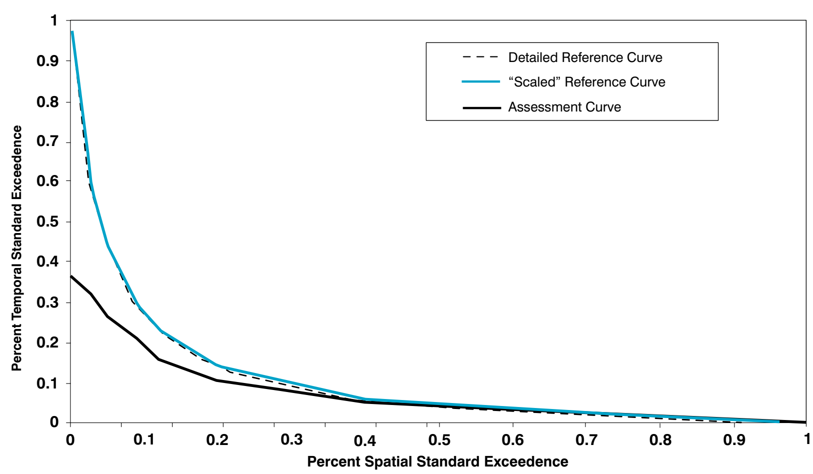


**Figure VII-7.** Scenario 2: noncompliance not established after one year of shallow-water monitoring.

complexities and interactions between adjacent segments of a single tributary, it is imperative to assess these tidal tributaries and segments as whole systems and not discontinue monitoring in one segment if noncompliance occurs after only a year or two of assessment.

The states should make the decision whether to continue shallow-water monitoring for the full three years or to move the monitoring to another segment after a year or two of sampling. In making such decisions, the state should consider the need to gather shallow-water data for the assessment of multiple criteria (dissolved oxygen, water clarity, and chlorophyll *a*) as well as other uses of the data (e.g., shallow-water water quality model development and calibration). The states will also need to consider if it makes sense (in terms of leveraging resources, coordinating, and understanding the relationship between segments and restoration activities) to discontinue a segment's monitoring after one or two years if noncompliance of the segment is shown. Finally, in the case of segments crossing two or more jurisdictional boundaries, all affected states will be involved in any decision to discontinue monitoring prior to the end of the full three-year assessment period.

Importantly, the scenario described above and illustrated in Figure VII-6 does not form an assessment that is lower in quality than one based on three years data. Noncompliance is clearly established; that status would not change no matter what takes place in ensuing years. The same approach may not be viable using alternative assessment strategies such as the water clarity-acres approach for the clarity criteria. Since the water clarity-acres assessment method relies on the mean of three years of data, non-compliance could not be established in fewer than three years. The reverse, however, may be true. However, if the segment's SAV restoration acreage goal was attained during any single year, then compliance would be established and the decision could be made to discontinue monitoring.

## SEGMENT PRIORITIZATION SCHEDULE

The states' prioritization schedule for assessing shallow water monitoring segments, (Figures VII-4 and VII-5) is based on several criteria—SAV coverage, maximization of resources, partnerships, and management needs such as dissolved oxygen criteria. Segment prioritization through SAV coverage is based on assessing segments that are close to meeting the state-adopted SAV restoration acreage goal for the individual segment. All states have agreed to assess attainment by each segment's single-best SAV acreage for the most recent three-year period with the jurisdiction's adopted segment–specific SAV restoration acreage (see Chapter 5 for further details). Many Chesapeake Bay segments range between 50 and 100 percent of meeting their restoration goals.

Appendix G lists all the Delaware, Maryland, Virginia, and the District of Columbia segments and their relative success (by percent) in reaching their respective state-adopted SAV restoration acreages. Those segments that have already met their SAV restoration acreages constitute a lower priority for shallow-water assessment. Segments that have not achieved any acres in meeting their SAV restoration acreage form a lower priority as well. The higher the percentage attainment in meeting a segment's SAV restoration acreage, the greater the priority was given for assessing the shallow waters of that segment.

On the states' 2006 303(d) lists, eight Maryland segments and six Virginia segments have met their adopted SAV restoration acreages. The segments that have already attained their shallow-water designated use are low priority for shallow-water assessment. Fourteen Maryland segments and five Virginia segments range between 50 and 100 percent of meeting their SAV restoration acreages (Appendix I). These segments were granted the highest priority for shallow-water monitoring (see Figures VII-4 and VII-5).

## DISSOLVED OXYGEN CRITERIA ASSESSMENTS USING SHALLOW-WATER MONITORING DATA

The Chesapeake Bay Shallow Water Monitoring Program has provided unprecedented volumes of spatially and temporally intensive Chesapeake Bay, tidal tributary, and embayment data to assess water quality criteria attainment. This wealth of data, however, provides new and unique analytical challenges within the regulatory framework. In the case of dissolved oxygen criteria, these challenges include: temporal variation of water quality parameters, spatial interpolations, and scaling and interpolation issues. Specific procedures for evaluation of the 7-day, 1-day, and instantaneous minimum open-water and deep-water dissolved oxygen criteria have not been fully developed at this time.

The assessment of the 30-day mean dissolved oxygen criteria for open-water designated-use habitats will rely on mid-channel fixed station data combined with Dataflow and Dataflow calibration profile data. As noted previously, the Dataflow vessel stops at five to eight locations throughout a segment to collect calibration measurements. Dissolved oxygen is measured from the surface to the bottom at these sites using the same procedure as the mid-channel data collection. The dissolved oxygen calibration data will provide an additional day of dissolved data each month, at five locations instead of one or two. The dissolved oxygen Dataflow and the corresponding Dataflow dissolved oxygen calibration data will be interpolated and analyzed, along with fixed-station dissolved oxygen data, using the Chesapeake Bay Program's interpolator and the CFD approach described in Chapter 2.

### TEMPORAL VARIATION

Dataflow cruises collect between 3,000 and 10,000 points over several hours in a segment. Data are normally collected between 7:00 a.m. and 5:00 p.m. with the boat traversing open and shallow waters on one side of a tidal tributary or embayment and repeating the process on the opposite side. The measurements can be interpolated to produce a continuous surface of data that can be evaluated for the percentage area of a segment that fails the applicable criterion.

The diel patterns of surface dissolved oxygen are well documented in both the literature and continuous monitoring data (www.eyesonthebay.net). In summer, dissolved oxygen normally declines to its lowest level during the early morning hours (3:00 a.m.) when algal and plant communities have been respiring throughout the night; it reaches its peak in mid-afternoon (3:00 p.m.) following photosynthetic activity. In some cases, this diel fluctuation can reach more than 15 $mg \cdot liter^{-1}$

dissolved oxygen. When interpolating water quality mapping data collected throughout the day, this variability presents a potential problem that is best illustrated by a map. Figure VII-8 shows that data collected early in the morning on one side of the Severn River in Maryland is substantially lower than data collected later in the day on the other side. If these measures were interpolated, it would appear that one side of the river is faring more poorly than the other when, in fact, the dichotomy merely represents a temporal artifact.

To produce a more representative spatial interpolation of surface dissolved oxygen data, estimating the diel dissolved oxygen trend from continuous monitoring instruments and using that trend estimate to adjust the Dataflow dissolved oxygen may prove more feasible. The University of Maryland investigated this procedure by comparing data from a nearshore continuous meter with those from a mid-channel continuous buoy. They found that the dissolved oxygen in the two locations responded differently to the local habitats and that nearshore dissolved oxygen dropped at night and the mid-channel dissolved oxygen was highly variable, often exceeding dissolved oxygen saturation during the day. Although the adjustment procedure improved the data set, the prediction error was high. Further research is needed to integrate the spatial and temporal monitoring data.

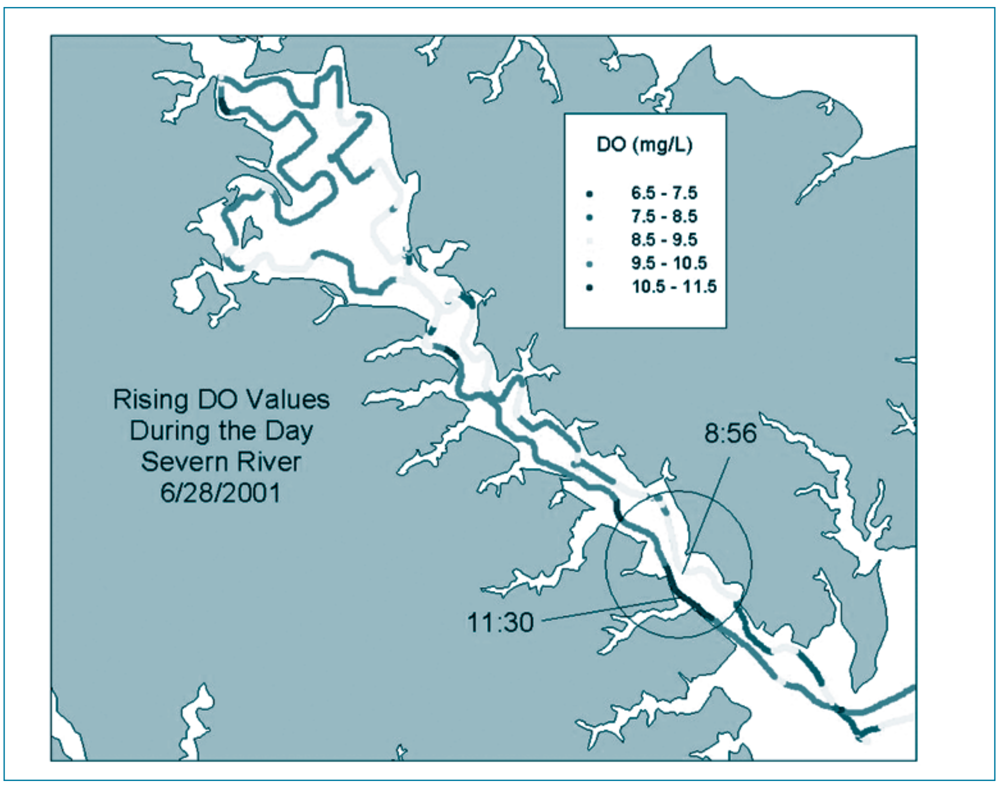


**Figure VII-8.** Illustration of rising dissolved oxygen concentrations during the day (June 28, 2001) in the Severn River, Maryland.

## SCALING AND INTERPOLATION ISSUES

The frequency and spatial coverage of water quality sampling will always remain lower in relation to the temporal and spatial scales at which estuarine phenomena occur. To overcome this reality, researchers must use innovative sample designs and statistical methods. Throughout the Chesapeake Bay Program's tidal data analysis and monitoring network design meetings, many of these issues regarding the interpretation of shallow water monitoring data have been raised, but all were not solved. The major issues relating to dissolved oxygen are highlighted below.

Water quality mapping of dissolved oxygen uses measures from a half-meter below the surface. Some consider this type of measurement a weakness given that most hypoxic events occur in deep-water or deep-channel habitats. The last five years of water quality mapping, however, have revealed that hypoxic events can affect surface and shallow waters more than initially recognized. Each mapping cruise collects calibration samples and water quality depth profiles at five to eight stations per segment. In much the same fashion that fixed station profiles are interpolated in three-dimensions using the Chesapeake Bay interpolator (see Chapter 2 and Appendix D), the surface mapping data could be interpolated along with calibration station and mid-channel, fixed-station depth profiles to enhance volumetric estimates of dissolved oxygen. Advancements in monitoring attainment technology that enable deployment of automated vertical profilers and surface and bottom buoy monitors could also support this effort. Overall, the integration of data types such as continuous monitoring, mapping, remote sensing, and fixed-station profiles poses one of the greatest challenges in criteria assessment.

Water quality mapping cruises cannot cover every shallow-water cove and creek in a segment, thus presenting a problem for spatial extrapolation of the data. Criteria assessment using the CFD method requires the use of an interpolated/extrapolated surface from the entire segment and does not allow for exclusion of unsampled areas. Almost certainly, many of the areas outside of the sampling boundary have far different conditions than those measured in the shallow waters of the main segment. These areas represent only a small percentage of each segment, but the question remains whether they contain more valuable habitat than the space they occupy on a percentage basis.

Annually, many of the larger fish kills in Chesapeake Bay occur in these small tidal creeks and embayments due to anthropogenic influences or natural conditions. Two months after torrential rains in June 2006, a Maryland Department of Natural Resources aerial photography survey of the state's Eastern Shore tributaries revealed that most small embayments were still clouded by silt and algal blooms to a far greater extent than adjacent open waters. To assess conditions adequately in these shallow-water tidal creeks and embayments, a probabilistic approach may be needed in conjunction with current shallow-water sampling design in which representative small tidal creeks and embayments are sampled by the surface mapping and the results become a surrogate for the percentage area that these creeks represent in a segment.

A STAC-convened expert panel (described in detail in Chapter 2) has reviewed the interpolation of spatial data. Several standardization decisions for interpolation methodology will need to be made to address the panel's recommendations for addressing shallow-water monitoring data (STAC 2006).

## WATER CLARITY CRITERIA ASSESSMENTS USING SHALLOW-WATER MONITORING DATA

The water clarity assessment uses data from the shallow-water water quality mapping to obtain high-resolution data in nearshore shallow waters. This section describes the data analysis protocols for application of high-resolution turbidity measurements to assess attainment of state-adopted water clarity criteria in shallow-water monitored tidal tributaries and embayments of the Chesapeake Bay.

During each day of water quality mapping with the Dataflow, the operator stops at five to eight locations (calibration stations) to measure photosynthetic active radiation (PAR) so that the light attenuation coefficient ($K_d$) can be calculated and correlated with the *in situ* turbidity values recorded simultaneously. The protocol followed to derive this correlation is described below.

The Chesapeake Bay water clarity criteria were published as the percent of light through water (see Table IV-1 on page 96 in U.S. EPA 2003a). Through the application of the equation:

$$PLW = 100 \exp(-K_d Z) \qquad \text{Equation 3}$$

the appropriate percent light-through-water value and the selected water clarity criteria application depth (Z) are inserted and the equation is solved for $K_d$. The methodology developed by the Chesapeake Bay Program for assessing criteria attainment involves a sequence of steps that leads to a cumulative frequency diagram (CFD) as described in eight steps in Table II-1 in Chapter 2. As part of step 3, equating the *in situ* collected values of turbidity to estimated $K_d$ values becomes necessary to determine exceedance of the water clarity criterion. It is critical to convert *in-situ* turbidity to estimates of $K_d$ prior to any data interpolation in order to reduce the error potential.

The relationship between turbidity and $K_d$, therefore, needs to be quantified to determine the turbidity threshold of the applicable water clarity criteria. This determination narrows the scope considerably from the traditional calibration curve in which the estimation of $K_d$ is based on measurements for a wide range of turbidity concentrations. In the current application, it is only necessary to accurately estimate $K_d$ from *in situ* measurements of turbidity in the neighborhood of the exceedance of the water clarity criteria.

## ANALYSIS ISSUES

In conducting the analysis to formulate the decision rules and calibration curves that relate *in situ* turbidity measurements with calibration station $K_d$ measurements, numerous issues were addressed. Many of these issues focus on lumping or dividing the data when computing calibration curves. The argument in favor of lumping (performing the analysis on an aggregation of data) reasons that better estimates are obtained when averaging large numbers of observations. Lumping calibration data over time (e.g., one year) was assumed valid because the light-scattering properties of a tributary's suspended sediments would remain relatively constant over time.

On the other hand, the turbidity-to-$K_d$ relationship may prove inconsistent across different segments or entire tidal tributaries. After reviewing the Maryland and Virginia shallow-water monitoring data for 2003 to 2005, it was decided to divide the data into similar groups for individual calibration models and to conduct a cluster analysis for the group of tributaries monitored from 2003 to 2005. Algorithms for each group were developed that led to better overall precision.

Other water quality parameters were tested for their ability to predict $K_d$. Chlorophyll and salinity from the calibration sites are also predictors of $K_d$ but their contribution is smaller than turbidity. Colored dissolved organic matter are likely to increase $K_d$, however, these measurements are not routinely collected by the Chesapeake Bay Water Quality Monitoring Program. Individual calibration curves may prove necessary for areas around the Bay where freshwater input from "blackwater" streams (e.g., the Pocomoke River) that drain extensive wetlands results in relatively high concentrations of colored dissolved organic matter.

## STATISTICAL MODELING

The continuous turbidity measurements are calibrated to predicted light attenuation through the water column ($K_d$) by using statistical relationships among simultaneous measurements of turbidity, chlorophyll, salinity measurements, and light attenuation profiles of underwater photosynthetically available radiation (PAR) from five to eight calibration stations within each Chesapeake Bay segment. A multiple regression model of $K_d$ vs. 1.5 root of turbidity [i.e., $(\text{turbidity})^{1/1.5}$] × chlorophyll × salinity provides the best fit of the $K_d$-to-turbidity relationship. The 1.5 root yielded the lowest root mean square prediction error and the highest r-square value.

Figure VII-9 shows simple linear regressions of predicted $K_d$ versus the 1.5 root of measured turbidity for each of the seven Virginia tidal tributaries having shallow-water monitoring data from 2003 through 2005. Some of the slopes are similar but clearly different than others, indicating that data from small groups of tributaries with similar slopes can be combined into one calibration curve.

The linear regression was further expanded to include terms for *in situ* chlorophyll and salinity. Like turbidity, the relationships between chlorophyll and $K_d$, and salinity and $K_d$ vary among tributaries. However, enough similarities between

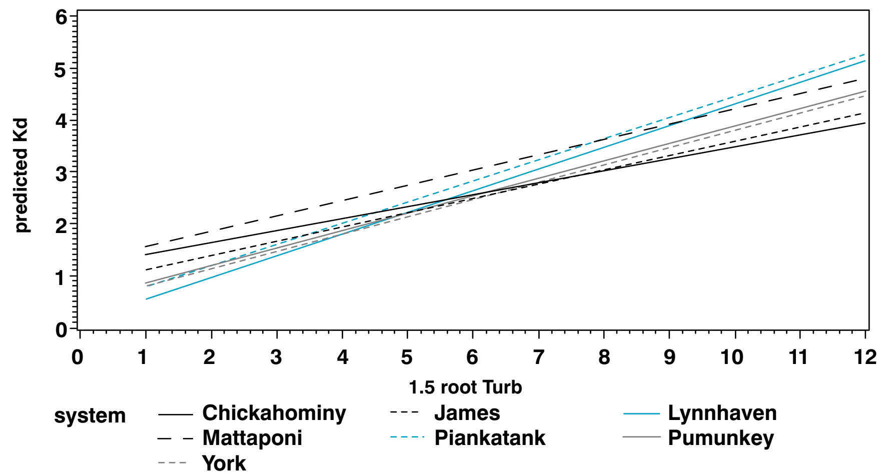


**Figure VII-9.** Simple linear regression of predicted $K_d$ versus the 1.5 root of measured turbidity using shallow water monitoring data from seven Virginia tidal tributaries (2003–2005).

Source: Virginia Institute of Marine Science—www2.vims.edu/vecos.

coefficients and intercepts occur to form groupings of tributary data for calibration purposes. The groupings developed to date reflect a strong geographic pattern, which strengthens their validity.

## INTERPOLATION

The very dense *in situ* measurements of turbidity from each sampling cruise track (Figure VII-10) are first converted to $K_d$. The natural log of the converted $K_d$ values are then interpolated using a standardized ordinary kriging procedure with ARC/GIS into a 25-meter square grid over the segment's entire surface area. Once interpolated, the resultant interpolated $K_d$ values are transformed back. Each interpolator cell within a segment's shallow-water area is then assessed against a specific $K_d$ value for each applicable water clarity criterion application depth. An interpolator cell value equal to or below this $K_d$ value is considered in attainment of the applicable water clarity criterion. A number above this value has failed to meet the applicable water clarity criterion.

The entire area within the shallow-water designated-use zone for each sampling cruise is then aggregated on an interpolator cell-by-cell basis to determine the total area either in attainment or failing to meet the applicable water clarity criterion. Water clarity attainment acres are determined for the total area within the shallow-water area of each segment from the shoreline out to the 2-meter depth contour excluding the delineated SAV no-grow zones (see Chapter 5 for details).

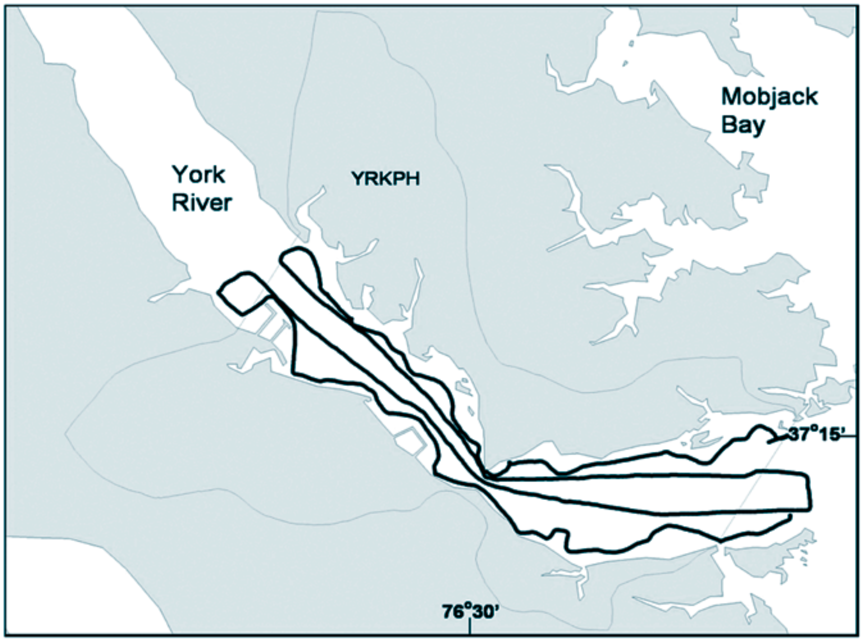


**Figure VII-10.** Example lower York River polyhaline segment YRKPH Dataflow sampling cruise track on August 25, 2003.
Source: Virginia Institute of Marine Science—www2.vims.edu/vecos..

Water clarity criteria attainment can also be assessed in each segment's shallow-water designated-use habitat through application of the CFD-based methodology described in Chapter 2 for each three-year assessment period. Exceedance is the cumulative frequency distribution of the portion of this zone that failed the $K_d$-equivalent of the application depth specific water clarity criterion determined for that segment compared to a reference CFD curve.

Naturally, environmental conditions will result in periodic exceedances of bay grass water clarity requirements; such exceedances are allowable for bay grass survival (U.S. EPA 2003a). Since allowable exceedances can be specific to salinity-based bay grass communities, biologically based reference curves are applied using measured water clarity exceedances established from existing bay grass beds for each salinity region using mid-channel water quality data (see Figures VI-1 and VI-2 in Chapter 5). Figure VII-11 shows a preliminary example of a biological reference curve of water clarity exceedances based on shallow-water monitoring data for established bay grass beds in the polyhaline lower York River segment (YRKPH) during the 2003 and 2004 growing seasons. This curve is plotted along with the previously published water clarity reference curve for mesohaline/polyhaline shallow-water bay grass designated-use habitats (U.S. EPA 2003a).

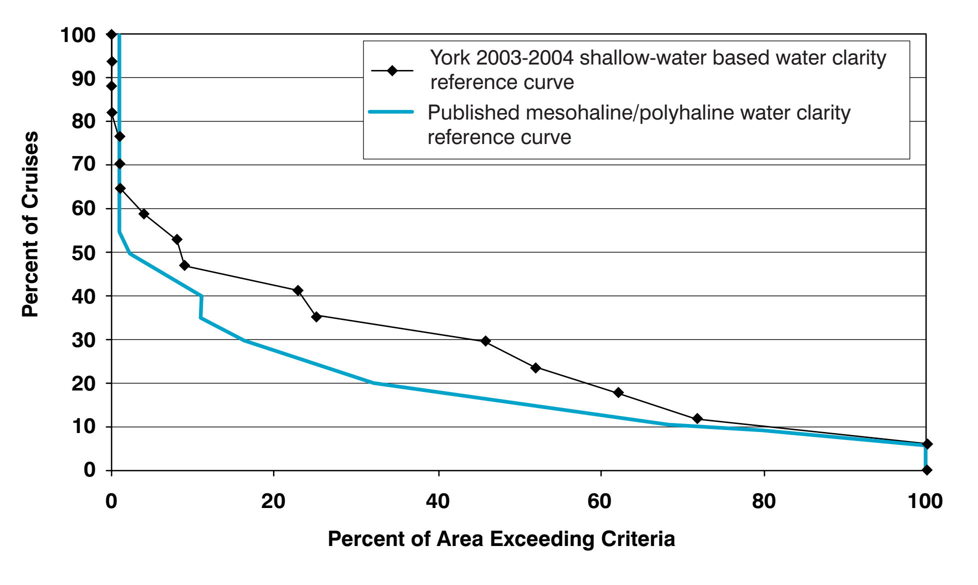


**Figure VII-11.** Comparison of the published mesohaline/polyhaline water clarity criteria biological reference curve based on mid-channel water clarity measurements and a preliminary example of a shallow-water monitoring-based water clarity criteria biological reference curve.

Source: : U.S. EPA 2003a; Virginia Institute of Marine Science—www2.vims.edu/vecos.

## CHLOROPHYLL *A* CRITERIA ASSESSMENTS USING SHALLOW-WATER MONITORING DATA

Attainment of the chlorophyll *a* criteria in the shallow-water designated use areas will be based upon the adjacent open-water designated use assessments. As with dissolved oxygen assessments, open-water chlorophyll *a* assessments will rely on the mid-channel fixed station data combined with Dataflow and Dataflow calibration profile data. These data will be interpolated and analyzed, along with the fixed-station chlorophyll *a* data, using the Chesapeake Bay Program's interpolator and CFD approach described in Chapter 2. The following sections describe the rationale for and development of protocols for using the *in-situ* fluorescence measurements from the Dataflow system to assess chlorophyll *a* criteria attainment in shallow and open-water tidal tributaries and embayments of Chesapeake Bay.

The Dataflow system generates a data set that better represents the spatial variability of chlorophyll. The Dataflow cruise track transverses both the open and shallow water designated use areas (see Figure VII-10), recording hundreds of fluorescent measurements, very quickly and less expensively than the collection and laboratory analysis of individual samples. However, the conversion of the fluorescence data to chlorophyll *a* must be done carefully to ensure that they are comparable to the chlorophyll *a* data upon which the chlorophyll *a* criteria were based.

The *in-situ* fluorescence method is more susceptible to bias and interferences than the laboratory method. Instrument manufacturers recognize that low temperatures and high turbidities can affect the fluorescence response and note that different phytoplankton species can fluoresce differently i*n-situ* even if the actual chlorophyll content is the same (YSI, Inc. 1999). To overcome these effects, it is a common practice to "calibrate" the *in-situ* data to the laboratory results by collecting and analyzing a set of chlorophyll *a* samples in the laboratory concurrent with *in-situ* measurements, and establishing a quantitative relationship, or "calibration" between the methods via simple linear regression. The calibration may be done for each day of sampling but better estimates may result if greater numbers of observations are incorporated into a statistical model.

## STATISTICAL MODELING

The usual approach for calibrating *in situ* fluorescence to *in vitro* chlorophyll is to develop a model of the form:

$$\text{Chlorophyll} = \mathbf{f}(\text{fluorescence, other variables}). \qquad \text{Equation 4}$$

Usually the function **f** is a linear regression model and the estimates of the coefficients for this model are obtained using least squares. With this model, a measured value of fluorescence may be used as an argument to obtain a predicted chlorophyll value. By evaluating other water quality variables measured by the monitoring program, it was determined that fluorescence, temperature, turbidity, pH, and seasonal variables be used as independent variables as described above.

One problem with this standard approach is that least squares estimation requires that data used as independent variables be measured without error. Clearly this assumption is not satisfied for fluorescence. An alternative approach that treats both *in vitro* and *in situ* chlorophyll as variables with measurement error estimates the logarithm of their ratio with a linear regression model:

$$\text{Log}(\mathbf{R}) = \text{Log}(\text{Chl}_1 / \text{Chl}_2) = \mathbf{f}(\text{other variables}) \qquad \text{Equation 5}$$

where:

$\text{Chl}_1$ = *in vitro* chlorophyll

$\text{Chl}_2$ = *in situ* chlorophyll (note: fluorometers used to collect data for this study convert the fluorescence signal to chlorophyll with a standard algorithm and this is the number recorded); and

**R** = the ratio of these two chlorophyll measures.

An estimate of *in vitro* chlorophyll is obtained from the *in situ* measurement by first estimating the logarithm of **R** given the independent variables, back-transforming to obtain an estimate of the ratio, and multiplying the *in situ* chlorophyll by the ratio to estimate the *in vitro* chlorophyll.

## MODELING APPROACH

Continuous monitoring data for Maryland and Virginia were analyzed to determine a method of post-calibrating fluorescence/chlorophyll to match extractive chlorophyll more precisely. Because the instruments are identical, it was assumed that the relationships between the Dataflow fluorescence and chlorophyll *a* would show similar patterns.  Maryland data were available for 2003 through 2005 for approximately 21 tidal tributaries (not all tributaries were sampled in all three years). Virginia data came from the York River. Initial tests indicated that no more variation occurred between Maryland and Virginia data than among the tidal tributaries in Maryland. This finding simplified the post-calibration model geographically by allowing combination of data from both states.

A second test of the data evaluated potential differences among years. This test also proved negative, which signified that all three years of data could be combined when developing the post-calibration model. Tests of season and tributary differences suggested that the final model would need to account for temporal and spatial differences. Further analyses indicated the need for two tributary groups and two season groups, meaning that four calibration curves will be required. Significant variables in the model also included water temperature, turbidity, and pH. Significance is defined here as a p-value of less than 0.05.

Initial results indicate that four calibration curves would be needed, two for season and two for tributary.  All four models contain fluorescence, water temperature, turbidity, and pH.

## ANALYSIS ISSUES

Several issues were addressed in conducting the analysis to formulate the decision rules and calibration curves. Similar to the turbidity/$K_d$ relationship, many of the issues related directly to the decision to lump or divide the data when computing calibration curves and decision rules. The argument in favor of lumping (to perform the analysis on a data aggregate) reasons that better estimates result when large numbers of observations are averaged. On the other hand, the *in situ* to *in vitro* relationship may not be consistent across all subsets of the data (i.e., between different tidal tributaries and embayments). If so, dividing the data and developing algorithms for each set may lead to better overall precision.

### Seasonal Patterns

Because species composition can affect the relationship of *in situ* to *in vitro* chlorophyll measurements, this relationship may change with the seasons. Thus, one aggregate-or-divide issue requiring resolution is the effect of seasons.

The *in situ*/*in vitro* difference generally follows a seasonal pattern consistent with known species composition patterns for Chesapeake Bay and its tidal tributaries. *In situ* chlorophyll measurements have a negative bias when phytoplankton populations shift toward a large component of blue-green algae. Blue-green algae increase in abundance during mid to late summer, particularly in tidal-fresh to low-salinity habitats. The calibration data from both the continuous monitors and the Dataflow water quality mapping show that the negative bias of the *in situ* measure becomes greater in summer. It was determined that two season groups would be needed.

It must be recognized that forming two season groups implements a model that captures the average condition, but may not capture the condition that exists in a particular tributary on a given date. The seasonal appearance of blue-green algae is not the same across tributaries and not even the same within a tributary from year to year. Even if the model predictions agree well with the observed data for the past three years, it is quite possible that a blue-green bloom could form at some unusual time of year in the future and lead to biased prediction. Truly reliable calibration of *in situ* chlorophyll to *in vitro* chlorophyll requires that some information on the concentration of blue-green cells be included in the calibration model.

### Geographic Patterns

Geography is another general factor that may influence the *in situ* to *in vitro* chlorophyll *a* relationship. Again, this influence is likely to be a phytoplankton species composition effect. Other factors (e.g., turbidity), however, may play a role. It is recommended that the analysis model the geography by treating locations (fixed-stations for continuous monitors or river systems for Dataflow) as discrete categorical predictors. If these predictors are statistically significant, the geography portion of the model should be simplified using surrogate variables, such as salinity and turbidity.

Spatial patterns emerge with data set analysis. These patterns, when viewed geographically, appear to follow arrangements expected based on phytoplankton species composition. In the Virginia Dataflow data, the trend is longitudinal within the estuaries. In the tidal-fresh region, the *in situ* and *in vitro* measurements appear similar, with a negative bias of *in situ* relative to *in vitro* emerging in downstream stations (Figure VII-12). In the upper tidal Mattaponi River, one region occurs in which *in situ* has a positive bias relative to *in vitro*. This situation may occur due to high background fluorescence from tannins (dissolved organic carbon) in the water. In Maryland, the negative bias (yellow squares) appears in regions where blue-green populations have been identified; however, the data do not show a longitudinal gradient similar to the Virginia data (Figure VII-13).

### Diel Patterns

In continuous monitoring data, many locations exhibit distinct diel patterns in the *in situ* chlorophyll. This diel pattern often shows that chlorophyll is higher at night and lower during the day. Other research has shown that fluorometric chlorophyll readings made in direct sunlight will be biased low because sunlight inhibits phytoplankton fluorescence. This finding, coupled with the observed pattern of lower *in situ* chlorophyll during the day, raised the concern that continuous monitoring of

**Figure VII-12.** Locations of the Virginia Chesapeake Bay Shallow-water Monitoring Program calibration stations. In each location, a circle indicates that no significant difference occurs between the *in situ* chlorophyll measures and the *in vitro* chlorophyll measures. A square indicates that the *in situ* measures are less than the *in vitro* measures. An X indicates that *in-situ* measures are greater than the *in-vitro* measures.

Source: Virginia Institute of Marine Science—www2.vims.edu/vecos.

*in situ* chlorophyll might be biased low during the day because of this measurement problem. A special study was conducted at the Jug Bay station on the tidal Patuxent River collecting hourly calibration samples for 24 hours. One set of samples was collected monthly from March to December in 2005. Analysis of the *in situ*/*in vitro* difference shows a very slight diel pattern in these data, but this variability became trivial when compared to other sources of variance.

## Collection Agency

The two principal agencies collecting these data—the Maryland Department of Natural Resources and the Virginia Institute of Marine Sciences—have devoted considerable effort to maintaining comparable shallow-water monitoring program field collection methodologies, instrumentation, and QA/QC procedures. Even so, because the two agencies work in geographically distinct regions, comparing results between agencies to determine if these data can be combined to estimate calibration curves should prove useful. Initial data evaluations indicate that no more variation exists between Maryland and Virginia data than among the tidal tributaries in Maryland. These evaluations suggest that any differences between Maryland and Virginia data may actually result from variations among the tidal tributaries and not from dissimilarities between the data-collecting agencies.

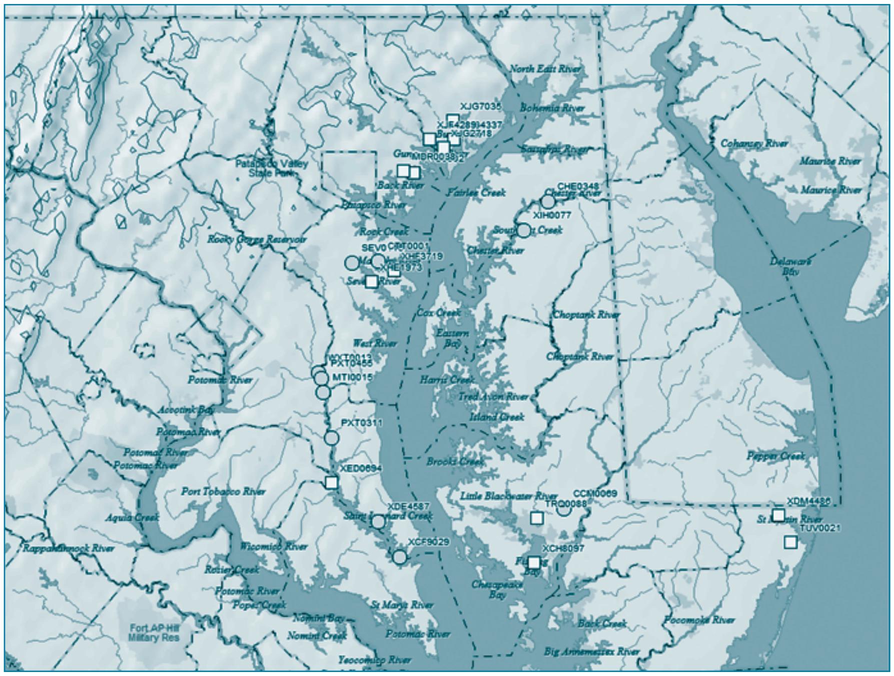


**Figure VII-13.** Locations of the Maryland Chesapeake Bay Shallow-water Monitoring Program continuous monitors. In each location, a circle indicates that no significant difference exists between the *in situ* chlorophyll measures and those for *in situ* chlorophyll. A square indicates that the *in situ* measures are less than the *in vitro* measures.

Source: Department of Natural Resources--www2.eyesonthebay.net.

## Background Fluorescence

In some Bay areas, the background fluorescence constitutes a significant component of the total fluorescence signal due to freshwater input from blackwater streams. Background fluorescence is the fluorescence measured on filtered water. This study will identify those areas where background fluorescence requires measurement and develop an algorithm to adjust for background fluorescence. Analysis indicates that background fluorescence is not significant in the systems assessed to date.

## Ancillary Data

While conventional wisdom holds that *in vitro* methods produce more accurate measures of chlorophyll than *in situ* methods, both are still subject to error. Using data collected independently of either type, the relative accuracy of the two methodologies will be assessed. For example, measurements taken as part of the nutrient suite (e.g., particulate nitrogen, total nitrogen, etc.) have some predictive power for chlorophyll. In cases where the *in situ* and *in vitro* measurements differ by more than expected due to sampling error, these ancillary data may resolve which is more reliable.

Often a time series of both *in situ* and *in vitro* chlorophyll will show that the two measurements compare quite well for much of the data record, with occasional large discrepancies. Because these large discrepancies are most problematic from a decision-rule point of view, they warrant special consideration. If one of the methods is more likely to be in error when these discrepancies occur, this finding will affect use of that method in the regulatory process.

To address this issue, separate models of *in situ* chlorophyll and *in vitro* chlorophyll need to be developed for which the independent variables are taken from the suite of nutrient measurements (e.g., total nitrogen, particulate nitrogen, etc.). A pilot project has shown that these models are fairly predictive. In a case where a large discrepancy between the *in situ* and the *in vitro* measurements exists, if one is in agreement with its predictive model and the other is not, then the one out of agreement is likely in error.

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chapter viii

# Framework for Chesapeake Bay Tidal Waters 303(d) List Decision-Making

## BACKGROUND

Section 303(d) of the Clean Water Act and EPA Regulation 40CFR 130.7 requires biennial identification of water segments that are not attaining water quality standards. These segments must have a total maximum daily load (TMDL) analysis completed and allocations established that result in water quality standards attainment. The states comply with this requirement through a process known as the Integrated Reporting Requirements which covers the assessment and listing requirements through Clean Water Act sections 305(d), 305(b), and 314 (U.S. EPA 2005b).

Given that the 2006 integrated reporting documents would be the first prepared under the states' newly adopted Chesapeake Bay water quality standards regulations, a collaborative effort (among the EPA and watershed states) began in spring 2005 to develop a decision-making framework for that portion of the 2006 submittals addressing the Chesapeake Bay system. The Chesapeake Bay Program partners reached agreement on several key assessment and listing issues. This chapter documents these agreements and presents the resultant flowchart for Chesapeake Bay tidal-water listing decisions to guide Delaware, Maryland, Virginia, and the District of Columbia in future 303(d) listing cycles.

## LISTING CATEGORY DECISIONS

Each state-adopted, tidal-water designated use by Chesapeake Bay Program segment (or formally adopted state sub-segment) is considered an individual spatial assessment unit for the purposes of each state's 303(d) list (U.S. EPA 2003a, 2003b, 2004a, 2004b, 2005a).

If a segment has been previously listed in category 5—recognizing the recent adoption of new Chesapeake Bay water quality standards—the original listing decision should stand until sufficient data are available to fully assess attainment for all applicable criteria components in each designated-use segment assessment unit. With sufficient data, states can justify moving an individual designated-use segment, or the segment as a whole, to another listing category. The lack of sufficient data for full assessment of the applicable criteria is not justification for moving a category 5 (impaired) segment to category 3 (insufficient data).

If a segment's designated use was not previously listed in category 5, it can be listed under category 3 if insufficient data exist to assess attainment of all applicable criteria components. Because an individual segment may have up to five tidal-water designated uses (see Table V-1 in Chapter 5), the states can place individual segments in multiple listing categories based on the criteria assessment results for each designated use in the segment.

## CRITERIA ATTAINMENT ASSESSMENTS

The preceding chapters document the different Chesapeake Bay water quality criteria assessments. Across all Bay criteria, non-attainment is defined as any percentage of non-attainment (even less than 1 percent) given that the CFD-based criteria attainment assessment method already factors in the small percentage of circumstances (in time and space) in which the criteria may be exceeded and still fully protect the tidal-water designated use (U.S. EPA 2003a).

## DISSOLVED OXYGEN CRITERIA ATTAINMENT ASSESSMENT

Given that multiple criteria often protect an individual designated use (e.g., separate 30-day mean, 7-day mean, and instantaneous minimum criteria required for protection of the open-water fish and shellfish designated use), full attainment of the dissolved oxygen criteria must involve assessment of each applicable criterion individually (U.S. EPA 2003a). In designated-use-segment assessment units for which data are available to assess all applicable dissolved oxygen criteria, the states can proceed with a full assessment of attainment of that segment's designated use. For those units with insufficient data for one or more of these criteria, states should not make any decisions on removing that designated-use segment from part 5 during that listing cycle.

Until the EPA publishes methodologies for assessing the 7-day and 1-day mean, along with the instantaneous minimum open-water and deep-water dissolved oxygen criteria components, the EPA recommends the states rely strictly on the assessment of the 30-day mean open-water and deep-water dissolved oxygen criteria for listing decisions. For those open- and deep-water designated-use segments for which the 30-day mean criteria are in non-attainment, the jurisdictions should list the segment on part 5 as impaired in the absence of data or methodologies for assessing the remaining criteria components. For those designated-use segments in which the 30-day mean open- or deep-water criteria are in attainment, the jurisdictions should generate additional data and apply criteria assessment procedures to determine attainment of the 7- and 1-day means as well as the instantaneous minimum criteria components. If a segment was first listed in 2006 based on the 30-day mean open-water and/or deep-water criteria and subsequent 30-day mean open-water and/or deep-water criteria data now shows the segment to be in attainment, then the segment may be delisted for these criteria.

## WATER CLARITY CRITERIA ATTAINMENT ASSESSMENT

The shallow-water bay grass designated use is in attainment if a sufficient number of acres of SAV occur within the segment or if enough acres of shallow-water habitat exist that meet the applicable water clarity criteria to support restoration of the desired acreage of SAV for that segment (U.S. EPA 2003a, 2003b). Assessment of either measure, or a combination of both, can serve as the basis for determining attainment or impairment of the shallow-water bay grass designated use.

Since SAV is the ultimate biological measure of attainment of the designated use, in the absence of sufficient shallow-water monitoring data necessary to determine the available water clarity acres or assess water clarity criteria attainment using the CFD-based criteria assessment procedure, EPA recommends the States assess shallow-water bay grass designated use attainment/impairment based on the acres of mapped SAV.

If a shallow-water bay grass designated-use segment meets its SAV restoration acreage, that designated use-segment is in attainment of the designated use and should be listed on part 2.

If such a segment does not meet its restoration acreage, the jurisdiction can then assess attainment using water clarity acres or water clarity criteria as described in Chapter 5. If the water clarity acres or water clarity criteria are attained based on shallow-water monitoring data, then that segment is in attainment of the shallow-water bay grasses designated use and should be listed on part 2.

Finally, if the water clarity restoration acres or water clarity criteria are not attained using the same data, or if there are insufficient data to make a determination using water clarity acres or water clarity criteria, then that segment is not in attainment of the shallow-water bay grasses designated use and should be listed on part 5.

Any attainment/non-attainment determination of water clarity criteria based on mid-channel-based monitoring is strictly diagnostic. These mid-channel data should not directly form the basis for any listing decision based on attainment/non-attainment of a segment's shallow-water bay grass designated use.

## CHLOROPHYLL *A* CRITERIA ATTAINMENT ASSESSMENT

As described in Chapter 6, numerical chlorophyll *a* criteria attainment is assessed by applying the appropriate numerical criteria over the applicable season for three years using the CFD-based criteria assessment methodology.

## BENTHIC INDEX OF BIOTIC INTEGRITY ASSESSMENT

The benthic community health assessment is conducted in three phases to support the states' tidal waters listing decisions (Llansó et al. 2005) (Appendices J and K). Phase I evaluates the sample size from the segment during the five-year assessment window. An impairment assessment based on benthic community health is not possible if the sample size requirement is not met. The data, however, may still prove useful as an adjunct to other aquatic life use data. If the sample size satisfies the requirements of the statistical method ($n \geq 10$), a formal assessment of status (i.e., impaired vs. supports aquatic life use) is determined using the "percent degraded area" statistical methodology (Phase II).

Phase II assesses aquatic life use impairment based on a comparison of the Chesapeake Bay benthic index of biotic integrity or benthic–IBI scores (Weisberg et al. 1997). This assessment is possible only when the number of benthic-IBI scores within a segment is sufficient to meet the sample size requirement of the approved statistical method ($n \geq 10$). Phase II can result in one of two possible outcomes: 1) the segment is not impaired for aquatic life use due to benthic community status (note that the segment may still be impaired due to failure of the other aquatic life use subcategories or criteria); or 2) the segment fails to support aquatic life use due to benthic community status and is assessed as impaired (part 5).

Phase III identifies the probable causes of assessed benthic impairment of the segment using a diagnostic tool that can pinpoint potential sources of stress affecting benthic community conditions in the Chesapeake Bay (Dauer et al. 2005). This methodology can also identify causes of stress and quantify the magnitude of degradation. In addition, it distinguishes stress due to contaminants from stress due to other factors (Appendix L).

## ASSESSMENT REPORTING FRAMEWORK

A Chesapeake Bay tidal-water designated-use criteria attainment assessment spreadsheet has been developed to assist the states in reporting listing decisions for each designated-use segment (Table VIII-1). The assessment reporting framework efficiently documents relevant information as each segment goes through the listing decision flowchart described below.

Table VIII-2 shows the example results of the Chesapeake Bay benthic analysis for the 2006 303(d) reporting cycle. The benthic-IBI assessments are separate from the Chesapeake Bay water quality criteria attainment assessment determinations and reported for the segments as stand-alone or supplemental information for the states to use in their 303(d) listing cycle decisions.

**Table VIII-1.** Chesapeake Bay tidal-water designated-use criteria attainment assessment reporting format

Attainment of Criteria
Insufficient Data to Assess
Non-Attainment of Criteria

**Date: 3/1/06**

| | | | | Water Quality Criteria | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Dissolved Oxygen | | | | | Water Clarity | | | Disposition by Segment/DU Pair | Listing Category |
| | | | | 30D | 7D | 1D | IM | Special Sturgeon | SAV Acres | WC Acres | SAV + WC*2.5 | | |
| CB1TF | Maryland | MSN | | | 6 | | 5 | | | | | Insufficient Data | 3 |
| | | SWSAV | | | | | | | 12,903 | | | Insufficient Data | 3 |
| | | OW | Summer | 5.5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | OW | ROY | 5.5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| CB2OH | Maryland | MSN | | | 6 | | 5 | | | | | Insufficient Data | 3 |
| | | SWSAV | | | | | | | 705 | | | Meets | 2 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Fails | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| CB3MH | Maryland | MSN | | | 6 | | 5 | | | | | Insufficient Data | 3 |
| | | SWSAV | | | | | | | 1,370 | | | Insufficient Data | 3 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Fails | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Fails | 5 |
| | | DC | Summer | | | | 1 | | | | | Fails | 5 |
| CB4MH | Maryland | MSN | | | 6 | | 5 | | | | | Insufficient Data | 3 |
| | | SWSAV | | | | | | | 2,533 | | | Insufficient Data | 3 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Fails | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Fails | 5 |
| | | DC | Summer | | | | 1 | | | | | Fails | 5 |
| CB5MH - ALL | MD & VA | SWSAV | | | | | | | 15,903 | | | Insufficient Data | 3 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Fails | 5 |
| | | DC | Summer | | | | 1 | | | | | Fails | 5 |
| CB5MH - MD | Maryland | SWSAV | | | | | | | 8,270 | | | Insufficient Data | 3 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Fails | 5 |
| | | DC | Summer | | | | 1 | | | | | Fails | 5 |
| CB5MH - VA | Virginia | SWSAV | | | | | | | 7,633 | | | Fails | 5 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Fails | 5 |
| | | DC | Summer | | | | 1 | | | | | Insufficient Data - Previously Listed | 5 |
| CB6PH | Virginia | SWSAV | | | | | | | 1,267 | | | Fails | 5 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Fails | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Fails | 5 |
| CB7PH | Virginia | SWSAV | | | | | | | 15,107 | | | Fails | 5 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Fails | 5 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data - Previously Listed | 5 |
| | | DW | Summer | 3 | | 2.3 | 1.7 | | | | | Insufficient Data - Previously Listed | 5 |
| CB8PH | Virginia | SWSAV | | | | | | | 11 | | | Fails | 5 |
| | | OW | Summer | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data | 3 |
| | | OW | ROY | 5 | 4 | | 3.2 | 4.3 | | | | Insufficient Data | 3 |

**Table VIII-2.** Examples of the array of results from the states' 2006 listing cycle evaluation of benthic community health.

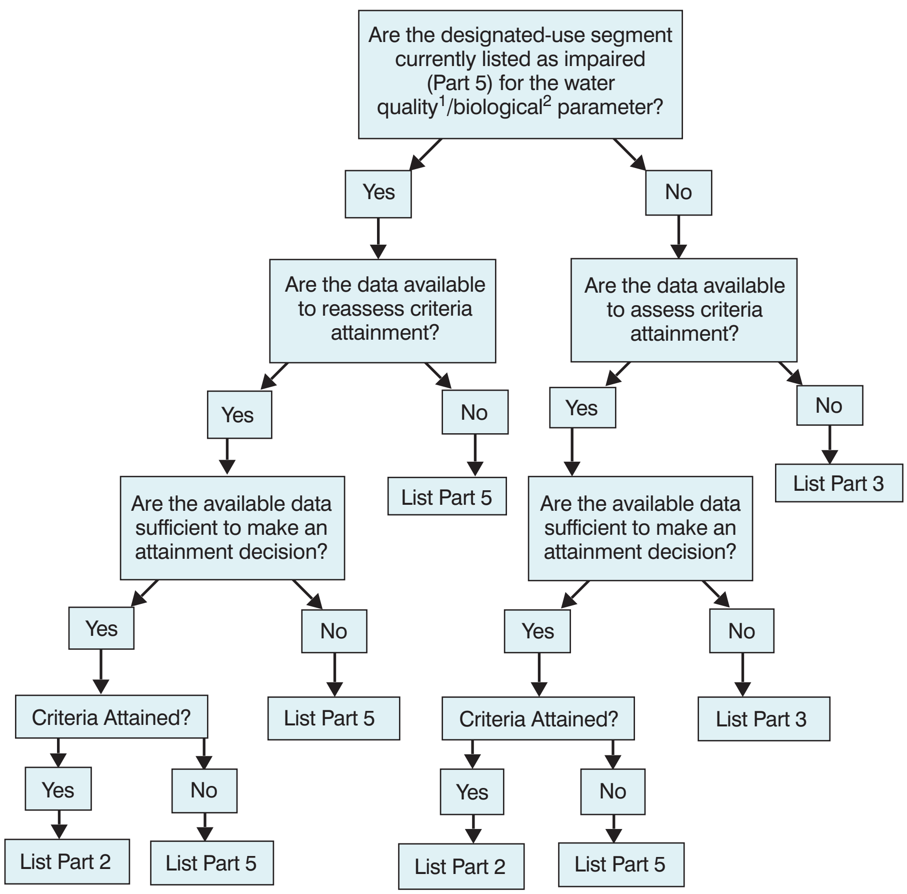
| Segment | Impaired: Degraded Area? | Mean B-IBI | Sample Size | Samples with contaminant Posterior Probability $p >= 0.90$; % of Total | Degraded Samples with excessive Abundance/Biomass; % of Total w/o Cont. | Degraded Samples with Insufficient Abundance/Biomass; % of Total w/o Cont. | Suspected Sources of Benthic Community Degradation |
|---|---|---|---|---|---|---|---|
| EBEMHa | Y | 2.2 | 15 | 60 | 0 | 0 | Sediment Contaminants |
| JMSMHb | Y | 2.4 | 16 | 50 | 0 | 0 | Sediment Contaminants |
| ELIPHa | Y | 2.8 | 17 | 17.65 | 5.88 | 5.88 | Unknown |
| MAGMH | Y | 2.3 | 17 | 11.76 | 5.88 | 29.41 | Low DO |
| CB4MH | Y | 2.3 | 28 | 7.14 | 21.43 | 42.86 | Low DO |
| YRKPHa | Y | 3 | 29 | 10.34 | 3.45 | 10.34 | Unknown |
| CHSMH | Y | 2.6 | 33 | 6.06 | 15.15 | 27.27 | Low DO |
| APPTFa | NA | 3 | 1 | 0 | 0 | 0 | Unknown |
| CHSTF | NA | 2 | 1 | 0 | 100 | 0 | Eutrophication |
| CHOTF | NA | 3 | 1 | 0 | 0 | 0 | Unknown |
| JMSTFa | N | 3.2 | 14 | 21.43 | 0 | 0 | Unknown |
| GUNOH | N | 2.9 | 15 | 6.67 | 6.67 | 20 | Unknown |
| CB8PHa | N | 3.4 | 15 | 0 | 0 | 13.33 | Unknown |
| CB6PHa | N | 3.3 | 18 | 5.56 | 5.56 | 11.11 | Unknown |
| CB1TF | N | 3.1 | 19 | 10.53 | 10.53 | 0 | Unknown |
| POTOH | N | 3.4 | 21 | 9.52 | 4.76 | 9.52 | Unknown |
| CB2OH | N | 3.8 | 40 | 0 | 0 | 0 | Unknown |
| CB7PHa | N (2) | 3.3 | 43 | 0 | 2.33 | 13.95 | Unknown |
| TANMH | N (2) | 3.2 | 48 | 2.08 | 0 | 10.42 | Unknown |

NA= Insufficient sample size for impairment decision.
* See Table 3 in Llansó et al. 2005

## LISTING DECISION FRAMEWORK

The Chesapeake Bay Program partners reached agreement on how to apply the results of the refined criteria assessment procedures most effectively in making Chesapeake Bay tidal-water listing decisions. The resultant decision-making framework, presented here in the form of a flowchart, can guide jurisdictional decisions in preparing future integrated reporting cycle submissions for the Chesapeake Bay system (Figure VIII-1).

All of the designated-use segment combinations for the five possible tidal-water designated uses—migratory fish spawning and nursery, shallow-water bay grass, open-water fish and shellfish, deep-water seasonal fish, and shellfish and deep-




[1]Dissolved oxygen, water clarity and chlorophyll *a*.
[2]SAV acreage and benthic index of biotic integrity.

**Figure VIII-1.** The 303(d) listing decision flow chart for assessing tidal waters designated uses in Chesapeake Bay and tidal tributaries.

channel seasonal refuge—along with the relevant dissolved oxygen, water clarity/SAV restoration acreage, and chlorophyll *a* criteria are applied through this listing decision flowchart. Benthic index of biotic integrity data are also evaluated for listing decisions.

The listing decision flowchart starts with each designated use-segment-applicable criterion combination, asking whether that segment was previously listed in category 5 as impaired based on the specific water quality (dissolved oxygen, water clarity, chlorophyll *a*) or biological (SAV acreage) criterion parameter. If yes, its initial listing status remains in category 5 pending new criteria attainment assessments. If no, then the flowchart questions whether data now exist to assess criteria attainment.

## SEGMENTS PREVIOUSLY LISTED AS IMPAIRED

At the second level, the flowchart queries whether the available data are sufficient to reassess criteria or index attainment. If yes, the third level asks if the applicable criteria or index is attained. If all applicable criteria components and indices have been attained, the designated-use segment is then listed in part 2. If no, the designated-use segment remains in part 5. If insufficient data exist at the second level to assess criteria attainment/index attainment, the designated-use segment previously listed as impaired remains in part 5.

## SEGMENTS NOT PREVIOUSLY LISTED AS IMPAIRED

At the second level, the flowchart queries whether the available data are sufficient to reassess criteria or index attainment. If yes, the third level determines whether the applicable criteria or index is attained. If all applicable criteria components and indices have been attained, the designated-use segment is then listed in part 2. If no, the designated-use segment is listed as impaired in part 5. If insufficient data exist at the second level to assess criteria attainment/index attainment, the designated-use segment remains in part 3.

## SHALLOW-WATER DESIGNATED-USE LISTING DECISIONS

If a shallow-water designated-use segment does not meet its SAV restoration acreage, the EPA recommends that the state list this designated-use segment in category 5 presuming the shallow-water monitoring data needed to assess water clarity acres/criteria attainment do not exist.

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# Acronyms

| | | | |
|---|---|---|---|
| 1 $d^{-2}$ | inverse of the distance squared | mg chla $m^2$ | milligrams of chlorophyll *a* per meter squared |
| $^{o}C$ | degrees Celsius | mg $liter^{-1}$ | milligrams per liter |
| CART | classification and regression tree | NASS | non-algal suspended solids |
| CBP | Chesapeake Bay Program | $NH_4$ | ammonium |
| CDOM | colored dissolved organic matter | $NO_2$ | nitrite |
| CFD | cumulative frequency diagram | $NO_3$ | nitrate |
| cells/ml | cells per milliliter | $O_2$ | oxygen |
| Chla | chlorophyll *a* | PAR | photosynthetically active radiation |
| DIN | dissolved inorganic nitrogen | $PO_4$ | dissolved inorganic phosphorous/ orthophosphorous |
| DO | dissolved oxygen | ppt | parts per thousand |
| g C $m^{-2}$ $d^{-1}$ | grams of carbon per meter squared per day | PSU | practical salinity unit |
| GLM | general linear model | QA/QC | quality assurance/quality control |
| HAB | harmful algal bloom | SAV | submerged aquatic vegetation |
| IDW | inverse-distance weighting | STAC | Science and Technical Advisory Committee |
| kg $m^3$ m | kilograms per cubic meter per meter | TMDL | total maximum daily load |
| km | kilometers | TSS | total suspended solids |
| LOAEL | lowest observable acute effects level | U.S. EPA | United States Environmental Protection Agency |
| m | meter | $\mu g$/kg | micrograms per kilogram |
| $m^3$ $s^{-1}$ | cubic meters per second | $\mu g$ $liter^{-1}$ | micrograms per liter |
| mg | milligram | % saturation | percent oxygen saturation |

appendix a

# The Cumulative Frequency Diagram Method for Determining Water Quality Attainment

**Report of the Chesapeake Bay Program STAC Panel to Review of Chesapeake Bay Program Analytical Tools**

STAC Publication 06-003
9 October 2006

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## EXECUTIVE SUMMARY

### BACKGROUND AND ISSUES

In accordance with the Chesapeake 2000 Agreement, the Chesapeake Bay Program has recently implemented important modifications to (1) ambient water quality criteria for living resources and, (2) the procedures to determine attainment of those criteria. A novel statistical tool for attainment, termed the Cumulative Frequency Diagram (CFD) approach, was developed as a substantial revision of previous attainment procedures, which relied upon a simple statistical summary of observed samples. The approach was viewed as advantageous in its capacity to represent degrees of attainment in both time and space. In particular, it was recognized that the CFD could represent spatial data in a synoptic way: data that is extensively collected across diverse platforms by the Chesapeake Bay Program Water Quality Monitoring Program. Because the CFD approach is new to Bay Program applications, underlying statistical properties need to be fully established. Such properties are critical if the CFD approach is to be used to rigorously define regional attainments in the Chesapeake Bay.

In Fall 2005, the Chesapeake Bay Program Scientific, Technical and Advisory Committee charged our working group to provide review and recommendations on the CFD attainment approach. As terms of reference we used guidelines of Best Available Science recently published by the American Fisheries Society and the Estuarine Research Federation. Statistical issues that we reviewed included,

1. What are the specific analytical/statistical steps entailed in constructing CFD attainment curves and how are CFDs currently implemented? (Section 2)
2. How rigorous is the spatial interpolation process that feeds into the CFD approach? Would alternative spatial modeling procedures (e.g., kriging) substantially improve estimation of water quality attainment? (Section 3)
3. What are the specific analytical/statistical steps entailed in constructing CFD reference curves? (Section 4)
4. What are the statistical properties of CFD curves? How does sampling density, levels of attainment, and spatial covariance affect the shape of CFD curves? What procedures are reliable for estimating error bounds for CFD curves? (Section 5)
5. From a statistical viewpoint, does the CFD approach qualify as best available science? (Section 6)
6. What are the most important remaining issues and what course of directed research will lead to a more statistically rigorous CFD approach over the next three years? (Section 7)

The central element of our work was a series of exercises on simulated datasets undertaken by Dr. Perry to better evaluate 1) sample densities in time and space, 2) varying levels of attainment, and 3) varying degrees of spatial and temporal covariance. Further, trials of spatial modeling on fixed station Chesapeake Bay water quality data by Dr.s Christman and Curriero were conducted to begin to evaluate spatial modeling procedures. These exercises, literature review and discussions leading to consensus opinion are the basis of our findings. In August 2006, the working group supplied preliminary findings and related text for use in the 2006 CBP Addendum to Ambient Water Quality Criteria that is now under review.

## FINDINGS

**1. The CFD approach is feasible and efficient in representing water quality attainment.**

The CFD approach can effectively represent the spatial and temporal dimensions of water quality data to support inferences on whether regions within the Chesapeake Bay attain or exceed water quality standards. The CFD approach is innovative but could support general application in water quality attainment assessments in the Chesapeake Bay and elsewhere. The CFD approach meshes well within the Chesapeake Bay Program's monitoring and assessment approaches, which have important conceptual underpinnings (e.g., segments defined by designated uses).

In accepting the CFD as the best available approach for using time-space data, the panel contrasted it with the previous method and those sustained by other jurisdictions. The previous method used by the Chesapeake Bay Program, similar to the approaches used in other states, was simply based on EPA assessment guidance in which all samples in a given spatial area were compiled and attainment was assumed as long as > 10% of the samples did not exceed the standard. In this past approach all samples were assumed to be fully representative of the specified space and time and were simply combined as if they were random samples from a uniform population. This approach was necessary at the time because the technology was not available for a more rigorous approach. But it neglected spatial and temporal patterns that are known to exist in the standards measures. The CFD approach was designed to better characterize those spatial and temporal patterns and weight samples according to the amount of space or time that they actually represent.

**2. CFD curves are influenced by sampling density and spatial and temporal covariance. These effects merit additional research. Conditional simulation offers a productive means to further discover underlying statistical properties and to construct confidence bounds on CFD curves, but further directed analyses are needed to test the feasibility of this modeling approach.**

The panel finds that the CFD approach in its current form is feasible, but that additional research is needed to further refine and strengthen it as a statistical tool. The CFD builds on important statistical theory related to the cumulative distribution function and as such, its statistical properties can be simulated and deduced. Through conditional simulation exercises, we have also shown that it is feasible to construct confidence ellipses that support inferences related to threshold curves or other tests of spatial and temporal compliance. Work remains to be done in understanding fundamental properties of how the CFD represents likely covariances of attainment in time and space and how temporal and spatial correlations interact with sample size effects. Further, more work is needed in analyzing biases across different types of designated use segments. The panel expects that a two-three year time frame of directed research and development will be required to identify and measure these sources of bias and imprecision in support of attainment determinations.

3. **The success of the CFD-based assessment will be dependent upon decision rules related to CFD reference curves. For valid comparisons, both reference and attainment CFDs should be underlain by similar sampling densities and spatial covariance structures.**

   CFD reference curves represent desired segment-designated use water quality outcomes and reflect sources of acceptable natural variability. The reference and attainment curves follow the same general approach in derivation: water quality data collection, spatial interpolation, comparison to biologically-based water quality criteria, and combination of space-time attainment data through a CFD. Therefore, the biological reference curve allows for implementation of threshold uncertainty as long as the reference curve is sampled similarly to the attainment curve. Therefore, we advise that similar sample densities are used in the derivation of attainment and reference curves. As this is not always feasible, analytical methods are needed in the future to equally weight sampling densities between attainment and reference curves.

4. **In comparison with the current IDW spatial interpolation method, kriging represents a more robust method and was needed in our investigations on how spatial covariance affects CFD statistical inferences. Still, the IDW approach may sufficiently represent water quality data in many instances and lead to accurate estimation of attainment. A suggested strategy is to use a mix of IDW and kriging dependent upon situations where attainment was grossly exceeded or clearly met (IDW) versus more-or-less "borderline" cases (kriging).**

   The current modeling approach for obtaining predicted attainment values in space is Inverse Distance Weighting (IDW), a non-statistical spatial interpolator that uses the observed data to calculate a weighted average as a predicted value for each location on the prediction grid. IDW has several advantages. It is a spatial interpolator and in general such methods have been shown to provide good prediction maps. In addition, it is easy to implement and automate because it does not require any decision points during an interpolation session. IDW also has a major disadvantage – it is not a statistical method that can account for sampling error.

   Kriging is also a weighted average but first uses the data to estimate the weights to provide statistically optimal spatial predictions. As a recognized class of statistical methods with many years of dedicated research into model selection and estimation, kriging is designed to permit inferences from sampled data in the presence of uncertainty. Thus the quantity and distribution of the sample data are reflected in those inferences. Indeed, the panel's initial trials on the role of spatial sources of error in the CFD have depended upon the ability to propagate kriging interpolation uncertainty through the CFD process in generating confidence intervals of attainment.

In comparison to IDW, kriging is more sophisticated but requires greater expertise in implementation. Kriging is available in commercial statistical software and also in the free open source R Statistical Computing Environment, and requires geostatistical expertise and programming skills for those software packages. Segment by segment variogram estimation and subsequent procedures would require substantial expert supervision and decision-making. Thus, this approach is not conducive to automation. On the other hand, there may be CBP applications where the decision on attainment is clearly not influenced to any substantial degree by the method of spatial interpolation. One suggested strategy is to use a mix of IDW and kriging - dependent upon situations where attainment was grossly exceeded or clearly met (IDW) versus more-or-less "borderline" cases (kriging).

5. **More intensive spatial and temporal monitoring of water quality will improve the CFD approach but will require further investigations on the influence of spatial and temporal covariance structures on the shape of the CFD curve. This issue is relevant in bringing 3-dimensional interpolations and continuous monitoring streams into the CFD approach.**

In the near future, the panel sees that the CFD approach is particularly powerful when linked to continuous spatial data streams made available through the cruise-track monitoring program, and the promise of continuous temporal data through further deployment of remote sensing platforms in the Chesapeake Bay (Chesapeake Bay Observing System: http://www.cbos.org/). These data sets will support greater precision and accuracy in both threshold and attainment determinations made through the CFD approach but will require directed investigations into how data covary over different intervals of time and space. Further, there may be important space-time interactions that confound the CFD attainment procedure.

Some of the assessments for the Bay such as that for dissolved oxygen require three dimensional interpolation, but the field of three dimensional interpolation is not as highly developed as that of two dimensional interpolation. Kriging can be advantageously applied in that it can use information from the data to develop direction dependent weighted interpolations (anisotropy). Kriging can include covariates like depth. Options for implementing 3-D interpolation include: custom IDW software, custom kriging software using GMS routines, or custom kriging software using the R-package.

## RECOMMENDATIONS

The panel identified critical research tasks that need resolution in the near future. The following is a list of critical aspects of that needed research. These research tasks appear roughly in order of priority. However, it must be recognized that it is difficult to formulate as set of tasks that can proceed with complete independence. For example, research on task 1 may show that the ability to conditionally simulate the water quality surface is critical to resolving the sample size bias issue. This discovery might eliminate IDW as a choice of interpolation under task 3. The Panel has made significant progress on several of these research tasks and CBP is encouraged to implement continued study in a way that maintains the momentum established by our panel.

## TASK

**1. Effects of Sampling Design on CFD Results**

(a) Continue simulation work to evaluate CFD bias reduction via conditional simulation.
(b) Investigate conditional simulation for interpolation methods other than kriging—this may lead to more simulation work.
(c) Implement and apply interpolation with condition simulation on CBP data.

**2. Statistical inference framework for the CFD**

(a) Conduct confidence interval coverage experiments.
(b) Investigate confidence interval methods for non-kriging interpolation methods.
(c) Implement and evaluate confidence interval procedures.

**3. Choice of Interpolation Method**

(a) Implement a file system and software utilizing kriging interpolation for CBP data.
(b) Compare interpolations and CFDs based on kriging and inverse distance weighting (IDW).
(c) Investigate nonparametric interpolation methods such as LOESS and spline approaches.

**4. Three-Dimensional Interpolation**

(a) Implement 2-D kriging in layers to compare to current approach of 2-D IDW in layers.
(b) Conduct studies of 3-D anisotrophy in CBP data.
(c) Investigate software for full 3-D interpolation.

**5. High Density Temporal Data**

(a) Develop methods to use these data to improve temporal aspect of CFD implementation.
(b) Investigate feasibility of 4-Dimensional interpolation.

## 1. INTRODUCTION

In June 2000, Chesapeake Bay Program (CBP) partners adopted the Chesapeake 2000 agreement (http://www.chesapeakebay.net/agreement.htm), a strategic plan that calls for defining the water quality conditions necessary to protect aquatic living resources. These water quality conditions are being defined through the development of Chesapeake Bay specific water quality criteria for dissolved oxygen, water clarity, and chlorophyll_a to be implemented as state water quality standards by 2005. One element of the newly defined standards is an assessment tool that addresses the spatial and temporal variability of these water quality measures in establishing compliance. This tool has become known as the Cumulative Frequency Diagram (CFD).

The (CFD) was first proposed as an assessment tool by Paul Jacobson, of Langhei Ecology (www.LangheiEcology.com). At that time Dr. Jacobson was consulting with the Chesapeake Bay Program as a member of the Tidal Monitoring Network Redesign Team. Within this group, the CFD concept gained immediate recognition and support as a novel approach that permitted independent modeling of the time and space dimensions of the continuous domain that underlies Chesapeake Bay water quality parameters. In addition, because preparation of the CFD uses spatial interpolation, the approach can allow integration of data collected on different spatial scales such as fixed station data and cruise track data.

While the benefits of the CFD approach has been recognized (U.S. EPA 2003) and the the CBP has begun implementation of the approach for certain water quality parameters and segments of the Chesapeake Bay, investigations of the statistical properties revealed that the underlying shape parameters of the CFD were sensitive not only to rates of compliance but also to sampling design elements such as sample density. The novelty of the approach coupled with concerns about its statistical validity motivated the Chesapeake Bay Program to request that its Scientific and Technical Advisory Committee (http://www.chesapeake.org/stac/) empanel a group with expertise in criteria assessment, spatial data interpolation, and statistics to assess the scientific defensibility of the CFD. Here we report the findings of this panel.

The primary goal of this panel is to provide an initial scientific review of the CFD compliance approach. This review addresses a wide range of issues including: bias and statistical rigor, uncertainty, practical implementation issues, and formulation of reference curves. Because of the novelty of the CFD approach, the panel has endeavored to research and explain the properties of the CFD and spatial modeling upon which the CFD approach depends to provide a basis for this evaluation. These activities are beyond the scope of the typical review. However, because so little is known about the CFD, it was necessary to expand the knowledge base.

The report is organized into 7 sections. In Section 2 of this report we present the CFD approach as a series of steps, each of which needs to be considered carefully in evaluating its statistical properties. Spatial interpolation is a critical but the most statistically nuanced step in the CFD approach. Spatial interpolation of water quality data in the CBP has to date received little statistical review. In Section 3 we evaluate alternative geostatistical methods as they pertain to the CFD approach. The CFD approach is an attainment procedure, which depends upon statistical comparison between attainment and reference curves. In Section 4, we present alternative types of references curves and discuss statistical properties of each. In Section 5 the statistical properties of CFD curves (applicable to both attainment and reference curves) is elucidated through a series of conditional simulation trials.

In addition to this primary charge, the panel is sensitive to the fact that the CFD will be employed in the enforcement of water quality standards. Use as a regulatory tool imposes a standard of credibility, which we review in Section 6. We use here "best available science" and "best science" criteria to evaluate the overall validity and feasibility of the CFD approach, following guidelines established by the American Fisheries Society and Estuarine Research Federation (Sullivan et al. 2006). These follow other similar criteria (e.g., The Daubert Criteria (Daubert v. Merrell Dow Pharmaceuticals, Inc., 1993) and include:

1. A clear statement of objective
2. A conceptual model, which is a framework for characterizing systems, sating assumptions, making predictions, and testing hypotheses.
3. A good experimental design and a standardized method for collecting data.
4. Statistical rigor and sound logic for analysis and interpretation.
5. Clear documentation of methods, results, and conclusions
6. Peer review.

The panel has made progress in better understanding statistical properties of the CFD approach and overall, we recommend it as a feasible approach and one that qualifies under most criteria for best available science. Still, we believe that our efforts should only represent the beginning of a longer term effort to (1) Use simulations and other means to support statistical comparisons of CFD curves; and (2) Support the CBP's efforts to model water quality data with sufficient rigor in both spatial and temporal dimensions. Research and implementation recommendations follow in Section 7.

## 2.0 BACKGROUND

### 2.1 THE CFD ASSESSMENT APPROACH

The water quality criteria assessment methodology currently proposed by the E.P.A. Chesapeake Bay Program (CBP) involves the use of a Cumulative Frequency Diagram (CFD) curve. This curve is represented in a two dimensional plane of percent time and percent space. This document briefly discusses the reasoning that lead to the development of this assessment tool. The proposed algorithm for estimating the CFD is given and illustrated with small data sets. Some properties and unresolved issues regarding the use of the CFD are briefly discussed. In Section 5, simulation studies explore in greater specificity the multiple issues related to error and bias in the CFD approach.

## Reasoning Behind the CFD Approach

The CFD assessment methodology evolved from a need to allow for variability in water quality parameters due to unusual events. For the water quality parameter to be assessed, a threshold criterion is established for which it is determined that water quality that exceeds this threshold is in a degraded state (For simplicity, we will speak of exceeding the threshold as representing degradation, even though for some water quality constituents such as dissolved oxygen, it is falling below a threshold that constitutes degradation). Because all water quality parameters are inherently variable in space and time, it is unlikely that a healthy bay will remain below the threshold in all places at all times. In the spatial dimension, there will be small regions that persistently exceed the threshold due to poor flushing or other natural conditions. It is recognized by CBP that these small regions of degraded condition should not lead to a degraded assessment for the segment surrounding this small region. Similar logic applies in the temporal dimension. For a short period of time, water quality in a large proportion of a segment may exceed the threshold, but if this condition is short lived and the segment quickly returns to a healthy state, this does not represent an impairment of the designated use of the segment. Recognition that ephemeral exceedances of the threshold in both time and space do not represent persistent impairment of the segment leads to an assessment methodology that will allow these conditions to be classed as acceptable while conditions of persistent and wide spread impaired condition will be flagged as unacceptable. The assessment methodology should first ask how much of the segment (for simplicity, a spatial assessment unit is called a segment, but more detail is given on spatial assessment units in Section 2) is not in compliance with the criteria (percent of space) for every point in time. In a second step the process should ask how often (percent of time) is a segment out of compliance by more than a fixed percent of space. The results from these queries can be presented in graphical form where percent of time is plotted against percent of space (Figure 2.1). It is arbitrary to treat space first and time second. A similar diagram could be obtained by first computing percent noncompliance in time and then considering the cumulative distribution of percent time over space.

If a segment is generally in compliance with the criterion, then one expects a high frequency of dates where the percent out of compliance is low. In this case, the CFD should descend rapidly from the upper left corner and pass not too far from the lower left corner and then proceed to the lower right corner. The trace in Figure 2.1 shows the typical hyperbolic shape of the CFD. The closer the CFD passes to the origin (lower left corner), the better the compliance of the segment being assessed. As the CFD moves away from the origin, a higher frequency of large percents of space out of compliance is indicated.

## Formulating an Estimate of the CFD

The algorithm developed by CBP for estimating the CFD is most easily described as a series of steps. These steps are given in bullet form to provide a frame work for the overall approach. The quickly defined framework is followed by a simple example. This in turn is followed by more detailed discussion of each step.

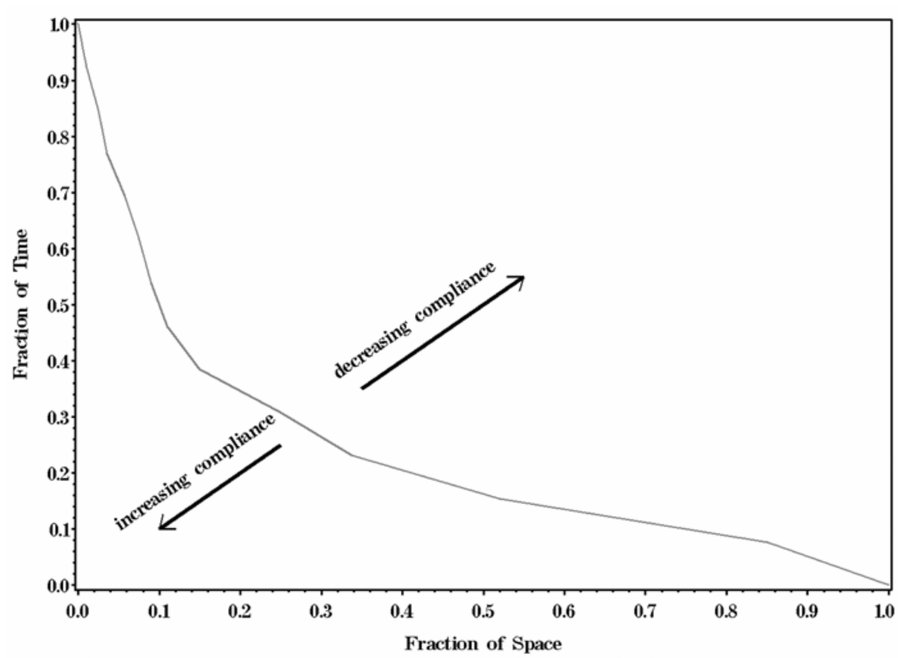


**Figure 2.1.** Illustration of CFD for 12 dates.

The steps:

1. Collect data from a spatial network of locations on a series of dates in a three year assessment period .
2. For each date, interpolate the data for the entire system (e.g. mainstem bay) to obtain estimates of water quality in a grid of interpolation cells.
3. For each interpolation cell assess whether or not the criterion is exceeded.
4. For each assessment unit (e.g. segment), compute the percentage of interpolator cells that exceed the criterion as an estimate of the percent of area that exceeds the criterion.
5. Rank the percent of area estimates for the set of all sample days in the assessment period from largest to smallest and sequentially assign to these ranked percents a value that estimates percent of time.
6. Plot the paired percent of time and percent of area data on a graph with percent of area on the abscissa and percent of time on the ordinate. The resulting curve is the Cumulative Frequency Diagram.
7. Compare the CFD from a segment being assessed to a reference CFD. If at any point the assessment CFD exceeds the reference CFD, that is, a given level of spatial noncompliance occurs more often than is allowed, then the segment is listed as failing to meet it's designated use.

## Simple Numerical CFD Example

For this example, assume a segment for which the interpolation grid is 4 cells by 4 cells. In reality, the number of grid cells is much larger. Also let data be collected on 5 dates. Typically data would be monthly for a total of 36 dates. Let the criterion threshold for this fictitious water quality parameter be 3. In what follows, you will find an illustration of the steps of computing the CFD for these simplified constraints. The three columns of the next page show the first three steps. Column 1 shows fictional data for five dates for five fixed locations in a 2 dimensional grid. Column 2 shows a fictional interpolation of these data to cover the entire grid. Column 3 shows the compliance status of each cell in the grid where 1 indicates noncompliance and 0 indicates compliance.

**Step 1. Collect data at known locations.**

date 1

| | | | |
|---|---|---|---|
| 3 | | | 3 |
| | | 5 | |
| | | | |
| 2 | | | 1 |

date2

| | | | |
|---|---|---|---|
| 1 | | | 1 |
| | | 3 | |
| | | | |
| 1 | | | 1 |

date3

| | | | |
|---|---|---|---|
| 4 | | | 2 |
| | | 2 | |
| | | | |
| 1 | | | 1 |

date4

| | | | |
|---|---|---|---|
| 1 | | | 4 |
| | | 2 | |
| | | | |
| 4 | | | 1 |

date5

| | | | |
|---|---|---|---|
| 1 | | | 3 |
| | | 2 | |
| | | | |
| 1 | | | 1 |

**Step 2. Interpolate the data to grid cells.**

date 1

| | | | |
|---|---|---|---|
| 3 | 4 | 5 | 3 |
| 4 | 4 | 5 | 2 |
| 3 | 3 | 4 | 1 |
| 2 | 3 | 3 | 1 |

date2

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 1 |
| 2 | 2 | 3 | 2 |
| 1 | 3 | 2 | 1 |
| 1 | 1 | 1 | 1 |

date3

| | | | |
|---|---|---|---|
| 4 | 3 | 2 | 2 |
| 3 | 2 | 2 | 1 |
| 2 | 2 | 1 | 1 |
| 1 | 1 | 1 | 1 |

date4

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 2 | 2 | 2 | 3 |
| 3 | 3 | 2 | 1 |
| 4 | 3 | 1 | 1 |

date5

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 3 |
| 2 | 2 | 2 | 2 |
| 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 |

**Step 3. Determine compliance status of each cell.**

date 1

| | | | |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 0 |
| 1 | 1 | 1 | 0 |
| 0 | 1 | 1 | 0 |

date2

| | | | |
|---|---|---|---|
| 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 0 |

date3

| | | | |
|---|---|---|---|
| 1 | 1 | 0 | 0 |
| 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

date4

| | | | |
|---|---|---|---|
| 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 0 |
| 1 | 1 | 0 | 0 |

date5

| | | | |
|---|---|---|---|
| 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

**Step 4: Percent compliance by date.**

| sample date | percent space |
|---|---|
| date 1 | 75.00% |
| date 2 | 18.75% |
| date 3 | 18.75% |
| date 4 | 43.75% |
| date 5 | 12.50% |

**Step 5. Rank the percent of space values and assign percent of time = (100*R/(M+1.0)), where R is rank and M is total number of dates.**

| sample date | ranked percent space | cumulative percent time |
|---|---|---|
| date 1 | 75.00% | 16.67 |
| date 4 | 43.75% | 33.33 |
| date 2 | 18.75% | 50.00 |
| date 3 | 18.75% | 66.67 |
| date 5 | 12.50% | 83.33 |

**Steps 6 and 7:** The plot of the CFD and the comparison to the reference curve are shown in Figure 2.2. For this hypothetical case the assessment area would be judged in noncompliance. For a percent area of 18.75, the allowable frequency on the reference curve is about 53%. That is, 18.75% of the segment area should not be out of compliance more that 53% of the time. For date 3, the estimated frequency of 18.75% noncompliance is 66.67%. Thus the frequency of 18.75% of space out of compliance is in excess of the 53% allowed. The reference curve is exceeded for dates 4 and 1 as well. Note: in this cumulative distribution framework, the actual date is not relevant. One should not infer that noncompliance occurred on that date if the data point associated with a date falls above the reference. Date is being used here as a label for each coordinate pair.

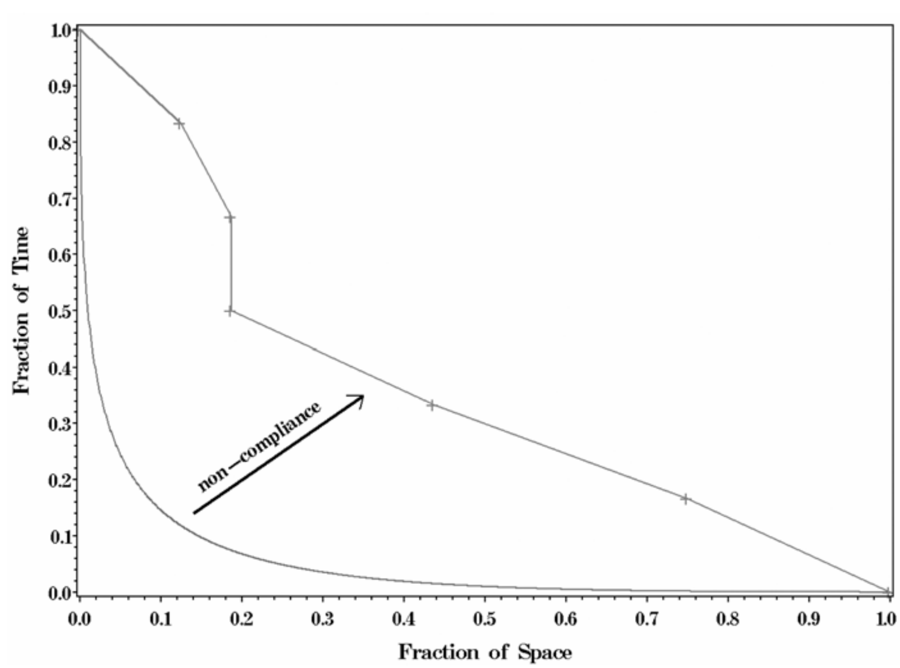


Figure 2.2. Graphical representation of CFD from the above example ('+') with hypothetical reference curve ( smooth).

## Defining the CFD Ideal

As defined above, the CFD is a data driven formulation. But the data used to formulate the CFD are a sample of points taken from a population. Defining the CFD becomes complex when one considers the many different levels for which it might be defined. At one level, the CFD might be defined based on the true state of a segment. Imagine that the state of a segment could be frozen for sufficient time to permit deployment of an analog sampler (that is one that measures water quality continuously rather than in discrete samples) to assess the percent of area out of compliance at that instant. Now stretch that imagination one step further to relax the condition that the segment be frozen and allow that these analog measurements of percent of area out of compliance be determined continuously in time. With this information, a determination of the CFD for the true state of the segment is possible. While the information needed to construct the ideal CFD is not obtainable, it is important to ask how well the CFD based on obtainable data represents this ideal (see also Section 5). Is a data driven CFD consistent for the ideal CFD in the statistical sense? Loosely speaking, consistency implies that the data driven CFD should get closer to the ideal CFD as more data are used. Is the data driven CFD unbiased for the ideal CFD? Unbiasedness implies that even with small amounts of data, the data driven CFD on average covers the ideal CFD.

One might argue that if both the assessment CFD and the reference CFD are data driven, then it is not important for the CFD to approximate the ideal. Even so, it is important to understand the behavior of the CFD as a function of samples size and the relative temporal and spatial contributions to the variance in the water quality parameter. If the curve changes shape as a more data are used, this could result in unfair comparisons between assessment and reference regions. In Section 4, statistical properties for both types of reference curves are evaluated further.

## Defining Reference Curves

Two approaches to defining the reference curve are being considered. One is a biologically based definition. The idea is to identify appropriate reference regions with healthy biological indicators and compute the reference CFD for these regions. For example, healthy benthic IBI scores might be used as indicators of adequate bottom dissolved oxygen. Thus after stratifying by salinity zone and perhaps other factors, a series of dissolved oxygen reference CDF curves could be computed from the existing 20+ year monitoring data base. When it is not possible to establish a reference condition some more arbitrary device must be employed. Alternatives are discussed in Section 4.0.

## Discussion of Each Step

**Step 1 - Data Collection.** One of the advantages of the CFD approach is that it will accommodate a variety of input data and still arrive at the same assessment endpoint. Data collection methods currently in place include: fix station data, cruise track data, continuous monitor data, aircraft flight path data, and satellite imagery data. Because of the interpolation step, all of these data can be used (and potentially combined) with varying degrees of success to estimate the total spatial (to the limit of interpolator pixel size) distribution of a water quality constituent. As noted above, one could construct this process by reversing the roles of time and space. That is, first interpolate over time and then build a cumulative distribution in space. In theory it is an abitrary choice to first standardize the data over space by interpolation and then construct the cumulative distribution in time. However, in practice, there is a greater diversity of sampling designs over space and therefore it is the sampling in the spatial dimension more than the temporal that creates many types of data that must be forced to a common currency.

**Step 2 - Interpolation.** Interpolation is the step that puts data collected at various spatial intensities on a common footing. On the one hand, this is advantageous because data collected at many spatial intensities are available for the assessment process. On the other hand, it can be misleading to accept interpolated surfaces from different data sources as equivalent without qualifying each interpolation with a measure of the estimation error that is associated with each type of data. Clearly an interpolation based on hundreds of points per segment (such as cruise track data) will more accurately reflect the true noncompliance percent when compared to an interpolation based on two or three points per segment (such a fixed station data). Of the various types of interpolation algorithms available, the method proposed for this assessment is kriging. Kriging offers the best available approach for the estimation error associated with interpolation.

**Step 3 - Pointwise Compliance.** Determining the percent of compliance of each cell from each interpolation would seem to be a simple step. If the estimated value for a cell exceeds the criterion then that cell is out of compliance.

While interpolation allows for a standardization of many types of data, pointwise compliance allows for standardization of many criteria. Because compliance is determined at points in time and space, it is possible to vary the compliance criteria in time and space. If different levels of a water quality constituent are acceptable in different seasons, then the criterion can vary by season. It is possible to implement different criteria over space for a segment that bridges oligohaline and mesohaline salinity regimes. It would even be possible to let the criterion be a continuous function of some ancillary variable such as temperature or salinity. All that is required is that the final determination be yes or no for each interpolator cell.

Even the simplicity of this concept becomes diminished when issues of interpolation error are considered. Consider the assessment of two interpolator cells from an interpolation based on cruise track data. One cell near the cruise track has an estimated value is 4 and a standard error of 0.1. A second cell far from the cruise track has an estimated value of 4 and a standard error of 1.0. If the criterion were 3.0, it is fairly certain that the first cell represents exceedance. It is much less certain that the second cell represents exceedance. In the simple assessment of non-compliance, they count the same.

**Step 4 - Percent Non-compliance in Space.** Computing a percentage should also be a simple step. The estimate is simply 100 times the number of cells out of compliance divided by the total number of cells. As a rule, the uncertainty of a binary process can be modeled using a binomial distribution. However, the issue of uncertainty described for step 3 propagates into computing the percent of compliance for a segment. Add to that the fact that estimated values for interpolator cells have a complex dependence structure which rules out a simple binomial model and the rules governing the uncertainty of this step are also complex. The number of interpolator cells, N, is relatively constant and under an independent binomial model the variance of the proportion of cells not in compliance, p, would be (p)(1-p)/N. Intuitively, one expects the variance of p to decrease as the number of data points that feeds the interpolation increases. This expectation has been confirmed by simulation, but the mathematical tools for modeling this propagation of error are yet to be developed.

**Step 5 - Percent of Time.** While the percent of space coordinate of the CFD has simple interpretation of the percent of the segment out of compliance on a given date, the percent of time coordinate is not simply the percent of time out of compliance at a given point. Instead the percent of time coordinate has an interpretation similar to that of a cumulative distribution function. The percent of time coordinate is the percent of time that the associated spatial percent of noncompliance is exceeded. For example, if the (percent space, percent time) coordinates for a point on the CFD are (90,10), one would say that the spatial percent of noncompliance is greater than or equal to 90% about 10% of the time.

This step is very similar to computing an empirical distribution function which is an estimator of a cumulative distribution function. Because of this similarity, one immediately thinks of statistical inference tools associated with empirical distribution functions, such as the Kolmogorov-Smirnov, Shapiro-Wilk, Anderson-Darling, or Cramer-von Mises, as candidates for inference about the CFD. These procedures model uncertainty as a function of sample size only; in this case the number of sample dates. The fact that it does not incorporate the uncertainty discussed the previous steps seems unsatisfactory.

A quick review of probability plotting will reveal several methods on estimating the percent of time coordinate in step 5. Formulae found in the literature include: (R/N), (R - 0.5) / (N - 1). and (R - 0.375) / (N + 0.5), where R is rank and N is sample size. These generally fall in to a family of given by (R - A)/(N - 2A + 1) for various values of A. They are approximately equal, but the choice should be fixed for a rule.

**Step 6 - Plotting the CFD.** Even the plotting of the points is subject to variation, although these variations are somewhat minor compared to the larger issue of assessing the uncertainty of the assessment curve. The simple approach used in the figures above is to connect the points by line segments. In the statistical literature, it is more common to use a step function. If the graph represents an empirical distribution function, each horizontal line segment is closed on the left and open on the right. Because the CFD is an inversion of an EDF it would be appropriate for these line segments to be closed on the right and open on the left.

**Step 7 - Comparing the Curves.** It is at the point of comparing the assessment curve to the reference curve that the issue of uncertainty becomes most important. From the preceding discussion it is clear that uncertainty in the assessment curve is an accumulation of uncertainty generated in and propagated through the preceding 6 steps. If the reference curve is biologically based, it is derived under the same system of error propagation. Developing the statistical algorithms to quantify this uncertainty is challenging.

Even if the uncertainty can be properly quantified, the issue of who gets the benefit of doubt due to this uncertainty is a difficult question to resolve. This is a broad sweeping issue regarding uncertainty in the regulatory process, not a problem specific to the CFD approach. None-the-less, it must be dealt with here as well as elsewhere. One option is to require that the assessment curve be significantly above the reference curve to establish noncompliance. This option protects the regulated party from being deemed out of compliance due to random effects, but if assessment CFD curves are not accurately determined, it could lead to poor protection of environmental health and designated uses. A second option is to require that the assessment curve be significantly below the reference curve to establish compliance. This results in strong protection of the environmental resource, but could lead to the regulated party implementing expensive management actions that are not necessary. Some compromise between these extremes is needed. The simplest compromise is to ignore variability and just compare the assessment curve to the reference curve. As long as unbiased estimation is implemented for both the assessment curve and the reference curve, this third option will result in roughly equal numbers of false positive (declaring noncompliance when in fact compliance exists) and false negative (declaring compliance when in fact noncompliance exists) results. This offers a balanced approach, but there is no mechanism to motivate a reduction of these false positive and false negative errors.

## 2.2 DATA AVAILABLE AND CURRENT METHODS

### OVERVIEW OF TYPES OF DATA AVAILABLE

The Chesapeake Bay monitoring program routinely monitors 19 directly measured water quality paramenters at 49 stations in the mainstem Bay and 96 stations in the tidal tributaries. The Water Quality Monitoring Program began in June 1984 with stations sampled once each month during the colder late fall and winter months and twice each month in the warmer months. A refinement in 1995 reduced the number of mainstem monitoring cruises to 14 per year. “Special” cruises may be added to record unique weather events. The collecting organizations coordinate the sampling times of their respective stations, so that data for each sampling event, or “cruise”, represents a synoptic picture of the Bay at that point in time. At each station, a hydrographic profile is made (including water temperature, salinity, and dissolved oxygen) at approximately 1 to 2 meter intervals. Water samples for chemical analysis (e.g., nutrients and chlorophyll) are collected at the surface and bottom, and at two additional depths depending on the existence and location of a pycnocline (region(s) of density discontinuity in the water column). Correlative data on sea state and climate are also collected.

In addition, Chesapeake Bay Program partner organizations Maryland Department of Natural Resources and the Virginia Institute of Marine Science have recently begun monitoring using a technology known as data flow. DATAFLOW is a system of shipboard water quality probes that measure spatial position, water depth, water

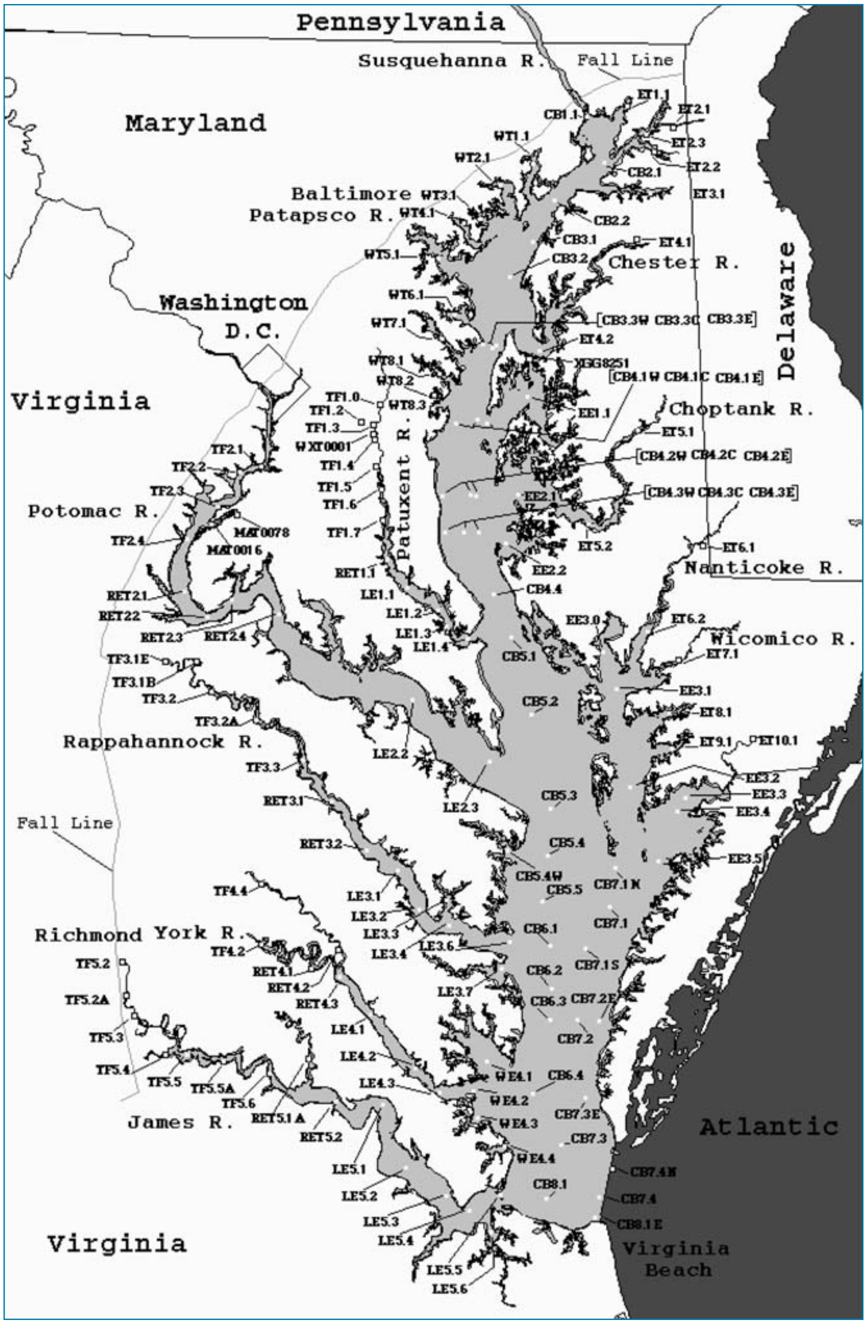


**Figure 2.3.** Map of the tidal water quality monitoring stations.

temperature, salinity, dissolved oxygen, turbidity (clarity of the water), and chlorophyll (indicator of plankton concentrations) from a flow-through stream of water collected near the water body's surface. This system allows data to be collected rapidly (approximately every 4 seconds) and while the boat is traveling at speeds up to 20 knots.

In 2005, the MDDNR Water Quality Mapping Program covered 16 Chesapeake Bay, Coastal Bay and Tributary systems. The St. Mary's, Patuxent, West, Rhode, South, Middle, Bush, Gunpowder, Chester, Eastern Bay, Miles/Wye, Little Choptank, Chicamacomico and Transquaking Rivers will be mapped, as well as Fishing Bay and the Maryland Coastal Bays. In Virginia, dataflow data are available for the Piankatank, York, Pamunkey and Mataponi Rivers.

Beginning in 1990, Chlorophyll-a concentrations were measured over the mainstem Chesapeake using aircraft remote sensing. From 1990-1995, the instrument used for this study was the Ocean Data Acquisition System (ODAS) which had three radiometers measuring water leaving radiance at 460, 490 and 520 nm. In 1996, an additional instrument was added, the SeaWiFS Aircraft Simulator (SAS II). SAS II has sensors at seen wavebands which improves detection of Chlorophyll in highly turbid areas. Since 1990, 25-30 flights per year have been made during the most productive times of year.

The data described above and additional information can be obtained from: www.chesapekebay.net mddnr.chesapeakebay.net/eyesonthebay/index.cfm

www2.vims.edu/vecos/

## Description of the Current Nearest Neighbor/IDW Interpolator

The current Chesapeake Bay Interpolator is a cell-based interpolator. Water quality predictions for each cell location are computed by averaging the nearest "n" neighboring water quality measurements, where "n" is normally 4, but this number is adjustable. Each neighbor included in the average is weighted by the inverse of the square of Euclidean distance to the prediction cell (IDW). Cell size in the Chesapeake Bay was chosen to be 1km (east- west) x 1km (north-south) x 1m (vertical), with columns of cells extending from surface to the bottom of the water column, thus representing the 3-dimensional volume as a group of equal sized cells extending throughout the volume. The tributaries are represented by various sized cells depending on the geometry of the tributary, since the narrow upstream portions of the rivers require smaller cells to accurately model the river's dimensions. This configuration results in a total of 51,839 cells by depth for the mainstem Chesapeake Bay (segments CB1TF-CB8PH), and a total of 238,669 cells by depth for all 77 segments which comprise the mainstem Bay and tidal tributaries.

The Chesapeake Bay Interpolator is unique in the way it computes values in 3 dimensions. The interpolator code is optimized to compute concentration values, which closely reflect the physics of stratified water bodies, such as Chesapeake Bay. The Bay is very shallow compared to its width or length; hence water quality varies much more vertically than horizontally. The Chesapeake Bay Interpolator uses a vertical filter to select the vertical range of data that are used in each calculation. For instance, to compute a model cell value at 5m deep, monitoring data at 5m deep are preferred. If fewer than n (typically 4) monitoring data values are found at the preferred depth, the depth window is widened to search up to d (normally +/-2m) meters above and below the preferred depth, with the window being widened in 0.5m increments until n monitoring values have been found for the computation. The smallest acceptable n value is selectable by the user. If fewer than n values are located, a missing value (normally a –9) is calculated for that cell. A second search radius filter is implemented to limit the horizontal distance of monitoring data from the cell being computed. Data points outside the radius selected by the user (normally 25,000m) are excluded from calculation. This filter is included so that only data that are near the location being interpolated are used.

In this version of the Interpolator, Segment and Region filters have been added. Segments are geographic limits for the interpolator model. For instance, the Main Bay is composed of 8 segments (CB1TF, CB2OH, …,CB8PH). The tributaries are composed of 77 additional segments, using the CBP 2003 segmentation. These segments divide the Bay into geographic areas that have somewhat homogeneous environmental conditions. This segmentation also provides a means for reporting results on a segment basis, which can show more localized changes compared to the whole Bay ecosystem.

Segment and bathymetry information use by the interpolator is stored in auxiliary files. Segment information allows the interpolator to report results on a segment basis which can show more localized changes compared to the whole Bay ecosystem. These segment and bathymetry files have been created for the main bay and all of the larger tributaries. The CBP segmentation scheme was replicated in these files by partitioning and coding the interpolator cells that fall within each segment.

The interpolator also identifies the geographic boundary that limits which monitoring station data are included in interpolation for a given segment through a region file. Use of data regions ensures that the interpolator does not “reach across land” to obtain data from an adjacent river which would give erroneous results. By using data regions, each segment of cells can be computed from their individual subset of monitoring data. Each adjacent data region should overlap by some amount so that there is a continuous gradient, and not a seam, across segment boundaries.

## Current Implementation of CFD

The Chesapeake Bay Program has initiated implementation of the CFD as an assessment tool. The Criteria Assessment Protocols (CAP) workgroup was formed in the fall of 2005 to develop detailed procedures for implementing criteria assessment. This workgroup has developed and implemented procedures that use the CFD process and conducted a CFD evaluation of dissolved oxygen for many designated assessment units.

The CFD methodology was first applied in the Chesapeake Bay for the most recent listing cycle which was completed in the Spring of 2006 and was based on data collected over the period 2002 through 2004. CFDs were developed and utilized primarily for the dissolved oxygen (DO) open- and deep-water monthly mean criteria because there were insufficient data collected to assess the higher-frequency DO criteria components. The clarity criteria were not assessed based on the CFD because there were few systems in which there was sufficient data for an assessment. Chlorophyll criteria were not available from the Chlorophyll criteria team in time to implement a chlorophyll assessment.

In general, the CFD analysis indicated that most of the Bay waters failed one or more of the open-water or deep-water DO criteria components. However, there were also many tributaries in which all of the DO criteria assessed indicated attainment. Thus in this initial application, the CFD method did appear to distinguish between impaired and unimpaired systems in a manner that is consistent with the expectations of the many stakeholders in the CAP workgroup.

In the 2006 application of the assessment methodology, there were many details that required resolution in order to fully implement the methodology. Procedures generally followed the theoretical description as described in Section 2.1, but some details were modified to address unforeseen complications. The following describes some of those details.

In general, data were obtained from the CBP CIMS data base and parameters included date, location, depth, salinity, temperature and the water quality parameter being assessed. Some State data were also incorporated and those data were obtained directly from the relevant State. Once all the data were compiled, they were assigned to a time period based on the sample date. Fixed-station data are normally collected during a monitoring cruise that covers the entire tidal Chesapeake Bay over several days. However, in order to provide a "snapshot" in water quality, the data collected within a cruise are assumed to be contemporaneous in order to perform a single spatial interpolation. For any data not associated with a cruise, a cruise number is assigned representing the closest cruise in time to the collection of each datum. Co-located data points in the same cruise were averaged.

The assessment procedure requires assessment over large areas rather than at points in space. Spatial interpolation using the CBP IDW interpolator was performed for each water-quality criteria parameter for each cruise. Clarity and surface chlorophyll were interpolated in the two horizontal dimensions using inverse distance squared weighting. Dissolved oxygen was first linearly interpolated in the vertical dimension within each column of data beginning at 0.5 meters and continuing at one meter intervals, not to exceed the deepest observation in that column. Each depth was then interpolated horizontally using inverse distance squared weighting. Data regions were specified for each segment in order to prevent the interpolation algorithm from using data points in neighboring tributaries.

Designated uses in the Chesapeake Bay are defined vertically in order separate stable water layers that have differing criteria levels for dissolved oxygen. The surface layer (open water) is that layer defined to be above the pycnocline and thus exposed to the atmosphere. The middle layer (deep water) is defined to be the layer between the upper and lower pycnocline. And the lower layer (deep channel) is defined to be the layer below the pycnocline. Given that the pycnocline is dynamic and moves up and down with each monitoring cruise, the designated use of each grid cell must also be defined based on the available data for each cruise.

The pycnocline is defined by the water density gradient over depth. Temperature and salinity are used to calculate density, which in turn is used to calculate pycnocline boundaries. Density is calculated using the method described in: *Algorithms for Computation of Fundamental Properties of Seawater* (Endorsed by UNESCO/SCOR/ ICES/IAPSO Joint Panel on Oceanographic Tables and Standards and SCOR Working Group 51. Fofonoff, N P; Millard, R C Jr. UNESCO technical papers in marine science. Paris , no. 44, pp. 53. 1983). For each column of temperature and salinity data, the existence of the upper and lower pycnocline boundary is determined by looking for the shallowest robust vertical change in density of 0.1 kg/m3/m for the upper boundary and deepest change of 0.2 kg/m3/m for the lower boundary. To be considered robust, the density gradient must not reverse direction at the next measurement and must be accompanied by a change in salinity, not just temperature.

The depths to the upper pycnocline boundary, where detected, and the fraction of the water column below the lower boundary are interpolated in two dimensions. If no lower boundary was detected the fraction was considered to be zero. The depth to the upper pycnocline boundary tends to be stable across horizontal space and so spatial definition of that boundary using interpolation generally worked well. However, interpolation of the lower boundary is more complicated because the results can conflict with the upper boundary definition or with the actual bathymetry of the Bay. As a result, interpolation of the lower boundary was performed based on “fraction of water column depth”. In that way, the constraints of the upper pycnocline boundary definition and the actual depth were imposed and errors related to boundary conflicts were eliminated.

Assessments were performed based on criteria specific averaging periods. The instantaneous assessment for deep channel dissolved oxygen was evaluated using the individual cruise interpolations. All monthly assessments were based on monthly averages of interpolated data sets. To calculate the monthly averages, each interpolated cruise within a month was averaged on a point-by-point basis. Generally, there were 2 cruises per month in the warmer months and 1 cruise per month in the cooler months. Spatial violation rates are calculated for each temporally aggregated interpolation in an assessment period. For example, for a three-year summer open-water dissolved oxygen assessment, the twelve monthly average interpolations representing the four summer months over three years were used.

## 3. PROTOCOL FOR INTERPOLATING WATER QUALITY

The CFD approach uses the proportion of space in attainment in any given month estimated using an approach based on a statistical model. The current method uses data collected in a specific month at a set of sampling locations within the segment of interest to estimate the parameters of the model. The estimated model is then used to interpolate likely values at unsampled locations, specifically at a set of prediction locations arranged in a grid over the segment. The predictions thus obtained are used to calculate the proportion of space in compliance that month. The current estimation procedure for obtaining predicted values is Inverse Distance Weighting (IDW), a non-statistical spatial interpolator that uses the observed data to calculate a weighted average as a predicted value for each location on the prediction grid. The method calculates the weight associated with a given observation as the inverse of the square of the distance between the prediction location and the observation.

The panel considered several interpolation methods in addition to IDW. Of these, kriging methods emerged as a principal alternative approach for populating the grid of prediction locations. Non-parametric methods were also considered. These include Loess regression or cubic spline methods. These approaches could be advantageous in that they are statistical methods that provide levels of error, but panel analyses and deliberations have been insufficient to provide definitive statements on this class of methods. Table 3.2 which appears in Section 3.3 summarizes our determinations.

## 3.1 KRIGING OVERVIEW

Kriging is a spatial interpolation technique that arose out of the field of geostatistics, a subfield of statistics that deals with the analysis of spatial data. Kriging and the field of geostatistics has been employed in a wide variety of environmental applications and is generally accepted as a method for performing statistically optimal spatial interpolations (Cressie 1991, Schabenberger and Gotway 2004, Diggle and Ribeiro 2006). Applications of kriging in water related research can be found in (Kitanidis 1997, Wang and Liu 2005,Ouyang et al. 2006). References on kriging methodology, geostatistics, and their related statistical development can be found in (Cressie 1991, Diggle et al. 1998, Schabenberger and Gotway 2004, Diggle and Ribeiro 2006).

Kriging can equivalently be formulated in terms of a general linear regression model

$$Y(\boldsymbol{s}) = \beta_0 + \beta_1 X_1(\boldsymbol{s}) \cdots + \beta_p X_p(\boldsymbol{s}) + \varepsilon(\boldsymbol{s}) \qquad (1)$$

with s representing a generic spatial location vector (usually 2-D) assumed to vary continuously over some domain of interest, $Y(\boldsymbol{s})$ the outcome of interest measured at $\boldsymbol{s}$, $X_1(\boldsymbol{s}), \ldots, X_p(\boldsymbol{s})$ potential covariates indexed by location s, and their associated regression effects $\beta_1, \ldots, \beta_p$. Note that covariates must be known at every prediction location. The elements of the spatial vector $\boldsymbol{s}$ can be used as covariates for modeling spatial trends. On the other hand water quality measures such as salinity which may have a strong association with the outcome of interest, is of limited value as a covariate because it is not known at all prediction locations. The uncertainty in this regression relationship is modeled with the random error term $\varepsilon(\boldsymbol{s})$ assumed to have zero mean and constant variance. Spatial data like the type sampled in the Chesapeake Bay water-quality criteria assessments often exhibit a property known as (positive) spatial dependence, observations closer together are more similar than those further away. This property is accounted for in model (1) by allowing $\varepsilon(\boldsymbol{s})$ to have a spatial correlation structure.

Some further specifics on $\varepsilon(\boldsymbol{s})$ are warranted. Common distributional assumptions on $\varepsilon(\boldsymbol{s})$ include normality or log-normality, although kriging can be performed based on other statistical distributions and data transformations (Christenson et al. 2001). The spatial correlation in $\varepsilon(\boldsymbol{s})$ is represented by positive definite functions. These functions can be assumed isotropic where correlation decay depends just on distance, or anisotropic where correlation decay depends on distance and direction. Variograms are another special type of mathematical function closely related to spatial correlation functions that can and are more often used to represent spatial correlation. For purposes here and in many kriging applications, variograms and spatial correlation functions provide equivalent representations of spatial structure. For consistency in what follows only the term variogram will be used in discussions of spatial structure.

While there is considerable flexibility in implementing the error structure of a kriging model, it is possible to generalize somewhat with respect to the error structure of Chesapeake Bay water quality data. Of the three water quality parameters being assessed, chlorophyll and clarity measures tend to follow the log-normal distribution and dissolved oxygen is reasonably approximated by the normal distribution. The horizontal decay rate of spatial correlation does not tend to be directionally dependent. Thus if the bay is viewed as a composite of horizontal layers, isotropic variograms are appropriate for kriging each layer. In a vertical direction, water quality can change rapidly and thus spatial correlation can decay over a short distance. A 3-D interpolation procedure would benefit from use of an anisotropic variogram in order to differentiate the vertical correlation decay from the horizontal correlation decay.

Note, in the literature model (1) is referred to as a universal kriging model. When covariates (the X's) are not considered to influence interpolation of Y the right hand side of model (1) contains just the constant term $\beta_0$ and $\varepsilon(s)$. The resulting model is referred to as the ordinary kriging model. When the spatial structure (variogram) for model (1) is known, statistically optimal predictions for the variable Y at unsampled locations (outside of estimation of possible regression effects) can be derived using standard statistical principles. The optimality criteria results in spatial predictions that are linear in the data, statistically unbiased, and minimize mean squared prediction error, hence referred to as best linear unbiased predictions (BLUPs). The minimized mean squared prediction error is also taken as a measure of prediction uncertainty. In practice, however, spatial structure of the data is unknown, the estimation of which via the variogram function is cornerstone to kriging applications.

To demonstrate let $\{y(s_1), \ldots, y(s_n)\}$ represent a set of spatial data, for example a water-quality parameter such as dissolved oxygen sampled at a set of n spatial locations $s_1, \ldots, s_n$. Assume this data to be a realization of the ordinary kriging version of model (1). The first step in kriging is variogram estimation. There are several methods available, method of moments and statistical likelihood based being two of the more common, all of which though are based on the sample data $\{y(s_1), \ldots, y(s_n)\}$. Without going into detail, this process ends with a chosen variogram function and its parameter estimation, describing the shape and strength (rate of decay) of spatial correlation. There is also a determination, again based on the sampled data, of whether the spatial structure is isotropic or anisotropic. The estimated variogram is then assumed known and kriged interpolations and their interpolated uncertainty are computationally straight forward to generate at numerous locations where data were not observed. Accounting for uncertainty in variogram parameter estimation has commonly been explored using Bayesian methods (Diggle and Ribeiro 2006).

## 3.2 IDW OVERVIEW

The inverse distance weighting method that is currently used in the CFD approach has already been described. Hence, this section provides a short review of IDW's technical details and a comparison of IDW to alternative interpolation methods.

The IDW method is essentially a deterministic, non-statistical approach to interpolating a two or three dimensional space. As a result it lacks statistical rigor so that estimates of the prediction errors are not calculable without additional assumptions. Similar to kriging, IDW predicts a value () at an unobserved site, say at location $s_0$, using a weighted average of the $N$ nearest observed neighbors ($N$ specified by the modeler):

$$\hat{Y}(s_0) = \sum_{i=1}^{N} w_i Y(s_i)$$

where the weights, $w_i$, are inversely related to the distance between locations $s_0$ and $s_i$

$$w_i = \frac{d(s_0, s_i)^{-2}}{\sum_{j=1}^{N} d(s_0, s_j)^{-2}} \quad ,$$

$d(s_0,s_i)$ is the Euclidean distance between locations $s_0$ and $s_i$, and the denominator of the weight is to ensure that the weights sum to 1. The IDW is an exact interpolator in that the predicted values for observed locations are the observed values and the maximum and minimum values of the interpolated surface can occur only at observed sites.

Recent research has compared IDW to other interpolation techniques, most notably variations in kriging (Table 3.1). The authors found that in some cases kriging was at least as good an interpolator as IDW and in some instances better. The non-parametric techniques (splines and similar methods) were not as precise as kriging and IDW. The method used for comparison in virtually all of the research was some variant of cross-validation, a method where some data are kept aside and not used in the model estimation phase and then using the resulting model to predict values for the data kept aside. The predicted and observed values are then compared and a statistic is calculated that summarizes the differences between the two sets of values (observed and predicted).

None of these studies used datasets with highly irregular edges such as are found in the Chesapeake Bay nor did they use any distance metric other than Euclidean distance. Whether one method is preferable to another in these more difficult situations remains unexplored.

Table 3.1. A short list of recent articles comparing the precision of IDW to a subset of other possible interpolation methods.

| Authors | Methods Compared | Variables Manipulated | Conclusions |
|---|---|---|---|
| Kravchenko (2003) | Inverse Distance Weighting (IDW), Ordinary Kriging (OK) | spatial structure and sample grid spacing | IDW better than OK unless sample sizes were fairly large |
| Dille, et al. (2002) | IDW, OK, Minimum Surface Curvature (MC), Multiquadric Radial Basis Function (MUL) | neighborhood size, spatial structure, power coefficient in IDW, sample grid spacing, quadrat size | No interpolator appears to be more precise than another. Sample grid spacing and quadrat size were deemed more important. |
| Valley, et al. (2005) | IDW, OK, Non-parametric Detrend + Splines | spatial structure, sample size, quadrat size | OK tended to be more precise but IDW was very similar |
| Lloyd (2005) | moving window Regression (MWR), IDW, OK, simple kriging with locally varying mean (SKlm), kriging with external drift (KED) | spatial structure, sample size | KED and OK best |
| Reinstorf, et al. (2005) | IDW, OK, KED + deterministic chemical transport models | single dataset was analyzed | OK best |
| Zimmerman, et al. (1999) | 2 types of IDW, UK, OK | spatial structure, sampling pattern, population variance | UK and OK better than IDW |

One final and important issue with IDW is that, as currently used, IDW is a deterministic method which makes no assumptions as to the probability distribution of the data being interpolated. Hence, it does not allow for estimating prediction errors, i.e. it does not allow for the possibility of random variation at interpolation sites. A simple question is whether IDW can be recast in the kriging framework given the similarity in prediction method (weighted average) and hence can a method be found to estimate prediction errors? The short answer is no – the distance function used by IDW, which is an implicit assumption about the autocorrelation function in the spatial field, does not meet the assumptions required for development of a valid variance-covariance matrix describing the spatial covariance. As a result, IDW cannot be modified to take advantage of the statistical knowledge that has been developed for geostatistical analyses such as kriging. This does not imply that other approaches to estimating prediction error are also not possible.

A non-parametric approach for estimating variance was proposed (Tomczak, 1998) in which jack-knifing was used to provide error estimates. 95% confidence intervals for the mean were calculated and then compared to the actual observed values. Not surprisingly, only 65% of the data were captured within their associated confidence interval. The method appears to have been misapplied—the jackknifing method as used estimates the standard error of the mean assuming independent observations. As a result, the confidence interval is not capturing the effect of the spatial dependencies nor is it based on the fact that we are predicting a value for the unobserved site rather than estimating a mean. The development described by Tomczak (1998) should be explored further and other alternatives such as block bootstrapping for variance estimation as well.

## 3.3 NON-PARAMETRIC INTERPOLATION METHODS

There are many variations on spatial interpolation in addition to kriging and IDW. See Cressie (1989) for a review. The committee did not have sufficient time to compare all models, but CBP in encouraged to continue this research. One promising category of models are for interpolation based on non-parametric methods that do not rely on measuring and accounting for spatial autocorrelation. All of the non-parametric approaches would be based on the assumption that the autocorrelation observed in the data is due to unobserved explanatory variables and hence alternative modeling approaches are not unreasonable. The particular set we mention are the regression type analyses with the locational indices (northings, eastings) used as explanatory variables. Examples include generalized additive models (Hastie and Tibshirani, 1990), high-order polynomials (Kutner, Nachtsheim, Neter, and Li, 2004), splines (Wahba, 1990), and locally weighted regression ("loess" or "lowess", Cleveland and Devlin, 1988). In some kriging and IDW methods, large-scale trend is modeled relatively smoothly using locational indices and local smaller-scale variation is modeled using the estimated autocorrelation in conjunction with the values of the variable at nearby observed sites. The nonparametric methods replace estimation of the local variation based on correlation functions with models of the large-scale trend that are less smooth and more responsive to the spatial variation in the observed data. A visual demonstration is given in Figure 3.1 which shows a one-dimensional dataset with Y as the variable to be predicted and X as the location along the one dimensional axis. For example, X could be distance from the mouth of a river and Y could be chlorophyll a concentration.

One advantage of these approaches is that each of the methods has extensive statistical research into estimation of model parameters as well as standard errors for those parameters and for predictions at interpolation sites. Another is that the main modeling decisions are related to bandwidth selection or degree order of polynomial to fit. These decisions can be automated by developing rules for roughness of fit based on reduction in MSE as compared to modeling a straight line (in X). Disadvantages are the same as for kriging, all model estimation is data dependent which means that the spatial configuration and number of sampling sites has a direct influence on the predictions and their error estimates. In addition, a study done by Laslett (1994) comparing kriging and splines indicated that the two methods are similar in predictive power but for certain sampling regimes kriging performs better. We recommend more study since the non-parametric approaches would be easier to implement than kriging.

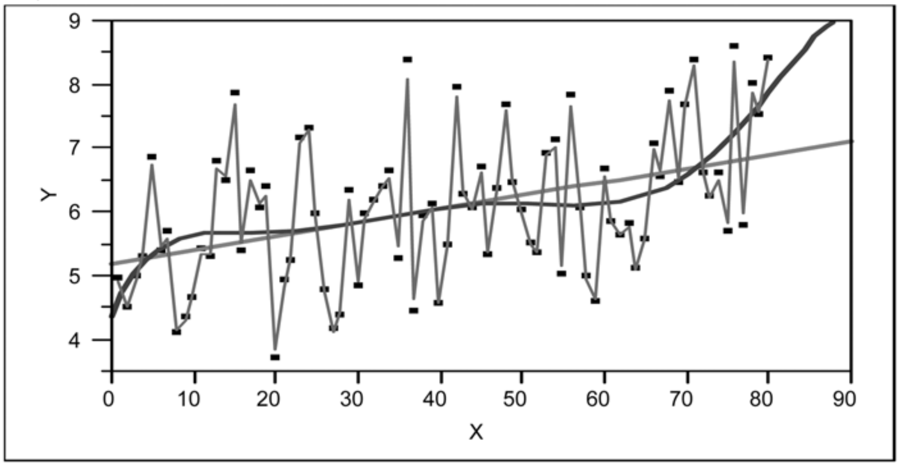


**Figure 3.1.** Bivariate fit of Y By X. Straight line is a linear large-scale trend fit ($R^2$ = 0.19); the moderately wavy line around the straight line is a 6th-order polynomial fit (X enters the model as X, $X^2$, $X^3$, …, and $X^6$; $R^2$ = 0.25); and the jagged line is a spline fit with a very small bandwidth (neighborhood used in local estimation at each X; $R^2$ = 0.90).

## 3.3 COMPARISON OF METHODS

The following describes some of the benefits and potential limitations of kriging in regards to CBP application with some comparisons to the IDW approach towards spatial interpolation outlined in the previous section. Nonparametric methods are not sufficiently developed to include in this comparison. A primary benefit of the kriging methodology compared to IDW is that it is a statistical technique. As such the field of statistics (including kriging) is designed to make inference from sampled data in the presence of uncertainty and the quantity and quality of the sample data are reflected in those inferences. However, kriging is a less than routine type of statistical analysis and requires a certain level of statistical expertise to carry out the process. The short description on variogram estimation provided above merely introduces this involved and often complicated step. This requirement for informed decision making limits the degree to which kriging can be automated and still maintain its flexibility and optimal properties.

Further issues regarding kriging and CBP applications are listed below.

- Kriging is flexible in that it is based on an estimate of the strength of spatial dependence in the data (variogram). Kriging can consider direction dependent weighted interpolations (anisotropy) and can include covariates (universal kriging) to potentially influence interpolations, either simple trends in easting and northing coordinates or water related measures such as sea surface temperature measured by satellite.
- A key feature of a statistical technique like kriging is that a measure of uncertainty (called the kriged prediction variance) is generated along with kriged interpolations. Research has been initiated (i.e., conditional simulation) to

propagate this interpolation uncertainty through the CFD process for generating confidence intervals for estimates of attainment.

- Kriging can be applied in situations where the data are sparse, as in CBP fixed station data, or densely sampled, as in CBP shallow water monitoring. Kriged and IDW spatial interpolations may very well produce near identical results for these two extreme scenarios. However it is the kriging approach that provides a statistical model, the uncertainty of which is influenced by the quantity and quality of data. Knowledge of interpolation uncertainty is crucial for discriminating the improved water quality assessment obtained from densely sampled networks relative to sparsely sampled networks.

As alluded to earlier kriging is an advanced statistical technique and like all such techniques should be carried out by well trained statistician(s) with experience in spatial or geostatistical methodology and experience analyzing water quality data. Assessing model fits (of the variogram and regression model) and kriging accuracy via cross validation and/or likelihood based criteria should be employed routinely.

To further exemplify this point consider kriging the densely sampled shallow water monitoring data which is generated by the DATAFLOW sampling. In addition to the other technical complexities mentioned within, this spatial sampling design may raise other issues not immediately recognized by untrained users (Deutsch 1984).

For kriging in CBP applications one potential methodological drawback is the issue of non-Euclidean distance (Curriero 2006). Current kriging methodology only allows the use of the straight line Euclidean distance as the measure of proximity. However, the irregular waterways in the Chesapeake Bay system may very well suggest other non- standard measures of distance. For example, the spatial design of the fixed station data including those in the Bay mainstem and tidal tributaries. The straight line Euclidean distance may very well intersect land particularly in regions containing convoluted shorelines. There has been research initiated on this topic (Curriero 2006, Jensen et al. 2006, Ver Hoef et al. 2007), however, results are not yet ready for universal use.

Three dimensional interpolations (including depth as the third dimension) are potentially required for CBP applications. The IDW and kriging methodologies, mathematically speaking, certainly extend to three dimensions. However the rapid change of water quality over depth would lead to significant anisotropies in the application three dimensional kriging that would complicate this approach far more than the application of IDW. On the other hand, a simplistic implementation of IDW that does not recognize the rapid decay of covariance over depth would inappropriately reach across the pycnocline when choosing nearest neighbors. Clearly the special properties of water quality in a highly stratified bay require innovation for 3-dimensional interpolations. Another approach would be to apply universal kriging where a third dimension (depth) is used as a covariate. The use of depth as an independent variable is motivated by the observation that often water quality exhibits a predictable trend over depth as for example the trend of DO decreasing with increasing depth. To include depth as a covariate, model (1) would be written as

$$Y(\mathrm{s}) = \beta_0 + \beta_1 \mathrm{Depth}(\mathrm{s}) + \gamma(\mathrm{s}):$$

A third approach to interpolation in three dimensions is to implement 2-D interpolation in layers. Note that the IDW interpolator currently implemented by CBP (Section 2.2) employs a layered strategy by severely restricting (+/- 2m) the vertical distance that may be searched for nearest neighbors. A similar strategy could be implemented using 2-D kriging to interpolate the layers. Which of these approaches is best suited to 3-D interpolation for the bay will depend on the data available and assumptions related to vertical structure. Full 3-D kriging interpolation treats the 3rd dimension as a spatial dimension in the error term $\gamma$ ($\boldsymbol{s}$). The covariate approach requires that the change over depth be a predictable trend. Interpolation in layers assumes that covariance decays so rapidly over depth that it is adequate to treat the layers as independent entities. Data sufficiency requirements increase for all approaches when considering three dimensional interpolations. When data are sparse, again a statistical based approach like kriging allows this to be reflected in prediction uncertainty.

In many applications, attainment or lack of attainment will be so extreme that the assessment end point is clear even without optimizing the error estimation of the CFD. In these extreme cases, IDW or kriging simplified for automation could be sufficient to support the attainment ruling without precise quantification of estimation uncertainty. For these cases, the customized IDW algorithm that is currently implemented by CBP provides a tool with which to begin testing the CFD assessment procedure, but kriging simplified for automation may offer some advantages. Kriging can be simplified for automation by fixing the variogram model to one mathematical form, say exponential, for all applications. With the variogram model fixed, kriging becomes like IDW in assuming the same mathematical form for the spatial dependence for all cases, but it is more flexible than IDW in that the rate of spatial correlation decay could be allowed to vary among applications. In addition, the simplified kriging opens the door for conditional simulation, with potential benefits that are discussed in Section 5. While a simplified kriging algorithm offers some advantages, there are also some potential drawbacks. Because variogram estimation typically entails use of an iterative procedure such as maximum likelihood or non-linear least squares, there is the potential that lack of convergence of these algorithms would be problematic for an automated implementation of kriging.

In terms of computing, IDW is available in commercial GIS software, requiring GIS skills for application. Kriging is available in commercial statistical software and also in the free open source R Statistical Computing Environment (R Development Core Team 2005, Ribeiro and Diggle 2001) and requires programming skills for those software packages.

In summary, kriging is more sophisticated than IDW, but requires greater expertise during implementation to fully exploit its full benefit. Table 3.2 provides a comparison of the capabilities of assessments based simply on: 1) percent of samples, 2) spatial interpolation based on IDW and 3) spatial interpolation based on kriging.

Table 3.2. Comparison of the capabilities of methods available for interpreting data collected for Chesapeake Bay water-quality criteria assessment.

| Attributes | Sample-based | IDW | Kriging |
|---|---|---|---|
| Provides Spatial Prediction | Yes | Yes | Yes |
| Provides Prediction Uncertainty | No | not routine | Yes |
| Uncertainty for CFD | No | No | Yes |
| Deal with Anisotropy | No | Possible, but not routine | Yes |
| Can Include Cruise Track/Fly over | No | Yes | Yes |
| Feasibility of 3 dimensional interpolations | No | Yes | Possible, but not routine |
| Feasibility of mainstem-tributary interpolations | No | Yes | Possible |
| Inclusion of covariates to improve prediction | No | No | Yes |
| Predictions of non-linear functions of predicted attainment surfaces P(y>c) | No | No | Yes |
| Level of Sophistication | Lowest | Low | Very High |
| Automation | Yes | Yes | Possible, but not routine |

## 4.0 CFD REFERENCE CURVES

There are several approaches to defining reference curves that are proposed for use in the CFD assessment methodology. One is a biologically based definition and other approaches are based on an arbitrary allowable frequency (see Section 2). Here we review these options in greater detail.

### 4.1. BIOLOGICAL REFERENCE CURVES

The idea behind biological reference curves is to identify regions of the Bay that have healthy biological indicators and are thus considered to be in attainment of their designated use. CFDs would be developed for these areas in the same way that CFDs would be developed elsewhere, but those curves developed for healthy areas would be considered "reference" curves. For example, healthy benthic IBI scores might be used as indicators of adequate bottom dissolved oxygen.

The success of the CFD-based assessment will be dependent upon decision rules related to the biological reference curves. These curves represent desired segment-designated use water quality outcomes and reflect sources of acceptable natural variability. The reference and attainment curves follow the same general approach in derivation—water quality data collection, spatial interpolation, comparison to biologically-based water quality criteria, and combination of space-time attainment data through a CFD. Therefore, the biological reference curve allows for implementation of threshold uncertainty as long as the reference curve is sampled similarly to the attainment curve. Bias and uncertainty are driven in CFD curves by sample densities in time and space. Therefore, we advise that similar sample densities are used in the derivation of attainment and reference curves. As this is not always feasible, analytical methods are needed in the future to equally weight sampling densities between attainment and reference curves.

## 4.2. CBP DEFAULT REFERENCE CURVE

In some cases, the development of biologically-based reference curve is not possible due to lack of data describing the health of the relevant species. In such cases, a more arbitrary approach is required since better information is not available. EPA recommends the use of a default curve in cases where a biologically-based one is not available. That default curve is defined by these properties:

1. symmetric about the 1:1 line,
2. hyperbolic,
3. total area = 0.1, and
4. pass through (1,0) and (0,1)

(see EPA, 2003; page 174). The equation that describes this figure is defined by the equation:

$$(x+b) * (y+b) = a$$

Where: $b = 0.0429945$

$a = b^2 + b$

This reference curve is illustrated in Figure 4.1 by curve 1.

An alternative default reference curve might be formulated by extending the arbitrary allowance of 10% exceedance into the two dimensional framework of the CFD.

The criterion threshold is a value that should be rarely exceeded by a population at healthy levels. When the population is unidimensional, say concentration in a point source effluent, then one can obtain this upper threshold based on the simple distribution of values in a healthy population (Figure 4.2). The ninetieth percentile of this distribution might be chosen as the criterion threshold. Thus in this example, 10% noncompliance is allowed because this level of noncompliance is expected in a healthy population. A standard technique for estimating distribution percentiles is to assume a mathematical form for the distribution, e.g., the normal distribution, and to estimate the percentile as some number of standard deviations above the mean. The 90th percentile of the normal distribution is 1.2815 standard deviations above the mean.

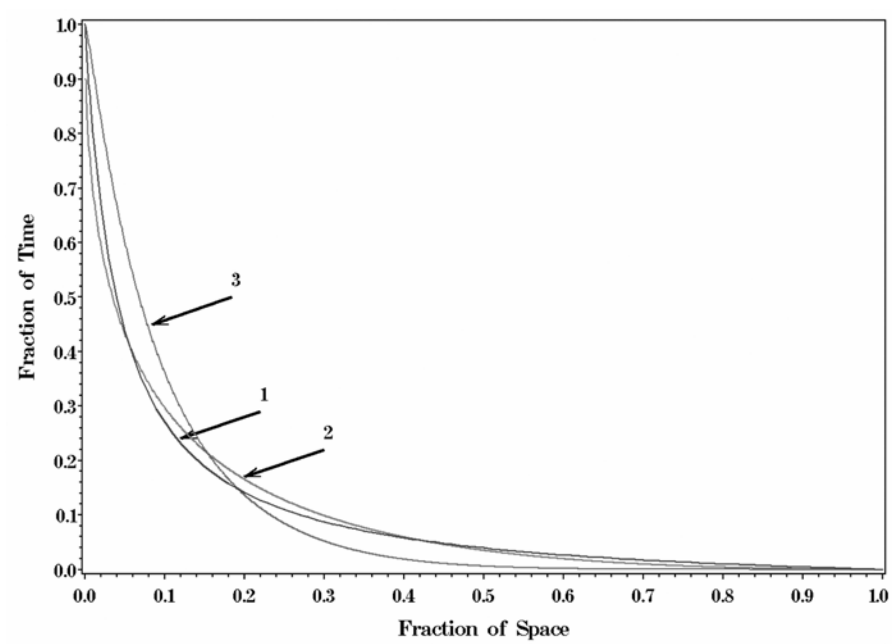


**Figure 4.1.** Illustrations of three reference curves: 1) the standard CBP reference curve derived to cover 10% of the percent space by percent time plane (curve 1); 2) a reference curve based on 10% exceedance frequency and a temporal-spatial variance ratio of 1.0 (curve 2); and 3) a reference curve based on 10% exceedance frequency and a temporal-spatial variance derived from chlorophyll data (curve 3).

When regulating populations that are distributed in both space and time, this simple concept for regulating noncompliance must be extended to account for the variability in each dimension. While there is some added complexity in the mathematics, the fundamental concept remains the same: That is, to set the criterion threshold at a certain distance above the mean so that exceedance of that threshold will be rare in a healthy population. In this case, the distance by which the threshold must exceed the mean is a function of both the spatial and temporal variance components as described below.

To establish these criteria thresholds for populations with two components of variance, assume the simple model:

$$Y_i(\boldsymbol{s}_j) = \mu + \alpha_i + \beta_i(\boldsymbol{s}_j)$$

where:

$\mu$ is the desired mean level of chlorophyll (in log space)
$\alpha_i$ is a random term for variation over time with variance $\sigma^2$,
$\beta_i(\boldsymbol{s}_j)$ is a random term for variation over space with variance $\sigma^2_\beta$
$Y_i(\boldsymbol{s}_j)$ is a water quality constituent measured at time i and location $\boldsymbol{s}_j$.

The variance of $x_{ij}$ is $\sigma^2_\alpha + \sigma^2_\beta = \sigma^2$. The standard dev of $x_{is}$ is sqrt($\sigma^2$) = $\sigma$. It is common to allow an overall 10% exceedance rate without declaring an assessment unit out of compliance. We would expect 10% of the $x_{is}$ to fall above $\mu$ + 1.2815*$\sigma$

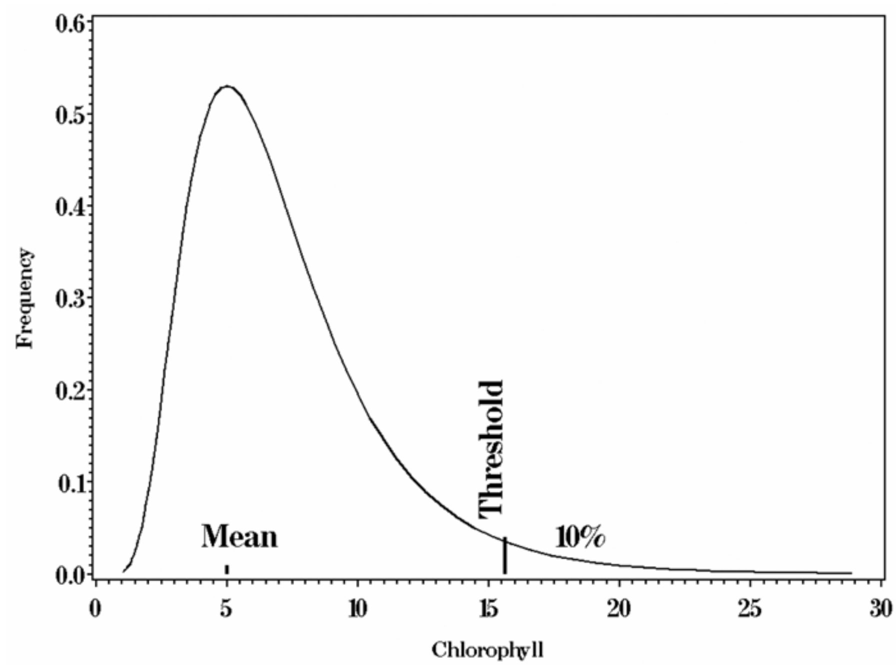


**Figure 4.2.** Hypothetical lognormal distribution that might be typical of Chlorophyll. The figure illustrates the relation of the geometric mean and the criterion threshold set at the 90th percentile.

where 1.2815 is the 90th percentile of the standard normal distribution. Thus (assuming normality) a population with spatial and temporal variance characterized by $\sigma^2_\alpha$ and $\sigma^2_\beta$ that has a mean that is 1.2815*$\sigma$ below the threshold criterion should have an exceedance rate of 10% over space and time. Note that the reference curve is determined by the ratio $\sigma^2_\alpha/\sigma^2_\beta$ and the distance in standard deviations of the mean from the threshold. The actual values of the variance components, the mean, and the threshold, are not important as long as the relationships hold. Thus as long as the variance ratio is consistent, and mean to threshold distance is a fixed number of standard deviations, the same reference curve will serve for all seasons and regions.

Letting chlorophyll observed in the decade of the 1960s serve as a reference population, the parameters in Table 4.1 can be used to construct this reference curve based on the variance ratio and the mean to threshold distance given in the table. The ratio $\sigma^2_\alpha/\sigma^2_\beta$ is computed as the ratio of the temporal variance term and the spatial variance term. The mean to threshold distance is computed to be 1.2815$\sigma$ for all regions and seasons. Based on there parameters, a reference curve for chlorophyll can be derived (curve 3 , Figure 4.1). For comparison a reference curve based on a variance ratio of 1.0 (curve 2, Figure 4.1) and the standard CBP reference curve (curve 1, Figure 4.1) are also shown.

**Table 4.1.** Chlorophyll criteria derived by computing and upper threshold based on predicted means for mid-flow1960s chlorphyll data.

| Season | Salinity Zone | Mean Log(chl) | GMmean (chl) | Temporal Variance | Spatial Variance | Std Dev log(chl) | Threshold Criterion log(chl) | Threshold Criterion (chl) |
|---|---|---|---|---|---|---|---|---|
| Spring | OH | 0.7684 | 5.87 | 0.0233 | 0.0658 | 0.2985 | 1.2594 | 18.17 |
| Summer | OH | 1.1693 | 14.77 | 0.0233 | 0.0658 | 0.2985 | 1.6603 | 45.74 |
| Spring | MH | 0.4137 | 2.59 | 0.0233 | 0.0658 | 0.2985 | 0.9047 | 8.03 |
| Summer | MH | 0.8626 | 7.29 | 0.0233 | 0.0658 | 0.2985 | 1.3536 | 22.58 |
| Spring | PH | 0.1386 | 1.38 | 0.0233 | 0.0658 | 0.2985 | 0.6296 | 4.26 |
| Summer | PH | 0.218 | 1.65 | 0.0233 | 0.0658 | 0.2985 | 0.709 | 5.12 |

Relative to the standard reference curves, the curve based on the observed variance ratio for chlorophyll is more restrictive of events where large portions of the population are out of compliance. For example, the CBP standard reference (curve 1) would allow 40% of area to exceed the criterion threshold up to about 6% of the time. The proposed chlorophyll reference curve (curve 3) would restrict occurrences of 40% of area out of compliance to about 2% of the time. Conversely, the proposed curve (curve 3) allows a higher frequency of events where a small percentage of space in out of compliance. For example, 10% of space is allowed out of compliance 36% of the time under the proposed curve and 27% of the time under the standard curve.

While there is mathematical and statistical logic underpinning this proposed chlorophyll reference curve, it is important to remember that it is based on parametric models and simplifying assumptions. It is recommended that validation exercises be performed to insure that the general shape of CFD curves generated from data collected in near reference conditions is approximated by the proposed curve.

### 4.3 ACCOMMODATING SEASONALITY IN REFERENCE CURVES

The degree of acceptable exceedance can vary with season. For example, benthos are less tolerant of hypoxia in warmer water temperatures. In addition, the threshold criterion may never be exceeded in some seasons and frequently be exceeded in others. By combining seasons, the acuteness of a specific seasonal exceedence is diluted by data from the acceptable season(s). To some extent, seasonal differences can be accommodated by changing the threshold criterion among seasons. However, there may still be a need to develop separate reference curves by season.

## 5.0 REVIEW CFD STATISTICAL PROPERTIES INCLUDING BIAS, PRECISION, AND INFERENCE

The CFD as an assessment tool is a relatively new and unstudied concept. Its close relationship to the empirical distribution function does give some insight on the mathematical behavior of the CFD. In this section we review some of the properties of the CFD and discuss the complications that arise from these properties when the CFD is used as an assessment tool. After defining the population which determines the CFD, we go on to discuss the currently proposed sampling and estimation scheme, sources of error in the estimation scheme, and problems that result from these. The goal is to succinctly define these problems and elucidate possible solutions. This section will cover: the behavior of the CFD as a function of temporal and spatial variance, methods for construction CFD reference curves, the influence of sampling and estimation variance on the CFD shape, and feasible methods for developing statistical inference tools.

## 5.1 REVIEW OF CFD PROPERTIES

With any statistical application, it is important to distinguish between the true descriptive model underlying the population being sampled and the estimate of this model derived from the data collected in a sample. As described above, the CFD has a data driven definition where the CFD is constructed based on a sample from a population for some water quality parameter. This population is a continuous random process over space and time.

In order to quantify the statistical properties of the CFD, the CFD is defined in terms of a population of experimental units. This approach is a discrete approximation of the continuous random process in both time and space. However, the estimation scheme involves interpolation to discrete units in a spatial dimension and discrete days in the temporal dimension. To facilitate an understanding of the relation of the estimator to the true population, it seems reasonable to use a discrete approximation as the model for the true population.

## 5.2 DEFINING THE CFD IDEAL

The population will be defined as having different sizes of experimental units in much the way we think of a population that gives rise to a nested design or repeated measures design. The Chesapeake Bay will be partitioned into segments. Assessment will be done for each segment based on a three year record of the segment. Thus a three year period for the segment defines the entire population that will be partitioned into experimental units. The continuous time dimension is partitioned into days to form the primary units which are the state of a segment for a day. Call this a **Segment-Day**. Let there be **M** segment-days in the assessment period (typically 3 x 365). The continuous spatial dimension is partitioned into **N** 3-dimensional **cells** (may range from hundreds to thousands). The state of each cell for a day will be a unit nested within the segment-day. The attribute of interest will be a measure of water quality for each cell for a day. Examples might be the mean level of Chlorophyll-a in the cell for one day or the minimum of dissolved oxygen in the cell during the day. Let **Y** be a random variable for the attribute of interest and consider the following model

$$Y_i(\boldsymbol{s}_j) = \mu + \alpha_i + \beta_i(\boldsymbol{s}_j) \qquad \textbf{Eqn 5.1.1.1}$$

the vector $\underline{\alpha}$ will be assumed to have expectation $\underline{\mathbf{0}}$ and variance $\sum_{\alpha}$ and each vector $\underline{\beta_{\mathbf{i}}}$ will be assumed to have expectation $\underline{\mathbf{0}}$ and variance $\sum_{\beta\mathbf{i}}$**.**
**i** is the ordinal index for days and
***s*** is a vector valued ordinal for spatial location.

Under this model, $\sum_{\alpha}$ defines the correlation over time at the segment-day level and $\sum_{\beta\mathbf{i}}$ defines correlation over space that occurs cell to cell within a day.

Let $\mathbf{C}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$ be a collection of threshold limits that define the acceptable criterion for the measured attribute. If $\mathbf{Y}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$ exceeds $\mathbf{C}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$ in a cell, that cell is called degraded. The criterion is allowed to vary in both time and space so that in theory each $\mathbf{Y}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$ might be compared to a unique $\mathbf{C}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$.. It may vary over time because different levels of **Y** may be acceptable in different seasons. It may vary over space because different levels of **Y** may be acceptable in different salinity regimes so that even within a segment, **C** may be a function of salinity. As a rule, it is anticipated that $\mathbf{C}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$ will be constant for regions of space and time such as salinity zones and seasons.

Now convert the measured attribute $\mathbf{Y}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})$ to a Boolean response as follows

$$\mathbf{TY}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}}) = \mathbf{I}(\mathbf{Y}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}}) > \mathbf{C}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}})) \quad \begin{aligned} &= 1 \text{ if } \mathbf{Y}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}}) > \mathbf{C}_{\mathrm{i}}(\boldsymbol{s}_{\mathrm{j}}) \\ &= 0 \text{ otherwise} \end{aligned} \qquad \textbf{Eqn 5.1.1.2}$$

Thus **TY** takes the value 1 when **Y** exceeds the threshold defined by **C**. Using **TY**, we summarize the state of a segment on one day as the fraction of that segment that is out of compliance

$$P_i = (1/N)\sum_{j=1}^{N} TY_i(s_j) \qquad \textbf{Eqn 5.1.1.3}$$

The CFD that we wish to estimate is one minus the cumulative distribution function of the $P_i$'s. If $P_{(i)}$ represents the ordered values of the $P_i$'s for any assessment period, then let

$$G(p) = (1/M)\sum_{i=1}^{M} I(P_{(i)}\,{}^{3}\,p) \qquad \textbf{Eqn 5.1.1.4}$$

**G** defines the CFD that if it were known would be used for an exact assessment. The cumulative distribution function is determined by the mean and variance of the ideal population. This population is defined with a spatial variance component and a temporal variance component. The final CFD shows the cumulative percent of time that a certain percent of space is below the criterion threshold. If the CFD shows that water quality in a segment is beyond the threshold for too much space and too much time, then the segment is classified as impaired.

For one assessment period, **G** can be considered exact as defined above, but recognize that even this is only one observation of the many possible observations of **G** that could result from sampling different assessment periods.

Assume for simplicity that **Y** is normal. If $\sum_{\alpha}$ were 0 so that **Y** had constant expectation over time and if $\sum_{\beta}$ were of the form $\boldsymbol{\sigma}^2\mathbf{I}$ then each cell on each day would have constant probability of exceeding a constant value of **C** given by $\mathbf{1 - \Phi(C)}$

where $\Phi$ is the normal cumulative density function. In this greatly simplified scenario, $\mathbf{P_i}$ would be the outcome of **N** independent Bernoulli trials. The ideal CFD would be the cumulative distribution function of **M** outcomes of a binomial random variable with **N** trials. If we allow $\sum_\beta$ to have positive off diagonal elements**,** then the Bernoulli trials become dependent (i.e. adjacent cells are more likely to either both exceed or both meet the standard than distant cells). This should make the distribution of the $\mathbf{P_i}$ more variable than under the independent binomial model, but the expectation of $\mathbf{P_i}$ would be constant over time. If we relax the assumption that $\sum_\alpha$ is 0, then the expectation of the $\mathbf{P_i}$ would vary over time which would increase the variability of the $\mathbf{P_i}$ even more.

Under the simplifying assumptions of independence, constant mean, and constant variance, it is possible to obtain an analytical formulation for the CFD based on the parameters of **Eqn 5.1.1.1**. However, when the more realistic time dependent, space dependent model with seasonal nonstationarity is considered, an analytical formulation is not tractable. The lack of an analytical formulation for this estimator under realistic dependence assumptions, e.g. non-trivial $\sum_\alpha$ and $\sum_\beta$, points toward computer intensive simulation techniques to develop statistical inference procedures for this problem. None-the-less, it is interesting to consider the behavior of the CFD under the simplified model.

## 5.3 CFD BEHAVIOR UNDER A SIMPLIFIED MODEL

In what follows, the behavior of the CFD under various parameter formulations for Equation 5.1.1.1 are presented in graphical form. There are four parameters involved: $\boldsymbol{\mu}$ the population mean, $\sigma_\mathbf{t}$ the temporal variance, $\sigma_\mathbf{s}$ the spatial variance, and **C** the criterion threshold. In the examples that follow, three of these parameters are held constant and the fourth is varied to illustrate the effect of the varied parameter.

In this exercise, the parameters of Equation 5.1.1.1 are simplified as follows: $\sum_\alpha = \sigma_\mathbf{t}$ **I** and $\sum_\beta = \sigma_\mathbf{s}$ **I,** where **I** is the identity matrix. Thus in both the temporal and spatial dimensions, independence and constant variance is assumed.

**Example 1.** Example 1 considers the effect of changing the population mean on the shape of the CFD.

**Table 5.1.** Parameter values and key for the family of curves shown in Figure 5.1.

| $\boldsymbol{\mu}$ | $\boldsymbol{\sigma_t}$ | $\boldsymbol{\sigma_s}$ | **c** | color | curve number |
|---|---|---|---|---|---|
| 5 | 1 | 1 | 5 | Red | 1 |
| 4 | 1 | 1 | 5 | Orange | 2 |
| 3 | 1 | 1 | 5 | Brown | 3 |
| 2 | 1 | 1 | 5 | Green | 4 |
| 1 | 1 | 1 | 5 | Blue | 5 |

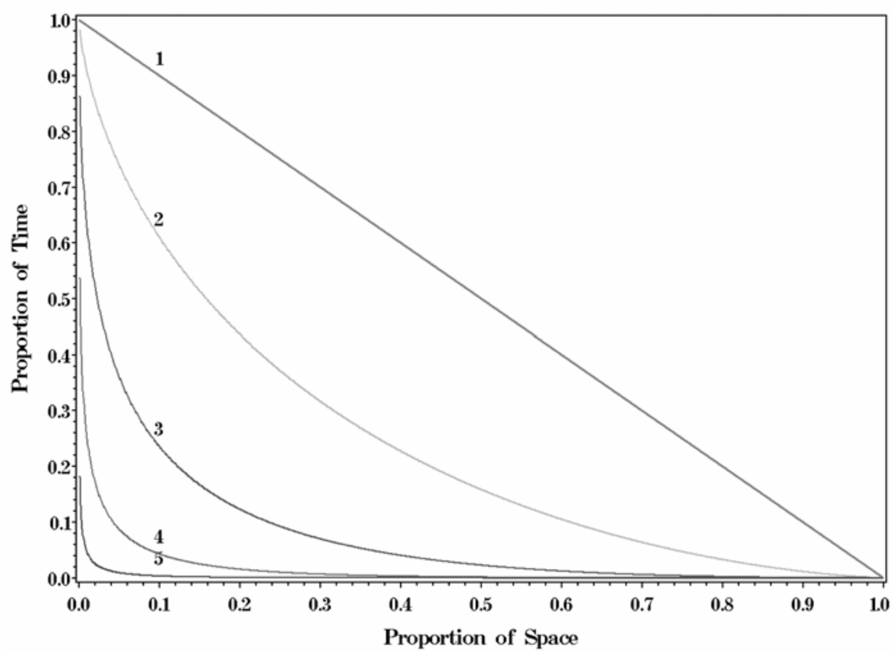


**Figure 5.1.** A family of curves illustrating the behavior of the CFD as the population mean decreases from the criterion threshold. The parameter values for each curve and the corresponding curve number are given in Table 5.1.

Note that when the population mean is equal to the criterion threshold, the CFD is a diagonal line from upper left to lower right (Figure 5.1, curve 1). This is largely an artifact of using symmetric distributions, the normal, for both the time and space variance components. That is, when the population median is equal to the criterion threshold, we expect an average of 50% noncompliance over time and we expect the exceed 50% noncompliance 50% of the time.

As the overall population mean decreases from the criterion threshold, the family of curves tends to move from the diagonal line toward the lower left corner. Thus a reference population, which should have a small probability of exceeding the criterion threshold might have a shape similar to the green curve. This illustrates the importance of the shape of the CFD in measuring compliance. A CFD from a highly compliant population will tend to hug to lower left corner similar to the blue and green curves. As the population mean approaches the criterion threshold, the CFD approaches curve 1. If the population mean were to exceed the criterion threshold, the CFD would tend toward the upper right corner.

**Example 2.** Example 2 considers the effect of changing the temporal variance on the shape of the CFD. Note that the population mean is held constant at 3 which corresponds to curve 2 of the preceding example.

**Table 5.2.** Parameter values and key for the family of curves shown in Figure 5.2

| $\mu$ | $\sigma_t$ | $\sigma_s$ | c | color | curve number |
|---|---|---|---|---|---|
| 3 | 1 | 1 | 5 | Red | 1 |
| 3 | 2 | 1 | 5 | Orange | 2 |
| 3 | 3 | 1 | 5 | Brown | 3 |
| 3 | 4 | 1 | 5 | Green | 4 |
| 3 | 5 | 1 | 5 | Blue | 5 |

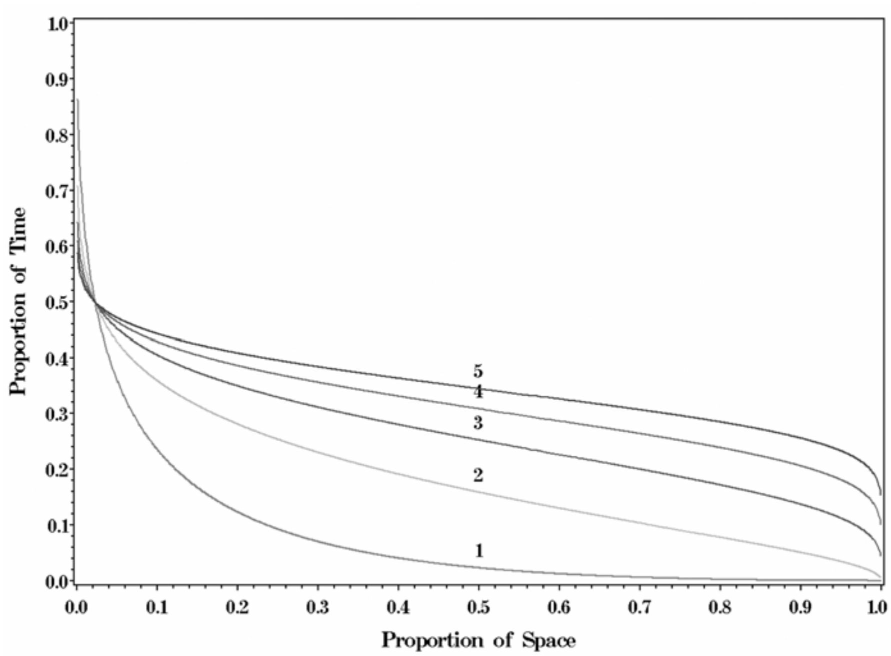


**Figure 5.2.** A family of curves illustrating the behavior of the CFD as the temporal population variance increases. The parameter values for each curve and the corresponding curve number are given in Table 5.2. Note that the curve 1 here has the same parameters as curve 2 in Figure 5.1.

As temporal variance increases, the frequency of large proportions of space going out of compliance increases (Figure 5.2, lower right). Conversely, the frequency of small proportions of space out of compliance (i.e. large proportions of space being in compliance) decreases (Figure 5.2, upper left). That is, shifting the daily mean either down or up tends to shift the entire segment toward or away from compliance.

In preparing water clarity CFDs for reference areas defined by having successful SAV beds, it is not unusual to find a curve shape similar to Figure 5.2 orange or yellow curves. This pattern suggests that SAV is tolerant of ephemeral events of spatially broad degraded water clarity. If water clarity is persistently degraded over portions of the area, SAV may be impaired.

**Example 3.** Example 3 considers the effect of changing the spatial variance on the shape of the CFD. Again the population mean is held constant at 3 which corresponds to the curve 2 of the first example.

**Table 5.3.** Parameter values and key for the family of curves shown in Figure 5.3

| $\mu$ | $\sigma_t$ | $\sigma_s$ | c | color | curve number |
|---|---|---|---|---|---|
| 3 | 1 | 1 | 5 | Red | 1 |
| 3 | 2 | 1 | 5 | Orange | 2 |
| 3 | 3 | 1 | 5 | Brown | 3 |
| 3 | 4 | 1 | 5 | Green | 4 |
| 3 | 5 | 1 | 5 | Blue | 5 |

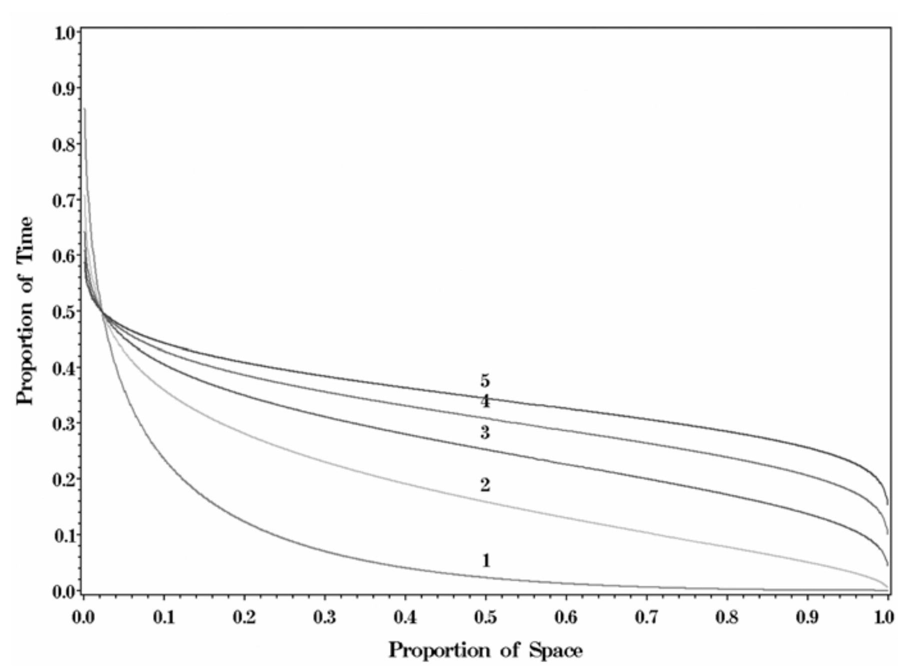


**Figure 5.3.** A family of curves illustrating the behavior of the CFD as the spatial population variance increases. The parameter values for each curve and the corresponding curve number are given in Table 5.3.

Increasing the spatial variance results in a family of curves that is complementary to those that follow an increase in temporal variance. Increasing spatial variance results in a higher frequency of small proportions being out of compliance. It is not so much an all-or-nothing phenomenon.

**Example 4.** Example 4 considers the effect of changing both temporal and spatial variance on the shape of the CFD.

Table 5.4. Parameter values and key for the family of curves shown in Figure 5.4.

| $\mu$ | $\sigma_t$ | $\sigma_s$ | c | color | curve number |
|---|---|---|---|---|---|
| 3 | 1 | 1 | 5 | Red | 1 |
| 3 | 2 | 2 | 5 | Orange | 2 |
| 3 | 3 | 3 | 5 | Brown | 3 |
| 3 | 4 | 4 | 5 | Green | 4 |
| 3 | 5 | 5 | 5 | Blue | 5 |

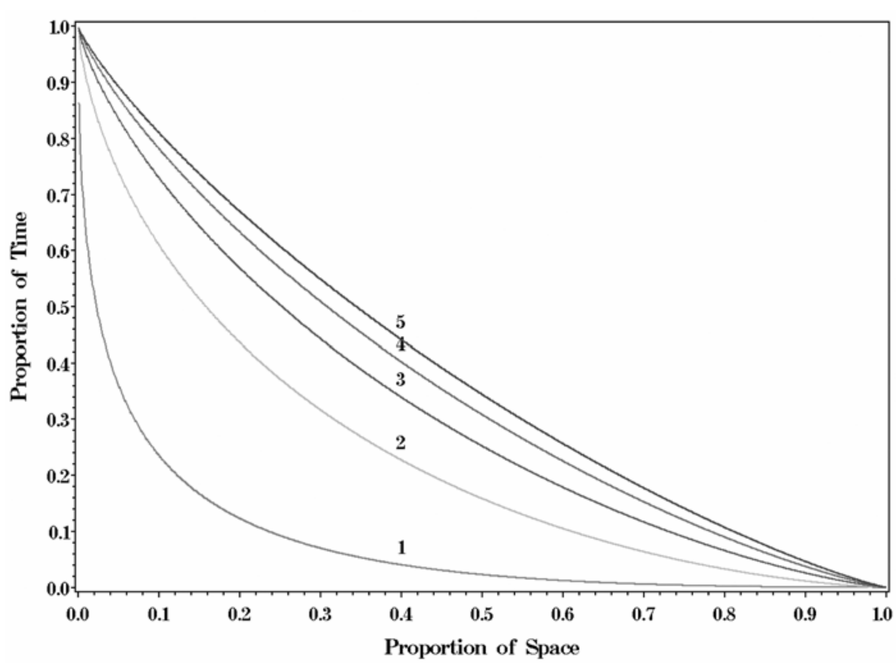


Figure 5.4. A family of curves illustrating the behavior of the CFD as both temporal and spatial variance increases. The parameter values for each curve and the corresponding curve number are given in Table 5.4.

Increasing the spatial and temporal variance together has the opposite effect of decreasing the population mean. The CFD tends to move in a direction of noncompliance. Thus compliance as measured by the CFD depends on the relative values of the population mean, the temporal and spatial variance, and the criterion threshold. Increasing the population mean has the same effect as decreasing the criterion threshold. Increasing population variance has the same effect as increasing the mean or decreasing the criterion threshold. In a sense, the CFD is measuring the distance between the population mean and the criterion threshold in units of variance analogous to a simple t-test. A nuance introduced here that has no analogy in the t-test is that the ratio of spatial to temporal variance controls the symmetry of the curve.

## 5.4 UNCERTAINTY AND BIAS

In Section 5.1., it was shown that the shape of the CFD is a critical element to determining compliance. Thus it is important that this shape be primarily determined by the state of compliance of a segment and not be influenced by factors not relating to the status of compliance. Because the CFD is constructed based on data that are a sample from the whole, it is clear that some uncertainty in the CFD will result. In addition, the CFD is a function of the empirical distribution function (EDF) of fraction of space in compliance. The shape of this EDF is determined by the mean and variance of the sample. Thus any factor, such as sample size, that affects the precision of the fraction of space estimate, will affect the shape of the CFD. In this section we review the effect of noncompliance factors on the shape of the CFD.

### Sample Size and Shape

As noted, because the CFD is a function of the EDF of estimates of "fraction of space", any factor affecting the precision of the estimate of fraction of space in exceedance will affect the shape of the CFD. In particular, the number of samples used for each p-hat (% exceedence) will affect precision. For a given segment, this fraction will be estimated more accurately if twelve samples are used to form the interpolated surface rather than six. Because of unknown spatial dependence in the data, it is difficult to analytically quantify the magnitude of this sample size effect. Therefore simulation analysis was employed to address this issue.

Numerous simulation tests were performed. These begin with a simulation of structurally simple data that have no temporal or seasonal trend and progress to simulated data that mimic the temporal and spatial structure of observed data. Because the results from this latter simulation are most relevant, these are the results that are presented and discussed.

### Simulation Experiment

Simulated data were created to mimic the properties of surface chlorophyll in the Patuxent estuary. Data were created to fill a 5 by 60 cell grid which approximates the long and thin nature of an estuary. These data have mean zero and a spatial variance-covariance structure chosen to approximate the spatial variance-covariance structure of cruise-track chlorophyll observed in the Patuxent estuary. Thirty-six grids of data were simulated to represent 36 months in a three year assessment period. The temporal and spatial trends were added to the simulated data by adding in means computed for each month and river kilometer during the period Jan 1, 1991 to Dec 31, 1993. Simulated data were created using the "grf" function of the Geostatistical Package "geoR" of the R-package.

After the full population of data was simulated for 3 year assessment period, a sampling experiment was conducted to assess the effect of sample size on the shape of the CFD. First, as a benchmark, a CFD was computed using all of the simulated data. To simulate the effect of sampling, a sample of fixed size was randomly selected from each the 36 5x60 grids of data. Using these samples, kriging (krige.conv function of geoR) was used to populate each monthly grid with estimates. These estimated chlorophyll surfaces were used to compute an estimate of the CFD which was graphically compared to the benchmark (Figure 5.5). For a fixed sample size, the process was repeated until it was clear whether the differences between the benchmark CFD and the estimated CFDs were due to variance or bias. To assess the effect of sample size, the process was repeated for several sample sizes.

The effect of sample size on the shape of the CFD is consistent with expectations based on the relation of the CFD to the empirical distribution function (Figure 5.5). As sample size decreases, the variance of the estimated values of fraction of space increases. This increase in variance results in the estimated CFD being to the left of the true curve for low values of fraction of space and to the right of the true curve for high values of fraction of space. This assessment has been repeated many times, varying the threshold criterion, systematic vs. random sampling, the level of variability in the simulated data, and so on. This sample size effect persists for every case where realistic estimation is employed.

### Sampling Scale and Shape

As shown above (Figures 5.2–5.4) the shape of the CFD is a function of the ratio of temporal and spatial variance. To the extent that the ratio of these variance components in the data represent the true state of nature, this is acceptable. However, under a model with strong spatial and temporal dependence, the ratio of these variance components might be influenced by the scale of sampling in the spatial and temporal dimensions. For example, samples collected far apart in time might reflect higher variance than samples collected close in time. If the ratio of temporal and spatial variance is influenced by the density of sampling in each dimension, then experimental design will have an effect on the asymmetry of the CFD estimate.

## 5.5 CONFIDENCE BOUNDS AND STATISTICAL INFERENCE

An investigation into the use of conditional simulation to obtain confidence bounds for the CFD showed that not only is this a promising technique for statistical inference, but also has potential in correcting bias associated with sample size effects that has been identified as a central problem in implementing the CFD approach. Correcting the bias of the CFD due to the sample size effect is important in obtaining confidence bounds on the CFD that cover the true CFD for a segment. Because bias correction is an important first step, this aspect of the conditional simulation exper-

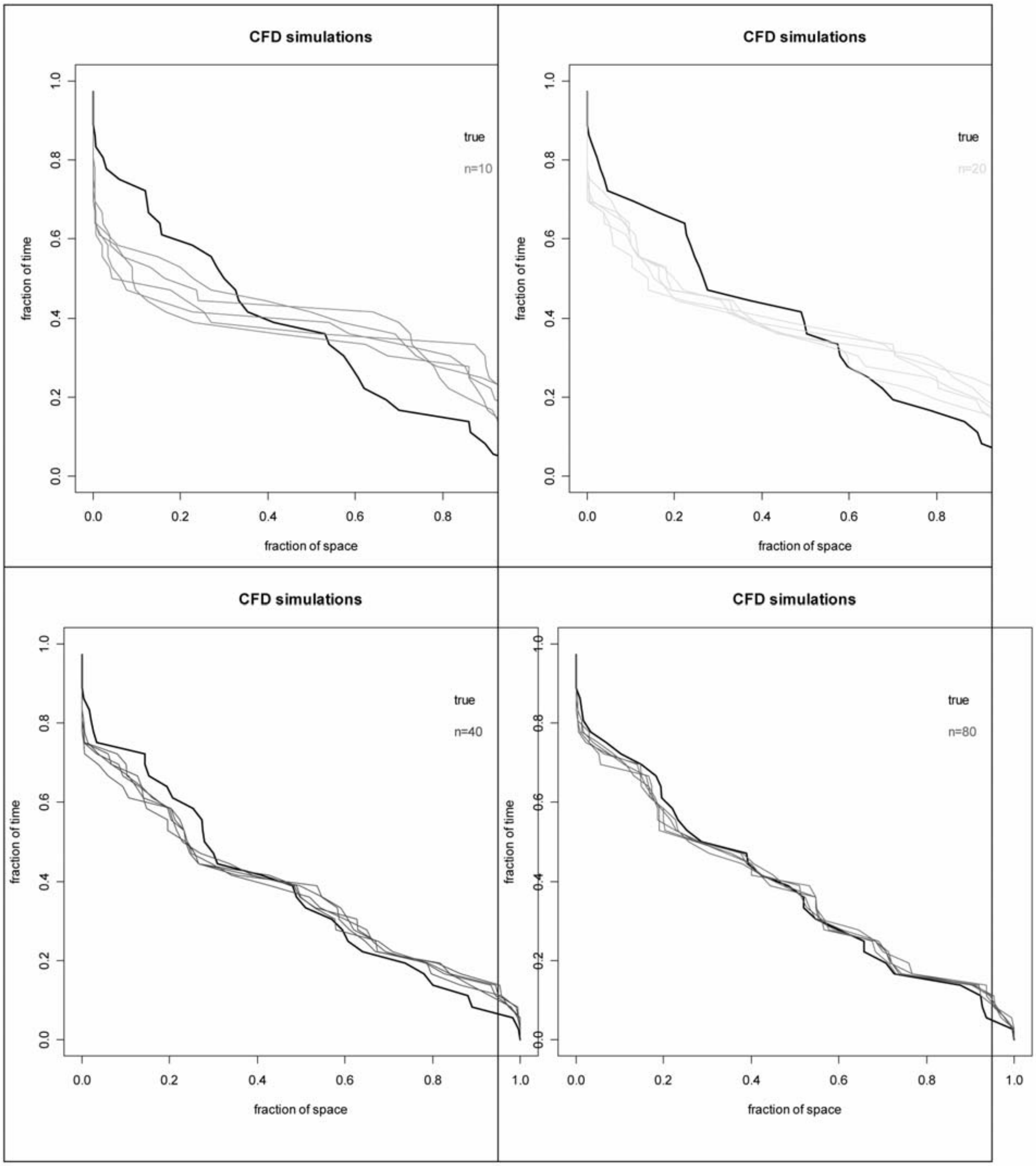


**Figure 5.5.** Illustration of the effect of sample size (n) on the shape of the CFD for sample sizes 10, 20, 40, and 80.

iments will be discussed first. Conditional simulation will then be evaluated in its efficacy in obtaining confidence intervals.

This section first outlines the basic concept of conditional simulation and provides an algorithm that employs conditional simulation to estimate confidence bounds for the CFD. The results of this experiment support the potential of conditional simulation for correcting the sample size bias. A heuristic discussion of the mechanism underlying this adjustment for sample size effect is presented with the hope of motivating additional analytical investigation of this effect.

Conditional simulation (Journel, 1974; Gotway, 1994) is a geostastical term for simulating a population conditional on information observed in a sample. In the case of kriging, a sample from a spatial population is used to estimate the variogram and mean for the population. The conditional simulation procedure generates a field of simulated values conditioned on the estimated mean and variogram from the sample. To the extent that the estimated mean and variogram approximate the true mean and variogram and the assumed distribution is a reasonable model for the true distribution, repeated simulations of this virtual population will represent the variability typical of the true population. It follows that statistics computed from the conditionally simulated fields will represent the expected variability of statistics from the true distribution. The CFD is a graphical representation of ordered statistics of percent compliance over time and it is a reasonable to assume that repeated conditional simulations will lead to effective confidence bounds for the CFD.

## Conditional Simulation Methods

In the computation of the CFD, conditional simulation is implemented at the interpolation step for each month. Interpolation produces an estimate of the spatial surface of the target parameter. From that estimate of the surface is obtained an estimate of the percent of noncompliance. Using conditional simulation, the surface can be reconstructed 1000 times. From the 1000 simulated surfaces are computed 1000 estimates of the proportion of noncompliance. When this is repeated for each month for say 36 months, the result is an array of 1000 sets of 36 values of the proportion of noncompliance. Each of the 1000 sets of 36 can then be ranked from largest to smallest to compute a CFD in the usual way which results in 1000 CFD estimates. The variability among these 1000 CFDs can be used to estimate confidence intervals.

To evaluate this concept, the following simulation experiment was conducted

1. The first step is to simulate a population that will be considered the "true" population for this exercise. A grid of dimensions 5x60 is populated using an exponential spatial variance model with variogram parameters set to (0.00625026, 2.67393446). These variogram parameters were estimated from Patuxent cruise track chlorophyll data. This grid is populated 36 times to represent 36 months. The mean and variogram are held constant for the 36 simulations to create a simplistic case with no seasonal or spatial trend. Using this set of data, the CFD is computed in the usual way and this is considered the "true" CFD.

2. A sample of size 40 is selected from each of the 36 simulations at random locations on the grid. Ordinary kriging is used to estimate the spatial surface for each simulation and from these 36 estimates of the monthly spatial surfaces, a CFD is computed. This is called the 'estimated' CFD.
3. For each of the kriged monthly surfaces, 1000 conditional surfaces are simulated based upon the mean and variogram estimated from the sample data. The Cholesky decomposition is used to reconstruct the covariance structure indicated by the estimated variogram. The conditionally simulated surfaces were processed to yield 1000 estimates of the proportion of noncompliance. The 1000x36 noncompliance values are used to compute 1000 CFDs, which are called the population of "conditionally simulated" CFDs.
4. Each "rank position" of the monthly ordered proportions of noncompliance has 1000 values in this simulated population. To assess variability in the simulated population, graphs of the miniumum, the 2.5th percentile, the 50th percentile, the 97.5th percentile, and the maximum at each rank position are plotted to illustrate a 95% confidence envelop for the CFD (Figure 5.6).

To test this procedure under various conditions, this basic simulation exercise was repeated varying the sample size and adding temporal and spatial trend to the simulation of the "true" population to reflect conditions more similar to real populations.

## Conditional Simulation Results

The results of this simulation exercise are presented graphically. In Figure 5.6 the line 1 represents the CFD computed for the true population computed from the original data. The line 2 is the estimated CFD computed from kriging estimates based on samples from the true population. The line 3 lines represent the min and max of the 1000 conditionally simulated CFDs. The two line 4s represent the 2.5 and 97.5 percentiles of the 1000 conditionally simulated CFDs, which is the proposed 95 percent confidence interval. The line 5 is the median of the 1000 CFD curves.

## Bias Assessment

The results in Figure 5.6 are unusual in several respects. First note that the line 2 shows the typical sample size bias for the CFD as described above (n=40). Relative to the true CFD (line 1) the estimated CFD is below line 1 for half the curve and above line 1 for the remainder. The first unusual feature is that the distribution of the conditionally simulated CFD curves is not centered on estimated CFD. In fact the estimated CFD is not completely within the bounds (min, max) of the conditionally simulated population. A surprising feature is that the median of the simulated population tracks fairly well with the true CFD (line 1). It is clear that the simulated CFD population is estimating something other than what is estimated by the estimated CFD (line 2). At the same time, it appears that the median of the simulated population is a good estimator of the true CFD and the proposed confidence bands (line 3) is reasonable confidence envelop about the true CFD.

What follows is a heuristic explanation for why CFD computed from conditional simulations might be a better estimator of the true CFD than a CFD computed from

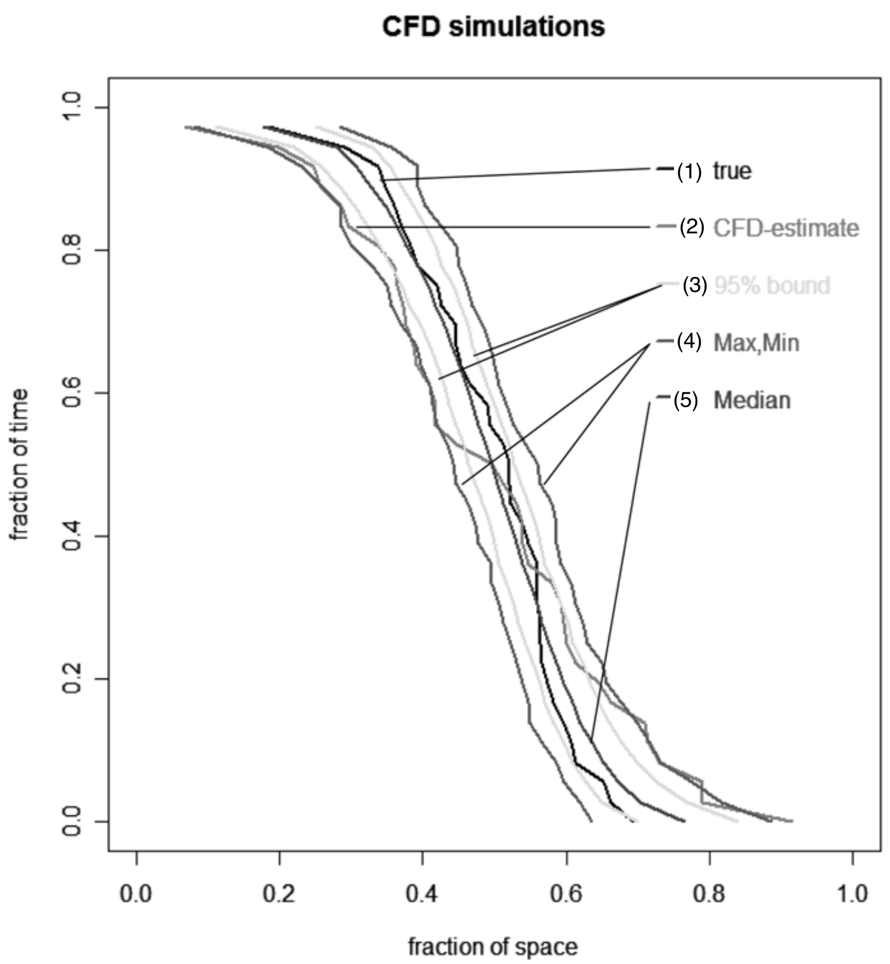


**Figure 5.6.** Confidence bounds computed based on quantiles of fraction of space computed on conditionally simulated surface estimates using variogram estimates from data. The base simulation has spatial correlation and no spatial or temporal trend. Sample size is 40.

the kriging estimator. Additional analyses test whether this property might hold in general or is an artifact of the simple conditions (no spatial or temporal trend) under which this experiment was performed.

In prior discussions we have noted that the CFD is the inverse of the CDF of the population of p's where p is fraction of space out of compliance with the criterion threshold. It is the variance of the p's that determines the steepness of the CFD: the smaller the variance, the steeper the CFD. In real applications, estimates of the p's have two important variance components. One variance component comes from true variance over time in the parameter being assessed. Another variance component comes from imperfect estimates due to sampling variability. In the base simulation with no spatial or temporal trend in the data, it is this second source of variance that controls the shape of the CFD.

Because the variance of the p's is critical to the shape of the CFD, consider the variance of p's computed from three sources in the experiment outlined above: 1) the true data, 2) a krig estimate based on a sample from the true data, and 3) conditionally simulated data based on a krig estimate of 2). To enhance our understanding of this comparison, the variance of the p's are discussed for two cases for each source. The first case assumes complete independence in the base simulation and does not use interpolation to estimate proportion of area out of compliance. This simplification allows us to easily infer the behavior of the CFD using analytical methods. The second case introduces an unknown spatial dependence in the base simulation and uses interpolated data to estimate the proportion of area out of compliance. These additional complexities make it difficult to implement analytical inference but conclusions may still be inferred by analogy to the simple independent case.

Consider the sequence of sources where the base simulations are generated under the simple constraints of constant mean, constant variance and the errors for each cell of the grid that are independent. For this case the exceedance probability is:

$$p = 1 - \Phi((x_s - \mu - C) / \sigma)$$

where : C is the criterion threshold,
$x_s$ is the data at location s,
$\mu$ is the mean used in the simulation,
$\sigma$ is the variance used in the simulation, and
$\Phi$ is the standard normal Cumulative Distribution Function.

The distribution of the true p's computed from all 300 cells of the 5x60 simulation grid would behave like that of a independent binomial with N=300 with a variance of (p(1-p)/300). From these independent data draw a sample of size 40. Using only the proportion of the sample that is out of compliance to estimate the p's, the distribution of the p's would be that of a independent binomial with N = 40 and variance (p(1-p)/40). Clearly the p's estimated from the sample of 40 have much larger variance than p's from the base simulation with 300 cells. Thus the true CFD computed using data from 300 cells will be steeper than the sample CFD computed from 40 data points. This pattern is illustrated by comparing the true CFD (line 1) and the estimated CFD (curve 2) in Figure 5.6. This increase in the variance of the p's due to small sample size is the kernel of the sample size problem with the CFD. Now consider the behavior of p's computed from conditional simulations based on the sample. Compute $\bar{x}$ and s as estimates of ③ and ⑨ from the sample of 40 in the usual way. The conditional simulation is done by populating the 5x60 grid with data from a normal distribution with mean $\bar{x}_i$ and variance $s^2_i$. The exceedance probability for these simulated data for the $i^{th}$ month is

$$p'_i = 1 - \Phi((xs_s - \bar{x}_i - C)/s^i)$$

where : $xs_s$ is simulated data at location s
$\bar{x}_i$ is the estimated mean used in the conditional simulation, and
$s_i$ is the estimated standard deviation used in the conditional simulation.

If the p' were constant over months, the variance of the p's estimated by conditional simulation would be (p'(1-p')/300). The sample size component of this variance has been standardized to 300 which is the same as the sample size component of the true p’s, but the variability of conditionally simulated p's will be greater than that of true p's because estimates of $\bar{x}_i$ and $s^2_i$ will vary over months. The parameter p and it's estimate p' will be close if $\bar{x}$ and s are close to ③ and ⑨. In the simple case with constant mean and independent errors, the CFD estimated by conditional simulation will better approximate the true CFD because both are based on binomial distributions with the same N and approximately the same p.

Now consider the same sequence of distributions where the assumption of independence is relaxed and interpolation of the data is used to estimate the proportion of noncompliance. The introduction of spatial covariance in the base simulation changes distribution of the true p's to a dependent binomial. The dependent binomial will have variance similar to an independent binomial with $N < 300$. Sample size that approximates the variance of the dependent binomial is termed Nb. The variance of the p's estimated from spatially dependent data is approximated by (p(1-p)/Nb) where $Nb < 300$ and thus the CFD from the independent case will be steeper than from the dependent case. The degree to which Nb is less than N will depend on the strength of the spatial correlation.

Next consider the effect of dependent data and interpolation on the distribution of the p's. When we interpolate the sample of 40 onto the grid of 300, the interpolated surface is smooth relative to the original data (compare curves 1 and 4 in Figure 5.2). Because of this increased dependence in the krig estimates, the estimates of p computed from the interpolated data behave more like binomial data with N=Ns (the sample size) than like binomial data with N=Nb (the number of grid cells). Because Ns is smaller than Nb, the variance of the population of p's computed from interpolated data will be greater. The greater variance explains why curve 1 in Figure 5.6is much flatter than line 1.

Finally consider the effect of conditional simulation on the distribution of the p's. When data are conditionally simulated and the mean and variogram estimated from the sampled data are accurate, then the character of the simulated data will be similar to that of the true data (compare the line 1 with line 3 in Figure 5.7). Like the simple independent case, the population of p's computed from the conditionally simulated data will have a binomial variance that is similar to a binomial with sample size Nb. The simulation experiment shows that the CFD computed from these conditionally simulated p's will have a shape similar to the true CFD. This effect is illustrated in Figure 5.6 where the median of the conditionally simulated CFDs (blue line) is more similar to the true CFD line 1 than is the CFD estimate based on kriging (red line). Additional analytical work is needed to formalize the heuristic concepts presented here, but this finding indicates a productive direction in developing statistical inference procedures in the CFD approach.

### Confidence Intervals

The most successful technique for computing confidence bounds for the CFD were obtained using conditional simulation based on kriging interpolation of the sample data. The 95% confidence bands (lines 2, Figure 5.6) are well centered over the true CFD (line 1) for the simplistic case where the true data have spatial dependence but no spatial or temporal trends. When these simplistic assumptions are relaxed (Figure 5.8) and the true data are simulated to have spatial dependence and temporal and

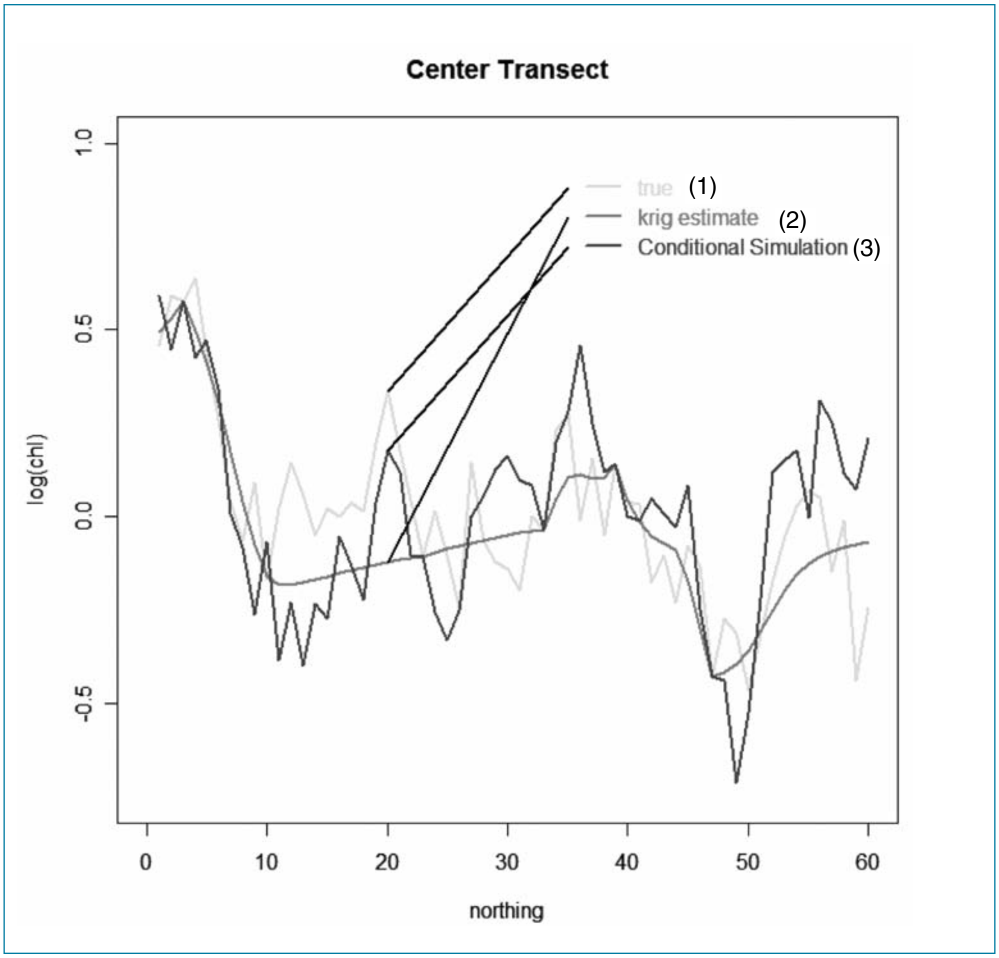


**Figure 5.7.** Simulated chlorophyll data, kriging estimates based on a sample of the simulated data, and conditionally simulated data where the simulation is conditioned on the data used obtain the kriging estimates.

spatial trends similar to chlorophyll data from the Patuxent estuary, the confidence bands cover the true CFD in this case as well. Experiments that varied the sample size also produced confidence bands with good coverage.

Additional evaluation of the confidence band procedure should include a series of confidence band coverage experiments to assess the true coverage rate in comparison to the nominal coverage rate (e.g., 95% in this example). This series of experiments should be conducted with simulated data where the simulations are designed to produce data with properties similar to the three primary assessment water quality parameters.

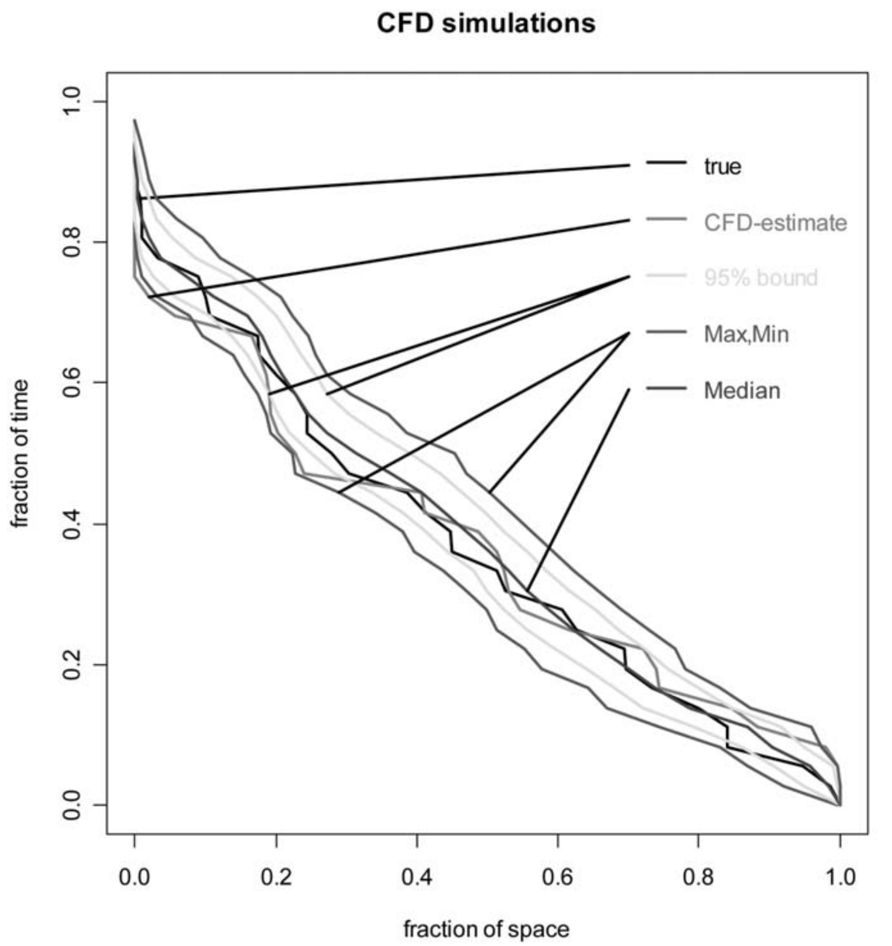


**Figure 5.8.** Confidence bounds based on quantiles of fraction of space computed on conditionally simulated surface estimates using variogram estimates from data. The base simulation has spatial and temporal trend estimated from Patuxent data. Sample size is 40.

# 6.0 FINDINGS—SCIENTIFIC ACCEPTANCE OF CFD COMPLIANCE APPROACH

## 6.1. CFD APPROACH AS BEST AVAILABLE SCIENCE

This report represents an initial expert review of the CFD compliance approach. In addition the panel undertook simulation tests on the effects of 1) sample densities in time and space, 2) varying levels of attainment, and 3) varying degrees of spatial and temporal covariance. Further, trials of spatial modeling on fixed station Chesapeake Bay water quality data were conducted to begin to evaluate spatial modeling procedures. Based upon review of underlying theory, initial statistical assessments, and implementation feasibility, the panel finds that the CFD approach currently represents best available science in its application to water quality attainment determinations in the Chesapeake Bay. Using criteria for Best Science and Best Available Science developed by the American Fisheries Society and the Estuarine Research Federation (Sullivan et al. 2006), we list relevant attributes of the CFD approach (Table 6.1).

The CFD builds on important statistical theory related to the cumulative distribution function and as such, its statistical properties can be simulated and deduced. We have also shown that it is feasible to construct confidence ellipses that support inferences related to threshold curves or other tests of spatial and temporal compliance. Work remains to be done in understanding fundamental properties of how the CFD represents likely covariances of attainment in time and space and how temporal and spatial correlations interact with sample size effects. Further, more work is needed in analyzing biases across regions and designated use segments. The panel expects that a two-three year time frame of directed research and development will be required to identify and measure these sources of bias and imprecision in support of attainment determinations.

Through simulations of the CFD approach, it is feasible to analyze bias and error for both temporal and spatial sources of attainment variability. In particular, conditional simulations merit additional investigation as a relatively unbiased approach for supporting statistical comparisons among CFD curves. Much work remains to be done in understanding fundamental properties of how the CFD represents likely covariances of attainment in time and space. Still, the panel finds the approach feasible: one which merits additional development, testing, and application. Indeed, the CFD approach is beginning to attract scientific and management attention outside the Chesapeake Bay community.

As shown by analyses in previous sections, the approach can efficiently combine spatial and temporal data to support inferences on whether regions within the Chesapeake Bay attain or exceed water quality standards. On the other hand, we recognize substantial bias and imprecision can occur due to small sample size, non-independence in temporal trends, and inadequate spatial interpolations. More work is needed in analyzing these biases across regions and designated use segments. Further, the old saw of needing more samples cannot be ignored. In particular, the panel is optimistic in the application of continuous spatial data streams made available through the cruise-track monitoring program, and the promise of continuous temporal data through further deployment of remote sensing platforms in the Chesapeake Bay (CBOS web site, etc). These data sets will support greater precision and accuracy in both threshold and attainment determinations made through the CFD approach.

In classifying the CFD approach as best available science, we seek to make several important distinctions (Table 6.1). First, the CFD approach is a scientifically based approach based upon its clear purpose, conceptual and design framework, empirical procedures, documentation, and intent to develop rigorous statistical and review procedures (Sullivan et al. 2006, Daubert v. Merrell Dow Pharmaceuticals, Inc., 1993). That the approach permits evaluation of uncertainty also supports its classification as best available science (Christman 2006). On the other hand, we do not believe that the CFD approach yet constitutes best science. Here, further analyses of underlying statistical properties of the approach (including sampling design and

**Table 6-1.** Evaluation of CFD approach as Best Science or Best Available Science according to AFS/ERF "Defining and Implementing Best Available Science for Fisheries and Environmental Science, Policy, and Management" (Sullivan et al. 2006).

| **Attribute** | **Best Science** | **Best Available Science** | **Current State of Development of CFD Approach** |
|---|---|---|---|
| Clear Objective | YES | YES | Using biological response standards, combine available water quality in time and space to determine levels of attainment of Bay segments. |
| Conceptual Model | YES | YES | 1. Bay divided into functional classifications – "Designated Uses."<br>2. Reference curves establish biologically relevant threshold levels for attainment.<br>3. CFD combines and weights equally temporal and spatial sources of water quality variability. |
| Experimental Design | NO | YES | 1. Bay segments are quasi-stratified for water quality data collection.<br>2. Stratification of water quality data by designated units does not yet occur.<br>3. Seasonal assessment of water quality attainment through spatial interpolation and the CFD approach is feasible but incompletely developed. |
| Statistical Rigor | NO | YES | 1. Procedures for quantifying uncertainty associated with sampling design, spatial interpolation and CFD approach are feasible but incompletely developed.<br>2. Procedures for interpolating water quality data are feasible but incompletely developed, particularly for 3-D interpolations of dissolved oxygen.<br>3. Procedures for testing inferences related to the CFD curve are feasible but incompletely developed. |
| Clear Documentation | YES | YES | CFD approach, water quality sampling design, and current interpolation procedures well documented in Chesapeake Bay Program Reports and on website. |
| Peer Review | NO | YES | 1. CFD approach and sampling design upon which it is based has not been peer-reviewed in the scientific literature.<br>2. This report comprises the first external review by scientists with statistical expertise.<br>3. Grey literature reports produced by CBP received expert and stakeholder input. |

interpolation elements) and vetting by outside experts is needed. Indeed, although the CFD approach is beginning to get featured in scientific venues, it has not yet been reviewed as part of the scientific literature. The panel sees this as an overdue next step for necessary for its acceptance, further development, evaluation, and application.

The panel contrasted the CFD approach with existing state and jurisdictional water quality criteria and attainment procedures that are based strictly upon the observed sample, where site selection is not based upon probability sampling, inferences are not based upon error structure, and monitoring does not involve a scientifically rational design. Indeed, standard practice for assessing compliance with water quality criteria throughout the US is to sample monthly at a fixed set of stations and make judgments about compliance strictly from those samples. Sampling stations are typically located for convenience (e.g., bridge overpasses), there is reluctance to re-evaluate and change location (so as to maintain a time series at a fixed point), and no consideration is given to representativeness of the sample for the space/time not sampled. Thus the previous method used by the Chesapeake Bay Program, similar to the approaches used in other states, was simply based on EPA assessment guidance in which all samples in a given spatial area were compiled and attainment was assumed as long as > 10% of the samples did not exceed the standard. In this past approach all samples were assumed to be fully representative of the specified space and time and were simply combined as if they were random samples from a uniform population. This approach was necessary at the time because the technology was not available for a more rigorous approach. But it neglected spatial and temporal patterns that are known to exist in the standards measures. The CFD approach was designed to better characterize those spatial and temporal patterns and weight samples according to the amount of space or time that they actually represent.

## 6.2 THE CFD APPROACH AND PEER REVIEW

The panel views the CFD approach as innovative, one that has general application in water quality attainment assessments, but scientific acceptance of the approach will require that it is subjected to more extensive and targeted peer-review in the scientific literature. Because the CFD is a regulatory tool, it is particularly important that the approach is effectively communicated to the scientific community at large, for general acceptance but more critically for the sustained research and development that the CFD, as a nascent approach, requires. As highlighted elsewhere, bias and imprecision that can occur due to small sample densities, non-independence in temporal trends, and inadequate spatial interpolations. Such work is novel and should elicit interest among biostatisticians as it addresses questions of both fundamental and applied consequence.

Although, continued working groups, involvement through STAC of expert biostatisticians, and related reports such as this one will remain important in scientific acceptance of the CFD approach, the panel recommends immediate attention in subjecting the CFD to traditional peer review. One or several review papers should be submitted by CFD principals that lay out the theory, general approach and lists emergent scientific issues to stimulate other scientists to begin to address such issues. Several such papers might be appropriate given potential interest by biostatisticians and environmental and regulatory scientists. Scientific interest will also be garnered by public and stakeholder interest. The CFD approach here presents a challenge as it is complex in explanation. Still with careful diagrams and examples, a brochure on the CFD approach should be extremely useful in getting uninitiated scientists and stakeholders on the same page.

### 6.3. BIOLOGICAL REFERENCE CURVES

The success of the CFD-based assessment will be dependent upon decision rules related to the biological reference curves. These curves represent desired segment-designated use water quality outcomes and reflect sources of acceptable natural variability. The reference and attainment curves follow the same general approach in derivation—water quality data collection, spatial interpolation, comparison to biologically-based water quality criteria, and combination of space-time attainment data through a CFD. Therefore, the biological reference curve allows for implementation of threshold uncertainty as long as the reference curve is sampled similarly to the attainment curve. Bias and uncertainty are driven in CFD curves by sample densities in time and space. Therefore, we advise that similar sample densities are used in the derivation of attainment and reference curves. As this is not always feasible, analytical methods are needed in the future to equally weight sampling densities between attainment and reference curves.

Conceptually, the CFD approach builds on the underlying view that water quality criteria are surrogates for Designated Uses (regions that define ecosystem function). Implicit is a bottom up model based upon eutrophication, which is expected to diminish the designated use. Reference curves represent thresholds related to the functioning of designated use regions. Therefore, choice of reference regions or periods and sampling design in developing reference curve is critical to the implementation of a scientifically-rigorous CFD approach. Choice of such regions is beyond the scope of this review, but we emphasize several relevant statistical issues in developing reference curves in Section 4.

## 7.0 RECOMMENDATIONS FOR FUTURE EVALUATION AND REFINEMENT OF THE CFD ASSESSMENT METHODOLOGY

As part of its conclusions, the STAC CFD Review Panel identified critical remaining issues that need resolution in the near future. The following is a list of critical aspects of that needed research. These research tasks appear roughly in order of priority. However, it must be recognized that it is difficult to formulate as set of tasks that can proceed with complete independence. For example, research on task 1 may show that the ability to conditionally simulate the water quality surface is critical to resolving the sample size bias issue. This discovery might eliminate IDW as a choice of interpolation under task 3. The Panel has made significant progress on several of these research tasks and CBP is encouraged to implement continued study in a way that maintains the momentum established by this research group (Table 7.1.).

**Table 7.1.** Research Tasks, examples of specific subtasks, and suggested time frame for continued CFD research.

| Task | Schedule |
|---|---|
| **1. Effects of Sampling Design on CFD Results**<br><br>(a) Continue simulation work to evaluate CFD bias reduction via conditional simulation.<br>(b) Investigate conditional simulation for interpolation methods other than kriging - this may lead to more simulation work.<br>(c) Implement and apply interpolation with condition simulation on CBP data. | 2006-2008 |
| **2. Statistical inference framework for the CFD**<br><br>(a) Implement and evaluate confidence interval procedures.<br>(b) Conduct confidence interval coverage experiments.<br>(c) Investigate confidence interval methods for non-kriging interpolation methods.<br>(c) Implement and evaluate confidence interval procedures. | 2006-2008 |
| **3. Choice of Interpolation Method**<br><br>(a) continue to investigate other more nonparametric interpolation methods (e.g. loess and splines).<br>(b) implement a file system and software utilizing the "best" interpolation for CBP data.<br>(b) compare interpolations and CFD's based on IDW and "best" method. | 2006-2008 |
| **4. Three-Dimensional Interpolation**<br><br>(a) Implement 2-D kriging in layers to compare to current approach of 2-D IDW in layers.<br>(b) Conduct studies of 3-D anisotrophy in CBP data.<br>(c) Investigate software for full 3-D interpolation. Examples of options include: custom IDW software, custom kriging software using GMS routines, custom kriging software using the R-package, or some other off the shelf product. | 2007-2009 |
| **5. High Density Temporal Data**<br><br>(a) Develop methods to use these data to improve temporal aspect of CFD in current implementation.<br>(b) Investigate feasibility of 4-dimensional interpolation. | 2008-2010 |

1. **Effects of Sampling Design on CFD Results.** The CFD is a special case of an unbiased estimator for a cumulative distribution function of a population. Like the cumulative distribution function, the CFD is a function of the mean and the variance of the population being assessed. And the better the mean and variance are characterized with sample data, the more accurate the shape of the CFD will be. As the sampling density increases, the estimated CFD begins to approach the true CFD. However, if the sampling density is low, then sampling error could become important and there is potential that it could affect the shape of the CFD and ultimately the accuracy of the compliance assessment. Furthermore the potential for the sample size to affect the shape could create a compliance assessment bias if the reference curve and assessment curve are based on different sampling densities. Conditional simulation methods developed by STAC panel members showed promise toward resolving these issues and mitigating potential biases caused by differences in sample size.
2. **Statistical inference framework for the CFD.** It is important in a regulatory process to differentiate an exceedance that is small and might have resulted from chance variability from those that are large and indicative of an inherent problem. This differentiation will require mathematical tools to quantify the variability in the CFD that occurs as a result of sampling. The STAC panel made progress on this issue by demonstrating a confidence interval procedure based on conditional simulation associated with kriging. It remains to be assessed whether or not confidence intervals produced by this algorithm perform at the nominal level of coverage, fore example, does a nominally 95% CFD confidence interval cover the true CFD 95% of the time.
3. **Choice of Interpolation Method.** The STAC panel considered several interpolation methods and outlined the features of each. Those features illustrate tradeoffs between ease of implementation and maximizing the information garnered from the data. Further work is needed to compare the features to the requirements of wide-scale implementation of assessment procedures and formulate a plan for tractable implementation that results in credible assessments. One strategy is to implement easily performed analysis (e.g. IDW) as a screening tool to identify cases where compliance / non-compliance is clear, and then implement more labor intensive methods (e.g. kriging) for cases where compliance is more difficult to resolve. One difficulty with implementing a full comparison of methods is that implementation of each method requires considerable work in terms of setting up file systems, interfacing software and data, and coupling the considerable bathymetry data of the bay. Thus it would be prudent to narrow the choices based on theoretical considerations where possible.
4. **Three-Dimensional Interpolation.** Assessments of the dissolved oxygen criteria require three-dimensional interpolation. However, the field of three-dimensional interpolation is not as highly developed as that of two-dimensional interpolation. While the mathematics of each method extend easily to three dimensions, there are relatively few examples of 3-D interpolation available in the literature and issues such as data density requirements for reliable results are not well studied. Efforts are needed to further evaluate research in three-dimensional interpolation and seek additional outside scientific input and

review with the goal of implementing the best available technology for this aspect of criteria assessment. One of the first efforts under this task is a study of the 3-D variance stucture of the data to be interpolated. A short term option is to implement the optimal 2-D interpolator in layers as is done with the current IDW interpolator.

5. **High Density Temporal Data.** As currently formulated, assessment for most of the open-waters of the Bay are based on "snapshots" in time of the spatial extent of criteria exceedence estimated via interpolation. Data collected for use in interpolation are actually spaced over multiple days due to the large expanse over which sampling must be conducted. It is clear that technology is becoming available that will produce high density data in both space and time. Interpolation should accommodate data that are collected densely in space. However, it is unclear how the CFD process will accommodate data that are high density in time. Further work is needed to evaluate methods to fully utilize the temporally intensive data that is currently being collected.

The panel discussed several mechanisms for the CBP to make progress on challenging tasks ahead (Table 7.1). We recommend that a review panel oversee the tasks over the next 3-5 year time frame. This panel would periodically review trials and other products conducted by individual external scientists (academic scientists or consultants) and existing teams of CBP scientists (e.g., the Criteria Assessment Protocols (CAP) workgroup). Tasks 1 and 2 are most immediate and critical and we recommend that these tasks by contracted out to external scientists, exploiting state-of-the-art approaches and knowledge. Task 3 could be conducted through CAP or other group of CBP scientists. Task 4 and 5 are less immediate but again will require substantial expertise and innovation and may be most efficiently accomplished by scientific expertise outside the immediate CBP community.

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appendix **b**

# Detailed Chesapeake Bay Water Quality Criteria Assessment Methodology

The methods in this appendix apply specifically to the evaluation of dissolved oxygen criteria. For water clarity criteria or chlorophyll *a* criteria evaluations, the individual methods are very similar to those described here. See chapters 5 and 6, respectively, for additional details. Chapter 7 also contains important information in using shallow-water data for criteria attainment assessment of all three parameters.

Data come from the Chesapeake Bay Program's Chesapeake Information Management System (CIMS) database or through the CIMS partners' networked databases. The parameters extracted include date, location, depth, salinity, temperature, and the water quality parameter under assessment. Data identified by the states, but collected from other than the Chesapeake Bay Water Quality Monitoring Program and Chesapeake Bay Shallow-water Monitoring Program, are also obtained. These data must be of known and documented quality as described in Chapter 3.

Once the data are compiled, they are assigned to a time period based on the sample date. Fixed-station data are normally collected during a monitoring cruise that covers the entire tidal Chesapeake Bay over several days. To provide a "snapshot" of water quality, however, the data collected within one cruise are considered contemporaneous to enable a single spatial interpolation. For information not associated with a cruise, such as state-supplied data, a cruise number is assigned representing the closest cruise in time to the collection of each data point. Co-located data points in the same cruise are averaged.

The criteria assessment procedure requires evaluation over large areas rather than at distinct points. Spatial interpolation is carried out for each water quality criteria parameter for each cruise (see Appendix D for details on the Chesapeake Bay interpolator and the interpolation process) with water clarity and chlorophyll *a* data interpolated in the two horizontal dimensions using inverse distance squared weighting and natural logarithm transformation. Dissolved oxygen data are first linearly interpolated vertically within each column of observed data beginning at 0.5 meters below the water surface and continuing at one-meter intervals, without exceeding the deepest observation in that water column. Data at each depth is then interpolated horizontally using inverse distance squared weighting. Data regions were specified for each segment to prevent the interpolation algorithm from using data points in neighboring tidal tributaries (described in the section below and in detail in Appendix D).

Some designated uses for dissolved oxygen during the summer in the Chesapeake Bay and its tidal tributaries and embayments are defined vertically to distinguish stable water layers with different criteria levels (U.S. EPA 2003a, 2003b). In areas and seasons for which vertical stratified criteria apply, the surface mixed layer (open water) is that layer above the pycnocline and, thus, exposed to the atmosphere. The transitional middle layer (deep water) is the layer between the upper and lower pycnocline boundaries. The lower layer (deep channel) is the water below the lower pycnocline boundary. Given that the pycnocline is dynamic and moves up and down with each monitoring cruise, the designated use of each interpolator grid cell must also be defined based on the data for each cruise.

Temperature and salinity are used to calculate density; density, in turn, is used to calculate pycnocline boundaries. Density is calculated using the method described in *Algorithms for Computation of Fundamental Properties of Seawater*[1]. For each column of temperature and salinity data, the upper and lower pycnocline boundaries are determined by looking for the shallowest robust vertical change in density of 0.1 $kg/m^3/m$ for the upper boundary and the deepest change of 0.2 $kg/m^3/m$ for the lower boundary. To be considered robust, the density gradient must not reverse direction at the subsequent measurement and must also demonstrate a change in salinity of at least 0.1 psu per meter (not merely a change in temperature). Chapter 7 in U.S. EPA 2004, pages 85-87, documents the detailed method for determination of both the vertical density profile and the pycnocline.

The depths to the upper pycnocline boundary (where detected) and the fraction of the water column below the lower boundary are interpolated in two dimensions. If no lower boundary was detected, then the fraction is set at zero. The depth to the upper pycnocline boundary tends to remain stable in the horizontal dimension, meaning that spatial definition of that boundary using interpolation generally works well. Interpolation of the lower boundary is more complicated because the results may conflict with the upper boundary definition or with the actual bathymetry of the Chesapeake Bay. Consequently, interpolation of the lower boundary is based on the fraction of water column depth. In this way, the constraints of the upper pycnocline boundary definition and the actual Bay bottom depth are imposed, eliminating errors related to boundary conflicts.

[1]Endorsed by UNESCO/SCOR/ ICES/IAPSO Joint Panel on Oceanographic Tables and Standards and SCOR Working Group 51. N.P. Fofonoff, and R.C. Millard, Jr., 1983. UNESCO Technical Papers in Marine Science. Paris, France. No. 44, p. 53.

Criteria assessments are based on each component criterion's specific averaging period. Assessments of attainment of the instantaneous minimum criteria are directly evaluated using the individual cruise interpolations. All 30-day mean criteria assessments rely on monthly averages of interpolated data sets. To calculate these averages, each interpolated cruise within a month is averaged on a point-by-point basis in matching interpolator grid cells. Generally, two cruises per month run through the warm season with one cruise per month during the cooler period. Spatial violation rates are calculated for each temporally aggregated interpolation in an assessment period. For example, the 12 monthly average interpolations representing the four summer months (June, July, August, September) over three years were used for a three-year summer open-water dissolved oxygen assessment.

Cumulative frequency diagrams (CFD) are generated from the spatial violation rates for each assessed designated use, water quality parameter, criterion, and averaging period using the Weibull plotting position (rank/(n+1)).

The assessment CFD is compared to a reference CFD to determine if unallowable exceedances of the criterion occur. The diagrams of both CFDs show three areas: non-exceedance (above the assessment curve), allowable exceedance (below both curves), and unallowable exceedance (below the assessment curve and above the reference curve). If the assessment CFD surpasses the reference CFD at any point, an unallowable exceedance exists.

Reference CFDs are continuous or generally have many more points than assessment CFDs. This situation can lead to spurious unallowable exceedances even without individual points in the assessment CFD topping reference CFD levels. To address this problem, reference curves are evaluated only at the temporal axis points in the assessment curve (see Figure II-7 in Chapter 2). For non-continuous biological reference curves, these points are interpolated from neighboring points.

The trapezoidal rule is used to calculate the areas. This rule is a method of approximate integration, which calculates the areas of discrete trapezoids that make up the area below a curve when summed. Since both the assessment and reference curves are piecewise linear, repeated application of the trapezoidal rule results in an exact, rather than approximate, value.

For dissolved oxygen criteria assessed without reference curves, the assessment space is divided in two—non-exceedance and unallowable exceedance.

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appendix C

# Evaluation of Options for Spatial Interpolation

Interpolation constitutes a critical element of CFD-based assessment methodology. It provides the spatial framework for data integration while allotting the appropriate weight to all data. The spatial framework consists of a grid made up of a network of cells that vary in size to cover the entire spatial domain. The size of the cells determines the scale of the assessment; smaller and more numerous cells in a given area provide a more spatially detailed assessment. Estimates for all cells come from a spatial interpolation algorithm.

To date, two spatial interpolation algorithms have been considered: inverse distance weighting (IDW) and kriging. In IDW, estimates of water quality levels are based on a weighted average derived from the closest measured data values. Weights depend upon the distance between the measurement point and the cell being estimated. Thus, measurements from the closest points are weighted most heavily and have the most influence. The second method is kriging—a well-known statistical form of spatial interpolation. The statistical details of kriging rest on ample research. This method, however, has not been used for water quality criteria. Both spatial algorithm methods can prove valuable for Chesapeake Bay water quality criteria assessment; one or both will likely be used in the future. Other methods (non-parametric regression methods such as Loess regression or cubic splines) are also available and could also be considered for future use. Further details on the IDW and kriging methods are provided below.

## SPATIAL INTERPOLATION NEEDS SPECIFIC TO CHESAPEAKE BAY WATER QUALITY CRITERIA ASSESSMENT

The Chesapeake Bay water quality criteria were established using the spatial definition of designated-use areas for the tidal waters of Chesapeake Bay (U.S. EPA 2003a, 2003b). These spatial definitions, along with the characteristics of the Bay itself, present several challenges for spatial interpolation. For example, the Chesapeake Bay shoreline is extremely complex with many small tidal tributaries, embayments, and inlets that occur at various scales throughout the water body. The small inlets present a challenge for spatial interpolation because they require extrapolation from measured areas into unmeasured areas, often around numerous bends and twists in a tidal river. Furthermore, they create the potential for interpolating from one tidal tributary to another, which may be inappropriate since tidal tributaries are often hydrodynamically independent. Most spatial interpolation algorithms operate in two dimensions in a relatively simple spatial domain. Thus, specific refinements need to be made for the algorithms used in Chesapeake Bay criteria assessment.

The Chesapeake Bay dissolved oxygen criteria depend on designated-use areas—specific volumetric areas with both vertical and horizontal dimensions (U.S. EPA 2003a, 2003b). Dissolved oxygen levels are naturally lower in bottom waters. Therefore, the designated-use areas were defined as vertically stratified layers to allow establishment of criteria levels that support the ecological communities residing in the lower depths of the Bay. Any spatial interpolation supporting dissolved oxygen criteria assessment must allow interpolation throughout the designated-use volumes in three dimensions. The IDW algorithm developed and used by the Chesapeake Bay Program was designed in this way and has been used consistently to provide baywide maps of dissolved oxygen concentrations (see Appendix D). Kriging, however, has not been used for three-dimensional interpolation in the Chesapeake Bay to date; in fact, only limited research has taken place to develop the capability of three-dimensional kriging for any purpose (STAC 2006). Thus, more research may be required for the use of kriging in the assessment of dissolved oxygen criteria.

The complexity of the Chesapeake Bay shoreline presents several obstacles for spatial interpolation in Bay tidal waters, mostly related to interpolating across land area. Most spatial interpolation algorithms assume a relatively simple spatial domain (e.g., rectangular) and interpolation takes place without regard to direction. In contrast, the Chesapeake Bay (for example, see Figure III-1 in Chapter 3) displays tidal flow patterns that make some locations independent or virtually independent. For Bay water quality criteria assessment, therefore, the influence between some locations must be limited when interpolating spatially. The current Chesapeake Bay Program interpolator provides limits by using data regions in which the data used to estimate values in given locations are limited to certain areas (see Appendix D for additional details). Similar or alternative methods may be required to apply kriging broadly.

As described above, the Chesapeake Bay Program collects two types of data for criteria assessment; these two data types supply information at different spatial scales. The fixed-station Chesapeake Bay Water Quality Monitoring Program collects data consistently for the entire Bay as well as its tidal tributaries and embayments. The Chesapeake Bay Shallow-water Monitoring Program offers much more detailed information within Bay tidal tributaries and across all shallow-water habitats. Given the different spatial scales of these two monitoring programs, it is unlikely that they can be used in the same interpolations. Thus, two separate interpolation approaches—each designed for specific types of criteria attainment assessments—may prove necessary.

Since the Chesapeake Bay water quality criteria and the CFD-based criteria assessment methodology were developed and published, interest has developed in creating a statistical basis for decision-making using the CFD (see pages 164–165 in U.S. EPA 2003a). Such a basis would allow the incorporation of error analysis into the criteria attainment assessment methodology. It would also allow the differentiation of an assessment based on a well-characterized system from one that was poorly characterized. Estimates of interpolation error are important to develop such a statistical framework. Such estimates allow decision-making to be based on the number (density) of sampling locations and promote greater statistical certainty (i.e., greater sampling density) in the assessment. The current Chesapeake Bay interpolation algorithm does not yield spatial error estimates (Appendix D); however, kriging is a possible alternative algorithm that can provide spatial interpolation error (STAC 2006).

Chesapeake Bay spatial interpolation requires the potential for automation. For many reasons, the Chesapeake Bay Program must compute many interpolations quickly. In developing the attainment figures for the 2006 listing cycle, for example, the program performed a total of 2328 interpolations for the final criteria assessment analysis of the 95 water quality segments). During development of the methodology, these interpolations were carried out repeatedly. Also, water quality models are often used to evaluate the potential benefits of management actions with the generation of multiple scenarios. Management action success is often defined in terms of water quality criteria, with results evaluated similarly to the actual measurements. Given the large number of data sets, automating the criteria assessment methodology and spatial interpolations would likely prove necessary. The current Chesapeake Bay interpolator allows automation and has been used in this way (Appendix D). Kriging, however, is a more detailed analysis that requires multiple decisions along the way, is not conducive to automation, and may not necessarily remain consistent within and between jurisdictions.

## DATA USED TO ASSESS CHESAPEAKE BAY WATER QUALITY CRITERIA

As stated, the Chesapeake Bay Program redesigned the tidal monitoring program specifically to support water quality criteria assessment. That redesign resulted in multiple monitoring program components, all of which address one or more of the objectives of the Chesapeake Bay Water Quality Monitoring Program. Two of the components that serve most of the current needs of criteria assessment include the Baywide Fixed-station Water Quality Monitoring Program and the Shallow-water Monitoring Program. These two long-term efforts will provide data useful at different scales.

The fixed-station monitoring program began in the mid 1980s and was designed to provide data for assessing long-term trends at key sites throughout the Chesapeake Bay and its tidal tributaries (Chesapeake Bay Program 1989). The program collects water quality samples at more than 150 sites (Figure C-1), including 49 stations in the mainstem Chesapeake Bay and 96 stations in the tidal tributaries. The samples go to a network of laboratories for analysis, compiling data on 19 water quality parameters. Fixed-station monitoring cruises run on a monthly basis throughout

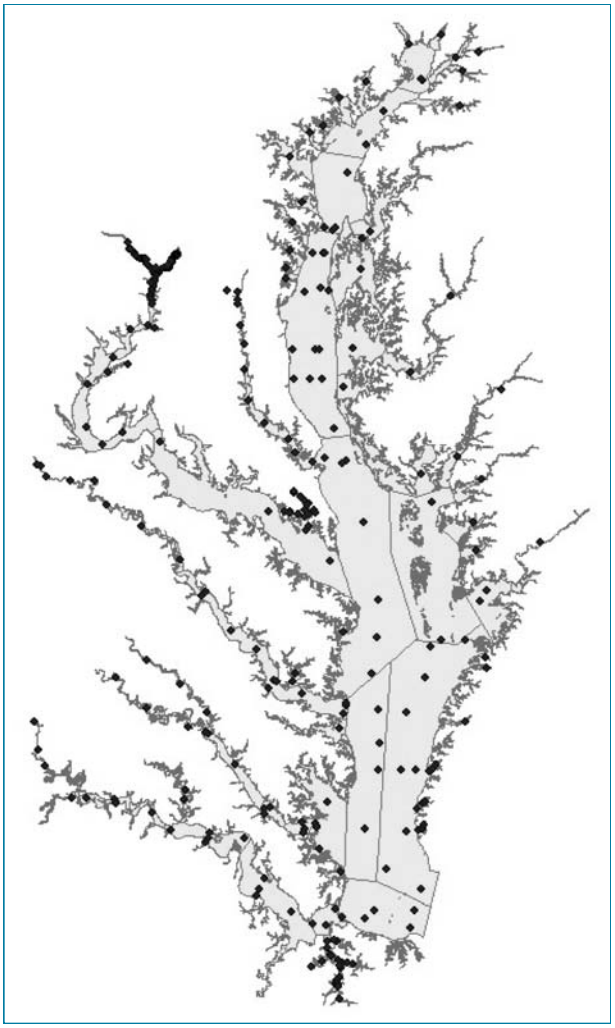

**Figure C-1.** The sites that make up the fixed-station network of the Chesapeake Bay Water Quality Monitoring Program.

Source: Chesapeake Bay Program 1989.

most of the year, but occur two times a month during the summer. At each station, samples are collected at multiple depths depending on the location of the pycnocline. In addition, technicians collect water quality sensor data—including water temperature, salinity, and dissolved oxygen—along vertical profiles at regular intervals.

The fixed-station network provides data to assess water quality in the mid-channel, open waters of the Bay mainstem as well as in the major tidal tributaries and embayments. The network does not assess conditions in the shallows since many of the stations were purposely located in the main channels and open tidal waters.

The Chesapeake Bay Program recently began monitoring shallow-water habitats using a technology known as DataFlow (see Chapter 7 for details). This new technology uses a system of shipboard water quality probes that measure spatial position, water depth, water temperature, salinity, dissolved oxygen, turbidity, and fluorescence from a flow-through stream of water collected near the water surface. This system allows rapid data collection (approximately every 4 seconds) while the boat is traveling at speeds up to 20 knots. Due to the speed of data collection, each cruise provides extremely detailed data sets useful for assessing highly variable water quality conditions, such as those expected in the Bay's shallow waters and small tidal tributaries. Thus, this monitoring program specifically assesses shallow waters (STAC 2005). The spatial density of data collected by the DataFlow system allows spatial interpolation. The current Chesapeake Bay Program interpolation software is not designed for data of this density, however, so new methods of interpolation need to be developed.

Due to the cost of the Shallow-water Monitoring Program, it cannot be implemented baywide concurrently. Rather, the program is being put into practice on a rotating basis, with the monitoring system deployed to selected assessment units long enough to evaluate attainment and then moved to another set of units (see Chapter 7 for further details). This set-up means that all shallow-water areas will not be assessed simultaneously, although a full assessment will take place over time. For example, the Maryland Department of Natural Resources' Water Quality Mapping Program covered 14 Chesapeake Bay and tributary systems in 2005.These systems include the St. Mary's, Patuxent, West, Rhode, South, Middle, Bush, Gunpowder, Chester, Eastern Bay, Miles/Wye, Little Choptank, Chicamacomico, and Transquaking rivers. In Virginia, DataFlow data are available for the Piankatank, York, Pamunkey, and Mattaponi rivers. Chapter 7 discusses additional details on plans for monitoring shallow-water systems.

Other alternative monitoring programs have been considered, but not fully implemented for criteria assessment. Beginning in 1990, chlorophyll *a* concentrations have been measured over the mainstem Chesapeake using aircraft remote sensing (Harding et al. 1992). Twenty-five to 30 flights per year took place during the most productive time periods. In addition, satellite remote sensing data have been considered for evaluating chlorophyll *a* concentrations in the Bay (Harding et al. 2004) although no detailed evaluation of the feasibility has been completed. Water quality sensors and data loggers mounted on buoys have also been evaluated as the best means to assess high-frequency dissolved oxygen criteria. This option is expensive, however, and only a limited (but growing) number of buoy systems have been deployed to date (http://www.cbos.org).

## INTERPOLATION METHODS CURRENTLY USED FOR CHESAPEAKE BAY WATER QUALITY CRITERIA ASSESSMENT

The current Chesapeake Bay Interpolator is a grid-based algorithm in which criteria measurement data are used to estimate values for all grid cells (see Appendix D for a detailed description). Estimates for cell locations are computed by interpolating the nearest "n" neighboring water quality measurements for which "n" is normally 4 but is adjustable. The interpolation uses an inverse distance weighted (IDW) algorithm in which the estimated value of each grid cell is based on the four nearest measurements. Each of the neighboring points is weighted by the inverse of the distance squared (i.e., 1 $d^{-2}$), however, so close neighbors have more influence than those farther away.

The cell size in the Chesapeake Bay interpolation grid is 1 km (east-west) x 1 km (north-south) x 1 m (vertical), with columns of cells extending from the water surface to the Bay bottom representing the three-dimensional volume as a group of equal-sized cells. Each tidal tributary is represented by variously sized cells depending on the river's geometry since the narrow upstream portions require smaller cells to model the dimensions accurately. Interpolator grid cells, however, remain the same size within individual segments. This designation results in a total of 51,839 cells by depth for the mainstem Chesapeake Bay (segments CB1TF–CB8PH), and a total of 238,669 cells by depth for all 78 segments making up the mainstem Chesapeake Bay and its tidal tributaries and embayments.

The Chesapeake Bay interpolator is optimized to compute concentration values that closely reflect the physics of stratified water bodies such as the Bay. Water quality varies much more markedly vertically as opposed to horizontally. To accommodate this attribute, each column of data is interpolated vertically to the same depths as the centroids of the interpolator cells, (i.e. 0.5, 1.5, 2.5 meters, etc). The interpolator then interpolates only in the horizontal dimension.

Up to four points are used for interpolation. If fewer than four points exist, interpolation is still carried out given at least one measured point. Without any measured data, a missing value (normally a –9) is calculated for that cell. A search radius filter limits the horizontal distance of monitoring data from the cell being computed. Data points outside the user-selected radius (normally 25,000 m or 25 km) are excluded from calculation. This filter ensures that only data near the location being interpolated are used.

Segment and region filters have also been added. Segments are aggregations of the interpolator cells. For instance, eight segments make up the mainstem Chesapeake Bay (CB1TF, CB2OH,…CB8PH). The tidal tributaries have 70 additional segments, created by the Chesapeake Bay Program's 2003 segmentation scheme (U.S. EPA 2004, 2005). These segments divide the Bay into geographic areas with somewhat homogeneous environmental conditions. This segmentation also allows the reporting of results on a segment basis, revealing more localized changes compared to the whole Bay ecosystem.

The region file identifies the geographic boundary that limits which monitoring station data are included in interpolation for a given segment (see Appendix D). The purpose of the data region is to select a subset of the monitoring data from the input data file and to use that subset for computing the values for each grid cell in a segment. Use of data regions ensures that the interpolator does not "reach across land" to obtain data from an adjacent tidal tributary—a process that would give erroneous results. By using data regions, each segment of grid cells can be computed from its individual monitoring data subset. Each adjacent data region overlaps so that a continuous gradient—not a seam—exists across segment boundaries. Data regions for criteria assessment vary somewhat from the data regions in the standard interpolator. These new regions were developed to exclude tributary measurements from mainstem interpolations and to include additional observed data from Virginia.

## EVALUATION OF THE INVERSE DISTANCE WEIGHTING SPATIAL INTERPOLATION ALGORITHM FOR ASSESSING CHESAPEAKE BAY WATER QUALITY CRITERIA

The current Chesapeake Bay interpolator is based on an IDW algorithm—a non-statistical spatial interpolator that uses observed data to calculate a weighted average (as a predicted value) for each location on the prediction grid (Appendix D). The method calculates the weight associated with a given observation as the inverse of the square of the distance between the prediction location and the observation. The IDW is a spatial interpolator; in general, such methods have provided good prediction maps (STAC 2006). Additionally, implementation is relatively simple since software exists to map IDW automatically. Further, the method does not require any decisions during an interpolation session. Commercial Geographic Information Systems (GIS) software contains IDW, requiring only GIS skills for application.

The IDW algorithm has several advantages for use in Chesapeake Bay water quality criteria attainment assessment (STAC 2006). First, since it is non-statistical, the algorithm is not constrained by prior theoretical assumptions concerning error structure. It is, therefore, simpler mathematically and can be adapted to interpolation in three dimensions (i.e., with depth). Second, due to its simplicity, IDW does not require operator decisions at interim steps. Thus, it is conducive to automation—running large numbers of interpolation without having to make decisions as part of the interpolation process. The algorithm is susceptible to problems with interpolating across land; however, methods exist to prevent such problems for Chesapeake Bay application (as described in previous sections and in detail in Appendix D). It can be applied at any scale, but is most appropriate for large scales where three-dimensional interpolation becomes a necessity and data collection sites may remain too dispersed to provide good estimates of error structure no matter which algorithm is used.

In addition to its advantages, IDW also has a major disadvantage: it is not a statistical method. The method is a deterministic approach without any sampling or model error assumed or accounted for (STAC 2006). In addition, IDW does not account for potential spatial autocorrelation among the observations and, therefore, does not fully utilize the information contained within the data. No method exists to estimate either source of error associated with a set of predicted values when using IDW and it cannot be used as a basis for statistical decision-making using the CFD. Dedicated research could determine whether IDW could be made more statistically defensible.

## EVALUATION OF KRIGING AS A SPATIAL INTERPOLATION ALGORITHM FOR ASSESSING CHESAPEAKE BAY WATER QUALITY

Kriging has been considered by the Chesapeake Bay Program as a principal alternative algorithm for spatial interpolation in CFD water quality criteria assessment methodology. Kriging is a spatial interpolation technique that arose from geostatistics, a subfield of statistics that analyzes spatial data. Kriging and the field of geostatistics have been used in a wide variety of environmental applications and are generally accepted methods for statistically optimal spatial interpolations (Cressie 1991, Schabenberger and Gotway 2004, Diggle and Ribeiro 2006). Kitanidis (1997), Wang and Liu (2005), and Ouyang et al. (2006) elaborate on the application of kriging in water-related research. References on kriging methodology, geostatistics, and their related statistical development can be found in Cressie (1991), Diggle et al. (1998), Schabenberger and Gotway (2004), and Diggle and Ribeiro (2006).

Kriging can be formulated equivalently in terms of a general linear regression model:

$$Y\,(s) = \beta_0 + \beta_1\, X_1(s) \cdots + \beta_p\, X_p(s) + \varepsilon(s) \qquad \text{Equation C-1}$$

with s representing a generic spatial location assumed to vary continuously over some domain of interest and Y (s) capturing the outcome of interest measured at s, $X_1(s), \ldots, X_p(s)$ potential covariates indexed by location s and their associated regression effects $\beta_1, \ldots, \beta_p$. The uncertainty in this regression relationship is modeled with the random error term $\varepsilon(s)$ assumed to have zero mean and constant variance. Spatial data, similar to the type sampled in Chesapeake Bay water quality criteria assessments, often exhibit a property known as (positive) spatial dependence; observations closer together are more similar than those further away. This property is accounted for in the model by allowing $\varepsilon$(s) to contain a spatial correlation structure.

Common distributional assumptions on $\varepsilon$(s) include normality and log normality, although kriging can be based on other statistical distributions and data transformations. Functions of a specific mathematical type (positive definite) represent the spatial correlation in $\varepsilon$(s) and are assumed isotropic (correlation depends only on distance) or anisotropic (correlation depends on both distance and direction). Variograms constitute another special type of mathematical function—closely related to spatial correlation functions—that are more often used to represent spatial correlation. In this case, and in many kriging applications, variograms and spatial correlation functions provide equivalent representations of spatial structure. For consistency, only the term "variogram" is used here in discussions of spatial structure.

In the literature, Equation C-1 is referred to as a universal kriging model. When covariates (the X's) don't influence interpolation of Y, the right hand side of model (Equation C-1) contains only the constant term $\beta_0$. The resulting model is called the ordinary kriging model. When the spatial structure (variogram) for the model (Equation C-1) is known, statistically optimal predictions for the variable Y at unsampled locations (outside of estimation of possible regression effects) can be derived using standard statistical principles. The optimality criteria result in spatial predictions that are linear in the data, statistically unbiased, and minimize mean squared prediction error—known as best linear unbiased predictions. The minimized mean squared prediction error is also a measure of prediction uncertainty. In practice, however, the spatial structure of the data remains unknown. The estimation of the spatial structure using the variogram function, therefore, is critical to kriging applications.

To demonstrate let $\{y(s_1), \ldots y(s_n)\}$ represent a sample set of spatial data such as dissolved oxygen collected at a set of n spatial locations $s_1, \ldots s_n$. Assume this data set to be a realization of the ordinary kriging version of model. The primary step in kriging is variogram estimation with several methods available; the method of moments and statistical likelihood based are two of the more common. All of these methods are based on the sample data $\{y(s_1), \ldots y(s_n)\}$. This process ends with a chosen variogram function and its parameter estimation, describing the shape and strength (rate of decay) of spatial correlation. A determination, also based on the sampled data, is made of whether the spatial structure is isotropic or anisotropic. The estimated variogram is then assumed known. Kriged interpolations and their interpolated uncertainty at numerous locations are computationally straightforward to generate.

The following describes some of the benefits and potential limitations of kriging for the Chesapeake Bay Program to use in criteria attainment assessment application (with some comparisons to the IDW approach of spatial interpolation outlined in the previous section). A primary benefit of kriging compared to IDW is that it is a statistical technique. Statistics (including kriging) can make inferences from sampled data even in the presence of uncertainty; the quantity and quality of the sample data are reflected in these inferences. Kriging, however, is a less-than-routine type of analysis and requires statistical expertise to execute. The short description on variogram estimation above merely introduces this involved and often complicated step.

Further issues regarding kriging and Chesapeake Bay Program applications are listed below.

- Kriging is flexible; it is based on an estimate of the strength of spatial dependence in the data (variogram). Kriging can consider direction-dependent weighted interpolations (anisotropy) and can include covariates (universal kriging) to influence interpolations—either simple trends in easting and northing coordinates or water-related measures such as salinity.
- A key feature of kriging is that a measure of uncertainty (called the kriged prediction variance) is generated along with kriged interpolations. Research has started to propagate this interpolation uncertainty through the CFD.
- Kriging can be applied in situations for which the data remain sparse (such as the Chesapeake Bay Water Quality Monitoring Program's fixed station data) or dense (such as the Chesapeake Bay Shallow-water Monitoring Program). Kriged and IDW spatial interpolations may very well produce near identical results for these two extreme scenarios. The kriging approach, however, provides a statistical model, the uncertainty of which is influenced by the quantity and quality of data. Interpolation uncertainty information is crucial for both sparsely and densely sampled networks.

In comparison to IDW, kriging is more sophisticated, but requires greater expertise in implementation. Kriging is available in commercial statistical software and also in free open-source applications, such at the R Statistical Computing Environment. Use of the technique requires geostatistical expertise programming skills for these two software packages. Segment-by-segment variogram estimation and subsequent procedures would require substantial expert supervision and decision-making. Chesapeake Bay Program managers may very well view this as a limitation in using kriging for certain Chesapeake Bay Program activities, such as criteria assessments, applications that need automated spatial interpolations. Furthermore, for some Chesapeake Bay Program applications, the decision on criteria attainment is clearly not influenced to any substantial degree by the method of spatial interpolation because the water quality conditions remain far out of attainment. One possible strategy is using a mix of IDW and kriging in situations for which attainment was grossly exceeded or clearly met (IDW) versus borderline cases (kriging). Table C-1 provides a comparison of the capabilities of assessments based on lumping data, spatial interpolation based on IDW, and spatial interpolation based on kriging.

**Table C-1.** Comparison of the capabilities of methods for interpreting data for Chesapeake Bay water quality criteria assessment.

| Attributes | Sample-based | IDW | Kriging |
|---|---|---|---|
| Provides Spatial Prediction | Yes | Yes | Yes |
| Provides Prediction Uncertainty | No | No | Yes |
| Uncertainty for CFD | No | No | Yes |
| Deal with Anisotropy | No | Possible, but not routine | Yes |
| Can include cruise track/ fly-over data | No | No | Yes |
| Feasibility of 3-dimensional interpolations | No | Yes | Possible, but not routine |
| Feasibility of mainstem-tributary interpolations | No | Yes | Possible |
| Inclusion of covariates to improve prediction | No | No | Yes |
| Predictions of non-linear functions of predicted attainment surfaces P(y>c) | No | No | Yes |
| Level of sophistication | Lowest | Low | Very High |
| Automation | Yes | Yes | No |

Source: STAC 2006.

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appendix d

# User Guide and Documentation for the Chesapeake Bay Interpolator

## INTRODUCTION

The Chesapeake Bay and Tidal Tributary Interpolator computes water quality concentrations throughout the Chesapeake Bay and/or tributary rivers from water quality measured at point locations. The purpose of the Interpolator is in compute water quality concentrations at all locations in the 2-dimensional plane (top or bottom depth) or throughout the 3-dimensional water volume. Results of the interpolation can then be compared over time to compute trends or individual interpolations can be overlaid with other data to visualize possible cause and effect relationships. One example is to compare water quality with living resource (fish, shellfish, aquatic vegetation) distributions. Results of the Chesapeake Bay Interpolator have been used since 1988 to determine trends in water quality for the Chesapeake Bay Program (http://www.chesapeakebay.net/).

Version 4.2 of the VOL3D software includes new code to: 1) import data from Microsoft ACCESS data tables; 2) draw improved graphics of tributary segments; 3) draw colors using categories, as before, or to draw using a color ramp of 255 colors; 4) draw longitudinal sections which represent the centerline of the Bay or Tributary River segments; 5) draw images of all Tributary Rivers in addition to the Bay; and, 6) compute composite images that represent the minimums or maximums over a time series.

Another tool, DART, which must be run on the CIMS network at the Chesapeake Bay Program Office, creates data sets for the Interpolator for any parameter in the historical water quality data base. DART is a very powerful tool which can create many data sets in a very short time. Anyone who needs to interpolate data held by the Bay Program, should investigate the use of DART.

## INTERPOLATOR DESCRIPTION

The Chesapeake Bay Interpolator is a cell-based interpolator. Fixed cell locations are computed by interpolating the nearest *n* neighboring water quality measurements, where *n* is normally 4, but this number is adjustable. Cell size in Chesapeake Bay was chosen to be 1km (east-west) x 1km (north-south) x 1m (vertical), with columns of cells extending from surface to the bottom of the water column, thus representing the 3-dimensional volume as a group of equal sized cells extending throughout the volume. The tributaries are represented by various sized cells depending on the geometry of the tributary, since the narrow upstream portions of the rivers require smaller cells to accurately model the river's dimensions. This configuration results in a total of 51,839 cells by depth for the Main Bay (Segments CB1TF-CB8PH), and a total of 238,669 cells by depth for all 77 segments which comprise the Main Bay and tributaries. Computation time on a Pentium 2 ghz PC running Windows XP is approximately 15 seconds for the Bay and tributary interpolator model.

The Chesapeake Bay Interpolator is unique in the way it computes values in 3-dimensions. The interpolator code is optimized to compute concentration values that closely reflect the physics of stratified water bodies, such as Chesapeake Bay. The Bay is very shallow compared to its width or length, hence water quality varies much more vertically than horizontally. The Chesapeake Bay Interpolator uses a vertical filter to select the vertical range of data that are used in each calculation. For instance, to compute a model cell value at 5m deep, monitoring data at 5m deep 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 +/-2m) meters above and below the preferred depth, with the window being widened in 0.5m increments until *n* monitoring values have been found for the computation. The smallest acceptable *n* value is selectable by the user. If fewer than *n* values are located, a missing value (normally a -9) is calculated for that cell.

A second search radius filter is implemented to limit the horizontal distance of monitoring data from the cell being computed. Data points outside the radius selected by the user (normally 25,000m) are excluded from calculation. This filter is included so that only data that are near the location being interpolated are used.

In this version of the Interpolator, Segment and Region filters have been added. Segments are geographic limits for the interpolator model. For instance, the Main Bay is composed of 8 segments (CB1TF, CB2OH, ...,CB8PH). The tributaries are composed of 69 additional segments, using the CBP 1998 segmentation scheme (Figure D-1). These segments divide the Bay into geographic areas that have somewhat homogeneous environmental conditions. This segmentation also provides a means for reporting results on a segment basis that can show more localized changes compared to the whole Bay ecosystem. To replicate the segmentation scheme, the segment boundaries were used to cookie-cutter out the Interpolator cells that fall within each segment. Each set of these cells are then identified inside the corresponding *.bth file that contains the bathymetry definitions. To compute the interpolated values for the Main Bay, the corresponding bathymetry file is named "cbay8.bth". This file contains the cell locations for the cells in the Main Bay Interpolator. A similar file, "bay_trib.bth" contains the cell definitions for the Main Bay

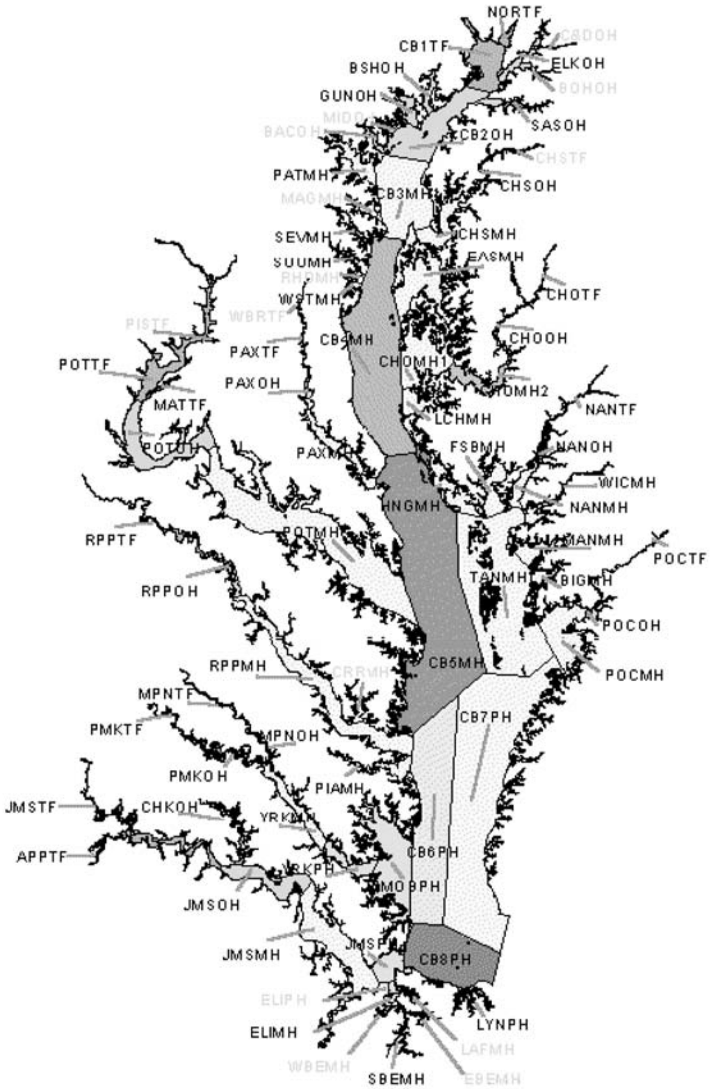


**Figure D-1.** Chesapeake Bay Program 1998 segmentation design.

and tributary interpolator. Other .bth files have also been created for individual river systems. Users that need specialized processing, such as finer resolution or additional segments in a particular area of interest, must create a new bathymetry file that defines the bathymetry of the area of interest at the desire cell-size.

Regions filters (cbay8.drg, bay_trib.drg, etc) are files which contain a closed polygon of x-y points that define an area larger than the corresponding *.bth file. The region file identifies the geographic boundary that limits which monitoring station data are included in interpolation for a given segment. The purpose of the data region is to select a subset of the monitoring data from the input data file, and to then use

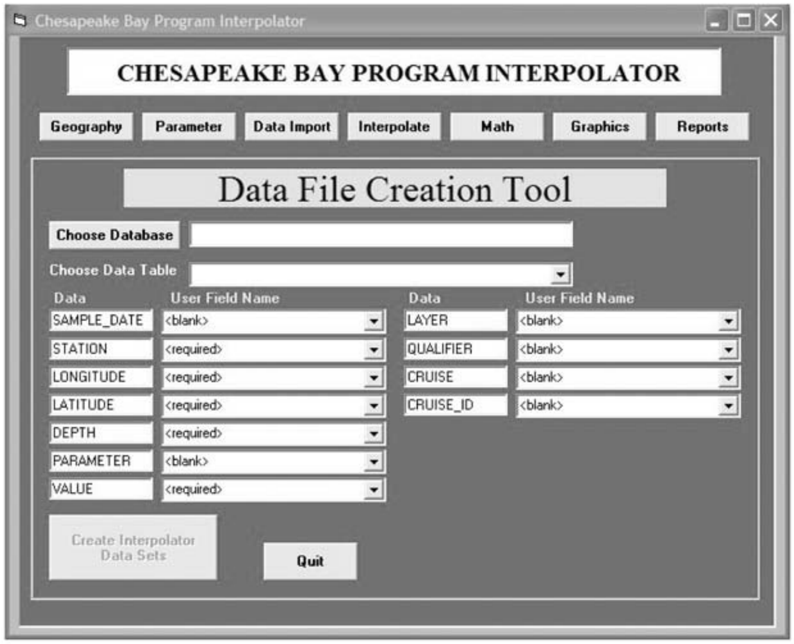


**Figure D-2.** Screen 1 includes seven navigation buttons and the *Data File Creation Tool* for importing data from an ACCESS data base and creating VOL3D data files.Once the user has selected the desired data fields in the data table (Figure D-3), the Data File Creation Tool opens a new screen that provides a range of options to the user for selecting and subsetting data from the ACCESS data table (Figure D-4). The Data Engine allows the user to select data by parameter, by date range, to set interpolation control parameters, to choose the desired bathymetry, to select data by depth ranges or layers, and finally to choose how the group the resulting data in one or more output files. The "Create Files" button, when pushed, will generate data files in the VOL3D ".d3d" file format. These files are then ready for interpolation.

that subset for computing the values for each cell in a segment. Use of data regions ensures that the interpolator does not "reach across land" to obtain data from an adjacent river which would give erroneous results. By using data regions, each segment of cells can be computed from their individual subset of monitoring data. Each adjacent data region should overlap by some amount so that there is a continuous gradient, and not a seam, across segment boundaries.

In the future, a pycnocline filter may be added to the Interpolator, so that water above, within, and below the pycnocline are not interpolated together. Since the water quality in various parts of the pycnocline can be so dramatically different, the Interpolator file structure will be modified to handle this requirement.

## INSTALLATION

The Vol3D Interpolator code and auxiliary files have been bundled together into a SETUP application and then PKZipped to reduce the overall file size. The Vol3D.zip file must first be unzipped into a directory on any standard PC running the Windows

95/98/XP operating system. Once unzipped, double click the SETUP.EXE file to start the installation process. It is suggested that the application be installed in the C:\VOL3D directory. The original zipped file can be deleted to regain disk space. A fast Pentium machine with 256 mb ram and 1 gb disk drive will prove useful.

## USING THE CHESAPEAKE BAY INTERPOLATOR

### PROCEDURE FOR USING THE VOL3D INTERPOLATOR

Begin using the VOL3D software by double clicking the VOL3D.EXE icon on the PC.

The first screen provides 7 buttons (Geography, Parameter, Data Import, Interpolate, Math, Graphics, and Reports) that step the user through the interpolation, graphics, and reporting process. Also on the first screen, is a *Data File Creation Tool*, that can be used to create VOL3D compatible data files from an external ACCESS data base. The ACCESS data base needs to contain data necessary for interpolation, as identified on Figure D-2. Essential data fields include STATION, LONGITUDE, LATITUDE, DEPTH, and VALUE. Other fields, including SAMPLE_DATE, PARAMETER name, LAYER, Qualifier (<, >), CRUISE, and CRUISE_ID, provide data that can be used to select or subset the monitoring data by cruise, layer, or date.

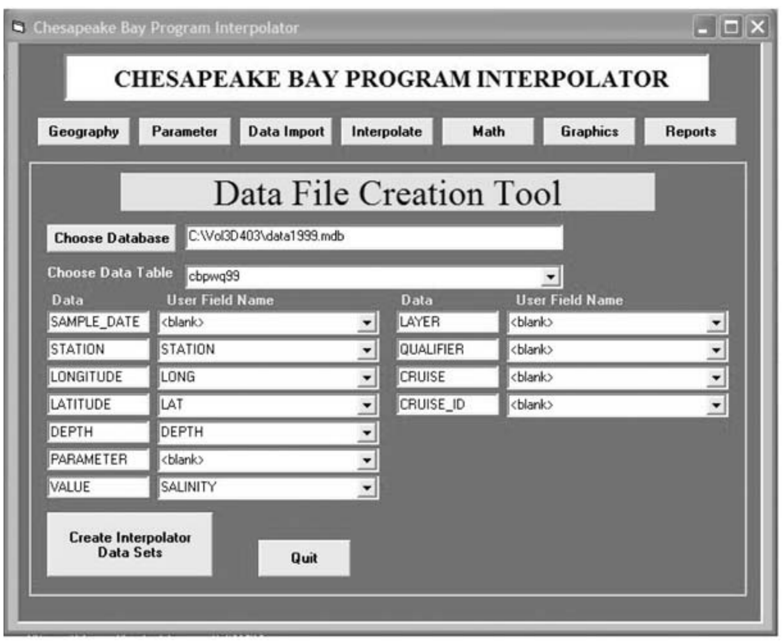


**Figure D-3.** Example of data fields selected from the "cbpwq99" data table in the "data1999.mdb" ACCESS data base. The *Data File Creation Tool* allows a user to extract data from an ACCESS table into desired data files for VOL3D

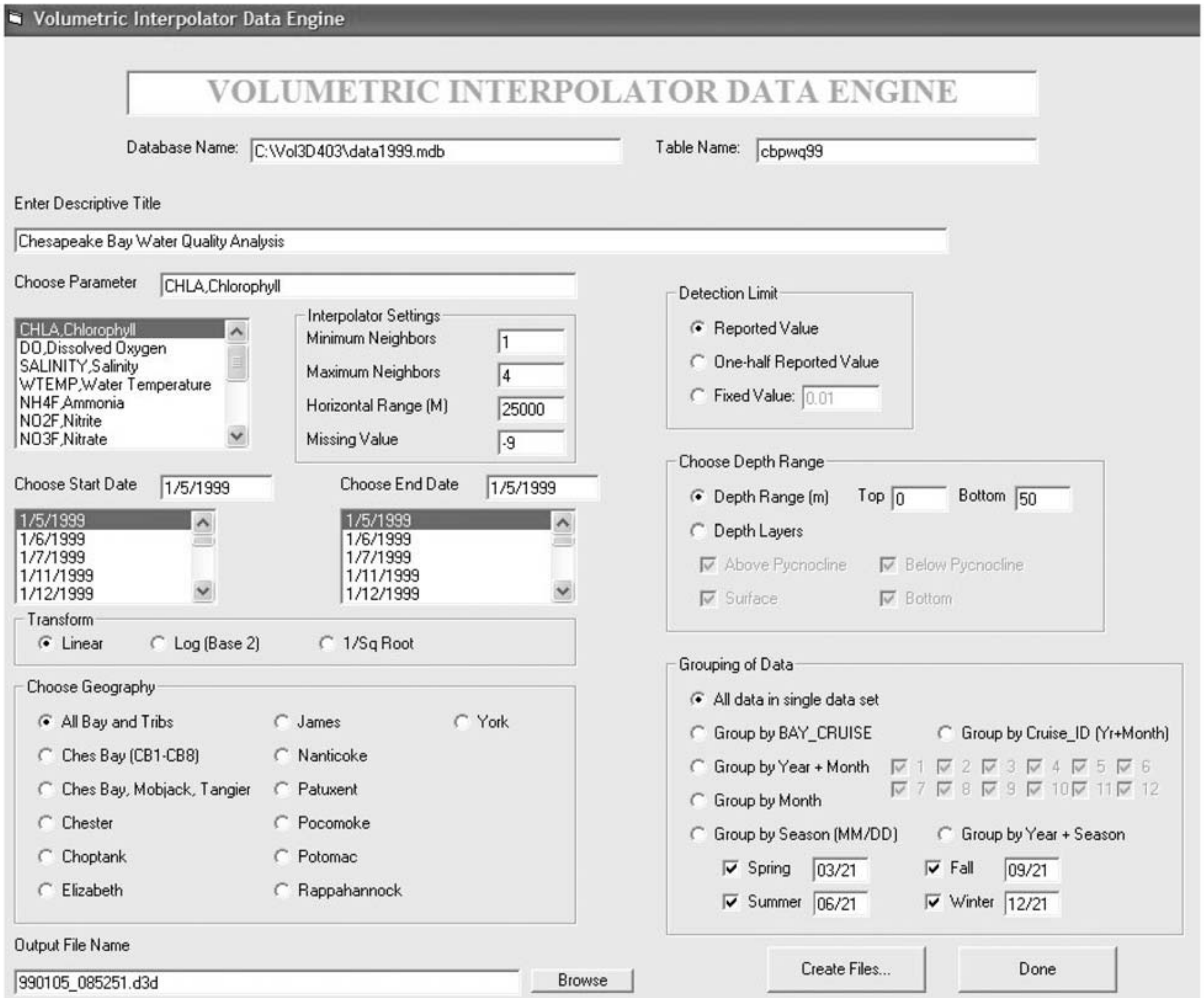


**Figure D-4.** The Data Engine screen provides many options for the user to aggregate data selected from an ACCESS data base table. Similar capabilities are built into the DART tool at the Chesapeake Bay Program, that allows access to the entire historical water quality data base.

## GEOGRAPHY BUTTON

Click the **Geography Button** to select the Geography screen. Select the bathymetry that matches your requirement, such as, Chesapeake Bay or Bay and tidal tributaries (Figure D-5).

## PARAMETER BUTTON

Click the **Parameter Button** to select the Parameter screen. Select the parameter that matches your requirement, such as, dissolved oxygen, salinity, or water temperature (Figure D-6). The number of significant digits of numerical precision is pre-selected for each parameter, but the value can be changed by the user in the Params.ini file.

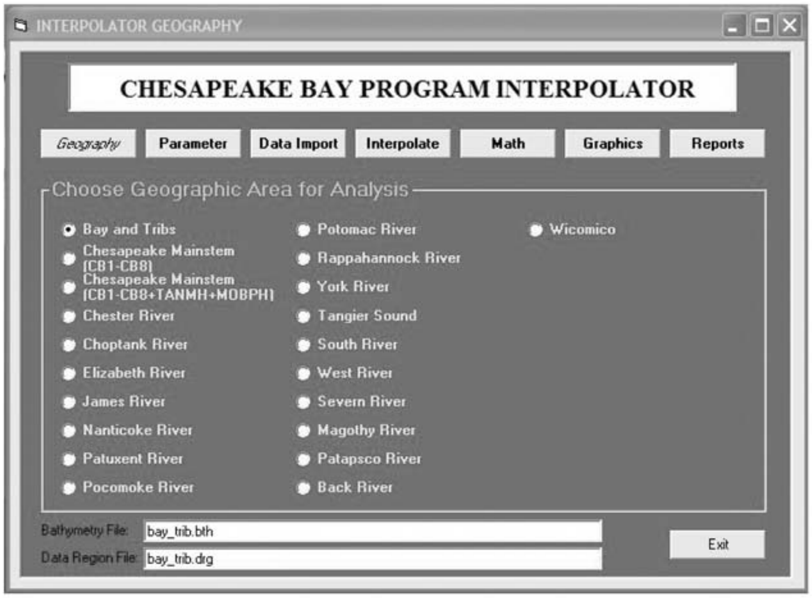


**Figure D-5.** Geography screen. Select desired bathymetry.

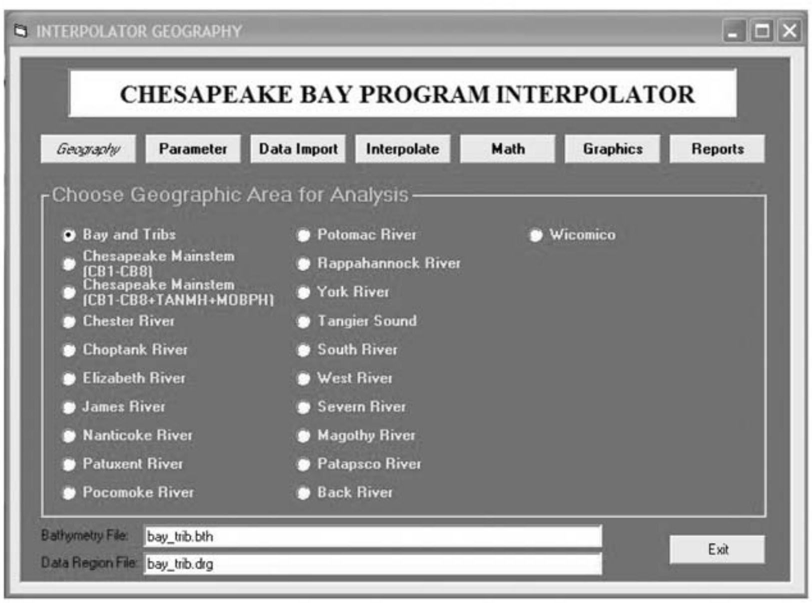


**Figure D-6.** Parameter screen. Choose desired parameter for analysis.

## DATA IMPORT BUTTON

Click the **Data Import Button** to select the Data Import screen. On this screen, click the "Get File Name" button to select the data file that contains the data that are to be interpolated (Figure D-7). The default file extension for data files is .d3d. d3d files include the X and Y coordinates (UTM Zone 18, NAD83 is recommended for interpolation. These are also required for the graphics tools.)

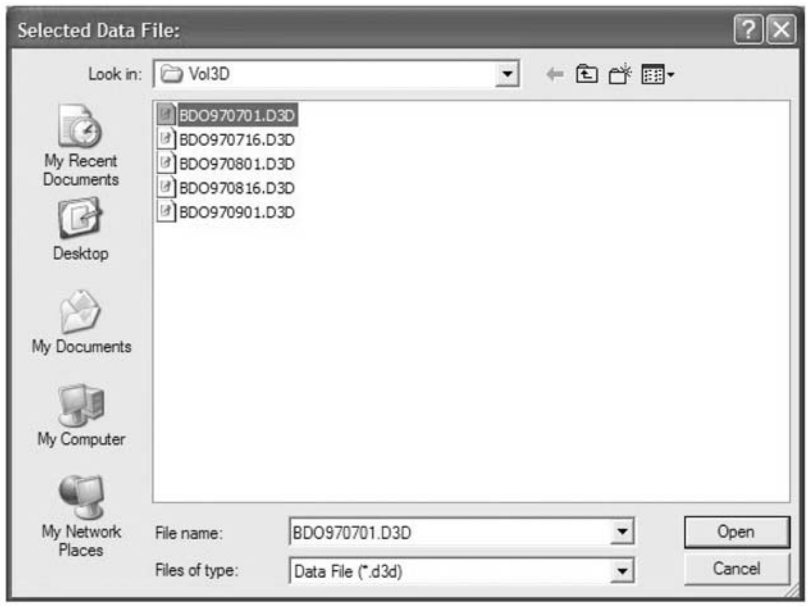


Figure D-7. Data Import screen, "Get File Name" window. Select a data file (.d3d) for analysis.

Once the file has been selected, the other fields on this screen will populate with information about the data file, including, start and end dates of the data, the number of observations, the date the file was created, the parameter name and code, and title (Figure D-8). Normally data do not need to be transformed, however, some data such as chlorophyll or TSS should be transformed with the log-transform to normalize the data. The data are transformed as they are read into the interpolator and the results are back-transformed to the original units in the output file. If the parameter is to be transformed by the natural log transform, any data values that are negative or zero will be set to a value of 0.0001. If the parameter is to be transformed by the square root transform, any data values that are negative will be set to 0.0.

Two buttons at the bottom of the screen can be used to convert latitude and longitude coordinates to UTM coordinates, which are recommended for interpolation (Figures D-9, D-10). The first converts the longitude and latitude coordinates in d3d formatted files to UTM coordinates, and vice versa. This is handy for checking data locations on maps. The second converts individual longitudes and latitudes to and from UTM coordinates. NAD27 to NAD83 conversion is not supported in this code. Improper use of NAD27 or NAD83 can result in coordinate errors in the 100 to 300 meter range.

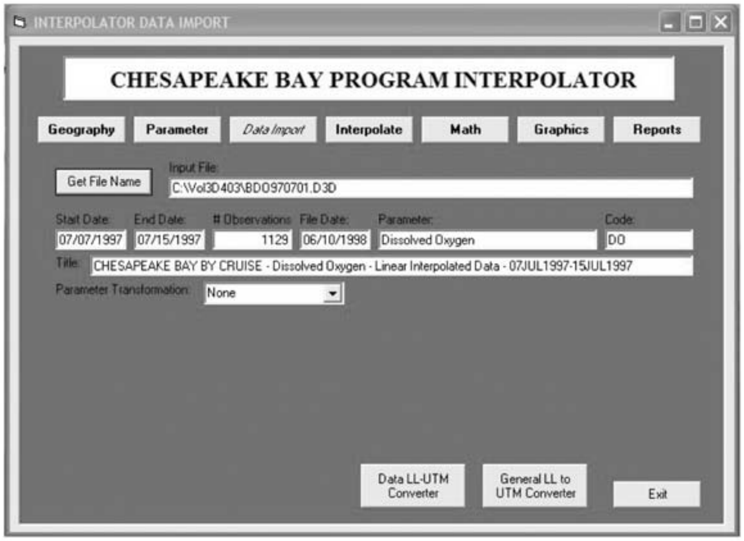


**Figure D-8.** Data Import screen with fields populated with data from the selected .d3d input file.

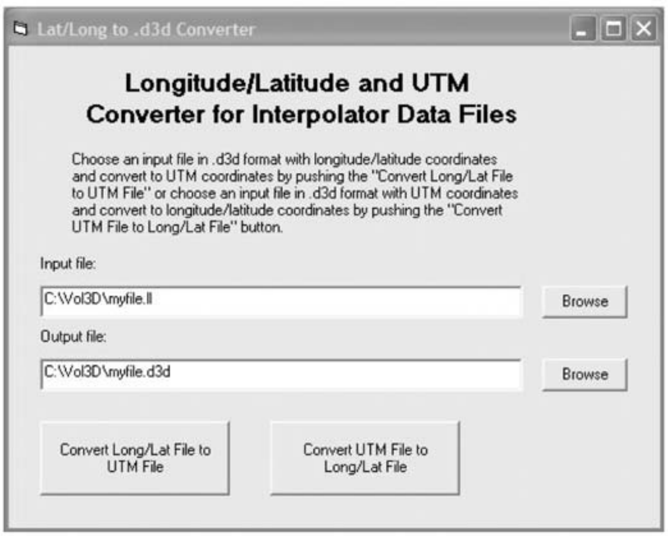


**Figure D-9.** Data Import screen file converter for converting longitude and latitude

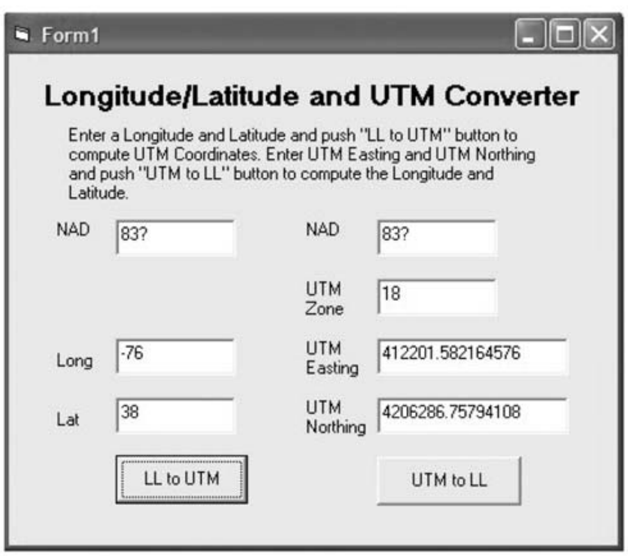


**Figure D-10.** Data Import screen general purpose UTM converter for converting longitude and latitude coordinates to UTM coordinates and vice versa. North American Datum (NAD) is assumed as NAD83 and does not convert from NAD27.

## INTERPOLATE BUTTON

Click the **Interpolate Button** to select the Interpolate screen (Figure D-11). Select the interpolator settings that match your requirements. The 3D Inverse-Distance Squared model is the 3-dimensional interpolator model. The 2D Inverse-Distance Squared model uses the same code as the 3D interpolator model except that only one layer of cells are computed—cells for each depth below the surface cell are set to missing (normally -9). The 2D Octant Search model computes values for cells in only one layer, however, the data used for computing each cell value are selected from data in each surrounding octant. For instance, for a given cell, the data used for calculation would include 4 data points from each surrounding octant, or a total of 32 data points. The model will use fewer than the total data in each octant if insufficient data exist. The model uses as many data as are available for each octant, up to the maximum requested number of data points. The octant search model is used to reduce the bias from sampling schemes that collect continuous strings of data, such as aircraft monitoring that collect many data points in well defined flight tracks. The run-time for the octant search model is significantly longer due to the extensive sorting required to select data from each data octant.

The "Trace Level" selects the amount of detail written to the ".LOG" file. A "Trace Level" of "2" provides general interpolator statistics. A "Trace Level" of "3" provides information about the data values used in the computations for each region. A "Trace Level" of "4" provides information about individual cell computations. A "Trace Level" of "5", "6", or "7" provides increasing information about data values, distances, and octants. Increasing the "Trace Level" value is useful for investigating the performance of the interpolator.

The "Convert .EST to .TXT" button will create a .txt file that can be imported into Arc/Info or ArcView. The .txt files are a full matrix of values, 57 columns wide, with all missing or non-existent cell values designated as missing values (normally -9), comma delimited, and column headings and text strings are enclosed in quotes. Each row in the .txt file represents numbers from 1 column of water from top to bottom, 1 cell wide by n cells deep. Additional columns are appended to the .txt file for bottom, minimum, maximum, mean, and sum values.

The "Convert .EST to .T3D" button will create a .txt file that can be imported other applications. The .t3d files are 4 columns wide, comma delimited, contain the x value, y value, negative z value, and the estimated value. There are no column headings. Missing values are included and are coded based on what was selected during the interpolation.

The interpolator mode can be set to "Interactive" or "Batch". In interactive mode, the chosen file is interpolated as defined in Figure D-11. In "Batch" mode, a job file is selected which provides the information needed to interpolate a series of files under machine control (Figure D-12). The ".job" file can be built interactively by pressing the "Save to Batch Job" button after selecting the run parameters for each desired file (Figure D-13). The "Batch Job" can be executed by pushing the "Run Batch Job" button.

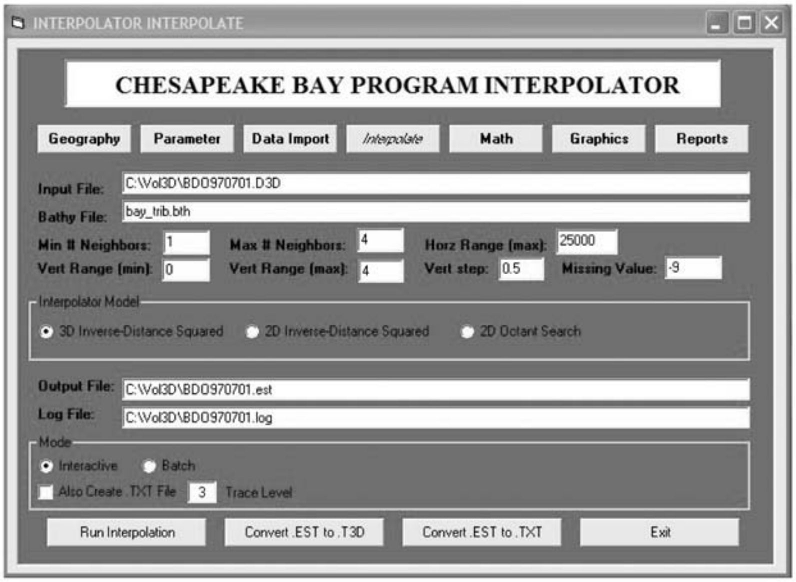


**Figure D-11.** 3D Inverse-Distance Squared Interpolate screen populated with entries after having made choices on previous screens. The 2D Inverse-Distance Squared Interpolate screen uses the same format as the 3D Inverse-Distance Squared model; however, only the surface depth value has computed values. Cell values at depths below surface are set to missing (generally -9). The 2D Octant Search Interpolator does not rely only on the closest data in all directions, but rather uses data from data from surrounding octants. For example, if 4 nearest neighbors are requested in each of 8 octants surrounding the cell being computed—up to 32 nearest neighbor values will be used to compute the value. If no nearest neighbor values are available, a missing value will be computed. Other buttons are available for creating data using specific formats for various GIS (.txt files) and graphics applications (.t3d files).

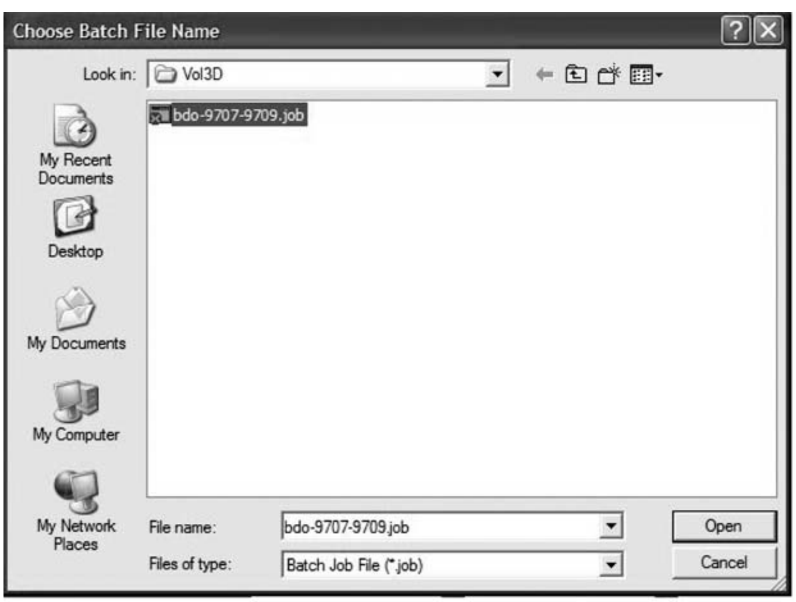


**Figure D-12.** Batch Job File Name selection window that displays after choosing "Batch" radio button on Interpolation screen.

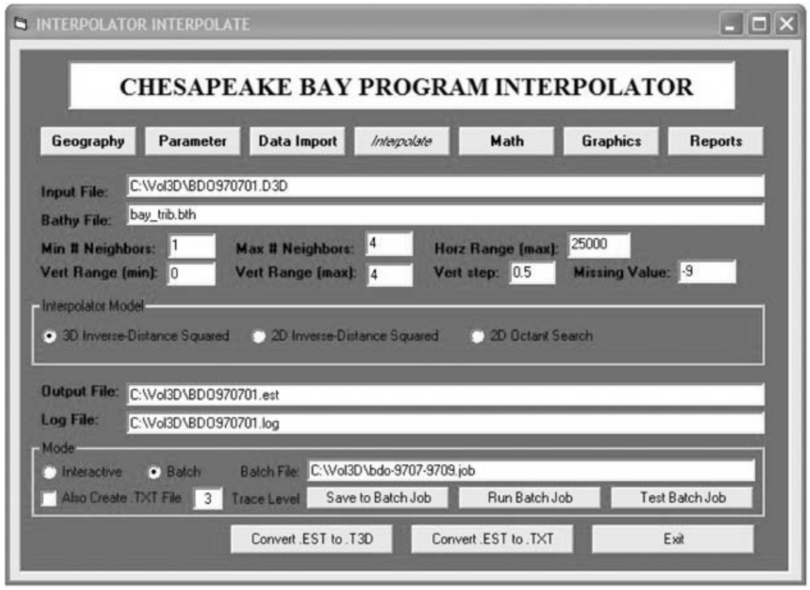


**Figure D-13.** Saving or running a batch job through the Interpolate screen. "Save to Batch Job" saves the values that have been entered in the fields on this screen into the "Batch File ('filename'.job)". If the 'filename'.job file already exists, the new entry is appended to the existing file. If it does not exist, a new file is created. The "Output File" file name entry is also written to a file ('filename'.fls) for use in creating volume and mass estimates by running batch jobs. The .fls file is simply a list of interpolated (.est) file names that can be processed sequentially. The "Test Batch Job" button executes a batch job but does not run the interpolator. This button can be used to test whether the needed files exist and the batch job is sound prior to execution of the interpolator.

## MATH BUTTON

Click the **Math Button** if you need to conduct special operations on one or more files. Four functions are provided: 1) Math operations which include adding, subtracting, multiplying, or dividing one interpolated file by another, or by a constant; 2) Recoding values to new values; 3) Conducting a change analysis over time; and, 4) Calculating the minimum or maximum values from a set of files.

Math functionality is provided so that special parameters can be calculated. Math is conducted on a cell by cell basis. For instance, to add two interpolated files, Cell 1 of input file A is added to Cell 1 of input file B and the sum is stored in Cell 1 of output file C, and so forth. Subtracting one file from another can be used to show change from one time to another (Figure D-14). Missing values are handled as in regular math—a non-missing value becomes missing if a math operation attempts to compare a real value with a missing value. Division by zero or other illegal math operation will cause the operation to stop.

The "Derive New Parameter" math operations can be performed sequentially to provide additional capability. For instance, five interpolated files (.est files) could be sequentially added together, then the resulting file could be divided by 5 to compute

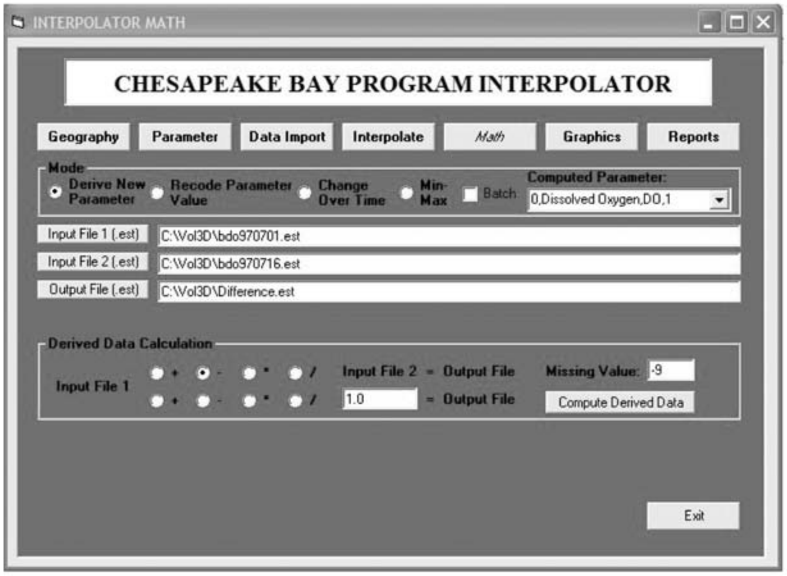


**Figure D-14.** Math screen with files chosen to "Derive New Parameter" of Dissolved Oxygen by subtracting File 2 from File 1 to create the output file.

the mean for the five files. Another example would be to subtract interpolated dissolved oxygen data from an interpolated saturated dissolved oxygen file to compute the oxygen deficit.

The code checks whether the input files have the same number of segments. If the input files ("Input .est File 1" and "Input .est File 2") do not have the same number of segments, they were generated from different bathymetry files, and the cell values in the two files can not be properly combined. An error message will be displayed if this condition occurs.

The "Recode Parameter Value" radio button provides the means to convert calculated values to new values (Figure D-15). The input file is not changed, but a new output file is created with new values in each cell which classify the data into new values or categories. For example, to compute the interaction of dissolved oxygen and water temperature:

1) Recode the dissolved oxygen .est file so that oxygen below 3 mg/l is set to "1" and oxygen above 3 is set to "0" (also set missing to -9).

2) Recode the water temperature .est file so that temperature below 25C is set to "0" and temperature above 25C is set to "10" (also set missing to -9).

3) Derive a new parameter "WD" by adding the recoded dissolved oxygen and water temperature .est files. The result is a wd.est file where: "0"=acceptable oxygen and temperature; "1"=unacceptable oxygen; "10"=unacceptable temperature; and "11"= unacceptable oxygen and unacceptable temperature (missing cells will = -9). This file can be graphed to show the distribution of these categories. The water column

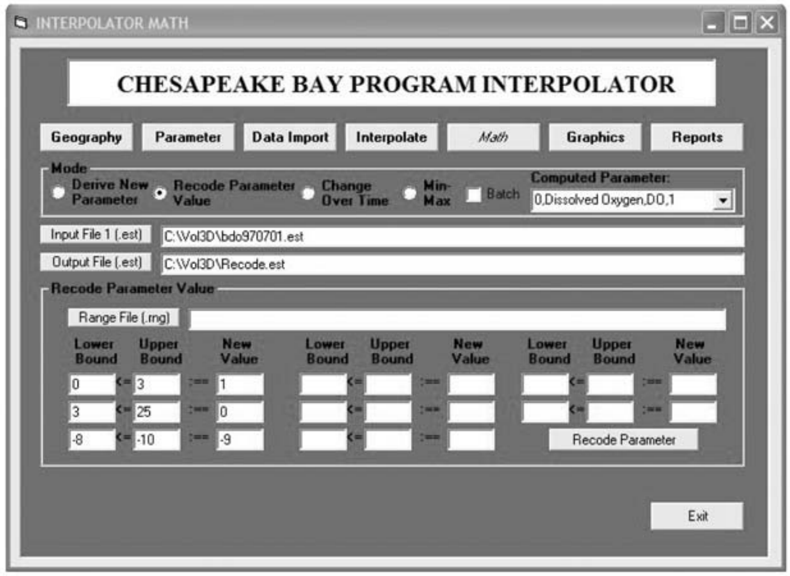


**Figure D-15.** Math screen with files chosen to "Recode Parameter Value" of Dissolved Oxygen by recoding values from 0-3 to the new value of "1", recoding values of above 3 to the new value of "0" and retaining missing values as –9, to create the new output file. Choosing a Range File is provided to load an existing set of ranges, which can then be modified on this screen for specialized analyses.

volume of these categories can also be computed to show critical ranges for habitat analysis.

Missing values are handled in a special way. Since missing values have no real value, they are not used in math operations. If a cell in either "Input File 1" or "Input File 2" are flagged as missing (normally –9), then no math is done, and the "Output File" value for that cell is set to missing (The "Missing Value" is set on the Interpolate screen).

## TRENDS ANALYSIS

Interpolated values can be analyzed for trends. The "Change Over Time" button allows the user to create a 3-dimensional (.est) file with linear percentage changes over time for each cell in the bathymetry (Figures D-16 and D-17).

As a simple example, a station may be sampled several times over a period of time. The measured values can be plotted with time on the x-axis and value on the y-axis. The resulting linear regression line can be plotted through these points and the slope and intercept can be used to compute the percentage increase or decrease between the beginning and end of the time series.

This same technique can be used with the interpolator. Each cell value from a series of .est files can be used to compute a linear regression, so that each cell has its own regression and resulting percentage change, either up or down, over time. By coding

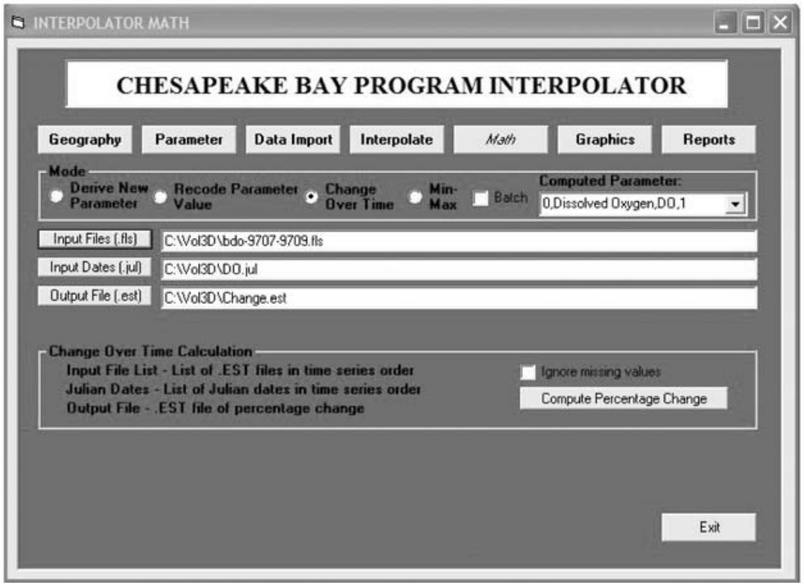


**Figure D-16.** Math screen with files chosen to "Change Over Time". The bdo-9707-9709.fls file contains file names of dissolved oxygen .EST files. The corresponding Julian dates for these .EST files are read from the do.jul file. In this example, a new .EST file – Change.est – is created which contains the linear trend for each cell over the time interval of the bdo-9707-9709.fls file. The Change.est cell values are percentage change over time, categorized by the selection criteria identified in the pc.rng file. In this example, "Ignore missing values" has not been selected.

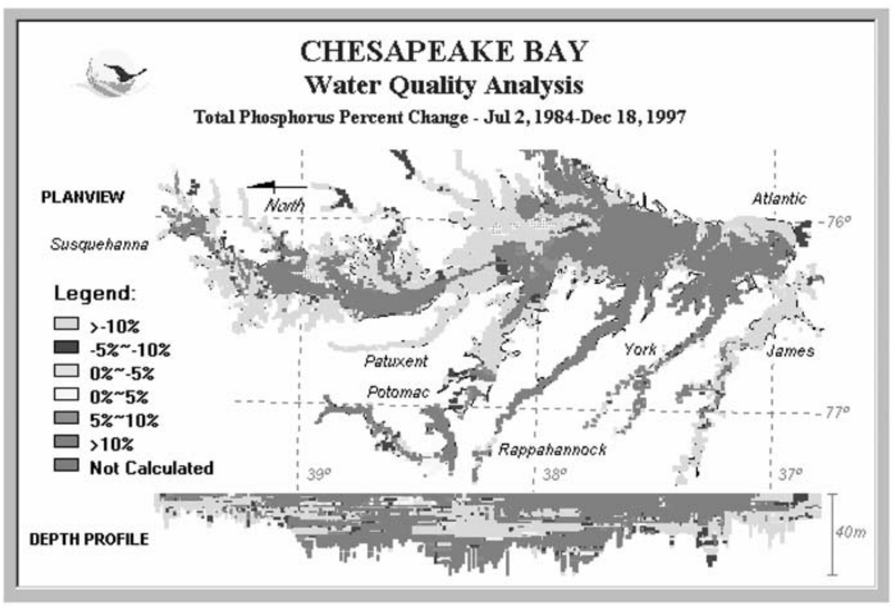


**Figure D-17.** Plot of total phosphorus as a "Change Over Time". In this example, a new .EST file – tp8497.est – was created which contains the linear trend for each cell over the time interval (July 1984 through December 1997) of the tp8497.fls file. The tp8497.est cell values are percentage change over time, categorized by the selection criteria identified in the pc.rng file. The percentage change categories for total phosphorus mass (kg) are: >10% increase (red); 5 to 10% increase (pink); 0 to 5% increase (yellow); 0 to 5% decrease (light blue); 5 to 10% decrease (dark blue); and greater than 10% decrease (green). In this example, "Ignore missing values" was selected so that a trend on any available data was calculated.

the result as the percent change, a .est file can be created that has a percentage change value for each cell. This .est file represents a 3D file of "Change Over Time". The plot of this file provides a graphical representation of the change. The categories used to display the changes graphically are defined in the pc.rng file. The default pc.rng file provides categories of: >+10%, +5 to +10%, 0 to +5%, –5 to 0%,–10 to –5 %, and >–10 % change. These categories should be modified to reflect the needs of the analysis.

Missing values in the analysis can be treated in two ways: 1) included, meaning they are propagated through the analysis; or, 2) ignored. The default is to include missing values. The result of including missing values is that if one value for a specific cell is missing anytime in the times series, then that cell is set to missing. The single missing value forces the whole series of values at that cell to be missing and no percentage change is calculated. The percentage change value is set to missing (-9 by default).

If missing values are set to be ignored, then each missing value in a time series for a given cell is ignored and the rest of the time series observations are used to compute the percentage change over time. The potential problem with this approach is that the trend may be skewed by the lack of having all of the desired data.

At least two points are required to compute a time series change. If the number of observations for any cell is less than 2, the resulting value for the percentage change is set to missing.

## MINIMUM-MAXIMUM ANALYSIS

The "Min-Max" button can be selected to locate the minimum or maximum values in a series of interpolated values. For instance, this function could be used to read ten interpolated files, and find for Cell 1 the minimum value and write that minimum value to the output file Cell 1. This process would be repeated for each cell, so the resulting output file would contain the minimum value for each cell in the series. The Maximum function could be chosen if desired to find the maximum cell values in a series of files. These functions are useful for determining, for example, the lowest salinity over a 10-year period, or the highest temperature over a year period, for each cell in the interpolated files. (Figures D-18 and D-19).

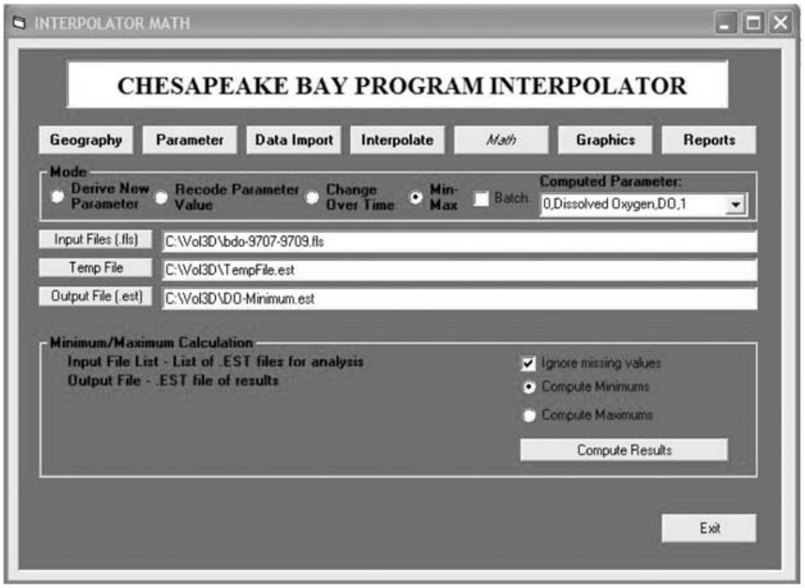


**Figure D-18.** Min-Max screen to capture the minimum oxygen values in each cell over the July-September timeframe in 1997. The bdo-9707-9709.fls file contains file names of interpolated dissolved oxygen .EST files. The Temp file is an intermediate working file that can be deleted after the job is completed. In this example, a new .EST file – do-minimum.est – is created which contains the minimum vale for each cell over the time interval of the bdo-9707-9709.fls file. In this example, "Ignore missing values" has been selected.

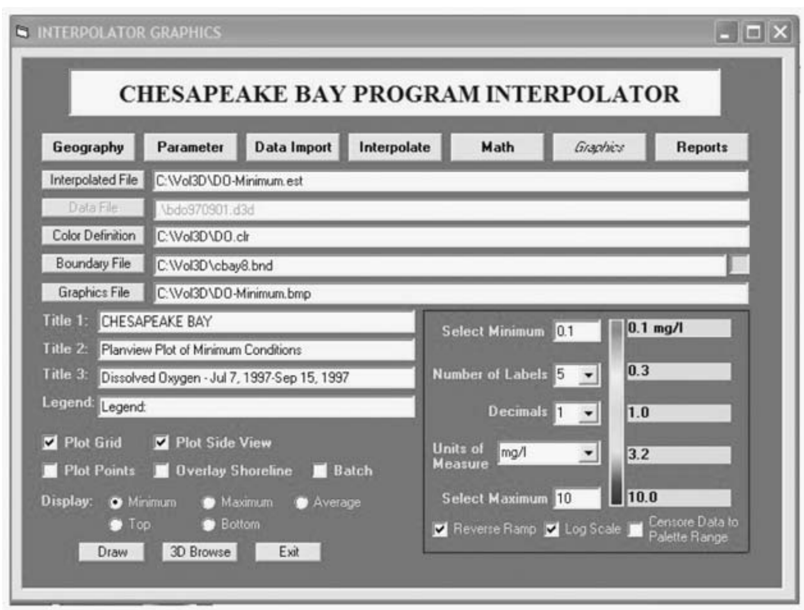


**Figure D-19.** Math screen with files chosen to "Change Over Time". The do97.fls file contains file names of dissolved oxygen .EST files. The corresponding Julian dates for these .EST files are read from the do.97.jul file. In this example, a new .EST file – dopc.est – is created which contains the linear trend for each cell over the time interval of the do97.fls file. The dopc.est cell values are percentage change over time, categorized by the selection criteria identified

## GRAPHICS BUTTON

Click the **Graphics Button** to select the Graphics screen. In this version, the graphical representation of the data is limited to a Plan view (looking down on the Bay and tidal tributary rivers) and a Side view (looking at the vertical dimension of the Bay and tidal tributaries from the West).

The Graphics screen provides a means to choose all of the variables need to create the Bay/Trib graphic (Figure D-20). Most of the choices are driven by the files being graphed, to help minimize typing in all of the required information. The graphic can be printed or saved to a .BMP file (Figure D-21).

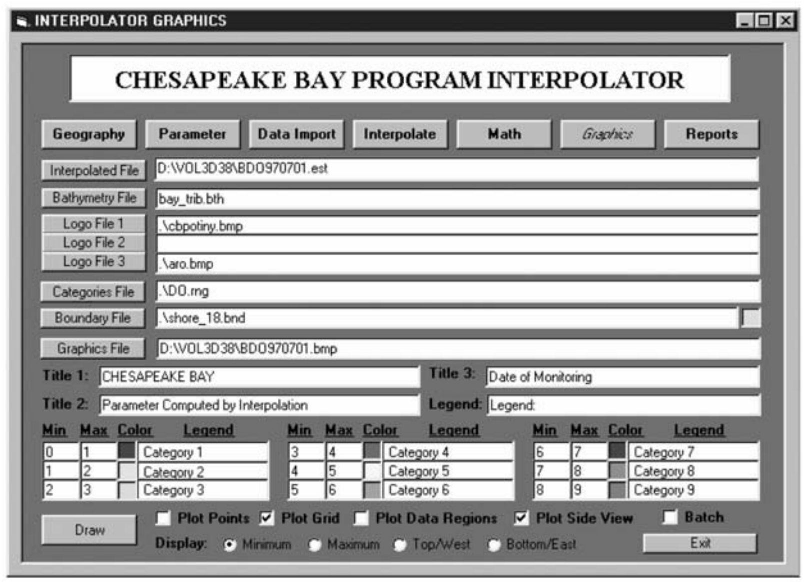


**Figure D-20.** Graphics screen with default values for graphing the selected ".est" file.

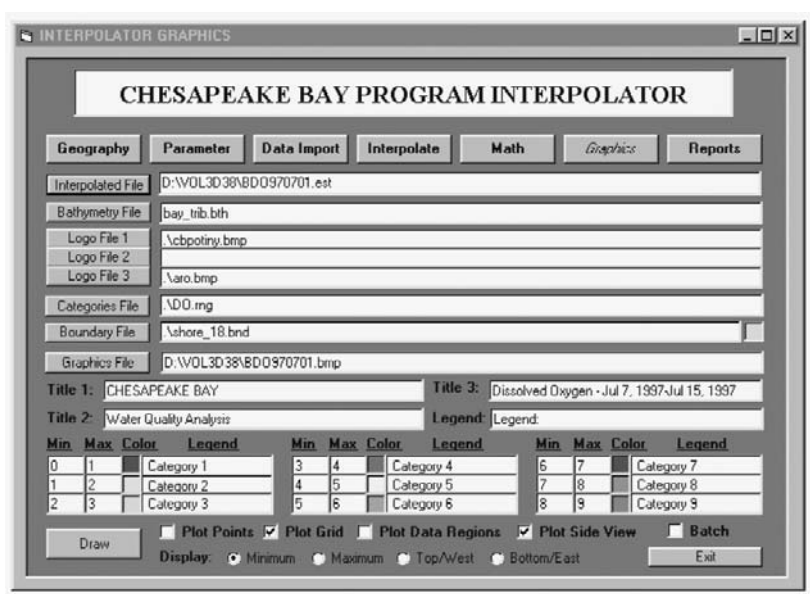


**Figure D-21.** Graphics screen with titles imported from the selected ".est" file. Click the "Interpolated File" button to load these titles to this screen. The titles can be edited directly on this screen.

The **Batch** checkbox can be selected to process a group of files (.est file names are read from a *.fls file) using the choices selected as shown in Figure D-22. If **Batch** is chosen, the program prompts the user to choose a *.fls file. **Title 3** and **Graphics File** will automatically change for each plot based on the information contained in the .est file. Other titles and legends will display based on what is displayed when the **DRAW** button is pushed. Each graphic will automatically be saved to the default graphics file name (D-23).

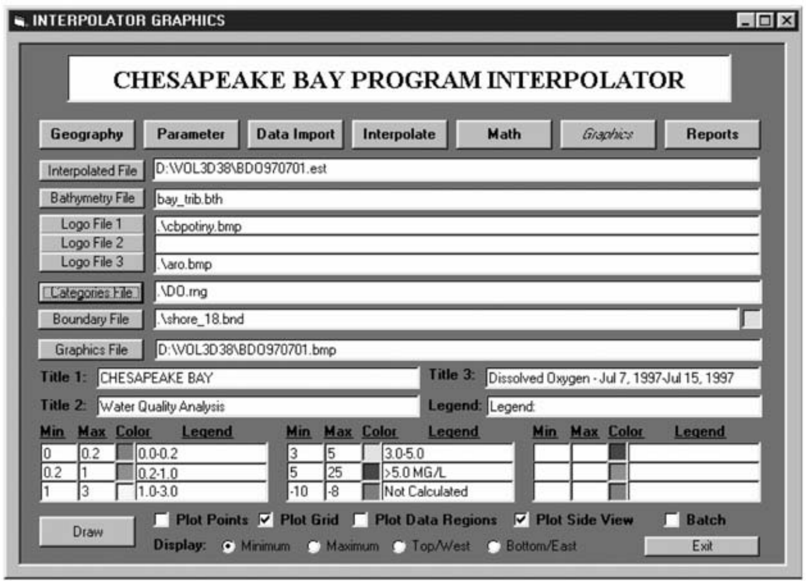


**Figure D-22.** Graphics screen with legend imported from the selected ".rng" file. Click the "Categories File" button to load these range categories to this screen. These category values and colors can be edited directly on the screen.

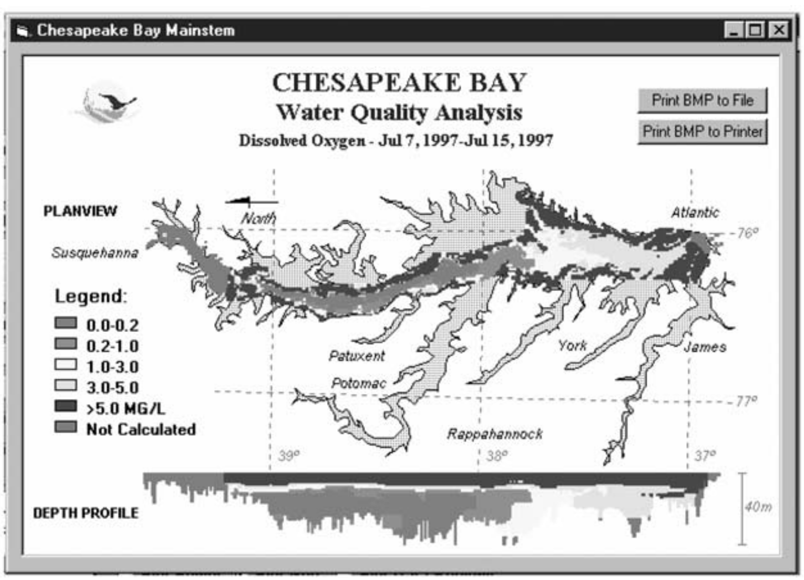


**Figure D-23.** Example graphic of interpolated Chesapeake Bay mainstem dissolved oxygen. The data are displayed so that the worst case data (low dissolved oxygen, in this case), regardless of depth, are visible in both the Plan- and Side views.

## REPORTS BUTTON

Click the **Reports Button** to generate files for volumetric and mass analysis (Figure D-24).

The “Layer Thickness” is set to 0-50 meters deep to include all cells in the interpolated file. This thickness could be set, for example, to 3-6 meters to calculate the volume and mass for the water 3 to 6 meters deep (Figure D-25).

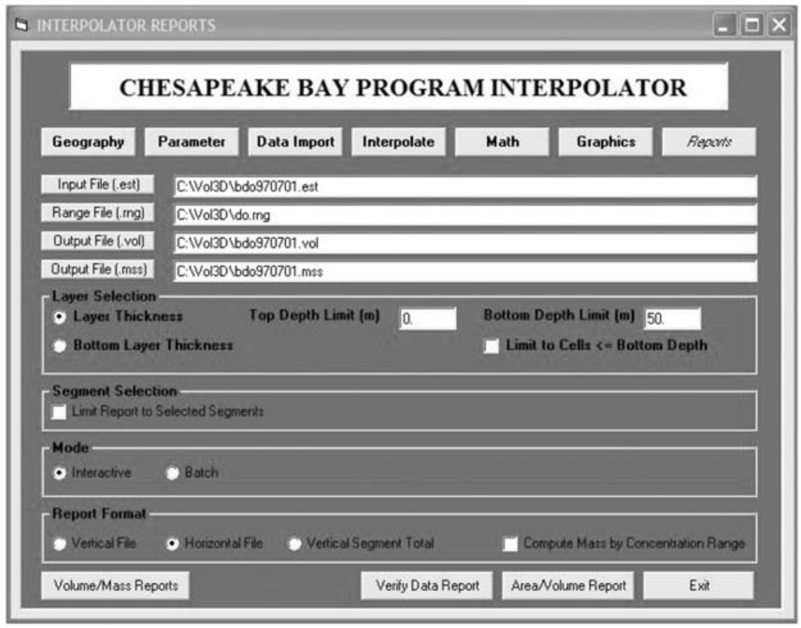


**Figure D-24.** The Reports screen is used to compute volume and mass. In Interactive mode, an interpolated file (.est) is processed to create a file of water volumes by parameter range category by segment. A file of parameter mass is also computed by segment. If the “Compute Mass by Concentration Range” is checked on, then the mass calculations are also separated by the same category ranges as the volume calculations.

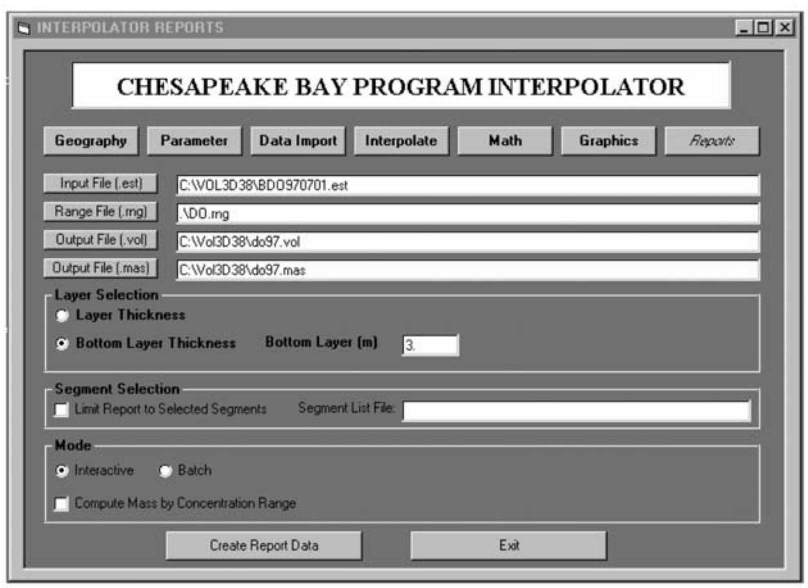


**Figure D-25.** The Reports screen with “Bottom Layer Thickness” selected and set to the bottom 3 meters of water column depth. Only the cells in the selected bottom layer will be processed for volume and mass calculations.

The resulting volume (.vol) and mass (.mas) files can be used for creating numerical or graphical reports, such as trends plots (Figure D-26).

Each successive set of computed numbers are appended to the same specified "Output File" (.vol and .mas).

Each successive set of computed numbers are appended to the same specified "Output File" (.vol and .mas) (Figure D-27).

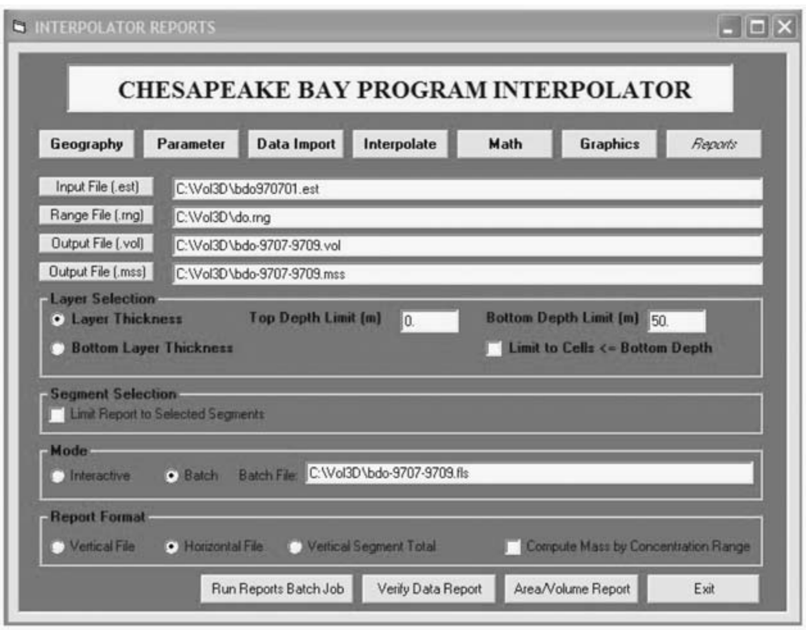


**Figure D-26.** The Reports screen with "Batch" mode selected. In Batch mode, a list of interpolated file names (.est) are processed sequentially to create a file of water volumes by parameter range category by segment. A file of parameter mass is also computed by segment. If the "Compute Mass by Concentration Range" is checked on, then the mass calculations are also separated by the same category ranges as the volume calculations. This example calculates volume and mass for the top

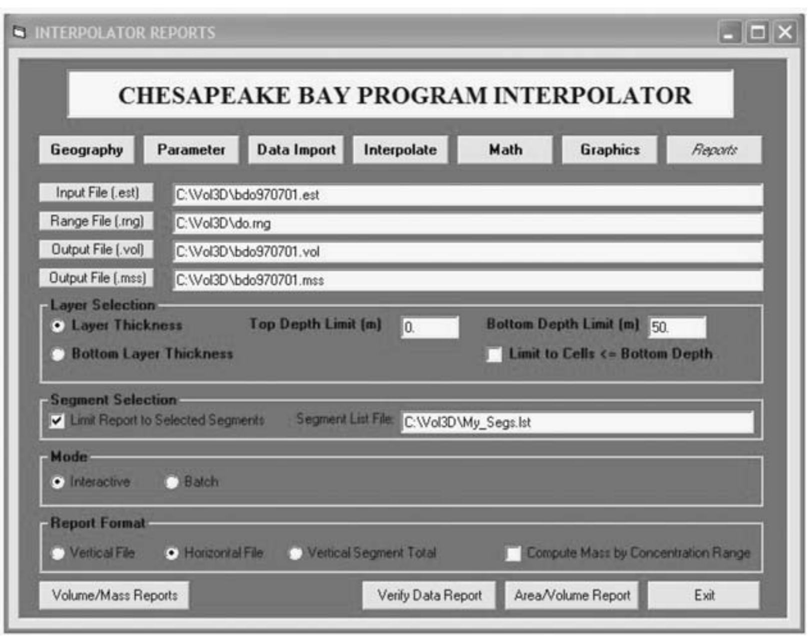


**Figure D-27.** The Reports screen is used to compute volume and mass. In Interactive mode, an interpolated file (.est) is processed to create a file of water volumes by parameter range category by segment. A file of parameter mass is also computed by segment. If the "Limit Report to Selected Segments" is checked on, then the volume and mass calculations are computed only for the segments identified in the "filename".lst file.

Figure D-28 illustrates a time series plot of the mass of total phosphorus computed by the procedure described in. The mass of total phosphorus was computed for Chesapeake Bay and tidal tributary rivers using monthly mean data for each station at each depth for the period of record. The “Date” and “Total” (sum of all columns in mass file) columns were used from the mass file (.mas) to make this plot. The linear trend line is superimposed to show the general rate of decline. This plot was created by opening the tp8497.mas file in Excel, selecting the line chart button, selecting the “Start_Date” and “Total” columns, and adjusting the legends and titles as necessary to create the time series plot. The linear trend was added by selecting the time series followed by “Chart:Add Linear Trendline”.

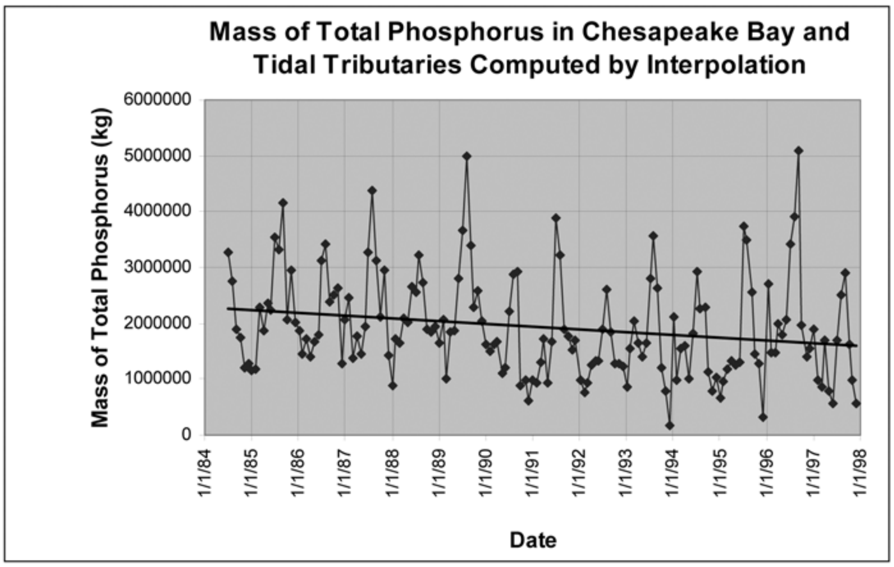


**Figure D-28.** TTime series plot of the mass of total phosphorus.

## FILE DEFINITIONS AND STRUCTURE

### INPUT DATA FILE (.d3d)

Monitoring data are required for the Interpolator to compute values. The file should contain one value per depth per station for which data exist. If replicate values were measured at some or all stations, they should be averaged at each station depth so that only one value exists per depth per station. The overall data can represent one cruise, a season of cruises, or a decade of data—there are no limitations on what the data represent—that is up to the user to determine. It is best, statistically, to provide as many data as possible. One method is to linearly interpolate values from surface to bottom before creating the data file for the Interpolator. This will provide more data for the Interpolator if it is valid to do so for the desired data. For the 2D interpolation models, only one value per station should be used, since the depth value is ignored. The file naming convention for the input file is ‘filename’.d3d. The input file has the following structure:

Line 1> contains a title that is meaningful to the user that identifies the contents of this dataset.
Line 2> contains a 2-digit parameter code, comma, and the spelled-out parameter name
Line 3> contains the start date, comma, and end date of the data
Line 4> contains the date and time the data were compiled
Line 5> contains the number of observations that follow
Lines 6+> contain the easting in UTM Zone 18 meters NAD83, comma, the northing in UTM Zone 18 meters NAD83, comma, the sample depth in meters, comma, the measured value of the parameter, comma, and the station ID

```
==========================================

CHESAPEAKE BAY AND TRIBS - Dissolved Oxygen - Measured Data -06JUL199315JUL1993
DO,Dissolved Oxygen
07/06/1993,07/15/1993
08/11/1997:15:11
1128
407056,4377577, 0.5,   7.7000,CB1.1
407056,4377577, 1.0,   6.8000,CB1.1
407056,4377577, 2.0,   6.2000,CB1.1
407056,4377577, 3.0,   5.7000,CB1.1
...
407056,4377577, 4.0,   5.5000,CB1.1
407056,4377577, 5.0,   5.2000,CB1.1
411793,4365898, 0.5,   5.9000,CB2.1
411793,4365898, 1.0,   5.7000,CB2.1
411793,4365898, 2.0,   5.7000,CB2.1
411793,4365898, 3.0,   5.7000,CB2.1
...
366939,4301041, 0.5,   7.5000,WT8.3
366939,4301041, 1.0,   7.3000,WT8.3
==========================================
```

## METADATA FILE (.met)

A metadata (documentation) file is created during the job. The default filename is ‘filename’.met.
Check this file (using the Notepad editor) to see what calculations were performed during the job.

```
==========================================
Statistics Report for C:\Vol3D\BDO930701.est

Title: CHESAPEAKE BAY AND TRIBS  Dissolved Oxygen  Measured Data
                                                        06JUL199315JUL1993
Parameter: Dissolved Oxygen  Parameter Code: DO
Data Period: 07/06/199307/15/1993
Data File Date: 08/11/1997:15:11
Observations: 1128
Maximum Number of Nearest Neighbors: 4
Minimum Number of Nearest Neighbors: 1
```

Maximum Vertical Search Window: 4
Minimum Vertical Search Window: 0
Vertical Search Window Step Size: .5
Maximum Horizontal Search Radius: 25000
Missing Value: 9
Interpolator Model: DepthRadiusInterpolator
Interpolation Date: 10/6/97 10:55:55 AM
Bathymetry File: bay_trib.bth
Number of Bathymetry Regions: 68
Data Region File: bay_trib.reg
Number of Data Regions: 68
 -  Bathymetry Region ID: 1001  Region Name: CB1TF  Data Points: 28 in data region 1001
 -- Cell Size  EW: 1000  NS: 1000  Vertical: 1
 --- 360 cells were interpolated in region CB1TF  Subtotal: 360 total cells
 ---- Region was calculated in 4 seconds.
 - Bathymetry Region ID: 1002  Region Name: CB2OH  Data Points: 48 in data region 1002
 --  Cell Size  EW: 1000  NS: 1000  Vertical: 1
 --- 1237 cells were interpolated in region CB2OH  Subtotal: 1597 total cells
 ---- Region was calculated in 1 seconds.
...
...

Total Number of Cells Interpolated: 173805
Total Number of NonMissing Value Cells Interpolated: 160558
Total Number of Missing Value Cells Interpolated: 13247

Nearest Neighbors: 4    # of Cells: 101978
Nearest Neighbors: 3    # of Cells: 12358
Nearest Neighbors: 2    # of Cells: 33517
Nearest Neighbors: 1    # of Cells: 12705

173805 cells were calculated in 244 seconds.

==========================================

## INTERPOLATED ESTIMATES FILE (.est)

An interpolated estimates file is created during the job. The default filename is ‘filename’.est. For the 3D interpolator model, this file contains the values for each cell interpolated during the job, from surface to bottom for each cell location. For the 2D interpolator models, this file contains the values for the top cell at each cell location. While the interpolated value is written to the surface cell location in this file, its value might represent the bottom value—i.e., the value might represent bottom layer dissolved oxygen. All cell values below the top value will be set to missing (usually -9). The file contents include:

Line 1>Input data file name
Line 2>Data file description
Line 3> 2 digit parameter code and parameter name
Line 4>Start and end dates of data
Line 5>Date and time data file was compiled
Line 6>Number of data points, nearest neighbors, minimum neighbors, maximum vertical window, minimum vertical window, vertical window step increase size, maximum search radius, missing value
Line 7>Name of interpolator used
Line 8>Date and time of job
Line 9>Bathymetry file used

Line 10>Data region file used
Line 11>Number of segments to interpolate
Line 12>Cell description for this segment:number of surface cells in segment, segment id, segment name, cell e-w dimension in meters, cell n-s dimension in meters, cell vertical depth in meters
Line 13+>cell easting, cell northing, cells deep, interpolated values from surface to bottom.

```
==========================================
C:\VOL3D\BDO970601.D3D
CHESAPEAKE BAY BY CRUISE - Dissolved Oxygen - Linear Interpolated Data -
   3JUN199712JUN1997
DO,Dissolved Oxygen
06/03/1997,06/12/1997
06/10/1998:8:55
1254,4,1,4,0,.5,25000,9
Interpolator Model: DepthRadiusInterpolator
6/17/98 10:24:26 AM
cbay8.bth
cbay8.reg
8
132,1001,CB1TF,1000,1000,1
403000,4384000,2,9.1,8.9
404000,4384000,5,9.1,8.9,8.8,8.8,8.8
404000,4383000,3,9.1,8.9,8.8
405000,4383000,8,10.3,9.9,9.5,8.8,8.8,8.8,8.8,8.8
405000,4382000,3,10.3,9.9,9.5
406000,4382000,1,9.9
...
...
405000,4082000,1,10.5
410000,4082000,4,10.5,10.5,10.4,10.3
404000,4081000,1,10.6
410000,4081000,3,10.5,10.5,10.4
405000,4079000,1,10.6

==========================================
```

## TXT FILE CREATED FROM ESTIMATES FILE (.txt)

Interpolated estimates files ( 'filename'.est) can be reformatted as 'filename'.txt files which can be readily imported into other applications, including Arc/Info and ArcView. The .TXT file contains the values for each cell in the original Estimates file, from surface to bottom for each cell location. In addition, each line in the file is padded with –9 values. So the file is a rectangular matrix of data with all values having a value. The file is comma delimited, and all extraneous blanks have been removed. The precision of the reported parameter values are assigned by the values set in the 'parameter.sys' file. The .TXT file contents include:

Line 1>Column Headings
Line 2+>cell easting, cell northing, segment name, cell e-w dimension in meters, cell n-s dimension in meters, cell vertical depth in meters, bathymetry depth in meters, interpolated values from surface to bottom, additional depths padded with –9 down to layer_45, then bottom, minimum, maximum, mean, and sum values for non-missing cells in this water column.

UTM_X,UTM_Y,Segment,EW_dim,NS_dim,Vert_dim,n,layer_1,layer_2,layer_3,layer_4,layer_5,layer_6,layer_7,layer_8,layer_9,layer_10,layer_11,layer_12,layer_13,layer_14,layer_15,layer_16,layer_17,layer_18,layer_19,layer_20,layer_21,layer_22,layer_23,layer_24,layer_25,layer_26,layer_27,layer_28,layer_29,layer_30,layer_31,layer_32,layer_33,layer_34,layer_35,layer_36,layer_37,layer_38,layer_39,layer_40,layer_41,layer_42,layer_43,layer_44,layer_45,Bottom,Minimum,Maximum,Mean,Sum
403000,4384000,CB1TF,1000,1000,1,2,-9.0,-9.0,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9.0,-9.0,-9.0,-9.0,-9.0
404000,4384000,CB1TF,1000,1000,1,5,-9.0,-9.0,-9.0,-9.0,-9.0,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9.0,-9.0,-9.0,-9.0,-9.0
...
383000,4338000,CB3MH,1000,1000,1,6,8.7,8.2,8.0,7.4,6.2,4.7,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,4.7,4.7,8.7,7.2,43.2
384000,4338000,CB3MH,1000,1000,1,5,8.7,8.2,8.0,7.4,6.2,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,6.2,6.2,8.7,7.7,38.5
385000,4338000,CB3MH,1000,1000,1,6,8.7,8.2,7.9,7.3,6.2,4.8,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,4.8,4.8,8.7,7.2,43.1
386000,4338000,CB3MH,1000,1000,1,6,8.7,8.1,7.9,7.3,6.2,4.9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,-9,4.9,4.9,8.7,7.2,43.1

==========================================

## T3D FILE CREATED FROM ESTIMATES FILE (.t3d)

Interpolated estimates files (‘filename’.est) can be reformatted as ‘filename’.t3d files which can be readily imported into other applications, such as, NoeSys and T3D. The .T3D file contains the values for each cell in the original Estimates file, with one cell value per line in the output file. The file is comma delimited, and all extraneous blanks have been removed. The precision of the reported parameter values are assigned by the values set in the ‘parameter.sys’ file. The .T3D file contents include:

Line 1+>cell centroid easting, cell centroid northing, negative cell centroid depth in meters, interpolated value for parameter

403000,4384000,-0.5,-9.0
403000,4384000,-1.5,-9.0
404000,4384000,-0.5,-9.0
404000,4384000,-1.5,-9.0
...
391500,4304000,-9.5,0.8
391500,4304000,-10.5,0.2
391500,4304000,-11.5,0.1
391500,4304000,-12.5,0.1

==========================================

## BATHYMETRY FILE (.bth)

Each interpolator job requires a bathymetry file which defines the cell structure of the desired body of water that is being interpolated. The following shows the contents of the *cbay8.bth* file:

Line 1>Number of segments to interpolate
Line 2>Number of surface cells in segment 1, segment id, segment name, e-w cell size in meters, n-s cell size in meters, cell depth in meters

Line 3>Cell centroid easting in meters, cell centroid northing in meters, number of cells (>0) from surface to bottom, cell centroid depths from surface to bottom. The Interpolator computes a value for each cell centroid identified in the .bth file which is output to the .est file.
(Repeat 2 & 3 for each segment.)

```
============================================
8
132,1001,CB1TF,1000,1000,1
403000,4384000,2,0.5,1.5
404000,4384000,5,0.5,1.5,2.5,3.5,4.5
404000,4383000,3,0.5,1.5,2.5
405000,4383000,8,0.5,1.5,2.5,3.5,4.5,5.5,6.5,7.5
405000,4382000,3,0.5,1.5,2.5
...
410000,4363000,6,0.5,1.5,2.5,3.5,4.5,5.5
411000,4363000,10,0.5,1.5,2.5,3.5,4.5,5.5,6.5,7.5,8.5,9.5
412000,4363000,4,0.5,1.5,2.5,3.5
270,1002,CB2OH,1000,1000,1
403000,4363000,3,0.5,1.5,2.5
404000,4363000,4,0.5,1.5,2.5,3.5
405000,4363000,3,0.5,1.5,2.5
406000,4363000,3,0.5,1.5,2.5
400000,4362000,1,0.5
...
385000,4107000,1,0.5
381000,4106000,2,0.5,1.5
381000,4105000,2,0.5,1.5
381000,4104000,1,0.5
============================================
```

## DATA REGIONS FILES (regions.sys, .reg)

Each interpolator job requires a data regions file which defines the geographic boundary of the **data** for the body of water that is being interpolated. 77 data regions have been created, one for each CBP segment. The data region is used to clip off data that fall outside the desired geographic area that is being interpolated. A data regions file includes one or more data region definitions that must match the bathymetry being interpolated. These data region file names are stored in a file, *regions.sys*, which is required by the Interpolator. This file can contain 25 defined regions files. The order of the entries in this file define the order presented to the user in the GEOGRAPHY screen during the job. The structure of the regions.sys file is:

Line 1+>Item identifier (sequential number of 1 to 25), comma, data region name, comma, corresponding bathymetry file name, comma, corresponding data region file name.
Repeat for each defined data region.

```
============================================
1,Bay and Tribs,bay_trib.bth,bay_trib.reg
2,Chesapeake Mainstem (CB1CB8),cbay8.bth,cbay8.reg
============================================
```

Each .reg file defined in the *regions.sys* file must have the following structure. The following shows the contents of the *cbay8.reg* file:

Line 1>Bathymetry file name

Line 2>Data region file name
Line 3>Number of segments to interpolate
Line 4>First segment ID and name
Line 5> Data region ID
Line 6>Number of x-y points in this data region
Line 7+>Data region x-y points. First and last in each polygon must be the same to close the polygon.
Repeat for each data region.

```
============================================
cbay8.bth
cbay8.reg
 8
1001,CB1TF
1001
8
398699,4385013
421073,4384159
413328,4355973
397839,4344869
383210,4352557
401281,4367077
398699,4385013
398699,4385013
…
…
1008,CB8PH
1008
13
410677,4131611
418631,4108780
422019,4095375
415538,4079614
408467,4086243
396978,4083150
384016,4087569
372968,4087569
372968,4095817
385194,4104508
374588,4117618
386372,4131464
410677,4131611

============================================
```

## PARAMETER NAMES FILE (params.sys)

Each parameter is identified by a 2-digit parameter code and spelled out parameter name. These codes and names are stored in the *params.sys* file. This file can accommodate 25 parameters. The order of the codes and names in this file determines the order of the parameters in the PARAMETERS screen (Figure D-3). This file can be edited as necessary by the user. The file structure is:

Line 1>Item number (up to 25 lines), comma, spelled out parameter name, comma, 2-digit parameter code, comma, number of digits precision to the right of the decimal in output file.

```
============================================
```

1,Dissolved Oxygen,DO,1

2,Chlorophyll,CH,1

3,Salinity,SA,1

4,Water Temperature,WT,1

5,Total Nitrogen,TN,2

6,Ammonia,NH,3

7,Nitrite,N2,3

8,Nitrate,N3,3

9,Total Phosphorus,TP,2

=========================================

## PARAMETER RANGE FILES (.rng)

Several files are required to compute report files of volume and mass and to graphically portray the interpolated results. These include:

1) the "filename".est file of estimated values;

2) the cbpotiny.bmp which is a small CBP logo file;

3) the aro.bmp which is a small north arrow;

4) shore_18.bnd which is a shoreline boundary file; and,

5) the "parameter_code".rng file. The range file is used by the volume and mass report procedures to subset the computed results into categories for reporting. For graphics, the .rng file defines how the graphics program assigns colors to each cell value in the "filename".est file. For drawing purposes, the first range in the .rng table has drawing priority over the second range, which has priority over the third range, etc, so the first range color will paint over ranges lower in the table. This order determines which colors have priority in the final graphic. The do.rng file serves as an example:

Line 1>For dissolved oxygen values of 0.0 to but less than 0.2, color 12, pattern 0, title 0.0-0.2
Line 2>For dissolved oxygen values of 0.2 to but less than 1.0, color 13, pattern 2, title 0.2-1.0
Line 3>For dissolved oxygen values of 1.0 to but less than 3.0, color 14, pattern 12, title 1.0-3.0
Line 4>For dissolved oxygen values of 3.0 to but less than 5.0, color 11, pattern 12, title 3.0-5.0
Line 5>For dissolved oxygen values of 5.0 to but less than 25.0, color 19, pattern 21, title >5.0 MG/L
Line 6>For dissolved oxygen values of -10.0 to but less than -8.0 (-9=missing value), color 8, pattern 8, title Not Calculated

Pattern is currently ignored in this version.

To categorize integer value ranges, it is best to bracket the range, for instance, to assign color 12 to the range of 2 (lower bound) to 2 (upper bound), set the lower bound to 1.9 and the upper bound to 2.1. Set the title to "2" to convey the intent that "2" is the range being presented. This bracketing is required to allow the code to select values equal to or greater than the lower bound and less than the upper bound.

Acceptable color codes are:

| | |
|---|---|
| 0 | Black |
| 1 | Blue |
| 2 | Green |
| 3 | Cyan |
| 4 | Red |
| 5 | Magenta |
| 6 | Yellow |
| 7 | White |
| 8 | Gray |
| 9 | Light Blue |
| 10 | Light Green |
| 11 | Light Cyan |
| 12 | Light Red |
| 13 | Light Magenta |
| 14 | Light Yellow |
| 15 | Bright White |

```
==========================================
0.0,0.2,12,0,0.00.2
0.2,1.0,13,2,0.21.0
1.0,3.0,14,12,1.03.0
3.0,5.0,11,12,3.05.0
5.0,25.0,9,21,>5.0 MG/L
10.0,8.0,8,8,Not Calculated

==========================================
```

## EXAMPLE BATCH JOB FILE (.job)

Individual interpolator runs can be computed sequentially by saving the necessary information for the run in a "Batch File" ('filename'.job). This "Batch File" is then used to calculate each of the files identified in the .job file. This file can be edited as necessary by the user. The file structure is:

```
Line 1>bathymetry file
Line 2>regions file
Line 3>input data file
Line 4> output interpolated (.est) file
Line 5> output metadata (.met) file
Line 6>parameter transformation
Line 7>minimum number of neighbors
Line 8>maximum number of neighbors
Line 9>horizontal range (m)
Line 10>vertical range minimum
Line 11>vertical range maximum
Line 12>Vertical step size
Line 13>missing value
Line 14>interactive/batch flag
Repeat lines 1-14 for each file to be interpolated

==========================================
```

```
cbay8.bth
cbay8.reg
C:\Vol3D\BDO970601.D3D
C:\Vol3D\BDO970601.est
C:\Vol3D\BDO970601.met
None
 1
 4
 25000
 0
 4
 .5
-9
1
cbay8.bth
cbay8.reg
C:\Vol3D\BDO970701.D3D
C:\Vol3D\BDO970701.est
C:\Vol3D\BDO970701.met
None
 1
 4
 25000
 0
 4
 .5
-9
1
```

===========================================

## EXAMPLE BATCH JOB FILE LIST (.fls)

Calculations on individual interpolator .est files can be computed sequentially by reading the .est file names from a "batch file list" ('filename'.fls). This file is created when the Batch Job File ('filename'.job) is created. This file can be edited as necessary by the user. The file structure is:

Line 1>interpolator (.est) file name

Repeat for each file to be processed.

===========================================

C:\Vol3D\BDO970601.est

C:\Vol3D\BDO970701.est

…

…

===========================================

## EXAMPLE JULIAN DATE FILE (.jul)

Calculations of "Change Over Time" require a julian date file which contains the dates which relate to the .est files identified in the .fls file. For this analysis, the julian dates are the X variable of the time series and the .est files are the Y variables of the time series. The julian dates represent dates and times that are based on the decimal numbering system, rather than years, months, and days (and time). The julian (or any linearly numbered scheme) date file must be created by the user. The following example was created by opening the appropriate .mas file in Excel, converting the "Start_Date" from mm/dd/yy format to decimal format, and cutting and pasting the reformatted date column into a flat file. The file structure is:

Line 1>julian date

Repeat for each file to be processed.

===========================================

30865.00

30895.00

30929.00

30956.00

…

…

===========================================

## EXAMPLE SEGMENTS LIST FILE (.lst)

Reports on individual segments can be computed sequentially by reading the .est file names from a "segments list file" ('filename'.lst). This file is created manually by the user. The file structure is:

Line 1>Number of segments to process
Line 2+>Segment name (spelling must match those in Appendix A).

Repeat for each segment to be processed.

===========================================

3

POCTF

POCOH

POCMH

===========================================

## EXAMPLE VOLUME REPORT FILE (.vol)

The volume of water that contains a specified range of concentrations of a parameter can be computed and saved to a volume report file ('filename'.vol). Volume estimates are reported in liters. The entire Bay and tributary volume based on the “Bay and Tributary” 77 segment bathymetry is 75,199,817,500 m^3, or 75.2x10^12 liters. The volume of Main Bay segments CB1TF-CB8PH totals 51.839x10^12 liters. Data from one job to another may be appended to the same output file so that a time series file is created that can be opened in a spreadsheet or database program for further graphing or analysis. The first line of the file is composed of ‘column headings’ contained within quotes. This file can be edited as necessary by the user. The file structure is:

Line 1>Column headings defined by the ‘Report’ job that is run, including data start date, data end date, depth of top layer analyzed, depth of bottom layer analyzed, volume for segment, volume by concentration range for that segment,…,…, repeat for each segment,…,grand total volume
Line 2>data accumulated from the input interpolated file (.est) for each column in line 1
Repeat for each interpolated file processed.

Note: Since data that are calculated may be appended to an existing file, there is a risk that the user may append data from different bathymetry jobs. The user must be careful not to mix 8 segment mainstem data with 77 segment mainstem and tributary data in this report, or else the column headings will not represent the data.

==========================================

“Start Date”,”End Date”,”Layer Top”,”Layer Bottom”,”CB1TF”,”CB1TF_0.0_0.2”,”CB1TF_0.2_1.0”,”CB1TF_1.0_3.0”,”CB1TF_3.0_5.0”,”CB1TF_5.0_25.0”,”CB1TF_-10.0_-8.0”,”CB2OH”,”CB2OH_0.0_0.2”,”CB2OH_0.2_1.0”,”CB2OH_1.0_3.0”,”CB2OH_3.0_5.0”,”CB2OH_5.0_25.0”,”CB2OH_-10.0_-8.0”,”CB3MH”,”CB3MH_0.0_0.2”,”CB3MH_0.2_1.0”,”CB3MH_1.0_3.0”,”CB3MH_3.0_5.0”,”CB3MH_5.0_25.0”,”CB3MH_-10.0_-8.0”,”CB4MH”,”CB4MH_0.0_0.2”,”CB4MH_0.2_1.0”,”CB4MH_1.0_3.0”,”CB4MH_3.0_5.0”,”CB4MH_5.0_25.0”,”CB4MH_-10.0_-8.0”,”CB5MH”,”CB5MH_0.0_0.2”,”CB5MH_0.2_1.0”,”CB5MH_1.0_3.0”,”CB5MH_3.0_5.0”,”CB5MH_5.0_25.0”,”CB5MH_-10.0_-8.0”,”CB6PH”,”CB6PH_0.0_0.2”,”CB6PH_0.2_1.0”,”CB6PH_1.0_3.0”,”CB6PH_3.0_5.0”,”CB6PH_5.0_25.0”,”CB6PH_-10.0_-8.0”,”CB7PH”,”CB7PH_0.0_0.2”,”CB7PH_0.2_1.0”,”CB7PH_1.0_3.0”,”CB7PH_3.0_5.0”,”CB7PH_5.0_25.0”,”CB7PH_-10.0_-8.0”,”CB8PH”,”CB8PH_0.0_0.2”,”CB8PH_0.2_1.0”,”CB8PH_1.0_3.0”,”CB8PH_3.0_5.0”,”CB8PH_5.0_25.0”,”CB8PH_-10.0_-8.0”,”Total”

“06/03/1997”,”06/12/1997”,0.,50.,359000000000.,0.,0.,0.,0.,359000000000.,0.,1237000000000.,0.,0.,0.,56000000000.,1181000000000.,0.,2391000000000.,0.,2000000000.,366000000000.,361000000000.,1662000000000.,0.,9237000000000.,0.,19000000000.,1974000000000.,1104000000000.,6140000000000.,0.,15377000000000.,0.,0.,0.,851000000000.,14526000000000.,0.,6503000000000.,0.,0.,0.,0.,6503000000000.,0.,13488000000000.,0.,0.,0.,0.,13488000000000.,0.,3150000000000.,0.,0.,0.,0.,3150000000000.,0.,51742000000000.,0.,21000000000.,2340000000000.,2372000000000.,47009000000000.,0.

“07/07/1997”,”07/15/1997”,0.,50.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,2391000000000.,134000000000.,51000000000.,150000000000.,168000000000.,1888000000000.,0.,9237000000000.,1937000000000.,1253000000000.,933000000000.,620000000000.,4494000000000.,0.,15395000000000.,1391000000000.,2236000000000.,1909000000000.,1069000000000.,8790000000000.,0.,6503000000000.,0.,0.,524000000000.,1063000000000.,4916000000000., 0.,13482000000000.,0.,0.,661000000000.,2978000000000.,9843000000000.,0.,2474000000000.,0.,0.,0.,114000000000.,2360000000000.,0.,49482000000000.,3462000000000.,3540000000000.,4177000000000.,6012000000000.,32291000000000.,0.

“07/16/1997”,”07/31/1997”,0.,50.,360000000000.,0.,0.,0.,0.,360000000000.,0.,1237000000000.,0.,0.,7000000000.,24000000000.,1206000000000.,0.,2391000000000.,0.,133000000000.,159000000000.,282000000000.,1817000000000.,0.,9237000000000.,0.,1620000000000.,1644000000000.,942000000000.,5031000000000.,0.,15388000000000.,0.,1453000000000.,2710000000000.,2005000000000.,9220000000000.,0.,6503000000000.,0.,0.,550000000000.,1231000000000.,5217000000000.,0.,13491000000000.,0.,0.,9000000000.,1793000000000.,11689000000000.,0.,3160000000000.,0.,0.,0.,0.,3160000000000.,0.,51767000000000.,0.,3206000000000.,4584000000000.,6277000000000.,37700000000000.,0.

========================================

## EXAMPLE MASS REPORT FILE (.mas)

The mass file report contains the mass of a parameter computed for each cell in the interpolated (.est) file then summed in one of two ways. The default method (below example) is to sum the mass by segment and total for all segments in the bathymetry.

The second method follows the format of the volume report and computes the mass by concentration range for each segment.

The mass that is computed and summed is saved to a mass report file (‘filename’.mas). It is assumed the input data are measured in [units]/[liter], such as mg/l or ug/l or counts/liter. In the mass report, the resulting mass estimates are computed by multiplying the [estimated concentration in the cell (often in mg/l)] * [the volume of the cell in m^3 (for instance, 1000m east-west x 1000m north-south x 1m deep)] * [1000 l/m^3 to convert from m^3 to liters]. Hence, if the input data were in mg/l and then the concentration is estimated to be 6mg/l in a cell, the resulting mass will be 6*10^9 mg for a 1km x 1km x 1 m cell. As a second example, if the input data were in mg/m^3, which is equivalent to ug/l, then the reported mass values would be in micrograms to account for the volume being reported in m^3 rather than liters. If the input data are counts (such as organism counts) per liter, then the mass report units would be total counts. If the input data are counts (such as organism counts) per cubic meter, then the total counts in the mass report must be divided by 1000 to account for the conversion from cubic meters to liters between the input data and the interpolated counts. The mass (or counts) for each cell is then summed for a total mass (or count) in the segment and also a grand sum of mass (or count) for the total for all segments under analysis. For instance, if the input data for CHLA were measured as ug/l and the resulting mass in Segment CB2OH was reported after interpolation as 13,000,000,000,000, that represents 1.3^13 ug CHLA for Segment CB2OH—i.e 1.3^13ug / 1.237^12 liters in CB2OH=10.5 ug/l average. As a second example, if the input data were for mg biomass of organisms per cubic meter and the resulting mass in Segment CB2OH was reported as 132,627,709,873,200, that represents 1.326^14 / 1000 mg for Segment CB2OH, since an adjustment for the input data must be made for the per cubic meter to per liter basis. A quick check can be made by multiplying the average input data value by the volume of a segment to determine if the results are within reason. For instance, if there were approximately

150 mg biomass per cubic meter in the monitoring data for CB2OH, that would be [150 mg/m^3] * [1,237,000,000 cubic meters in Segment CB2OH] = 1.86^11 mg biomass in the Segment CB2OH, which is close to the interpolated value of 1.326^11 mg, above.

Data from one job to another may be appended to the same output file so that a time series file is created that can be opened in a spreadsheet or database program for further graphing or analysis. The first line of the file is composed of 'column headings' contained within quotes. This file can be edited as necessary by the user. The file structure is:

Line 1>Column headings defined by the 'Report' job that is run, including data start date, data end date, depth of top layer analyzed, depth of bottom layer analyzed, mass of parameter by segment,…,…, repeat for each segment,…,grand total mass
Line 2>data accumulated from the input interpolated file (.est) for each column in line 1

Repeat for each interpolated file processed.

Note: Since data that are calculated may be appended to an existing file, there is a risk that the user may append data from different bathymetry jobs. The user must be careful not to mix 8 segment mainstem data with 77 segment mainstem and tributary data in this report, or else the column headings will not represent the data.

==========================================

"Start Date","End Date","Layer Top","Layer Bottom","CB1TF","CB2OH","CB3MH","CB4MH","CB5MH","CB6PH","CB7PH","CB8PH","Total"
"06/03/1997","06/12/1997",0.,50.,33956000.,99418000.,165733000.,602087001.,1229455000.,563523000.,1121378003.,301820000.,4117370004.
"07/07/1997","07/15/1997",0.,50.,0.,0.,149745000.,378545000.,726926999.,429706000.,871456001.,173612000.,2729991001.
"07/16/1997","07/31/1997",0.,50.,21746000.,82626000.,150816000.,438919000.,795246002.,428770000.,917109001.,243880000.,3079112003.
"08/04/1997","08/14/1997",0.,50.,22096000.,73961000.,128601000.,465053000.,824646000.,456154001.,940162001.,236345001.,3147018002.
"08/18/1997","08/28/1997",0.,50.,19932000.,82306000.,158793000.,460818001.,885485001.,470413001.,1010405001.,231651001.,3319803005.
"09/02/1997","09/15/1997",0.,50.,19748000.,76169000.,128181000.,517683000.,1009546002.,459632001.,949621002.,227962000.,3388542005.
"10/06/1997","10/15/1997",0.,50.,0.,0.,173127001.,576579000.,1004260004.,482547000.,963827000.,200433996.,3400774001.

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## EXAMPLE INTERPOLATOR JOB

1) Double click the Vol3D.exe icon to run the Interpolator program.

2) Click the GEOGRAPHY button to display the GEOGRAPHY screen.

3) Choose "Chesapeake Mainstem (CB1-CB8)" to interpolate the Main Bay.

4) Click the PARAMETER button to display the PARAMETER screen.

5) Choose "DO- Dissolved Oxygen" as the parameter.

6) Click the DATA IMPORT button to display the DATA IMPORT screen.

7) Click Get File Name button and select the "C:\Vol3D\BDO970701.D3D" data file. The file name, start and end dates, number of observations, file date, parameter, code, and title should appear in the Data Import screen. If not, you selected an incorrect file.

8) Click the INTERPOLATE button to display the INTERPOLATE screen. The input file should read "C:\Vol3D\BDO970701.D3D", the output file should read "C:\Vol3D\BDO970701.est", Bathy file should read "cbay8.bth", and metadata file should read "C:\Vol3D\BDO970701.met".

9) Click the "Run Interpolation" button to create the standard *.est file or click the "Also Create TXT File" to create a "filename".txt file that can be imported into Arc/Info or ArcView as a table. The text ArcView file will be approximately 2.3 mb in size.

10) If you created an interpolated .est file, you can view the results by clicking the GRAPHICS button to display the GRAPHICS screen. If you created a .txt file to load into an ArcView table, you can quit the Interpolator program and continue working with the output file in ArcView.

11) At the GRAPHICS screen, the Interpolated file should read "C:\Vol3D\BDO970701.est". Click the Interpolated File button to load titles and dates for the graphic.

12) The Bathymetry file should read "cbay8.bth", the Logo File 1 should read ".\cbpotiny.bmp", the Logo File 3 should read ".\aro.bmp", the Categories File should read ".\DO.rng". Click the Categories File button to load the categories for the graphic. The Boundary File should read ".\shore_18.bnd", the output Graphics File name should read "C:\Vol3D\BDO970701.bmp". The titles and legends were loaded by pushing the Interpolated File and Categories File buttons. The background color of the boundary file is set by clicking the small grey box to the right of the Boundary File name. Click "Plot Points" ON if you want to display the location of the monitoring stations. Click "Plot Data Regions" ON if you wish to see the Data Region polygons. Choose "Minimum" if you wish to display the minimum color value (where minimum is the worst case, such as dissolved oxygen), or choose "Maximum" if you wish to display the maximum color value (where maximum is the worst case, such as temperature), or choose the "Top/West" edge or "Bottom/East" edge to display the desired side.

Titles, categories, colors, and legends can be modified on this screen and will be reflected in the resulting drawing. Clicking the "DRAW" button will draw the image in a graphics window. The graphics window can be saved to a file or printed. This version of the Interpolator does not allow graphical editing. The saved "filename".bmp file can be edited in a commercial graphics editing package, such as Lview Pro or Corel Draw. The .bmp file can be converted to gif or jpeg format for publication on the web.

APPENDIX

Segment Name, EW-Dimension, NS-Dimension, Depth Dimension, Number Cells in Segment, Segment Volume
CB1TF,1000,1000,1,360,360000000
CB2OH,1000,1000,1,1237,1237000000
CB3MH,1000,1000,1,2391,2391000000
CB4MH,1000,1000,1,9237,9237000000
CB5MH,1000,1000,1,15416,15416000000
CB6PH,1000,1000,1,6503,6503000000
CB7PH,1000,1000,1,13523,13523000000
CB8PH,1000,1000,1,3172,3172000000
NORTF,500,500,1,106,26500000
C&DOH,100,100,1,2413,24130000
ELKOH,500,500,1,405,101250000
BOHOH,250,250,1,272,17000000
SASOH,250,250,1,1347,84187500
CHSTF,50,50,1,1345,3362500
CHSOH,250,250,1,462,28875000
CHSMH,500,500,1,1821,455250000
EASMH,500,500,1,3987,996750000
CHOTF,50,50,1,6129,15322500
CHOOH,250,250,1,722,45125000
CHOMH2,500,500,1,1067,266750000
CHOMH1,1000,1000,1,945,945000000
LCHMH,500,500,1,833,208250000
HNGMH,100,100,1,18568,185680000
FSBMH,1000,1000,1,143,143000000
NANTF,50,50,1,2646,6615000
NANOH,50,50,1,18000,45000000
NANMH,500,500,1,389,97250000
WICMH,100,100,1,5642,56420000
MANMH,500,500,1,358,89500000
BIGMH,250,250,1,698,43625000
POCTF,50,50,1,1788,4470000
POCOH,50,50,1,7200,18000000
POCMH,500,500,1,1418,354500000
TANMH,1000,1000,1,4019,4019000000
BSHOH,500,500,1,197,49250000
GUNOH,500,500,1,257,64250000
MIDOH,250,250,1,400,25000000
BACOH,250,250,1,358,22375000
PATMH,500,500,1,1806,451500000
MAGMH,250,250,1,1224,76500000
SEVMH,250,250,1,1815,113437500
SOUMH,250,250,1,1072,67000000
RHDMH,250,250,1,325,20312500
WSTMH,250,250,1,326,20375000
PAXTF,50,50,1,4410,11025000
PAXOH,100,100,1,2718,27180000
PAXMH,500,500,1,2244,561000000
PISTF,100,100,1,285,2850000
MATTF,250,250,1,152,9500000
POTTF,500,500,1,1939,484750000
POTOH,500,500,1,3409,852250000
POTMH,1000,1000,1,5792,5792000000

RPPTF,250,250,1,1719,107437500
RPPOH,100,100,1,5358,53580000
RPPMH,500,500,1,5929,1482250000
CRRMH,250,250,1,1051,65687500
PIAMH,250,250,1,3223,201437500
MPNTF,50,50,1,6135,15337500
MPNOH,100,100,1,3539,35390000
PMKTF,50,50,1,11452,28630000
PMKOH,100,100,1,6668,66680000
YRKMH,500,500,1,1102,275500000
YRKPH,500,500,1,1603,400750000
MOBPH,500,500,1,5370,1342500000
APPTF,100,100,1,151,1510000
CHKOH,250,250,1,777,48562500
JMSTF,250,250,1,4579,286187500
JMSOH,500,500,1,1726,431500000
JMSMH,1000,1000,1,977,977000000
JMSPH,1000,1000,1,434,434000000
WBEMH,100,100,1,631,6310000
SBEMH,100,100,1,2773,27730000
EBEMH,50,50,1,2584,6460000
ELIMH,100,100,1,5339,53390000
LAFMH,100,100,1,339,3390000
ELIPH,500,500,1,246,61500000
LYNPH,100,100,1,1673,16730000
Total Volume (m^3) = 75199817500

appendix e

# Potential Methods for Assessing Shorter Duration Dissolved Oxygen Criteria

## POTENTIAL METHODS

The 2003 Chesapeake Bay water-quality criteria document described three alternatives for assessing attainment of the short duration dissolved oxygen criteria (U.S. EPA 2003). Those include: 1) logistic regression; 2) a time series statistical method and 3) continuous dissolved oxygen data collection using meters that are deployed for an extended period of time. Each of these approaches has strengths and drawbacks. Appropriate implementation of logistic regression or time series statistical methods may require continuous dissolved oxygen data. To develop the full capacity to assess the shorter duration dissolved oxygen criteria—7-day mean, 1-day mean and instantaneous minimum, EPA recommends a phased approach in which the methods that are easiest to implement are employed initially while continuing to work on development and implementation of the more detailed and/or expensive methods.

### LOGISTIC REGRESSION

The instantaneous minimum criteria imply the requirement that waters within the respective designated use be at or above the defined concentration everywhere all the time. Stated in this way, the logistic regression approach clearly has application to the challenge of assessing attainment of instantaneous minimum criteria. In the context of criteria attainment, logistic equations are developed from the long term dissolved oxygen data record, which predict the probability that the defined criteria concentrations were met, based on observed monthly mean concentration.

The logistic regression approach utilizes a well-established statistical procedure (U.S. EPA 2004) and has been employed in the past in Chesapeake Bay to estimate instantaneous minima (Jordan et al. 1992). It is relatively simple to use and only requires regular updating to keep the predictive models relevant to current conditions. The limitation of this approach is that it is based on an extrapolation of the fixed-station data and is likely to have higher error than the other methods.

The logistic regression approach could be also be adapted to assess attainment of the 7-day and 1-day mean criteria components as well as other duration-specific criteria, where and when a body of observational data is available at frequencies relevant to the time frame. High frequency 'buoy' data sited at sentinel locations, where continuous records extend over days, weeks and months, would offer opportunities to develop logistic models of the relationship between exceedance/attainment and the temporal means. EPA recommends that this method be actively developed for possible employment for attainment assessments of the instantaneous minimum dissolved oxygen criteria (see next section for details) while additional high frequency data are collected and more complex, detailed methods described below are being developed.

## SPECTRAL ANALYSIS METHOD

The time series approach utilizes a statistical procedure known as spectral analysis to synthesize a complete record of dissolved oxygen concentrations at short interval time steps over time. The synthetic record is developed using continuous measurement data from nearby locations to develop a model that predicts the short-interval variations in concentration. That model is combined with the long-term pattern of variability derived from data collected routinely, monthly to twice monthly, at the fixed-stations located in the assessment unit. The synthetic dissolved oxygen record can then be used in the same way that data collected using a continuous meter would be used. This time series approach has only been applied in a limited way to date and further development is needed in order for it to fully meet the needs of a publishable Chesapeake Bay dissolved oxygen criteria assessment methodology (see pages 183-185 in U.S. EPA 2003). EPA recommends that this development work proceed simultaneously with the development of the logistic regression and that the spectral analysis method replace the logistic regression in the future should it prove a more robust method.

## COLLECTION OF CONTINUOUS MEASURES OF DISSOLVED OXYGEN CONCENTRATION

The most rigorous approach for assessing attainment of the high frequency dissolved oxygen criteria would be to collect continuous measures of dissolved oxygen concentration at representative locations and depths throughout each spatial assessment unit. The temporal and spatial density of such data would need to be sufficient to enable all of the dissolved oxygen criteria to be assessed simply by calculating means at the appropriate time scales (e.g. 30-day, 7-day, 1-day) or by observing violations of the instantaneous minimum criteria values. However, continuous collection of high frequency dissolved oxygen concentration in the Bay is expensive both in purchasing the equipment and maintaining it. It is also difficult or impossible to find sufficiently representative locations where the equipment can be affixed to buoys or fixed pilings. Finally, it is expensive and labor-intensive to maintain the equipment and sensor calibration once it is deployed due to the effects of weather, turbulence, biological fouling and human interferences (e.g. accidents, thefts). Nevertheless, the collection of at least some continuous dissolved oxygen data will be critical for use in the other two statistical analysis-based assessment methods described above. Therefore, EPA recommends that the States continue to seek funds to support this type of data collection in order to directly generate the data supporting attainment assessment of the full array of applicable dissolved oxygen criteria.

## APPLICATION OF LOGISTIC REGRESSION TO ASSESS SHORT-DURATION DISSOLVED OXYGEN CRITERIA COMPONENTS

In the prior sections, it was noted that the data collection frequency of the long term, fixed-station water quality monitoring program is inadequate to assess attainment of short-duration criteria components. However, the greater than 20-year record of dissolved oxygen measurements collected relatively synoptically throughout the mainstem Bay, tidal tributaries and embayments, and collected regularly throughout the annual cycle provides a very substantial data base from which to derive inferences and define quantitative relationships between seasonal and monthly mean dissolved oxygen concentrations and the frequency of observations above and below specified criterion concentrations. Where relationships are strong, the logistic regression procedure produces models in the form of simple equations that estimate/predict the likelihood that the criterion threshold concentration was attained or violated during the period.

This method was explored originally to measure attainment of the 1992 Chesapeake Bay dissolved oxygen restoration goal (Jordan et al. 1992) and was adapted for assessing attainment of the 2003 Chesapeake Bay dissolved oxygen instantaneous minimum (see Chapter 5, pages 27-62, in U.S. EPA 2004). The 2003 method modifications included spatial and temporal refinements to the predictive models, with consequent improvements to their goodness of fit. The early (1992) models estimated exceedance based on segment-specific seasonal means and whether the means were from depths above or below pycnocline. The 2003 method update was enriched with an additional decade of monitoring data (1990-2000) for the regression analysis and provided segment-specific models for individual months and depths. Recent progress on this work again includes several additional years of new fixed-station and continuous monitoring buoy data (2001-2005) and modifications to implementation procedures that could provide results for attainment assessment through the CFD methodology in a format consistent with other dissolved oxygen criteria.

In this latest iteration, logistic regression models for the individual instantaneous minima are developed for each *station*. The independent variables are, as before, mean dissolved oxygen, month and water depth. The addition of a depth-squared variable for deep stations is being tested, but not yet implemented. The dependent variable is an indicator that the minimum threshold (e.g., the instantaneous criterion concentration) is violated. (Since the CFD methodology is based on percent failure, the dependent variable is based on exceedance rather than attainment.) This model-building step currently uses the entire 1985-2005 water quality data record at each station. Over time, however, if trends in ambient dissolved oxygen indicate significant, sustained change in a segment, then the extent of the historical record to be included in this step should be re-examined.

The collection of station models is used to estimate a predicted probability of exceedance for each station, for each month in the 3-year, multi-month seasonal assessment period, at each meter of depth. Then, for each month, the predicted probabilities are spatially interpolated to estimate probabilities for all interpolator cells that represent the bathymetry of the Bay, its tidal tributaries and embayments. The interpolator cells that are contained within the designated use where the criterion applies are parsed out by segment and the probabilities calculated for each cell are evaluated cell-by-cell against a threshold of probability which indicates an unacceptably high risk that the dissolved oxygen criterion was exceeded (Jordan et al 1992). The volume of water represented by the interpolator cells exceeding the threshold as a percentage of the total volume in the designated use is tallied for each segment, for each month in the assessment period.

There are several elements of the logistic regression approach which should be evaluated as part of the attainment assessment procedure. Each of the station-specific logistic models has its own goodness-of-fit measure. Each station will have a result from the predictive model, i.e., the probability of exceeding the instantaneous minimum over the assessment unit. Each segment will have an estimate of the percent volume exceeding the criteria, based on spatial interpolation of the station probabilities. As with other components of the dissolved oxygen criteria, these results can also be assessed and visualized using the CFD methodology, although this is not mandatory.

The limitations of this methodology have been noted earlier, particularly the temporal frequency on which the models are based. In addition, the lack of good spatial representation in the tidal tributaries and embayments is a concern. Most of the fixed-stations are situated more or less longitudinally in mid-channel and there is insufficient lateral coverage of the flanks, where different oxygen conditions and different model relationships may exist. Data now being collected through the Chesapeake Bay Shallow Monitoring Program will help answer where and to what extent this is true.

## LITERATURE CITED

Jordan, J., C. Stenger, M. Olson, R. Batiuk and K. Mountford. 1992. *Chesapeake Bay Dissolved Oxygen Goal for Restoration of Living Resource Habitats.* CBP/TRS 88/93. Chesapeake Bay Program, Annapolis, Maryland.

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

appendix f

# Data Used in Deriving the Open-Water, Deep-Water and Deep-Channel Dissolved Oxygen Criteria Summer Biological

**Table F-1.** Designated use, segment, year combinations found to be "good" using the Benthic-IBI summer reference curve area locator method described in Chapter 4.

| CBP Segment | Year | Designated Use | CBP Segment | Year | Designated Use |
|---|---|---|---|---|---|
| CB6PH | 1985 | DW | CB7PH | 1988 | OW |
| CB7PH | 1985 | OW | JMSMH | 1988 | OW |
| CB8PH | 1985 | OW | JMSPH | 1988 | OW |
| JMSPH | 1985 | OW | NANMH | 1988 | OW |
| LCHMH | 1985 | OW | PAXMH | 1988 | OW |
| NANOH | 1985 | OW | PMKTF | 1988 | OW |
| RPPOH | 1985 | OW | RPPMH | 1988 | OW |
| CB6PH | 1986 | DW | YRKMH | 1988 | OW |
| CB8PH | 1986 | OW | CB2OH | 1989 | OW |
| CHOMH1 | 1986 | OW | CB3MH | 1989 | DW |
| CHSMH | 1986 | OW | CB8PH | 1989 | OW |
| CHSMH | 1986 | DW | JMSPH | 1989 | OW |
| CHSMH | 1986 | DC | POTMH | 1989 | OW |
| JMSOH | 1986 | OW | CB1TF | 1990 | OW |
| JMSPH | 1986 | OW | CB7PH | 1990 | OW |
| RPPOH | 1986 | OW | CB8PH | 1990 | OW |
| YRKMH | 1986 | OW | CHOOH | 1990 | OW |
| CB3MH | 1987 | DW | CHSMH | 1990 | DW |
| CB6PH | 1987 | DW | CHSOH | 1990 | OW |
| CB8PH | 1987 | OW | JMSPH | 1990 | OW |
| CHOMH1 | 1987 | OW | JMSTF | 1990 | OW |
| CHSMH | 1987 | DW | PAXOH | 1990 | OW |
| JMSOH | 1987 | OW | RPPMH | 1990 | OW |
| JMSPH | 1987 | OW | CB6PH | 1991 | DW |
| NANMH | 1987 | OW | CB7PH | 1991 | OW |
| PMKTF | 1987 | OW | CB8PH | 1991 | OW |
| RPPMH | 1987 | OW | CHOMH2 | 1991 | OW |
| RPPMH | 1987 | DW | JMSMH | 1991 | OW |
| RPPOH | 1987 | OW | JMSPH | 1991 | OW |
| CB2OH | 1988 | OW | JMSTF | 1991 | OW |

| CBP Segment | Year | Designated Use | CBP Segment | Year | Designated Use |
|---|---|---|---|---|---|
| PMKTF | 1991 | OW | CB8PH | 1995 | OW |
| POTMH | 1991 | DW | JMSPH | 1995 | OW |
| RPPMH | 1991 | OW | MIDOH | 1995 | OW |
| RPPMH | 1991 | DW | NANMH | 1995 | OW |
| CB1TF | 1992 | OW | PAXTF | 1995 | OW |
| CB2OH | 1992 | OW | PMKTF | 1995 | OW |
| CB5MH | 1992 | OW | RPPMH | 1995 | OW |
| CB6PH | 1992 | OW | SASOH | 1995 | OW |
| CB6PH | 1992 | DW | SEVMH | 1995 | OW |
| CB8PH | 1992 | OW | SOUMH | 1995 | OW |
| CHOTF | 1992 | OW | TANMH | 1995 | OW |
| CHSMH | 1992 | OW | YRKPH | 1995 | DW |
| CHSMH | 1992 | DC | CB7PH | 1996 | DW |
| CHSOH | 1992 | OW | CB8PH | 1996 | OW |
| ELKOH | 1992 | OW | CHOOH | 1996 | OW |
| JMSPH | 1992 | OW | CHSMH | 1996 | DC |
| JMSTF | 1992 | OW | FSBMH | 1996 | OW |
| PMKTF | 1992 | OW | JMSPH | 1996 | OW |
| POTMH | 1992 | DW | LCHMH | 1996 | OW |
| POTTF | 1992 | OW | MIDOH | 1996 | OW |
| RPPMH | 1992 | OW | MPNOH | 1996 | OW |
| SASOH | 1992 | OW | NANMH | 1996 | OW |
| CB3MH | 1993 | DW | PMKOH | 1996 | OW |
| CB6PH | 1993 | OW | RPPTF | 1996 | OW |
| CB6PH | 1993 | DW | SASOH | 1996 | OW |
| CB7PH | 1993 | OW | SEVMH | 1996 | OW |
| CB8PH | 1993 | OW | WICMH | 1996 | OW |
| CHOMH2 | 1993 | OW | WSTMH | 1996 | OW |
| CHSMH | 1993 | DW | BIGMH | 1997 | OW |
| CHSMH | 1993 | DC | CB3MH | 1997 | DW |
| JMSPH | 1993 | OW | CB6PH | 1997 | DW |
| JMSTF | 1993 | OW | CB8PH | 1997 | OW |
| PMKTF | 1993 | OW | CHOMH2 | 1997 | OW |
| CB2OH | 1994 | OW | CHSOH | 1997 | OW |
| CB5MH | 1994 | DW | FSBMH | 1997 | OW |
| CB7PH | 1994 | OW | JMSTF | 1997 | OW |
| CB8PH | 1994 | OW | MANMH | 1997 | OW |
| CHOMH2 | 1994 | OW | MIDOH | 1997 | OW |
| CHSMH | 1994 | OW | MPNTF | 1997 | OW |
| HNGMH | 1994 | OW | NANMH | 1997 | OW |
| JMSMH | 1994 | OW | RHDMH | 1997 | OW |
| JMSPH | 1994 | OW | RPPTF | 1997 | OW |
| LCHMH | 1994 | OW | SOUMH | 1997 | OW |
| PMKTF | 1994 | OW | BIGMH | 1998 | OW |
| BSHOH | 1995 | OW | CB3MH | 1998 | OW |
| CB1TF | 1995 | OW | CB3MH | 1998 | DW |
| CB3MH | 1995 | OW | CB4MH | 1998 | DW |
| CB6PH | 1995 | OW | CB6PH | 1998 | OW |
| CB6PH | 1995 | DW | CB6PH | 1998 | DW |

| CBP Segment | Year | Designated Use | CBP Segment | Year | Designated Use |
|---|---|---|---|---|---|
| CB8PH | 1998 | OW | YRKPH | 2000 | OW |
| CHOMH2 | 1998 | OW | CB2OH | 2001 | OW |
| CHOOH | 1998 | OW | CB3MH | 2001 | DC |
| CHSMH | 1998 | OW | CB6PH | 2001 | DW |
| CHSMH | 1998 | DW | CHSMH | 2001 | DW |
| GUNOH | 1998 | OW | ELKOH | 2001 | OW |
| JMSPH | 1998 | OW | FSBMH | 2001 | OW |
| MPNOH | 1998 | OW | HNGMH | 2001 | OW |
| MPNTF | 1998 | OW | MANMH | 2001 | OW |
| PAXTF | 1998 | OW | MOBPH | 2001 | OW |
| POCOH | 1998 | OW | PMKTF | 2001 | OW |
| POTTF | 1998 | OW | RPPTF | 2001 | OW |
| RPPTF | 1998 | OW | SASOH | 2001 | OW |
| WICMH | 1998 | OW | WICMH | 2001 | OW |
| CB3MH | 1999 | DW | CB2OH | 2002 | OW |
| CB4MH | 1999 | DW | CB5MH | 2002 | DW |
| CB6PH | 1999 | OW | CB7PH | 2002 | DW |
| CB7PH | 1999 | OW | CHKOH | 2002 | OW |
| CB7PH | 1999 | DW | CHOMH1 | 2002 | OW |
| CB8PH | 1999 | OW | CRRMH | 2002 | OW |
| CHSMH | 1999 | OW | NANOH | 2002 | OW |
| CHSMH | 1999 | DC | PAXTF | 2002 | OW |
| JMSPH | 1999 | OW | PMKTF | 2002 | OW |
| JMSTF | 1999 | OW | RPPOH | 2002 | OW |
| LYNPH | 1999 | OW | RPPTF | 2002 | OW |
| POCMH | 1999 | OW | YRKPH | 2002 | DW |
| RHDMH | 1999 | OW | BIGMH | 2003 | OW |
| WICMH | 1999 | OW | CB2OH | 2003 | OW |
| WSTMH | 1999 | OW | CB6PH | 2003 | OW |
| BSHOH | 2000 | OW | CB8PH | 2003 | OW |
| CB2OH | 2000 | OW | CHSOH | 2003 | OW |
| CB7PH | 2000 | DW | JMSPH | 2003 | OW |
| CB8PH | 2000 | OW | MIDOH | 2003 | OW |
| CHKOH | 2000 | OW | MPNOH | 2003 | OW |
| CHSOH | 2000 | OW | POCMH | 2003 | OW |
| EASMH | 2000 | OW | APPTF | 2004 | OW |
| ELKOH | 2000 | OW | BOHOH | 2004 | OW |
| HNGMH | 2000 | OW | CB1TF | 2004 | OW |
| JMSPH | 2000 | OW | CB2OH | 2004 | OW |
| JMSTF | 2000 | OW | CB6PH | 2004 | OW |
| LAFMH | 2000 | OW | CB8PH | 2004 | OW |
| MIDOH | 2000 | OW | CHKOH | 2004 | OW |
| MPNTF | 2000 | OW | CHOMH1 | 2004 | OW |
| NANOH | 2000 | OW | CHOTF | 2004 | OW |
| PMKOH | 2000 | OW | CHSMH | 2004 | OW |
| PMKTF | 2000 | OW | CHSOH | 2004 | OW |
| POTOH | 2000 | OW | CRRMH | 2004 | OW |
| RPPTF | 2000 | OW | GUNOH | 2004 | OW |
| SEVMH | 2000 | OW | MANMH | 2004 | OW |

| **CBP Segment** | **Year** | **Designated Use** |
|---|---|---|
| MPNTF | 2004 | OW |
| NORTF | 2004 | OW |
| RPPOH | 2004 | OW |
| CB1TF | 2005 | OW |
| CB7PH | 2005 | DW |
| CHOMH2 | 2005 | OW |
| FSBMH | 2005 | OW |
| PMKOH | 2005 | OW |
| SASOH | 2005 | OW |
| TANMH | 2005 | OW |

appendix g

# Equations for the Open-Water, Deep-Water and Deep-Channel Dissolved Oxygen Criteria Summer Biological Reference Curves

A biological reference curve of acceptable violation rates is generated using a cumulative frequency distribution (CFD) of violation rates for "healthy" designated uses. The violation rates are sorted in ascending order, ranked in descending order, and graphed on a quantile plot:

- Violation rates are plotted on the x-axis, with plotting position on the y-axis.
- Plotting position represents the probability, i/n, of being less than or equal to a given violation rate, or x, and is plotted on the y-axis as a function of rank, or "i", and sample size, or "n".
- The x-axis is labeled "Percentage of Volume" because the violation rate represents the fraction of volume that is in violation.
- The y-axis is labeled as "Percentage of Time" because "probability" represents the probable amount of time that a given violation rate will be observed.
- The Chesapeake Bay Program currently uses the Wiebull plotting position to plot the cumulative distribution function. The Wiebull equation for calculating probability, y, for each violation rate with rank "i" is: $y = i/(n+1)$; $i$ = rank.

In order to generate a graph of the CFD:

- $X_1$, $x_2$, $x_3$,…$x_n$ = violation rates provided herein, sorted in ascending order, with rank (i) assigned in descending order.
- $y_i = i/(n+1)$.
- After plotting the data's violation rates and probabilities, two additional points should be added to the distribution in order to complete the CFD curve:
  Insert $(x_0, y_0) = (0,1)$ before the first data point; and
  Insert $(x_{n+1}, y_{n+1}) = (1,0)$ after the last data point.

## DEEP CHANNEL INSTANTANEOUS VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| | 0 | 1 |
| 39 | 0 | 0.975 |
| 38 | 0 | 0.95 |
| 37 | 0 | 0.925 |
| 36 | 0 | 0.9 |
| 35 | 0 | 0.875 |
| 34 | 0 | 0.85 |
| 33 | 0 | 0.825 |
| 32 | 0 | 0.8 |
| 31 | 0 | 0.775 |
| 30 | 0 | 0.75 |
| 29 | 0 | 0.725 |
| 28 | 0 | 0.7 |
| 27 | 0 | 0.675 |
| 26 | 0 | 0.65 |
| 25 | 0 | 0.625 |
| 24 | 0 | 0.6 |
| 23 | 0 | 0.575 |
| 22 | 0 | 0.55 |
| 21 | 0 | 0.525 |
| 20 | 0 | 0.5 |
| 19 | 0 | 0.475 |
| 18 | 0 | 0.45 |
| 17 | 0 | 0.425 |
| 16 | 0 | 0.4 |
| 15 | 0 | 0.375 |
| 14 | 0 | 0.35 |
| 13 | 0.1229698 | 0.325 |
| 12 | 0.1377778 | 0.3 |
| 11 | 0.1869919 | 0.275 |
| 10 | 0.192 | 0.25 |
| 9 | 0.1938775 | 0.225 |
| 8 | 0.2833333 | 0.2 |
| 7 | 0.3069767 | 0.175 |
| 6 | 0.3857374 | 0.15 |
| 5 | 0.5 | 0.125 |
| 4 | 0.6338462 | 0.1 |
| 3 | 0.7984496 | 0.075 |
| 2 | 1 | 0.05 |
| 1 | 1 | 0.025 |
| | 1 | 0 |

## DEEP WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| | 0 | 1 |
| 155 | 0 | 0.993589744 |
| 154 | 0 | 0.987179487 |
| 153 | 0 | 0.980769231 |
| 152 | 0 | 0.974358974 |
| 151 | 0 | 0.967948718 |
| 150 | 0 | 0.961538462 |
| 149 | 0 | 0.955128205 |
| 148 | 0 | 0.948717949 |
| 147 | 0 | 0.942307692 |
| 146 | 0 | 0.935897436 |
| 145 | 0 | 0.929487179 |
| 144 | 0 | 0.923076923 |
| 143 | 0 | 0.916666667 |
| 142 | 0 | 0.91025641 |
| 141 | 0 | 0.903846154 |
| 140 | 0 | 0.897435897 |
| 139 | 0 | 0.891025641 |
| 138 | 0 | 0.884615385 |
| 137 | 0 | 0.878205128 |
| 136 | 0 | 0.871794872 |
| 135 | 0 | 0.865384615 |
| 134 | 0 | 0.858974359 |
| 133 | 0 | 0.852564103 |
| 132 | 0 | 0.846153846 |
| 131 | 0 | 0.83974359 |
| 130 | 0 | 0.833333333 |
| 129 | 0 | 0.826923077 |
| 128 | 0 | 0.820512821 |
| 127 | 0 | 0.814102564 |
| 126 | 0 | 0.807692308 |
| 125 | 0 | 0.801282051 |
| 124 | 0 | 0.794871795 |
| 123 | 0 | 0.788461538 |
| 122 | 0 | 0.782051282 |
| 121 | 0 | 0.775641026 |
| 120 | 0 | 0.769230769 |
| 119 | 0 | 0.762820513 |
| 118 | 0 | 0.756410256 |
| 117 | 0 | 0.75 |
| 116 | 0 | 0.743589744 |
| 115 | 0 | 0.737179487 |
| 114 | 0 | 0.730769231 |
| 113 | 0 | 0.724358974 |
| 112 | 0 | 0.717948718 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 111 | 0 | 0.711538462 |
| 110 | 0 | 0.705128205 |
| 109 | 0 | 0.698717949 |
| 108 | 0 | 0.692307692 |
| 107 | 0 | 0.685897436 |
| 106 | 0.0011772 | 0.679487179 |
| 105 | 0.0027367 | 0.673076923 |
| 104 | 0.0053908 | 0.666666667 |
| 103 | 0.0058608 | 0.66025641 |
| 102 | 0.0071155 | 0.653846154 |
| 101 | 0.0082474 | 0.647435897 |
| 100 | 0.0086758 | 0.641025641 |
| 99 | 0.0105042 | 0.634615385 |
| 98 | 0.0119522 | 0.628205128 |
| 97 | 0.014231 | 0.621794872 |
| 96 | 0.0143416 | 0.615384615 |
| 95 | 0.015544 | 0.608974359 |
| 94 | 0.0186097 | 0.602564103 |
| 93 | 0.0186104 | 0.596153846 |
| 92 | 0.0186916 | 0.58974359 |
| 91 | 0.0229885 | 0.583333333 |
| 90 | 0.0242872 | 0.576923077 |
| 89 | 0.0290657 | 0.570512821 |
| 88 | 0.0303867 | 0.564102564 |
| 87 | 0.0341702 | 0.557692308 |
| 86 | 0.0372195 | 0.551282051 |
| 85 | 0.0394495 | 0.544871795 |
| 84 | 0.0442319 | 0.538461538 |
| 83 | 0.0468541 | 0.532051282 |
| 82 | 0.0492611 | 0.525641026 |
| 81 | 0.053407 | 0.519230769 |
| 80 | 0.0596184 | 0.512820513 |
| 79 | 0.0646766 | 0.506410256 |
| 78 | 0.0669035 | 0.5 |
| 77 | 0.0749625 | 0.493589744 |
| 76 | 0.0772947 | 0.487179487 |
| 75 | 0.0773381 | 0.480769231 |
| 74 | 0.0819209 | 0.474358974 |
| 73 | 0.0830704 | 0.467948718 |
| 72 | 0.0842912 | 0.461538462 |
| 71 | 0.0843786 | 0.455128205 |
| 70 | 0.0914286 | 0.448717949 |
| 69 | 0.0922064 | 0.442307692 |
| 68 | 0.096124 | 0.435897436 |
| 67 | 0.0967341 | 0.429487179 |

## DEEP WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 66 | 0.0986842 | 0.423076923 |
| 65 | 0.1003289 | 0.416666667 |
| 64 | 0.1030177 | 0.41025641 |
| 63 | 0.1073883 | 0.403846154 |
| 62 | 0.1123967 | 0.397435897 |
| 61 | 0.1133005 | 0.391025641 |
| 60 | 0.1142857 | 0.384615385 |
| 59 | 0.1153846 | 0.378205128 |
| 58 | 0.1340996 | 0.371794872 |
| 57 | 0.1351351 | 0.365384615 |
| 56 | 0.1405229 | 0.358974359 |
| 55 | 0.1536643 | 0.352564103 |
| 54 | 0.1561065 | 0.346153846 |
| 53 | 0.1613475 | 0.33974359 |
| 52 | 0.1666667 | 0.333333333 |
| 51 | 0.1690574 | 0.326923077 |
| 50 | 0.177641 | 0.320512821 |
| 49 | 0.1888889 | 0.314102564 |
| 48 | 0.193999 | 0.307692308 |
| 47 | 0.2019704 | 0.301282051 |
| 46 | 0.2030651 | 0.294871795 |
| 45 | 0.2064298 | 0.288461538 |
| 44 | 0.2138837 | 0.282051282 |
| 43 | 0.2144487 | 0.275641026 |
| 42 | 0.2149758 | 0.269230769 |
| 41 | 0.2301587 | 0.262820513 |
| 40 | 0.2398477 | 0.256410256 |
| 39 | 0.2399356 | 0.25 |
| 38 | 0.2473721 | 0.243589744 |
| 37 | 0.2550629 | 0.237179487 |
| 36 | 0.2568941 | 0.230769231 |
| 35 | 0.2744511 | 0.224358974 |
| 34 | 0.2754491 | 0.217948718 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 33 | 0.2863962 | 0.211538462 |
| 32 | 0.2887439 | 0.205128205 |
| 31 | 0.2992831 | 0.198717949 |
| 30 | 0.304324 | 0.192307692 |
| 29 | 0.3064989 | 0.185897436 |
| 28 | 0.3065134 | 0.179487179 |
| 27 | 0.3125 | 0.173076923 |
| 26 | 0.313253 | 0.166666667 |
| 25 | 0.3192771 | 0.16025641 |
| 24 | 0.3256059 | 0.153846154 |
| 23 | 0.3313559 | 0.147435897 |
| 22 | 0.3367199 | 0.141025641 |
| 21 | 0.3522608 | 0.134615385 |
| 20 | 0.3867069 | 0.128205128 |
| 19 | 0.4039409 | 0.121794872 |
| 18 | 0.4058394 | 0.115384615 |
| 17 | 0.4066776 | 0.108974359 |
| 16 | 0.4071428 | 0.102564103 |
| 15 | 0.4091904 | 0.096153846 |
| 14 | 0.4172932 | 0.08974359 |
| 13 | 0.4230019 | 0.083333333 |
| 12 | 0.4251208 | 0.076923077 |
| 11 | 0.4340449 | 0.070512821 |
| 10 | 0.4419155 | 0.064102564 |
| 9 | 0.4548346 | 0.057692308 |
| 8 | 0.4548849 | 0.051282051 |
| 7 | 0.4679803 | 0.044871795 |
| 6 | 0.5176327 | 0.038461538 |
| 5 | 0.5266618 | 0.032051282 |
| 4 | 0.5465729 | 0.025641026 |
| 3 | 0.5878661 | 0.019230769 |
| 2 | 1 | 0.012820513 |
| 1 | 1 | 0.006410256 |
|  | 1 | 0 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| | 0 | 1 |
| 868 | 0 | 0.998849252 |
| 867 | 0 | 0.997698504 |
| 866 | 0 | 0.996547756 |
| 865 | 0 | 0.995397008 |
| 864 | 0 | 0.99424626 |
| 863 | 0 | 0.993095512 |
| 862 | 0 | 0.991944764 |
| 861 | 0 | 0.990794016 |
| 860 | 0 | 0.989643268 |
| 859 | 0 | 0.98849252 |
| 858 | 0 | 0.987341772 |
| 857 | 0 | 0.986191024 |
| 856 | 0 | 0.985040276 |
| 855 | 0 | 0.983889528 |
| 854 | 0 | 0.98273878 |
| 853 | 0 | 0.981588032 |
| 852 | 0 | 0.980437284 |
| 851 | 0 | 0.979286536 |
| 850 | 0 | 0.978135788 |
| 849 | 0 | 0.97698504 |
| 848 | 0 | 0.975834292 |
| 847 | 0 | 0.974683544 |
| 846 | 0 | 0.973532796 |
| 845 | 0 | 0.972382048 |
| 844 | 0 | 0.9712313 |
| 843 | 0 | 0.970080552 |
| 842 | 0 | 0.968929804 |
| 841 | 0 | 0.967779056 |
| 840 | 0 | 0.966628308 |
| 839 | 0 | 0.96547756 |
| 838 | 0 | 0.964326812 |
| 837 | 0 | 0.963176064 |
| 836 | 0 | 0.962025316 |
| 835 | 0 | 0.960874568 |
| 834 | 0 | 0.95972382 |
| 833 | 0 | 0.958573072 |
| 832 | 0 | 0.957422325 |
| 831 | 0 | 0.956271577 |
| 830 | 0 | 0.955120829 |
| 829 | 0 | 0.953970081 |
| 828 | 0 | 0.952819333 |
| 827 | 0 | 0.951668585 |
| 826 | 0 | 0.950517837 |
| 825 | 0 | 0.949367089 |
| 824 | 0 | 0.948216341 |
| 823 | 0 | 0.947065593 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 822 | 0 | 0.945914845 |
| 821 | 0 | 0.944764097 |
| 820 | 0 | 0.943613349 |
| 819 | 0 | 0.942462601 |
| 818 | 0 | 0.941311853 |
| 817 | 0 | 0.940161105 |
| 816 | 0 | 0.939010357 |
| 815 | 0 | 0.937859609 |
| 814 | 0 | 0.936708861 |
| 813 | 0 | 0.935558113 |
| 812 | 0 | 0.934407365 |
| 811 | 0 | 0.933256617 |
| 810 | 0 | 0.932105869 |
| 809 | 0 | 0.930955121 |
| 808 | 0 | 0.929804373 |
| 807 | 0 | 0.928653625 |
| 806 | 0 | 0.927502877 |
| 805 | 0 | 0.926352129 |
| 804 | 0 | 0.925201381 |
| 803 | 0 | 0.924050633 |
| 802 | 0 | 0.922899885 |
| 801 | 0 | 0.921749137 |
| 800 | 0 | 0.920598389 |
| 799 | 0 | 0.919447641 |
| 798 | 0 | 0.918296893 |
| 797 | 0 | 0.917146145 |
| 796 | 0 | 0.915995397 |
| 795 | 0 | 0.914844649 |
| 794 | 0 | 0.913693901 |
| 793 | 0 | 0.912543153 |
| 792 | 0 | 0.911392405 |
| 791 | 0 | 0.910241657 |
| 790 | 0 | 0.909090909 |
| 789 | 0 | 0.907940161 |
| 788 | 0 | 0.906789413 |
| 787 | 0 | 0.905638665 |
| 786 | 0 | 0.904487917 |
| 785 | 0 | 0.903337169 |
| 784 | 0 | 0.902186421 |
| 783 | 0 | 0.901035673 |
| 782 | 0 | 0.899884925 |
| 781 | 0 | 0.898734177 |
| 780 | 0 | 0.897583429 |
| 779 | 0 | 0.896432681 |
| 778 | 0 | 0.895281933 |
| 777 | 0 | 0.894131185 |
| 776 | 0 | 0.892980437 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 775 | 0 | 0.891829689 |
| 774 | 0 | 0.890678941 |
| 773 | 0 | 0.889528193 |
| 772 | 0 | 0.888377445 |
| 771 | 0 | 0.887226697 |
| 770 | 0 | 0.886075949 |
| 769 | 0 | 0.884925201 |
| 768 | 0 | 0.883774453 |
| 767 | 0 | 0.882623705 |
| 766 | 0 | 0.881472957 |
| 765 | 0 | 0.880322209 |
| 764 | 0 | 0.879171461 |
| 763 | 0 | 0.878020713 |
| 762 | 0 | 0.876869965 |
| 761 | 0 | 0.875719217 |
| 760 | 0 | 0.87456847 |
| 759 | 0 | 0.873417722 |
| 758 | 0 | 0.872266974 |
| 757 | 0 | 0.871116226 |
| 756 | 0 | 0.869965478 |
| 755 | 0 | 0.86881473 |
| 754 | 0 | 0.867663982 |
| 753 | 0 | 0.866513234 |
| 752 | 0 | 0.865362486 |
| 751 | 0 | 0.864211738 |
| 750 | 0 | 0.86306099 |
| 749 | 0 | 0.861910242 |
| 748 | 0 | 0.860759494 |
| 747 | 0 | 0.859608746 |
| 746 | 0 | 0.858457998 |
| 745 | 0 | 0.85730725 |
| 744 | 0 | 0.856156502 |
| 743 | 0 | 0.855005754 |
| 742 | 0 | 0.853855006 |
| 741 | 0 | 0.852704258 |
| 740 | 0 | 0.85155351 |
| 739 | 0 | 0.850402762 |
| 738 | 0 | 0.849252014 |
| 737 | 0 | 0.848101266 |
| 736 | 0 | 0.846950518 |
| 735 | 0 | 0.84579977 |
| 734 | 0 | 0.844649022 |
| 733 | 0 | 0.843498274 |
| 732 | 0 | 0.842347526 |
| 731 | 0 | 0.841196778 |
| 730 | 0 | 0.84004603 |
| 729 | 0 | 0.838895282 |
| 728 | 0 | 0.837744534 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 727 | 0 | 0.836593786 |
| 726 | 0 | 0.835443038 |
| 725 | 0 | 0.83429229 |
| 724 | 0 | 0.833141542 |
| 723 | 0 | 0.831990794 |
| 722 | 0 | 0.830840046 |
| 721 | 0 | 0.829689298 |
| 720 | 0 | 0.82853855 |
| 719 | 0 | 0.827387802 |
| 718 | 0 | 0.826237054 |
| 717 | 0 | 0.825086306 |
| 716 | 0 | 0.823935558 |
| 715 | 0 | 0.82278481 |
| 714 | 0 | 0.821634062 |
| 713 | 0 | 0.820483314 |
| 712 | 0 | 0.819332566 |
| 711 | 0 | 0.818181818 |
| 710 | 0 | 0.81703107 |
| 709 | 0 | 0.815880322 |
| 708 | 0 | 0.814729574 |
| 707 | 0 | 0.813578826 |
| 706 | 0 | 0.812428078 |
| 705 | 0 | 0.81127733 |
| 704 | 0 | 0.810126582 |
| 703 | 0 | 0.808975834 |
| 702 | 0 | 0.807825086 |
| 701 | 0 | 0.806674338 |
| 700 | 0 | 0.80552359 |
| 699 | 0 | 0.804372842 |
| 698 | 0 | 0.803222094 |
| 697 | 0 | 0.802071346 |
| 696 | 0 | 0.800920598 |
| 695 | 0 | 0.79976985 |
| 694 | 0 | 0.798619102 |
| 693 | 0 | 0.797468354 |
| 692 | 0 | 0.796317606 |
| 691 | 0 | 0.795166858 |
| 690 | 0 | 0.79401611 |
| 689 | 0 | 0.792865362 |
| 688 | 0 | 0.791714614 |
| 687 | 0 | 0.790563867 |
| 686 | 0 | 0.789413119 |
| 685 | 0 | 0.788262371 |
| 684 | 0 | 0.787111623 |
| 683 | 0 | 0.785960875 |
| 682 | 0 | 0.784810127 |
| 681 | 0 | 0.783659379 |
| 680 | 0 | 0.782508631 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 679 | 0 | 0.781357883 |
| 678 | 0 | 0.780207135 |
| 677 | 0 | 0.779056387 |
| 676 | 0 | 0.777905639 |
| 675 | 0 | 0.776754891 |
| 674 | 0 | 0.775604143 |
| 673 | 0 | 0.774453395 |
| 672 | 0 | 0.773302647 |
| 671 | 0 | 0.772151899 |
| 670 | 0 | 0.771001151 |
| 669 | 0 | 0.769850403 |
| 668 | 0 | 0.768699655 |
| 667 | 0 | 0.767548907 |
| 666 | 0 | 0.766398159 |
| 665 | 0 | 0.765247411 |
| 664 | 0 | 0.764096663 |
| 663 | 0 | 0.762945915 |
| 662 | 0 | 0.761795167 |
| 661 | 0 | 0.760644419 |
| 660 | 0 | 0.759493671 |
| 659 | 0 | 0.758342923 |
| 658 | 0 | 0.757192175 |
| 657 | 0 | 0.756041427 |
| 656 | 0 | 0.754890679 |
| 655 | 0 | 0.753739931 |
| 654 | 0 | 0.752589183 |
| 653 | 0 | 0.751438435 |
| 652 | 0 | 0.750287687 |
| 651 | 0 | 0.749136939 |
| 650 | 0 | 0.747986191 |
| 649 | 0 | 0.746835443 |
| 648 | 0 | 0.745684695 |
| 647 | 0 | 0.744533947 |
| 646 | 0 | 0.743383199 |
| 645 | 0 | 0.742232451 |
| 644 | 0 | 0.741081703 |
| 643 | 0 | 0.739930955 |
| 642 | 0 | 0.738780207 |
| 641 | 0 | 0.737629459 |
| 640 | 0 | 0.736478711 |
| 639 | 0 | 0.735327963 |
| 638 | 0 | 0.734177215 |
| 637 | 0 | 0.733026467 |
| 636 | 0 | 0.731875719 |
| 635 | 0 | 0.730724971 |
| 634 | 0 | 0.729574223 |
| 633 | 0 | 0.728423475 |
| 632 | 0 | 0.727272727 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 631 | 0 | 0.726121979 |
| 630 | 0 | 0.724971231 |
| 629 | 0 | 0.723820483 |
| 628 | 0 | 0.722669735 |
| 627 | 0 | 0.721518987 |
| 626 | 0 | 0.720368239 |
| 625 | 0 | 0.719217491 |
| 624 | 0 | 0.718066743 |
| 623 | 0 | 0.716915995 |
| 622 | 0 | 0.715765247 |
| 621 | 0 | 0.714614499 |
| 620 | 0 | 0.713463751 |
| 619 | 0 | 0.712313003 |
| 618 | 0 | 0.711162255 |
| 617 | 0 | 0.710011507 |
| 616 | 0 | 0.708860759 |
| 615 | 0 | 0.707710012 |
| 614 | 0 | 0.706559264 |
| 613 | 0 | 0.705408516 |
| 612 | 0 | 0.704257768 |
| 611 | 0 | 0.70310702 |
| 610 | 0 | 0.701956272 |
| 609 | 0 | 0.700805524 |
| 608 | 0 | 0.699654776 |
| 607 | 0 | 0.698504028 |
| 606 | 0 | 0.69735328 |
| 605 | 0 | 0.696202532 |
| 604 | 0 | 0.695051784 |
| 603 | 0 | 0.693901036 |
| 602 | 0 | 0.692750288 |
| 601 | 0 | 0.69159954 |
| 600 | 0 | 0.690448792 |
| 599 | 0 | 0.689298044 |
| 598 | 0 | 0.688147296 |
| 597 | 0 | 0.686996548 |
| 596 | 0 | 0.6858458 |
| 595 | 0 | 0.684695052 |
| 594 | 0 | 0.683544304 |
| 593 | 0 | 0.682393556 |
| 592 | 0 | 0.681242808 |
| 591 | 0 | 0.68009206 |
| 590 | 0 | 0.678941312 |
| 589 | 0 | 0.677790564 |
| 588 | 0 | 0.676639816 |
| 587 | 0 | 0.675489068 |
| 586 | 0 | 0.67433832 |
| 585 | 0 | 0.673187572 |
| 584 | 0 | 0.672036824 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 583 | 0 | 0.670886076 |
| 582 | 0 | 0.669735328 |
| 581 | 0 | 0.66858458 |
| 580 | 0 | 0.667433832 |
| 579 | 0 | 0.666283084 |
| 578 | 0 | 0.665132336 |
| 577 | 0 | 0.663981588 |
| 576 | 0 | 0.66283084 |
| 575 | 0 | 0.661680092 |
| 574 | 0 | 0.660529344 |
| 573 | 0 | 0.659378596 |
| 572 | 0 | 0.658227848 |
| 571 | 0 | 0.6570771 |
| 570 | 0 | 0.655926352 |
| 569 | 0 | 0.654775604 |
| 568 | 0 | 0.653624856 |
| 567 | 0 | 0.652474108 |
| 566 | 0 | 0.65132336 |
| 565 | 0 | 0.650172612 |
| 564 | 0 | 0.649021864 |
| 563 | 0 | 0.647871116 |
| 562 | 0 | 0.646720368 |
| 561 | 0 | 0.64556962 |
| 560 | 0 | 0.644418872 |
| 559 | 0 | 0.643268124 |
| 558 | 0 | 0.642117376 |
| 557 | 0 | 0.640966628 |
| 556 | 0 | 0.63981588 |
| 555 | 0 | 0.638665132 |
| 554 | 0 | 0.637514384 |
| 553 | 0 | 0.636363636 |
| 552 | 0 | 0.635212888 |
| 551 | 0 | 0.63406214 |
| 550 | 0 | 0.632911392 |
| 549 | 0 | 0.631760644 |
| 548 | 0 | 0.630609896 |
| 547 | 0 | 0.629459148 |
| 546 | 0 | 0.6283084 |
| 545 | 0 | 0.627157652 |
| 544 | 0 | 0.626006904 |
| 543 | 0 | 0.624856157 |
| 542 | 0 | 0.623705409 |
| 541 | 0 | 0.622554661 |
| 540 | 0 | 0.621403913 |
| 539 | 0 | 0.620253165 |
| 538 | 0 | 0.619102417 |
| 537 | 0 | 0.617951669 |
| 536 | 0 | 0.616800921 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 535 | 0 | 0.615650173 |
| 534 | 0 | 0.614499425 |
| 533 | 0 | 0.613348677 |
| 532 | 0 | 0.612197929 |
| 531 | 0 | 0.611047181 |
| 530 | 0 | 0.609896433 |
| 529 | 0 | 0.608745685 |
| 528 | 0 | 0.607594937 |
| 527 | 0 | 0.606444189 |
| 526 | 0 | 0.605293441 |
| 525 | 0 | 0.604142693 |
| 524 | 0 | 0.602991945 |
| 523 | 0 | 0.601841197 |
| 522 | 0 | 0.600690449 |
| 521 | 0 | 0.599539701 |
| 520 | 0 | 0.598388953 |
| 519 | 0 | 0.597238205 |
| 518 | 0 | 0.596087457 |
| 517 | 0 | 0.594936709 |
| 516 | 0 | 0.593785961 |
| 515 | 0 | 0.592635213 |
| 514 | 0 | 0.591484465 |
| 513 | 0 | 0.590333717 |
| 512 | 0 | 0.589182969 |
| 511 | 0 | 0.588032221 |
| 510 | 0 | 0.586881473 |
| 509 | 0 | 0.585730725 |
| 508 | 0 | 0.584579977 |
| 507 | 0 | 0.583429229 |
| 506 | 0 | 0.582278481 |
| 505 | 0 | 0.581127733 |
| 504 | 0 | 0.579976985 |
| 503 | 0 | 0.578826237 |
| 502 | 0 | 0.577675489 |
| 501 | 0 | 0.576524741 |
| 500 | 0 | 0.575373993 |
| 499 | 0 | 0.574223245 |
| 498 | 0 | 0.573072497 |
| 497 | 0 | 0.571921749 |
| 496 | 0 | 0.570771001 |
| 495 | 0 | 0.569620253 |
| 494 | 0 | 0.568469505 |
| 493 | 0 | 0.567318757 |
| 492 | 0 | 0.566168009 |
| 491 | 0 | 0.565017261 |
| 490 | 0 | 0.563866513 |
| 489 | 0 | 0.562715765 |
| 488 | 0 | 0.561565017 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 487 | 0 | 0.560414269 |
| 486 | 0 | 0.559263521 |
| 485 | 0 | 0.558112773 |
| 484 | 0 | 0.556962025 |
| 483 | 0 | 0.555811277 |
| 482 | 0 | 0.554660529 |
| 481 | 0 | 0.553509781 |
| 480 | 0 | 0.552359033 |
| 479 | 0 | 0.551208285 |
| 478 | 0 | 0.550057537 |
| 477 | 0 | 0.548906789 |
| 476 | 0 | 0.547756041 |
| 475 | 0 | 0.546605293 |
| 474 | 0 | 0.545454545 |
| 473 | 0 | 0.544303797 |
| 472 | 0 | 0.543153049 |
| 471 | 0 | 0.542002301 |
| 470 | 0 | 0.540851554 |
| 469 | 0 | 0.539700806 |
| 468 | 0 | 0.538550058 |
| 467 | 0 | 0.53739931 |
| 466 | 0 | 0.536248562 |
| 465 | 0 | 0.535097814 |
| 464 | 0 | 0.533947066 |
| 463 | 0 | 0.532796318 |
| 462 | 0 | 0.53164557 |
| 461 | 0 | 0.530494822 |
| 460 | 0 | 0.529344074 |
| 459 | 0 | 0.528193326 |
| 458 | 0 | 0.527042578 |
| 457 | 0 | 0.52589183 |
| 456 | 0 | 0.524741082 |
| 455 | 0 | 0.523590334 |
| 454 | 0 | 0.522439586 |
| 453 | 0 | 0.521288838 |
| 452 | 0 | 0.52013809 |
| 451 | 0 | 0.518987342 |
| 450 | 0 | 0.517836594 |
| 449 | 0 | 0.516685846 |
| 448 | 0 | 0.515535098 |
| 447 | 0 | 0.51438435 |
| 446 | 0 | 0.513233602 |
| 445 | 0 | 0.512082854 |
| 444 | 0 | 0.510932106 |
| 443 | 0 | 0.509781358 |
| 442 | 0 | 0.50863061 |
| 441 | 0 | 0.507479862 |
| 440 | 0 | 0.506329114 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 439 | 0 | 0.505178366 |
| 438 | 0 | 0.504027618 |
| 437 | 0 | 0.50287687 |
| 436 | 0 | 0.501726122 |
| 435 | 0 | 0.500575374 |
| 434 | 0 | 0.499424626 |
| 433 | 0 | 0.498273878 |
| 432 | 0 | 0.49712313 |
| 431 | 0 | 0.495972382 |
| 430 | 0 | 0.494821634 |
| 429 | 0 | 0.493670886 |
| 428 | 0 | 0.492520138 |
| 427 | 0 | 0.49136939 |
| 426 | 0 | 0.490218642 |
| 425 | 0 | 0.489067894 |
| 424 | 0 | 0.487917146 |
| 423 | 0 | 0.486766398 |
| 422 | 0 | 0.48561565 |
| 421 | 0 | 0.484464902 |
| 420 | 0 | 0.483314154 |
| 419 | 0 | 0.482163406 |
| 418 | 0 | 0.481012658 |
| 417 | 0 | 0.47986191 |
| 416 | 0 | 0.478711162 |
| 415 | 0 | 0.477560414 |
| 414 | 0 | 0.476409666 |
| 413 | 0 | 0.475258918 |
| 412 | 0 | 0.47410817 |
| 411 | 0 | 0.472957422 |
| 410 | 0 | 0.471806674 |
| 409 | 0 | 0.470655926 |
| 408 | 0 | 0.469505178 |
| 407 | 0 | 0.46835443 |
| 406 | 0 | 0.467203682 |
| 405 | 0 | 0.466052934 |
| 404 | 0 | 0.464902186 |
| 403 | 0 | 0.463751438 |
| 402 | 0 | 0.46260069 |
| 401 | 0 | 0.461449942 |
| 400 | 0 | 0.460299194 |
| 399 | 0 | 0.459148446 |
| 398 | 0 | 0.457997699 |
| 397 | 0 | 0.456846951 |
| 396 | 0 | 0.455696203 |
| 395 | 0 | 0.454545455 |
| 394 | 0 | 0.453394707 |
| 393 | 0 | 0.452243959 |
| 392 | 0 | 0.451093211 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 391 | 0 | 0.449942463 |
| 390 | 0 | 0.448791715 |
| 389 | 0 | 0.447640967 |
| 388 | 0 | 0.446490219 |
| 387 | 0 | 0.445339471 |
| 386 | 0 | 0.444188723 |
| 385 | 0 | 0.443037975 |
| 384 | 0 | 0.441887227 |
| 383 | 0 | 0.440736479 |
| 382 | 0 | 0.439585731 |
| 381 | 0 | 0.438434983 |
| 380 | 0 | 0.437284235 |
| 379 | 0 | 0.436133487 |
| 378 | 0 | 0.434982739 |
| 377 | 0 | 0.433831991 |
| 376 | 0 | 0.432681243 |
| 375 | 0 | 0.431530495 |
| 374 | 0 | 0.430379747 |
| 373 | 0 | 0.429228999 |
| 372 | 0 | 0.428078251 |
| 371 | 0 | 0.426927503 |
| 370 | 0 | 0.425776755 |
| 369 | 0.0005089 | 0.424626007 |
| 368 | 0.0005304 | 0.423475259 |
| 367 | 0.0005965 | 0.422324511 |
| 366 | 0.0006126 | 0.421173763 |
| 365 | 0.000801 | 0.420023015 |
| 364 | 0.0009697 | 0.418872267 |
| 363 | 0.0011871 | 0.417721519 |
| 362 | 0.0014519 | 0.416570771 |
| 361 | 0.0016221 | 0.415420023 |
| 360 | 0.0016335 | 0.414269275 |
| 359 | 0.0021645 | 0.413118527 |
| 358 | 0.0021645 | 0.411967779 |
| 357 | 0.0021684 | 0.410817031 |
| 356 | 0.0022422 | 0.409666283 |
| 355 | 0.0024594 | 0.408515535 |
| 354 | 0.0024882 | 0.407364787 |
| 353 | 0.0025445 | 0.406214039 |
| 352 | 0.0029858 | 0.405063291 |
| 351 | 0.0035562 | 0.403912543 |
| 350 | 0.0042328 | 0.402761795 |
| 349 | 0.0044582 | 0.401611047 |
| 348 | 0.0048011 | 0.400460299 |
| 347 | 0.0049478 | 0.399309551 |
| 346 | 0.0050706 | 0.398158803 |
| 345 | 0.0055944 | 0.397008055 |
| 344 | 0.005598 | 0.395857307 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 343 | 0.005618 | 0.394706559 |
| 342 | 0.0056497 | 0.393555811 |
| 341 | 0.0056497 | 0.392405063 |
| 340 | 0.0056497 | 0.391254315 |
| 339 | 0.0057741 | 0.390103567 |
| 338 | 0.0060024 | 0.388952819 |
| 337 | 0.0064935 | 0.387802071 |
| 336 | 0.0064935 | 0.386651323 |
| 335 | 0.0064935 | 0.385500575 |
| 334 | 0.0064935 | 0.384349827 |
| 333 | 0.006993 | 0.383199079 |
| 332 | 0.0072816 | 0.382048331 |
| 331 | 0.0077864 | 0.380897583 |
| 330 | 0.0081425 | 0.379746835 |
| 329 | 0.0083485 | 0.378596087 |
| 328 | 0.009176 | 0.377445339 |
| 327 | 0.009772 | 0.376294591 |
| 326 | 0.0100344 | 0.375143843 |
| 325 | 0.0108696 | 0.373993096 |
| 324 | 0.011236 | 0.372842348 |
| 323 | 0.0112994 | 0.3716916 |
| 322 | 0.0113636 | 0.370540852 |
| 321 | 0.0122877 | 0.369390104 |
| 320 | 0.0129206 | 0.368239356 |
| 319 | 0.0133457 | 0.367088608 |
| 318 | 0.0135135 | 0.36593786 |
| 317 | 0.0135135 | 0.364787112 |
| 316 | 0.0138099 | 0.363636364 |
| 315 | 0.0141643 | 0.362485616 |
| 314 | 0.0145985 | 0.361334868 |
| 313 | 0.0152119 | 0.36018412 |
| 312 | 0.0153473 | 0.359033372 |
| 311 | 0.0163934 | 0.357882624 |
| 310 | 0.0169367 | 0.356731876 |
| 309 | 0.0173661 | 0.355581128 |
| 308 | 0.0178716 | 0.35443038 |
| 307 | 0.0181209 | 0.353279632 |
| 306 | 0.0190476 | 0.352128884 |
| 305 | 0.0195954 | 0.350978136 |
| 304 | 0.0201126 | 0.349827388 |
| 303 | 0.020657 | 0.34867664 |
| 302 | 0.021121 | 0.347525892 |
| 301 | 0.0213471 | 0.346375144 |
| 300 | 0.0220096 | 0.345224396 |
| 299 | 0.0222782 | 0.344073648 |
| 298 | 0.0227457 | 0.3429229 |
| 297 | 0.0228091 | 0.341772152 |
| 296 | 0.0235199 | 0.340621404 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 295 | 0.0238095 | 0.339470656 |
| 294 | 0.0238095 | 0.338319908 |
| 293 | 0.0238095 | 0.33716916 |
| 292 | 0.0238095 | 0.336018412 |
| 291 | 0.0238095 | 0.334867664 |
| 290 | 0.0238095 | 0.333716916 |
| 289 | 0.0242139 | 0.332566168 |
| 288 | 0.0243704 | 0.33141542 |
| 287 | 0.0248963 | 0.330264672 |
| 286 | 0.0251828 | 0.329113924 |
| 285 | 0.025533 | 0.327963176 |
| 284 | 0.0257611 | 0.326812428 |
| 283 | 0.025804 | 0.32566168 |
| 282 | 0.02595 | 0.324510932 |
| 281 | 0.0277429 | 0.323360184 |
| 280 | 0.0282486 | 0.322209436 |
| 279 | 0.0285016 | 0.321058688 |
| 278 | 0.0300546 | 0.31990794 |
| 277 | 0.0310473 | 0.318757192 |
| 276 | 0.0312355 | 0.317606444 |
| 275 | 0.0321381 | 0.316455696 |
| 274 | 0.0321381 | 0.315304948 |
| 273 | 0.0328082 | 0.3141542 |
| 272 | 0.0341186 | 0.313003452 |
| 271 | 0.0349206 | 0.311852704 |
| 270 | 0.0363636 | 0.310701956 |
| 269 | 0.0364963 | 0.309551208 |
| 268 | 0.0366795 | 0.30840046 |
| 267 | 0.0374777 | 0.307249712 |
| 266 | 0.0380952 | 0.306098964 |
| 265 | 0.0381803 | 0.304948216 |
| 264 | 0.0391608 | 0.303797468 |
| 263 | 0.0399501 | 0.30264672 |
| 262 | 0.0408163 | 0.301495972 |
| 261 | 0.0422037 | 0.300345224 |
| 260 | 0.042328 | 0.299194476 |
| 259 | 0.0423729 | 0.298043728 |
| 258 | 0.0427173 | 0.29689298 |
| 257 | 0.043956 | 0.295742232 |
| 256 | 0.0444942 | 0.294591484 |
| 255 | 0.0452794 | 0.293440736 |
| 254 | 0.0464169 | 0.292289988 |
| 253 | 0.0470397 | 0.291139241 |
| 252 | 0.0486772 | 0.289988493 |
| 251 | 0.0486772 | 0.288837745 |
| 250 | 0.0492197 | 0.287686997 |
| 249 | 0.0511788 | 0.286536249 |
| 248 | 0.0519084 | 0.285385501 |
| 247 | 0.0521231 | 0.284234753 |
| 246 | 0.0529101 | 0.283084005 |
| 245 | 0.0529101 | 0.281933257 |
| 244 | 0.0530612 | 0.280782509 |
| 243 | 0.0536869 | 0.279631761 |
| 242 | 0.0536869 | 0.278481013 |
| 241 | 0.0536869 | 0.277330265 |
| 240 | 0.0541126 | 0.276179517 |
| 239 | 0.0541126 | 0.275028769 |
| 238 | 0.0541126 | 0.273878021 |
| 237 | 0.0541126 | 0.272727273 |
| 236 | 0.0541126 | 0.271576525 |
| 235 | 0.0579235 | 0.270425777 |
| 234 | 0.0586084 | 0.269275029 |
| 233 | 0.0587911 | 0.268124281 |
| 232 | 0.0596465 | 0.266973533 |
| 231 | 0.0604396 | 0.265822785 |
| 230 | 0.0614422 | 0.264672037 |
| 229 | 0.0618847 | 0.263521289 |
| 228 | 0.0620364 | 0.262370541 |
| 227 | 0.0625508 | 0.261219793 |
| 226 | 0.0653824 | 0.260069045 |
| 225 | 0.0658002 | 0.258918297 |
| 224 | 0.0684039 | 0.257767549 |
| 223 | 0.0695876 | 0.256616801 |
| 222 | 0.0708995 | 0.255466053 |
| 221 | 0.0713287 | 0.254315305 |
| 220 | 0.0714866 | 0.253164557 |
| 219 | 0.0717703 | 0.252013809 |
| 218 | 0.0739236 | 0.250863061 |
| 217 | 0.0756155 | 0.249712313 |
| 216 | 0.0757415 | 0.248561565 |
| 215 | 0.0760522 | 0.247410817 |
| 214 | 0.0779468 | 0.246260069 |
| 213 | 0.0781759 | 0.245109321 |
| 212 | 0.0784933 | 0.243958573 |
| 211 | 0.0793651 | 0.242807825 |
| 210 | 0.0813397 | 0.241657077 |
| 209 | 0.0836718 | 0.240506329 |
| 208 | 0.0852341 | 0.239355581 |
| 207 | 0.0852341 | 0.238204833 |
| 206 | 0.0852341 | 0.237054085 |
| 205 | 0.0858202 | 0.235903337 |
| 204 | 0.0859692 | 0.234752589 |
| 203 | 0.0862069 | 0.233601841 |
| 202 | 0.0867133 | 0.232451093 |
| 201 | 0.0889352 | 0.231300345 |
| 200 | 0.0924318 | 0.230149597 |

## OPEN WATER MONTHLY VALUES

| Fraction Volume | Fraction Time |
|---|---|
| 0.0926076 | 0.228998849 |
| 0.094402 | 0.227848101 |
| 0.0951807 | 0.226697353 |
| 0.0953661 | 0.225546605 |
| 0.0980392 | 0.224395857 |
| 0.0986222 | 0.223245109 |
| 0.0995439 | 0.222094361 |
| 0.1013514 | 0.220943613 |
| 0.1056534 | 0.219792865 |
| 0.1097062 | 0.218642117 |
| 0.1108631 | 0.217491369 |
| 0.1108631 | 0.216340621 |
| 0.1110075 | 0.215189873 |
| 0.1119293 | 0.214039125 |
| 0.1123596 | 0.212888377 |
| 0.1135513 | 0.211737629 |
| 0.113798 | 0.210586881 |
| 0.1141304 | 0.209436133 |
| 0.1160355 | 0.208285386 |
| 0.1222826 | 0.207134638 |
| 0.1235521 | 0.20598389 |
| 0.1259259 | 0.204833142 |
| 0.1260344 | 0.203682394 |
| 0.1269841 | 0.202531646 |
| 0.1270358 | 0.201380898 |
| 0.1300254 | 0.20023015 |
| 0.1310766 | 0.199079402 |
| 0.1316527 | 0.197928654 |
| 0.1342461 | 0.196777906 |
| 0.1372868 | 0.195627158 |
| 0.1389115 | 0.19447641 |
| 0.14 | 0.193325662 |
| 0.14 | 0.192174914 |
| 0.140647 | 0.191024166 |
| 0.1415645 | 0.189873418 |
| 0.1419069 | 0.18872267 |
| 0.1435523 | 0.187571922 |
| 0.1449735 | 0.186421174 |
| 0.1455978 | 0.185270426 |
| 0.1514339 | 0.184119678 |
| 0.1538896 | 0.18296893 |
| 0.1542142 | 0.181818182 |
| 0.1566434 | 0.180667434 |
| 0.1587452 | 0.179516686 |
| 0.1595922 | 0.178365938 |
| 0.1611479 | 0.17721519 |
| 0.1614429 | 0.176064442 |
| 0.162963 | 0.174913694 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 151 | 0.1631854 | 0.173762946 |
| 150 | 0.1643766 | 0.172612198 |
| 149 | 0.1650579 | 0.17146145 |
| 148 | 0.1661578 | 0.170310702 |
| 147 | 0.1686848 | 0.169159954 |
| 146 | 0.1688742 | 0.168009206 |
| 145 | 0.1706892 | 0.166858458 |
| 144 | 0.1722272 | 0.16570771 |
| 143 | 0.1731602 | 0.164556962 |
| 142 | 0.1735369 | 0.163406214 |
| 141 | 0.1756757 | 0.162255466 |
| 140 | 0.1779041 | 0.161104718 |
| 139 | 0.1805116 | 0.15995397 |
| 138 | 0.1805379 | 0.158803222 |
| 137 | 0.1830601 | 0.157652474 |
| 136 | 0.190725 | 0.156501726 |
| 135 | 0.1914525 | 0.155350978 |
| 134 | 0.1941337 | 0.15420023 |
| 133 | 0.199403 | 0.153049482 |
| 132 | 0.201087 | 0.151898734 |
| 131 | 0.2013652 | 0.150747986 |
| 130 | 0.2039852 | 0.149597238 |
| 129 | 0.2189781 | 0.14844649 |
| 128 | 0.227972 | 0.147295742 |
| 127 | 0.2337085 | 0.146144994 |
| 126 | 0.2359882 | 0.144994246 |
| 125 | 0.2374406 | 0.143843498 |
| 124 | 0.2409669 | 0.14269275 |
| 123 | 0.2419833 | 0.141542002 |
| 122 | 0.2432432 | 0.140391254 |
| 121 | 0.2444856 | 0.139240506 |
| 120 | 0.2445605 | 0.138089758 |
| 119 | 0.2457132 | 0.13693901 |
| 118 | 0.2472826 | 0.135788262 |
| 117 | 0.2478753 | 0.134637514 |
| 116 | 0.2583187 | 0.133486766 |
| 115 | 0.2593284 | 0.132336018 |
| 114 | 0.2593284 | 0.13118527 |
| 113 | 0.2593284 | 0.130034522 |
| 112 | 0.2611517 | 0.128883774 |
| 111 | 0.2736842 | 0.127733026 |
| 110 | 0.2866706 | 0.126582278 |
| 109 | 0.2889755 | 0.12543153 |
| 108 | 0.2900763 | 0.124280783 |
| 107 | 0.2905174 | 0.123130035 |
| 106 | 0.3018642 | 0.121979287 |
| 105 | 0.3043062 | 0.120828539 |
| 104 | 0.3130724 | 0.119677791 |

## OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 103 | 0.319855 | 0.118527043 |
| 102 | 0.3289125 | 0.117376295 |
| 101 | 0.3301158 | 0.116225547 |
| 100 | 0.3326345 | 0.115074799 |
| 99 | 0.3344764 | 0.113924051 |
| 98 | 0.350166 | 0.112773303 |
| 97 | 0.350417 | 0.111622555 |
| 96 | 0.3507276 | 0.110471807 |
| 95 | 0.3753799 | 0.109321059 |
| 94 | 0.3762215 | 0.108170311 |
| 93 | 0.37668 | 0.107019563 |
| 92 | 0.3773917 | 0.105868815 |
| 91 | 0.3793436 | 0.104718067 |
| 90 | 0.3807623 | 0.103567319 |
| 89 | 0.3879781 | 0.102416571 |
| 88 | 0.3998882 | 0.101265823 |
| 87 | 0.4010152 | 0.100115075 |
| 86 | 0.4038889 | 0.098964327 |
| 85 | 0.4038889 | 0.097813579 |
| 84 | 0.4038889 | 0.096662831 |
| 83 | 0.4038889 | 0.095512083 |
| 82 | 0.4038889 | 0.094361335 |
| 81 | 0.4146816 | 0.093210587 |
| 80 | 0.4163347 | 0.092059839 |
| 79 | 0.4233177 | 0.090909091 |
| 78 | 0.4269663 | 0.089758343 |
| 77 | 0.429676 | 0.088607595 |
| 76 | 0.4300699 | 0.087456847 |
| 75 | 0.4304933 | 0.086306099 |
| 74 | 0.4374046 | 0.085155351 |
| 73 | 0.4423898 | 0.084004603 |
| 72 | 0.4565826 | 0.082853855 |
| 71 | 0.456869 | 0.081703107 |
| 70 | 0.4570895 | 0.080552359 |
| 69 | 0.4570895 | 0.079401611 |
| 68 | 0.4570895 | 0.078250863 |
| 67 | 0.464702 | 0.077100115 |
| 66 | 0.4692463 | 0.075949367 |
| 65 | 0.4841679 | 0.074798619 |
| 64 | 0.5085324 | 0.073647871 |
| 63 | 0.5108851 | 0.072497123 |
| 62 | 0.5263544 | 0.071346375 |
| 61 | 0.545568 | 0.070195627 |
| 60 | 0.5625 | 0.069044879 |
| 59 | 0.5701425 | 0.067894131 |
| 58 | 0.575 | 0.066743383 |
| 57 | 0.576076 | 0.065592635 |
| 56 | 0.6036122 | 0.064441887 |

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 55 | 0.6200294 | 0.063291139 |
| 54 | 0.6237785 | 0.062140391 |
| 53 | 0.6320347 | 0.060989643 |
| 52 | 0.6437941 | 0.059838895 |
| 51 | 0.6469252 | 0.058688147 |
| 50 | 0.6567556 | 0.057537399 |
| 49 | 0.663745 | 0.056386651 |
| 48 | 0.7578948 | 0.055235903 |
| 47 | 0.7717455 | 0.054085155 |
| 46 | 0.8227364 | 0.052934407 |
| 45 | 0.8384528 | 0.051783659 |
| 44 | 0.97 | 0.050632911 |
| 43 | 0.9949544 | 0.049482163 |
| 42 | 1 | 0.048331415 |
| 41 | 1 | 0.047180667 |
| 40 | 1 | 0.046029919 |
| 39 | 1 | 0.044879171 |
| 38 | 1 | 0.043728423 |
| 37 | 1 | 0.042577675 |
| 36 | 1 | 0.041426928 |
| 35 | 1 | 0.04027618 |
| 34 | 1 | 0.039125432 |
| 33 | 1 | 0.037974684 |
| 32 | 1 | 0.036823936 |
| 31 | 1 | 0.035673188 |
| 30 | 1 | 0.03452244 |
| 29 | 1 | 0.033371692 |
| 28 | 1 | 0.032220944 |
| 27 | 1 | 0.031070196 |
| 26 | 1 | 0.029919448 |
| 25 | 1 | 0.0287687 |
| 24 | 1 | 0.027617952 |
| 23 | 1 | 0.026467204 |
| 22 | 1 | 0.025316456 |
| 21 | 1 | 0.024165708 |
| 20 | 1 | 0.02301496 |
| 19 | 1 | 0.021864212 |
| 18 | 1 | 0.020713464 |
| 17 | 1 | 0.019562716 |
| 16 | 1 | 0.018411968 |
| 15 | 1 | 0.01726122 |
| 14 | 1 | 0.016110472 |
| 13 | 1 | 0.014959724 |
| 12 | 1 | 0.013808976 |
| 11 | 1 | 0.012658228 |
| 10 | 1 | 0.01150748 |
| 9 | 1 | 0.010356732 |
| 8 | 1 | 0.009205984 |

### OPEN WATER MONTHLY VALUES

| rank | Fraction Volume | Fraction Time |
|---|---|---|
| 7 | 1 | 0.008055236 |
| 6 | 1 | 0.006904488 |
| 5 | 1 | 0.00575374 |
| 4 | 1 | 0.004602992 |
| 3 | 1 | 0.003452244 |
| 2 | 1 | 0.002301496 |
| 1 | 1 | 0.001150748 |
|  | 1 | 0 |

appendix h

# Equations for the Water Clarity Criteria Biological Reference Curves

A biological reference curve of acceptable violation rates is generated using a cumulative frequency distribution (CFD) of violation rates for "healthy" designated uses. The violation rates are sorted in ascending order, ranked in descending order, and graphed on a quantile plot:

- Violation rates are plotted on the x-axis, with plotting position on the y axis.
- Plotting position represents the probability, i/n, of being less than or equal to a given violation rate, or x, and is plotted on the y-axis as a function of rank, or "i", and sample size, or "n".
- The x-axis is labeled "space" because the violation rate represents the fraction of volume that is in violation.
- The y-axis is labeled as "time" because "probability" represents the probable amount of time that a given violation rate will be observed.
- The Chesapeake Bay Program currently uses the Wiebull plotting position to plot the cumulative distribution function. The Wiebull equation for calculating probability, y, for each violation rate with rank "i" is: $y = i/(n+1)$; $i$ = rank.

In order to generate a graph of the CFD:

- $X_1$ , $x_2$, $x_3$,…$x_n$ = violation rates provided herein, sorted in ascending order, with rank (i) assigned in descending order.
- $y_i = i/(n+1)$.
- After plotting the data's violation rates and probabilities, two additional points should be added to the distribution in order to complete the CFD curve:
  Insert $(x_0, y_0) = (0,1)$ before the first data point; and
  Insert $(x_{n+1}, y_{n+1}) = (1,0)$ after the last data point.

## TIDAL FRESH/OLIGOHALINE

| rank | volume | time |
|---|---|---|
| | 0 | 1 |
| 406 | 0 | 0.997542998 |
| 405 | 0 | 0.995085995 |
| 404 | 0 | 0.992628993 |
| 403 | 0 | 0.99017199 |
| 402 | 0 | 0.987714988 |
| 401 | 0 | 0.985257985 |
| 400 | 0 | 0.982800983 |
| 399 | 0 | 0.98034398 |
| 398 | 0 | 0.977886978 |
| 397 | 0 | 0.975429975 |
| 396 | 0 | 0.972972973 |
| 395 | 0 | 0.970515971 |
| 394 | 0 | 0.968058968 |
| 393 | 0 | 0.965601966 |
| 392 | 0 | 0.963144963 |
| 391 | 0 | 0.960687961 |
| 390 | 0 | 0.958230958 |
| 389 | 0 | 0.955773956 |
| 388 | 0 | 0.953316953 |
| 387 | 0 | 0.950859951 |
| 386 | 0 | 0.948402948 |
| 385 | 0 | 0.945945946 |
| 384 | 0 | 0.943488943 |
| 383 | 0 | 0.941031941 |
| 382 | 0 | 0.938574939 |
| 381 | 0 | 0.936117936 |
| 380 | 0 | 0.933660934 |
| 379 | 0 | 0.931203931 |
| 378 | 0 | 0.928746929 |
| 377 | 0 | 0.926289926 |
| 376 | 0 | 0.923832924 |
| 375 | 0 | 0.921375921 |
| 374 | 0 | 0.918918919 |
| 373 | 0 | 0.916461916 |
| 372 | 0 | 0.914004914 |
| 371 | 0 | 0.911547912 |
| 370 | 0 | 0.909090909 |
| 369 | 0 | 0.906633907 |
| 368 | 0 | 0.904176904 |
| 367 | 0 | 0.901719902 |
| 366 | 0 | 0.899262899 |
| 365 | 0 | 0.896805897 |
| 364 | 0 | 0.894348894 |
| 363 | 0 | 0.891891892 |
| 362 | 0 | 0.889434889 |
| 361 | 0 | 0.886977887 |
| 360 | 0 | 0.884520885 |
| 359 | 0 | 0.882063882 |

| rank | volume | time |
|---|---|---|
| 358 | 0 | 0.87960688 |
| 357 | 0 | 0.877149877 |
| 356 | 0 | 0.874692875 |
| 355 | 0 | 0.872235872 |
| 354 | 0 | 0.86977887 |
| 353 | 0 | 0.867321867 |
| 352 | 0 | 0.864864865 |
| 351 | 0 | 0.862407862 |
| 350 | 0 | 0.85995086 |
| 349 | 0 | 0.857493857 |
| 348 | 0 | 0.855036855 |
| 347 | 0 | 0.852579853 |
| 346 | 0 | 0.85012285 |
| 345 | 0 | 0.847665848 |
| 344 | 0 | 0.845208845 |
| 343 | 0 | 0.842751843 |
| 342 | 0 | 0.84029484 |
| 341 | 0 | 0.837837838 |
| 340 | 0 | 0.835380835 |
| 339 | 0 | 0.832923833 |
| 338 | 0 | 0.83046683 |
| 337 | 0 | 0.828009828 |
| 336 | 0 | 0.825552826 |
| 335 | 0 | 0.823095823 |
| 334 | 0 | 0.820638821 |
| 333 | 0 | 0.818181818 |
| 332 | 0 | 0.815724816 |
| 331 | 0 | 0.813267813 |
| 330 | 0 | 0.810810811 |
| 329 | 0 | 0.808353808 |
| 328 | 0 | 0.805896806 |
| 327 | 0 | 0.803439803 |
| 326 | 0 | 0.800982801 |
| 325 | 0 | 0.798525799 |
| 324 | 0 | 0.796068796 |
| 323 | 0 | 0.793611794 |
| 322 | 0 | 0.791154791 |
| 321 | 0 | 0.788697789 |
| 320 | 0 | 0.786240786 |
| 319 | 0 | 0.783783784 |
| 318 | 0 | 0.781326781 |
| 317 | 0 | 0.778869779 |
| 316 | 0 | 0.776412776 |
| 315 | 0 | 0.773955774 |
| 314 | 0 | 0.771498771 |
| 313 | 0 | 0.769041769 |
| 312 | 0 | 0.766584767 |
| 311 | 0 | 0.764127764 |
| 310 | 0 | 0.761670762 |
| 309 | 0 | 0.759213759 |
| 308 | 0 | 0.756756757 |

### TIDAL FRESH/OLIGOHALINE

| rank | volume | time |
|---|---|---|
| 307 | 0 | 0.754299754 |
| 306 | 0 | 0.751842752 |
| 305 | 0 | 0.749385749 |
| 304 | 0 | 0.746928747 |
| 303 | 0 | 0.744471744 |
| 302 | 0 | 0.742014742 |
| 301 | 0 | 0.73955774 |
| 300 | 0 | 0.737100737 |
| 299 | 0 | 0.734643735 |
| 298 | 0 | 0.732186732 |
| 297 | 0 | 0.72972973 |
| 296 | 0 | 0.727272727 |
| 295 | 0 | 0.724815725 |
| 294 | 0 | 0.722358722 |
| 293 | 0 | 0.71990172 |
| 292 | 0 | 0.717444717 |
| 291 | 0 | 0.714987715 |
| 290 | 0 | 0.712530713 |
| 289 | 0 | 0.71007371 |
| 288 | 0 | 0.707616708 |
| 287 | 0 | 0.705159705 |
| 286 | 0 | 0.702702703 |
| 285 | 0 | 0.7002457 |
| 284 | 0 | 0.697788698 |
| 283 | 0 | 0.695331695 |
| 282 | 0 | 0.692874693 |
| 281 | 0 | 0.69041769 |
| 280 | 0 | 0.687960688 |
| 279 | 0 | 0.685503686 |
| 278 | 0 | 0.683046683 |
| 277 | 0 | 0.680589681 |
| 276 | 0 | 0.678132678 |
| 275 | 0 | 0.675675676 |
| 274 | 0 | 0.673218673 |
| 273 | 0 | 0.670761671 |
| 272 | 0 | 0.668304668 |
| 271 | 0 | 0.665847666 |
| 270 | 0 | 0.663390663 |
| 269 | 0 | 0.660933661 |
| 268 | 0 | 0.658476658 |
| 267 | 0 | 0.656019656 |
| 266 | 0 | 0.653562654 |
| 265 | 0 | 0.651105651 |
| 264 | 0 | 0.648648649 |
| 263 | 0 | 0.646191646 |
| 262 | 0 | 0.643734644 |
| 261 | 0 | 0.641277641 |
| 260 | 0 | 0.638820639 |
| 259 | 0 | 0.636363636 |
| 258 | 0 | 0.633906634 |
| 257 | 0 | 0.631449631 |

| rank | volume | time |
|---|---|---|
| 256 | 0 | 0.628992629 |
| 255 | 0 | 0.626535627 |
| 254 | 0 | 0.624078624 |
| 253 | 0 | 0.621621622 |
| 252 | 0 | 0.619164619 |
| 251 | 0 | 0.616707617 |
| 250 | 0 | 0.614250614 |
| 249 | 0 | 0.611793612 |
| 248 | 0 | 0.609336609 |
| 247 | 0 | 0.606879607 |
| 246 | 0 | 0.604422604 |
| 245 | 0 | 0.601965602 |
| 244 | 0 | 0.5995086 |
| 243 | 0 | 0.597051597 |
| 242 | 0 | 0.594594595 |
| 241 | 0 | 0.592137592 |
| 240 | 0 | 0.58968059 |
| 239 | 0 | 0.587223587 |
| 238 | 0 | 0.584766585 |
| 237 | 0 | 0.582309582 |
| 236 | 0 | 0.57985258 |
| 235 | 0 | 0.577395577 |
| 234 | 0 | 0.574938575 |
| 233 | 0 | 0.572481572 |
| 232 | 0 | 0.57002457 |
| 231 | 0 | 0.567567568 |
| 230 | 0 | 0.565110565 |
| 229 | 0 | 0.562653563 |
| 228 | 0 | 0.56019656 |
| 227 | 0 | 0.557739558 |
| 226 | 0 | 0.555282555 |
| 225 | 0 | 0.552825553 |
| 224 | 0 | 0.55036855 |
| 223 | 0 | 0.547911548 |
| 222 | 0 | 0.545454545 |
| 221 | 0 | 0.542997543 |
| 220 | 0 | 0.540540541 |
| 219 | 0 | 0.538083538 |
| 218 | 0 | 0.535626536 |
| 217 | 0 | 0.533169533 |
| 216 | 0 | 0.530712531 |
| 215 | 0 | 0.528255528 |
| 214 | 0 | 0.525798526 |
| 213 | 0 | 0.523341523 |
| 212 | 0 | 0.520884521 |
| 211 | 0 | 0.518427518 |
| 210 | 0 | 0.515970516 |
| 209 | 0 | 0.513513514 |
| 208 | 0 | 0.511056511 |
| 207 | 0 | 0.508599509 |
| 206 | 0 | 0.506142506 |

## TIDAL FRESH/OLIGOHALINE

| rank | volume | time |
|---|---|---|
| 205 | 0 | 0.503685504 |
| 204 | 0 | 0.501228501 |
| 203 | 0 | 0.498771499 |
| 202 | 0 | 0.496314496 |
| 201 | 0 | 0.493857494 |
| 200 | 0 | 0.491400491 |
| 199 | 0 | 0.488943489 |
| 198 | 0 | 0.486486486 |
| 197 | 0 | 0.484029484 |
| 196 | 0 | 0.481572482 |
| 195 | 0 | 0.479115479 |
| 194 | 0 | 0.476658477 |
| 193 | 0 | 0.474201474 |
| 192 | 0 | 0.471744472 |
| 191 | 0 | 0.469287469 |
| 190 | 0 | 0.466830467 |
| 189 | 0 | 0.464373464 |
| 188 | 0 | 0.461916462 |
| 187 | 0 | 0.459459459 |
| 186 | 0 | 0.457002457 |
| 185 | 0 | 0.454545455 |
| 184 | 0 | 0.452088452 |
| 183 | 0 | 0.44963145 |
| 182 | 0 | 0.447174447 |
| 181 | 0 | 0.444717445 |
| 180 | 0 | 0.442260442 |
| 179 | 0 | 0.43980344 |
| 178 | 0 | 0.437346437 |
| 177 | 0 | 0.434889435 |
| 176 | 0 | 0.432432432 |
| 175 | 0 | 0.42997543 |
| 174 | 0 | 0.427518428 |
| 173 | 0 | 0.425061425 |
| 172 | 0 | 0.422604423 |
| 171 | 0 | 0.42014742 |
| 170 | 0 | 0.417690418 |
| 169 | 0 | 0.415233415 |
| 168 | 0 | 0.412776413 |
| 167 | 0 | 0.41031941 |
| 166 | 0 | 0.407862408 |
| 165 | 0 | 0.405405405 |
| 164 | 0 | 0.402948403 |
| 163 | 0 | 0.4004914 |
| 162 | 0 | 0.398034398 |
| 161 | 0 | 0.395577396 |
| 160 | 0 | 0.393120393 |
| 159 | 0 | 0.390663391 |
| 158 | 0 | 0.388206388 |
| 157 | 0 | 0.385749386 |
| 156 | 0 | 0.383292383 |
| 155 | 0 | 0.380835381 |

| rank | volume | time |
|---|---|---|
| 154 | 0.0054 | 0.378378378 |
| 153 | 0.0108 | 0.375921376 |
| 152 | 0.0108 | 0.373464373 |
| 151 | 0.0108 | 0.371007371 |
| 150 | 0.0108 | 0.368550369 |
| 149 | 0.0108 | 0.366093366 |
| 148 | 0.0196 | 0.363636364 |
| 147 | 0.0215 | 0.361179361 |
| 146 | 0.0215 | 0.358722359 |
| 145 | 0.0215 | 0.356265356 |
| 144 | 0.0215 | 0.353808354 |
| 143 | 0.0215 | 0.351351351 |
| 142 | 0.0261 | 0.348894349 |
| 141 | 0.0269 | 0.346437346 |
| 140 | 0.0269 | 0.343980344 |
| 139 | 0.0278 | 0.341523342 |
| 138 | 0.0278 | 0.339066339 |
| 137 | 0.0278 | 0.336609337 |
| 136 | 0.0323 | 0.334152334 |
| 135 | 0.0323 | 0.331695332 |
| 134 | 0.0455 | 0.329238329 |
| 133 | 0.0556 | 0.326781327 |
| 132 | 0.0719 | 0.324324324 |
| 131 | 0.0784 | 0.321867322 |
| 130 | 0.1111 | 0.319410319 |
| 129 | 0.1176 | 0.316953317 |
| 128 | 0.1237 | 0.314496314 |
| 127 | 0.1307 | 0.312039312 |
| 126 | 0.1307 | 0.30958231 |
| 125 | 0.1389 | 0.307125307 |
| 124 | 0.1389 | 0.304668305 |
| 123 | 0.1389 | 0.302211302 |
| 122 | 0.1389 | 0.2997543 |
| 121 | 0.1438 | 0.297297297 |
| 120 | 0.1505 | 0.294840295 |
| 119 | 0.1667 | 0.292383292 |
| 118 | 0.1667 | 0.28992629 |
| 117 | 0.1944 | 0.287469287 |
| 116 | 0.1989 | 0.285012285 |
| 115 | 0.2151 | 0.282555283 |
| 114 | 0.2222 | 0.28009828 |
| 113 | 0.25 | 0.277641278 |
| 112 | 0.2742 | 0.275184275 |
| 111 | 0.2778 | 0.272727273 |
| 110 | 0.3116 | 0.27027027 |
| 109 | 0.3203 | 0.267813268 |
| 108 | 0.3659 | 0.265356265 |
| 107 | 0.3889 | 0.262899263 |
| 106 | 0.3889 | 0.26044226 |
| 105 | 0.4167 | 0.257985258 |
| 104 | 0.4167 | 0.255528256 |

## TIDAL FRESH/OLIGOHALINE

| rank | volume | time |
|---|---|---|
| 103 | 0.4444 | 0.253071253 |
| 102 | 0.4444 | 0.250614251 |
| 101 | 0.5538 | 0.248157248 |
| 100 | 0.5581 | 0.245700246 |
| 99 | 0.5752 | 0.243243243 |
| 98 | 0.5948 | 0.240786241 |
| 97 | 0.6136 | 0.238329238 |
| 96 | 0.6136 | 0.235872236 |
| 95 | 0.6202 | 0.233415233 |
| 94 | 0.6237 | 0.230958231 |
| 93 | 0.6434 | 0.228501229 |
| 92 | 0.6434 | 0.226044226 |
| 91 | 0.6434 | 0.223587224 |
| 90 | 0.6434 | 0.221130221 |
| 89 | 0.6899 | 0.218673219 |
| 88 | 0.7209 | 0.216216216 |
| 87 | 0.7209 | 0.213759214 |
| 86 | 0.7364 | 0.211302211 |
| 85 | 0.7519 | 0.208845209 |
| 84 | 0.7597 | 0.206388206 |
| 83 | 0.7597 | 0.203931204 |
| 82 | 0.7674 | 0.201474201 |
| 81 | 0.7727 | 0.199017199 |
| 80 | 0.7796 | 0.196560197 |
| 79 | 0.7974 | 0.194103194 |
| 78 | 0.8062 | 0.191646192 |
| 77 | 0.8188 | 0.189189189 |
| 76 | 0.8225 | 0.186732187 |
| 75 | 0.8225 | 0.184275184 |
| 74 | 0.8333 | 0.181818182 |
| 73 | 0.837 | 0.179361179 |
| 72 | 0.8611 | 0.176904177 |
| 71 | 0.8864 | 0.174447174 |
| 70 | 0.8864 | 0.171990172 |
| 69 | 0.8889 | 0.16953317 |
| 68 | 0.8992 | 0.167076167 |
| 67 | 0.8992 | 0.164619165 |
| 66 | 0.8992 | 0.162162162 |
| 65 | 0.9058 | 0.15970516 |
| 64 | 0.938 | 0.157248157 |
| 63 | 0.9457 | 0.154791155 |
| 62 | 0.9477 | 0.152334152 |
| 61 | 0.9545 | 0.14987715 |
| 60 | 0.9545 | 0.147420147 |
| 59 | 0.9612 | 0.144963145 |
| 58 | 0.9674 | 0.142506143 |
| 57 | 0.9722 | 0.14004914 |
| 56 | 0.9739 | 0.137592138 |
| 55 | 0.9767 | 0.135135135 |
| 54 | 0.9767 | 0.132678133 |
| 53 | 0.9773 | 0.13022113 |

| rank | volume | time |
|---|---|---|
| 52 | 0.9804 | 0.127764128 |
| 51 | 0.9804 | 0.125307125 |
| 50 | 0.9804 | 0.122850123 |
| 49 | 0.9935 | 0.12039312 |
| 48 | 0.9935 | 0.117936118 |
| 47 | 1 | 0.115479115 |
| 46 | 1 | 0.113022113 |
| 45 | 1 | 0.110565111 |
| 44 | 1 | 0.108108108 |
| 43 | 1 | 0.105651106 |
| 42 | 1 | 0.103194103 |
| 41 | 1 | 0.100737101 |
| 40 | 1 | 0.098280098 |
| 39 | 1 | 0.095823096 |
| 38 | 1 | 0.093366093 |
| 37 | 1 | 0.090909091 |
| 36 | 1 | 0.088452088 |
| 35 | 1 | 0.085995086 |
| 34 | 1 | 0.083538084 |
| 33 | 1 | 0.081081081 |
| 32 | 1 | 0.078624079 |
| 31 | 1 | 0.076167076 |
| 30 | 1 | 0.073710074 |
| 29 | 1 | 0.071253071 |
| 28 | 1 | 0.068796069 |
| 27 | 1 | 0.066339066 |
| 26 | 1 | 0.063882064 |
| 25 | 1 | 0.061425061 |
| 24 | 1 | 0.058968059 |
| 23 | 1 | 0.056511057 |
| 22 | 1 | 0.054054054 |
| 21 | 1 | 0.051597052 |
| 20 | 1 | 0.049140049 |
| 19 | 1 | 0.046683047 |
| 18 | 1 | 0.044226044 |
| 17 | 1 | 0.041769042 |
| 16 | 1 | 0.039312039 |
| 15 | 1 | 0.036855037 |
| 14 | 1 | 0.034398034 |
| 13 | 1 | 0.031941032 |
| 12 | 1 | 0.029484029 |
| 11 | 1 | 0.027027027 |
| 10 | 1 | 0.024570025 |
| 9 | 1 | 0.022113022 |
| 8 | 1 | 0.01965602 |
| 7 | 1 | 0.017199017 |
| 6 | 1 | 0.014742015 |
| 5 | 1 | 0.012285012 |
| 4 | 1 | 0.00982801 |
| 3 | 1 | 0.007371007 |
| 2 | 1 | 0.004914005 |

## TIDAL FRESH/OLIGOHALINE

| rank | volume | time |
|---|---|---|
| 1 | 1 | 0.002457002 |
| | 1 | 0 |

## MESOHALINE/POLYHALINE

| rank | volume | time |
|---|---|---|
| | 0 | 1 |
| 390 | 0 | 0.997442455 |
| 389 | 0 | 0.99488491 |
| 388 | 0 | 0.992327366 |
| 387 | 0 | 0.989769821 |
| 386 | 0 | 0.987212276 |
| 385 | 0 | 0.984654731 |
| 384 | 0 | 0.982097187 |
| 383 | 0 | 0.979539642 |
| 382 | 0 | 0.976982097 |
| 381 | 0 | 0.974424552 |
| 380 | 0 | 0.971867008 |
| 379 | 0 | 0.969309463 |
| 378 | 0 | 0.966751918 |
| 377 | 0 | 0.964194373 |
| 376 | 0 | 0.961636829 |
| 375 | 0 | 0.959079284 |
| 374 | 0 | 0.956521739 |
| 373 | 0 | 0.953964194 |
| 372 | 0 | 0.95140665 |
| 371 | 0 | 0.948849105 |
| 370 | 0 | 0.94629156 |
| 369 | 0 | 0.943734015 |
| 368 | 0 | 0.941176471 |
| 367 | 0 | 0.938618926 |
| 366 | 0 | 0.936061381 |
| 365 | 0 | 0.933503836 |
| 364 | 0 | 0.930946292 |
| 363 | 0 | 0.928388747 |
| 362 | 0 | 0.925831202 |
| 361 | 0 | 0.923273657 |
| 360 | 0 | 0.920716113 |
| 359 | 0 | 0.918158568 |
| 358 | 0 | 0.915601023 |
| 357 | 0 | 0.913043478 |
| 356 | 0 | 0.910485934 |
| 355 | 0 | 0.907928389 |
| 354 | 0 | 0.905370844 |
| 353 | 0 | 0.902813299 |
| 352 | 0 | 0.900255754 |
| 351 | 0 | 0.89769821 |
| 350 | 0 | 0.895140665 |
| 349 | 0 | 0.89258312 |
| 348 | 0 | 0.890025575 |

| rank | volume | time |
|---|---|---|
| 347 | 0 | 0.887468031 |
| 346 | 0 | 0.884910486 |
| 345 | 0 | 0.882352941 |
| 344 | 0 | 0.879795396 |
| 343 | 0 | 0.877237852 |
| 342 | 0 | 0.874680307 |
| 341 | 0 | 0.872122762 |
| 340 | 0 | 0.869565217 |
| 339 | 0 | 0.867007673 |
| 338 | 0 | 0.864450128 |
| 337 | 0 | 0.861892583 |
| 336 | 0 | 0.859335038 |
| 335 | 0 | 0.856777494 |
| 334 | 0 | 0.854219949 |
| 333 | 0 | 0.851662404 |
| 332 | 0 | 0.849104859 |
| 331 | 0 | 0.846547315 |
| 330 | 0 | 0.84398977 |
| 329 | 0 | 0.841432225 |
| 328 | 0 | 0.83887468 |
| 327 | 0 | 0.836317136 |
| 326 | 0 | 0.833759591 |
| 325 | 0 | 0.831202046 |
| 324 | 0 | 0.828644501 |
| 323 | 0 | 0.826086957 |
| 322 | 0 | 0.823529412 |
| 321 | 0 | 0.820971867 |
| 320 | 0 | 0.818414322 |
| 319 | 0 | 0.815856777 |
| 318 | 0 | 0.813299233 |
| 317 | 0 | 0.810741688 |
| 316 | 0 | 0.808184143 |
| 315 | 0 | 0.805626598 |
| 314 | 0 | 0.803069054 |
| 313 | 0 | 0.800511509 |
| 312 | 0 | 0.797953964 |
| 311 | 0 | 0.795396419 |
| 310 | 0 | 0.792838875 |
| 309 | 0 | 0.79028133 |
| 308 | 0 | 0.787723785 |
| 307 | 0 | 0.78516624 |
| 306 | 0 | 0.782608696 |
| 305 | 0 | 0.780051151 |
| 304 | 0 | 0.777493606 |
| 303 | 0 | 0.774936061 |
| 302 | 0 | 0.772378517 |
| 301 | 0 | 0.769820972 |
| 300 | 0 | 0.767263427 |
| 299 | 0 | 0.764705882 |
| 298 | 0 | 0.762148338 |
| 297 | 0 | 0.759590793 |

## MESOHALINE/POLYHALINE

| rank | volume | time |
|---|---|---|
| 296 | 0 | 0.757033248 |
| 295 | 0 | 0.754475703 |
| 294 | 0 | 0.751918159 |
| 293 | 0 | 0.749360614 |
| 292 | 0 | 0.746803069 |
| 291 | 0 | 0.744245524 |
| 290 | 0 | 0.74168798 |
| 289 | 0 | 0.739130435 |
| 288 | 0 | 0.73657289 |
| 287 | 0 | 0.734015345 |
| 286 | 0 | 0.731457801 |
| 285 | 0 | 0.728900256 |
| 284 | 0 | 0.726342711 |
| 283 | 0 | 0.723785166 |
| 282 | 0 | 0.721227621 |
| 281 | 0 | 0.718670077 |
| 280 | 0 | 0.716112532 |
| 279 | 0 | 0.713554987 |
| 278 | 0 | 0.710997442 |
| 277 | 0 | 0.708439898 |
| 276 | 0 | 0.705882353 |
| 275 | 0 | 0.703324808 |
| 274 | 0 | 0.700767263 |
| 273 | 0 | 0.698209719 |
| 272 | 0 | 0.695652174 |
| 271 | 0 | 0.693094629 |
| 270 | 0 | 0.690537084 |
| 269 | 0 | 0.68797954 |
| 268 | 0 | 0.685421995 |
| 267 | 0 | 0.68286445 |
| 266 | 0 | 0.680306905 |
| 265 | 0 | 0.677749361 |
| 264 | 0 | 0.675191816 |
| 263 | 0 | 0.672634271 |
| 262 | 0 | 0.670076726 |
| 261 | 0 | 0.667519182 |
| 260 | 0 | 0.664961637 |
| 259 | 0 | 0.662404092 |
| 258 | 0 | 0.659846547 |
| 257 | 0 | 0.657289003 |
| 256 | 0 | 0.654731458 |
| 255 | 0 | 0.652173913 |
| 254 | 0 | 0.649616368 |
| 253 | 0 | 0.647058824 |
| 252 | 0 | 0.644501279 |
| 251 | 0 | 0.641943734 |
| 250 | 0 | 0.639386189 |
| 249 | 0 | 0.636828645 |
| 248 | 0 | 0.6342711 |
| 247 | 0 | 0.631713555 |
| 246 | 0 | 0.62915601 |

| rank | volume | time |
|---|---|---|
| 245 | 0 | 0.626598465 |
| 244 | 0 | 0.624040921 |
| 243 | 0 | 0.621483376 |
| 242 | 0 | 0.618925831 |
| 241 | 0 | 0.616368286 |
| 240 | 0 | 0.613810742 |
| 239 | 0 | 0.611253197 |
| 238 | 0 | 0.608695652 |
| 237 | 0 | 0.606138107 |
| 236 | 0 | 0.603580563 |
| 235 | 0 | 0.601023018 |
| 234 | 0 | 0.598465473 |
| 233 | 0 | 0.595907928 |
| 232 | 0 | 0.593350384 |
| 231 | 0 | 0.590792839 |
| 230 | 0 | 0.588235294 |
| 229 | 0 | 0.585677749 |
| 228 | 0 | 0.583120205 |
| 227 | 0 | 0.58056266 |
| 226 | 0 | 0.578005115 |
| 225 | 0 | 0.57544757 |
| 224 | 0 | 0.572890026 |
| 223 | 0 | 0.570332481 |
| 222 | 0 | 0.567774936 |
| 221 | 0 | 0.565217391 |
| 220 | 0 | 0.562659847 |
| 219 | 0 | 0.560102302 |
| 218 | 0 | 0.557544757 |
| 217 | 0 | 0.554987212 |
| 216 | 0 | 0.552429668 |
| 215 | 0 | 0.549872123 |
| 214 | 0.0037 | 0.547314578 |
| 213 | 0.0037 | 0.544757033 |
| 212 | 0.0037 | 0.542199488 |
| 211 | 0.0054 | 0.539641944 |
| 210 | 0.0054 | 0.537084399 |
| 209 | 0.0073 | 0.534526854 |
| 208 | 0.0094 | 0.531969309 |
| 207 | 0.011 | 0.529411765 |
| 206 | 0.0147 | 0.52685422 |
| 205 | 0.0147 | 0.524296675 |
| 204 | 0.0154 | 0.52173913 |
| 203 | 0.0154 | 0.519181586 |
| 202 | 0.0162 | 0.516624041 |
| 201 | 0.0162 | 0.514066496 |
| 200 | 0.0162 | 0.511508951 |
| 199 | 0.0162 | 0.508951407 |
| 198 | 0.0162 | 0.506393862 |
| 197 | 0.0162 | 0.503836317 |
| 196 | 0.0162 | 0.501278772 |
| 195 | 0.0204 | 0.498721228 |

## MESOHALINE/POLYHALINE

| rank | volume | time |
|---|---|---|
| 194 | 0.0204 | 0.496163683 |
| 193 | 0.022 | 0.493606138 |
| 192 | 0.022 | 0.491048593 |
| 191 | 0.0235 | 0.488491049 |
| 190 | 0.0256 | 0.485933504 |
| 189 | 0.0256 | 0.483375959 |
| 188 | 0.027 | 0.480818414 |
| 187 | 0.027 | 0.47826087 |
| 186 | 0.027 | 0.475703325 |
| 185 | 0.0282 | 0.47314578 |
| 184 | 0.0378 | 0.470588235 |
| 183 | 0.0432 | 0.468030691 |
| 182 | 0.0476 | 0.465473146 |
| 181 | 0.0476 | 0.462915601 |
| 180 | 0.0513 | 0.460358056 |
| 179 | 0.0513 | 0.457800512 |
| 178 | 0.0513 | 0.455242967 |
| 177 | 0.0612 | 0.452685422 |
| 176 | 0.0615 | 0.450127877 |
| 175 | 0.0615 | 0.447570332 |
| 174 | 0.0615 | 0.445012788 |
| 173 | 0.0615 | 0.442455243 |
| 172 | 0.0615 | 0.439897698 |
| 171 | 0.0615 | 0.437340153 |
| 170 | 0.0623 | 0.434782609 |
| 169 | 0.0659 | 0.432225064 |
| 168 | 0.0659 | 0.429667519 |
| 167 | 0.0696 | 0.427109974 |
| 166 | 0.0703 | 0.42455243 |
| 165 | 0.0728 | 0.421994885 |
| 164 | 0.0769 | 0.41943734 |
| 163 | 0.0806 | 0.416879795 |
| 162 | 0.0811 | 0.414322251 |
| 161 | 0.0939 | 0.411764706 |
| 160 | 0.102 | 0.409207161 |
| 159 | 0.102 | 0.406649616 |
| 158 | 0.1077 | 0.404092072 |
| 157 | 0.1077 | 0.401534527 |
| 156 | 0.1081 | 0.398976982 |
| 155 | 0.1127 | 0.396419437 |
| 154 | 0.1136 | 0.393861893 |
| 153 | 0.1209 | 0.391304348 |
| 152 | 0.1221 | 0.388746803 |
| 151 | 0.1224 | 0.386189258 |
| 150 | 0.1224 | 0.383631714 |
| 149 | 0.1224 | 0.381074169 |
| 148 | 0.1224 | 0.378516624 |
| 147 | 0.1224 | 0.375959079 |
| 146 | 0.1224 | 0.373401535 |
| 145 | 0.1224 | 0.37084399 |
| 144 | 0.1224 | 0.368286445 |

| rank | volume | time |
|---|---|---|
| 143 | 0.1224 | 0.3657289 |
| 142 | 0.1224 | 0.363171355 |
| 141 | 0.1224 | 0.360613811 |
| 140 | 0.1224 | 0.358056266 |
| 139 | 0.1231 | 0.355498721 |
| 138 | 0.1231 | 0.352941176 |
| 137 | 0.1231 | 0.350383632 |
| 136 | 0.1231 | 0.347826087 |
| 135 | 0.1282 | 0.345268542 |
| 134 | 0.1297 | 0.342710997 |
| 133 | 0.1319 | 0.340153453 |
| 132 | 0.1351 | 0.337595908 |
| 131 | 0.1385 | 0.335038363 |
| 130 | 0.1429 | 0.332480818 |
| 129 | 0.1502 | 0.329923274 |
| 128 | 0.1538 | 0.327365729 |
| 127 | 0.1538 | 0.324808184 |
| 126 | 0.1575 | 0.322250639 |
| 125 | 0.1612 | 0.319693095 |
| 124 | 0.1612 | 0.31713555 |
| 123 | 0.1633 | 0.314578005 |
| 122 | 0.1633 | 0.31202046 |
| 121 | 0.169 | 0.309462916 |
| 120 | 0.1795 | 0.306905371 |
| 119 | 0.1837 | 0.304347826 |
| 118 | 0.1868 | 0.301790281 |
| 117 | 0.1995 | 0.299232737 |
| 116 | 0.2 | 0.296675192 |
| 115 | 0.2041 | 0.294117647 |
| 114 | 0.2088 | 0.291560102 |
| 113 | 0.2108 | 0.289002558 |
| 112 | 0.2113 | 0.286445013 |
| 111 | 0.2254 | 0.283887468 |
| 110 | 0.2308 | 0.281329923 |
| 109 | 0.2308 | 0.278772379 |
| 108 | 0.2308 | 0.276214834 |
| 107 | 0.2308 | 0.273657289 |
| 106 | 0.2378 | 0.271099744 |
| 105 | 0.2394 | 0.268542199 |
| 104 | 0.2432 | 0.265984655 |
| 103 | 0.2449 | 0.26342711 |
| 102 | 0.2449 | 0.260869565 |
| 101 | 0.2486 | 0.25831202 |
| 100 | 0.2541 | 0.255754476 |
| 99 | 0.2564 | 0.253196931 |
| 98 | 0.2582 | 0.250639386 |
| 97 | 0.2653 | 0.248081841 |
| 96 | 0.2653 | 0.245524297 |
| 95 | 0.2811 | 0.242966752 |
| 94 | 0.2857 | 0.240409207 |
| 93 | 0.2857 | 0.237851662 |

## MESOHALINE/POLYHALINE

| rank | volume | time |
|---|---|---|
| 92 | 0.2857 | 0.235294118 |
| 91 | 0.2973 | 0.232736573 |
| 90 | 0.3081 | 0.230179028 |
| 89 | 0.3187 | 0.227621483 |
| 88 | 0.3216 | 0.225063939 |
| 87 | 0.3239 | 0.222506394 |
| 86 | 0.3243 | 0.219948849 |
| 85 | 0.3265 | 0.217391304 |
| 84 | 0.3405 | 0.21483376 |
| 83 | 0.3451 | 0.212276215 |
| 82 | 0.3469 | 0.20971867 |
| 81 | 0.348 | 0.207161125 |
| 80 | 0.359 | 0.204603581 |
| 79 | 0.359 | 0.202046036 |
| 78 | 0.359 | 0.199488491 |
| 77 | 0.3592 | 0.196930946 |
| 76 | 0.3622 | 0.194373402 |
| 75 | 0.3692 | 0.191815857 |
| 74 | 0.3838 | 0.189258312 |
| 73 | 0.3846 | 0.186700767 |
| 72 | 0.3892 | 0.184143223 |
| 71 | 0.3919 | 0.181585678 |
| 70 | 0.392 | 0.179028133 |
| 69 | 0.4 | 0.176470588 |
| 68 | 0.4 | 0.173913043 |
| 67 | 0.4 | 0.171355499 |
| 66 | 0.4054 | 0.168797954 |
| 65 | 0.4202 | 0.166240409 |
| 64 | 0.4286 | 0.163682864 |
| 63 | 0.4324 | 0.16112532 |
| 62 | 0.439 | 0.158567775 |
| 61 | 0.4432 | 0.15601023 |
| 60 | 0.4615 | 0.153452685 |
| 59 | 0.4703 | 0.150895141 |
| 58 | 0.4769 | 0.148337596 |
| 57 | 0.4812 | 0.145780051 |
| 56 | 0.4872 | 0.143222506 |
| 55 | 0.4872 | 0.140664962 |
| 54 | 0.4872 | 0.138107417 |
| 53 | 0.5077 | 0.135549872 |
| 52 | 0.5077 | 0.132992327 |
| 51 | 0.5092 | 0.130434783 |
| 50 | 0.5094 | 0.127877238 |
| 49 | 0.5102 | 0.125319693 |
| 48 | 0.5128 | 0.122762148 |
| 47 | 0.5128 | 0.120204604 |
| 46 | 0.5231 | 0.117647059 |
| 45 | 0.5385 | 0.115089514 |
| 44 | 0.5495 | 0.112531969 |
| 43 | 0.5657 | 0.109974425 |
| 42 | 0.5692 | 0.10741688 |

| rank | volume | time |
|---|---|---|
| 41 | 0.5838 | 0.104859335 |
| 40 | 0.5897 | 0.10230179 |
| 39 | 0.6 | 0.099744246 |
| 38 | 0.6054 | 0.097186701 |
| 37 | 0.6154 | 0.094629156 |
| 36 | 0.6315 | 0.092071611 |
| 35 | 0.641 | 0.089514066 |
| 34 | 0.6462 | 0.086956522 |
| 33 | 0.6667 | 0.084398977 |
| 32 | 0.6714 | 0.081841432 |
| 31 | 0.6923 | 0.079283887 |
| 30 | 0.6923 | 0.076726343 |
| 29 | 0.6923 | 0.074168798 |
| 28 | 0.7077 | 0.071611253 |
| 27 | 0.7077 | 0.069053708 |
| 26 | 0.7297 | 0.066496164 |
| 25 | 0.7347 | 0.063938619 |
| 24 | 0.7538 | 0.061381074 |
| 23 | 0.7551 | 0.058823529 |
| 22 | 0.7568 | 0.056265985 |
| 21 | 0.7949 | 0.05370844 |
| 20 | 0.7959 | 0.051150895 |
| 19 | 0.8239 | 0.04859335 |
| 18 | 0.838 | 0.046035806 |
| 17 | 0.8498 | 0.043478261 |
| 16 | 0.8571 | 0.040920716 |
| 15 | 0.8571 | 0.038363171 |
| 14 | 0.8615 | 0.035805627 |
| 13 | 0.9121 | 0.033248082 |
| 12 | 0.9385 | 0.030690537 |
| 11 | 0.9388 | 0.028132992 |
| 10 | 1 | 0.025575448 |
| 9 | 1 | 0.023017903 |
| 8 | 1 | 0.020460358 |
| 7 | 1 | 0.017902813 |
| 6 | 1 | 0.015345269 |
| 5 | 1 | 0.012787724 |
| 4 | 1 | 0.010230179 |
| 3 | 1 | 0.007672634 |
| 2 | 1 | 0.00511509 |
| 1 | 1 | 0.002557545 |
|  | 1 | 0 |

appendix i

# Evaluation of Maryland and Virginia Chesapeake Bay Segment SAV Acreages from 2003 to 2005 for Prioritizing Shallow-water Monitoring by Segment

| MARYLAND | | | | | | | |
|---|---|---|---|---|---|---|---|
| Chesapeake Bay Program Segments/ Subsegments | 2003 Acres | 2004 Acres | 2005 Acres | 2003–2005 Single Best Year Acres | State-adopted SAV Restoration Acreage | Single Best Year as % of SAV Restoration Acreage | Status |
| CHSOH | 0 | 4 | 228 | 228 | 77 | 3 | Pass |
| BSHOH | 390 | 1,025 | 726 | 1,025 | 350 | 3 | Pass |
| BOHOH | 288 | 730 | 918 | 918 | 354 | 3 | Pass |
| CB2OH | 212 | 1,303 | 1,071 | 1,303 | 705 | 2 | Pass |
| PAXTF | 217 | 220 | 324 | 324 | 205 | 2 | Pass |
| SASOH | 371 | 1,272 | 1,476 | 1,476 | 1,168 | 1 | Pass |
| C&DOH | 0 | 8 | 9 | 9 | 7 | 1 | Pass |
| PAXOH | 106 | 106 | 125 | 125 | 115 | 1 | Pass |
| GUNOH | 489 | 2,392 | 1,733 | 2,392 | 2,432 | 1 | Fail |
| MATTF | 612 | 601 | 770 | 770 | 792 | 1 | Fail |
| ELKOH | 346 | 1,913 | 1,964 | 1,964 | 2,034 | 1 | Fail |
| PISTF | 212 | 507 | 757 | 757 | 789 | 1 | Fail |
| POTTF(MD) | 885 | 1,256 | 2,029 | 2,029 | 2,142 | 1 | Fail |
| NORTF | 46 | 84 | 78 | 84 | 89 | 1 | Fail |
| SEVMH | 222 | 388 | 426 | 426 | 455 | 1 | Fail |
| CB1TF | 7,574 | 10,110 | 9,193 | 10,110 | 12,903 | 1 | Fail |
| MIDOH | 391 | 671 | 454 | 671 | 879 | 1 | Fail |
| PATMH | 7 | 183 | 279 | 279 | 389 | 1 | Fail |

## MARYLAND *(continued)*

| Chesapeake Bay Program Segments/ Subsegments | 2003 Acres | 2004 Acres | 2005 Acres | 2003–2005 Single Best Year Acres | State-adopted SAV Restoration Acreage | Single Best Year as % of SAV Restoration Acreage | Status |
|---|---|---|---|---|---|---|---|
| POTOH(MD) | 1,384 | 1,408 | 1,888 | 1,888 | 2,802 | 1 | Fail |
| CB3MH | 23 | 909 | 567 | 909 | 1,370 | 1 | Fail |
| HNGMH | 2,844 | 3,433 | 4,376 | 4,376 | 7,761 | 1 | Fail |
| MAGMH | 169 | 300 | 308 | 308 | 579 | 1 | Fail |
| CHOMH1 | 2,972 | 3,774 | 2,293 | 3,774 | 8,184 | 0 | Fail |
| POTMH(MD) | 2,430 | 3,063 | 2,893 | 3,063 | 7,088 | 0 | Fail |
| BIGMH | 451 | 550 | 710 | 710 | 2,043 | 0 | Fail |
| LCHMH | 784 | 1,221 | 260 | 1,221 | 4,076 | 0 | Fail |
| EASMH | 1,639 | 1,040 | 768 | 1,639 | 6,209 | 0 | Fail |
| CHSMH | 117 | 731 | 462 | 731 | 2,928 | 0 | Fail |
| TANMH(MD) | 4,725 | 4,554 | 5,801 | 5,801 | 24,757 | 0 | Fail |
| CB5MH(MD) | 700 | 398 | 919 | 919 | 8,270 | 0 | Fail |
| WSTMH | 23 | 0 | 0 | 23 | 238 | 0 | Fail |
| SOUMH | 14 | 46 | 10 | 46 | 479 | 0 | Fail |
| MANMH | 235 | 291 | 410 | 410 | 4,353 | 0 | Fail |
| FSBMH | 15 | 17 | 7 | 17 | 197 | 0 | Fail |
| POCMH(MD) | 58 | 69 | 69 | 69 | 877 | 0 | Fail |
| PAXMH | 37 | 42 | 0 | 42 | 1,634 | 0 | Fail |
| CB4MH | 21 | 10 | 0 | 21 | 2,533 | 0 | Fail |
| CHOMH2 | 0 | 1 | 0 | 0 | 1,621 | 0 | Fail |
| CHOOH | 0 | 0 | 0 | 0 | 72 | 0 | Fail |
| NANMH | 0 | 0 | 0 | 0 | 3 | 0 | Fail |
| NANOH | 0 | 0 | 0 | 0 | 12 | 0 | Fail |
| RHDMH | 0 | 0 | 0 | 0 | 60 | 0 | Fail |
| WICMH | 0 | 0 | 0 | 0 | 3 | 0 | Fail |
| BACOH | 0 | 30 | 0 | 30 | - | N/A | No SAV |
| CHOTF | 0 | 0 | 0 | 0 | - | - | No SAV |
| CHSTF | 0 | 0 | 1 | 1 | - | - | No SAV |
| NANTF | 0 | 0 | 0 | 0 | - | - | No SAV |
| POCOH | 0 | 0 | 0 | 0 | - | - | No SAV |
| POCTF | 0 | 0 | 0 | 0 | - | - | No SAV |
| WBRTF | 0 | 0 | 0 | 0 | - | - | NO SAV |

## VIRGINIA

| Chesapeake Bay Program Segments/ Subsegments | 2003 Acres | 2004 Acres | 2005 Acres | 2003–2005 Single Best Year Acres | State-adopted SAV Restoration Acreage | Single Best Year as % of SAV Restoration Acreage | Status |
|---|---|---|---|---|---|---|---|
| MPNTF | 184 | 179 | 296 | 296 | 85 | 3 | Pass |
| PMKTF | 217 | 334 | 585 | 585 | 187 | 3 | Pass |
| POTOH(VA) | 1,950 | 2,326 | 2,627 | 2,627 | 1,503 | 2 | Pass |
| CHKOH | 425 | 432 | 697 | 697 | 535 | 1 | Pass |
| RPPTF | 0 | 24 | 81 | 81 | 66 | 1 | Pass |
| POTTF(VA) | 761 | 1,197 | 2,336 | 2,336 | 2,093 | 1 | Pass |
| CB8PH | 5 | 6 | 9 | 9 | 11 | 1 | Fail |
| CB7PH | 9,192 | 7,157 | 8,139 | 9,192 | 15,107 | 1 | Fail |
| JMSOH | 9 | 0 | 0 | 9 | 15 | 1 | Fail |
| CB6PH | 707 | 488 | 642 | 707 | 1,267 | 1 | Fail |
| MOBPH | 8,457 | 7,549 | 7,205 | 8,457 | 15,901 | 1 | Fail |
| JMSPH | 132 | 74 | 0 | 132 | 300 | 0 | Fail |
| POCMH(VA) | 1,608 | 1,094 | 1,716 | 1,716 | 4,066 | 0 | Fail |
| CRRMH | 43 | 224 | 292 | 292 | 768 | 0 | Fail |
| TANMH(VA) | 4,682 | 3,990 | 5,036 | 5,036 | 13,579 | 0 | Fail |
| CB5MH(VA) | * | 1,833 | 2,464 | 2,464 | 7,633 | 0 | Fail |
| YRKPH | 887 | 597 | 438 | 887 | 2,793 | 0 | Fail |
| LYNPH | 0 | 9 | 19 | 19 | 107 | 0 | Fail |
| PIAMH | 447 | 443 | 561 | 561 | 3,479 | 0 | Fail |
| RPPMH | 21 | 33 | 198 | 198 | 1,700 | 0 | Fail |
| POTMH(VA) | 55 | 339 | 444 | 444 | 4,250 | 0 | Fail |
| JMSTF | 75 | 12 | 53 | 75 | 1,200 | 0 | Fail |
| JMSMH | 2 | 2 | 0 | 2 | 200 | 0 | Fail |
| APPTF | 0 | 0 | 0 | 0 | 379 | 0 | Fail |
| YRKMH | 0 | 0 | 0 | 0 | 239 | 0 | Fail |
| EBEMH | 0 | 0 | 0 | 0 | - | - | No SAV |
| ELIMH | 0 | 0 | 0 | 0 | - | - | No SAV |
| ELIPH | 0 | 0 | 0 | 0 | - | - | No SAV |
| LAFMH | 0 | 0 | 0 | 0 | - | - | No SAV |
| MPNOH | 0 | 0 | 0 | 0 | - | - | No SAV |
| PMKOH | 0 | 0 | 0 | 0 | - | - | No SAV |
| RPPOH | 0 | 0 | 4 | 4 | - | - | No SAV |
| SBEMH | 0 | 0 | 0 | 0 | - | - | No SAV |
| WBEMH | 0 | 0 | 0 | 0 | - | - | No SAV |

## DELAWARE

| Chesapeake Bay Program Segments/ Subsegments | 2003 Acres | 2004 Acres | 2005 Acres | 2003–2005 Single Best Year Acres | State-adopted SAV Restoration Acreage | Single Best Year as % of SAV Restoration Acreage | Status |
|---|---|---|---|---|---|---|---|
| NANTF(DE) | | | | | | | |

## DISTRICT OF COLUMBIA

| Chesapeake Bay Program Segments/ Subsegments | 2003 Acres | 2004 Acres | 2005 Acres | 2003–2005 Single Best Year Acres | State-adopted SAV Restoration Acreage | Single Best Year as % of SAV Restoration Acreage | Status |
|---|---|---|---|---|---|---|---|
| POTTF (DC) | | | | | | | |
| ANATF (DC) | | | | | | | |

PASS (>100% of Goal)

FAIL (50%-<100% of Goal)

FAIL (<50% of Goal)

No SAV Goal

*Partial data available that year

appendix j

# Chesapeake Bay Estuarine Benthic Communities Assessment Protocol for Maryland and Virginia 305b/303d Integrated Reports

Maryland (Department of the Environment, Department of Natural Resources), Virginia (Department of Environmental Quality) and U.S. EPA (Region 3 Water Protection Division and Chesapeake Bay Program Office) reached agreement on the protocol to assess Chesapeake Bay benthic community health. This appendix documented the assessment protocol supporting the States evaluation of Chesapeake Bay benthic community data as part of their 305b/303d Integrated Reports. This assessment protocol builds directly on the more detailed assessment methods recommended by Llansó et al. 2005 (see Appendix K).

The overall decision protocol is shown in Figure J-1. Phase I consists of the evaluation of the sample size (*i.e.*, number of B-IBI scores) available from the waterbody segment during the five-year assessment window. If the sample size satisfies the requirements of the statistical method ($N \geq 10$), a formal assessment of status (i.e. impaired vs. supports aquatic life use) is determined utilizing the "percent degraded area" statistical methodology (Phase II). If the sample size requirement is not met an impairment assessment based solely on these analyses is not possible. Results for segments with insufficient sample size should still be examined for possible use in conjunction with other assessment data of the 305b/303d reporting process.

Phase II consists of the impairment assessment of aquatic life use attainment based on a comparison of Benthic Index of Biotic Integrity (B-IBI) scores and can only be performed when the number of B-IBI scores within a specified waterbody segment is sufficient to meet the sample size requirement of the approved statistical method ($N \geq 10$). Phase II can result in one of two possible outcomes: (1) the segment is not impaired for Aquatic Life use due to benthic community status (note that the segment may still be impaired for aquatic life use due to failure of other aquatic life use criteria), or (2) the segment fails to support aquatic life use due to benthic community status and is assessed as impaired. Best professional judgment can be

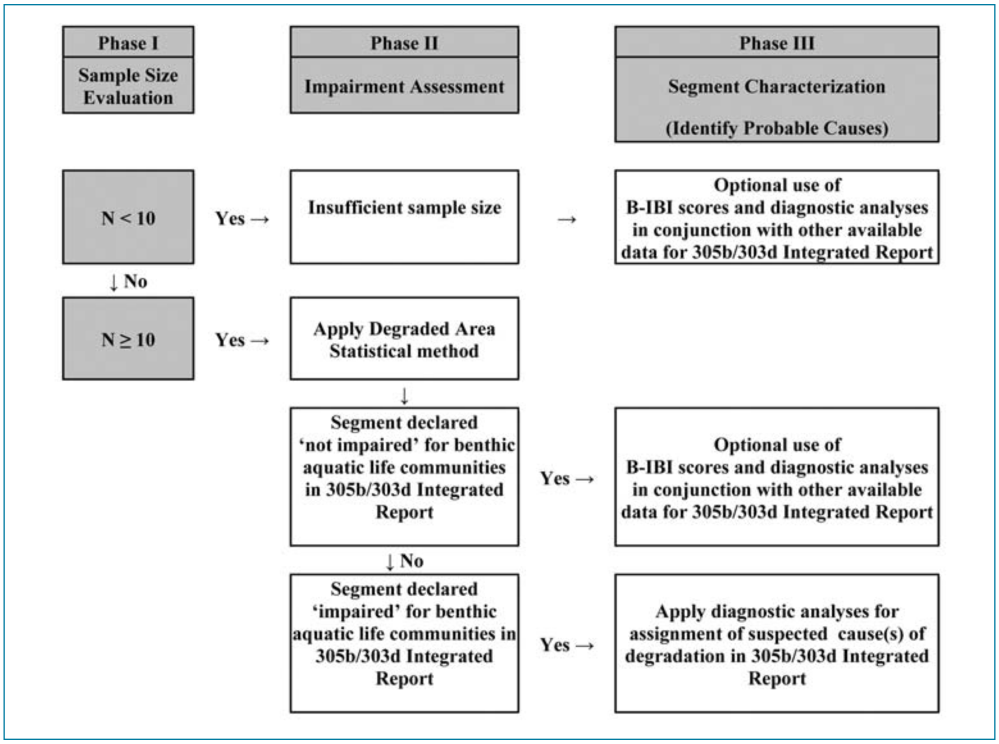


**Figure J-1.** Overall Chesapeake Bay benthic index of biotic integrity assessment decision protocol.

applied to override (reverse) the outcome of the formal statistical analysis results, but such reversals must be justified and documented.

Phase III consists of the identification of probable causes of benthic impairment of the waterbody segment based upon benthic stressor diagnostic analyses. It is a two-step procedure that involves (1) Site Classification, and (2) Segment Characterization.

1. **Site classification:** The first step is to assign probable cause of benthic degradation to each individual "degraded" benthic sample. For purposed of these diagnostic analyses, a sample is considered degraded if the B-IBI score is less than 2.7.

   **Site Classification—Step 1a:** The application of a formal statistical linear discriminant function calculates the 'inclusion probability' of each degraded site belonging to a 'contaminant caused' group or an 'other causes' group, based upon its B-IBI score and associated metrics. If a site is assigned to the 'Contaminant' Group with a probability $\geq 0.9$, this site is considered impacted by contaminated sediment and no further classification is required.

   **Site Classification—Step 1b:** If a site is classified as degraded due to 'other causes' (i.e., not contaminant-related), an evaluation of the relative abundance (and/or biomass) of the benthos is examined. Scores for both abundance and biomass are considered to be bipolar for the Chesapeake Bay Benthic IBI. For either metric; a high score of 5, indicating desirable conditions, falls in the mid-range of the abundance/biomass distributions, while a low score of 1, indicating undesirable conditions, can result either from insufficient abundance/biomass or excessive abundance/biomass. The scoring thresholds for these two metrics vary with habitat type (salinity regime and substrate type) as summarized in Figure J-2. In this process, a site is classified as degraded by "low dissolved oxygen" if the abundance (and/or biomass) metric scores a 1 due to insufficient abundance (and/or biomass). Alternatively, if the abundance (and/or biomass) metric scores a 1 because of excessive abundance (and/or biomass) the site is classified as degraded by "eutrophication".

2. **Segment classification:** The assignment of probable causes of benthic degradation for the overall segment is accomplished using a simple 25% rule. If the percent of total sites in a segment impacted by a single cause (i.e. sediment contaminants, low dissolved oxygen, or eutrophication) exceeds 25%, then that cause is assigned. If no causes exceed 25%, the cause is considered unknown. The cause(s) should be identified as a suspected (vs. verified) cause of benthic community degradation in the ADB database.

Table J-1 shows the possible conclusions from applying the above protocol. The States should carefully review the results from application of the protocol to ensure all findings and conclusions are rational and reasonable. Best profession judgment, common sense, and ancillary information about each segment should be utilized as necessary and available.

| Habitat | Metric | Lower Limit (Metric Score=1) | Upper Limit (Metric Score=1) |
|---|---|---|---|
| **Tidal Freshwater** | Abundance (# m-2) | <800 | ≥ 5500 |
| | Biomass (g m-2) | --- | --- |
| **Oligohaline** | Abundance (# m-2) | <180 | ≥ 4050 |
| | Biomass (g m-2) | --- | --- |
| **Low Mesohaline** | Abundance (# m-2) | <500 | ≥ 6000 |
| | Biomass (g m-2) | <1 | ≥ 30 |
| **High Mesohaline Sand** | Abundance (# m-2) | <1000 | ≥ 5000 |
| | Biomass (g m-2) | <1 | ≥ 50 |
| **High Mesohaline Mud** | Abundance (# m-2) | <1000 | ≥ 5000 |
| | Biomass (g m-2) | <0.5 | ≥ 50 |
| **Polyhaline Sand** | Abundance (# m-2) | <1500 | ≥ 8000 |
| | Biomass (g m-2) | <1 | ≥ 50 |
| **Polyhaline Mud** | Abundance (# m-2) | <1000 | ≥ 8000 |
| | Biomass (g m-2) | <0.5 | ≥ 30 |

**Figure J-2.** Metric scoring for eutrophication and low dissolved oxygen causes.
Source: Llansó 2002, Table 9, pages 24-26.

**Table J-1.** Possible conclusions from application of the assessment protocol.

**n>=10 - sufficient sample size for assessment**

| | Impairment Analysis | | Stressor Diagnostic Analyses | | |
|---|---|---|---|---|---|
| **Scenario** | **CL-L ($P-P_0$) (Table 3 of VERSAR Technical Report)** | **Impaired: Degraded Area method? (Table 3 of VERSAR Technical Report)** | **Samples with contaminant Posterior Prob. *p*>= 0.90; % of Total (Table 5 of VERSAR Technical Report)** | **Degraded Samples with excessive Abundance/Biomass; % of Total w/o Cont. (Table 5 of VERSAR Technical Report)** | **Degraded Samples with Insufficient Abundance/Biomass; % of Total w/o Cont. (Table 5 of VERSAR Technical Report)** |
| 1 | ≤0 | No | review as supplemental info | review as supplemental info | review as supplemental info |

- A small, non-significant fraction of IBI scores are within or below the lower range of the reference distribution so water quality conditions in this segment support the benthic community (no impairment).
- Where community samples are degraded, the stressor analyses may provide information that supports other assessment data.

| | | | | | |
|---|---|---|---|---|---|
| 2 | >0 | Yes | ≤ 25% of Total Samples | ≤ 25% of Total Samples | ≤ 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses do not suggest dominant stressors affecting community composition. Cause of degradation is "unknown".

| | | | | | |
|---|---|---|---|---|---|
| 3 | >0 | Yes | > 25% of Total Samples | ≤ 25% of Total Samples | ≤ 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses suggest sediment contaminants as a likely pollutant affecting benthic community structure.

| | | | | | |
|---|---|---|---|---|---|
| 4 | >0 | Yes | > 25% of Total Samples | > 25% of Total Samples | ≤ 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses suggest sediment contaminants as a likely pollutant affecting benthic community structure. Observation of high biomass or abundance is indicative of eutrophic conditions as an additional stressor affecting the benthic community.
-

| | | | | | |
|---|---|---|---|---|---|
| 5 | >0 | Yes | > 25% of Total Samples | ≤ 25% of Total Samples | > 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses suggest sediment contaminants as a likely pollutant affecting benthic community structure. Samples observed with low biomass or abundance are indicative of low dissolved oxygen as an additional stressor affecting the benthic community.

| | | | | | |
|---|---|---|---|---|---|
| 6 | >0 | Yes | ≤ 25% of Total Samples | > 25% of Total Samples | ≤ 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses do not suggest sediment contaminants as a stressors affecting community composition. Samples observed with high biomass or abundance are indicative of eutrophic conditions (excessive nutrients) as a stressor affecting the benthic community.

| | | | | | |
|---|---|---|---|---|---|
| 7 | >0 | Yes | ≤ 25% of Total Samples | > 25% of Total Samples | > 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses do not suggest sediment contaminants as stressor affecting community composition. Samples observed with high biomass or abundance are indicative of eutrophic conditions within the segment while other samples observed with low biomass or abundance are indicative of low dissolved oxygen as another stressor within the segment.

| | | | | | |
|---|---|---|---|---|---|
| 8 | >0 | Yes | ≤ 25% of Total Samples | ≤ 25% of Total Samples | > 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses do not suggest sediment contaminants as a stressor affecting community composition. Samples observed with low biomass or abundance are indicative of low dissolved oxygen as a stressor affecting the segment.

| | | | | | |
|---|---|---|---|---|---|
| 9 | >0 | Yes | > 25% of Total Samples | > 25% of Total Samples | > 25% of Total Samples |

- A large, significant fraction of IBI scores are within or below the lower range of the reference distribution, so water quality conditions in this segment do not support the benthic community (impaired condition).
- Stressor diagnostic analyses suggest sediment contaminants as a likely pollutant affecting benthic community structure. Samples observed with high biomass or abundance are indicative of eutrophic conditions within the segment while other samples observed with low biomass or abundance are indicative of low dissolved oxygen as an additional stressor within the segment.

**Table J-1.** *(continued)*

**n<10 – small sample size, insufficient for analysis**

| | **Impairment Analysis** | | **Stressor Diagnostic Analyses** | | |
|---|---|---|---|---|---|
| **Scenario** | **CL-L ($P-P_0$) (Table 3 of VERSAR Technical Report)** | **Impaired: Degraded Area? (Table 3 of VERSAR Technical Report)** | **Samples with contaminant Posterior Prob. *p*>= 0.90; % of Total (Table 5 of VERSAR Technical Report)** | **Degraded Samples with excessive Abundance/Biomass; % of Total w/o Cont. (Table 5 of VERSAR Technical Report)** | **Degraded Samples with Insufficient Abundance/Biomass; % of Total w/o Cont. (Table 5 of VERSAR Technical Report)** |
| 1 | n/a | Unknown, Not Assessed | review as supplemental info | review as supplemental info | review as supplemental info |

- There are too few samples to define the confidence interval of benthic sample IBIs, so in this segment – the biological community condition is unknown.
- Where community samples are identified as degraded, information from the stressor diagnostic analyses may provide supplemental information that may support other assessment data.

## LITERATURE CITED

Llansó, R.J. 2002. *Methods for Calculating the Chesapeake Bay Benthic Index of biotic Integrity*. Versar Inc., Columbia, Maryland http://www.baybenthos.versar.com/docs/ChesBayBIBI.PDF

Llansó , R.J., J.H. Vølstad, D.M. Dauer, and M.F. Lane. 2005. *2006 303(D) Assessment Methods For Chesapeake Bay Benthos*. Final Report Submitted to Virginia Department of Environmental Quality, Richmond, Virginia. September 2005.

appendix k

# 2006 303(d) Assessment Methods for Chesapeake Bay Benthos

Final Report Submitted to:
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Richmond, Virginia 23230

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September 2005

## FOREWORD

This report, 2006 303(d) Assessment Methods for Chesapeake Bay Benthos, was prepared by Versar at the request of the Virginia Department of Environmental Quality, under Purchase Order # 11646 between Versar, Inc. and the Commonwealth of Virginia. Old Dominion University contributed to the diagnostic (discriminant tool) assessment and to project conceptualization and evaluation. The statistical analyses for the 2006 impairment assessment were conducted by Dr. Ed Weber and Ms. Jody Dew, of Versar. Dr. Weber also contributed to the development of the Degraded Area method presented in this report.

## 1.0 INTRODUCTION

To meet the requirements of the Clean Water Act, the States of Maryland and Virginia are using benthic biological criteria for reporting overall condition and identification of impaired waters in Chesapeake Bay. The Chesapeake Bay benthic index of biotic integrity (B-IBI) is the basis for these biological criteria. Previous work conducted by Versar and Old Dominion University had two objectives: to develop a methodology for the assessment of benthic community status for 303(d) impairment decisions and to produce an assessment for each of the Chesapeake Bay segments and sub-segments containing benthic community data. A statistical procedure was developed that tests whether the distribution of B-IBI scores from probability-based samples collected from a Bay segment is significantly different from the distribution of scores from reference sites (Llansó et al. 2003). This procedure, a stratified Wilcoxon rank sum test, was evaluated and applied to the 2004 assessment data. The assessment resulted in 26 segments considered impaired based upon benthic community condition. The Wilcoxon approach, however, was sensitive to small shifts in B-IBI scores relative to the reference condition, even in some cases where a majority of the B-IBI scores in a segment met the restoration goals. For stratified data (i.e., the habitat types of the B-IBI, see below) it was not possible to estimate the magnitude of the shift, for example by using a Hodges-Lehman confidence interval. Thus, with the Wilcoxon approach we were unable to estimate the magnitude of degradation: the difference between the segment and the reference condition. A small difference could be statistically significant but of little ecological relevance. It was recommended that alternative methods be evaluated, especially those that take into account magnitude of departure from reference conditions and whether this magnitude is above specific thresholds of protection that the States may wish to implement. For the 2006 303(d) report, we developed a new method that quantifies magnitude of degradation. We call this method “Degraded Area.” In the present report, we describe the Degraded Area method, apply this method and the Wilcoxon approach to the 2006 assessment data, and compare the results.

In addition, a benthic diagnostic tool has been developed that can be used to identify potential sources of stress affecting benthic community condition in the Chesapeake Bay (Dauer et al. 2002). The tool can distinguish stress due to contaminants versus stress due to other factors (e.g., low dissolved oxygen, or unknown). This screening tool was used to identify which impaired segments have a high probability of sediment contamination. These segments could then be targeted for additional sampling or evaluation. The B-IBI metric scores for abundance and biomass were also used to identify (1) insufficient abundance patterns consistent with a low dissolved oxygen effect and (2) excessive abundance patterns consistent with eutrophication effects.

## 2.0 OBJECTIVES

1. Develop a new method for the assessment of Chesapeake Bay benthic community status for 303(d) impairment decisions.
2. Produce an assessment for the 2006 303(d) report using both the new method and the Wilcoxon approach.
3. Apply the benthic diagnostic tool and the insufficient/excessive abundance criteria to the 2006 assessment data.

## 3.0 METHODS

### 3.1. DATA

Like the Wilcoxon (described in Llansó et al. 2003), the Degraded Area method compares reference data sets to assessment data sets. The reference data set consisted of the calibration and validation data used to develop the Chesapeake Bay benthic index of biotic integrity (B-IBI). The Chesapeake Bay B-IBI is described in Weisberg et al. (1997) and Alden et al. (2002). The B-IBI consists of benthic community metrics and scoring thresholds (metric values) that were developed separately for seven habitat types (Table 1). The numbers of reference samples in each habitat used to develop the B-IBI, the Wilcoxon approach, and the method described in this report are listed in Table 2. The reference samples were either "good" (=undegraded, collected at sites known to have good sediment and water quality) or "degraded" (collected at sites with low dissolved oxygen, organic enrichment, or high sediment contaminant concentrations and toxicity). To develop the B-IBI, Weisberg et al. (1997) used averages of three replicate samples per site for mesohaline and polyhaline habitats, while Alden et al. (2002) used single replicate samples for tidal fresh and oligohaline habitats. We used the same metrics values produced by these two studies, but re-calculated B-IBI scores from these metrics to be consistent with the latest B-IBI methodology. The methods for the calculation of the Chesapeake B-IBI are described in the World Wide Web at: http://www.baybenthos.versar.com/ referenc.htm.

The assessment data for the 2006 303(d) report consisted of random samples collected from 2000 to 2004 throughout the Chesapeake Bay. A total of 1,430 samples (single replicates) were used, including 750 samples collected by the Maryland Chesapeake Bay benthic monitoring program, 500 samples collected by the Virginia Chesapeake Bay benthic monitoring program, 150 samples collected by the Elizabeth River benthic biological monitoring program, and 10 samples collected for a gear comparison study in each of Mobjack Bay, the tidal fresh Mattaponi River, and the Nansemond River. All assessment samples were collected with a Young grab (440 $cm^2$ surface area, 0.5-mm screen). For sample collection methods, see the benthic monitoring program comprehensive reports posted at the World Wide Web address given above.

Assessments were produced for each of 85 Chesapeake Bay Program segments and sub-segments containing benthic data. Segments (TMWA 1999) are Chesapeake Bay regions having similar salinity and hydrographic characteristics. In Virginia, segments were sub-divided into smaller units by the Virginia Department of Environmental Quality. Sub-segments were produced for each of the mainstems of rivers and bays (e.g., James River mesohaline) and for some of the smaller systems opening into the mainstem (e.g., Pagan River). Assessment samples were assigned to segments and sub-segments using GIS software. Hydrographic data collected synoptically with the benthic data were used to assign each sample to one of seven habitat classes used in the calculation of the B-IBI. These are the same habitat classes used in the reference data set.

## 3.2. DEGRADED AREA

The new method developed for the 2006 assessment was based on the confidence limit and bootstrap simulation concepts described in Alden et al. (2002). Specifically, bootstrap simulation (Efron and Tibshirani 1998) was applied to incorporate uncertainty in reference conditions. Bootstrap simulation is used to assess the accuracy of an estimate by randomly sampling n times, with replacement, from an original data set. In our case, we wished to estimate the score corresponding to the $5^{th}$ percentile of the B-IBI reference distributions for the good sites (by habitat). Because the reference distributions were based on small sample sizes, the percentiles were not well defined and would likely vary if different sets of reference sites were sampled. Thus the need to estimate this parameter more accurately with bootstrap simulations. Bootstrap simulations make no assumptions, except that the reference data are a representative sample from a "super population" of reference sites.

For each habitat, a threshold based on the 5th percentile B-IBI score of the reference data set for the good sites (or the maximum B-IBI score observed for the degraded sites, see below), was determined. This threshold was not intended to serve as a criterion for classifying individual B-IBI scores, rather it was used to categorize the segment as impaired or not based on the proportion of sites below the threshold (i.e., degraded area) and the variance associated with this estimate. The variance in the estimates of proportions for each segment was estimated by the simulations.

The B-IBI scores for the reference good and degraded sites had degrees of overlap that ranged from quite high in the tidal freshwater and oligohaline habitats to moderately low in the mesohaline and polyhaline habitats. An assessment sample is more likely to come from an impaired benthic community if the B-IBI score for this sample is within the range of scores observed for sites known to be degraded. Therefore, two criteria were established for determining the threshold: its score had to be within the lower bound of the good reference distribution (i.e., 5th percentile), and it had to be within the upper range of observed scores for known degraded sites (i.e., the reference degraded sites). If the 5th percentile score for a simulation run was not within the range of scores for the reference degraded sites, then the maximum B-IBI score for the reference degraded sites was selected as the threshold. Thus, in this study, sites with low B-IBI scores below thresholds were likely to be impaired and unlikely to come from good reference areas.

In each simulation run, a subset of the reference good sites for each habitat was selected at random, and the B-IBI threshold for this subset was determined (i.e., the IBI score at the 5th percentile, or the maximum score for the reference degraded samples). The scores of the assessment data for each habitat were then compared to the threshold to estimate the proportion of sites below the threshold. By repeating this process over and over again (5,000 runs) we were able to estimate the variance in the proportion of sites below the threshold from the bootstrap estimates. This variance reflects variability in the thresholds as well as sampling variability in the assessment data.

In the final step of the method, segments were declared impaired if the proportion of sites below the threshold (i.e., degraded area) was significantly higher than expected under the null hypothesis. Under the null hypothesis, a small number of sites (defined as 5% of the sites) would be expected to have low IBI scores even if all sites in a segment were in good condition (i.e., no low dissolved oxygen, contaminant, or nutrient enrichment problems). This is because of natural variability in the benthic communities, the effects of natural stressors, and sampling and methodological error. For a segment to be declared as impaired, the lower bound of the 95% confidence interval of the estimate had to be higher than 5% (the expected proportion under the null hypothesis), with a minimum sample size of 10. A 5% level was used in agreement with standard statistical practice.

The steps described above are summarized below and in Appendix A:

1. Thresholds are set for each of seven benthic habitats in Chesapeake Bay.
2. The threshold is set as the smaller of two values: 5th percentile IBI score for the good reference sites or maximum observed IBI score for the degraded reference sites.
3. The 5th percentile score and its variance is estimated by bootstrap simulations.
4. For each iteration of the bootstrap simulation, a subset (of same sample size) of the good reference sites for each habitat is selected at random (with replacement), and the 5th percentile score determined.
5. At each iteration, the threshold is set according to #2.
6. At each iteration, the assessment data are compared to the reference data to estimate the proportion of sites (P) with scores below the threshold. This is done for each of one or more habitats within a segment.
7. P is averaged over all the iterations.
8. Under the null hypothesis, 5% of the sites (Po) would be expected to have low IBI scores, even if all sites in a segment were in good condition.
9. Segments are declared impaired if P — Po > 0 (greater than expected under the null hypothesis, with 95% confidence) (See Schenker and Gentleman 2001).

## 3.3. WILCOXON

A stratified Wilcoxon rank sum test was applied as described in Llansó et al. (2003) using Proc-StatXact 5 software (Cytel Software Corporation 2002). B-IBI scores were grouped into three ordered condition categories (1.0-2.0, 2.1-2.9, 3.0-5.0) and the distribution of scores in each category within a segment was compared for each habitat to the distribution of scores for the good reference condition. Under the null hypothesis (Ho) of no impairment, the two populations (segment and reference) were considered to have the same underlying multinomial distributions of samples among the ordered categories. The assessment of impairment was based on a one-sided exact test of Ho against the alternative hypothesis that the segment had a distribution shifted towards lower B-IBI scores than for the reference condition. The ranking was done separately by habitat, and then combined across habitats. Segments with a minimum of 10 samples for which the test was significant at the 1% alpha level and 90% power, were considered impaired under this method.

## 3.4. BENTHIC DIAGNOSTIC TOOL

The benthic diagnostic tool allows environmental managers to identify potential sources of anthropogenic stress to benthic communities within Chesapeake Bay. The development and application of the tool was described in detail in Dauer et al. (2002, 2005). The benthic diagnostic tool is based on a linear discriminant function that classifies sites in Chesapeake Bay identified as having degraded benthic communities into categories distinguished by the type of stress experienced by those communities. Presently, the function is capable of discriminating contaminated sites from sites affected by all other potential sources of stress in any of the seven benthic habitat types of Chesapeake Bay. Sites are classified into two groups: 1) a contaminant group and 2) the other group representing all other potential sources of stress (eutrophication, low dissolved oxygen, etc.). This function is a linear combination of variables that includes over 60 measures of diversity, dominance, and function of benthic communities. The score for the function is used to calculate the probabilities that a sample is drawn from both groups and the sample is assigned to the group to which it has the highest probability of belonging. These probabilities are typically referred to as posterior probabilities of group membership.

For this assessment, sites with B-IBI scores < 2.7 were defined as "degraded" for benthic diagnostic tool application purposes. A score of 2.7 is used in the Chesapeake Bay benthic monitoring programs to define benthic community degradation. This cutoff value may differ from the threshold used by the Degraded Area method to determine proportion of sites with degraded benthic communities, but it should be very close to that threshold. Because cutoff values differ, diagnostic tool percentages should only be used as a general guide for identifying potential causes of degradation. For each "degraded" site, benthic metric values were submitted to the function and posterior probabilities of group membership calculated. Posterior probabilities for impaired segments were then used to identify the most likely source of stress affecting benthic communities in these segments. Sites with posterior probabilities of membership in the contaminant group that were greater than 0.50 were classified as putatively contaminated.

## 3.5. INSUFFICIENT AND EXCESSIVE ABUNDANCE OR BIOMASS

Insufficient and excessive abundance or biomass was determined from the abundance and biomass metric scores for all sites not classified as putatively contaminated. In the B-IBI, a score of 1 is assigned to total species abundance and total biomass if the value of these metrics for the site being evaluated is below the 5th percentile or above the 95th percentile of corresponding reference values. A score of 1 is assigned for both insufficient and excessive abundance or biomass because abundance and biomass of organisms respond bimodally to pollution. An increase in abundance or biomass is expected at polluted sites when stress from pollution is moderate, such as at sites where there is organic enrichment of the sediment. Excessive abundance and excessive biomass are phenomena usually associated with eutrophic conditions. A decrease in abundance and biomass is expected at sites with high degrees of stress from pollution; for example, sites affected by low dissolved oxygen. The insufficient and excessive abundance or biomass criteria can then be used to determine the likelihood of low dissolved oxygen problems versus eutrophic conditions for each of the Chesapeake Bay segments evaluated.

## 4.0 RESULTS

### 4.1. DEGRADED AREA

Based on the bootstrap-degraded area procedure, 22 segments with sample size of at least 10 were considered impaired (Table 3). Impaired segments were sorted according to the lower 95% bound of the confidence interval of the difference between the proportion of sites in the segment below threshold (P) and the proportion of sites below threshold under the null hypothesis (Po), from high to low. The estimated P for the impaired segments ranged from 28 to 76%, and the average B-IBI score was below 3.0 for most segments (Table 3). The estimates for CB4MH and CB5MH exclude the deep trough (>12 m) of the mainstem which is not monitored because this area is subjected to summer anoxia and has consistently be found to be azoic.

Nineteen of the segments declared impaired in this assessment were also declared impaired by the Wilcoxon test in the 2004 assessment. Three segments (JMSMHb, PMKOHa, MOBPHa) were declared impaired in this assessment but not in the 2004 assessment, and seven segments (LAFMHa, POCMH, POTOH, GUNOH, TANMH, NANMH, CB7PHa) were declared impaired in the 2004 assessment but not in the current assessment. Of the new impaired segments, the Nansemond River (JMSMHb) and Mobjack Bay (MOBPHa) were sampled with additional effort in 2004. Previously, these two segments and the Pamunkey River (PMKOHa) had sample size <10. Of the segments that are no longer classified as impaired, only the Pocomoke River mesohaline (POCMH) had sample size <10 in the current assessment.

### 4.2. WILCOXON

The stratified Wilcoxon rank sum test identified 27 segments with sample size of at least 10 as impaired (Table 3). Segments impaired by the Wilcoxon test but not impaired by the Degraded Area method were the lower Bay meainstem (CB7PHa), Tangier Sound (TANMH), the Lafayette River (LAFMHa), Severn River (SEVMH), and Gunpowder River (GUNOH). Except for the Severn River, these segments were also identified as impaired in the 2004 assessment.

## 4.3. DIAGNOSTIC TOOL AND INSUFFICIENT AND EXCESSIVE ABUNDANCE OR BIOMASS

The diagnostic tool and the insufficient and excessive abundance/biomass criteria can be used as ancillary information to determine most likely source of stress affecting benthic communities in segments classified as impaired. The results of this part of the assessment should be used only as a screening tool to identify probable causes of degradation and to prioritize segments for further study.

There is always a risk of misclassifying sites as affected by toxic contamination, low dissolved oxygen, or nutrient enrichment, so independent measurements of sediment and water quality should be made whenever possible. Table 4 presents the results of the diagnostic tool and the insufficient and excessive abundance/biomass characterization for sites with contaminant group posterior probabilities >=0.50, and Table 5 presents the results for sites with contaminant group posterior probabilities >=0.90. A general decision tree for segment assessment and characterization is provided in Figure 1. Results are summarized below.

### James River

The percentages of degraded samples with a contaminant effect ranged from 67% in the upper James River (JMSTFa) to 78% in the middle James River (JMSOHa) for P >=0.5, with average contaminant group posterior probabilities ranging from 0.64 to 0.79. At P >=0.9 contaminant percentages ranged from 33-50% (Table 4). At the James River mouth (JMSPHa) no samples were classified as contaminated. In addition, an examination of all samples collected indicated that only one sample had excessive abundance/biomass and only one had insufficient abundance/biomass. In the Nansemond River (JMSMHb), 90% of the degraded samples were classified as contaminated with an average contaminant group posterior probability of 0.87. Eighty percent of degraded samples had contaminant group posterior probabilities of at least 0.90. Only three samples were collected in the Chuckatuck River/Pagan River segment (JMSMHc), and three in the Warwick River (JMSMHd). Although the low number of samples makes reliable assessments difficult, degraded samples were collected in both segments and each was classified as contaminated with high posterior probabilities of contaminant group membership. Although only three samples were collected in Willoughby Bay (JMSPHd), each sample was classified as contaminated. Contaminated samples in this segment had an average contaminant group posterior probability of 0.84. Additional samples are required in these segments to determine the extent of benthic degradation and potential sources of stress.

In summary, results indicate that contaminants may account for a large portion of the degradation in the James River, except for the James River mouth. The primary source of degradation in the Nansemond River appears to be anthropogenic contamination. Sampling was not sufficient for a reliable assessment in the Chucktuck/Pagan River and Warwick River segments.

## Elizabeth River

Percentages of degraded samples with a contaminant effect ranged from 50% in the lower Elizabeth River mainstem (ELIPHa) to nearly 91% in the Eastern Branch (EBEMHa). At least 80% of degraded samples were classified as contaminated in both the Southern Branch (SBEMHa) and the Lafayette River (LAFMHa) and 68% were classified as contaminated in the upper Elizabeth River mainstem (ELIMHa). Of the remaining degraded samples without a contaminant effect, excessive abundance/biomass was found in 9.1%, 12.5%, and 5.3% in the Western Branch (WBEMHa), Southern Branch (SBEMHa) and upper Elizabeth River mainstem (ELIMHa), respectively, indicating the potential of stress due to eutrophication. Only one sample had excessive abundance in the lower Elizabeth River mainstem (ELIPHa). Insufficient abundance/biomass was found in 12.5%, 5.9%, and 15.8% of the degraded samples without a contaminant effect in the Southern Branch (SBEMHa), the Lafayette River (LAFMHa) and the upper Elizabeth River (ELIMHa), respectively, indicating low dissolved oxygen as an additional source of stress to benthic communities in these segments.

In summary, the predominant source of stress to benthic communities within the Elizabeth River is anthropogenic contamination. Both eutrophication and low dissolved oxygen appear to be additional sources of stress within the Southern Branch (SBEMHa) and upper Elizabeth River mainstem (ELIMHa).

## York River

None of the upper Pamunkey River (PMKTF) samples had B-IBI scores <2.7, so none were assessed by the diagnostic tool. Over 57% of the lower Pamunkey River (PMKOH) degraded samples were classified as contaminated by the tool, but the average contaminant group posterior probability was low at 0.62. One additional sample in this last segment was not classified as contaminated and had insufficient abundance/biomass. Few samples were degraded in the upper Mattaponi River (MPNTFa), and 67% of these were classified as contaminated. However, the average contaminant group posterior probability was low at 0.65 and no samples collected had a probability of contaminant group membership >=0.90. No samples were classified as having excessive or insufficient abundance/biomass within this segment. In the lower Mattaponi River (MPNOHa) 80% of the degraded samples were classified as contaminated. The average contaminant group posterior probability in this segment was high at 0.87 and group membership probabilities for all samples classified as contaminated were >=0.90. No uncontaminated degraded samples had excessive or insufficient abundance/biomass. In the middle York River (YRKMHa) 64% of the degraded samples were classified as contaminated. An additional 9.1% of degraded samples had excessive abundance/biomass and were not classified as contaminated by the tool, while 12.1% of the uncontaminated degraded samples had insufficient abundance/biomass. In the lower York River (YRKPHa) only 46% of the degraded samples were classified as contaminated. An additional 9.1% and 27.3% of uncontaminated degraded samples were found with excessive abundance/biomass and insufficient abundance/biomass, respectively, in this segment. In Mobjack Bay (MOBPHa), 50% of the degraded samples were classified as contaminated, all with contaminant group posterior probabilities >=0.90. An additional 12.5% and 25% of uncontaminated degraded samples were found with excessive abundance/biomass and insufficient abundance/biomass, respectively. Insufficient sample size in Severn Creek (MOBPHe), Ware River (MOBPHf), and East River (MOBPHh), precluded reliable assessments of degradation within these segments.

In summary, contaminants are likely to be substantial contributors to benthic community degradation in the York River, particularly in the lower Mattaponi River (MPNOHa) and the middle York River (YRKMHa). Contamination sources of stress are unlikely in both the lower York River (YRKPHa) and Mobjack Bay (MOBPHa), but both eutrophication and low dissolved oxygen may affect benthic communities in these segments, as well as in the lower York River (YRKMHa).

### Rappahannock River

All of the degraded samples in the upper Rappahannock River (RPPTFa) were classified as contaminated. Only five samples were collected in the middle Rappahannock River (RPPOH), making assessments of benthic community degradation unreliable. In the lower Rappahannock River (RPPMHa), 67% of the degraded samples were classified as contaminated, with an average contaminant group posterior probability of 0.67. The remaining degraded samples that were not classified into the contaminant group had insufficient abundance/biomass. Only eight samples were collected in the Corrotoman River. One of these samples was classified as contaminated and another as uncontaminated with insufficient abundance/biomass.

In summary, degradation in the upper Rappahannock River (RPPTFa) appears to be the result of anthropogenic contamination while degradation in the lower Rappahannock River may be the result of a combination of contamination and low dissolved oxygen effects. The small number of samples collected makes assessments of overall benthic community condition in the middle Rappahannock River (RPPOHa) and Corrotoman River (CRRMHa) difficult but, the degradation observed appears to be from a variety of sources in both segments.

### Potomac River

Fifty percent of the degraded samples in the upper Potomac River (POTTF) were classified as contaminated by the diagnostic tool. None of the uncontaminated degraded samples had excessive or insufficient abundance/biomass. In the middle Potomac River (POTOH), 80% of the degraded samples were classified as contaminated. Of the uncontaminated degraded samples, 20% had excessive abundance/biomass and none had insufficient abundance/biomass. In the lower Potomac River (POTMH), 31% of the degraded samples were classified as contaminated. Of the remaining degraded samples classified as uncontaminated, 65% had insufficient abundance/biomass while only 2.6% had excessive abundance/biomass.

In summary, benthic community degradation in much of the upper Potomac River (POTTF) appears to be the result of anthroprogenic contamination. In the middle Potomac River (POTOH), the primary source of stress appears to be contamination;

however, eutrophication is likely to also affect benthic communities in this segment, as indicated by the samples with excessive abundance/biomass.

The predominant source of stress in the lower Potomac River (POTMH) appears to be from low dissolved oxygen, as indicated by the high percentage of samples classified as uncontaminated and having insufficient abundance/ biomass.

### Patuxent River

An inadequate number of samples were collected in the upper Patuxent River (PAXTF) and middle Patuxent River (PAXOH) for assessing benthic community degradation using the benthic diagnostic tool. In the upper Patuxent River (PAXTF), two samples were classified as contaminated and one had excessive abundance/biomass without likelihood of contamination. In the middle Patuxent River (PAXOH), three samples were classified as contaminated and none had excessive or insufficient abundance/biomass. In the lower Patuxent River (PAXMH), 46% of the degraded samples were classified as contaminated, with an average posterior probability of contaminant group membership of 0.51. Of the remaining uncontaminated samples, 50% had insufficient abundance/biomass while only 1.5% had excessive abundance/biomass.

In summary, accurate assessment of benthic community degradation in the upper Patuxent River (PAXTF) and middle Patuxent River (PAXOH) requires additional sampling; however, available data suggest contaminants may be a source of stress in these segments. Degradation in the lower Patuxent River (PAXMH) is likely to be the result of a combination of contamination and low dissolved oxygen stress.

### Chester River

Over 38% of the degraded samples in the lower Chester River (CHSMH) were classified as contaminated. Of the remaining uncontaminated samples, 11% had excessive abundance/biomass and 33% had insufficient abundance/biomass. Benthic community degradation in this segment would appear to be the result of contamination, eutrophication, and low dissolved oxygen effects. All other segments in the Chester River had low sample size.

### Choptank River

Accurate assessment of benthic degradation the upper Choptank River (CHOTF), middle Choptank River (CHOOH) and Choptank River mouth (CHOMH1) will require additional sampling. In the lower Choptank River (CHOMH2), 67% of the degraded samples were classified as contaminated, with group membership probabilities >0.90. Of the remaining uncontaminated degraded samples, 22% had excessive abundance/biomass while 11% had insufficient abundance/biomass. Contamination appears to account for most of the benthic community degradation in the lower Choptank River (CHOMH2), but eutrophication and low dissolved oxygen are also likely to play a role.

## Pocomoke River

Pocomoke River segments had low sample size; however, most of the degraded samples in the lower Pocomoke were classified as contaminated.

## Pocomoke Sound

Again, Pocomoke Sound had low sample size; however, 75% of the degraded samples were classified as contaminated by the benthic diagnostic tool. Twenty-five percent of the uncontaminated samples had insufficient abundance/biomass. Results suggest that benthic community degradation in this segment stems from a combination of contaminants and low dissolved oxygen.

## Manokin River

Of the Maryland small Eastern Tributaries, only the Manokin River (MANMH) had adequate sample size. Seventy-five percent of the degraded samples were classified as contaminated. Of the remaining uncontaminated and degraded samples, 25% had insufficient abundance/biomass.

## Maryland Upper Western Tributaries

In the Gunpowder River (GUNOH), only 17% of the samples were classified as contaminated. Of the uncontaminated samples, 50% had insufficient abundance/biomass and another 17% had excessive abundance/biomass. The predominant source of stress to benthic communities in this segment appears to be low dissolved oxygen. In the Magothy River (MAGMH), 38% of the degraded samples were classified as contaminated. Excessive abundance/ biomass was observed in 13% and insufficient abundance/biomass in 50% of the uncontaminated degraded samples. Results suggest a mixed source of stress. In the Patapsco River (PATMH), 58% of the degraded samples were classified as contaminated. The remaining degraded samples had insufficient abundance/biomass, suggesting contaminants and low dissolved oxygen as sources of stress. In the Severn River (SEVMH), 60% of the degraded samples were classified as contaminated. An additional 20% and 40% of the uncontaminated degraded samples had excessive and insufficient abundance/biomass, respectively. Results suggest a variety of sources of stress for this segment.

## Chesapeake Bay Mainstem

Sixty-seven percent of the upper Chesapeake Bay (CB1TF) degraded samples had possible contaminant effects, and 17% of the remaining degraded samples had excessive abundance/biomass. Segment CB2OH, on the other hand, had no degraded samples. In Segment CB3MH, 55% of the degraded samples were classified as contaminated while 32% of the remaining degraded samples had insufficient abundance/biomass. In Segment CB4MH, 35% of the degraded samples were classified as contaminated, 25% of the uncontaminated degraded samples had excessive abundance/biomass, and 35% had insufficient abundance/biomass. Few samples in Tangier Sound were degraded. In Segment CB5MH, 18% of degraded samples were classified as contaminated and 82% of the uncontaminated degraded had insufficient abundance/biomass, indicating a low dissolved oxygen effect. In the lower mainstem, Segment CB6PH had 67% of the degraded samples classified as contaminated and 33% of the uncontaminated degraded samples classified with insufficient abundance/biomass. Segment CB7PHa had 63% of the degraded samples classified as contaminated, but none had contaminant group posterior probabilities above 0.90 and the average probability for the segment was 0.58. Of the degraded samples not classified as contaminated in this last segment, 13% had excessive abundance/biomass and 25% had insufficient abundance/biomass. Finally, none of the samples near the Bay mouth in Segment CB8PHa were classified as contaminated.

In summary, contaminants were likely sources of stress to benthic communities in CB1TF and CB3MH, while a variety of stresses were likely in CB4MH. Low dissolved oxygen was the predominant source of stress in CB5MH, contaminants and low dissolved oxygen in CB6PHa and CB7PHa, and low dissolved oxygen alone in CB8PHa.

## 5.0 REFERENCES

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**Table 1.** Habitat classification for the Chesapeake Bay B-1B1.

| Habitat Class | Bottom Salinity (psu) | Silt-clay (<62 μ) content by Weight (%) |
|---|---|---|
| 1. Tidal freshwater | 0-0.5 | N/A |
| 2. Oligohaline | ≥0.5-5 | N/A |
| 3. Low mesohaline | ≥5-12 | N/A |
| 4-1. High mesohaline sand | ≥12-18 | 0-40 |
| 4-2. High mesohaline mud | ≥12-18 | >40 |
| 5-1. Polyhaline sand | ≥18 | 0-40 |
| 5-2. Polyhaline mud | ≥18 | >40 |

**Table 2.** Number of samples by habitat in the original index development data files used by Weisberg et al. (1997) and Alden et al. (2002). Calibration (Cal) and validation (Val) samples combined. Habitat Class designations as in Table 1.

| | Habitat Class | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4-1 | 4-2 | 5-1 | 5-2 |
| Cal + Val | | | | | | | |
| Reference Degraded | 136 | 92 | 49 | 5 | 81 | 7 | 136 |
| Reference Good | 75 | 32 | 20 | 14 | 39 | 39 | 24 |

**Table 3.** Degraded Area and Wilcoxon rank sum test results for 85 Chesapeake Bay segments and sub-segments for the period 2000-2004. Shown is sample size, proportion of sites in segment below threshold (P), proportion of sites below threshold under the null hypothesis ($P_o$), difference between P and $P_o$, lower 95% confidence limit bound for the difference (CL-L), upper 95% confidence limit bound for the difference (CL-U), power and p-values for the Wilcoxon test, impaired segments by the Degraded Area method (lower 95% confidence bound for the difference > 0), impaired segments for the Wilcoxon test (reference and segment B-IBI score distributions differ, with lower scores in segment than in reference), mean B-IBI value, number of sites in segment with B-IBI scores equal to or greater than 2.7, number of sites in segment with B-IBI scores equal to or greater than 3.0, percent of sites in segment with B-IBI scores equal to or grater than 2.7, and percent of sites in segment with B-IBI scores equal to or greater than 3.0. $P-P_o$ confidence limits for segments with small sample size (<10) were not calculated.

| | | Degraded Area Results | | | | | Wilcoxon Results | | Impaired | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | Sample Size | P | Po | P-Po | CL- L(P-Po) | CL-U(P-Po) | Power | p-value | Degraded Area | Wilcoxon | mean B-IBI | N >=2.7 | N >=3.0 | % >=2.7 | % >=3.0 |
| POTMH | 91 | 0.76 | 0.05 | 0.71 | 0.60 | 0.82 | 1.00 | 0.0000 | Yes | Yes | 1.7 | 14 | 12 | 15 | 13 |
| SBEMHa | 47 | 0.70 | 0.05 | 0.65 | 0.49 | 0.80 | 1.00 | 0.0000 | Yes | Yes | 2.0 | 7 | 2 | 15 | 4 |
| CB4MH | 28 | 0.67 | 0.05 | 0.62 | 0.42 | 0.82 | 1.00 | 0.0000 | Yes | Yes | 2.3 | 8 | 7 | 29 | 25 |
| PAXMH | 112 | 0.49 | 0.05 | 0.44 | 0.31 | 0.58 | 1.00 | 0.0000 | Yes | Yes | 2.4 | 44 | 34 | 39 | 30 |
| PATMH | 49 | 0.52 | 0.05 | 0.47 | 0.31 | 0.63 | 1.00 | 0.0000 | Yes | Yes | 2.4 | 18 | 17 | 37 | 35 |
| CHSMH | 33 | 0.53 | 0.05 | 0.48 | 0.28 | 0.68 | 1.00 | 0.0000 | Yes | Yes | 2.6 | 15 | 13 | 45 | 39 |
| CB3MH | 61 | 0.44 | 0.05 | 0.39 | 0.24 | 0.54 | 1.00 | 0.0000 | Yes | Yes | 2.7 | 30 | 28 | 49 | 46 |
| ELIMHa | 37 | 0.48 | 0.05 | 0.43 | 0.23 | 0.64 | 1.00 | 0.0000 | Yes | Yes | 2.5 | 18 | 12 | 49 | 32 |
| EBEMHa | 15 | 0.57 | 0.05 | 0.52 | 0.22 | 0.82 | 1.00 | 0.0000 | Yes | Yes | 2.2 | 4 | 1 | 27 | 7 |
| RPPMHa | 98 | 0.37 | 0.05 | 0.32 | 0.18 | 0.45 | 1.00 | 0.0000 | Yes | Yes | 2.6 | 49 | 43 | 50 | 44 |
| YRKMHa | 64 | 0.43 | 0.05 | 0.38 | 0.15 | 0.61 | 1.00 | 0.0000 | Yes | Yes | 2.5 | 31 | 20 | 48 | 31 |
| JMSMHa | 46 | 0.37 | 0.05 | 0.32 | 0.14 | 0.51 | 1.00 | 0.0000 | Yes | Yes | 2.7 | 21 | 19 | 46 | 41 |
| CHOMH2 | 22 | 0.41 | 0.05 | 0.36 | 0.13 | 0.60 | 1.00 | 0.0012 | Yes | Yes | 2.9 | 13 | 12 | 59 | 55 |
| CB5MH | 44 | 0.32 | 0.05 | 0.27 | 0.11 | 0.43 | 1.00 | 0.0000 | Yes | Yes | 2.7 | 27 | 21 | 61 | 48 |
| YRKPHa | 29 | 0.38 | 0.05 | 0.33 | 0.11 | 0.56 | 1.00 | 0.0000 | Yes | Yes | 3.0 | 18 | 14 | 62 | 48 |
| JMSMHb | 16 | 0.45 | 0.05 | 0.40 | 0.11 | 0.70 | 1.00 | 0.0000 | Yes | Yes | 2.4 | 6 | 6 | 38 | 38 |
| MAGMH | 17 | 0.41 | 0.05 | 0.36 | 0.08 | 0.63 | 1.00 | 0.0000 | Yes | Yes | 2.3 | 9 | 6 | 53 | 35 |
| PMKOHa | 11 | 0.46 | 0.05 | 0.41 | 0.07 | 0.75 | 1.00 | 0.0009 | Yes | Yes | 2.6 | 4 | 4 | 36 | 36 |
| MOBPHa | 20 | 0.36 | 0.05 | 0.31 | 0.06 | 0.56 | 1.00 | 0.0000 | Yes | Yes | 3.0 | 12 | 11 | 60 | 55 |

**Table 3.** (continued)

| | | Degraded Area Results | | | | | Wilcoxon Results | | Impaired | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | Sample Size | P | Po | P-Po | CL- L(P-Po) | CL-U(P-Po) | Power | p-value | Degraded Area | Wilcoxon | mean B-IBI | N >=2.7 | N >=3.0 | % >=2.7 | % >=3.0 |
| ELIPHa | 17 | 0.39 | 0.05 | 0.34 | 0.05 | 0.63 | 1.00 | 0.0017 | Yes | Yes | 2.8 | 11 | 10 | 65 | 59 |
| WBEMHa | 19 | 0.36 | 0.05 | 0.31 | 0.04 | 0.59 | 1.00 | 0.0000 | Yes | Yes | 2.4 | 8 | 4 | 42 | 21 |
| JMSOHa | 22 | 0.28 | 0.05 | 0.23 | 0.01 | 0.45 | 1.00 | 0.0030 | Yes | Yes | 2.9 | 13 | 11 | 59 | 50 |
| CB7PHa | 43 | 0.15 | 0.05 | 0.10 | -0.04 | 0.24 | 1.00 | 0.0000 | No | Yes | 3.3 | 35 | 28 | 81 | 65 |
| TANMH | 48 | 0.13 | 0.05 | 0.08 | -0.05 | 0.20 | 1.00 | 0.0000 | No | Yes | 3.2 | 40 | 30 | 83 | 63 |
| LAFMHa | 27 | 0.31 | 0.05 | 0.26 | -0.06 | 0.57 | 1.00 | 0.0000 | No | Yes | 2.4 | 10 | 5 | 37 | 19 |
| SEVMH | 13 | 0.26 | 0.05 | 0.21 | -0.09 | 0.50 | 1.00 | 0.0009 | No | Yes | 2.7 | 8 | 6 | 62 | 46 |
| POTOH | 21 | 0.16 | 0.05 | 0.11 | -0.09 | 0.31 | 1.00 | 0.1524 | No | No | 3.4 | 16 | 14 | 76 | 67 |
| GUNOH | 15 | 0.22 | 0.05 | 0.17 | -0.09 | 0.44 | 1.00 | 0.0062 | No | Yes | 2.9 | 9 | 8 | 60 | 53 |
| MPNOHa | 11 | 0.25 | 0.05 | 0.20 | -0.11 | 0.52 | 1.00 | 0.0212 | No | No | 2.6 | 6 | 6 | 55 | 55 |
| CB2OH | 40 | 0.00 | 0.05 | -0.05 | -0.12 | 0.02 | 1.00 | 0.0251 | No | No | 3.8 | 40 | 40 | 100 | 100 |
| CB6PHa | 18 | 0.15 | 0.05 | 0.10 | -0.12 | 0.32 | 1.00 | 0.0232 | No | No | 3.3 | 15 | 14 | 83 | 78 |
| CB8PHa | 15 | 0.00 | 0.05 | -0.05 | -0.17 | 0.07 | 0.93 | 0.1670 | No | No | 3.4 | 13 | 13 | 87 | 87 |
| CB1TF | 19 | 0.10 | 0.05 | 0.05 | -0.17 | 0.26 | 1.00 | 0.3010 | No | No | 3.1 | 13 | 13 | 68 | 68 |
| MPNTFa | 13 | 0.00 | 0.05 | -0.05 | -0.17 | 0.07 | 1.00 | 0.2139 | No | No | 3.5 | 10 | 10 | 77 | 77 |
| MANMH | 13 | 0.10 | 0.05 | 0.05 | -0.20 | 0.29 | 1.00 | 0.0195 | No | No | 3.1 | 9 | 9 | 69 | 69 |
| RPPTFa | 11 | 0.07 | 0.05 | 0.02 | -0.20 | 0.24 | 1.00 | 0.2356 | No | No | 3.5 | 9 | 9 | 82 | 82 |
| POTTF | 12 | 0.08 | 0.05 | 0.03 | -0.20 | 0.26 | 1.00 | 0.4703 | No | No | 3.1 | 8 | 8 | 67 | 67 |
| JMSTFa | 14 | 0.02 | 0.05 | -0.03 | -0.20 | 0.15 | 1.00 | 0.1250 | No | No | 3.2 | 8 | 7 | 57 | 50 |
| JMSPHa | 10 | 0.12 | 0.05 | 0.07 | -0.36 | 0.49 | 0.97 | 0.4675 | No | No | 3.4 | 10 | 9 | 100 | 90 |
| WICMH | 9 | 0.42 | 0.05 | 0.37 | - | - | 0.98 | 0.0053 | - | - | 2.8 | 5 | 5 | 56 | 56 |
| POCMH | 9 | 0.29 | 0.05 | 0.24 | - | - | 1.00 | 0.0001 | - | - | 2.6 | 5 | 3 | 56 | 33 |
| BSHOH | 9 | 0.24 | 0.05 | 0.19 | - | - | 0.98 | 0.0272 | - | - | 2.6 | 6 | 5 | 67 | 56 |
| NANMH | 9 | 0.13 | 0.05 | 0.08 | - | - | 1.00 | 0.0097 | - | - | 3.0 | 6 | 5 | 67 | 56 |
| SOUMH | 8 | 0.88 | 0.05 | 0.83 | - | - | 1.00 | 0.0000 | - | - | 2.1 | 1 | 1 | 13 | 13 |
| CHOMH1 | 8 | 0.38 | 0.05 | 0.33 | - | - | 1.00 | 0.0006 | - | - | 2.6 | 5 | 3 | 63 | 38 |

**Table 3.** (continued)

| | | Degraded Area Results | | | | | Wilcoxon Results | | Impaired | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | Sample Size | P | Po | P-Po | CL-L(P-Po) | CL-U(P-Po) | Power | p-value | Degraded Area | Wilcoxon | mean B-IBI | N >=2.7 | N >=3.0 | % >=2.7 | % >=3.0 |
| CRRMHa | 8 | 0.23 | 0.05 | 0.18 | - | - | 1.00 | 0.0074 | - | - | 2.4 | 5 | 4 | 63 | 50 |
| ELKOH | 8 | 0.15 | 0.05 | 0.10 | - | - | 0.91 | 0.3037 | - | - | 3.2 | 6 | 6 | 75 | 75 |
| POCOH | 7 | 0.49 | 0.05 | 0.44 | - | - | 0.95 | 0.0001 | - | - | 2.5 | 1 | 1 | 14 | 14 |
| RHDMH | 7 | 0.43 | 0.05 | 0.38 | - | - | 0.34 | 0.0419 | - | - | 2.9 | 4 | 4 | 57 | 57 |
| PAXOH | 7 | 0.40 | 0.05 | 0.35 | - | - | 0.87 | 0.0075 | - | - | 2.8 | 3 | 3 | 43 | 43 |
| LCHMH | 6 | 0.31 | 0.05 | 0.26 | - | - | 0.92 | 0.0032 | - | - | 2.5 | 3 | 2 | 50 | 33 |
| CHSOH | 6 | 0.17 | 0.05 | 0.12 | - | - | 0.84 | 0.5341 | - | - | 3.2 | 5 | 5 | 83 | 83 |
| PAXTF | 6 | 0.17 | 0.05 | 0.12 | - | - | 1.00 | 0.0709 | - | - | 2.6 | 2 | 2 | 33 | 33 |
| HNGMH | 5 | 0.21 | 0.05 | 0.16 | - | - | 1.00 | 0.0001 | - | - | 2.8 | 4 | 2 | 80 | 40 |
| CHOOH | 5 | 0.21 | 0.05 | 0.16 | - | - | 1.00 | 0.0228 | - | - | 2.7 | 3 | 2 | 60 | 40 |
| RPPOHa | 5 | 0.06 | 0.05 | 0.01 | - | - | 1.00 | 0.3063 | - | - | 3.5 | 3 | 3 | 60 | 60 |
| BIGMH | 5 | 0.03 | 0.05 | -0.02 | - | - | 0.82 | 0.0141 | - | - | 2.9 | 4 | 2 | 80 | 40 |
| CHKOHa | 5 | 0.00 | 0.05 | -0.05 | - | - | 1.00 | 0.2488 | - | - | 3.7 | 5 | 5 | 100 | 100 |
| EASMH | 4 | 0.75 | 0.05 | 0.70 | - | - | 0.83 | 0.0056 | - | - | 2.1 | 1 | 1 | 25 | 25 |
| BACOH | 4 | 0.44 | 0.05 | 0.39 | - | - | 0.76 | 0.0006 | - | - | 2.1 | 2 | 0 | 50 | 0 |
| NANOH | 4 | 0.25 | 0.05 | 0.20 | - | - | 0.78 | 0.0828 | - | - | 3.5 | 3 | 2 | 75 | 50 |
| FSBMH | 4 | 0.25 | 0.05 | 0.20 | - | - | 0.36 | 0.1383 | - | - | 3.6 | 3 | 3 | 75 | 75 |
| NORTF | 4 | 0.08 | 0.05 | 0.03 | - | - | 1.00 | 0.2526 | - | - | 3.2 | 2 | 2 | 50 | 50 |
| PMKTFa | 4 | 0.00 | 0.05 | -0.05 | - | - | 0.94 | 0.2105 | - | - | 3.9 | 4 | 4 | 100 | 100 |
| JMSPHd | 3 | 0.91 | 0.05 | 0.86 | - | - | 0.86 | 0.0004 | - | - | 1.7 | 0 | 0 | 0 | 0 |
| JMSMHd | 3 | 0.34 | 0.05 | 0.29 | - | - | 0.91 | 0.0287 | - | - | 2.8 | 2 | 1 | 67 | 33 |
| JMSMHc | 3 | 0.33 | 0.05 | 0.28 | - | - | 0.80 | 0.3049 | - | - | 3.1 | 2 | 2 | 67 | 67 |
| MIDOH | 3 | 0.00 | 0.05 | -0.05 | - | - | 0.42 | 0.6203 | - | - | 3.4 | 3 | 3 | 100 | 100 |
| SASOH | 3 | 0.00 | 0.05 | -0.05 | - | - | 0.99 | 0.5239 | - | - | 3.2 | 2 | 2 | 67 | 67 |
| RPPMHm | 2 | 0.50 | 0.05 | 0.45 | - | - | 0.85 | 0.3929 | - | - | 3.1 | 1 | 1 | 50 | 50 |

**Table 3.** (continued)

| | | Degraded Area Results | | | | | Wilcoxon Results | | Impaired | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | Sample Size | P | Po | P-Po | CL-L(P-Po) | CL-U(P-Po) | Power | p-value | Degraded Area | Wilcoxon | mean B-IBI | N >=2.7 | N >=3.0 | % >=2.7 | % >=3.0 |
| MOBPHh | 2 | 0.00 | 0.05 | -0.05 | - | - | 0.40 | 0.0067 | - | - | 2.7 | 2 | 0 | 100 | 0 |
| MOBPHf | 1 | 1.00 | 0.05 | 0.95 | - | - | 0.00 | 0.1250 | - | - | 1.3 | 0 | 0 | 0 | 0 |
| MOBPHg | 1 | 1.00 | 0.05 | 0.95 | - | - | 0.12 | 0.0400 | - | - | 1.7 | 0 | 0 | 0 | 0 |
| RPPMHd | 1 | 1.00 | 0.05 | 0.95 | - | - | 0.12 | 0.0400 | - | - | 1.7 | 0 | 0 | 0 | 0 |
| WSTMH | 1 | 1.00 | 0.05 | 0.95 | - | - | 0.00 | 0.0952 | - | - | 2.2 | 0 | 0 | 0 | 0 |
| YRKPHd | 1 | 1.00 | 0.05 | 0.95 | - | - | 0.12 | 0.0400 | - | - | 1.3 | 0 | 0 | 0 | 0 |
| MATTF | 1 | 0.73 | 0.05 | 0.68 | - | - | 0.00 | 0.1212 | - | - | 1.7 | 0 | 0 | 0 | 0 |
| YRKMHb | 1 | 0.73 | 0.05 | 0.68 | - | - | 0.00 | 0.1250 | - | - | 1.7 | 0 | 0 | 0 | 0 |
| YRKPHe | 1 | 0.37 | 0.05 | 0.32 | - | - | 0.00 | 0.0800 | - | - | 2.7 | 1 | 0 | 100 | 0 |
| CHSTF | 1 | 0.19 | 0.05 | 0.14 | - | - | 0.00 | 0.1212 | - | - | 2.0 | 0 | 0 | 0 | 0 |
| CHOTF | 1 | 0.00 | 0.05 | -0.05 | - | - | 0.00 | 0.8485 | - | - | 3.0 | 1 | 1 | 100 | 100 |
| APPTFa | 1 | 0.00 | 0.05 | -0.05 | - | - | 0.00 | 0.6711 | - | - | 3.0 | 1 | 1 | 100 | 100 |
| BOHOH | 1 | 0.00 | 0.05 | -0.05 | - | - | 0.00 | 0.6711 | - | - | 4.0 | 1 | 1 | 100 | 100 |
| MOBPHe | 1 | 0.00 | 0.05 | -0.05 | - | - | 0.00 | 0.1333 | - | - | 2.7 | 1 | 0 | 100 | 0 |
| POCTF | 1 | 0.00 | 0.05 | -0.05 | - | - | 0.00 | 0.3421 | - | - | 2.5 | 0 | 0 | 0 | 0 |

**Table 4.** Diagnostic assessment of benthic community degradation for random sites sampled within Chesapeake Bay segments and sub-segments for the period 2000-2004. Presented is the mean B-IBI score in each segment, the total number of samples collected, the mean posterior probability of membership in the Contaminant group (Cont. Post. Prob.), and the total number, percentage of degraded, and percentage of the total samples for the following: (1) samples with posterior probability of contaminant group membership >=0.50, (2) degraded samples with excessive abundance or biomass, and (3) degraded samples with insufficient abundance or biomass. w/o Cont. = Percentage of samples (of degraded or total) not classified in the contaminant group. Segments in bold were classified as impaired by the Degraded Area analysis.

A. James River and Elizabeth River

| | | | | Samples with Contaminant Posterior Prob. >=0.50 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| APPTFa | 3.0 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| CHKOHa | 3.7 | 5 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| JMSTFa | 3.2 | 14 | 0.7190 | 4 | 66.67 | 28.57 | 1 | 16.67 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **JMSOHa** | 2.9 | 22 | 0.7892 | 7 | 77.78 | 31.82 | 1 | 11.11 | 0.00 | 0.00 | 6 | 66.67 | 11.11 | 4.55 |
| **JMSMHa** | 2.7 | 46 | 0.6422 | 18 | 72.00 | 39.13 | 6 | 24.00 | 4.00 | 2.17 | 10 | 40.00 | 4.00 | 2.17 |
| **JMSMHb** | 2.4 | 16 | 0.8690 | 9 | 90.00 | 56.25 | 7 | 70.00 | 0.00 | 0.00 | 4 | 40.00 | 0.00 | 0.00 |
| JMSMHc | 3.1 | 3 | 0.9855 | 1 | 100.00 | 33.33 | 1 | 100.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| JMSMHd | 2.8 | 3 | 0.9547 | 1 | 100.00 | 33.33 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| JMSPHa | 3.4 | 10 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| JMSPHd | 1.7 | 3 | 0.8388 | 3 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **WBEMHa** | 2.4 | 19 | 0.7383 | 8 | 72.73 | 42.11 | 7 | 63.64 | 9.09 | 5.26 | 3 | 27.27 | 0.00 | 0.00 |
| LAFMHa | 2.4 | 27 | 0.8793 | 15 | 88.24 | 55.56 | 11 | 64.71 | 0.00 | 0.00 | 3 | 17.65 | 5.88 | 3.70 |
| **SBEMHa** | 2.0 | 47 | 0.7986 | 32 | 80.00 | 68.09 | 26 | 65.00 | 12.50 | 10.64 | 10 | 25.00 | 12.50 | 10.64 |
| **EBEMHa** | 2.2 | 15 | 0.8904 | 10 | 90.91 | 66.67 | 7 | 63.64 | 0.00 | 0.00 | 1 | 9.09 | 0.00 | 0.00 |
| **ELIMHa** | 2.5 | 37 | 0.6758 | 13 | 68.42 | 35.14 | 5 | 26.32 | 5.26 | 2.70 | 7 | 36.84 | 15.79 | 8.11 |
| **ELIPHa** | 2.8 | 17 | 0.4849 | 3 | 50.00 | 17.65 | 1 | 16.67 | 16.67 | 5.88 | 2 | 33.33 | 16.67 | 5.88 |

**Table 4.** (continued)

B. York River

| | | | | Samples with Contaminant Posterior Prob. >=0.50 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| PMKTFa | 3.9 | 4 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| **PMKOHa** | 2.6 | 11 | 0.6200 | 4 | 57.14 | 36.36 | 3 | 42.86 | 0.00 | 0.00 | 1 | 14.29 | 14.29 | 9.09 |
| MPNTFa | 3.5 | 13 | 0.6501 | 2 | 66.67 | 15.38 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| MPNOHa | 2.6 | 11 | 0.8684 | 4 | 80.00 | 36.36 | 2 | 40.00 | 0.00 | 0.00 | 2 | 40.00 | 0.00 | 0.00 |
| **YRKMHa** | 2.5 | 64 | 0.6433 | 21 | 63.64 | 32.81 | 17 | 51.52 | 9.09 | 4.69 | 10 | 30.30 | 12.12 | 6.25 |
| YRKMHb | 1.7 | 1 | 0.0937 | 0 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 |
| **YRKPHa** | 3.0 | 29 | 0.4256 | 5 | 45.45 | 17.24 | 1 | 9.09 | 9.09 | 3.45 | 4 | 36.36 | 27.27 | 10.34 |
| YRKPHd | 1.3 | 1 | 0.8476 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| YRKPHe | 2.7 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| **MOBPHa** | 3.0 | 20 | 0.5545 | 4 | 50.00 | 20.00 | 1 | 12.50 | 12.50 | 5.00 | 6 | 75.00 | 25.00 | 10.00 |
| MOBPHe | 2.7 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| MOBPHf | 1.3 | 1 | 0.5064 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| MOBPHg | 1.7 | 1 | 0.5968 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| MOBPHh | 2.7 | 2 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |

**Table 4.** (continued)

D. Maryland Eastern Tributaries: Chester River, Choptank River and Pocomoke River

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| CHSTF | 2.0 | 1 | 0.0008 | 0 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 |
| CHSOH | 3.2 | 6 | 0.9996 | 1 | 100.00 | 16.67 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **CHSMH** | 2.6 | 33 | 0.3800 | 2 | 11.11 | 6.06 | 5 | 27.78 | 27.78 | 15.15 | 10 | 55.56 | 50.00 | 27.27 |
| CHOTF | 3.0 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| CHOOH | 2.7 | 5 | 0.9252 | 1 | 50.00 | 20.00 | 1 | 50.00 | 50.00 | 20.00 | 0 | 0.00 | 0.00 | 0.00 |
| CHOMH1 | 2.6 | 8 | 0.3992 | 1 | 33.33 | 12.50 | 0 | 0.00 | 0.00 | 0.00 | 2 | 66.67 | 66.67 | 25.00 |
| **CHOMH2** | 2.9 | 22 | 0.7173 | 6 | 66.67 | 27.27 | 6 | 66.67 | 22.22 | 9.09 | 4 | 44.44 | 11.11 | 4.55 |
| POCTF | 2.5 | 1 | 0.9637 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| POCOH | 2.5 | 7 | 0.8117 | 4 | 66.67 | 57.14 | 4 | 66.67 | 16.67 | 14.29 | 1 | 16.67 | 0.00 | 0.00 |
| POCMH | 2.6 | 9 | 0.5791 | 1 | 25.00 | 11.11 | 0 | 0.00 | 0.00 | 0.00 | 3 | 75.00 | 50.00 | 22.22 |

**Table 4.** (continued)

C. Rappahannock River, Potomac River and Patuxent River

| | | | | Samples with Contaminant Posterior Prob. >=0.50 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| RPPTFa | 3.5 | 11 | 0.9873 | 2 | 100.00 | 18.18 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| RPPOHa | 3.5 | 5 | 0.5421 | 1 | 50.00 | 20.00 | 1 | 50.00 | 50.00 | 20.00 | 0 | 0.00 | 0.00 | 0.00 |
| **RPPMHa** | 2.6 | 98 | 0.6720 | 33 | 67.35 | 33.67 | 8 | 16.33 | 0.00 | 0.00 | 35 | 71.43 | 32.65 | 16.33 |
| RPPMHd | 1.7 | 1 | 0.5447 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| RPPMHm | 3.1 | 2 | 0.9911 | 1 | 100.00 | 50.00 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| CRRMHa | 2.4 | 8 | 0.2693 | 1 | 33.33 | 12.50 | 0 | 0.00 | 0.00 | 0.00 | 2 | 66.67 | 33.33 | 12.50 |
| MATTF | 1.7 | 1 | 0.9511 | 1 | 100.00 | 100.00 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| POTTF | 3.1 | 12 | 0.6016 | 2 | 50.00 | 16.67 | 2 | 50.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| POTOH | 3.4 | 21 | 0.6851 | 4 | 80.00 | 19.05 | 2 | 40.00 | 20.00 | 4.76 | 2 | 40.00 | 0.00 | 0.00 |
| **POTMH** | 1.7 | 91 | 0.3637 | 24 | 31.17 | 26.37 | 5 | 6.49 | 2.60 | 2.20 | 68 | 88.31 | 64.94 | 54.95 |
| PAXTF | 2.6 | 6 | 0.3861 | 2 | 50.00 | 33.33 | 1 | 25.00 | 25.00 | 16.67 | 0 | 0.00 | 0.00 | 0.00 |
| PAXOH | 2.8 | 7 | 0.6677 | 3 | 75.00 | 42.86 | 1 | 25.00 | 0.00 | 0.00 | 1 | 25.00 | 0.00 | 0.00 |
| **PAXMH** | 2.4 | 112 | 0.5080 | 31 | 45.59 | 27.68 | 5 | 7.35 | 1.47 | 0.89 | 55 | 80.88 | 50.00 | 30.36 |

**Table 4.** (continued)

E. Maryland Eastern Tributaries: Smaller tributaries

| | | | | Samples with Contaminant Posterior Prob. >=0.50 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| BIGMH | 2.9 | 5 | 0.8676 | 1 | 100.00 | 20.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| BOHOH | 4.0 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| ELKOH | 3.2 | 8 | 0.4419 | 1 | 50.00 | 12.50 | 2 | 100.00 | 50.00 | 12.50 | 0 | 0.00 | 0.00 | 0.00 |
| MANMH | 3.1 | 13 | 0.6549 | 3 | 75.00 | 23.08 | 0 | 0.00 | 0.00 | 0.00 | 3 | 75.00 | 25.00 | 7.69 |
| NANOH | 3.4 | 4 | 0.9984 | 1 | 100.00 | 25.00 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| NANMH | 3.0 | 9 | 0.5083 | 1 | 33.33 | 11.11 | 1 | 33.33 | 0.00 | 0.00 | 1 | 33.33 | 33.33 | 11.11 |
| SASOH | 3.2 | 3 | 0.4439 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| WICMH | 2.8 | 9 | 0.8935 | 4 | 100.00 | 44.44 | 2 | 50.00 | 0.00 | 0.00 | 1 | 25.00 | 0.00 | 0.00 |

**Table 4.** (continued)

F. Maryland Upper Western Tributaries

| | | | | Samples with Contaminant Posterior Prob. >=0.50 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| BACOH | 2.1 | 4 | 0.7865 | 2 | 100.00 | 50.00 | 1 | 50.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| BSHOH | 2.6 | 9 | 0.6381 | 2 | 66.67 | 22.22 | 1 | 33.33 | 0.00 | 0.00 | 1 | 33.33 | 33.33 | 11.11 |
| GUNOH | 2.9 | 15 | 0.2969 | 1 | 16.67 | 6.67 | 1 | 16.67 | 16.67 | 6.67 | 3 | 50.00 | 50.00 | 20.00 |
| **MAGMH** | 2.3 | 17 | 0.4106 | 3 | 37.50 | 17.65 | 2 | 25.00 | 12.50 | 5.88 | 6 | 75.00 | 50.00 | 23.53 |
| **PATMH** | 2.4 | 49 | 0.5638 | 18 | 58.06 | 36.73 | 6 | 19.35 | 0.00 | 0.00 | 22 | 70.97 | 38.71 | 24.49 |
| RHDMH | 2.9 | 7 | 0.6777 | 2 | 66.67 | 28.57 | 1 | 33.33 | 0.00 | 0.00 | 2 | 66.67 | 33.33 | 14.29 |
| SEVMH | 2.7 | 13 | 0.5965 | 3 | 60.00 | 23.08 | 3 | 60.00 | 20.00 | 7.69 | 2 | 40.00 | 40.00 | 15.38 |
| SOUMH | 2.1 | 8 | 0.7354 | 5 | 71.43 | 62.50 | 4 | 57.14 | 0.00 | 0.00 | 2 | 28.57 | 14.29 | 12.50 |
| WSTMH | 2.2 | 1 | 0.6504 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |

**Table 4.** (continued)

G. Chesapeake Bay Mainstem and Associated Segments

| | | | | Samples with Contaminant Posterior Prob. >=0.50 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| EASMH | 2.1 | 4 | 0.3610 | 1 | 33.33 | 25.00 | 1 | 33.33 | 0.00 | 0.00 | 2 | 66.67 | 66.67 | 50.00 |
| FSBMH | 3.6 | 4 | 0.1219 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 25.00 |
| HNGMH | 2.8 | 5 | 0.2766 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 20.00 |
| LCHMH | 2.5 | 6 | 0.1671 | 0 | 0.00 | 0.00 | 1 | 33.33 | 33.33 | 16.67 | 2 | 66.67 | 66.67 | 33.33 |
| MIDOH | 3.4 | 3 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| NORTF | 3.2 | 4 | 0.5267 | 1 | 50.00 | 25.00 | 1 | 50.00 | 50.00 | 25.00 | 1 | 50.00 | 0.00 | 0.00 |
| TANMH | 3.2 | 48 | 0.2974 | 2 | 25.00 | 4.17 | 0 | 0.00 | 0.00 | 0.00 | 6 | 75.00 | 50.00 | 8.33 |
| CB1TF | 3.1 | 19 | 0.5671 | 4 | 66.67 | 21.05 | 4 | 66.67 | 16.67 | 5.26 | 0 | 0.00 | 0.00 | 0.00 |
| CB2OH | 3.8 | 40 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| **CB3MH** | 2.7 | 61 | 0.5487 | 17 | 54.84 | 27.87 | 3 | 9.68 | 3.23 | 1.64 | 23 | 74.19 | 32.26 | 16.39 |
| **CB4MH** | 2.3 | 28 | 0.3903 | 7 | 35.00 | 25.00 | 7 | 35.00 | 25.00 | 17.86 | 12 | 60.00 | 35.00 | 25.00 |
| **CB5MH** | 2.7 | 44 | 0.2125 | 3 | 17.65 | 6.82 | 1 | 5.88 | 5.88 | 2.27 | 17 | 100.00 | 82.35 | 31.82 |
| CB6PHa | 3.3 | 18 | 0.6078 | 2 | 66.67 | 11.11 | 1 | 33.33 | 0.00 | 0.00 | 2 | 66.67 | 33.33 | 5.56 |
| CB7PHa | 3.3 | 43 | 0.5762 | 5 | 62.50 | 11.63 | 1 | 12.50 | 12.50 | 2.33 | 6 | 75.00 | 25.00 | 4.65 |
| CB8PHa | 3.4 | 15 | 0.0199 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 2 | 100.00 | 100.00 | 13.33 |

**Table 5.** Diagnostic assessment of benthic community degradation for random sites sampled within Chesapeake Bay segments and sub-segments for the period 2000-2004. Presented is the mean B-IBI score in each segment, the total number of samples collected, the mean posterior probability of membership in the contaminant group (Cont. Post. Prob.), and the total number, percentage of degraded, and percentage of the total samples for the following: (1) samples with posterior probability of contaminant group membership >=0.90, (2) degraded samples with excessive abundance or biomass, and (3) degraded samples with insufficient abundance or biomass. w/o Cont. = Percentage of samples (of degraded or total) not classified in the contaminant group. Segments in bold were classified as impaired by the Degraded Area analysis.

A. James River and Elizabeth River

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| APPTFa | 3.0 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| CHKOHa | 3.7 | 5 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| JMSTFa | 3.2 | 14 | 0.7190 | 3 | 50.00 | 21.43 | 1 | 16.67 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **JMSOHa** | 2.9 | 22 | 0.7892 | 3 | 33.33 | 13.64 | 1 | 11.11 | 0.00 | 0.00 | 6 | 66.67 | 44.44 | 18.18 |
| **JMSMHa** | 2.7 | 46 | 0.6422 | 8 | 32.00 | 17.39 | 6 | 24.00 | 12.00 | 6.52 | 10 | 40.00 | 28.00 | 15.22 |
| **JMSMHb** | 2.4 | 16 | 0.8690 | 8 | 80.00 | 50.00 | 7 | 70.00 | 0.00 | 0.00 | 4 | 40.00 | 0.00 | 0.00 |
| JMSMHc | 3.1 | 3 | 0.9855 | 1 | 100.00 | 33.33 | 1 | 100.00 | 0.00 | 0.00 | 1 | 100.00 | 0.00 | 0.00 |
| JMSMHd | 2.8 | 3 | 0.9547 | 1 | 100.00 | 33.33 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| JMSPHa | 3.4 | 10 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| JMSPHd | 1.7 | 3 | 0.8388 | 1 | 33.33 | 33.33 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **WBEMHa** | 2.4 | 19 | 0.7383 | 7 | 63.64 | 36.84 | 7 | 63.64 | 9.09 | 5.26 | 3 | 27.27 | 9.09 | 5.26 |
| LAFMHa | 2.4 | 27 | 0.8793 | 13 | 76.47 | 48.15 | 11 | 64.71 | 5.88 | 3.70 | 3 | 17.65 | 5.88 | 3.70 |
| **SBEMHa** | 2.0 | 47 | 0.7986 | 27 | 67.50 | 57.45 | 26 | 65.00 | 17.50 | 14.89 | 10 | 25.00 | 15.00 | 12.77 |
| **EBEMHa** | 2.2 | 15 | 0.8904 | 9 | 81.82 | 60.00 | 7 | 63.64 | 0.00 | 0.00 | 1 | 9.09 | 0.00 | 0.00 |
| **ELIMHa** | 2.5 | 37 | 0.6758 | 7 | 36.84 | 18.92 | 5 | 26.32 | 15.79 | 8.11 | 7 | 36.84 | 26.32 | 13.51 |
| **ELIPHa** | 2.8 | 17 | 0.4849 | 3 | 50.00 | 17.65 | 1 | 16.67 | 16.67 | 5.88 | 2 | 33.33 | 16.67 | 5.88 |

**Table 5.** (continued)

B. York River

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| MPNOHa | 2.6 | 11 | 0.8684 | 4 | 80.00 | 36.36 | 2 | 40.00 | 0.00 | 0.00 | 2 | 40.00 | 0.00 | 0.00 |
| MPNTFa | 3.5 | 13 | 0.6501 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **PMKOHa** | 2.6 | 11 | 0.6200 | 3 | 42.86 | 27.27 | 3 | 42.86 | 0.00 | 0.00 | 1 | 14.29 | 14.29 | 9.09 |
| PMKTFa | 3.9 | 4 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| **YRKMHa** | 2.5 | 64 | 0.6433 | 16 | 48.48 | 25.00 | 17 | 51.52 | 18.18 | 9.38 | 10 | 30.30 | 18.18 | 9.38 |
| YRKMHb | 1.7 | 1 | 0.0937 | 0 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 |
| **YRKPHa** | 3.0 | 29 | 0.4256 | 3 | 27.27 | 10.34 | 1 | 9.09 | 9.09 | 3.45 | 4 | 36.36 | 27.27 | 10.34 |
| YRKPHd | 1.3 | 1 | 0.8476 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 |
| YRKPHe | 2.7 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| **MOBPHa** | 3.0 | 20 | 0.5545 | 4 | 50.00 | 20.00 | 1 | 12.50 | 12.50 | 5.00 | 6 | 75.00 | 25.00 | 10.00 |
| MOBPHe | 2.7 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| MOBPHf | 1.3 | 1 | 0.5064 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 |
| MOBPHg | 1.7 | 1 | 0.5968 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 |
| MOBPHh | 2.7 | 2 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |

**Table 5.** (continued)

C. Rappahannock River, Potomac River and Patuxent River

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| RPPTFa | 3.5 | 11 | 0.9873 | 2 | 100.00 | 18.18 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| RPPOHa | 3.5 | 5 | 0.5421 | 1 | 50.00 | 20.00 | 1 | 50.00 | 50.00 | 20.00 | 0 | 0.00 | 0.00 | 0.00 |
| **RPPMHa** | 2.6 | 98 | 0.6720 | 21 | 42.86 | 21.43 | 8 | 16.33 | 4.08 | 2.04 | 35 | 71.43 | 53.06 | 26.53 |
| RPPMHd | 1.7 | 1 | 0.5447 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 |
| RPPMHm | 3.1 | 2 | 0.9911 | 1 | 100.00 | 50.00 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| CRRMHa | 2.4 | 8 | 0.2693 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 2 | 66.67 | 66.67 | 25.00 |
| MATTF | 1.7 | 1 | 0.9511 | 1 | 100.00 | 100.00 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| POTTF | 3.1 | 12 | 0.6016 | 2 | 50.00 | 16.67 | 2 | 50.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| POTOH | 3.4 | 21 | 0.6851 | 2 | 40.00 | 9.52 | 2 | 40.00 | 20.00 | 4.76 | 2 | 40.00 | 40.00 | 9.52 |
| **POTMH** | 1.7 | 91 | 0.3637 | 15 | 19.48 | 16.48 | 5 | 6.49 | 2.60 | 2.20 | 68 | 88.31 | 76.62 | 64.84 |
| PAXTF | 2.6 | 6 | 0.3861 | 1 | 25.00 | 16.67 | 1 | 25.00 | 25.00 | 16.67 | 0 | 0.00 | 0.00 | 0.00 |
| PAXOH | 2.8 | 7 | 0.6677 | 1 | 25.00 | 14.29 | 1 | 25.00 | 25.00 | 14.29 | 1 | 25.00 | 25.00 | 14.29 |
| **PAXMH** | 2.4 | 112 | 0.5080 | 16 | 23.53 | 14.29 | 5 | 7.35 | 2.94 | 1.79 | 55 | 80.88 | 67.65 | 41.07 |

**Table 5.** (continued)

D. Maryland Eastern Tributaries: Chester River, Choptank River and Pocomoke River

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| CHSTF | 2.0 | 1 | 0.0008 | 0 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 |
| CHSOH | 3.2 | 6 | 0.9996 | 1 | 100.00 | 16.67 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| **CHSMH** | 2.6 | 33 | 0.3800 | 2 | 11.11 | 6.06 | 5 | 27.78 | 27.78 | 15.15 | 10 | 55.56 | 50.00 | 27.27 |
| CHOTF | 3.0 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| CHOOH | 2.7 | 5 | 0.9252 | 1 | 50.00 | 20.00 | 1 | 50.00 | 50.00 | 20.00 | 0 | 0.00 | 0.00 | 0.00 |
| CHOMH1 | 2.6 | 8 | 0.3992 | 1 | 33.33 | 12.50 | 0 | 0.00 | 0.00 | 0.00 | 2 | 66.67 | 66.67 | 25.00 |
| **CHOMH2** | 2.9 | 22 | 0.7173 | 6 | 66.67 | 27.27 | 6 | 66.67 | 22.22 | 9.09 | 4 | 44.44 | 11.11 | 4.55 |
| POCTF | 2.5 | 1 | 0.9637 | 1 | 100.00 | 100.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| POCOH | 2.5 | 7 | 0.8117 | 4 | 66.67 | 57.14 | 4 | 66.67 | 16.67 | 14.29 | 1 | 16.67 | 0.00 | 0.00 |
| POCMH | 2.6 | 9 | 0.5791 | 1 | 25.00 | 11.11 | 0 | 0.00 | 0.00 | 0.00 | 3 | 75.00 | 50.00 | 22.22 |

**Table 5.** (continued)

E. Maryland Eastern Tributaries: Smaller tributaries

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| BIGMH | 2.9 | 5 | 0.8676 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 20.00 |
| BOHOH | 4.0 | 1 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| ELKOH | 3.2 | 8 | 0.4419 | 0 | 0.00 | 0.00 | 2 | 100.00 | 100.00 | 25.00 | 0 | 0.00 | 0.00 | 0.00 |
| MANMH | 3.1 | 13 | 0.6549 | 1 | 25.00 | 7.69 | 0 | 0.00 | 0.00 | 0.00 | 3 | 75.00 | 50.00 | 15.38 |
| NANOH | 3.4 | 4 | 0.9984 | 1 | 100.00 | 25.00 | 1 | 100.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| NANMH | 3.0 | 9 | 0.5083 | 1 | 33.33 | 11.11 | 1 | 33.33 | 0.00 | 0.00 | 1 | 33.33 | 33.33 | 11.11 |
| SASOH | 3.2 | 3 | 0.4439 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| WICMH | 2.8 | 9 | 0.8935 | 3 | 75.00 | 33.33 | 2 | 50.00 | 0.00 | 0.00 | 1 | 25.00 | 0.00 | 0.00 |

**Table 5.** (continued)

F. Maryland Upper Western Tributaries

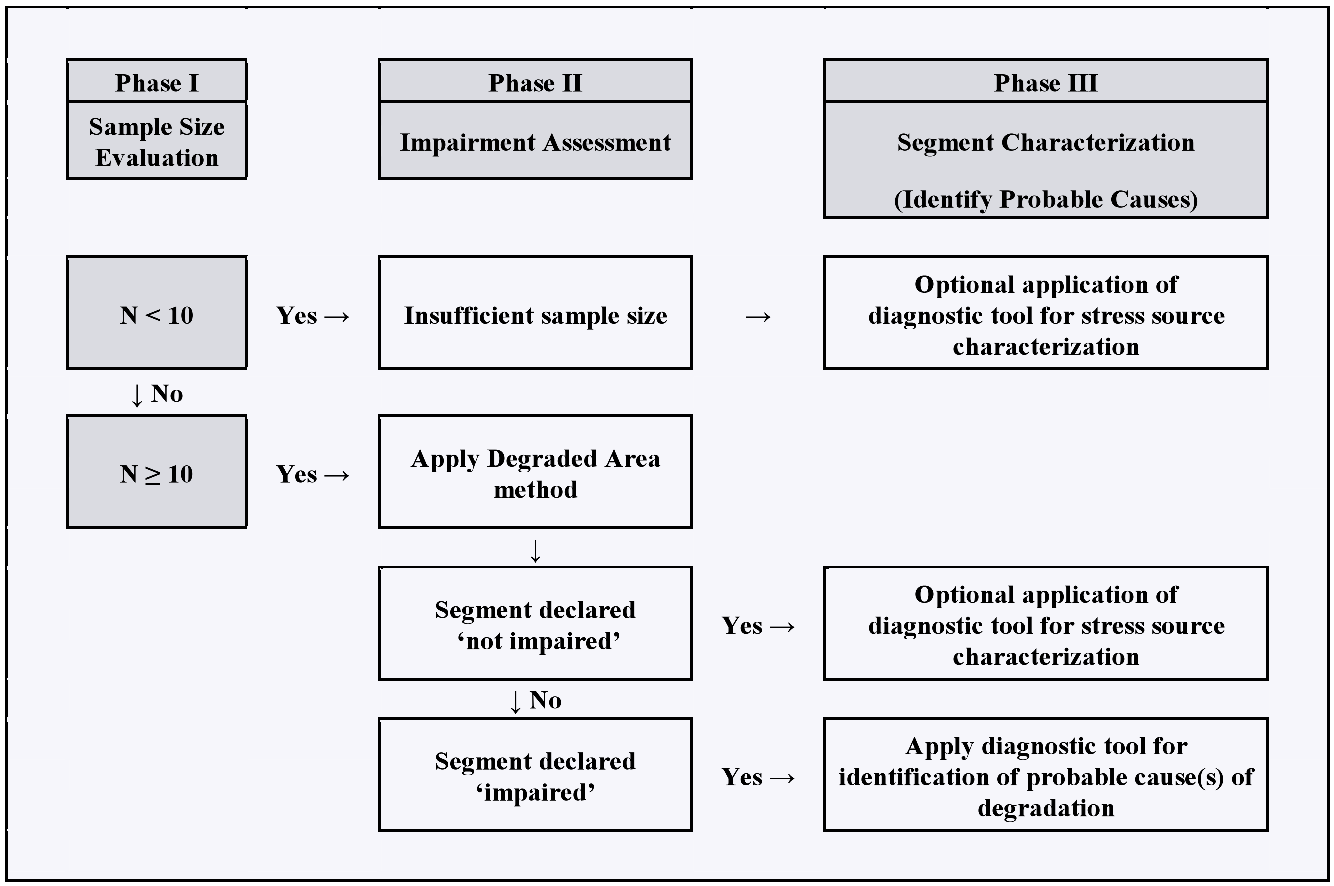
| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Total Count | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| BACOH | 2.1 | 4 | 0.7865 | 1 | 50.00 | 25.00 | 1 | 50.00 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 |
| BSHOH | 2.6 | 9 | 0.6381 | 1 | 33.33 | 11.11 | 1 | 33.33 | 0.00 | 0.00 | 1 | 33.33 | 33.33 | 11.11 |
| GUNOH | 2.9 | 15 | 0.2969 | 1 | 16.67 | 6.67 | 1 | 16.67 | 16.67 | 6.67 | 3 | 50.00 | 50.00 | 20.00 |
| **MAGMH** | 2.3 | 17 | 0.4106 | 2 | 25.00 | 11.76 | 2 | 25.00 | 12.50 | 5.88 | 6 | 75.00 | 62.50 | 29.41 |
| **PATMH** | 2.4 | 49 | 0.5638 | 10 | 32.26 | 20.41 | 6 | 19.35 | 3.23 | 2.04 | 22 | 70.97 | 58.06 | 36.73 |
| RHDMH | 2.9 | 7 | 0.6777 | 2 | 66.67 | 28.57 | 1 | 33.33 | 0.00 | 0.00 | 2 | 66.67 | 33.33 | 14.29 |
| SEVMH | 2.7 | 13 | 0.5965 | 1 | 20.00 | 7.69 | 3 | 60.00 | 60.00 | 23.08 | 2 | 40.00 | 40.00 | 15.38 |
| SOUMH | 2.1 | 8 | 0.7354 | 4 | 57.14 | 50.00 | 4 | 57.14 | 14.29 | 12.50 | 2 | 28.57 | 14.29 | 12.50 |
| WSTMH | 2.2 | 1 | 0.6504 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 100.00 |

**Table 5.** (continued)

G. Chesapeake Bay Mainstem and Associated Segments

| | | | | Samples with Contaminant Posterior Prob. >=0.90 | | | Degraded Samples with Excessive Abundance/Biomass | | | | Degraded Samples with Insufficient Abundance/Biomass | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | B-IBI | Number of Samples | Cont. Post. Prob. | Total # | % of Degraded | % of Total | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. | Total # | % of Degraded | % of Degraded w/o Cont. | % of Total w/o Cont. |
| EASMH | 2.1 | 4 | 0.3610 | 1 | 33.33 | 25.00 | 1 | 33.33 | 0.00 | 0.00 | 2 | 66.67 | 66.67 | 50.00 |
| FSBMH | 3.6 | 4 | 0.1219 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 25.00 |
| HNGMH | 2.8 | 5 | 0.2766 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 1 | 100.00 | 100.00 | 20.00 |
| LCHMH | 2.5 | 6 | 0.1671 | 0 | 0.00 | 0.00 | 1 | 33.33 | 33.33 | 16.67 | 2 | 66.67 | 66.67 | 33.33 |
| MIDOH | 3.4 | 3 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| NORTF | 3.2 | 4 | 0.5267 | 0 | 0.00 | 0.00 | 1 | 50.00 | 50.00 | 25.00 | 1 | 50.00 | 50.00 | 25.00 |
| TANMH | 3.2 | 48 | 0.2974 | 1 | 12.50 | 2.08 | 0 | 0.00 | 0.00 | 0.00 | 6 | 75.00 | 62.50 | 10.42 |
| CB1TF | 3.1 | 19 | 0.5671 | 2 | 33.33 | 10.53 | 4 | 66.67 | 33.33 | 10.53 | 0 | 0.00 | 0.00 | 0.00 |
| CB2OH | 3.8 | 40 | - | 0 | - | 0.00 | 0 | - | - | 0.00 | 0 | - | - | 0.00 |
| **CB3MH** | 2.7 | 61 | 0.5487 | 9 | 29.03 | 14.75 | 3 | 9.68 | 3.23 | 1.64 | 23 | 74.19 | 54.84 | 27.87 |
| **CB4MH** | 2.3 | 28 | 0.3903 | 2 | 10.00 | 7.14 | 7 | 35.00 | 30.00 | 21.43 | 12 | 60.00 | 60.00 | 42.86 |
| **CB5MH** | 2.7 | 44 | 0.2125 | 2 | 11.76 | 4.55 | 1 | 5.88 | 5.88 | 2.27 | 17 | 100.00 | 88.24 | 34.09 |
| CB6PHa | 3.3 | 18 | 0.6078 | 1 | 33.33 | 5.56 | 1 | 33.33 | 33.33 | 5.56 | 2 | 66.67 | 66.67 | 11.11 |
| CB7PHa | 3.3 | 43 | 0.5762 | 0 | 0.00 | 0.00 | 1 | 12.50 | 12.50 | 2.33 | 6 | 75.00 | 75.00 | 13.95 |
| CB8PHa | 3.4 | 15 | 0.0199 | 0 | 0.00 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 2 | 100.00 | 100.00 | 13.33 |

**Figure 1.** General decision tree for segment assessment and characterization of B-IBI results.



# APPENDIX

## POWERPOINT PRESENTATION

# Benthic Index of Biotic Integrity (B-IBI) for 2006 303(d) List

## Alternative Assessment Methodology

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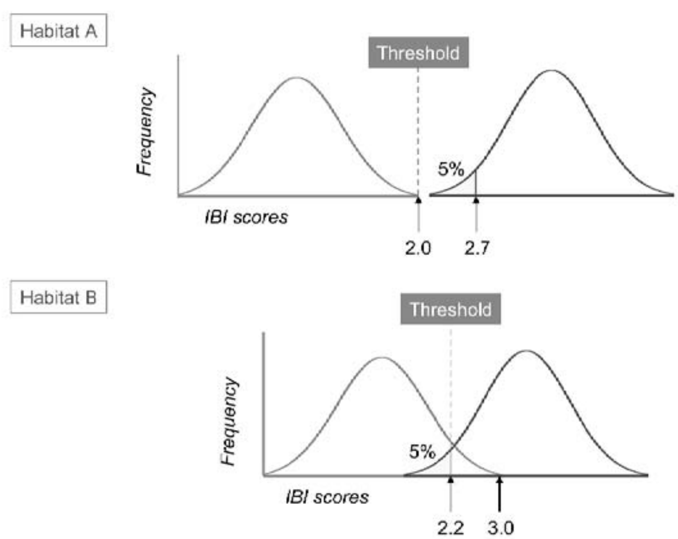
August 23, 2005

## Summary

- The impairment assessment for each segment is based on the proportion of samples with "low" B-IBI scores (i.e., below a threshold)
- Two steps, estimate:
  1. Proportion of sites in a segment with scores below a threshold (P)
  2. Difference between P and the expected proportion under the null hypothesis ($P_o$), i.e., if the segment were in good condition (no low DO, contaminant, or nutrient enrichment problems), we would still expect a small proportion of sites to have "low" scores (e.g., because of natural variability); this proportion under the null hypothesis is defined as 5%.

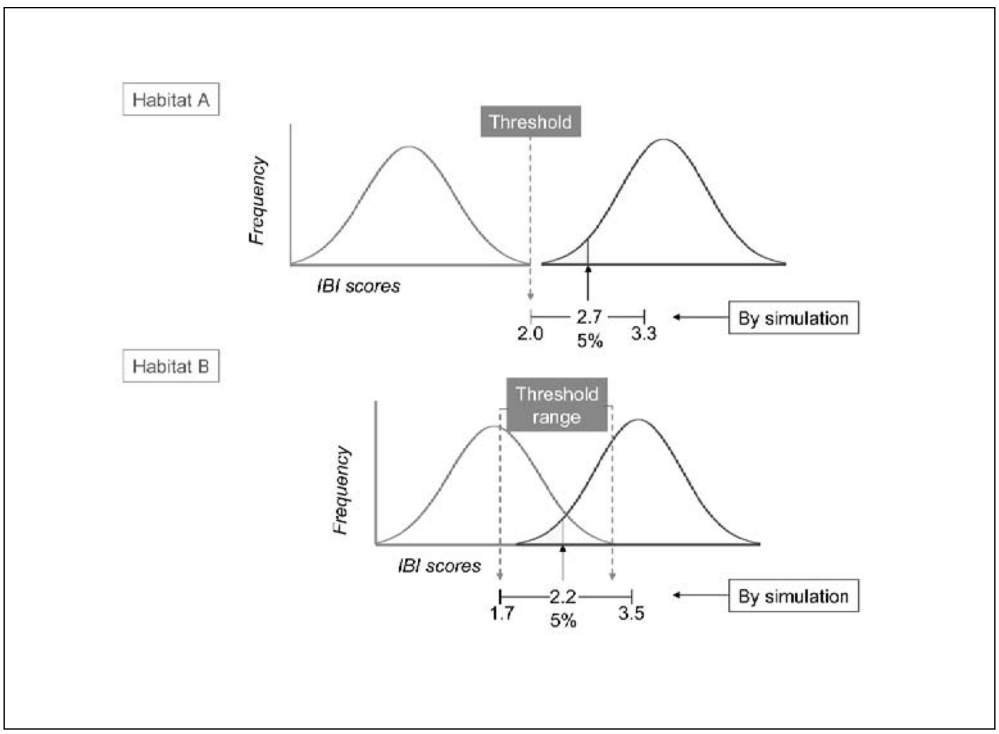
## Summary (cont.)

- Thresholds are set for each of seven benthic habitats in Chesapeake Bay: tidal fresh, oligohaline, low mesohaline, high mesohaline sand, high mesohaline mud, polyhaline sand, polyhaline mud.
- The threshold is set as the smaller of two values:
  1. 5$^{Th}$ percentile IBI score for the good reference distribution (i.e., sites with low scores are unlikely to come from good reference conditions)
  2. Maximum observed IBI score for the degraded reference distribution (i.e, sites with low scores are likely to come from degraded conditions)
- See example next slide for two hypothetical habitats: 1) Habitat A, the distributions of scores for the good and the degraded reference sites do not overlap, 2) Habitat B, the distributions overlap.



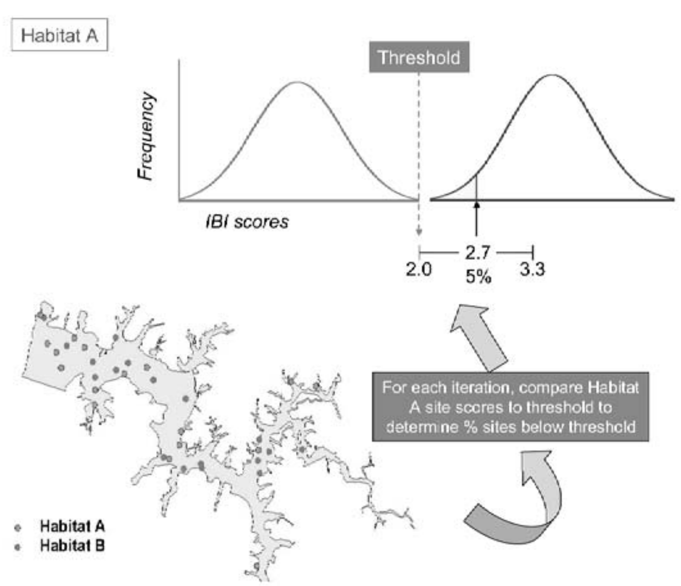
## Summary (cont.)

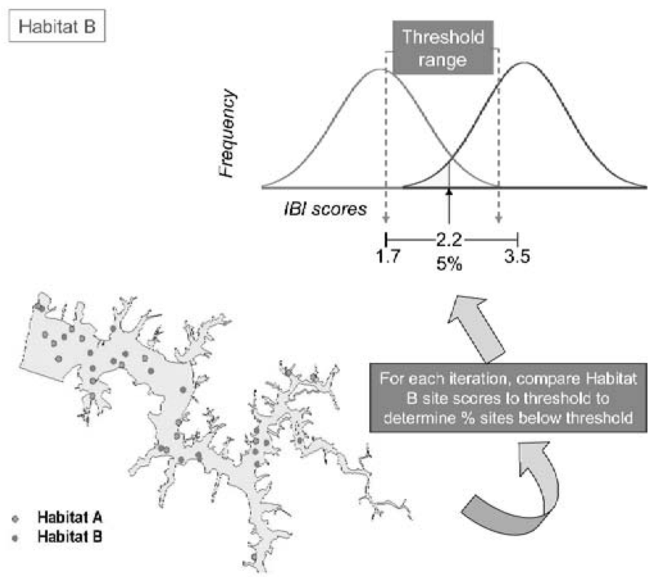
- Reference distributions are sometimes based on a small number of samples; therefore the 5th percentile score is not well defined
- The 5th percentile score and its variance was estimated by bootstrap simulations
- For each iteration of the bootstrap simulation, a subset of the good reference data for each habitat was selected at random, and the 5th percentile score determined
- Over all the iterations, the 5th percentile score varied, and at each iteration the threshold was established according to the rule described earlier
- See next slide for the two habitat examples



## Summary (cont.)

- For each iteration of the bootstrap simulation, the assessment data are compared to the reference data to estimate proportion of sites with scores below the threshold
- This is done for each of one or more habitats within a segment (i.e., some segments have sites in more than one habitat)
- See next slides for the two examples






# Summary (cont.)

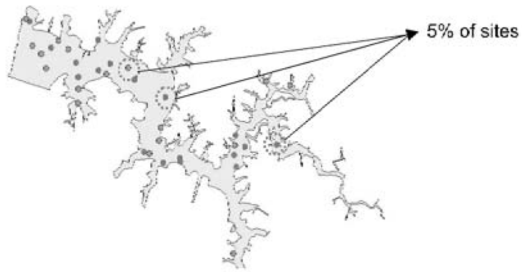
- Example of calculations for a hypothetical segment with two habitats:

| | Habitat A | | | Habitat B | | | |
|---|---|---|---|---|---|---|---|
| Iteration | n | threshold | P <threshold | n | threshold | P <threshold | P < threshold for A + B* |
| 1 | 10 | 2.0 | 0.40 | 40 | 2.2 | 0.30 | 32.0 |
| 2 | 10 | 2.0 | 0.40 | 40 | 2.6 | 0.40 | 40.0 |
| 3 | 10 | 2.0 | 0.40 | 40 | 1.7 | 0.28 | 30.4 |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| n | 10 | 2.0 | 0.40 | 40 | 3.0 | 0.48 | 46.4 |
| | | | | | | P total < threshold = | Average + SE |

*$(nP_a + nP_b)/(n_a + n_b)$, expressed as percent

## Summary (cont.)

- Under the null hypothesis, 5% of the sites ($P_o$) would be expected to have low IBI scores, even if all sites in a segment were in good condition (i.e, no low DO, contaminant, nutrient enrichment problems)




- Segments declared impaired if *P* greater than expected under the null hypothesis

  $P - P_0 > 0$ (with 95% confidence)

## Summary (cont.)

- Variance components in *P* added
  - Variance in P due to estimating thresholds – from bootstrap
  - Sampling variation within segment – binomial
- Confidence interval of $P - P_o$ =

  $P - P_o \pm 1.96(SE_P + SE_{P_o})$ $= P - P_o \pm 1.96 * SQRT(Var_P + Var_{P_o})$

  $Var_P$ = Variance from bootstrap = $\sum_{i=1}^{i=5000} \frac{(P_i - \overline{P})^2}{5000-1}$ plus variance from segment = (pq/N-1)

## Advantages of new method over Wilcoxon's

### Wilcoxon

- evaluates differences in distributions based on ranks, cannot quantify magnitude of shift
- sensitive to small shifts in distribution of B-IBI scores

### New method

- estimates proportion of area below thresholds and magnitude of departure from reference conditions
- tests if this magnitude is above specific thresholds of protection
- incorporates uncertainty in reference conditions as well as sampling variability in the assessment data
- does not require purchase of special statistical analysis package (Wilcoxon does)
- Both methods are suitable for data segregated into multiple habitats for which reference distributions are not homogeneous

appendix I

# Addendum to the Report

## Development of Diagnostic Approaches to Determine Sources of Anthropogenic Stress Affecting Benthic Community Conditions in the Chesapeake Bay

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## 1. INTRODUCTION

Dauer et al. (2002) submitted a report to the US EPA Chesapeake Bay Program Office on the development of diagnostic approaches to determine sources of anthropogenic stress affecting benthic community condition in the Chesapeake Bay. The objective of the study was to develop analytical tools capable of classifying regions in Chesapeake Bay identified as having degraded benthic communities into categories distinguished by the type of stress experienced by those communities. The tool was successful at identifying regions with high probabilities of sediment contamination. However, prior to implementation, it was recommended that the operational effectiveness of the diagnostic tool be further tested using additional validation data sets.

In this Addendum the results of two additional tasks are presented. First, the linear discriminant function was independently derived to verify the accuracy of the development of the function. Second, two additional putative validation data sets were used to assess the validity of the linear discriminant function.

## 2. LINEAR DISCRIMINANT FUNCTION

In this task it was discovered that four samples from the original calibration data set were not included in the derivation of the final linear discriminant function originally reported in Dauer et al. 2002. The final validation of the linear discriminant function with these additional four samples was identical to that reported in Table 21 for the Baywide scenario, i.e. using the All Province sediment contaminant classification, namely, with an overall percent correct classification of 75.14%. The new coefficients for this function are given in Table 1 of this Addendum (revised Table 24 of Dauer et al. 2002).

## 3. ADDITIONAL VALIDATION DATA SETS

Two putative data sets were used for further validation of the Contaminant Discriminant Tool (CDT) as presented in Dauer et al. 2002.

### ELIZABETH RIVER WATERSHED

The first putative data set consisted of 125 random samples collected in 1999 from the Elizabeth River watershed (Dauer and Llansó 2003). An additional 100 random samples collected 25 per year from 2000-2003 were also used (Dauer 2001, 2002, 2003, 2004). All samples were analyzed using the CDT function and placed into categories based upon the posterior probability of inclusion into the Contaminant Group. Due to the high levels of contaminants recorded historically in the Elizabeth River watershed (Hall et al., 1992, 1997, 2002; Padma et al. 1998; Conrad et al. 2004), the *a priori* expectation was that a high percentage of samples declared degraded by the Benthic Index of Biotic Integrity would be placed into the Contaminant Group. The results from the Elizabeth River watershed are compared to results from the Virginia Mainstem that is characterized as having low levels of contaminants and accordingly classified as of no environmental concern (USEPA 1999).

Our *a priori* expectation was that all branches of the Elizabeth River would show a higher percent area placed into the Contaminant Group compared to the Virginia Mainstem. For the Virginia Mainstem the number of sites placed into the Contaminant Group represented 11% of the entire stratum. Consistent with our *a priori* expectation, all strata in the Elizabeth River had higher proportions placed into the Contaminant Group, ranging from 40-92% (Table 2; Figure 1). These results indicate strong support for the CDT.

### 1996–2002 RANDOM DATA FOR CHESAPEAKE BAY

The second putative data set consisted of random samples collected as part of the Maryland and Virginia Benthic Monitoring Program from 1996-2002. All samples were analyzed using the CDT function and placed into categories based upon the posterior probability of inclusion into the sediment Contaminant Group. The *a priori* expectation was that more samples collected near highly urbanized or industrialized watersheds would be placed into the Contaminant Group. Results are more difficult to interpret but the pattern of location of samples placed into the Contaminant Group is non-random (Table 3; Figure 2), and can be interpreted to be consistent with known patterns of sediment contaminant distributions for the entire Chesapeake Bay (e.g. see USEPA 1999). GIS maps show patterns of location that agree well with a priori expectations within highly contaminated regions of the Bay such as Baltimore Harbor (Figure 3) and the Elizabeth River (Figure 4). The maps were made with data placed on a 100 m grid and interpolated using a two-dimensional surface fitting algorithm.

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**Table 1.** Revised Table 24 of Dauer et al. (2002). Coefficients and cutoff values for the Baywide linear discriminant function for classifying severely degraded and degraded sites into the Contaminant and Other stress groups using "uncorrected" data.

| Variable | Coefficient | Variable | Coefficient |
|---|---|---|---|
| Isopoda abundance | 2.01518 | Nereidae abundance | -0.28511 |
| Isopoda diversity | -3.07226 | Nereidae richness | -0.53535 |
| Isopoda proportional abundance | 9.45420 | Nereidae proportional abundance | 12.23099 |
| Amphipoda abundance | 0.38084 | Oligochaeta abundance | 0.43911 |
| Amphipoda richness | -0.32010 | Oligochaeta richness | 1.37409 |
| Amphipoda proportional abun. | -4.25029 | Oligochaeta proportional abundance | -5.05367 |
| Haustoriidae abundance | -3.85522 | Tubificidae abundance | 0.33669 |
| Haustoriidae diversity | -1.39235 | Tubificidae richness | 0.96057 |
| Haustoriidae proportional abun. | 34.61687 | Tubificidae proportional abundance | -2.27273 |
| Ampeliscidae abundance | -1.57316 | Deep deposit feeder abundance | -1.07320 |
| Ampeliscidae richness | -1.79716 | Deep deposit feeder richness | -2.43057 |
| Ampeliscidae proportional abun. | 25.88958 | Deep deposit feeder proportional abun. | 12.57963 |
| Corophiidae abundance | 37.26499 | Suspension feeder abundance | 1.05255 |
| Corophiidae richness | -18.36548 | Suspension feeder richness | -1.25065 |
| Corophiidae proportional abun. | -2329.15377 | Suspension feeder proportional abun. | 2.17966 |
| Mollusca abundance | 2.52241 | Interface feeder abundance | 0.84134 |
| Mollusca richness | 0.74909 | Interface feeder richness | -0.47052 |
| Mollusca proportional abundance | -1.43165 | Interface feeder proportional abundance | 4.50630 |
| Bivalvia abundance | -4.43466 | Carnivore-Omnivore abundance | -0.05179 |
| Bivalvia richness | 1.28499 | Carnivore-Omnivore richness | -0.00602 |
| Bivalvia proportional abundance | -0.27727 | Carnivore-Omnivore proportional abun. | 3.13784 |
| Gastropoda abundance | -1.23734 | Total Abundance | 0.18311 |
| Gastropoda richness | -0.15477 | Total biomass | 4.75310 |
| Gastropoda proportional abun. | -3.82240 | Biomass to abundance ratio | -123.97124 |
| Polychaeta abundance | 0.05506 | Infaunal species richness | -0.04107 |
| Polychaeta richness | 0.46294 | Infaunal Shannon Wiener diversity | 1.22042 |
| Polychaeta proportional abun. | -5.08183 | Infaunal species evenness | -2.50732 |
| Spionidae abundance | -0.02286 | Epifauna to Infaunal abundance ratio | 4.41998 |
| Spionidae richness | -1.89087 | Epifauna species richness | -0.96505 |
| Spionidae proportional abundance | 4.02486 | Epifaunal Shannon Wiener diversity | -1.11725 |
| Capitellidae abundance | 0.48588 | Epifaunal species evenness | 5.85736 |
| Capitellidae richness | 2.55550 | | |
| Capitellidae proportional abun. | -1.67289 | | |

Cutoff Value = 2.56645

**Table 2.** Percent of the Elizabeth River 1999 strata placed into the sediment contaminant effect group using the contaminant discriminant function of Dauer et al. 2002 (posterior probability > 0.5). Scuffletown, Gilligan, Jones, and Paradise creeks are subsystems of the Southern Branch. Paradise Creek sampled in 2000. The Elizabeth River strata are compared to the Virginia Mainstem Stratum.

| Stratum | Percentage of Stratum in Contaminant Group |
|---|---|
| Mainstem of the Elizabeth River | 40 |
| Lafayette River | 60 |
| Eastern Branch | 64 |
| Western Branch | 72 |
| Southern Branch | 64 |
| Scuffletown Creek | 60 |
| Gilligan/Jones Creek | 68 |
| Paradise Creek (2000) | 92 |
| Entire Elizabeth River watershed* | 54 |
| Virginia Mainstem | 11 |

* Area weighted value

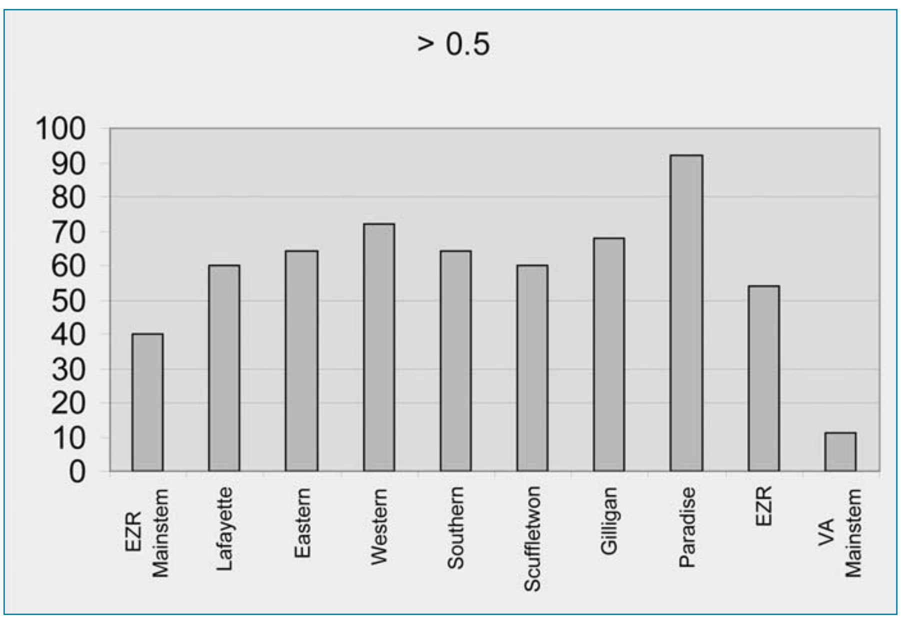


**Figure 1.** Percentage of stratum with a B-IBI value < 2.7 and placed into the Contaminant Group with a posterior probability > 0.5.

**Table 3.** Percent of the stratum placed into the sediment contaminant effect group using the contaminant discriminant function of Dauer et al. 2002 (posterior probability > 0.5). Data from 1996-2002. Elizabeth River data includes the intensive 1999 event and 25 random samples of the watershed from 2000-2002.

| Stratum | N | Percentage of stratum in Contaminant Group |
|---|---|---|
| Lower (VA) Mainstem | 175 | 10.9 |
| Upper Bay Mainstem | 175 | 17.7 |
| MD Eastern Tributaries | 175 | 16.6 |
| Patuxent River | 175 | 20.0 |
| MD Middle Mainstem | 175 | 17.1 |
| MD Western Tributaries | 175 | 24.6 |
| Potomac River | 175 | 31.4 |
| James River | 175 | 30.9 |
| Rappahannock River | 175 | 37.1 |
| York River | 175 | 38.3 |
| Elizabeth River | 275 | 52.4 |

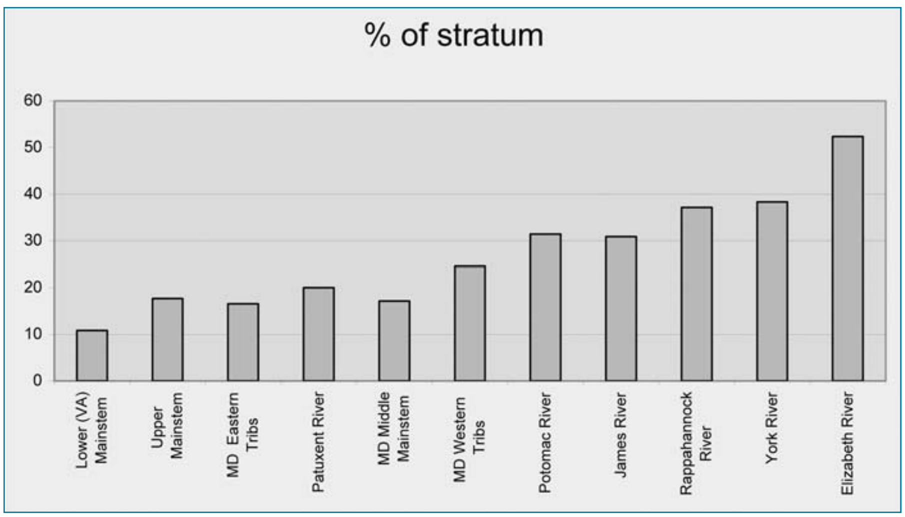


**Figure 2.** Percentage of stratum with a B-IBI value < 2.7 and placed into the Contaminant Group with a posterior probability > 0.5.

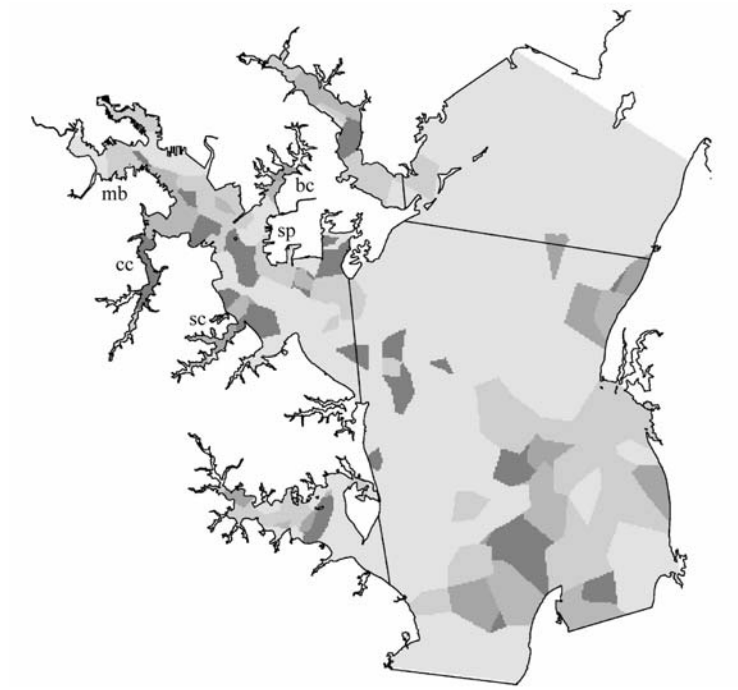


**Figure 3.** Diagnostic discriminant tool results and an interpolation fitting algorithm were used to classify Baltimore Harbor benthic communities into categories distinguished by the type of stress experienced by those communities. Red shading indicates degraded benthic communities stressed by toxic contamination (posterior probability in Contaminant Group > 0.5), with higher color intensity indicating higher probabilities of contaminant effects (>0.5 to <0.7; >=0.7 to <0.9; >=0.9). Salmon shading indicates degraded benthic communities stressed by other sources, most likely low dissolved oxygen (posterior probability in Contaminant Group <=0.5). Green indicates good benthic community condition. Middle Branch (mb), Curtis Creek (cc), Stony Creek (sc), and Bear Creek (bc) show contamination as likely source of stress. The deep basin north of Curtis Bay and the deep channel southwest of Sparrows Point (sp) shows other stress (low DO) as probable cause of degradation.

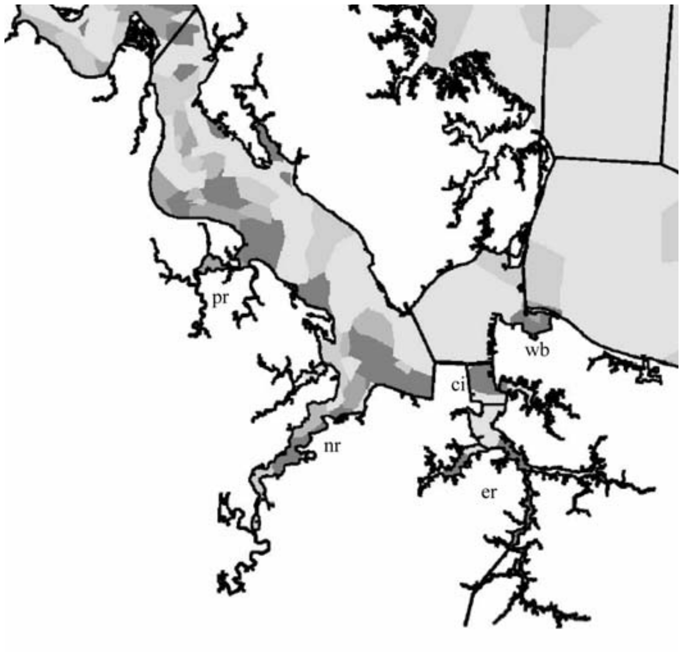


**Figure 4.** Diagnostic discriminant tool results and an interpolation fitting algorithm used here to classify lower James River benthic communities into categories distinguished by the type of stress experienced by those communities. Red shading indicates degraded benthic communities stressed by toxic contamination (posterior probability in Contaminant Group > 0.5), with higher color intensity indicating higher probabilities of contaminant effects (>0.5 to <0.7; >=0.7 to <0.9; >=0.9). Salmon shading indicates degraded benthic communities stressed by other sources (posterior probability in Contaminant Group <=0.5). Green indicates good benthic community condition. The Elizabeth River (er), Craney Island (ci), Willoughby Bay (wb), Nansemond River (nr), and Pagan River (pr) show contamination as likely source of stress.