appendix H

Derivation of Cumulative Frequency Distribution Criteria Attainment Reference Curves

Building from the descriptions of reference curves in Chapter VI, this appendix provides more detailed description of the process and options considered in deriving the open-water and deep-water dissolved oxygen reference curves and the water clarity criteria reference curves.

DISSOLVED OXYGEN REFERENCE CURVES

The Chesapeake Bay dissolved oxygen criteria have several duration components: 30-day mean, 7-day mean, 1-day mean and instantaneous minimum. At this time, reference curves have been developed only for the 30-day mean component.

OPEN-WATER CRITERIA REFERENCE CURVES

The open-water designated use includes surface and surface-mixed water above a pycnocline. It also includes waters deeper in the water column where there is no vertical density barrier (pycnocline) or where a vertical barrier is present but does not prevent exchange with oxygenated water horizontally.

The dissolved oxygen criteria are based primarily on target species that are ecologically and commercially valuable and have high oxygen requirements. If the criteria are protective of these species, then by default they are protective of other species with lower oxygen requirements. Ideally, a reference curve for the open-water criteria would be based on dissolved oxygen data collected in this habitat at times and places where these sensitive species are known to thrive. Unfortunately, there is a lack of open-water column estuarine fish/shellfish-based indices of biotic integrity, or similar biological indicator, in addition to the lack of adequate fisheries-independent data over the necessary geographic area and time period. Therefore, surrogate indicators of ‘healthy’ open-water water quality conditions were employed. To validate the reference areas, the same indicators were used to identify ‘unhealthy conditions.’ Criteria attainment curves were derived for both groups for comparison.

Four approaches to defining 'healthy' locations by Chesapeake Bay Program segment were examined for the open-water designated use. Approach 1 identified Chesapeake Bay Program segments with 'good' and 'poor' water quality conditions using water quality parameters not including dissolved oxygen. Reference and validation curves were derived using interpolated dissolved oxygen concentration data from the reference and validation segments. Approach 2 ranked the Chesapeake Bay Program segments in order based on seasonal median dissolved oxygen concentration (spring and summer, separately). Criteria attainment curves of the highest and lowest 14 segments (10 percent and 10 percent, respectively for a total of 20 percent) were used to derive reference and validation curves using the interpolated dissolved oxygen monitoring data. In Approach 3, all the polyhaline Chesapeake Bay Program segments were selected and similarly processed for comparison with the other approaches, given these segments were the most likely to have the highest dissolved oxygen values and least impaired biological communities. Approach 4 involved selecting open-water CBP interpolator cells from locations (segment, year and season) where healthy and stressed benthic communities were found (see "Deep-Water Reference Curves," below, for more details). All the data for this analysis came from the Chesapeake Bay Water Quality Monitoring Program database, with the years 1985 through 1994 selected to reflect the years of hydrology currently evaluated through the Chesapeake Bay water quality model (see Chapter VI).

Approach 1: Reference and Validation Curves Using Water Quality Status

The Chesapeake Bay Program's Tidal Monitoring and Analysis Workgroup developed a procedure to assess relative status for situations in which an absolute point of reference for a water quality parameter is not available (Alden and Perry 1997). That procedure uses the (logistic) distribution of the parameter in a 'benchmark' data set as a standard against which individual data points are assessed. The assessments are done separately within salinity classification and generally within depth layers. The median score of the individual data points is then calculated for any user-specified time and space grouping. In the present context, the benchmark distribution is divided roughly into thirds, which are defined as 'good,' 'fair' and 'poor'. These terms relate only to each other, not necessarily to actual water quality requirements of living resources.

For this analysis, the combined status assessments for total nitrogen, total phosphorus, chlorophyll *a* and total suspended solids were used to select reference and validation locations. Using the above procedure, surface concentrations of the four parameters for each Chesapeake Bay Program segment, year and season (spring and summer) were assessed to yield an assessment of 'good', 'fair' or 'poor' for each parameter. Each segment/year/season was further evaluated. To qualify as a reference location, at least three out of four water quality parameters had to be 'good' and only one parameter could be 'fair'. To qualify as a validation location, at least three parameters had to be 'poor,' the other could be 'fair' and none could be 'good.' The lists of reference and validation locations using this approach are found in Tables H-1 through H-4.

Table H-1. Reference locations for spring open-water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

Segment	Years									
BOHOH	1994									
CB2OH	1985	1986	1988	1989	1990	1991	1992	1993	1994	
CB4MH	1985	1989	1992							
CB5MH	1985	1986	1989	1991	1992					
CB6PH	1989									
CB7PH	1989									
CB8PH	1989	1991	1992							
CHKOH	1985	1986	1987							
CRRMH	1985	1986	1988	1989	1992					
EASMH	1987									
ELKOH	1991									
JMSOH	1985	1986	1987							
JMSTF	1992	1993								
MIDOH	1993									
MPNOH	1985									
MPNTF	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
PAXMH	1992									
PIAMH	1985	1986	1989	1992	1994					
PMKTF	1985	1986	1987	1988	1989	1990	1991	1993	1994	
RPPMH	1989									
RPPOH	1985	1986	1987							
RPPTF	1985	1986	1987	1991	1992					
TANMH	1986									

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Table H-2. Validation locations for spring open water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

Segment	Years
BIGMH	1990
BOHOH	1986 1990 1992 1993
C&DOH	1986 1987
CB3MH	1990
CB6PH	1993
CB7PH	1993
CB8PH	1987 1993
CHOMH2	1986 1989 1990 1994
CHOOH	1985 1987 1988 1993 1994
CHSMH	1985
CHSOH	1985 1986 1988 1990 1991 1992 1993 1994
EBEMH	1989 1991 1993 1994
ELIPH	1987 1988 1989 1990 1991 1992 1993
ELKOH	1986 1987
FSBMH	1986 1987 1990 1991 1993
GUNOH	1988 1991
JMSMH	1988 1989 1991 1992 1993
JMSOH	1990
JMSPH	1985 1986 1987 1988 1990 1991 1992 1993 1994
LAFMH	1989 1990
MAGMH	1985 1986 1989 1990
MANMH	1987 1990 1994
MOBPH	1987 1993 1994
NANMH	1986 1987 1988 1990 1991 1992 1993 1994
NANTF	1986 1988 1990 1992 1993
PAXMH	1986 1990
PAXOH	1986 1988
PAXTF	1986 1989 1990 1991 1994
POCMH	1993 1994
POTMH	1990 1991
RHDMH	1991
RPPMH	1990 1991
SBEMH	1989 1991 1993 1994
SEVMH	1991 1993
SOUMH	1985 1990 1992
TANMH	1987
WBEMH	1989 1990 1991 1992 1993 1994
WICMH	1986 1987 1988 1989 1990 1991 1992 1993 1994
WSTMH	1986 1988 1991
YRKMH	1989 1991 1992
YRKPH	1986 1987 1988 1990 1991 1993 1994

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Table H-3. Reference locations for summer open-water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

Segment	Years									
BIGMH	1993									
CB1TF	1985	1986	1987	1990	1991	1992	1993	1994		
CB2OH	1985	1986	1987	1988	1990	1991	1992	1993	1994	
CB3MH	1992	1993								
CB4MH	1985	1986	1987	1988	1990	1991	1992	1993	1994	
CB5MH	1985	1986	1987	1988	1990	1991	1992	1993	1994	
CB7PH	1986	1987								
CB8PH	1986	1987	1988	1990	1991					
CHKOH	1985	1992								
CRRMH	1987	1988	1991	1992						
EASMH	1986									
ELKOH	1991	1992	1994							
GUNOH	1985									
JMSOH	1985	1986	1987	1990	1994					
JMSTF	1991	1992								
LCHMH	1986									
MATTF	1987									
MIDOH	1990	1991	1993	1994						
MPNOH	1985	1986								
MPNTF	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
PIAMH	1985	1986	1987	1992	1993					
PISTF	1986	1987								
PMKOH	1985									
PMKTF	1985	1986	1987	1988	1989	1990	1991	1994		
POTMH	1985	1986	1987	1991						
POTOH	1986	1987	1988	1989	1990					
POTTF	1987	1989	1990							
RPPMH	1985	1986	1987							
RPPOH	1985	1986	1987	1988	1991	1992	1994			
RPPTF	1992	1994								
TANMH	1986									

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Table H-4. Validation for summer open-water, dissolved oxygen criteria reference curve based on water quality parameters (Approach 1).

CBP Segment	Years								
APPTF	1988	1990	1991	1992	1993				
BOHOH	1986	1987	1988	1989	1992	1994			
BSHOH	1985	1989							
CB6PH	1989								
CHOMH2	1989	1990	1991	1994					
CHOOH	1985	1986	1987	1990	1991	1994			
CHSMH	1989	1990	1993						
CHSOH	1985	1986	1987	1988	1989	1990	1991	1992	1993 1994
ELIPH	1985	1986	1987	1988	1989	1990	1991	1992	1993
FSBMH	1988	1989							
GUNOH	1993								
JMSMH	1989								
JMSPH	1987	1989	1991	1992	1993	1994			
LAFMH	1989	1990							
LCHMH	1989								
MAGMH	1986	1987	1988	1989	1990	1991	1994		
MANMH	1986	1987	1988	1989	1990	1991	1993	1994	
MOBPH	1986	1989	1990	1991	1993				
NANMH	1986	1987	1988	1989	1990	1991	1993	1994	
NANTF	1989	1990	1992	1993	1994				
NORTF	1989								
PATMH	1985	1986	1987	1988	1989	1990	1991	1992	1993 1994
PAXMH	1988	1989	1993						
PAXOH	1986	1989	1992	1994					
PAXTF	1985	1986	1987	1988	1989	1990	1991	1992	1993 1994
POCMH	1989	1994							
POTTF	1994								
RHDMH	1985	1986	1987	1988	1989	1990	1991	1992	
SASOH	1986	1987	1988	1989	1990	1991	1993		
SBEMH	1992	1993	1994						
SEVMH	1985	1987	1988	1989	1990	1991	1992	1994	
SOUMH	1987	1988	1989	1990	1991	1994			
WBEMH	1989	1990	1991	1992					
WICMH	1986	1987	1988	1989	1990	1991	1993	1994	
WSTMH	1985	1987	1988	1989	1990	1991	1994		
YRKMH	1987	1989	1990	1991	1993				
YRKPH	1986	1988	1989	1990	1991	1992	1993		

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Monthly mean dissolved oxygen concentration data were then interpolated basinwide for each month, 1985 to 1994. In addition, a basinwide 'master' interpolated 3-dimensional grid file was created in which each cell has a Chesapeake Bay segment assignment and a static Designated Use assignment (open-water [OW], deep-water [DW] and deep-channel [DC]) based on proposed tidal water designated use boundaries (U.S. EPA 2003). Each cell could thus be identified by the appropriate dissolved oxygen concentration(s) associated with its respective designated use.

For each monthly baywide interpolation, the dissolved oxygen concentration in each open-water designated use cell was compared to the appropriate criteria concentration for the season, and the percent of cells passing/failing the criteria calculated for each segment/designated use. Using the respective lists of 'good' and 'bad' locations (segment_years), the data for the reference and validation segments were extracted and pooled in separate groups. For example, segment POCMH in spring 1993 and 1994 were identified as validation locations. The percent volume failing the criterion in POCMH was calculated for each month—February, March, April and May of 1993 and 1994—and pooled with the percent-volume-failing data from other similarly identified locations. Then, the cumulative frequency distribution attainment curves were derived for each pooled group. Figures H-1 and H-2 show the open-water designated use dissolved oxygen criteria reference and validation curves for the spring and summer seasons generated applying water quality status approach.

It is clear that both reference (hatched line) and validation (solid line) areas meet the spring 30- day 5 mg liter^{-1} criterion almost all if not 100 percent of the time. If there are areas that do not meet this criterion in spring, this method does not detect them. There also is little apparent distinction between the illustrated reference and validation curves in summer (Figure H-2).

However, when the summer data are separated by salinity zone (figures H-3 and H-4), there are distinct differences between the reference and validation curves. In tidal fresh and oligohaline segments, overall exceedance is low, but reference areas have more apparent exceedance than validation areas. The reverse is true for meso-

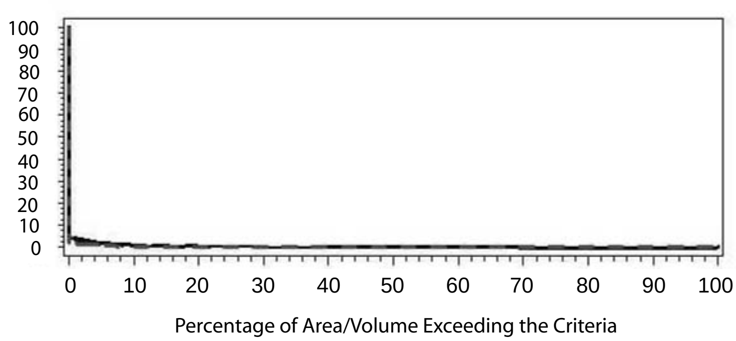

Figure H-1: Spring open-water reference (hatched line) and validation (solid line) curves: water quality status approach.

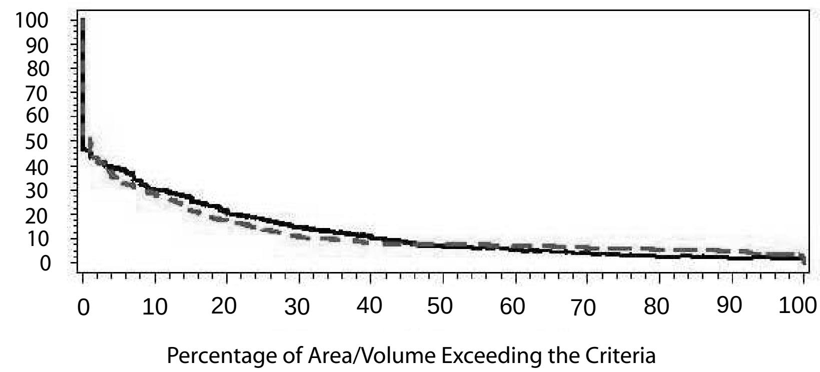

Figure H-2: Summer open-water reference (hatched) and validation (solid line) curves: water quality status.

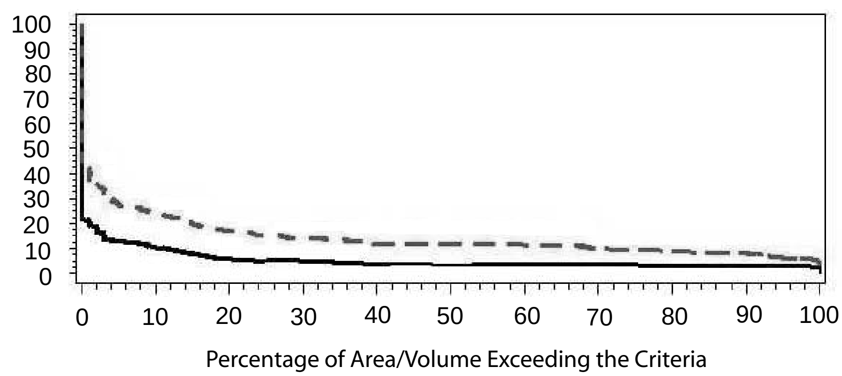

Figure H-3: Lower salinity summer open water reference (hatched line) and validation (solid line) curves: water quality status approach.

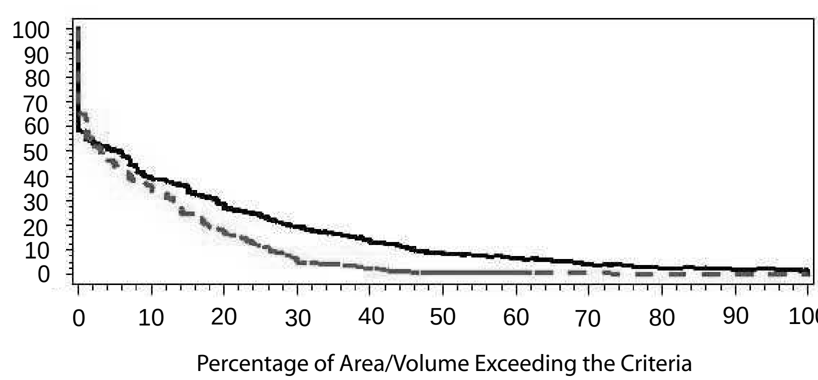

Figure H-4: Higher salinity summer open water reference (hatched line) and validation (solid line) curves: water quality status approach.

haline-polyhaline segments where exceedance is generally greater. An important point to remember is that, while we usually think of the open-water habitat as the surface-mixed layer, the open-water criteria are applicable throughout the water column in areas that do not experience chronic vertical stratification. There are such areas in the basin that are quite deep but usually do not have a pycnocline. These areas are more commonly found in mesohaline and polyhaline segments than in the tidal-fresh and oligohaline waters. This is one likely factor in the difference between the reference and validation curves. Another factor could be that surface waters in the validation segments in the tidal-fresh and oligohaline zones are more affected by the oxygen-generating processes of algal blooms, whereas the mesohaline and polyhaline validation segments are more affected by oxygen-consumptive processes occurring in the deep water layers beneath them.

The cumulative frequency distribution curves for reference locations using the water quality status method show that areas with low nutrients, chlorophyll *a* and suspended solids levels also have dissolved oxygen levels that do not greatly exceed the applicable criterion. On the other hand, the validation curves suggest these parameters are not good indicators of locations with dissolved oxygen criteria attainment levels. The mesohaline and polyhaline curve shows some nonattainment, but conditions are far better than those reflected in the validation curve derived from the ranking exercise described below. This result is essentially as expected since, in most of the Chesapeake Bay and tidal tributaries, the link between the water quality parameters and dissolved oxygen has a number of intermediate steps and the dissolved oxygen response to water quality parameters is often displaced in time or space or both.

Approach 2: Segments with Highest and Lowest Long-term Dissolved Oxygen Concentrations

The ranking procedure for selecting reference and validation segments was based on observed (i.e., not interpolated) data. Dissolved oxygen measurements are available for each monitoring station at 1- to 2-meter intervals from surface to bottom. The depth of the pycnocline, if one existed, also is available. For this analysis, all dissolved oxygen measurements above the pycnocline, or the shallower of all measurements above 7 meters or above the bottom if there was no pycnocline, were assumed to be in open-water designated use habitats. To control for supersaturating conditions, dissolved oxygen concentrations that were above saturation levels (calculated from temperature and salinity measured concurrently) were set down to the saturation level.

Spring (March through May) and summer (June through September) data were averaged first by date and station; then by month and segment; then the 10th, 50th and 90th percentiles of the monthly segment averages were calculated for spring and summer seasons over the 1985-1994 period. The seasonal median, i.e., 50th percentile, was used to rank the segments (tables H-5 and H-6). Some segments were excluded, resulting in 67 segments that were ranked. The excluded Chesapeake Bay Program

Table H-5. Chesapeake Bay Program segments listed in order of spring open-water designated use, seasonal median dissolved oxygen concentration.

CBP Segment	Median	Mean	10th percentile	90th percentile
WICMH	8.0	8.4	6.2	11.5
PMKTF	8.0	8.1	6.3	10.1
YRKMH	8.0	8.1	6.3	10.3
POCTF	8.1	7.9	5.4	10.2
MPNOH	8.1	8.1	6.1	10.3
PMKOH	8.1	8.2	6.2	10.3
CHOOH	8.6	8.9	7.2	10.9
MPNTF	8.7	8.6	6.9	10.5
PAXOH	8.7	8.8	7.0	10.8
YRKPH	8.7	8.7	7.0	10.3
ELIMH	8.8	8.8	6.5	11.0
ELIPH	8.8	8.8	7.1	10.7
JMSMH	8.9	9.0	7.4	10.7
FSBMH	8.9	9.3	7.4	11.7
RPPTF	9.0	9.3	7.3	11.3
CHSOH	9.1	9.1	7.3	10.8
MANMH	9.1	9.1	7.4	10.9
JMSPH	9.1	9.2	7.5	11.1
NANMH	9.1	9.3	7.4	11.1
MOBPH	9.1	9.2	7.7	10.7
RPPOH	9.2	9.2	7.4	11.0
POTOH	9.2	9.4	7.8	11.4
APPTF	9.2	9.4	8.0	11.2
POCMH	9.2	9.3	7.9	10.9
BIGMH	9.3	9.3	7.5	11.1
CB8PH	9.3	9.3	8.0	10.9
PAXTF	9.3	9.2	7.3	10.6
TANMH	9.4	9.3	7.4	11.2
PATMH	9.4	9.4	7.7	11.0
RPPMH	9.4	9.2	7.3	10.9
CHOMH2	9.4	9.4	7.6	11.4
CRRMH	9.4	9.2	7.1	10.9
CHKOH	9.4	9.2	7.1	11.1
JMSOH	9.5	9.4	7.9	11.0
CB7PH	9.5	9.4	7.9	10.9
PIAMH	9.6	9.6	8.0	11.2
PAXMH	9.6	9.3	6.9	11.2
MAGMH	9.6	9.7	7.5	11.5
NANTF	9.6	9.5	7.5	11.4
CHSMH	9.6	9.8	8.1	11.7
POTTF	9.7	9.8	7.9	11.8
RHDMH	9.7	9.6	7.8	11.6
WSTMH	9.7	9.7	7.4	11.9
CB6PH	9.7	9.7	8.0	11.2
JMSTF	9.7	9.6	8.2	10.8
CB3MH	9.7	9.4	7.6	11.2
SOUMH	9.7	9.2	5.8	11.5
CB2OH	9.7	9.8	7.5	11.8
POTMH	9.7	9.7	7.9	11.7
BSHOH	9.8	10.0	8.1	12.0
C&DOH	9.8	10.0	8.0	12.0
BACOH	9.9	9.9	8.0	12.0
EASMH	9.9	9.9	8.0	11.5
PISTF	9.9	10.1	7.9	11.9
SEVMH	9.9	9.8	7.7	11.7
LCHMH	9.9	9.8	8.3	11.4
CB5MH	10.0	10.0	8.3	11.5
MATTF	10.0	10.0	8.5	11.7
ELKOH	10.0	10.1	8.3	12.1
CB4MH	10.1	9.9	8.1	11.4
CHOMH1	10.1	9.8	7.8	11.3
SASOH	10.1	10.1	8.4	11.9
MIDOH	10.3	10.3	8.7	12.2
NORTF	10.4	10.5	9.2	12.3
BOHOH	10.4	10.2	8.6	12.4
GUNOH	10.5	10.4	8.6	12.1
CB1TF	11.0	10.7	8.6	12.5

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Table H-6. Chesapeake Bay segments listed in order of summer dissolved oxygen designated use, seasonal median dissolved oxygen concentration.

CBP Segment	Median	Mean	10th percentile	90th percentile
SOUMH	4.2	4.5	2.7	7.1
MAGMH	4.7	4.8	3.3	6.9
PMKTF	4.9	5.0	4.4	5.8
MPNOH	4.9	4.9	4.0	5.6
POCTF	4.9	5.1	3.7	7.1
PMKOH	5.0	4.9	4.1	5.7
YRKMH	5.2	5.2	4.5	5.8
PAXMH	5.4	5.4	4.8	6.1
YRKPH	5.5	5.5	4.9	6.2
MPNTF	5.5	5.5	4.6	6.4
ELIMH	5.6	5.7	4.4	7.1
ELIPH	5.6	5.7	4.6	6.8
WICMH	5.8	5.7	4.6	6.8
CRRMH	5.9	5.8	4.5	6.8
SEVMH	5.9	5.9	5.1	7.6
PAXOH	5.9	5.9	4.9	7.0
CHOMH2	6.0	6.0	5.3	6.8
PATMH	6.1	6.0	4.8	7.0
POTMH	6.1	6.1	5.4	6.8
WSTMH	6.1	6.1	5.0	7.5
JMSMH	6.2	6.2	5.6	6.7
RPPMH	6.2	6.2	5.5	6.7
CB3MH	6.2	6.1	5.4	6.8
CHOOH	6.3	6.3	5.4	7.2
POTOH	6.3	6.3	5.6	.1
CB2OH	6.4	6.3	5.6	6.8
NANMH	6.4	6.4	5.7	7.4
CHKOH	6.5	6.4	5.3	7.4
C&DOH	6.5	6.5	5.8	7.2
TANMH	6.5	6.5	5.9	7.1
MOBPH	6.5	6.4	5.6	7.0
JMSPH	6.5	6.6	6.0	7.2
MANMH	6.6	6.6	5.9	7.2
RPPOH	6.6	6.5	5.7	7.3
FSBMH	6.6	6.5	5.8	7.3
ELKOH	6.6	6.5	5.8	7.2
CHSMH	6.6	6.5	5.8	7.3
RHDMH	6.6	6.6	5.5	7.9
POTTF	6.6	6.6	6.0	7.2
JMSOH	6.7	6.7	6.1	7.2
CB6PH	6.7	6.8	6.2	7.5
POCMH	6.7	6.7	6.3	7.3
LCHMH	6.7	6.7	5.9	7.5
PIAMH	6.7	6.6	5.7	7.4
CB4MH	6.7	6.6	6.0	7.2
CB7PH	6.8	6.9	6.4	7.3
CHOMH1	6.8	6.9	6.3	7.6
SASOH	6.8	6.5	4.1	8.0
CB5MH	6.9	6.9	6.4	7.5
BIGMH	6.9	6.9	6.3	7.4
EASMH	6.9	6.9	6.2	7.5
CB8PH	6.9	6.9	6.4	7.5
BOHOH	7.0	7.1	5.7	8.3
CB1TF	7.0	7.0	6.4	7.8
JMSTF	7.0	7.0	6.4	7.5
PISTF	7.0	6.7	5.4	7.6
APPTF	7.2	7.1	5.8	8.0
RPPTF	7.2	7.2	6.6	8.0
PAXTF	7.2	7.1	6.0	8.1
MIDOH	7.3	7.1	5.7	8.0
CHSOH	7.3	7.2	6.1	8.3
NANTF	7.4	7.1	5.9	8.3
GUNOH	7.5	7.3	6.1	8.5
BACOH	7.7	7.3	5.5	8.5
BSHOH	7.8	7.4	5.5	8.7
NORTF	7.9	7.8	7.2	8.4
MATTF	7.9	7.9	7.4	8.6

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

segments were: the Western Branch of the Patuxent River (WBRTF) because it is a small water body dominated by a waste water treatment plant; the mesohaline tributaries of the Elizabeth River (SBEMH, EBEMH, and WBEMH) because the dissolved oxygen interpolations did not extend to those segments or the data record was too short; and the Lafayette River (LAFMH) because it contains no water quality monitoring station. Within season, the highest ranked 14 segments made up the list of reference locations and the lowest ranked 14 segments constituted the list of validation locations.

Monthly mean dissolved oxygen concentration data were then interpolated basin-wide for each spring and summer month, 1985 to 1994. For each interpolation, the dissolved oxygen concentration in each cell qualifying as open-water was compared to the appropriate criteria concentration for the month, and the percent of cells passing/failing the criteria was calculated for each segment or designated use. Using the respective lists of 'good' and 'bad' locations, the data for the reference and validation segments were extracted, pooled and plotted (Figure H-5).

The reference curve (hatched line) using this approach looks too good to be true. The Chesapeake Bay Program segments with the highest dissolved oxygen levels include a number of segments known to be eutrophic, with high chlorophyll *a* concentrations. These segments are likely to have elevated daytime dissolved oxygen concentrations due to the addition of oxygen from photosynthesis, but these are also frequently associated with nighttime dissolved oxygen sags when photosynthesis stops and respiration increases. This curve is, therefore, not a valid reference curve.

Approach 3: Using only Polyhaline Segments

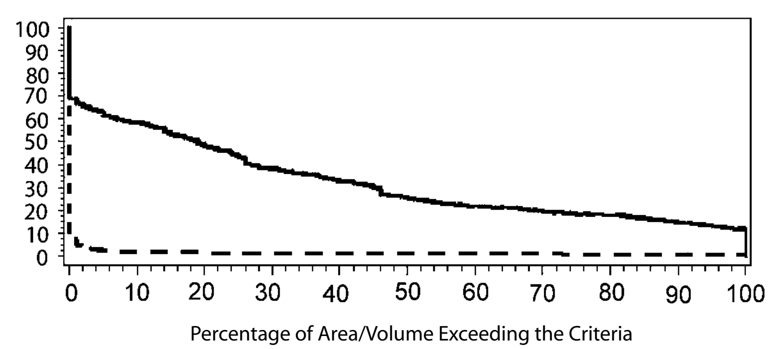

Figure H-5: Open water reference and validation curves for summer based on the best and worst ~20 percent of all segments approach.

In this exercise, the interpolated data sets from Chesapeake Bay Program segments western lower Chesapeake Bay (CB6PH), eastern lower Chesapeake Bay (CB7PH), mouth of the Chesapeake Bay (CB8PH), mouth of the York River (YRKPH), Mobjack Bay (MOBPH), mouth of the James River (JMSPH) and Elizabeth River (ELIPH) were processed as described above. The percent attainment for each month in spring and summer seasons was calculated for the open-water designated use cells in each polyhaline segment. These data were pooled and a cumulative frequency distribution curve generated for each season. The cumulative frequency distribution curve for summer is shown below (Figure H-6). In the ranking exercise above, the York (YRKPH) and Elizabeth (ELIPH) river segments fell in the lowest ranked group of 14 segments while the other polyhaline segments were scattered in the middle range in both spring and summer seasons (see tables H-5 and H-6, respectively).

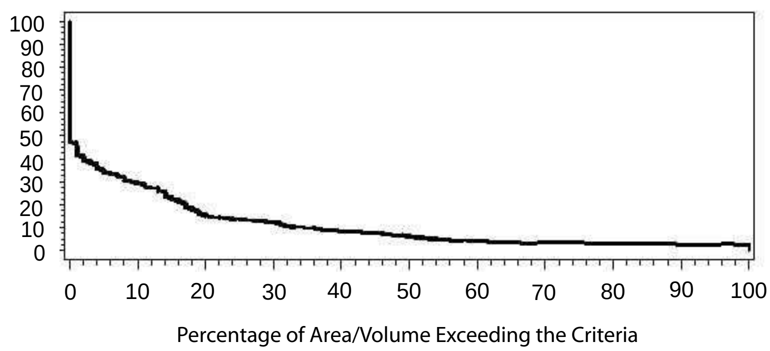

Figure H-6: Summer open water reference curve: polyhaline segments only approach.

With regard to this reference curve and all of the validation curves, it should be noted that summer temperature and salinity conditions, particularly in the Elizabeth River and occasionally elsewhere, can be such that oxygen saturation concentrations are below the open-water dissolved oxygen criterion concentration, and it is impossible to meet the criteria due to natural physical conditions. According to proposed implementation guidance, nonattainment is forgiven under those conditions. In this analysis, nonattainment for this reason was not taken into account and, depending on how often such conditions occurr, this and the other curves may be more accurate.

Approach 4: Reference and Validation Curves using Benthic Community Health

Benthic community health is the reference and validation site identifier for the deep-water reference curves. In the absence of other biologically-based indicators for open-water, open-water reference curves based on benthic health were explored for comparison with the other approaches. The logic was that Chesapeake Bay benthic organisms have a high tolerance for low dissolved oxygen concentrations, thus healthy benthos in open-water habitat would not necessarily indicate that the 30-day mean of 5 mg liter^{-1} was met. On the other hand, a stressed benthic community in an open-water designated use habitat could indicate that dissolved oxygen criteria in the habitat zone were *not* met.

Reference and validation locations (tables H-7 and H-8, respectively) were identified by methods described below (see section titled "Deep Water Criteria Reference Curves") and the frequency and extent of criterion attainment were processed as described below and similar to the other approaches for open-water. Figure H-7 shows the curves resulting from pooling all reference and validation segments in their respective groups. Figures H-8 and H-9 show the results further segregating segments by salinity zone.

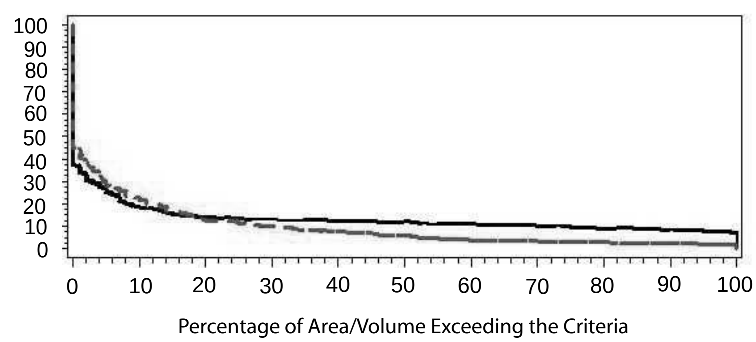

Figure H-7: Summer open-water dissolved oxygen criteria reference (hatched line) and validation (solid line) curves based on the benthic index of biotic integrity.

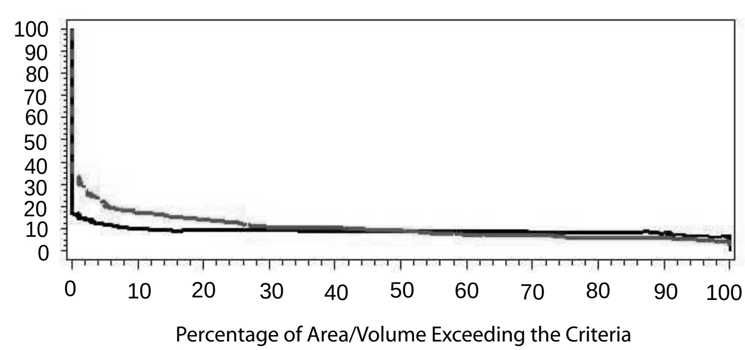

Figure H-8: Lower salinity summer open-water reference (hatched line) and validation (solid line) curves: benthic community health approach.

Table H-7. Reference locations based on benthic index =3 for summer open-water dissolved oxygen criteria reference curve (Approach 4).

CBP Segment	Years								
CB1TF	1985	1987	1990	1991	1992				
CB2OH	1986	1988							
CB3MH	1988	1993	1994						
CB6PH	1986	1990	1991	1992	1993				
CB7PH	1988	1990	1992	1993	1994				
CB8PH	1985	1986	1987	1989	1990	1991	1992	1993	1994
CHOMH1	1987								
CHOMH2	1986	1993	1994						
CHSMH	1986	1987							
CHSOH	1992								
ELKOH	1986	1992							
JMSMH	1985	1988	1990	1991	1992	1994			
JMSOH	1988								
JMSPH	1985	1986	1987	1988	1989	1990	1991	1992	1993 1994
JMSTF	1985	1986	1987	1988	1989	1990	1991	1992	1993 1994
NANMH	1986	1988							
PAXMH	1987	1988							
PAXOH	1986	1987							
PAXTF	1987	1994							
PMKTF	1991	1992	1993	1994					
POTOH	1986	1987	1988						
POTTF	1988								
RPPMH	1985	1986	1987	1988	1990	1992			
RPPOH	1988	1992							
SASOH	1992								
YRKMH	1985	1986	1987	1988	1990				

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Table H-8. Validation locations based on benthic index <3 for summer open-water dissolved oxygen criteria reference curve (Approach 4).

CBP Segment	Years						
BIGMH	1994						
CB1TF	1986	1989					
CB2OH	1987						
CB5MH	1986	1987	1989	1992			
CB6PH	1987	1988					
CB8PH	1988						
CHOMH1	1986	1988	1994				
CHOMH2	1988						
CHOOH	1986	1987	1988	1992	1994		
CHOTF	1991	1992					
CHSMH	1990						
EASMH	1994						
ELKOH	1987	1989	1990	1994			
HNGMH	1994						
JMSMH	1986	1987	1989	1993			
JMSOH	1985	1986	1987	1989	1991	1992	1994
LCHMH	1985	1994					
PATMH	1985	1987					
PAXOH	1994						
PAXTF	1989						
PMKTF	1985	1986	1987	1988	1990		
POTTF	1986						
RPPMH	1994						
RPPOH	1985	1986	1987	1990	1991	1993	1994
SASOH	1991						
SBEMH	1989	1990	1991	1992	1993		
YRKMH	1993	1994					

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

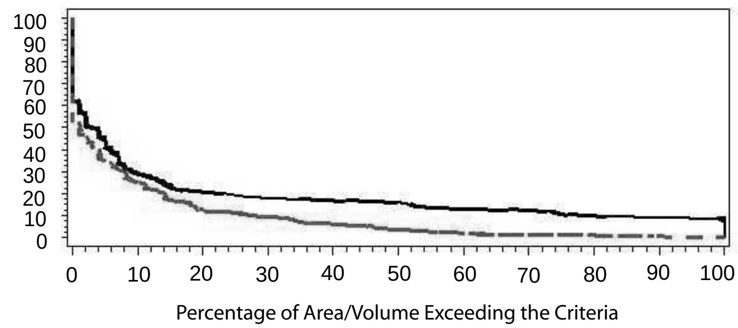

Figure H-9: Higher salinity summer open-water reference (hatched line) and validation (solid line) curves: benthic community health approach.

In the tidal-fresh and oligohaline group, the two curves based on benthic health are not very different from one another and both show little overall exceedance (Figure H-8). Nevertheless, the reference curve appears to have slightly more exceedance than the validation curve. By contrast, the two curves in the higher salinity group are differentiated from each other and the reference curve shows more attainment (i.e., less exceedance) than the validation curve (Figure H-8).

DEEP-WATER CRITERIA REFERENCE CURVES

Chesapeake Bay benthic communities are relatively tolerant of lower oxygen concentrations and able to compensate for periodic hypoxia. A dissolved oxygen concentration of 2 mg liter^{-1} is considered the lower threshold below which benthic communities start to become severely stressed. A healthy benthic community, therefore, could indicate that dissolved oxygen conditions are meeting the deep-water 30-day mean 3 mg liter^{-1} criterion, but would not necessarily indicate that the open-water 30-day mean 5 mg liter^{-1} criterion was met.

A baywide, long-term benthic monitoring program has been in place since before 1985. Samples are collected at fixed and random locations in the summer season, usually in August/September. A benthic index of biological integrity (benthic-IBI) has been developed to assess the status of benthic communities (Weisberg et al. 1997). The benthic IBI is based on a number of parameters, some depending on salinity zone. Abundance, biomass, species diversity and pollution sensitivity are some of the attributes on which the index is based. Each of the attributes is scored on a scale of 1 to 5 against a benchmark community. The benthic-IBI is the average of these scores and also ranges from 1 to 5.

Chesapeake Bay Program segments with benthic communities having an index of 3 were considered healthy. It was further assumed that if the community was not stressed, then the dissolved oxygen conditions were likely to have been adequate for the previous one to two months of the summer. Thus, in this analysis, if a healthy benthic sample identified a reference location and it was not otherwise disqualified by a sample indicating stress, then data for the whole season for that segment/designated use/season_year were included in the reference distribution. Each benthic sample is identified by latitude/longitude, segment and bottom depth. This analysis identified each site by year (assuming months June through September), segment and depth. It did not take into account a station's specific location within the segment.

The Chesapeake Bay benthic-IBI results from 1985 through 1994 were assessed as either 3 ('healthy'/'good') or <3 ('stressed'/'not good') and then associated with season_year (in this case summer), segment and designated use, based on season and sample depth. 'Healthy' locations were accumulated as the reference distribution. 'Stressed' locations were accumulated as the validation distribution. If both healthy and stressed sites occurred within the same segment, designated use and season_year, the location was excluded from both reference and validation distributions. A listing of the reference and validation locations identified in this way is attached (tables H-9 and H-10, respectively).

For this exercise, like those described earlier, a baywide master grid file was used in which each cell has a Chesapeake Bay Program segment assignment and fixed designated use assignment. In a few segments, both open-water and deep-water designations occur at the same depth. Because of time limitations,the location of healthy benthic samples was identified only by segment and depth, not by specific latitude/longitude, i.e., not by specific grid cell. (Note: Using GIS to locate the comparable grid cell precisely for each sample would improve the analysis greatly, but complicate the process.) Thus, when a 'healthy' benthic sample was found at a segment depth where both open-water and deep-water designated uses were defined, both were included in their respective list of reference or validation locations.

Monthly mean dissolved oxygen concentration data were interpolated basinwide for each summer month, June through September, from 1985 through 1994. For each interpolation, each cell's dissolved oxygen concentration was compared to the appropriate criteria concentration for the month and designated use, as indicated in the master grid, and the percent of cells passing/failing the criteria calculated for

Table H-9 Reference locations based on benthic index 3 for summer deep-water dissolved oxygen criteria reference curve.

CBP Segment	Years							
CB3MH	1992							
CB6PH	1985	1986	1987	1988	1991	1992	1993	1994
CB7PH	1985	1986	1991					
CHSMH	1992	1993						
PAXMH	1992							

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Table H-10. Validation locations based on benthic index <3 for summer deep-water dissolved oxygen criteria reference curve.

CBP Segment	Years							
CB3MH	1989	1990	1991	1993				
CB4MH	1986	1988	1989	1990	1991	1992	1993	1994
CB5MH	1989	1990	1991	1992	1993	1994		
CB6PH	1990							
CB7PH	1987							
CHSMH	1989							
EASMH	1986							
PATMH	1989	1990	1991	1992	1993	1994		
PAXMH	1987	1988	1989	1990	1993	1994		
POTMH	1985	1986	1987	1988	1990	1991	1993	1994
RPPMH	1985	1986	1988	1990	1991	1993	1994	
YRKPH	1988	1990	1991	1992	1993	1994		

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay/net.data

each segment/designated use. Using the respective lists of locations/dates, the data for the reference and validation locations were extracted, pooled and plotted (Figure H-10). This approach illustrates a substantial difference between the attainment curves of healthy and stressed sites. The curves would likely be different (i.e., likely reduce nonattainment in the reference curve and increasing nonattainment in the validation curve) if the location selection process were made more specific as described earlier.

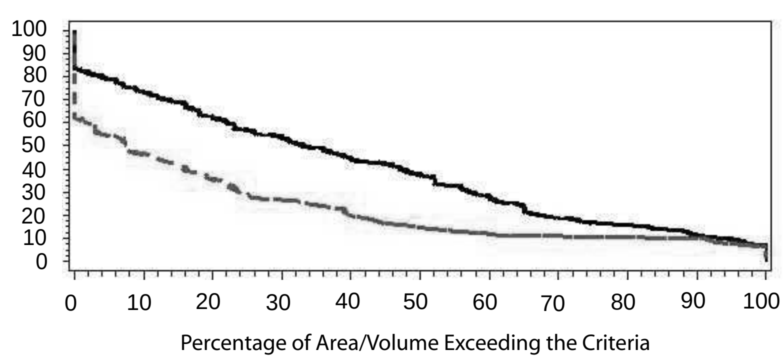

Figure H-10: Summer deep-water reference (hatched line) and validation (solid line) curves: benthic community healt approach.

WATER CLARITY CRITERIA REFERENCE CURVES

The water clarity criteria were developed to be protective of underwater bay grasses. The criteria apply to the months within the underwater bay grasses growing seasons and are specific to salinity zone. Reference areas in each salinity zone were selected by a team of resource managers and underwater bay grasses scientists based on an extensive review of the available distribution and abundance data record (over 20 years). Chesapeake Bay Program segments or partial segments were identified where underwater bay grasses distributions had increased significantly in recent years and had been present historically (Table H-11). Reference curves were developed for percent light-through-water (PLW), which is obtained by PLW=100exp(-K_dZ), where Z is the applicaton depth and K_d is a light factor, derived here from Secchi depth (K_d= 1.45/Secchi depth); see Chapter VI for more detail on implementation of the water clarity criteria. Application depth (Z) was based on photographic or other evidence of growth at that depth plus one-half the tide depth in the segment. The empirical evidence, with the one-half tide height added, provided a range of depths from which an appropriate depth was selected for inclusion in the PLW calculation. In some segments, full attainment was achieved at the deepest depth of the range. In those cases, Z was increased at 0.1 meter increments until exceedance was detected.

Table H-11. Chesapeake Bay Program segments or partial segments used to establish the water clarity criteria reference curves.

CBP Segment	Restoration Target Depth (meters)	Minimum Retoration Target Depth (meters)	Maximum Restoration Target Depth (meters)	Selected Restoration Target Depth (meters)
CB1TF	2.0	0.5	1.3	0.9
GUNOH	2.0	0.25	0.8	0.5
MATTF	2.0	0.25	0.8	0.5
PISTF	2.0	0.5	1.5	0.5
POTTF	2.0	0.5	1.4	0.6
POTOH	2.0	0.5	1.2	0.75
CB6PH	2.0	0.5	1.3	1.3
CB7PH	1.0	0.5	1.3	1.3
CHOMH1	2.0	0.5	1.3	1.25
EASMH	2.0	0.25	0.8	1.1
MOBPH	2.0	0.5	1.5	1.2
TANMH	2.0	0.5	1.3	0.9
YRKPH	2.0	0.25	1.0	1.2

Source: Chesapeake Bay Water Quality Monitoring Program database
http://www.chesapeakebay.net/data

Like the methods used to determine attainment of the dissolved oxygen criteria, ambient light data collected as part of the Chesapeake Bay water quality monitoring program were averaged monthly and interpolated (using the log transformation). PLW was calculated for each surface cell using the selected Z depth and the interpolated (back transformed) value for K_d. The PLW value for each cell was compared to the appropriate criterion for the segment's salinity zone and the cell area designated as failing or passing the criterion. The spatial extent of attainment, i.e., the percent area failing the criterion, was tallied for each month in the underwater bay grass growing season for all years 1985 through 1994, and also for more recent years through 2000. The monthly figures for percent attainment in each segment were pooled within salinity classification: tidal-fresh oligohaline and mesohaline polyhaline and the cumulative frequency distribution calculated and plotted. Note that segment CB7PH was not included in order to balance the relative contributions from the different salinity zones. The plots were very similar with and without segment CB7PH. The reference curves from the 1985-94 period (figures H-11 and H-12) are consistent with the curves developed for the other criteria. The reference curves for 1995-2000 are shown for comparison (figures H-13 and H-14).

It should be noted that the PLW minimum light requirement parameter was originally developed as a seasonal median measure. For assessing the criteria attainment, light availability is evaluated on a monthly basis, recognizing that available light could be less than the requirement level (i.e, 13 percent and 22 percent in lower and higher salinity waters, respectively) about half the time, and that exceedances will be more frequent than if the criteria were assessed on a seasonal basis. Because both criteria attainment and reference curves will be assessed in the same way, the additional exceedance should be accounted for by the reference curve. Figures H-15 and H-16 illustrate the lower and higher salinity water clarity reference curves, respectively, resulting from assessment on a seasonal median basis.

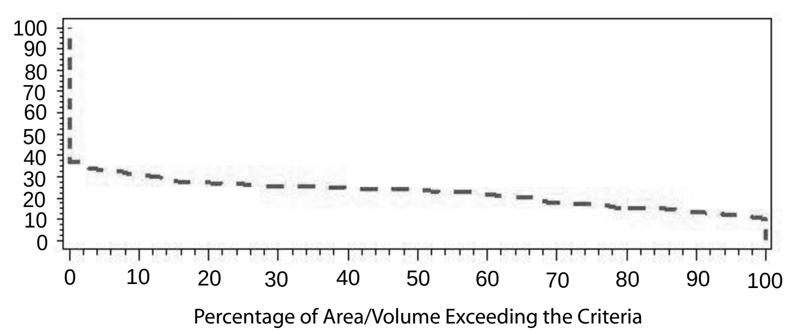

Figure H-11. Lower salinity water clarity reference curve: 1985–1994.

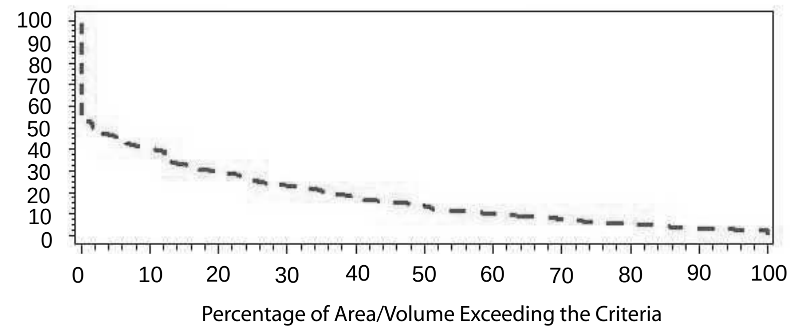

Figure H-12. Higher salinity water clarity reference curve: 1985–1994.

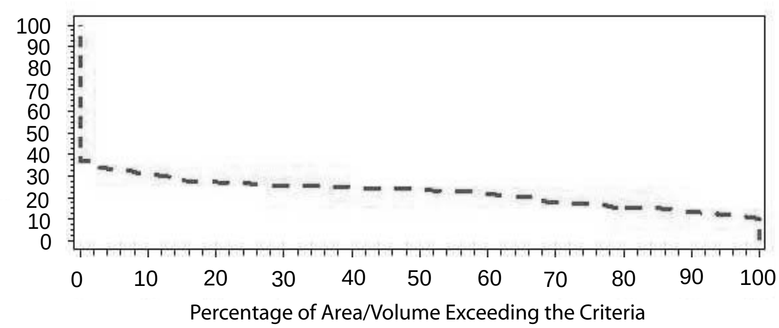

Figure H-13. Lower salinity water clarity reference curve: 1995–2000.

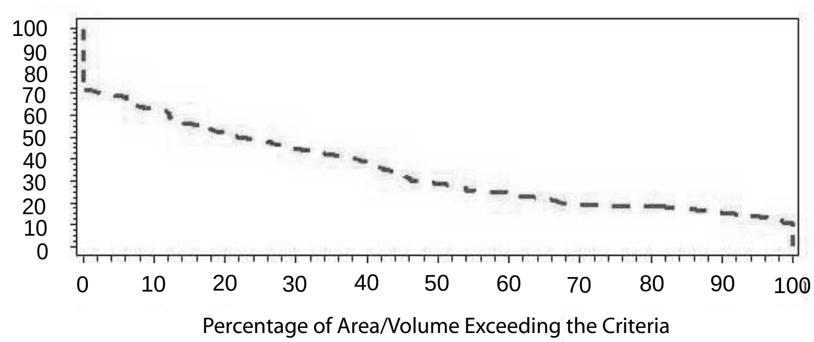

Figure H-14: Higher salinity water clarity reference curve: 1995–2000.

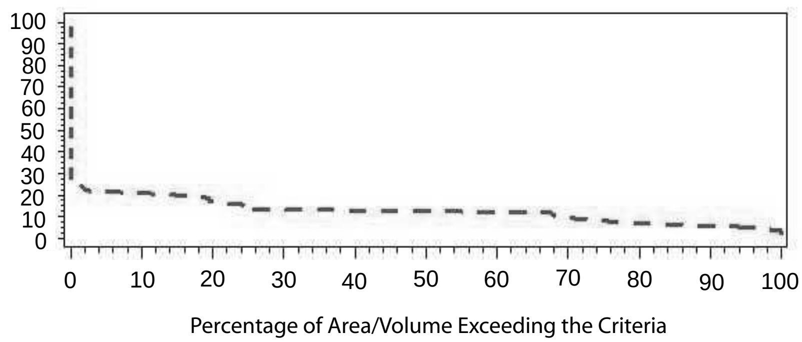

Figure H-15: Higher salinity water clarity reference curve: seasonal median

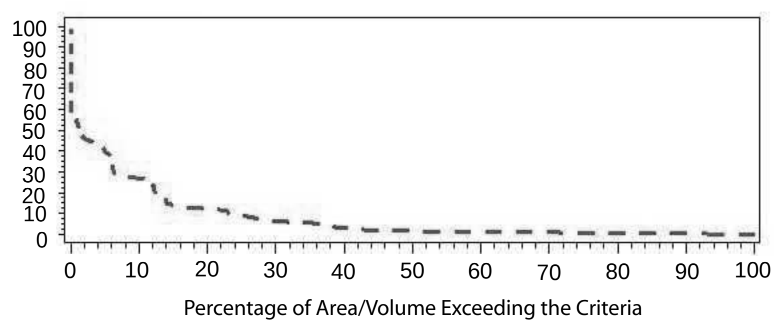

Figure H-16: Higher salinity water clarity reference curve: seasonal median.

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