chapter vii

Diagnostic Procedures for Natural Processes and Criteria Nonattainment

ADDRESSING NATURAL EXCEEDANCE OF THE CHESAPEAKE BAY CRITERIA

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

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

NATURAL EXCURSIONS OF LOW DISSOLVED OXYGEN CONDITIONS

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

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

Temperature and Salinity Effects

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

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

High or Low River Flow Events

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

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

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

Upwelling of Hypoxic Water

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

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

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

Natural Diel Fluctuations

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

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

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

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

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

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

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

Release of Organic Materials from Tidal Wetlands

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

Studies of South Carolina estuaries demonstrate that small tidal salt marsh creeks have significantly lower dissolved oxygen levels than large tidal creeks (Van Dolah et al., in press). Cai et al. (1999, 2000) determined that a significant export of high dissolved inorganic carbon from marshes was responsible for the low dissolved oxygen concentrations observed in five estuaries in South Carolina and Georgia. In a series of studies of the York River estuary, Raymond et al. (2000) showed that the system is supersaturated with respect to carbon dioxide pressure (pCO_2); conservative mixing diagrams demonstrated a mid-estuary source of dissolved organic carbon, which caused respiration to exceed production in the system. Further studies by Neubauer and Anderson (2003) showed that the export of dissolved inorganic carbon from tidal freshwater and saltwater marshes could account for approximately 47 percent of the excess dissolved inorganic carbon observed by Raymond et al. (2000) in the York River estuary.

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

NATURAL REDUCTIONS IN WATER CLARITY LEVELS

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

High Flow Events

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

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

Wind-Driven Events

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

Estuarine Turbidity Maximum Zones

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

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

Natural Water Color

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

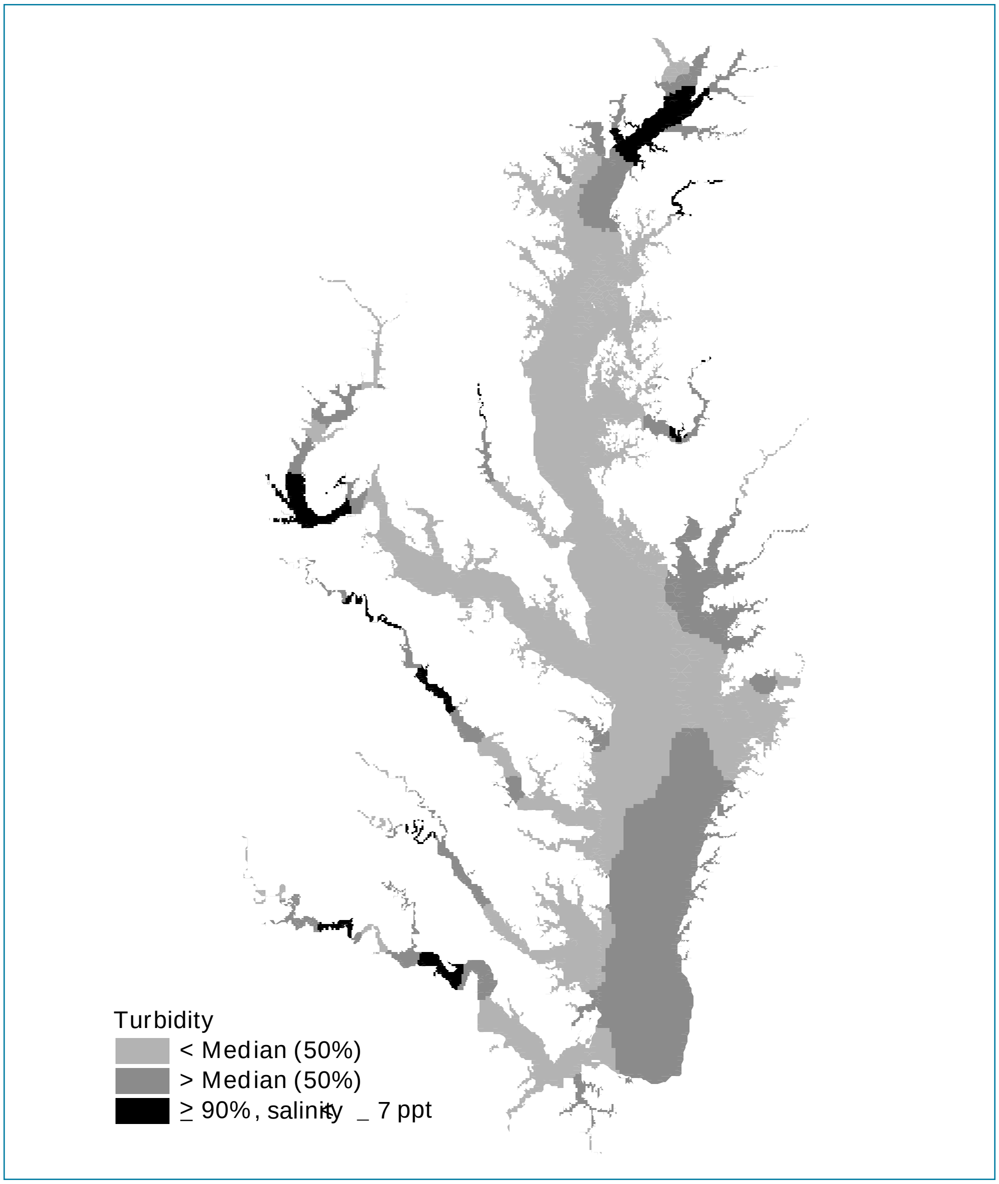

Figure VII-1. The estuarine turbidity maximum zone is generally found at the interface of fresh and salt water. It is illustrated here as the region within each river basin where mean concentration of total suspended solids is at or above the 90th percentile of concentrations measured within that basin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

NATURAL ELEVATED CHLOROPHYLL *A* CONCENTRATIONS

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

High Residence Time and Reduced Flushing Rates

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

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

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

Channel Morphology

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

Natural Algal Blooms Independent of Nutrient Conditions

Although anthropogenic nutrient loading is a principal factor in the overall primary productivity of the Chesapeake Bay system, its relationship to blooms of specific taxa is not well understood. Such blooms have been observed to occur in the absence of elevated nutrient conditions as a result of a complex set of physical, chemical and biological stimuli. Species composition data from the Chesapeake Bay Phytoplankton Monitoring Program should be consulted to determine if the observed algal bloom conditions are due principally to species that fall within this category. These phytoplankton monitoring data can be accessed through the Chesapeake Bay Program website at http://www.chesapeakebay.net/data.

DIAGNOSING CAUSES OF CRITERIA NONATTAINMENT

DISSOLVED OXYGEN CRITERIA

Percent Saturation

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

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

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

Chesapeake Bay Water Quality Model

As explained in Chapter VI, the Chesapeake Bay water quality model is linked to the Chesapeake Bay hydrodynamic model and uses complex nonlinear equations describing 26 state variables relevant to the simulation of dissolved oxygen, chlorophyll *a* and water clarity. Dissolved oxygen is simulated as the mass balance calculation of reaeration at the surface; respiration of algae, benthos and underwater bay grasses; photosynthesis of algae, benthic algae and underwater bay grasses; and the diagenesis, or decay of organics, by microbial processes in the water column and bottom sediments. This mass balance calculation is made for each model cell and for associated bottom sediment cells at each hourly time step. Estimates of dissolved oxygen from nutrient loads from the watershed and airshed are simulated in the tidal waters of the 35 major segments of the Chesapeake Bay and its tidal tributaries. This state-of-the-science modeling tool is available to management agencies and others to help diagnose the reasons behind nonattainment of the Chesapeake Bay dissolved oxygen criteria.

For the dissolved oxygen criteria, the daily output of dissolved oxygen concentration for 10 years (1985–1994) for the 13,000 cells provides a detailed estimate of the transport and transformation of nutrients and organic matter that ultimately consume oxygen in the waters of the Chesapeake Bay and its tidal tributaries. Influential aspects, such as the limiting nutrient, seasonal changes in dissolved oxygen, changes in the nutrient flux of bottom sediments that change with bottom-water oxygen levels, and other temporal and spatial aspects of dissolved oxygen concentrations and dynamics, can be diagnosed by evaluating water quality model output to gain insights into the reasons behind nonattainment of the dissolved oxygen criteria.

WATER CLARITY CRITERIA

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

Water-Column Light Attenuation Diagnostic Tool

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

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

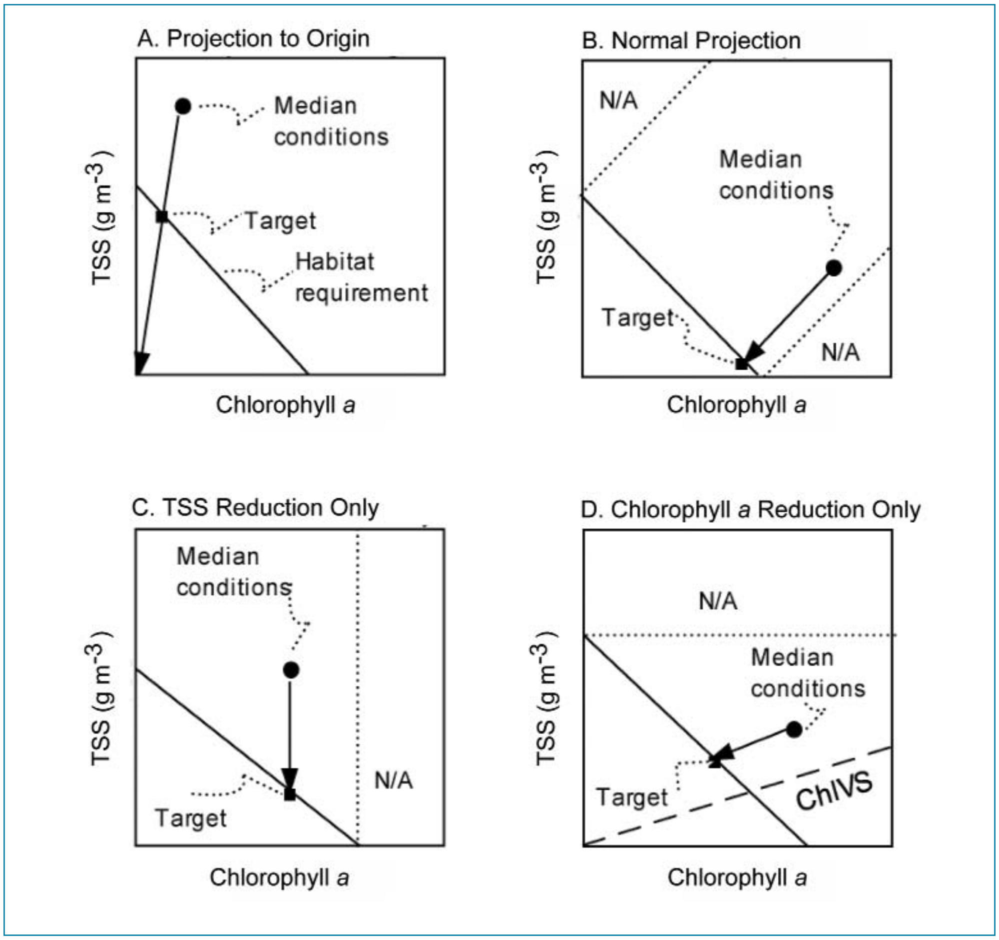

Figure VII-2. Illustration of management options for determining target concentrations of chlorophyll *a* and total suspended solids. It illustrates the use of the diagnostic tool to calculate target growing-season median concentrations of total suspended solids (TSS) and chlorophyll *a* for restoration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

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

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

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

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

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

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

Evaluating Management Options. Option 1 will likely be the most useful for generating target concentrations because it always results in the calculation of positive concentrations. Also, most efforts to control loadings involve a reduction of total runoff, which reduces both suspended solids and nutrients. Under certain conditions managers may choose to apply Option 3, when data plots indicate that attenuation is dominated by flood-borne or resuspended sediments (Figure VII-3a). Similarly, Option 4 may be useful when diagnostic plots indicate that light attenuation is dominated by algal blooms (Figure VII-3b). For details on how best to evaluate the four possible management options, refer to *Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat-Based Requirements and Restoration Targets: A Second Technical Synthesis* (Batiuk et al. 2000, pp. 47-49).

Leaf Surface Light Attenuation Diagnostic Tool

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

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

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

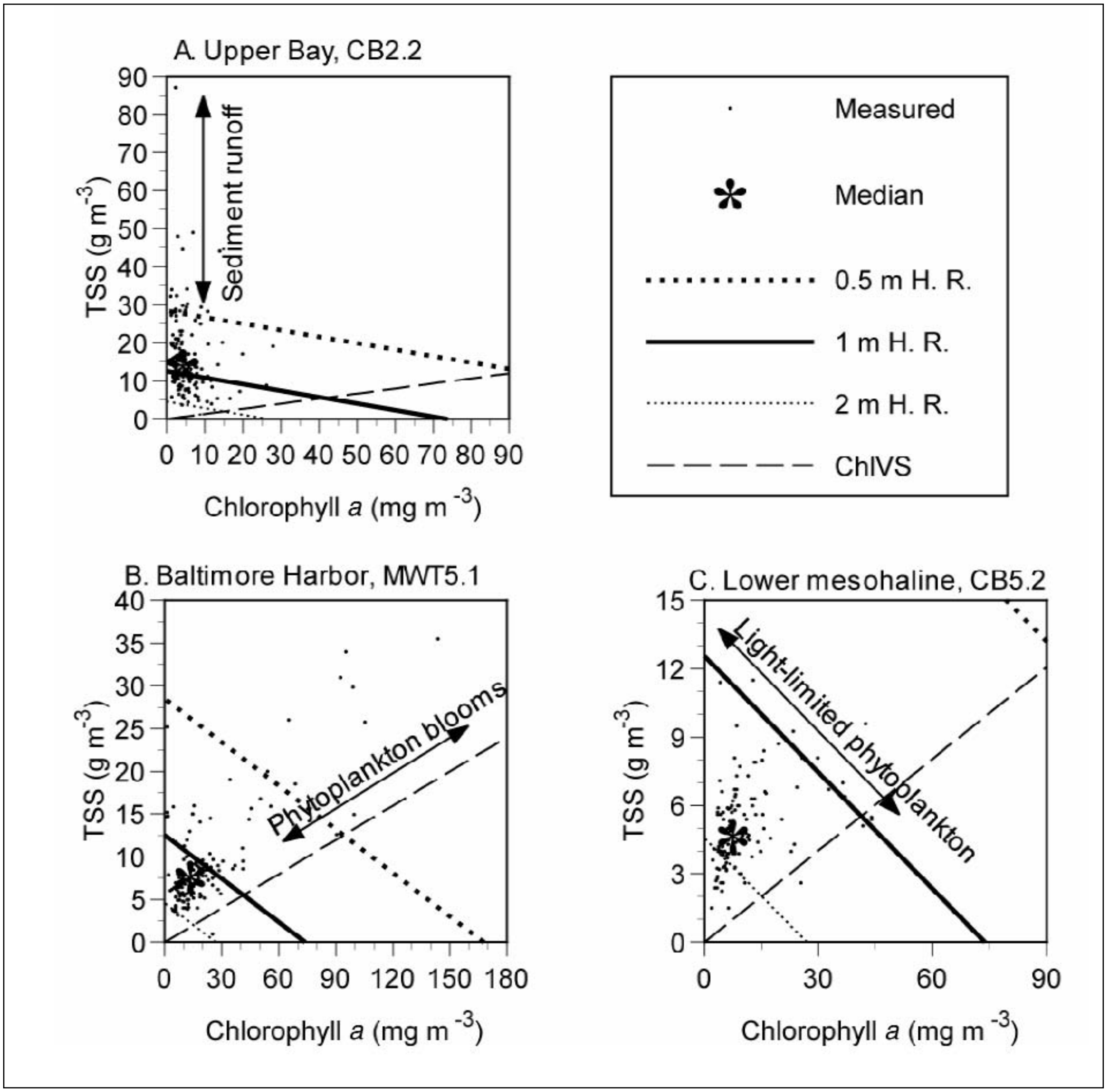

Figure VII-3. Application of the water column light attenuation diagnostic tool to two mainstem Chesapeake Bay stations and one tidal tributary station, which demonstrates three primary modes of variation in the data: (A) variation in diffuse attenuation coefficients is dominated by (flow-related) changes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

Sources: Batiuk et al. 2000; Gallegos 2001.

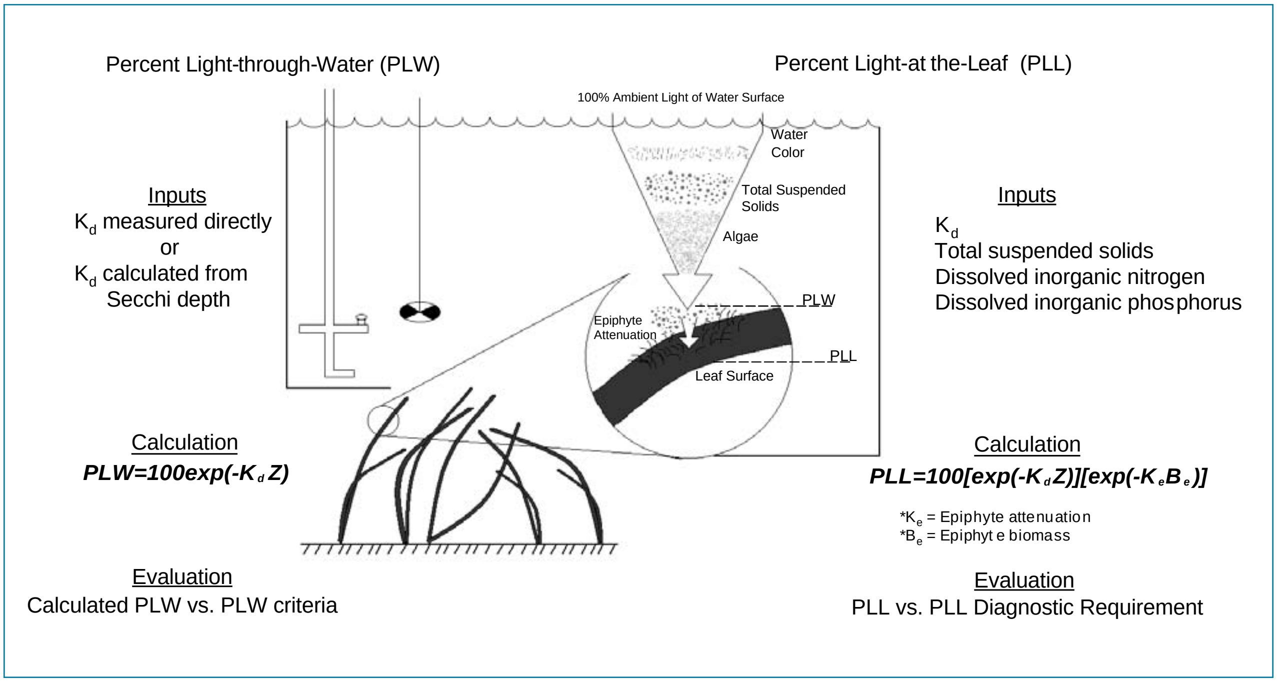

Figure VII-4. Illustration of percent light-at-the-leaf (PLL) and percent light-through-water (PLW) calculation comparisons for underwater bay grasses in the Chesapeake Bay.
Source: Batiuk et al. 2000

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

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

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

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

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

Source: Batiuk et al. 2000.

Chesapeake Bay Water Quality Model

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

CHLOROPHYLL *A* CRITERIA

Chesapeake Bay Water Quality Model

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

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